Drimeotus; Cholevidae- Cholevinae: *Catops, Choleva*), and the third is made up of typical troglobitic and troglophilic cave species, which rarely enter the MSS and then only in small numbers. The second community is composed of soil-dwellers that actively enter the MSS for food and humidity, or drift in with the flow of meteoric water. Some are the food supply for zoophagous species (for example Collembola and Diptera), while others, such as Chilopoda, Araneae, Pseudoscorpiones, or some Coleoptera, are predators, or parasites such as Hymenoptera. Depending on the temperature and humidity, MSS species move vertically upwards toward the soil horizon (mainly in spring and autumn) or downwards toward the deeper network of fissures within the bedrock (in winter and partially in summer). Characteristic MSS faunas present the same morphological (lack of eyes, loss of pigmentation, and absence of wings) and physiological adaptive features as eucavernicolous faunas.

The evolution of the MSS is cyclic, with three phases: (1) a juvenile stage, with colonization by soil- or cave-dwellers; (2) a mature stage, with an equilibrium community; and (3) an old stage, characterized by collapsed voids and disappearance of the fauna. The average time for one of these cycles ranges from ten thousand years to perhaps a hundred thousand years. In the Central Pyrenees, the most recent cycle involving the genesis of MSS in screes began 12000–13000 years ago, when forests replaced the post-Würm (post-Devensian) steppe cover (Juberthie, Dupré & Jalut, 1990).

It has been demonstrated that the route for cave colonization by the ancestors of cave-dwellers is not only via the karst surface and cave entrances, but also via the MSS. In volcanic areas, new lava tubes are colonized by existing troglobites from the volcanic MSS and older lava tubes.

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Works Cited

Howarth, F.G. 1981. Non-relictual terrestrial troglobites in the tropical Hawaiian caves. In *Proceedings of the 8th International Congress of Speleology, Bowling Green, Kentucky,* vol. 1, edited by B.F.Beck, Huntsville, Alabama: National Speleological Society: 539–41

Juberthie, C. 1983. Le milieu souterrain: étendue et composition. *Mémoires de Biospéologie,* 10:17–64

Juberthie, C. 2000. The diversity of the karstic and pseudokarstic hypogean habitats in the world. In *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F.Humphreys, Amsterdam and New York: Elsevier

Juberthie, C., Delay, B. & Bouillon, M. 1980. Extension du milieu souterrain en zone non calcaire: description d'un nouveau milieu et de son peuplement par les Coléoptères troglobies. *Mémoires de Biospéologie,* 7:19–52

Juberthie, C., Delay, B., Decu, V. & Racovitza, G. 1981. Premières données sur la faune des microespaces du milieu souterrain superficiel de Roumanie. *Travaux de l'Institut de Spéologie Emile Racovitza,* 20:103–11

Juberthie, C., Dupré, E. & Jalut, C. 1990. *Aphaenops rebereti,* espèce "endogée" du sous genre *Geaphaenops* présente dans le MSS de la vallée d'Ossau, daté 12000 B.P. *Mémoires de Biospéologie,* 17: 181–90

Oromí, P., Medina, A.L. & Tejedor, M.L. 1986. On the existence of a superficial underground compartment in the Canary Islands. *Barcelona,* vol. 2:147–51 In *Proceedings of the 9th International Congress of Speleology,* Ueno, S.I. 1981. A remarkable new trechine beetle found in a superficial subterranean habitat near Tokyo, Central Japan. *Journal of the Speleological Society of Japan,* 6:1–10

Further Reading

Juberthie, C. & Decu, V. 1994. Structure et diversité du domain souterrain; particularités des habitats et adaptations des espèces. In *Encyclopaedia Biospeologica,* vol. 1, edited by C.Juberthie & V.Decu, Moulis and Bucharest: Société de Biospéologie

INVERTEBRATES: MINOR GROUPS

While molluscs, annelids, arthropods, and vertebrates include groups that may be abundant in hypogean habitats, particularly caves, some groups of invertebrates are less numerous (at least in caves), less important, or simply less noticeable. This entry will cover all these in limited detail, and therefore includes a very heterogeneous assemblage of fauna, mostly non-segmented (Porifera and Ameria), but with some oligomerous or even chordate groups (Oligomeria and Chordonia, or Deuterostomia).

Sponges (Porifera or Spongiaria) are sessile, marine, or freshwater organisms. Their bodies are bag-shaped and consist of a system of channels and chambers that filter water to obtain suspended particulate food. Marine or freshwater sponges often occur at high densities in dark or cave-like habitats, and even in true caves, where there is no competition for space with algae. In shallow-marine caves some deep-sea or relict elements have been recorded, e.g. the tiny glass sponge (Hexactinellida) *Oopsacas minuta,* the uniquely carnivorous sponges *Asbestopluma* sp. (Cladorhizidae), and a number of different species of calcareous sponges (Calcarea) from the group Pharetronida (Vacelet, 1996). Some probably stygobiotic species of Demospongiae, such as *Cinachyra subterranea,* have been described from euha line anchialine caves in the Bahamas (Van Soest & Sass, 1981). Another anchialine species, *Higginsia ciccaresei,* has been described from anchialine cave waters in southern Italy (Pansini & Pesce, 1998). The only true stygobitic freshwater species (Demospongiae: Spongillidae), *Eunapius subterraneus,* was found in the Dinaric caves of western Croatia, near Ogulin, where at least two races occur (Sket & Velikonja, 1986).

Flatworms (Platyhelminthes: Turbellaria) are mostly leafshaped, soft-bodied, hermaphroditic organisms with a ciliate skin, which creep along the bed of water bodies, feeding as predators. They range in size from a few millimetres to several centimetres long. Small species of different taxonomic groups inhabit the marine mesopsammal zone, and different families or even higher taxa may be characteristic of particular ecological zones. Planarians (Tricladida), of which over 150 stygobiotic species are known, are the most common in caves. The genus *Phagocata* has a number of cave species in Europe, Asia, and North America; *Dendrocoelum* has even more species, but is apparently limited to Europe, while species of the family Kenkiidae, mainly *Shalloplana,* are limited to North America and eastern Asia (Gourbault, 1994). A terrestrial species has been found in a cave in Slovenia, but has not yet been described. Cave tricladids are mostly 10–20 mm long.

Another interesting turbellarian group is the epizoic or parasitic Temnocephalida. While only one species is known from surface waters in Europe, a series of species were found to live on decapod shrimps and one on amphipods in the caves of the southern European Dinarides. They were also found on cave shrimps of the Caucasus. All European species belong to the family Scutariellidae (e.g. genera *Scutariella*, *Troglocaridicola*, *Bubalocerus*), they are tiny, on average 1 mm long, and are characterized by two diversely shaped tentacles on the anterior end, and a simple or complex sucker on the posterior end.

Cnidaria (jellyfish, hydra, sea anemones, and corals) are primarily sessile aquatic organisms with bag-shaped bodies called polyps. During their life cycle they undergo a free-swimming stage called medusa. However, each of the stages may be absent (e.g. the medusa stage is absent in sea anemones and corals.) Around the apical mouth in the polyp, as well as along the outer rim of the medusa, are tentacles armed with stinging intracellular structures called cnidae or nematocysts, which are mainly used to capture and kill the animal prey. Specimens of the freshwater *Hydra* spp. are often swept into caves or interstitial waters. Only *Velkovrhia enigmatica* (Hydrozoa: Bougainvilliidae), a tiny colonial species from the Dinaric caves, is known to be stygobiotic (Matjašič & Sket, 1971). On the polyps are budding vestigial, permanently fixed, medusae (gonophores) with male or female gonads. The dark walls of marine caves are often adorned with different non-specialized cnidarians, in addition to sponges and bryozoans. A number of tiny species inhabit the marine mesopsammal habitat. *Halammohydra* spp. (Hydrozoa: Halammohydridae) are reduced hydroid medusae consisting of a long mouth tube (manubrium) with tentacles around the umbrella, which is reduced to a small sucker on the proximal end of the manubrium. *Stylocoronella* spp. (Scyphozoa: Lucernariida) are so-called polypo-medusae, i.e. polyps with their apical part developed into a medusoid shape and structure.

Ribbon worms (Nemertini or Nemertea) are creeping animals, sometimes superficially resembling very narrow turbellarians; at least this is the case for all hypogean species. Their main characteristic is an eversible proboscis, which may be armed with stylets and poison glands for capturing living prey. A number of species inhabit the marine mesopsammal zone, the most numerous of which are the virtually thread-like *Ototyphlonemertes* spp., which are on average 10 mm long. Cave species of the freshwater genus *Prostoma*, occurring in Western Europe and Dinarides (Pust, 1990) are much broader although not much longer.

Roundworms or nematodes (Nematoda) constitute an extremely rich and ecologically diverse group, but paradoxically with extreme morphological conservativism. Nearly all are more or less elongate spindle-shaped, covered by a smooth and thick cuticle. They have a variety of feeding habits: detritus, bacteria, plant rootlets, and live animals, and approximately half the known species are parasitic. While some parasitic forms are large, all free-living species are smaller (from a few microns up to 2 mm). Most inhabit soil or littoral or freshwater benthic sediments. A number of species have been found only in caves, although this does not assure their stygobiotic nature, since the group is very poorly studied. *Desmoscolex aquaedulcis* had been found in a cave in Slovenia (Stammer, 1935) and was considered to be a marine relict. A number of other species of this morphologically very aberrant (with a characteristic ring structure) and presumably marine interstitial genus were later found in soils in other parts of Europe.

Arrow-worms or chaetognaths (Chaetognatha) are primarily predatory marine planktonic animals. Their bodies are elongate spindle-shaped, mostly transparent, and usually less than 2 cm long. They possess two groups of grasping bristles beside the terminal mouth which can be used to capture prey, and two pairs of horizontal lateral fins and a caudal fin. They are hermaphroditic. The few benthic species are shorter, with an otherwise unchanged morphology. *Paraspadella anops*, from an euhaline anchihaline cave in the Bahamas (Bowman & Bieri, 1989), is eyeless and can be considered to be stygobiotic, while some probably less specialized species have been found in other marine caves.

Interstitial Fauna

A number of other invertebrate groups inhabit either solely interstitial waters or surface and interstitial waters, occurring only rarely in cave waters. Gnathostomulids (Gnathostomulida) (Ax, 1956) resemble very slender turbellarians. Most of these are less than 1 mm long. However, their epithelial cells are monociliated, and in the pharynx they have cuticular jaws. There are about 80 species which inhabit the marine mesopsammal and a number of them are limited to layers with very little or no oxygen.

Gastrotrichs (Gastrotricha) are usually microscopic in size, the body is skittle- or tap-shaped, and covered with a cuticle that is often scaly or spiny, with ventral ciliated belts and long cilia on the head. The worm-like body of the group Macrodasyoida has adhesive tubes scattered all over the body surface; the group is almost exclusively marine interstitial. The mainly skittle-shaped Chaetonotoidea also live in freshwater benthic habitats and possess only one pair of caudal adhesion tubes. The diversity of the marine mesopsammal gastrotrichs is therefore particularly high. Few of the species appear to be freshwater psammobionts.

Rotifers (Rotatoria=Rotifera) are usually microscopic in size; the body can be very diverse in shape, but with a characteristic ciliary organ called the corona. This is usually a circular or bicircular group of cilia in the mouth region, which beat in turn, driving particulate food to the mouth or propelling the organism when it is not attached. The rotifers are a predominantly freshwater benthic group, but a number of species live interstitially in the marine as well as in the freshwater mesopsammal zone. The few presumed cave species are most probably not completely restricted to such habitats.

Roundworms (Nematoda) have already been mentioned. Although few, if any, cave-limited species exist, the group is extremely richly represented and diverse in the marine mesopsammal zone. A comparatively large number of these species show very aberrant shapes. The number of species is high and if the habitat is supplied with large amounts of detritus, the biomass of the nematodes may be twice as high as the rest of the fauna.

Kinorhynch (Kinorhyncha) are skittle-shaped organisms < 1 mm in length. All are benthic marine taxa, and some are restricted to the marine mesopsammal zone. Their chitinous cuticle is divided into rings; the anterior region (introvert), which can be protruded or withdrawn, is protected by a neck region with brisde-shaped appendages called scalids.

Loricifera are an entirely marine mesopsammal group first described in 1983 (Kristensen, 1983), the first of these species being *Nanaloricus mysticus*. The organisms are barrel-shaped and strongly armoured, with a large anterior introvert, armed with rings of very diversely shaped scalids. The adults will adhere to sand grains, while the so-called Higgins larvae are mobile. At less than 0.5 mm in length, their bodies consist of more than 10000 cells.

Priapulida are sausage-shaped marine animals with a somewhat globular anterior introvert, densely set with short hooks; differently shaped vesicular appendages may be present on the posterior end. Some long species (up to 30 cm) burrow in benthic sediments, but a few species, about 1 mm long, live interstitially.

Kamptozoa (=Entoprocta) are goblet-shaped marine (rarely freshwater) animals up to 1 mm in length; tentacles on the upper end surround all of the openings, including the mouth and anus. Most are sessile and many are colonial, but some are solitary and mobile in spite of their polypoid appearance, for example *Loxosoma isolata,* which is a mesopsammobiont found in the northern Adriatic. Other mesopsammal species may also exist.

Water bears (Tardigrada) are tiny animals, mostly less than 1 mm long, with a stout cylindrical body with four pairs of unjointed legs carrying different numbers of claws. They are aquatic, although the water film in moss cushions can accommo date numerous individuals. Some species seem to be restricted to fresh interstitial waters, e.g. *Macrobiotus longipes* from the far north of Sweden. There is a rich assemblage of marine mesopsammal species which may be very aberrantly shaped; for example *Batillipes* spp., which have "fingers" with adhesive discs on their legs, or *Florarctus salvati* which have a broad membranaceous border around their trunks.

Sipunculans (Sipuncula) are sausage-shaped marine animals with a thick cuticle; the terminal mouth is surrounded by short tentacles and the terminal part of the body can invert itself up to the anus, which opens on the neck. Most species are several centimetres long. *Aspidosiphon exiguus* (which is about 3 mm long) seems to be restricted to marine or brackish interstitial waters in the Caribbean.

Bryozoans (Bryozoa=Ectoprocta) are sessile and colonial marine or freshwater animals. The body of a single specimen (zooid) consists of a box-like cystid, covered with cuticula which may even be calcified, and a polyp-like polypid which may retract into the cystid. The terminal mouth is surrounded by ciliated tentacles, and the anal opening is on its neck. Out of the few marine mesopsammal species, *Monobryozoon* spp. are the only solitary members of this group.

Lamp shells (Brachiopoda) are marine animals resembling bivalve molluscs, but with dorsal and ventral valves (rather than right and left valves). The organism itself has a paired and often spirally coiled holder of ciliated tentacles. Some species can be found attached to the walls of marine caves, while the tiny (1 mm or less) *Gwynia capsula* also occurs in the mesopsammal zone.

Sea cucumbers (Echinodermata: Holothurioidea) are mostly sausage-shaped marine animals related to starfish and sea urchins, a feature which is reflected in their internal structure. The mouth and anal openings are at opposite ends; the former is surrounded by tentacles. They can reach 45 cm in length, and the few interstitial species are only 2–5 mm long. *Leptosynapta minuta* (5 mm in size) has a distribution ranging from the western Mediterranean to the North Sea.

Sea squirts or ascidians (Tunicata=Urochordata: Ascidia) are sessile, solitary, or colonial marine animals, ranging from a few millimetres to several centimetres in length. Their bagshaped bodies are covered by a thick layer of tunicine (similar to cellulose in plants), with two openings or siphons; at the oral siphon, the water enters a wide respiratory and filtering basket, which is the modified fore-gut. The tadpole-shaped larva has a tubular nerve cord, and a notochord in its tail, but the latter later degenerates. Some millimetre-long species of sea squirt inhabit the interstitial waters of very coarse sands.

BORIS SKET

Works Cited

Ax, P. 1956. Die Gnathostomulida, eine raetselhafte Wurmgruppe aus dem Meeressand. *Abhandlungen der Mathematischnaturwissenschaftlichen Klasse, Akademie der Wissenschaften und der Litteratur in Mainz,* 8:1–32

Bowman, T.E. & Bieri, R. 1989. *Paraspadella anops,* new species, from Sagittarius Cave Grand Bahama Island, the second troglobitic chaetognath. *Proceedings of the Biological Society of Washington,* 102(3):586–89

Gourbault, N. 1994. Turbellaria, Tricladida. In *Encyclopaedia Biospeologica,* vol. 1, edited by C.Juberthie & V.Decu, Moulis and Bucharest: Société de Biospéologie

Kristensen, R.M. 1983. Loricifera, a new phylum with Aschelminthes characters from the meiobenthos. *Zeitschrift fuer zoologische Sytematik und Evolutionsforschung,* 21:163–80

Matjašič J. & Sket, B. 1971. Jamski hidroid s slovenskega krasa (A cave hydroid from Slovene karst). *Biološki Vestnik,* 19:139–45

Pansini, M. & Pesce, G.L. 1998. *Higginsia ciccaresei* sp. nov. (Porifera: Demospongiae) from a marine cave on the Apulian coast (Mediterranean sea). *Journal of the Marine Biological Association of the UK,* 78:1083–91

Pust, J. 1990. Untersuchungen zur Systematik Morphologie und Oekologie der in westphalischen Hoehlen vorkommenden aquatischen Hoehletiere. *Abhandlungen aus dem Westphalischen Museum fuer Naturkunde,* 52(4):1–188

Sket, B. & Velikonja, M. 1986. Troglobitic freshwater sponges (Porifera, Spongillidae) found in Yugoslavia. *Stygologia,* 2(3): 254–66

Stammer, H.-J. 1935. *Desmoscolex aquaedulcis* n.sp., der erste suesswasserbewohnende Desmoscolecide aus einer slowenischen Hoehle (Nemat.). *Zoologischer Anzeiger,* 109:311–18

Vacelet, J. 1996. Deep-sea sponges in a Mediterranean cave. In *Deep-sea and Extreme Shallow-water Habitats: Affinities and Adaptations,* edited by F.Uiblein, J.Ott & M.Stachowitsch, Vienna: Österreichische Akademie der Wissenschaften

Van Soest, R.W.M. & Sass, D.B. 1981. Marine sponges from an inland cave on San Salvador Island, Bahamas. *Bijdragen tot de Dierkunde,* 51(2):332–44

Further Reading

Botosaneanu, L. (editor) 1986. *Stygofauna Mundi, A Faunistic, Distributional, and Ecological Synthesis of the World Fauna Inhabiting Subterranean Waters (Including the Marine Interstitial),* Leiden: Brill

Higgins, R.P. & Kristensen, R.M. 1986. New Loricifera from southeastern United States coastal waters. *Smithsonian Contributions to Zoology,* 438:1–70

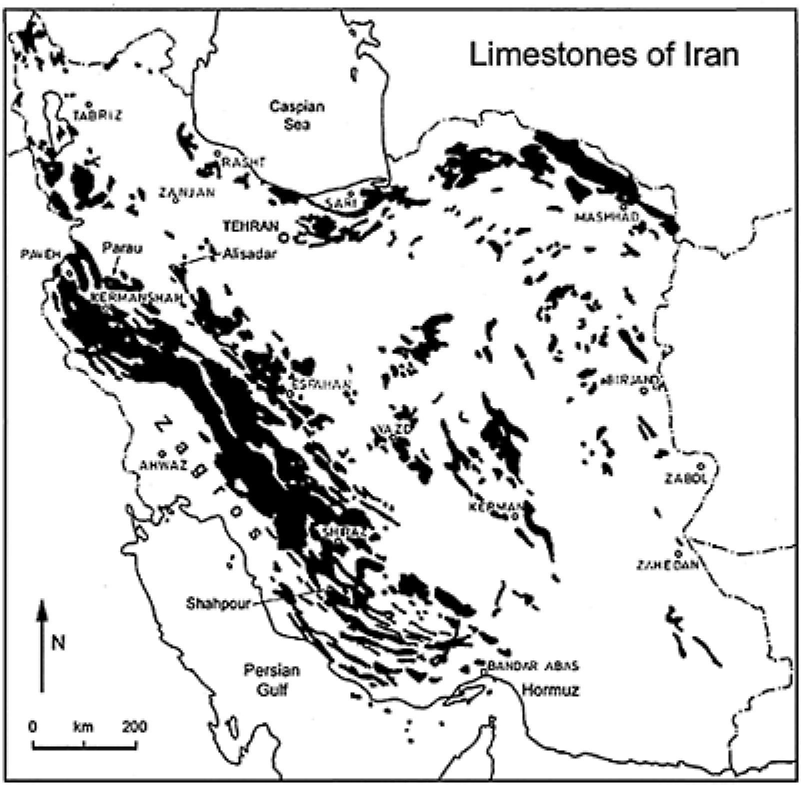
Juberthie, C. & Decu, V. (editors) 1994. *Encyclopaedia Biospeologica,* 2 vols, Moulis and Bucharest: Société de Biospéologie

IRAN

Iran is geologically a part of the Alpine—Himalayan orogenic belt. Five major structural zones can be distinguished in Iran (Stocklin, 1968): Zagros Range; Sanandaj-Sirjan Range; Central Iran; East and Southeast Iran; and the Alborz and Kopet-Dagh Ranges. The Zagros is sub-divided into the three structural zones of Khozestan Plain, the Simply Folded Zone, and the Thrust Zone. The Zagros folded zone, with a width ranging from 150 to 250 km, is a sequence of late Precambrian to Pliocene shelf sediments about 12 km thick, mainly consisting of limestone, marl, gypsum, sandstone, and conglomerate. The Zagros Thrust Zone is composed of crushed limestone, radiolarite, and ultrabasic and metamorphic rocks. The Sanandaj-Sirjan Range consists mainly of granite, diorite, and metamorphic rocks. Central Iran is composed of Precambrian metamorphic basement overlain by shelf sediments and a chain of volcanoes. The Alborz Range consists of volcanics, sandstone, shale, siltstone, and limestone, and the Kopet Dagh Range consists of Mesozoic-Tertiary limestone, shale, and sandstone.

Karstic carbonate formations cover about 185000 km^2 (which is 11% of Iran's land area) of which 55% is in the Zagros, 24% in Central Iran, 15% in the Alborz, and 5% in East and Southeast Iran (Figure 1). Most of the carbonate rocks are Cretaceous and Tertiary in age. The most important karst features in the Zagros Range are karren, grikes, springs, and to a lesser extent, caves and dolines. The main source of recharge is direct rainfall and snowmelt. Most of the springs are permanent (see photo of Margoon Spring in Springs entry) and high percentages of the spring waters are baseflow. Karst water in the Zagros Range is usually of good quality, and it is one of the most important sources of drinking water in the area. The Zagros fold zone is characterized by a repetition of long and regular anticlinal mountains. Most of the karst formations are sandwiched between two impermeable formations, so that they form independent highland aquifers. The general direction of groundwater flow is mostly parallel to the strike, towards cross-cutting gorges that determine local base levels.

Though there is an ever-increasing interest in cave research in Iran, only a few attempts have been made to establish a complete published inventory of the caves that have been explored so far. Most of the cave studies concentrate merely on visiting, photography, and/or mapping the explored caves. Sometimes the complete information about a cave has not been published or it cannot easily be found. The speleological committee of Iran has started to collect cave data, but this has not yet been published. Marefat (1994) reported 258 caves, but the report does not cover all the caves in Iran, and has only partial informa- tion about location, altitude, survey, and length of some of the caves; neither geological settings nor hydrologic features are reported.



Iran: Figure 1. Distribution map of carbonate karst formation in Iran (Raeisi & Kowsar, 1997).

In spite of the large extent of karst in Iran, the number and lengths of caves are less than might be expected. There are many highland karst aquifers without any cave systems yet known, while big springs emerge at their bases of erosion. Several levels of caves are expected in the karst mountains of Iran, as a result of the rapid rates of uplifting and local valley incision. There are two main reasons for the small number of known caves. First, most of the karst areas are high mountains with steep slopes, so that many cave entrances have been filled in by talus or transported sediments or have been blocked by entrance breakdown in the high-risk earthquake regions of Iran. Second, many springs with high discharges are of the vauclusian type, with no explorable dry cave systems. Conduit systems of these springs, which have developed at higher levels in the past, cannot presently be seen on the surface. The short length of caves is also to be expected as the rapid rates of uplift and incision reduce the time for cave development at any one level. Water in the cave conduits leaks to lower levels and prevents further cave development. Also, recharge is mainly diffuse flow in the majority of the karst sites, so cave development is only initiated where branches of diffuse flow join each other beneath the surface.

The deepest cave in Iran is Ghar Parau, 751 m deep and 1365 m long, located just north of Kermanshah (Judson, 1973). It is developed in Cretaceous limestone below a sinkhole entrance at an elevation of 3050 m. It has 26 shafts along a small steeply descending canyon passage that has not been followed beyond a sumped section in a small local syncline. Most of the deep caves in Iran are located in Kermanshah province.

Ghar Alisadar is developed in Jurassic limestone which overlies schist and sandstone in the Sanandaj-Sirjan Zone (Laumanns *et al.*, 2001). It is the longest (11440 m) and most visited cave in Iran (400000 visitors per year). More than 4 km of the cave passages lie at the water table, forming lakes of clear water up

Iran: Figure 2. Calcite rimstone deposits from an older higher lake level form this mushroom island in the cave of Ghar Sarab. (Photo by Simon Brooks)

to 15 m deep, and the public underground boat tour is 2010 m long. Calcite and aragonite deposits are found in ledges a few metres above the present lake surface in most parts of the cave, implying that water levels in the cave were at fixed elevations for long periods in the past. Oscillation of the water table due to climate changes created up to nine of these ledges, at different elevations. The cave most likely developed under the water table by the influence of ascending volcanic CO_2. The average temperature, electrical conductivity, pH, and dissolved oxygen are 12°C, 270 μmhos cm^{-1}, 8.3, and 7.4 mg 1^{-1}

respectively. Ghar Sarab, 7 km south of Ghar Alisadr, also contains spectacular rimstone deposits (Figure 2) and has been subject to recent exploration (Brooks, 2002).

The Katelahkor cave, 2500 m long, lies 155 km south of Zanjan, and is also open as a tourist cave. It is an anastomatic multilevel cave, formed in Tertiary limestone. Ghori-Ghaleh, located near Paveh, is formed at the contact of the Jurassic limestone and conglomerate. It is a cave with a single passage about 1205 m long and mostly 2–3 m high. An underground stream flows through the whole length of the cave and emerges from the cave entrance with discharges that vary from 23 to 33001s^{-1}. This cave is under study for making it accessible as a tourist attraction. Shapour Cave, 80 km south of Shiraz, is an archeological and touristic attraction. It is a single anastomatic tiered cave 1229 m long. At the initial stage of subaerial exposure of the karstic Tertiary Asmari limestone, the Shapour River started entrenching a valley, and leakage from the river through joint and bedding plane fissures enlarged the cave (Raeisi & Kowsar, 1997). Remarkable salt caves in the Hormoz region have recently been surveyed by Czech speleologists, amongst them the 5010 m long Tri Nahaci Cave (Bosák *et al.*, 1999).

EZZAT RAEISI

Works Cited

Bosák, P., Bruthans, J., Filippi, M., Svoboda, T. & Smid, J. 1999. Karst and caves in salt diapirs, SE Zagros Mts. (Iran). *Acta Carsologica,* 28(2):41–75

Brooks, S. 2002. Iran 2001. *International Caver 2001* 82–83.

Judson, D.M. 1973. The discovery and exploration of Ghar Parau, Iran. *Transactions of the Cave Research Group of Great Britain,* 15(1):19–26

Laumanns, M., Brooks, S., Dorsten, I., Kaufmann, G., Lopez-Correa, M. & Koppen, B. 2001. *Speleological Project Ghar Alisadr (Hamadan/Iran),* Berlin: Speläoclub Berlin (Berliner Höhlenkundliche Berichte, 4)

Marefat, A. 1994. *Kuhha va Gahrhai Iran* [Mountains and Caves of Iran], Tehran: Goli (in Farsi)

Raeisi, E. & Kowsar, N. 1997. Development of Shahpour Cave, southern Iran. *Cave and Karst Science,* 24(1), 27–34

Stocklin, J. 1968. Structural history and tectonics of Iran: A review. *American Association of Petroleum Geologists Bulletin*, 52(7):1229–58

Further Reading

Afrasibian, A. 1998. *Field Trip Guide: 2nd International Symposium on Karst Water Resources,* Tehran: Iran Karst Research Center, Ministry of Energy

Judson, D. 1973. *Ghar Parau,* London: Cassell and New York: Macmillan

Waltham, A.C. & Ede, D.P. 1973. The karst of Kuh-e-Parau, Iran. *Transactions of the Cave Research Group of Great Britain,* 15:27–40

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JEITA CAVE, LEBANON

Jeita Cave with its subterranean river is the most famous cave in Lebanon and has a history of exploration stretching back to 1836. The natural entrance of the cave is 18 km north of Beirut. The cave's main passage drains west along the northern side of the Nahr el Kelb (the Dog River). In 1971, a tunnel was excavated at Daraya to make a second access to the cave, at its upstream end (see map).

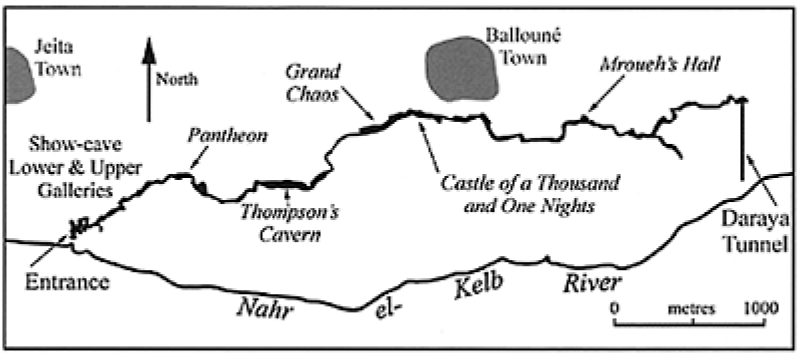
The first written document about the Jeita springs and their probable underground source is a letter sent by Father Fromage in 1736 that includes a remarkable hydrogeological description of the springs and mentions that there is a big cave with a huge lake inside the rocks. The first documented speleological activity was in 1836, when William Thomson progressed some 50 m until he reached an underground lake. Explorations between 1856 and 1902 reached 1000 m into the cave. Their main objective was assessment of the hydraulic potential of the underground river—an important water source for the city of Beirut. Between 1926 and 1927 two expeditions progressed a further 730 m and the cave was not extended further until the start of the Lebanese period of exploration in 1946 when a team reached 1950 m from the entrance. Further expeditions followed, and by 1958 they had reached the end of the cave and discovered several side galleries, giving about 9 km of total development (see map). Only minor discoveries have been made since.

Jeita Cave is completely formed in the Jurassic Kesrouane Formation, which is 1000 m thick. Fossiliferous micritic limestone makes up this formation but the lower part features later dolomitization, and most of Jeita Cave is formed within these dolostones.

Orogenesis in the Upper Jurassic led to a period of emergence and aerial exposure, when carbonate was fractured and karstified before burial in the Cretaceous. This early karstification was reactivated in the Neogene and subsequently when the present topography evolved. The western mountain chain is characterized by steep flanks and a maximum altitude of 3083 m, between the Mediterranean Sea and the Bekaa valley. This chain is cut by deep east-west valleys, one of which is Nahr el Kelb where the Jeita Cave is located. The steep topography together with an annual precipitation exceeding 1200 mm, mostly falling within six months of the year, have contributed in intensifying the recent karstification.

The major underground river in Jeita Cave has an average discharge of 2.3 $m^3 s^{-1}$ and is used to supply about one million people with potable water. The cave plays the role of a lateral collector in the deeply karstified Jurassic aquifer. Many vertical caves lie in the limestone mass above Jeita Cave, but no connection has yet been made. The cave system drains a large area, extending beyond the hydrological basin of the Nahr el Kelb. Dye tracing has proven flow from the southern adjacent hydrological basin, from caves that are 18 km away, including Fouar Dara and Qattine Azar. The cave's outlet is on the stratigraphic contact with less permeable younger formations (Upper Jurassic volcanic rocks, Lower Cretaceous sand) forming a hydrogeological boundary that forced the underground river to rise to the surface. This barrier is also responsible for the large chambers (with a maximum height exceeding 60 m) in the cave.

The general plan of the cave is a sinuous line with the river flowing westward (see map). At the end of the cave, two branches from the inland extremity of the cave, each end with a siphon. The total slope gradient between the terminal siphon and the cave entrance is around 1/100. This illustrates the general flat passages characterizing the cave and its subterranean river, but small cascades and rapids break this monotonous topography. Jeita Cave begins with a big hall within a zone of large-scale meanders. The main passages of the cave then become more or less straight and two more large halls follow. There, the overall dimension becomes narrower through some rapids. Then the cave turns into a tunnel-shaped gallery for hundreds of metres. It becomes even larger with the Thompson's Cavern (250 m long and 60 m wide), before the Grand Chaos, a chamber over 500 m long where large collapsed blocks form the floor. This continues into the Castle of a Thousand and One Nights, a



Jeita Cave, Lebanon: Outline map (surveyed by the Spéléo-Club du Liban)

well-decorated hall. A series of lakes connected by small cascades lead to Mroueh's Hall (200 m long and 50m wide) also featuring large collapsed blocks. This is followed by a series of rapids to a broad junction floored with gravel. The northern branch is the longer and contains a beautiful sandy section before a series of lakes ends with a big terminal sump.

In January 1969, the Upper Gallery was opened to the public and became a major attraction of Lebanese tourism at that time. This new section is the most beautiful part of the cave with huge and delicate speleothems. Following the beginning of the 1970s, the Lebanese strife started, and in the early 1970s the show cave was closed and not reopened until 1995, five years after the end of the Lebanese war. The Lower Gallery can be visited in electric boats for a distance of 500 m. The 800 m long Upper Gallery lies more than 60 m above this lake and here tourists are left to wander on an elegantly designed path and to enjoy a wide variety of large speleothems. In some places, one can see down to the waters of the Lower Gallery. Conservation measures taken by the cave management include closing for one month per year, non-continuous and non-heating lighting, and electric boats. Since its re-opening, the show cave has received around 280000 visitors per year.

FADI NADER

Further Reading

Bulletin of the Spéléo-Club du Liban Al Ouat'Ouate, 5 (1990) Special issue to commemorate the 50th anniversary of the first Lebanese expedition

http://www.jeitagrotto.com/

JOURNALS ON CAVES

By the end of the 20th century, there were at least 2000 caving journals worldwide, but just 120 years earlier none existed. Their history is therefore far shorter than that of caving books (see related entry) and began only at the end of the 19th century, when the first caving clubs were formed in Austria, Italy, and France. Until that time, papers on caves were scattered in nonspecific periodical publications.

The best-known early journal, completely devoted to speleology, was the French *Spelunca*, the bulletin of the Société de Spéléologie printed since 1895. This was followed a year later by *Mémoires de la Société de Spéléologie* (see Figure), which started in 1896. Both still exist, though they have had some gaps and/ or changes in format; moreover, *Mémoires* changed its title twice, becoming *Annales de Spéléologie* (1946–75), then *Spelunca,* and finally *Karstologia* (1983). These two bulletins, the only ones started in the 19th century, dealt with all the fields of speleology and, in their first issues, hosted several papers by the French caver Édouard Alfred Martel, commonly regarded as the founder of modern speleology (see Speleologists).

In the first decades of the 20th century, only a few other journals appeared, all printed in Europe: in Italy *Rivista Italiana di Speleologia* (1903–04), *Mondo Sotterraneo* (1904), *Le Grotte d'Italia* (1927), and *Memorie dell'Istituto Italiano di Speleologia* (1931); in Hungary *Barlangkutatás* (1913–44); in Austria *Spelälogisches Jahrbuch* (1920–36). The *Proceedings of the University of Bristol Spelaeological Society* started in 1920 and is still being produced. Six years later, *Mitteilungen über Höhlen und karstforschung* (1926–40) started in Germany.

In 1940, the first two caving journals were printed outside Europe: *NSS (National Speleological Society) News* and the *Bulletin of the National Speleological Society,* which took this name from the second issue (1941), the first being named *Bulletin of the*

Speleological Society of the District of Columbia. The *NSS Bulletin* later became the *Journal of Cave and Karst Studies*.

In the next two decades, tens of new caving journals appeared each year so that, in the early 1960s, over 500 caving bulletins were printed in five continents. Some of them had a tremendous impact on the development of speleology in their own countries, but many disappeared after a relatively short time. Among the most famous of such journals were: *Ceskoslovenski Kras* (Czechoslovakia, 1948–90), *Rassegna Speleologica Italiana* (Italy, 1948– *73), Speleon* (Spain, 1950–83), *Travaux de L'Institute de Spéléologie Émile Racovitza* (Romania, 1963–97), and *Serie Espeleologica* (Cuba, 1967–74).

The exact number of current caving journals is not known, due to their fast dynamics and normally short lifetime, but it

Journals on Caves: Addresses of the UIS Documentation Centres

Argentina
Library "Dr Emilio Maury", Grupo Espeleológico Argentino, Heredia 426 (C1427CNF) Buenos Aires. Email gea@mail.retina.ar

Austria
Speläologisches Dokumentationszentrum des Institutes für Höhlenforschung, c/o Naturhistorisches Museum, Burgring 7, A–1014 Wien

Belgium
Centre Documentation, Union Belge de Spéléologie UBS/SSW, Maison de la spéléologie, rue Belvaux 93. B–4030. Email caving.service@speleo.be

France
Documentation Fédération Française de Spéléologie, 28 rue Delandine, F-69002 Lyon. Email FFS.biblio@wanadoo.fr

Germany
Bibliothek des Verbandes der Deutschen Höhlen-und Karstforscher Dechenhöhle 5, D-5 8644 Iserlohn. Email dechenhoehle@t-oniine.de

Italy
Centro documentazione speleologica, Isituto Italiano di speleologia, c/o Università, Via Zamboni 67, I–40127 Bologna. Email ssibib@geomin.unibo.it

Japan

Library of "Kras I speleologia", Laboratory of Research and Documentation of Karst Environment, University of Silesia, ul. Bedzinska 60, 41–200 Sosnowiec. Email atyc@us.edu.pl

Romania
Institut de spéleologie, c/o V Decu, 11 rue Frumoasa, R–78114 Bucharest 12. Email alex.petrulescu@dataline.ro

Slovenia
Institut za Raziskovanje Krasa ZRC SAZU, Titov trg 2, 6230 Postojna. Email kranjc@zrc-sazu.si

Spain
Centre de documentació espeleologica, Ap.C.32110, E–08080 Barcelona 6

Switzerland
Centre de Documentation UIS, c/o Bibliothèque de la Société Suisse de spéléologie, CH–1614 Granges. Email ssslib@vtx.ch

United Kingdom
British Cave Research Association Library, c/o Roy Paulson, Holt House, Holt Lane, Lea, Matlock, Derbyshire, DE4 5GQ. Email librarian@bcra.org.uk

United States
National Speleological Society Library, 2813 Cave Avenue, Huntsville, Alabama 35810. Email nss@caves.org

Natural Science Museum, c/o Dr Uéno, Hyakunin-cho 3–23–1, Shinjuku, Tokyo 160

Portugal
Biblioteca Sociedade portuguesa de espeleologia, rua Saraiva de Carvalho 233, P–1350 Lisboa. Email spe.nacional@clix.pt

Venezuela
Biblioteca Sociedad Venezolana de espeleologia, Apartado 47.334, Caracas 1041–1. Email kghneim@yahoo.com

certainly exceeds 2000. They may be grouped into three different categories. By far the largest number is that of the local or regional bulletins issued by caving clubs and regional Federations, which represent over 95% of the whole. Their audience is normally limited to the members of the group editing the journal and only few tens of copies circulate outside that group. The papers printed in these journals deal with every aspect of speleology but are rarely of more than local interest. However, some of these are worth noting, due to their outstanding scientific level: *Atti e Memorie* of the Commissione Grotte E.Boegan in Trieste (Italy, 1962), *Proceedings of the University of Bristol Spelaeological Society, Endins* of the Speleological Group of Mallorca (Spain, 1974), *and Journal of Sydney University Speleological Society* (Australia, 1950).

The second category consists of the journals (40–60) edited by the national speleological organizations: most countries in Europe, North America, and Oceania have their own bulletin, while in Africa, Asia, and Central and South America, only a few countries with a well-developed speleology have an official national bulletin. For example, in South Africa (*The Bulletin of SASA*, 1956); in Asia, Lebanon (*Al Ouat'Ouate*, 1955), Israel (*Nikrot Zurim*, 1980), China (*Carsologica Sinica*, 1982) and Japan (*Journal of the Speleological Society of Japan*, 1975); and in South America, Venezuela (*Boletin de la Sociedad Venezolana de Espelelologia*, 1967) and Brazil (*Espeleo Tema*, 1970). The target of the national journals are the cavers of that country and, therefore, their circulation may be minimal (a hundred or few hundred copies) but it may exceed 10000 (such as *NSS News*, United States, the speleological journal with the greatest print run in the world), ranging normally between 1000 and 2000 copies. Some tens or hundreds of copies of these journals circulate outside their country of origin, mainly reaching the other national speleological societies. Sometimes the national organization prints more than one journal: in this case the second is always a scientific bulletin in which studies and research of general interest are printed. Some of the most renowned are: *Caves and Caving* (1937) in England, which was one of the parents of the present *Cave and Karst Science* (the other being *Transactions of the British Cave Research Association*), *Acta Carsologica* (1955) in Slovenia, *Theoretical and Applied Karstology* (1984) in Romania, and the already cited *Karstologia* in France, *Le Grotte d'Italia* in Italy, and *NSS Bulletin* in the United States.

The third and last category corresponds to the international caving journals: only four are currently printed and all are official journals of international societies. Three of them are journals of the International Union of Speleology (UIS) and cover different caving fields: *UIS Bulletin* (1970) reports the relevant information for the activity of UIS itself, the *International Journal of Speleology* (1964) accepts only scientific papers in all the speleological fields, and *Speleological Abstracts* (1964) is a bibliographic bulletin. The last international journal is *Mémoires de Biospéologie*, edited since 1978 by the Société Internationale de Biospéologie. Finally, it must be noted that an attempt to print a private international magazine on cave exploration was first made in Canada (*Caving International*, 1978–92) and then in England (*International Caver*, 1991–97): these attempts were well accepted in the speleological world but survived only 14 and 25 issues respectively due to lack of financial support. However,

Journals on Caves: Title page of one of the first issues of the *Mémoires de la Société de Spéléologie*.

International Caver has published an irregular yearbook since 1997.

Although, or perhaps because it falls into none of the above categories, special mention should be made of *Descent,* which is the only commercial caving journal that is independent of any club or national body. First published in 1969 by Bruce Bedford, the magazine is now produced by Wild Places Publishing of Cardiff, United Kingdom, under the editorship of Chris Howes. There are six issues per year.

How to get information

The extremely high number of caving journals, together with their average very low circulation, irregularity in publication or frequent sudden death, causes extreme difficulty in searching for articles on a given caving topic. For this reason, as soon as the number of journals started to increase dramatically, just after World War II, several national speleological associations begun to print bibliographical bulletins, the first of which was *Internationale Bibliographie fur Speläologie* (1950–60), edited annually by the Austrian Speleological Society, as a supplement to their official journal *Die Höhle* (1950). In 1958, the National Speleological Society started printing *Speleo Digest,* in which the most important papers appearing in the local bulletins and journals of the United States were reprinted. From 1961 to 1991, the British Cave Research Association printed *Current Titles in Speleology,* while other national associations such as in Belgium *(Bibliographie Spéléologique Belge)* and Spain *(Bibliografia Espeleològica Hispànica)* published similar bibliographical lists, even if for a shorter timespan. The defect of all these publications was that they were not truly "general", reflecting the home territory of the editor, and moreover suffered from lack of worldwide distribution.

The UIS decided to solve this problem by supporting the Swiss Speleological Society in printing *Speleological Abstracts,* which, since its first issue, tried to be truly international. Presently this bibliographic magazine has over 70 collaborators from around 20 different countries and reports on about 5000 papers scattered in over 1000 journals. From 2002 it is possible to consult its last six issues directly through the net. However, knowledge of the existence of a paper is not useful unless one can obtain copies of it. The scarcity of available issues for many of the caving journals of the world precludes the possibility of having most of them at least in the national speleological libraries. For this reason, the UIS set up a network of *Documentation Centres* (see Table), covering all the main speleological areas of the world: they are, upon request, ready to supply copies from the journals present in their library.

PAOLO FORTI

See also **Exploration Societies**

K

KAIJENDE ARÊTE AND PINNACLE KARST, PAPUA NEW GUINEA

The arête and pinnacle karst of Mt Kaijende is located in the Western Highlands district of Papua New Guinea, between the settlements of Laiagam and Porgera (5° 30′S). It was first brought to the attention of scientists by Jennings and Bik (1962) and investigated further by Williams (1972). Karst in the region is developed in Lower Miocene limestone of more than 1000 m stratigraphic thickness. Exposures in cliff faces show it to be extremely massively bedded, with some beds of the order of 150 m. Mt Kaijende is a triangular block, faulted on its northwest, southwest, and eastern sides, and tilted gently to the southsoutheast. Fault scarps vary in height, some reaching almost 1500 m high. The region was probably first uplifted and exposed to denudation in the early Pliocene.

The arête and pinnacle karst occurs near the summit of Mt Kaijende, which rises to about 3500 m. It covers an area of 8–10 km^2, although the extent of bare karst is less. The arêtes are naked, reticulated, saw-topped ridges with spires, with practically vertical side slopes *c.* 120 m high. They are crudely aligned, dominantly northnortheast-southsouthwest. Photolineaments, presumably representing master joints, strike at 5°, 25°, 85°, 115°, and 155°. These have been enlarged and deepened by solution, and their intersection has produced a network of deep chasms that isolate massive, sheer-faced, polyhedral blocks as much as 20 ha in area at their base. The retreat of their walls has reduced the immense intervening joint blocks to a series of spired ridges with pinnacles. The walls are corrugated by nearvertical rock drains typically 2–3 m in semicircular diameter, tens of metres in length and often terminating in gaping holes. The converging heads of these solution gutters from different flanks of the blocks impart a sinuosity to the arête ridges. The bare pinnacle tops are probably sharp and fluted with rillenkarren, but investigation has not been close enough to determine details. Vertical perforations within the blocks have expanded into irregularly fluted cylindrical depressions, about 70–100 m wide at their top, and perhaps exceeding 100 m deep.

Although Jennings and Bik named the morphology “arêteand-doline karst”, Williams considered it misleading to imply that the enclosed depressions resemble dolines as they are normally understood, because of their very steep rock sides and intimate connection to the arête ridges. Therefore he preferred to omit the term doline from the description of the terrain, which he described as “arête and pinnacle karst” (see photo).

The rock surfaces are essentially bare on their crests, being steep and in an exposed, hostile environment near the upper limit of montane forest (the regional tree-line is at about 3700 m). However, the limestone faces gradually gain an increasingly dense plant cover as the surfaces descend into the more sheltered

Kaijende Arête and Pinnacle Karst: The spectacular arête and pinnacle karst on the slopes of Mt Kaijende, seen from the air. (Photo by Paul Williams)

environment of joint canyons, along which the bottoms of closed depressions are aligned. Thus most of the enclosed depressions within the arête and pinnacle terrain are vegetated at their base. However, authoritative detail is imprecise, because the topography has been studied from the air and approached from below, but, because of its extreme inaccessibility, has never been explored very far or been the subject of a field survey. Consequently, there are no measurements of the height of the arête ridges, but they appear to be of the order of 100 m or more. At an elevation of about 3200 m, thick, virtually impenetrable moss-forest, swirling in mist, clings like a sodden cloak to the rugged slopes. The daytime temperature at that height was measured as 11°C, and water dripping from the moss-draped branches had a pH of 3.9. The upper slopes of Mt Kaijende summit are almost always cloud-covered, so fog-drip must make a large contribution to the annual precipitation. Rainfall at Porgera, which is 8 km to the west and at 2200 m in the nearby valley, has been measured at about 3700 mm, so it is likely to be considerably more at the summit. Solutional denudation rates have not been measured, but must be at the upper end of international estimates.

Consideration of the lapse rate indicates that the mean annual temperature of the summit of Mt Kaijende is about 10°C, and the tropical location implies little seasonal variation. Nevertheless, there is a significant diurnal variation, with a range of about 12°C being measured at 2800 m. Night-time frosts are common above 2430 m, so freezing conditions must often affect the arête and pinnacle terrain. Frost shattering was probably common during the last glacial maximum, because at that time climatic conditions suitable for glacier ice formation existed from about 3600 m upwards.

On the lower slopes of the mountain, at around 2900 m, arête and pinnacle karst progressively gives way to a plateau incised with polygonal karst of relatively subdued relief. This is completely clothed in rain forest, except for the bottoms of some of the larger depressions which are covered with coarse grassland (locally called "kunai") and tree-ferns, the forest having being excluded by frost drainage.

Further examples of arête and pinnacle karst have been reported but not described on mountains to the west. Similar landforms are found in the tsingy of Madagascar, the pinnacles of Mount Api in Mulu National Park, Sarawak, and the stone forest of Lunan in China, although the Kaijende pinnacles are much higher and more dramatic than those of the stone forest (Salomon, Ford & Williams, 1996).

PAUL W.WILLIAMS

See also **Karren; Madagascar; Mulu; Shilin Stone Forests**

Works Cited

Jennings, J.N. & Bik, M.J. 1962. Karst morphology in Australian New Guinea. *Nature,* 194:1036–38

Salomon, J.-N., Ford, D.C. & Williams, P.W. 1996. Les forêts de pierres. *Karstologia,* 28(2):25–40

Williams, P.W. 1972. Morphometric analysis of polygonal karst in New Guinea. *Bulletin of the Geological Society of America,* 83: 761–96

KANIN MASSIF, SLOVENIA-ITALY

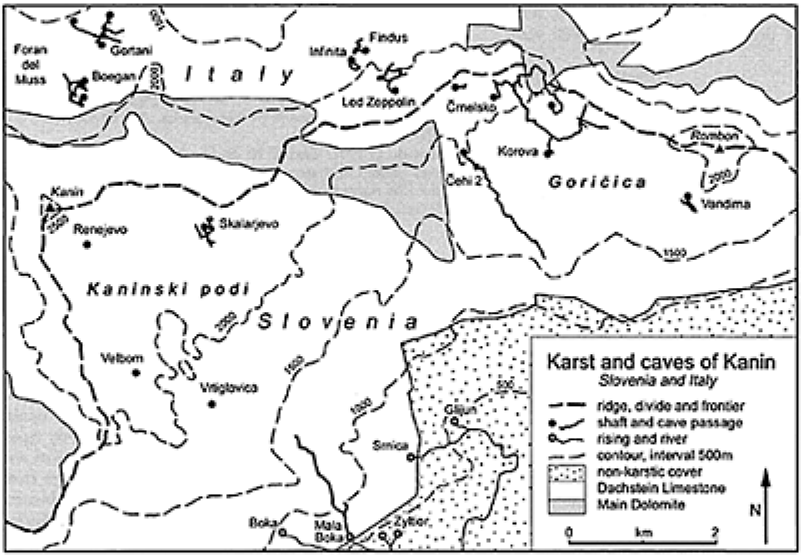
The Kanin (Canin) Massif (see map), with its high concentration of deep cave systems, some of the world's deepest shafts, and its spectacular glaciokarstic landscape, is one of the finest examples of alpine karst in the world (see also photograph in Alpine Karst entry). The massif straddles the border between Slovenia and Italy, and is bounded by several fluvioglacial valleys. It forms part of the western Julian Alps, the highest point being Mt Kanin at an altitude of 2587 m.

The massif basically comprises an Upper Triassic series of Norian dolomite (the Main Dolomite) overlain by up to several hundred metres of Dachstein Limestone, which is calcareous dolomitic or totally calcareous in composition. The main geological structure is an east—west-trending anticline, cut by an east—west fault dipping southwards at an inclination between 60° and 80°. In addition, the anticline has been dissected into blocks by four sets of subvertical faults.

The neighbouring valleys contain several karst springs at altitudes between 350 m and 870 m. Their mean discharges are up to 1000 ls^{-1}, with maxima up to 100 m^3s^{-1}. The altitude difference between the highest cave entrances of the massif and the lowest part of the caves at the base of the mountain is about 2000 m. This makes Kanin potentially a massif with some of the world's deepest cave systems. Several water-tracing experiments, in which dyes were injected into the cave streams, have proven some of the drainage directions; sinks on Kaninski podi drain to the Boka, Mala Boka and Zyltior risings, while sinks on Goričica drain to Zyltior and Glijun (Audra, 2000).

Serious cave exploration on both sides of the border started in the 1960s, when numerous caves were investigated. In the 1970s a depth of 920 m was reached in Abisso Michelle Gortani, on the Italian side of the border. The longest system within the massif is Complesso del Foran del Muss—also in Italy. It was first explored in the early 1970s. Many deep and independent caves have been investigated, and some of the latter have been found to be connected to the main system, the explored portion of which now reaches a depth of 1140 m, extends over 20 km and has 23 entrances (Benedetti & Mossetti, 2000). Probably the most explored system is the Complesso del Col delle Erbe, including the Abisso Gortani. Its present length is 15 km, with a depth of 935 m. At least 15 independent caves or cave systems on the Italian side are deeper than 600 m, and four of these are longer than 7 km.

On the Slovenian side of the massif, a depth of 911 m was reached in Skalarjevo Brezno in 1988. At the beginning of the 1990s three caves deeper than 1000 m were explored on the Goričica Plateau. Two of these, Črnelsko brezno and Čehi 2 were investigated by Italian teams, and Vandima was explored by Slovenians. Recent exploration in Renejevo brezno, on the Kaninski podi plateau, have revealed passages down to a depth of 1068 m. In the 1990s, two extremely deep single shafts were explored; Brezno pod velbom has a 501 m deep entrance shaft in a cave 852 m deep, and Vrtiglavica is a single shaft 643 m deep.



Kanin Massif, Slovenia-Italy: Map of the main features of the Kanin massif (after compilation by Philippe Audra). The cave passages of Complesso del Foran del Muss and Renejevo brezno are not marked; Gortani is the main entrance to the Complesso del Col delle Erbe.

Different parts of the massif exhibit different cave morphologies. Systems of phreatic channels at 1400–1800 m altitude are typical for large caves on the northwest, Italian side (Complesso del Foran del Muss, Complesso del Col delle Erbe). On the other hand, phreatic features are rarely observed on Pala Celar (on the Italian northeastern side) and the Kaninski podi plateau (on the Slovenian southwestern side). There the caves are guided by the main subvertical tectonic structures. Shafts connected by straight and meandering canyons (known as pitchramp series) are a characteristic pattern. Many deep single shafts were explored in the area.

The deepest caves of the massif are located on Goričica plateau (on the southeast, Slovenian side). Pitch-ramp series down through the Dachstein Limestone terminate at the contact with the Main Dolomite. From there, in Čehi 2 and Črnelsko brezno, vadose canyons dip down the contact to depths of 1533 m and 1380 m respectively. A similar but less pronounced pattern can be observed in Abisso Led Zeppelin on the Italian side.

Several caves have abandoned passages of phreatic origin at different levels. The position and orientation of these passages provide a record of the ancient water tables. The passages are preQuaternary in origin and were formed in hydrological settings completely different to those prevailing at the present day. Some contain speleothems and clastic sediments. An attempt was made to U—Th date the speleothems, but they proved to be too old (>*c.* 350 ka) for this method to be used. Some varves and car-

Kanin Massif, Slovenia-Italy: The deepest cave systems of the Kanin massif (as at the end of 2002)

Cave	Country	Depth (m)	Length (km)
Čehi 2	Slovenia	1533	5
Črnelsko brezno	Slovenia	1380	9
Vandima	Slovenia	1182	3
Sistema Foran del Muss	Italy	1140	20
Renejevo brezno	Slovenia	1068	2
Abisso Led Zeppelin	Italy	960	4
Complesso del Col delle Erbe	Italy	932	15
Skalarjevo brezno	Slovenia	911	3
Brezno pod velbom	Slovenia	852	1

bonates in Črnelsko brezno exhibited reverse polarity in their paleomagnetism, and are therefore older than 780000 years (Audra, 2000).

FRANCI GABROVŠEK

See also photo in **Alpine Karst**

Works Cited

Audra, P. 2000. Le karst haut du Kanin (Alpes Juliennes, Slovénie-Italie). *Karstologia,* 35:27–38

Benedetti, G. & Mosetti, A. 2000. Il Complesso del Foran del Muss (Monte Canin-Friuli-Venezia Giulia). *Speleologia,* 43:3–21

Further Reading

Cassagrande, G., Cucchi, F., Manca, P. & Zini, L. 1999. Deep hypogean karst phenomena of Mt. Canin (Western Julian Alps): a synthesis of the state of present research. *Acta Carsologica,* 28(1):57–69

Gabrovšek, F. 1997. Two of the world’s deepest shafts on Kaninski podi plateau in western Julian Alps, Slovenia. In *Proceedings of the 12th International Congress of Speleology,* vol. 4, La-Chaux-de-Fonds, Switzerland: International Union of Speleology

KARREN

Limestone that outcrops over large areas as bare and rocky surfaces is furrowed and pitted by characteristic sculpturing landforms that generate a distinctive karstic landscape. These solutional forms, ranging in size from less than 1 mm to more than 30 m, are collectively called karren, an anglicized version of the old German word Karren (the equivalent of the French terms lapiés and lapiaz). The terms karren and lapiés were formerly used to describe both the great array of individual karren forms and the great exposures of solutional features superimposed on bare limestone terrains. Currently, these groups of complex karren forms tend to be called karrenfields or Karrenfelder, in order to differentiate such large-scale exokarst landforms from their smaller karren components (see Table).

Several attempts at karren classification were made during the second half of the 20th century, especially after the pioneer works on the alpine and Dinaric karsts by Eckert (1902) and Cvijić (1924). More recent classifications of karren features (e.g. Bögli, 1980; Ford & Williams, 1989) include the process that generated each karren form, the size of the resulting features, the topographical pattern of their distribution over the rock surface, the presence or absence of a soil cover, and the kind of water action on the limestone (direct rainfall, standing water accumulation, sheet wash, channellized flow, melting of glacier or snow patches, and percolating water). Recent advances in karren studies are related to experimental simulations using plaster of Paris (Dzulynski, Gil & Rudnicki, 1988) and to investigations of the morphometrics of individual features (Ginés, 1996; Goldie & Cox, 2000).

Several different weathering processes may produce microkarren over limestone surfaces. Some of the microkarren features, such as biokarstic borings, are the result of specific solutional processes induced by cyanobacteria, fungi, algal coatings, and lichens. At this scale, many different patterns of minute hollows and pits are common, especially in arid environments, because the occasional wetting of the rock produces irregular etching, frequently coupled with biokarstic action (Fiol, Fornós & Ginés, 1996). Microrills are the smallest karren form showing a distinctive rilling appearance. Microrills consist of very tiny and sinuous runnels, 0.5–1 mm wide, rarely more than 5 cm long; they are caused by dew and thin water films, enhanced in coastal locations by supralittoral spray. Some other specific karren features develop near the coastline.

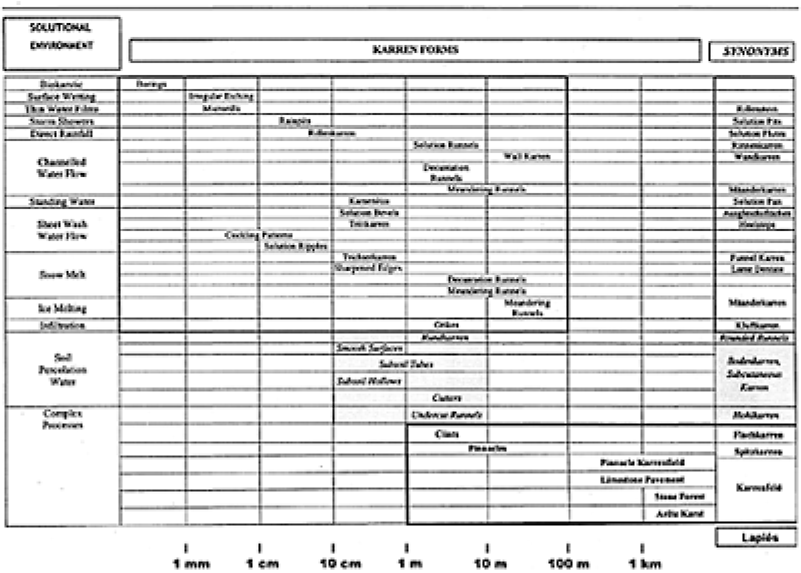
The majority of etched surfaces in semiarid environments display a rather complex microtopography that rarely presents linear patterns, the only exception being microrills. The general trend is a chaotic and holey limestone surface in which focused corrosion dominates, without any kind of integration in drainage patterns. These solutional features related to focused corrosion, give rise to depressions of different sizes, more or less circular in plan, such as the rainpit and the kamenitza karren types. Rainpits are small cup-like hollows, sub-circular in plan and nearly parabolic in cross section, whose diameter ranges from 0.5–5 cm and rarely exceed 2 cm in depth; they appear clustered in groups, or even packed by coalescence. The kamenitza karren type (Figure 1) consists of solution pans, generally flat-bottomed, from a few square centimetres to several square metres in size, that are produced by the solutional action of still water that accumulates after rainfall; their borders, frequently elliptical or circular in plan, are overhanging and may have small outlet channels.

Many types of karren are linear in form, controlled by the direction of channelled waters flowing along the slope under the effect of gravity. Most of the conspicuous furrowed appearance shown by karren terrains is due to this group of longitudinal landforms. The smaller ones are called rillenkarren (Figure 2) and are easy to distinguish from solution runnels or rinnenkarren (see below) by their trough width, which rarely exceeds 4 cm. Rillenkarren can be defined as narrow solution flutes, closely packed, less than 2.5 cm in mean width, consisting of straight grooves separated by sharp parallel ribs, that are initiated at the rock edges and disappear downwards. Rillenkarren are remarkable for the regularity of the herringbone pattern that they form on the top of the rocks and by their individual linear rills, parabolic in cross section and up to 60 cm long, and whose shape is constant along their whole length. Rillenkarren are produced by direct rainfall and their limited extent seems to be explained by the increase of water depth attaining a critical value that inhibits further rill growth downslope. Neither dendritic patterns nor tributary channels can be recognized in rillenkarren flutes, as opposed to the normal (or Hortonian) erosional rills.

Solution runnels are not as straight and regular in form as rillenkarren, being greater and more diversified in shape and origin. Solution runnels or rinnenkarren are normal (Hortonian) rills and develop where threads of runoff water are collected into channels. Classification of solution runnels is difficult because of the great diversity of topographic conditions, the complex processes involved, and the specific kind of water supply feeding the channel. Rinnenkarren is the common term to describe the equivalent of Horton’s first-order rills on soluble rocks; they result from the breakdown of surface sheetflows that concentrate into a channelled way and they are also wider than rillenkarren. These solution runnels are sculpted by the water runoff pouring down the flanks of the rocks and have distinctive sharp rims separating the channels; their width and depth range from 5–50 cm, being very variable in length (commonly from 1–10 m, but in some cases exceeding 20 m long). Rundkarren are rounded solution runnels developed under soil cover; they differ from rinnenkarren in the roundness of the rims between troughs and can be considered good indicators of formerly soil-covered karren. Many transitional types from rundkarren to rinnenkarren can be found, due to deforestation and re-shaping of the rocks after subsequent soil removal by erosion. Undercut runnels or hohlkarren are associated with semi-covered conditions, as suggested by the bag-like cross sections of the channel, resulting from enhanced corrosion at the soil contact. Decantation runnels are rills, which reduce in width and depth downslope because the solvent supply is not directly related to rainfall, but corresponds to overspilling stores of water, such as moss clumps, small snow banks, or soil remnants. On steeper rock outcrops, the runnels are nearly parallel along the slope, but on moderate slopes some kind of dendritic or wandering patterns can be found. Wall karren are the typical straight runnel forms developing on sub-vertical slopes, but meandering runnels are more frequent on moderately inclined surfaces or where some kind of decantation feeding occurs over flat areas or gentle slopes. Wall karren, fed from local decantation points, as well as some proglacial ice-melting meandering runnels, may attain remarkable dimensions exceeding

30 m in length. Obviously, transitional forms of runnels are abundant in the majority of karren outcrops, with the exception of areas with arid climates.

Karren: Classification of karren forms. Shaded areas indicate karren forms developed under soil cover. Faint-line upper frame encloses free karren single forms. Bold-line lower frame encloses complex large-scale landforms.



Other types of karren features are linear forms controlled by fractures. Grikes or kluftkarren are solutionally widened joints or fissures, whose widths range from 10 cm to 1 m, being deeper than 0.5 m and several metres long. Grikes are one of the commonest and widespread karren features and separate limestone blocks into tabular intervening pieces, called clints in the British literature and Flachkarren in German. For this reason, clint and grike topography is the most typical trend in the limestone pavements, such as the Burren (Ireland; see separate entry) and Ingleborough (northwest England; see Yorkshire Dales entry). The term “cutters” is commonly used in North America as a synonym for grike, although it is best applied to a variety of grike that develops beneath soil cover. Giant grikes, larger than 2 m wide to over 30 m deep, are called bogaz or corridors. Corridor karst or labyrinth karst constitutes the greatest expression of this type of fracture-controlled karrenfield. Splitkarren are similar smallerscale features, resulting from solution of very small weakness planes, being less than 1 cm deep and 10 cm long

Karren: Figure 1. Kamenitza, Malta. (Photo by John Gunn)

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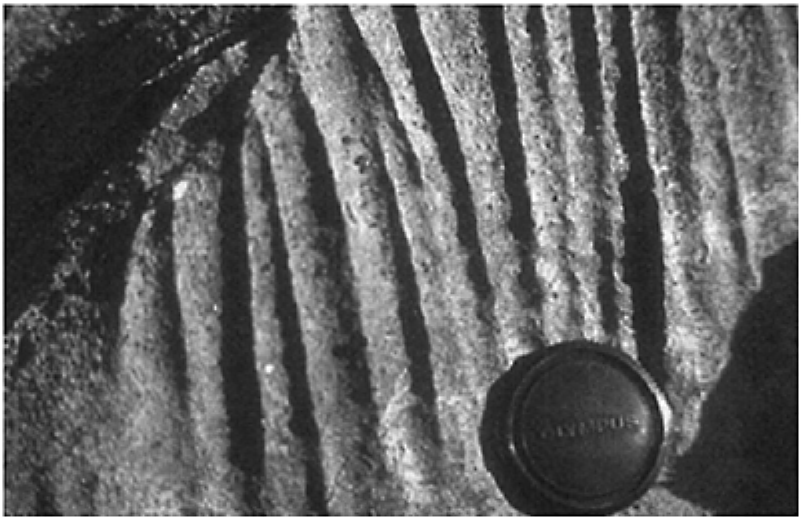
Finally, there is a group of karren features closely related to the solutional action of unchannelled washing by water sheets. Many of them, particularly trittkarren and solution ripples, show a characteristic trend that is transverse to the rock slope. At the



Karren: Figure 2. Rillenkarren, northwest Nelson, New Zealand. (Photo by John Gunn)

Karren: Figure 3. Typical assemblage of karren features at the Serra de Tramuntana mountains (Mallorca, Balearic Islands). The vertical solution runnels are intensely fluted by conspicuous rillenkarren 1 to 2.5 cm wide. Note the stepped pattern horizontally carved into the rock slope. (Photo by Àngel Ginés)

foot of rillenkarren exposures, subhorizontal belts of unchannelled surfaces can be observed; they are called solution bevels and appear as smoothed areas flattened by sheet water corrosion. More distinctive forms are trittkarren or heelsteps, which are the result of complex solutional processes involving both horizontal and headward corrosion resulting from the thinning of water sheets flowing upon a slope fall. The single trittkarren consists of a flat tread-like surface, 10–40 cm in diameter, and a sharp back-slope or riser, 3–30 cm in height. On steep surfaces, high velocity shallow flows produce cockling patterns, some of them more or less transversal to the slope direction. Pulsating flow can also produce several kinds of solution ripples, apparently related to eddies of the water flow.

A wide variety of peculiar karren forms are produced by special conditions, such as where solution takes place in contact with snow patches or damp soil. Trichterkarren are funnel-shaped forms that resemble trittkarren, but are formed at the foot of steep outcrops where snow accumulates. Sharpened edges or "lame dentate", as funnel karren features, are developed beneath snow cover. Rounded smooth surfaces, associated with subsoil tubes and hollows are very common subcutaneous forms, due to the slow solution produced in contact with aggressive water percolating through the soil.

In Bögli's classifications, two kinds of complex karren forms are recognized: clints or flachkarren, and pinnacles or spitzkarren. These latter, three-dimensional forms, range from 0.5–30 m in height and several metres wide, and are formed by assemblages of single karren rock features, being the constituents of larger-scale groups of complex forms, the karrenfields or karrenfelder. Clints or flachkarren are flattened blocks of rock, outcropping more or less parallel to the bedding, that become isolated by the solutional widening of intervening joints. Pinnacles or spitzkarren are pyramidal blocks characterized by sharp edges, resulting from the solutional removal of rock from their sides, as well as from cutting through furrow karren features. Pinnacles are exceptionally well developed in the tropics, where spectacular landscapes constituted by very steep ridges and spikes have been reported. In some cases, such as the Shilin or Stone Forest of Lunan (see Shilin Stone Forest), the presence of transitional forms, evolving from subsoil dissected stone pinnacles sometimes called "dragons' teeth" to huge and rilled pinnacles more than 30 m in height, can be observed. The particular karren assemblage that develops on limestone coasts is considered in the entry on Coastal Karst.

Karrenfields are bare, or partly bare, extensions of karren features, from a few hectares to a few hundred square kilometres. At the end of the 19th century, karrenfields were described in alpine and mediterranean karst environments, but recent explorations of karstified terrains in the tropics have documented many impressive karrenfield landscapes, such as the Tsingy Bemaraha (see Madagascar entry) and the Gunung Mulu National Park (Sarawak, Malaysia; see Mulu entry). Additional work is needed to clarify the relation between karren assemblages and climate, on the basis of the current knowledge accumulated in the last decades from arctic, alpine, humid-temperate, mediterranean, semiarid, and humid-intertropical karsts. Some well-known karrenfields correspond to formerly glaciated areas, such as the Gottesackerplateau (Allgäu Alps, Germany), the Desert de Platé (Haute Savoie, France), the Lapis de Tsanfleuron (Valais, Switzerland), and Glattalp (Schwyz, Switzerland) in the Alps; as well as the limestone pavements of the Burren (County Clare) in Ireland and the Hutton Roof Crag (Westmorland) in England. Karrenfields are also a major constituent of the typical bare-rock landscapes that are associated with deforested mediterranean karst, as occurs in the Velebit mountains (Dalmatia, Croatia) and the pinnacle karrenfields of the Tramuntana ranges (Mallorca Islands, Spain). Some extreme examples of karrenfields are the so-called crevice karst and arête karst, described from locations such as Mt Kaijende (New Guinea; see separate entry), where pinnacles can attain more than 40 m. Many celebrated karst sceneries are in fact karrenfields, being considered a significant tourist resource. This is the case of the Ubajara National Park (Ceará, Brazil) and especially the famous Shilin of Lunan (Yunnan, China), known in the literature as the Shilin Stone Forest, which attracts more than 1 million visitors each year.

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Works Cited

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)

Cvijić, J. 1924. The evolution of lapiés: A study in karst physiography. *Geographical Review,* 14:26–49

Dźulyński, S., Gil, E. & Rudnicki, J. 1988. Experiments on Kluftkarren and related Lapies forms. *Zeitschrift für Geomorphologie,* 32(1):1–16

Eckert, M. 1902. Das Gottesackerplateau. Ein Karrenfeld im Allgäu. Studien zur Lösung des Karrenproblems. *Zeitschrift des D.U.O. Alpenvereins, Wissenschaftliche Ergänzungshefte,* 1(3):1–108

Fiol, L.A., Fornós, J.J. & Ginés, A. 1996. Effects of biokarstic processes on the development of solutional rillenkarren in limestone rocks. *Earth Surface Processes and Landforms,* 21:447–52

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Ginés, A. 1996. Quantitative data as a base for the morphometrical definition of rillenkarren features found on limestones. In *Karren Landforms,* edited by J.J.Fornós & A.Ginés, Palma de Mallorca: Universitat de les Illes Balears

Goldie, H.S. & Cox, N.J. 2000. Comparative morphometry of limestone pavements in Switzerland, Britain and Ireland. *Zeitschrift für Geomorphologie,* Suppl.-Bd. 122:85–122

Further Reading

Ford, D.C. & Lundberg, J. 1987. A review of dissolutional rills in limestone and other soluble rocks. *Catena,* Suppl. 8:119–40

Fornós, J.J. & Ginés, A. (editors) 1996. *Karren Landforms,* Palma de, Mallorca: Universitat de les Illes Balears

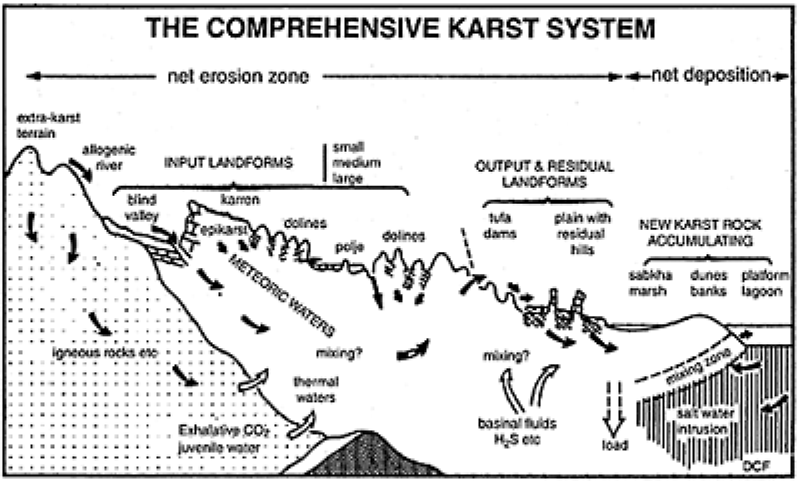
Ginés, A, 1995. Deforestation and karren development in Majorca, Spain. In Environmental Effects on Karst Terrains, edited by I. Bárány-Kevei, Szeged: Attila József University (special issue of *Acta Geographica Szegediensis*)
Trudgill, S.T. 1985. *Limestone Geomorphology*, London and New York: Longman

KARST

Karst is terrain with distinctive hydrology and landforms arising from the combination of high rock solubility and well-developed solution channel (secondary) porosity underground. Aqueous dissolution is the key process. It creates the secondary porosity and may be largely or wholly responsible for a given landform on the surface. Where it is not quantitatively predominant, it is the essential (trigger) process that permits others to operate, e.g. where a doline forms by mechanical collapse of insoluble strata into a solution cavity below. In hydrogeology, a karst aquifer is one modified from earlier granular and/or fracture aquifer conditions by development of interconnected solutional channels ("caves" where big enough for human entry): their larger aperture and efficient interconnection usually imply that water will circulate much more rapidly than in an unmodified aquifer. In the study of landforms, the karst geomorphic system is distinguished from the fluvial, glacial, eolian, coastal, and other systems because of the leading role of dissolution, which results in water circulating underground rather than running off at the surface in river channels.

Derivation of the Term

"Karst" is a germanicization of a regional place name, "Kras" (Slovenian) or "Il Carso" (Italian) given to the hinterland of Trieste Bay in the northwest Dinaric area (Gams, 1993). It is believed to derive from a pre-Indo-European word "karra" meaning stone, although this has been disputed by Hromníc (2001). Already in Roman times (Latin=carsus) it defined "stony ground". This particular terrain was bare and stony because deforestation, followed by overgrazing with sheep and goats, had caused loss of all soil on its limestones into underlying solutional cavities. The name was promulgated by travellers in the 17th and 18th centuries and in the 19th century became widely adopted to describe the similar limestone landscapes extending from north Italy to Greece. The "father" of karst studies,



Karst: A schematic illustration of the components of the karst system in carbonate rocks and their interrelationships. From Ford & Williams (1989).

Jovan Cvijić, confirmed it when he entitled the first major Western monograph on solutional landscapes *Das Karstphänomen* in 1893. Sawicki (1909) expanded it as the global term for such topographies when describing tropical sites he had visited. It is the accepted term in China, the other great historic centre of dissolutional landscape studies (Yuan, 1991).

The Karst System

On Earth the principal karst rocks are, in descending order of solubility, salt, sulfates (gypsum and anhydrite), and carbonates (limestone and dolostone). There is limited development of karst features and hydrologic behaviour on some sandstones, quartzites, and even on granites.

The greatest range of form and development occurs on the carbonate rocks. Components of the karst system found in them are illustrated schematically in the diagram. Karst dissolution occurs during deposition of the youngest rocks, such as modern coral reefs, and extends to dolostones 3.4 billion years or more in age containing the earliest fossil traces of life. Most karst is created by meteoric water that fell as rain or snow, but intruding sea waters, trapped interstitial waters being expelled by compression (basinal fluids), and juvenile waters released from consolidating magmas (lavas) are also effective locally. On the Earth's surface it is useful to distinguish between forms created where water passes underground ("input landforms" such as dolines) and those where it returns ("output" forms such as sapped gorges or deposits of travertine). Underground, dissolution is known to occur to depths of five kilometres or more, where "pressure solution" may remove as much as 40% of the original thickness of a consolidated limestone, expelling it in the basin fluids.

Classifying Karst

There are many classifications in the international literature, serving different aims. The most widely used include the following. "Holokarst" describes terrain where all water passes underground within short distances, prohibiting development of surface stream channels except inside closed depressions. Where such karst discharges onto adjoining insoluble terrain it may be termed "karst barré. Cvijić (1893) limited "holokarst" to terrains extending to the sea coast; i.e. there are no river channels downstream of them. "Merokarst" or "halbkarst" were terms for mixed karst and stream channel topography found on less pure limestones but are not now in common use. "Fluviokarst" (see separate entry) describes the case where large rivers flowing off other rocks ("allogenic rivers") are able to maintain surface courses across a karst because of their magnitude; it is also used occasionally in the sense of merokarst.

Many authors classify karst assemblages by climate. At the extreme, nine distinctive types have been recognized—"temperate" (rain all year), "Mediterranean" (summer dry), "tropical humid", "arid", "semi-arid", "glacial" or "alpine", "periglacial" or "nival", "coastal tropical", and "coastal temperate" (Jennings, 1985).

At the surface a karst may be "bare", "subsoil" where covered by its insoluble residuum, or "mantled" where covered by transported detritus such as glacial till (Quinlan, 1972). Where it is overlain by later consolidated but insoluble rocks, there is "intrastratal" dissolution along bedding planes and fractures within the soluble rock or "interstratal" dissolution if that unit is entirely removed. This is "subjacent" karst where the water is of direct meteoric origin, and "covered" if it is expressed by collapse dolines, sinking streams, or other features at the surface. The distinctive caves and karst created by ascending thermal waters are "hypogene" features.

"Paleokarst" describes ancient surface and underground karst that has been buried by later rocks and is now inert; "buried karst" is equivalent (Bosák *et al.*, 1989). Where there is renewed groundwater flow with dissolution through such karst, it is "rejuvenated". If erosion exposes it at the surface it is "exhumed". "Relict" karst describes surface forms (usually towers) created under past climatic conditions, surviving in the present landscape. "Relict" caves have been abandoned by their formative streams but remain open cavities. "Fossil karst" can mean any of these conditions.

"Pseudokarst" describes karst-like forms created by processes other than dissolution. The chief forms are caves and collapse dolines (sinkholes). Chief processes are lava flow ("volcanokarst"), melting of glaciers or ground-ice masses ("thermokarst"), and mechanical washout of pipes in silt, sand, or gravel ("piping").

DEREK FORD

See also **Asia, Northeast: History; Carbonate Karst; Evaporite Karst; Kras, Slovenia; Paleokarst; Pseudokarst**

Works Cited

Bosák, P., Ford, D.C., Glazek, J. & Horacek, I. (editors) 1989. *Paleokarst: A Systematic and Regional Review,* Amsterdam and New York: Elsevier
Cvijić, J. 1893. Das Karstphänomen. *Geographisches Abhandlung,* 5(3):218–329
Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman
Gams, I. 1993. Origin of the term "karst", and transformation of the classical karst (kras). *Environmental Geology,* 21(3):110–14
Hromníc, C.A. 2001. Karst, Kras or Karaśattu: Whence the name? *Cave and Karst Science,* 28(2):79–88
Jennings, J.N. 1985. *Karst Geomorphology,* 2nd edition, Oxford and New York: Blackwell
Quinlan, J.F. 1972. Karst-related mineral deposits and possible criteria for the recognition of paleokarsts. *Proceedings of the 24th International Geological Congress, Montreal,* Montreal: McGill University
Sawicki, L. 1909. Ein Beitrag zum geographischen Zyklus im Karst. *Geographisches Zeitschrift,* 15:185–204
Yuan D. 1991. *Karst of China,* Beijing: Geological Publishing House

Further Reading

Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwells
Milanović, P.T. 1981. *Karst Hydrogeology,* Littleton, Colorado; Water Resources Publications
Salomon, J.-N. 2000. *Précis de Karstologie,* Pressac: Presses Universitaires de Bordeaux
Sweeting, M.M. 1972. *Karst Landforms,* London: Macmillan, and New York: Columbia University Press, 1973
Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society
White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

KARST EVOLUTION

Karst evolution concerns the way in which surface and subterranean features of karst rocks develop over time. These rocks have the common property of being especially soluble in water, and include evaporites (rock salt, anhydrite, and gypsum) and carbonates (limestone, marble, and dolomite). Karst terrains are also subject to erosion by other natural processes, but solution (sometimes called corrosion) has the greatest effect on them, and karst landforms are the direct or indirect consequence of these solution processes. Rocks that do not develop karst features, such as granite and schist, are also subject to solution, but it has only a minor effect on them as compared with other natural processes. The evaporate rocks are so soluble that in humid climates they are reduced to a very low relief; whereas the moderate solubility and greater physical strength of the carbonate rocks gives them more resistance and hence they are the most globally significant host rocks for karst. Nevertheless, not all carbonates develop significant karst, especially if they are argillaceous (muddy) or extremely porous (like coral). Karst develops best on pure, dense, thick limestones and marble. Carbonate rocks in general outcrop or are close to the surface over about 12% of the ice-free continental area, and well-karstified carbonates cover about 7–10%. Surface and subsurface evaporite rocks occur beneath approximately 25% of the continental sur face, although they show fewer exposures than carbonate rocks (Ford & Williams, 1989).

Karst takes its name from the Dinaric Mountains beside the Adriatic Sea, inland from Trieste and centred on Slovenia, where the terms “carso” (Italian) and “kras” (Slovenian, Czech, Slovakian, and Polish) are used to describe the local landscape (see Kras, Slovenia). The term “karstification” is applied to the combination of processes, chemical and physical, that give rise to the features of karst both below and above ground.

To understand the evolution of karst it is best to imagine a geologically simple situation of dense, well-bedded limestones covered in places with remnants of still uneroded clastic caprock, and incised by a few deep valleys. The thick limestones extend well below sea level and dip gently towards the coast. The climate is humid and mild enough for water to be in a liquid state for all or most of the year. The natural processes that lead to the development of karst in such a terrain can be conceptualized as an open system comprising two interacting hydrological and geochemical subsystems. The hydrological cycle provides the main source of natural energy that powers the evolution of karst, because water is the solvent that dissolves karst rocks and then carries them away in solution. Geochemical processes control the rate of dissolution (the speed with which solid rock is converted into ions in solution), which in a carbon-ate karst context depends very strongly on the extent to which the water has become acidified by dissolved carbon dioxide (which produces carbonic acid) during its passage through the atmosphere and soil layer before making contact with the limestone. The concentration of carbon dioxide (CO_2) in the open atmosphere is about 0.03% by volume, whereas it is commonly 2% in the soil, and can even reach 10%. A factor of 100 increase in the concentration of CO_2 results in a roughly fivefold increase in the solutional denudation rate (White, 1984). Although this is important, the amount of rainfall is even more significant, the wettest places in the world having the fastest rate of limestone solution. For example, limestone denudation by solution processes has been estimated to be as high as 760 $m^3\ a^{-1}\ km^{-2}$ in very wet places such as parts of Papua New Guinea, where rainfall can reach 12000 mm a^{-1}, but as low as 5 $m^3\ a^{-1}\ km^{-2}$ in some arid zones like the Nullarbor Plain in southern Australia, with a rainfall of less than 350 mm a^{-1}. The amount of solutional attack on the limestone rock therefore depends on the concentration of the solute (determined by geochemical processes) and the volume of solvent (determined by the rainfall).

Evolution of the Hydrological System

Karst will only evolve if water can get underground and dissolve caves, which provide conduits for the evacuation of materials in solution (as well as insoluble residues) that were dissolved at and near the surface. Critical in the evolution of karst, therefore, is the development of a plumbing system that permits water to sink underground and to circulate through the karst rocks. This first involves the enlargement of fissures in the rock into tiny interconnected passages sufficient to permit the passage of water from the highlands where it sinks underground to the bottom of neighbouring valleys. The small passages that develop are of the order of millimetres in diameter. They can be envisaged as proto-caves, and their development is explained more fully in the Speleogenesis entries. It is sufficient to note here that this is the first and essential step in karst evolution.

The development of karst hydrology also depends on the manner in which water enters the karst. Rainwater that falls directly onto the limestone outcrop is known as autogenic recharge. It infiltrates diffusely into the rock via countless fissures. By contrast, rain that falls on to impervious non-karstic caprock but later flows on to the karst is known as allogenic recharge. It runs off as organized streams, which sink underground soon after encountering the limestone. It contrasts with the diffuse nature of autogenic recharge by being high-volume point recharge. Not only that, but it has had a different geochemical history, because in its runoff path it encountered different vegetation, soils, and rock mineralogy. Thus the chemical aggressivity (power to dissolve rock) of autogenic and allogenic waters towards limestone often differs. Autogenic waters are mainly acidified by carbonic acid, but allogenic waters may have flowed from peat bogs (and hence contain organic acids) or have encountered sulfide minerals when draining from shales, and hence contain sulfurous acid. They also tend to have a greater mechanical load, which can abrade limestone and help to incise cave floors.

Given the existence of proto-cave conduits from the highland surface to springs in the valleys, point recharge then enlarges some of these pathways into caves in which sinking rivers establish their subterranean flow paths. Sinking streams along the allogenic input boundary converge underground and emerge at springs at the output boundary of the system, thereby establishing dendritic subterranean drainage networks. This process was modelled physically by Ford and Ewers (1978) and is explained in detail by Ford and Williams (1989).

Even if there were no cover beds shedding allogenic water, diffuse autogenic recharge alone is capable of developing protoconduits and establishing a karst groundwater circulation system, although the conduits formed are not as large as those developed by point recharge from allogenic streams. Diffuse recharge subjects the entire surface to solution, but since most of the acidification of the infiltrating water is achieved in the soil zone, most of the solutional attack is just beneath the soil, where the percolating water has its greatest aggressivity and first encounters the bedrock. Up to 90% of the total solution can be achieved in the top 10 m or so of the limestone outcrop, and since water mainly penetrates the rock by means of joints and faults, these fissures become more widened by corrosion near the surface than they are at greater depth. The surface of the karst is therefore very permeable, but permeability (the capacity to transmit water) in the rock decreases with depth. This highly corroded superficial zone is termed the epikarst or subcutaneous zone (discussed more fully in the entry on Dolines).

Evolution of Surface Landforms

As soon as subsurface drainage is established, karst landforms can develop on the surface. Whereas the most characteristic subterranean features of karst are caves, the most typical surface landforms are closed depressions, especially dolines, which are enclosed bowl- or saucer-shaped depressions of usually a few hundred metres in diameter and some tens of metres deep. When dolines occupy all the available space, the surface has a relief like an egg-box and is known as polygonal karst, but this does not always develop and often dolines are dispersed or in clusters across an undulating surface. For a fuller discussion of the development of dolines and polygonal karst see the entry on Dolines.

The solution doline has a role in the karst landscape that resembles that of the valley in the fluvial landscape: it collects rainwater and discharges it from the surface. Solution dolines develop in the subcutaneous zone and drain water centripetally to enlarged fissures that discharge it vertically to the deep groundwater system. Small allogenic streams also develop enclosed depressions, termed stream-sinks or swallow holes, where they disappear underground. Large allogenic streams penetrate farther into the karst in well-defined valleys before they sink, and they produce landforms known as blind valleys, because their valleys usually terminate abruptly in a cliff or steep slope. The sinking streams give rise to caves, and if their roof is close to the surface it sometimes collapses, producing a cylindrical or crater-like depression termed a collapse doline. Subterranean rivers at a shallow depth beneath the surface can have their courses revealed by lines of collapse dolines, and in cases where collapse has proceeded for a long time the cave can be almost entirely unroofed, producing a gorge of cavern collapse (although not all gorges in karst are produced in this way).

As solution depressions evolve, some enlarge laterally and coalesce, producing compound closed depressions known as uvalas. Between the depressions are residual hills. Where the rate of vertical incision of dolines is significantly greater than the rate of solutional denudation of the surrounding land, the interdoline areas develop into hills. This is particularly common in humid tropical karsts, where the residual hills can be so well developed that they visually dominate the landscape, which is sometimes described as cone karst, a well-known example being the Gunung Sewu in Java (see Sewu Cone Karst). “Fengcong” is the term used in China to describe such karsts, with “fengcongdepression” recognizing both the positive and negative elements of the landscape. In Jamaica, the depressions in such karsts are known as cockpits (see Cockpit Country Cone Karst).

When vertical denudation eventually reduces the bottom of dolines/cockpits to the level of the regional water-table, they can incise no farther, so instead they widen their floors, with the result that the residual hills between them become isolated. Sometimes the lower slopes of these hills become over-steepened by undercutting and collapse at their base, a process brought about by the corrosional attack of swamp waters—made particularly vigorous if allogenic rivers periodically flood the intervening plains. The landscape is then transformed into tower karst (see separate entry), superb examples being known in southern China (where it is called “fenglin”) and Vietnam. In this process the caves are drained and dismembered and their remnant passages are left at various elevations within the towers. Eventually, even the residual hills are removed by solution, and only a corrosion plain is left. In the Kinta Valley in Malaysia, the alluvial veneer over a corrosion plain has been removed in the process of alluvial tin mining to reveal the pinnacled corroded surface beneath. Another superb example of a corrosion plain is the Gort lowland of counties Clare and Galway in western Ireland, where Pleistocene glaciers have stripped away the mantle of residual soil, alluvium, and loose rock to reveal the karstified bedrock beneath.

If tectonic uplift were to elevate an old karst surface, then its erosion systems would be rejuvenated and new caves and landforms would develop. But whereas in the first cycle of karstification the rock was unweathered and had only primary porosity, in the second cycle there is an inheritance of landforms on the surface and secondary porosity underground. Thus a new phase of karst evolution would exploit the inherited features and develop them further.

In practice, many karst areas have developed on rocks that have been folded and faulted. These tectonic influences considerably complicate karst evolution and are of major significance in guiding groundwater flow and denudation of the surface. Faulted terrains often provide the conditions in which the largest enclosed karst depressions—known as poljes—are developed, some exceeding 100 km^2 in area (see entry on Poljes).

Modelling Karst Evolution

Various attempts have been made to model the processes described above. Early conceptual models of karst landscape development were presented by Grund (1914) and Cvijić (1918) (translations into English are available in Sweeting, 1981), but it was not until the late 20th century that models became quantitative. Ford and Ewers (1978) used a physical laboratory model to elucidate the development of proto-caves and successive flow paths. White (1984) developed a theoretical expression showing the relationship between chemical and environmental factors in the solutional denudation of limestones that convincingly demonstrated the relative importance of the factors involved. Subsequent progress in this area is discussed in Erosion Rates: Theoretical Models, and modelling of conduit development is discussed in Speleogenesis: Computer Models. Ahnert and Williams (1997) developed a three-dimensional model of surface karst landform development (see Figure) that started with a ter- rain in which proto-conduit connections were already established and then showed how the relief might develop given different assumptions about starting conditions, such as randomly disposed sites of greater permeability or random variations in initial relief. This model illustrated sequential steps in the development of doline and polygonal karst and revealed the importance of divergent and convergent flow paths for giving spatial variations in solutional denudation that were sufficient to explain the development of residual cones between incising depressions.

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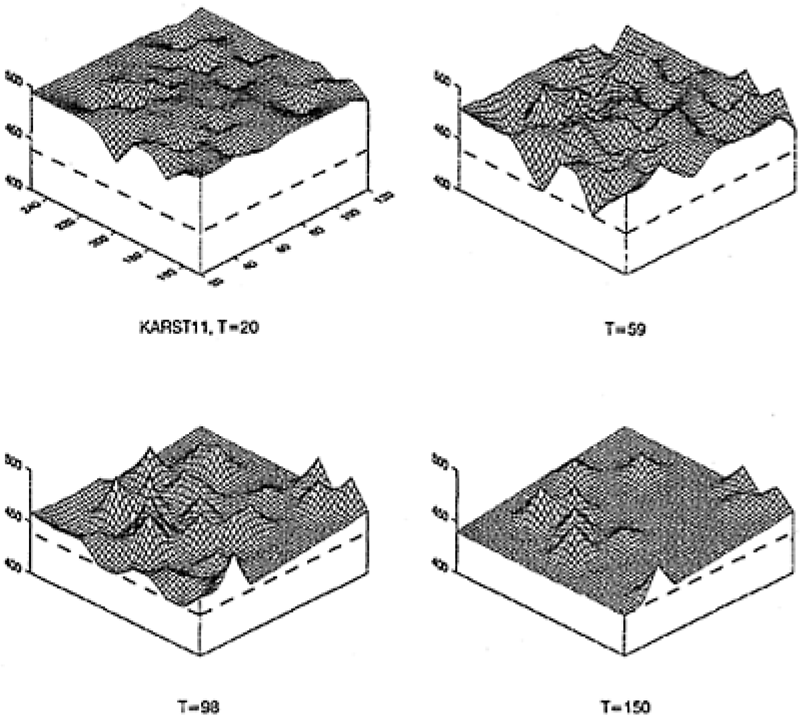

Karst Evolution: Model KARST 11 from Ahnert and Williams (1997). The water table in the karst slopes down a hydraulic gradient towards baselevel (z=440) at the left edge (the outflow margin) of the block diagram. Doline karst is developed by the 20th iteration of the computer model (T=20) and doline bottoms reach the water-table level by T=59. Doline floors widen and converge at water-table level, producing a corrosion plain with the same slope as the hydraulic gradient, the beginning of which is evident by T=98.

See also **Speleogenesis**

Works Cited

Ahnert, F. & Williams, P.W. 1997. Karst landform development in a three-dimensional theoretical model. *Zeitschrift für Geomorphologie,* Supplementband 108:63–80
Cvijić, J. 1918. Hydrographie souterraine et evolution morphologique du karst. *Receuil des Traveaux de l'Institut Géographie Alpine,* 6(4):375–426
Ford, D.C. & Ewers, R.O. 1978. The development of limestone cave systems in the dimensions of length and breadth. *Canadian Journal of Earth Science,* 15:1783–98
Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman
Grund, A. 1914. Der geographische Zyklus im Karst. *Ges. Erdkunde,* 52:621–40
Sweeting, M.M. (editor) 1981. *Karst Geomorphology,* Stroudsburg, Pennsylvania: Hutchinson Ross Translations of the Cvijić, Grund, and other classic papers.
White, W.B. 1984. Rate processes: Chemical kinetics and karst landform development. In *Groundwater as a Geomorphic Agent,* edited by R.G.LaFleur, Boston and London: Allen and Unwin

KARST HYDROLOGY: HISTORY

Caves are known to have been of importance to humans in prehistoric times and karst springs would also have been important for water supply. In historic times, probably the earliest record of karst hydrology is the visit, in 1100 BC, of Tiglath Pileser, King of Assyria, to a stream cave close to one of the springs that form the sources of the Tigris in Kurdistan (Shaw, 1992). The earliest example of what may be termed "karst water resource management" took place around 700 BC when natural cave passages and shafts beneath Jerusalem were adapted and enlarged so that water from the Gihon spring could be brought into the city. There is a major area of karst terrain in southern Greece, and karst phenomena made a great impression on the Greek philosophers as well as being important in the development of their civilization (Crouch, 1993). The earliest known statement on the origin of springs is that of Anaxagoras (500–428 BC), who supposed that they originated from large underground reservoirs supplied by rainfall. The term "katavothron" was applied by the ancient Greeks to the point at which a surface stream disappears underground (see Ponors) and Sophocles (496–406 BC) was the first to report on a katavothron on the river Inachos. Plato (427–347 BC) put forward two quite different hypotheses on the source of springs, one involving water within the Earth, the other, less well known, involving rainfall. Aristotle (384–322 BC), one of the earliest writers to specifically mention underground rivers in the Peloponnese, believed that springs originated from rainfall. Eratosthenes (275–194 BC), as reported by Strabo in his Book 8, described the connection between katavothra in the Pheneos polje to Ladon Spring in the Peloponnese. He also correlated spring rains and the discharge of karst springs. There was probably parallel work in China, and a book on caves in North China containing a description of cave hydrography is reputed to have been written about 221 BC, although there are some doubts over this.

About 30 BC, an extensive shallow artificial tunnel system in indurated calcareous dune sands was used to siphon off fresh water from salt water at a Palace at Mersah Matruh in the coastal zone just west of Alexandria, Egypt. This system is still in use and was the first development of water from a freshwater lens in a coastal karst aquifer.

Strabo (63 BC-20 AD) devoted the eighth of his 17 books on *Geography* to the "Karst Phenomena of the Poljes" and other karst phenomena, and in 37 AD the Jewish historian Josephus Flavius recorded, in *The History of the Jewish War*, the study of a water source from the Jordan and the use of chaff by Tetrach of Trachonitis to trace an underground stream. Seneca (4 BC– 65 AD) was perhaps the most important Roman philosopher and in his book III, *Naturales Questinones*, he describes solution processes and the development of large caves, and he explains the disappearance and reappearance of streams in karst. The first known map locating a karst feature was by a Roman cartographer who marked the location of the Fonte Timavi, or Timavo karst springs near Trieste.

"An Encyclopedia of Knowledge" was compiled in 52 epistles around 970 AD by members of the Arabian Order of the Brothers of Purity (Ikhwanus Safa). In these documents Arabian monks wrote about caves inside mountains and springs discharging the water stored in caves. They contributed many new concepts relating to hydrology and geology. An example is the writings of the famous Arabian Abdul Hasan Ali Masudi on hydrogeology, geological cross sections, artesian conditions, and karst concepts.

The Hongshan Karst Spring in Jiexiu County, Shanxi Province, China has been in use since the Song Dynasty (1000 AD). In 1040 AD the spring's discharge was measured as 3 $m^3 s^{-1}$ and separated into three channels to irrigate nearly 400 km^2.

The first recorded attempt to prove a connection between the Škocjanske jama stream-sink and the Timavo karst springs in Slovenia was made about the end of the 16th century by Imperato. During the 17th and 18th centuries a great variety of qualitative investigations were undertaken in European karst areas. For example, Athanasius Kircher, in his *Mundus Subterraneus* (1665) interpreted fluctuations of water in a polje as due to the seasons, and theorized on the connection of underground streams. Melchior Goldast reported on the Blautopf, one of Germany's largest springs, and between 1747 and 1748, Johannes Antonius Nagel, a mathematician, was assigned by the Hapsburgs to study poljes and caves. Between 1778 and 1779, Balthasar Hacquet, in a four-volume work, described many karst hydrologic phenomena, including limestone dissolution and the relationship between streams in a karst area, and poljes.

Toward the end of the 19th century, Jovan Cvijić (see Geoscientists) provided a systematic treatment of karren, dolines, karst rivers, karst valleys, and poljes in the Adriatic coastal area. This work and that from early researchers in Germany, France, and Italy formed the basis for the earliest quantitative testing in karst. Large scale karst-water tracing was accomplished by injecting sodium fluorescein and potassium chloride in swallow holes of the Danube in 1877, and in 1907, Truseus and Bartman, using lithium chloride and pitchblende, carried out tracing studies in the Istrian Karst. In 1926 the first plant spores were used for tracing; owing to their small size, and the fact that they formed an emulsion of solid bodies, they were thought to provide an ideal tracing medium although subsequently they have largely been abandoned in favour of fluorescent dyes (see Water Tracing: History). In the early 20th century, A.Grund recognized the zone of saturation in karst during studies in the Adriatic region where he noted that sea level was the base level for the karst hydrologic system.

By the later part of the 19th century, quantitative methods for determining groundwater velocity and permeability had been developed, although these were only applicable to water moving through homogeneous granular material with infinite character and isotropic conditions. These conditions do not usually apply in karst areas but in 1935, Victor Stringfield used a potentiometric map to interpret regional groundwater flow in the Floridan limestone aquifer. Similarly, in 1959, Cooper reported on the dynamic balance between fresh water and salt water in the Biscayne aquifer in Florida, and applied pumping test methods using the Theis equation during a large-scale pumping test on the Floridan aquifer at Fernandina, Florida. These methods were then successfully applied in the Huntsville, Alabama area with major pumping tests in hard dense, karstified limestones of Mississippian age. Subsequently they were applied to storm flow and recession analysis, and to a great variety of hydrological problems associated with quarrying, landfill siting, and water supply development.

With the many new instruments and techniques that have evolved during the later part of the 20th century, it is possible to describe more precisely the physical character of karst geological systems enabling quantitative methods to be applied to fractured rocks with solution conduits. More meaningful results can also be obtained from pumping tests on karst aquifers (see Groundwater in Karst: Borehole Hydrology).

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See also **Speleogenesis Theories: Early**

Further Reading

Back, W. & LaMoreaux, P.E. (editors) 1983. V.T.Stringfield Symposium, Processes in karst hydrology. *Journal of Hydrology,* 61(1–3):1–355

Crouch, D.P. 1993. *Water Management in Ancient Greek Cities,* Oxford and New York: Oxford University Press

Drew, D. & Hötzl, H. (editors) 1999. *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* Rotterdam: Balkema

LaMoreaux, P.E., Prohic, E., Zötl, J., Tanner, J.M. & Roche, B.N. (editors) 1989. *Hydrology of Limestone Terranes, Annotated Bibliography of Carbonate Rocks, Volume Four,* Hannover: Heinz Heise

Milanović, P.T. 2000. *Geological Engineering in Karst. Dams, Reservoirs, Grouting. Groundwater Protection, Water Tapping, Tunneling,* Yugoslavia: Zebra

Pfeiffer, D. 1963. Die geschichtliche Entwicklung der Anschauungen uber das Karstgrundwasser [The history of karst hydrology]. *Beihefte zum Geologischen Jahrbuch,* 57:1–111

Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society

Soliman, M.M., LaMoreaux, P.E., Memon, B.A., Assaad, F.A., & LaMoreaux, J.W. 1998. *Environmental Hydrogeology,* Boca Raton, Florida: Lewis Publishers

White, W.B. & White, E.L. 1989. *Karst Hydrology,* New York: Van Nostrand Reinhold

Zötl, J. 1974. *Karsthydrogeologie,* Vienna and New York: Springer

KARST RESOURCES AND VALUES

Karst areas offer a remarkable number of economic, scientific, and cultural-human values. The overview which appears here is largely based upon that which first appeared in the IUCN/ WCPA Guidelines for Cave and Karst Protection (Watson *et al.*, 1997), and relates also to many other entries in this encyclopedia dealing with archaeology, conservation, flora, forests, human occupation of caves, religious sites, soils, speleotherapy, and tourist caves.

Most of the world's population is dependent upon agriculture, and agriculture is ultimately dependent upon the upper few centimetres of the Earth's surface. Some karsts offer rich and highly productive soils that are utilized for both general and specialized agriculture. Millions of people live in karst areas, but karst soils are often particularly vulnerable due to degradation by a variety of karst-specific processes that add to the usual pressures on soil. Caves are sometimes used for some specialized forms of agriculture and industry, including fish breeding, mushroom growing, and cheese production. In Southeast Asia, the natural occurrence of cave swiftlets provides a multimillion dollar industry in harvesting of nests for bird's-nest soup.

It is estimated that at least one quarter of the world's population gain their water supplies from karst, either from discrete springs or from karst groundwater. Thus in some karsts settlement patterns have been strongly influenced by sources of water. Ancient Mayan people made extensive use of caves and cenotes. On a world scale, major engineering works have been, and continue to be, undertaken to provide for the effective utilization of spring or ground waters. An interesting example is the ongoing redevelopment of the water supply system in Iran where karst ground waters are being utilized to replace the traditional qanat (ghanat) system that had been very seriously damaged by military action. Irrigation and the generation of hydroelectric energy are other major uses to which karst waters are put. Water supply may be particularly difficult to obtain in karst areas upstream of major springs, either for agriculture or human consumption.

In some karsts, major forest resources exist, or have previously existed. Where they have been removed by clear felling, they are rarely replaced as the stresses of soil erosion and regular periods of aridity prevent natural regeneration. However, where the soils are particularly suitable for forestry, plantation forests—often of exotic species—have replaced the natural forests. Many of these offer high levels of productivity.

Limestone is an important resource with application in many areas of agriculture and industry, for example, as a flux in steel making, and it is also used to reduce some forms of industrial pollution, for example, removal of sulfur dioxide gases. Limestone is also extracted for building construction, agriculture, road construction, cement manufacture, or other industrial purposes. Important mineralization has occurred in some karsts, and mining of these other minerals is often extremely profitable. Some limestones are also hosts to hydrocarbons (oil and gas).

Tourism is a major economic activity in some karsts, including the use of both developed and undeveloped caves, and surface scenery, thereby generating local employment. Each year many millions of people visit tourist caves globally, with some single cave areas receiving as many as two million people. It is sometimes difficult to neatly define tourist caves, but using the wider contemporary definition of such caves as including, for instance, the many temple caves of Asia, there are probably several thousand worldwide. Remote appreciation is also possible by means of films, videos, and photographic volumes, the production of which can be a significant component of some local economies. Such media also reinforce the value of caves and karst for tourism and as environments that need caring for.

In some parts of the world caves are used for various forms of speleotherapy and as sanitoria generally for respiratory ailments, especially where hot springs are also present, as in Budapest (Hungary). Some caves are still used for permanent residence. Others are used for occasional shelter, and as sites of refuge from air raids or for military activities. However, virtually all of the so-called caves that received considerable publicity in the recent conflict in Afghanistan consisted of artificially constructed underground tunnels and rooms; a similar example is the extensive underground tunnels in Vietnam.

It is commonly said with a high degree of truth, that “Caves are the books in the library of the history of the earth.” Karst offers bedrock geologists clear exposures of lithological units, geological structures, and minerals. The fossils contained in the limestone are often readily visible and so offer paleontologists ready access to important sites. Geomorphologists derive insight into landform evolution and climate change over broad areas from the morphology of particular caves and the study of cave sediments. The cave floors with their layers of sediment contain invaluable and commonly readily dated evidence of geoclimatic and other earth history. Clastic fragments often provide evidence of tectonic and other geomorphological change. Although speleothems provide much of the beauty in caves, they also provide evidence of the past.

Some of the world’s most important, and best-preserved archaeological and paleontological material has been found in floors of caves. Such deposits have provided much of our knowledge about evolutionary patterns that gave rise to our contemporary mammal fauna and even the human race. Thus the floors are amongst the most important components of any cave system.

Karst provides an extremely important habitat for a wide range of specialized plant and animal species, both on the surface and underground. To commence with the surface, karst provides an environment that favours plants that can tolerate seasonal aridity, prefer alkaline soils, and have low fire resistance. The result is that a number of species are found only on karst. Further, climatic change may lead to some vegetation communities being isolated and continuing to survive on karst even though they no longer occur on neighbouring lands. In turn, a number of animal species are often associated with those plants and so are most commonly found on karst. A small number may even occur only on karst.

A major factor that underlies the character of the surface environment is that the surface of karst is often highly irregular with a multitude of small-scale erosional landforms and this often provides a great diversity of micro-climates and a variety of small soil pockets. These demonstrate a very high degree of endemicity and biodiversity. This is most evident amongst the snail populations, where any one hill in a tower karst area may house a number of species found only on that hill.

The underground environment has a very high proportion of specialized species found only in the subterranean environment. These range from microscopic species found only in tiny fissures and in the groundwater to various invertebrates that inhabit the meso-cavernous voids that cannot be entered by scientists. However, invertebrates from meso-cavernous voids do enter caves and can be studied there along with other species found only in the caves. Again, there is a very high level of endemicity and localization of species. Thus karst provides an ideal environment for the study of adaptive radiation and other aspects of evolutionary change.

Karst appears to have virtually always been a place of importance and interest to people and to have exerted a considerable influence on cultural patterns. Thus cave and karst sites have long provided for particular modes of dwelling, for spiritual religious functions, for aesthetic appreciation and artistic creativity, and for recreational purposes.

The use of caves as dwellings commenced in the pre-human hominoids, remained dominant through the Stone Age and continues in a few cultures to the present. The early use of caves as dwellings provides, of course, for their present archaeological importance. Caves may also be used in emergencies as a place of shelter or even as hospitals, or for other special purposes.

In many parts of the world caves and other limestone landforms are recognized as important sacred sites or temples by, for example, the Mayan people of Central America, and the Hindu, Buddhist, and Christian societies. Some Buddhist communities also build temples that mimic caves, as with the great temple of Sokkurum in South Korea and temples built in Yangoon for the World Buddhist Conference. In some cases spiritual values relate to underground waters. Mayan priests prayed for assistance in water management to the water god Chac. Certain karst springs, such as those at Muktinath in Nepal, are sacred to both Buddhists and Hindus. Few western tourist caves lack a "cathedral chamber", further emphasizing the spiritual connections some feel with cave environments. Around the world caves continue to be used as burial sites, and places of worship continue to be erected amid karst, for example in the karst towers of southern China and Malaysia.

Many of the world's most scenic environments owe much of their appeal to karstic phenomena, including many mountain areas that not only attract cavers, but also walkers, climbers, photographers, artists, poets, novelists, and nature lovers. Classical Western art includes a multitude of cave images, as sacred sites or as places of beauty and fantasy. The tower karst of China is commemorated in many thousands of art works and pervades the written literature, appearing even in the poetry of Mao Tsetung.

Karst is also a major resource for both mass tourism and for popular recreation, ranging from opportunities for family picnics to the most extreme physical challenges of cave exploration and cave diving. Speleology provides many extremely valuable and successful examples of partnership between amateurs (the recreational speleologists) and professional scientists. Organized speleology in itself supports a large number of major local and national organizations as well as several international bodies, all of which sponsor regular conferences dealing with issues in cave management, conservation, and research.

The various economic, spiritual, and scientific values of karst are often readily demonstrated in a compact area, and commonly make caves and karst areas splendid examples for education. The ecological chains of cause and effect, and the complex determinants of both environmental integrity and the relationship between the environment and human settlements, are rarely so clearly evident. Surprisingly, the use of karst parks for this purpose is still in its infancy but some have now developed professionally staffed education centres with on-site accommodation and learning facilities.

Cultural resource management is often an important consideration in karst areas. Some springs and caves have long served as foci for human settlement or activity and now contain valuable records of the evolution of societies layer by layer, in sediment or in art upon the cave walls. The prehistoric legacy found in some caves is well known and has contributed in a major way to knowledge of our ancestors. The historical archaeology of some karsts is also important, including such features as water reticulation systems established in some Chinese karsts. Again, these provide a wonderful resource for learning about human cultural history.

Considerable heritage value can be attached to the built environment in some karst areas, ranging from some prehistoric constructions in caves to some cave resorts in Europe and the distinctive cave-associated tourist hotels of Australia and the United States. Probably few other kinds of landscapes or land systems attract such a remarkable diversity of human and cultural interest, while also serving important economic and scientific purposes. Many of the authors contributing to this volume are people who have spent many years of their life in the pursuit of speleological inquiry. Often this commenced as recreation, but in due course led to a fully developed professional career. But whether as amateurs or professionals, most share an immense joy in and commitment to cave experience and cave inquiry. This encyclopedia in itself is, in fact, a major symbol of the many values which people place upon caves and karst. Caves can be virtually all things, to somebody, somewhere. Further, many of those with a lifetime experience of caves follow a series of more-or-less parallel interests and live surrounded by not only working materials, but an accumulation of literature, images, and sounds from the whole spectrum of caving interests.

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Works Cited

Watson, J., Hamilton-Smith, E., Gillieson, D. & Kiernan, K. (editors) 1997. *Guidelines for Cave and Karst Protection,* Cambridge and Gland, Switzerland: International Union for Conservation of Nature and Natural Resources

Further Reading

Vermeulen, J. & Whitten, T. 1999. *Biodiversity and Cultural Property in the Management of Limestone Resources,* Washington, DC: World Bank

KARST WATER RESOURCES

Large numbers of people live in areas underlain by carbonate rocks and it has been estimated that up to a quarter of the global population is supplied largely or entirely by karst waters, including over 100 million people in China and a significant proportion of the population in many European countries. However, water supply in karst regions is often a limiting factor in human occupation and development, because it is so variable in both quality and accessibility in time and space. Paradoxically, karst water is often abundant deep underground, but successful exploitation requires equipment and capital. Utilizing karst water resources therefore requires an understanding of the location of the water and consideration of the technology available; location determines accessibility and hydrogeological factors determine the quality and quantity of water; technology determines whether the water is practically available and potable.

The primary control on water resources is climate, and as karst occurs in all climatic zones, this dictates the overall water resource conditions. The high permeability of karst rocks often results in little surface water, but enhanced groundwater recharge. Surface runoff is occasionally retained in “dew ponds” in locally impermeable depressions, but these have limited capacity and duration, and are prone to contamination by surface activities. In the shallow subsurface the epikarst aquifer may retain water for many months, sometimes sustaining small, temporary springs in the side of depressions. High permeability also results in a low-gradient water table, which translates into a thick unsaturated zone. Recharge water descends through the unsaturated zone to the water table, beneath which it is stored in the matrix and fractures, travelling along a limited number of conduits to emerge briefly at karst windows, or permanently at springs. Karst aquifers also receive recharge from allogenic sinking streams. In contrast to autogenic recharge, allogenic water tends to be variable in quality and quantity, in part because disappearing streams seem to lend themselves so naturally to waste disposal! A disconcerting paradox of karst water resources is that spring water is not necessarily pure, but may become contaminated with sediment, pathogens, and pollutants, especially during high flows. Some karst regions are traversed by surface rivers, often occupying deep gorges, making the water inaccessible.

Readily accessible water resources are therefore restricted in their distribution and reliability (see Table), but may be somewhat enhanced by development. Dew ponds can be artificially constructed, deepened or sealed, or runoff can be retained in cisterns. Excavations in the epikarst can tap the shallow aquifer.

Karst Water Resources: Karst water resource classification.

Location	Resource	Origin	Quality	Quantity
Surface	dew ponds, cisterns	surface runoff	soft, vulnerable	limited transient
	epikarst springs	epikarstic aquifer	moderate, vulnerable	small, short-lived
	springs/karst	autogenic aquifer	hard, reliable	abundant, steady

	windows	allogenic aquifer	variable, vulnerable	variable
	rivers	surface runoff aquifers	variable, vulnerable	variable
Underground	adits	aquifer	good-poor	good
	dug wells	aquifer		variable
	drilled wells	aquifer		variable

In all cases the objective is provision of sufficient storage to sustain supply through dry periods. In contrast, many settlements have developed around karst springs that can provide much more abundant and reliable water supply, sustained by the karst aquifer. However, springs vary a great deal in quantity and quality of water supply, reflecting the mode of recharge and the storage capacity of the associated aquifer. Allogenic recharge routed through a discrete conduit to an overflow spring can result in intermittent flooding by contaminated water, whereas a large, confined, autogenic aquifer may provide sustained excellent quality water supply. Sometimes, karst water reserves can be enhanced by damming springs and rivers. In successful cases, the resulting elevation of the water table significantly amplifies the storage capacity beyond that of the apparent surface reservoir. However, the permeability of karst rock means that any form of surface barrage tends to be bypassed quite quickly by leakage and only at great expense can effective grout barriers be installed in the subsurface (see Dams and Reservoirs on Karst).

Access to subsurface karst water has sometimes been possible through caves, and in some cases horizontal tunnels have been driven to tap the aquifer. The great thickness of the karst unsaturated zone makes for demanding construction of vertical dug wells, and the rubbly, eroded character of weathered carbonates can make modern rotary and air track drilling somewhat difficult due to loss of circulation pressure and collapse of the bore wall. Drilled wells revolutionize exploitation of karst water because they permit more arbitrary access to water, freeing settlements from limited surface occurrences. However, karst aquifers are heterogeneous, and this results in very diverse production from wells; those encountering exclusively matrix storage have very low yields, whereas those encountering conduits can have massive yields, sometimes sufficient for cities or industries with demands beyond the normal viability of groundwater exploitation. Most wells have intermediate performance in terms of yield, or can have their yield enhanced by “development” using intensive pumping or pressurized injection of hydrochloric acid or dry ice. A simple strategy, occasionally used in regions with explored caves, is to drill directly into a cave stream, although this demands quite precise mapping. Some success has been gained by drilling along surface fracture traces, or fracture intersections, because these zones are taken to indicate the likely presence of enhanced solutional development in the subsurface. There has been relatively little success with the use of subsurface geophysics to locate reliable karst water supply.

The theory of groundwater exploitation through wells is based on easily defined porous or equivalent porous media in which the hydraulic head in a well is reduced by pumping, inducing a radially symmetrical inward flow, and “drawdown” (lowering) of the water table in a characteristic cone of depression centred on the well. The depth and extent of the cone of depression depends on the size of the well, the pumping rate, and the hydraulic properties of the rock. The theory has been extended in recent years to define "capture zones" for wells: the area from which water is drawn to provide the flow from the well. Such definition is important, not just in defining the practical limits of well spacing, but in determining the possible risk or source of groundwater contamination.

Drawdown and capture zones in karst aquifers are much more difficult to determine because of heterogeneity. Most wells intersect only small conduits, a few centimetres or less in aperture, and have capture zones that may be elongated in the direction of the conduit. Occasionally a large conduit is intersected by a well; such a conduit acts essentially as an extension of the well. The drawdown is focused not just on the well, but also on the conduit, drawing water from the adjacent fractures and matrix. The resulting cone of depression will be highly eccentric, being dependent as much on the conduit(s) as on the forcing well. Some karst aquifers show metres or even tens of metres of water table rise in response to a rain storm, and the resulting flow field in the aquifer and well is rather complex. Capture zones for karst wells are therefore not only highly eccentric, but will vary with time, frustrating application of standard management practices.

Many aquifers are currently compromised or threatened by over-exploitation or contamination. Excessive withdrawal of water from karst aquifers was not possible with self-regulating springs, but pumped wells can more completely drain an aquifer

Karst Water Resources: Sulphur Spring, a major rising exploited for its water resources in the lowland karst of central Florida. (Photo by Tony Waltham)

and its springs. It is therefore common to monitor groundwater levels using passive observation or monitoring wells. The high-permeability connection of major conduits to springs results in lower heads in the conduits than in the surrounding fractured bedrock. The water table is thus not a simple planar surface, and requires a large number of well-water levels for adequate definition. Contamination of karst aquifers is often rapid in entry and transmission, and poorly attenuated compared to porous media. Contaminants may be difficult to detect and track in monitoring wells, so that *a priori* planning may be required in anticipation of possible problems.

A number of specialized techniques for monitoring karst groundwater have been developed. Foremost has been the use of tracers for defining groundwater trajectories, and defining catchment areas, prior to occurrence of contamination (see Water Tracing). Second has been use of springs to provide a monitoring point which integrates flow from a large area. These methods work well in karst where sinking streams and springs are accessible. However, many karst aquifers lack such convenient access points, or information may be required for areas removed from primary conduits. Monitoring wells provide the key here, and appropriate techniques have been slowly developed. Collecting data from both springs and wells gives a more complete understanding of a carbonate aquifer than either can alone; springs provide information on the conduit network and wells (in a rather idiosyncratic manner) provide information on matrix and fracture hydrogeology. The behaviour of karst aquifers often varies dramatically with flow. It is therefore essential to implement continuous or high-frequency monitoring and sampling if such conditions are to be identified and characterized. Idiosyncratic short-term responses of wells to recharge events arise from the connectivity of the particular well to the various levels in the aquifer, and may misrepresent broader aquifer conditions.

Karst groundwaters are a major resource around the world, but in many cases the water is poorly managed due to the absence of regulation, or the application of inappropriate methods of waste management and water use. In general, it is best to take a precautionary approach and presume that carbonate aquifers are karstic, and assume that there may be rapid recharge and rapid flow through the aquifer via a conduit network. In the worst case such groundwater has similar properties to surface river water with its attendant problems of turbidity, pathogens, and chemical contaminants, and requires appropriate filtration and sterilization treatment.

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See also **Groundwater in Karst**

Further Reading

Domenico, P.A. & Schwartz, F.W. 1998. *Physical and Chemical Hydrogeology,* New York: Wiley

Drew, D.P & Hötzl, H. 1999. *Karst Hydrology and Human Activities: Impacts, Consequences and Implications,* Rotterdam: Balkema

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Price, M. 1996. *Introducing Groundwater,* 2nd edition, London and New York: Chapman and Hall

Quinlan, J.F. & Ewers, R.O. 1989. Subsurface drainage in the Mammoth Cave area. In *Karst Hydrology: Concepts from the Mammoth Cave Area,* edited by W.B.White & E.L.White, New York: Van Nostrand Reinhold

White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

Worthington, S.R.H., Davies, G.J. & Ford, D.C. 2000. Matrix, fracture and channel components of storage and flow in a Paleozoic limestone aquifer. In *Groundwater Flow and Contaminant Transport in Carbonate Aquifers,* edited by C.M. Wicks & I.D.Sasowsky, Rotterdam: Balkema

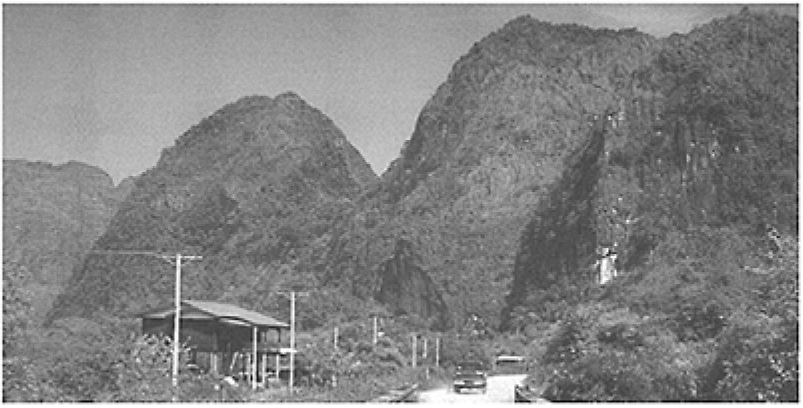
KHAMMOUAN, LAOS-VIETNAM

The Khammouan Karst is 290 km long and 40 km wide in Central Laos, continuing for 40 km into Vietnam, with a 60 km wide northern branch and a 15 km wide southern branch. In Laos, it is mainly an arcuate, northwest-southeast-trending faulted anticlinorium following the Thakhek Fault, one of the largest in Southeast Asia. In Vietnam, synclines are more developed.

The 1100 m thick main carbonate sequence is mainly middle Carboniferous to lower Permian, consisting of limestones, dolomitic to a variable extent, and of dolomites. Advanced diagenesis makes the rock extremely hard. Devonian, and some Visean carbonates are also present. Middle Triassic Indosinian tectonic events generated huge erosion. Karst formed and was subsequently buried under thick Mesozoic fluvial sandstones and shales. A new uplift started at the beginning of the Tertiary and still continues. Erosion has stripped off 2700 m or more of cover rocks in parts of Khammouan. Present karst features result from this long history.

The karst is drained west into the Mekong River and east to the Tonkin Gulf toward the China Sea, with a divide close to the political border. The Mekong flows at an altitude of 140 m at low waters and the karst uplands are mainly between 600 and 800 m, with some summits up to 1146 m. The monsoon-related, tropical climate has a dry season from November to mid-May and a rainy season with a peak in August. Annual rainfall is at least 1900 to 2750 mm. Temperatures are 25–26°C near the Mekong River and on the Vietnam coast. The main allochthonous streams have a varying perennial flow. Specific river discharge is 521 s^{-1} km^{-2} on the reference Xé Bang Fai River, Laos. Calculated flows in Xé Bang Fai Cave are 68 m^3 s^{-1} on average (600 maximum, 2.2 minimum) and 11 m^3 s^{-1} l on average in Nam Hin Boun Cave (100 maximum, 0.4 minimum), on a daily computation basis. At the Phong Nha Cave outlet, Vietnam, 10 m^3 s^{-1} are reported at the dry season. Evidence for a 40–50 m water rise in at least 40×40 m cross-section passages has been reported from both countries.

Flash floods do occur in binary karsts, especially where sandstone and shale cuestas dominate the karst boundary, as to the northeast in Laos. In Nam Non Cave, enormous quantities of sandstone boulders (average size 20 cm and up to 60 cm) are found throughout the 5 km wide karst crossing. Karst drains are commonly sub-horizontal in most of the area, but vauclusian springs (dived to a depth of 54 m) are present along main valleys and near the Mekong River, where karst aquifers have been successfully drilled.



Khammouan, Laos and Vietnam: Figure 1. Rugged limestone hills form complex massifs between alluviated basins in the Khammouan karst on the Laotian side of the border with Vietnam. (Photo by Tony Waltham)

Surface morphology combines fengcong karst, tower karst and plains, plus cone karst in Vietnam. Massifs are bounded by steep slopes and long cliffs, 200 and even 400 m high (Figure 1). The holokarst surface is extremely irregular with dry valleys, corridors, and many dolines, with extremely developed karren features, including tsingy pinnacles up to 10m high with razorsharp edges. A few open shafts are up to 50 m deep. Shaliness and dolomite content variations determine several types of landscape, with somewhat different landforms and vegetation.

Impressive poljes show different stages of maturity. Mature hyperpoljes are comprised of high carbonate cliffs surrounding a core of substratum rocks, as in the Nam Pha Thène basin. Cliff foot dissolution and subsequent collapse generate lateral enlargement. Polje drainage may include peripheral springs, underground rivers below polje floors, and caves with sinking streams. Ponor lakes, emissive in the rainy season, are found in both poljes and karst plains, some being fed by moderately enlarged fissures.

Khammouan, Laos and Vietnam: Figure 2. The Hin Boun River Cave which local people navigate on fishtail-powered longboats to travel between villages in the karst basins of Laos. (Photo by Tony Waltham)

Active caves usually open at the base of cliffs, though a number of relict caves are known up to 300 m above plains and polje floors. Caves are commonly huge, especially when they collect allochthonous water, such as the 50×50 m passage sections in Hang Vom, Phong Nha, and Xé Bang Fai Caves, or the 50 to 100m wide sections in Nam Hin Boun Cave and many fossil galleries. Several large chambers are known: 260×240 m in Tham En, and 210×155 m in Tham Koun Dôn. The largest cave entrance is 215 m wide and 30 m high (Tham En). Relict entrances are commonly closed by boulders and the remaining section may be small. Phreatic and vadose features co-exist, the phreatic ones maybe representing either older evolutionary stages or a morphology acquired during high water periods. Sloping relict conduits (up to 30°) in several caves are probably drains of formerly drowned areas. Long sumps are known, some being open in the dry season. Shafts are rare and are usually not deep, with so far two exceptions in Laos; several are located in thick sand and boulder passage fills and formed under pressure variations associated with fluctuating water level in underlying conduits.

Cave morphology reflects various flowing conditions: ceiling cupolas (phreatic conditions), scallops, potholes, and rocky floors (fast flows), underground karren on walls and floors (decreasing water flow), etc. Water pressure during large floods destabilizes walls (as in Kagnung Cave) and removes large boulders. Fast allochthonous streams generate relatively linear caves, as the Xé Bang Fai and the Nam Hin Boun (Figure 2). Sandstone boulders and pebbles from flash floods are common and may be imbricated, even in the 30 m wide Nam Non galleries. Gravel and sands are common and clay is encountered near sumps and remaining pools. Antidunes, sand waves, current ripples, and climbing ripples characterize flows of decreasing energy in the passages. Meander bars exist in Nam Hin Boun Cave. Speleothems are frequent in relict passages and more developed in the higher, older ones. They are present in the upper sections of active passages with only occasional flooding. All classical speleothem types are found, and shields and common cave pearls are also found. Rimstone pools are present in several cave streams (such as Hang Lanh).

The longest caves are the Nam Non (22.1 km), Hang Khe Ry (18.9 km), the longest part of Hang Vom (15.5 km) and Nam Hin Boun (12.4 km). Surveyed development is 130 km in Laos, 44.5 km for the Phong Nha System, and 32 km for the Hang Vom System, Vietnam. The deepest cave is Hang Khe Ry (141 m deep) and the second deepest Tham En (122 m deep). Tham Phi Seua in Laos gently rises up to +315 m.

CLAUDE MOURET

See also **Asia, Southeast for location map**

Further Reading

Limbert, H. 2002. Vietnam 2001, Ha Giang, Cao Bang and Quang Binh provinces. *International Caver 2001,* 60–65

Milner, S. 1999. Vietnam ’99. *Australian Caver,* 149:16–19

Mouret, C. 2001. Les grands poljés du karst du Khammouane, Laos Central. [The large poljes of Khammouan karst, Central Laos], *Proceedings of the 4th European Exploration Speleology Congress, May 2000,* Profondeville, Belgium: Union Belge de Spéléologie: 83–89

Mouret, C. 2001. Le karst du Khammouane au Laos Central. Dix ans d’exploration. *Spelunca,* 84:7–32

Waltham, A.C. & Middleton, J. 2000. The Khammouan karst of Laos. *Cave and Karst Science,* 27(3):113–20

KRAS, SLOVENIA

The Kras is a karst plateau to the northeast of Trieste Bay (Adriatic Sea, Mediterranean), on both sides of the Slovene-Italian border (see map in Dinaric Karst entry). From the name of the plateau—Kras in Slovene, Karst in German, Carso in Italian, comes from the root “kar/gar”, meaning rock—the international term karst has developed. The region is elongate in the northwest-southeast Dinaric trend, and is 40 km long and up to 13 km wide, covering about 550 km^2. The rocks, which form the Kras, are Cretaceous and Tertiary limestone and dolomite, being carbonate deposits of shallow, warm-water shelf environments. They range in age from the lower Cretaceous to Eocene, and were followed by flysch deposition.

The terrain is dominated by two ridges in the Dinaric direction, with the great depression of Dol between them. Dol is probably a dry valley of the Reka River or may even have a tectonic origin. The plateau has very little large-scale relief but has numerous collapse and dissolutional dolines (Figure 1). There are huge expanses of rocky terrain, with exposed white limestone that is *in situ* or broken, where a sparse vegetation of grasses and shrubs is rooted in the fissures that contain the only soil. Dolines are so numerous that much of the ground is a polygonal karst. This is the classical karst of "rocky ground".

The annual precipitation is 1400–1650 mm, but on the Kras there are no surface streams. A considerable part of the rainwater sinks very fast and feeds the deep karst aquifer. Allogenic drainage is important for aquifer recharge, especially by the River Reka sinking in Škocjanske Jame (Škocjan Caves, see separate entry) and also by losses from the rivers Vipava, Soča, and Raša, and some other superficial streams from the non-karstic border. The Reka River reappears in the Timavo springs on or near the Adriatic coast, after an underground flow length of about 41 km. One part flows to the north of a dolomitic barrier and the other through the Abisso Trebiciano (Labodnica) to the south of the barrier. The flows merge again before reappearing in the springs. Comparison of the lowest discharges of the Reka (at drought below 1 $m^3 s^{-1}$) and the Timavo springs (9.1 $m^3 s^{-1}$), shows that the aquifer is substantially fed by other sources. Due to a high degree of karstification and consequently almost immediate infiltration, and due also to the relatively high amount of precipitation, the autochthonous infiltration of rainwater is important, contributing about 65% of annual spring flow.

Kras, Slovenia: A large dissolutional doline is a component of the landscape of broken rocks, patchy grass cover, and stands of woodland that characterize the Kras. (Photo by Tony Waltham)

The Kras inner structure is heterogeneous: a complex system in which the primary drainage channels are interconnected with smaller interconnected channels and fissures. In the main passages, water drains by fast flow (300 m h^{-1}) but the karst aquifer shows typical heterogeneity. Its exploitation is complicated by the great depth down to the phreatic zone. In the eastern part of the aquifer, the water is found during low water level at altitudes of 292 m and 210 m (Škocjanske Jame). The water level lowers towards Kačna Jama (156 m) and Abisso Trebiciano (12m), while the Timavo springs are at sea level. Heavy rainfall is followed by a rapid increase in this level, with underground water level increasing by 30 m in the western part and by more than 100 m in the east. In such conditions, the Reka has a discharge of about 300 $m^3 s^{-1}$ and the Timavo springs yield 127 $m^3 s^{-1}$. The mean flows of the Reka River and Timavo springs are 8.3 $m^3 s^{-1}$ and 30.2 $m^3 s^{-1}$, respectively. The first tracing of the Reka was realized in 1864, when researchers used not only hydrological observations (discharge, observations of water level, measurements of rainfall) but also a series of tracing methods, including eels, salts, and dyes. The Timavo springs were renowned for being the most suitable for ships' water supply in the 4th century BC, and these springs and those of Brojnice, at Aurisina, provide the water supply to Trieste. At Brestovica there is a borehole where water is pumped from the phreatic zone at sea level and pumped to the Kras plateau, up to 500 m higher.

Some caves of Kras are important paleolithic and prehistoric sites. Cave tourism started as early as the 17th century at Vilenica Cave. People descended to the bottom of Velika Dolina (collapse doline) of Škocjanske Jame in the 18th century; in 1808 Pečina na Hudem letu was made a show cave, and in 1819 the visitor's book of Škocjanske Jame was introduced. There are now ten show caves on Kras.

Speleological research began in 1839 with the first attempts to follow the Reka underground. In 1841, the bottom of Abisso Trebiciano was reached at a depth of 329 m, making it the world's deepest explored cave for about 50 years. From 1884 to 1890, Škocjanske Jame was surveyed to the sump (dived in 1991). In 1889 Kačna Jama was discovered with its 200 m entrance shaft, and followed to reach the Reka in 1972. Among thousands of caves on Kras, Škocjanske Jame (5.8 km long, 250 m deep), Brezno pri Risniku (230 m deep), Kačna Jama (12.5 km long, 280 m deep), Abisso Trebiciano (329 m deep), and Lazaro Jerko (0.5 km long, 380 m deep) are notable. Grotta Gigante and Škocjanske Jame both have very big underground chambers: Martel's Hall, in the latter, has a volume of 2.2 million m^3

ANDREJ KRANJC

See also **Dinaric Karst (location map); Škocjanske Jame, Slovenia**

Further Reading

Civita, M., Cucchi, F., Garavoglia, S., Maranzana, F. & Vigna, B. 1995. The Timavo hydrogeologic system: an important reservoir of supplementary water resources to be reclaimed and protected. *Acta Carsologica,* 24:169–86

An explanation and up-to-date data on the Timavo hydrological system, relating to the hydrology of Kras.

Habič, P., Knez, M., Kogovšek, J., Kranjc, A., Mihevc, A., Slabe, T., Šebela, S. & Zupan, N. 1989. Škocjanske Jame speleological revue, *International Journal of Speleoleology,* 18 (1–2):1–42

Detailed physical speleological description of Škocjanske Jame, including the history of exploration and arrangements for tourists.

Kranjc, A. 1994. About the name and the history of the region Kras. *Acta Carsologica,* 23:82–90

Explanation of the name Kras and how the name has been transformed into the international term "karst".

Kranjc, A. (editor) 1997. *Slovene Classical Karst,* Ljubljana, Slovenia: Kras

Detailed description of Kras from different points of view, from natural history to human, with emphases on karst morphology and hydrology.

KRUBERA CAVE, GEORGIA

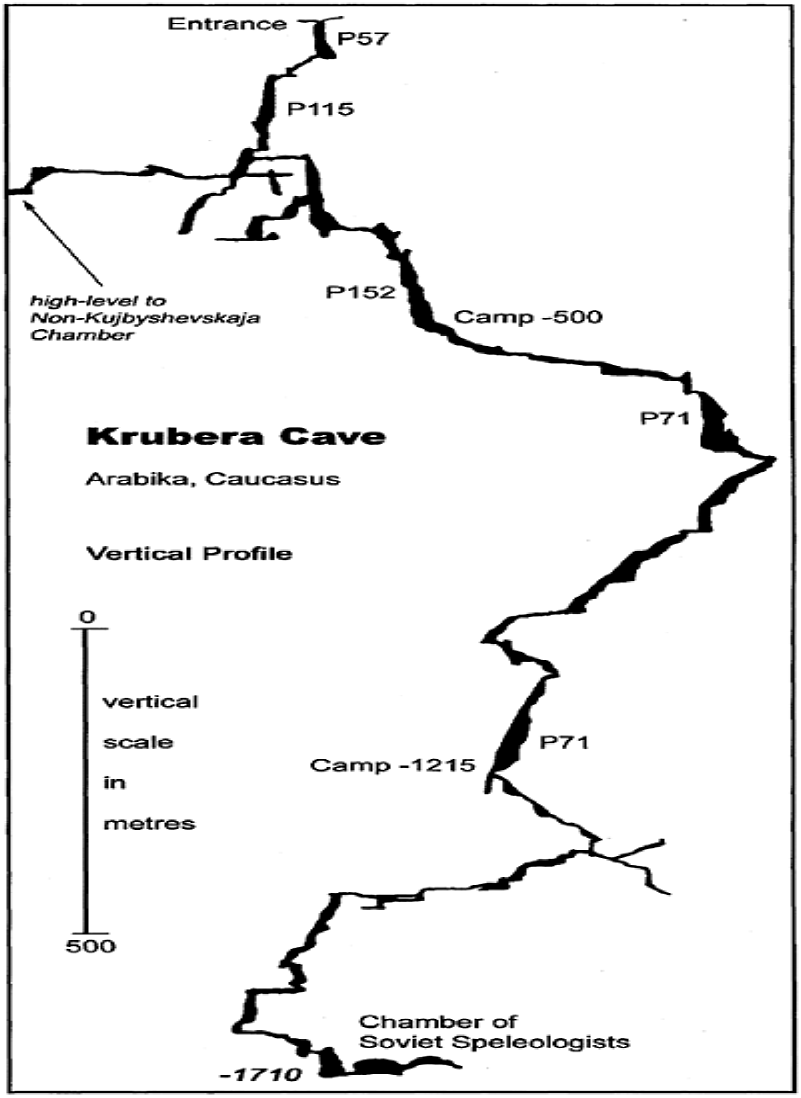
At the dawn of the new millennium, Krubera (Voronja) Cave in the Arabika Massif, western Caucasus, became the deepest known cave in the world, with a depth of 1710 m, although it lost the record to France's Gouffre Mirolda early in 2003.

The Arabika Massif is one of the largest limestone massifs of the western Caucasus. It is located in Abkhasia, a republic currently within Georgia (for location, see maps in Russia and Ukraine and in Caucasus entries). The massif, with its strongly pronounced glaciokarstic landscape at elevations ranging between 1900 and 2500 m (the highest peak, the Peak of Speleologists, rises to an altitude of 2705 m), is composed of Lower Cretaceous and Upper Jurassic limestones. In the central part of Arabika the Cretaceous beds are retained only in a few ridges and peaks, as well as in small outcrops along the synclinal cores. The central part of the massif is composed of Upper Jurassic strata that dip continuously to and beneath the Black Sea shore. The massif is highly tectonized, with a fault-block structure strongly controlling both cave development and groundwater flow systems. To the northwest, northeast, and east, Arabika is bordered by the deeply incised canyons of the Sandripsh, Gega, and Bzyb rivers. The latter separates Arabika from the adjacent Bzybsky Massif, another area with major speleological prospects in the western Caucasus, including Snezhnaja-Mezhonogo (−1370 m) and Pantjukhina (−1508 m), among many other significant caves (see Caucasus, Georgia).

Among the several hundred caves known in the Arabika Massif, some deep caves explored during the 1980s stand out, including the Iljukhina system (−1240 m), the Arabikskaja system (Kujbyshevskaja-Genrikhova Bezdna; −1110 m), Dzou Cave (−1080 m), Moskovskaja Cave (−970 m), and Cherepash'ja Cave (−650 m). In 2001 Sarma Cave, previously explored to −700 m, was pushed to a depth of 1530 m. The deepest cave, Krubera (Voronja), is located in the Ortobalagan glaciated trough valley, some 300 m to the southeast of and 60 m above Kujbyshevskaja Cave, the main entrance to the Arabikskaja system. Although Krubera Cave is not connected directly with the Arabikskaja system, it is most probably part of a single linked hydrological system.

An open-mouthed 60 m shaft was first documented by Georgian researchers in the early 1960s, who named it after Alexander Kruber, a founder of karst science in Russia. The early exploration was stalled by an impassable squeeze in a meandering passage which led off from the foot of the entrance shaft. During the 1980s the speleological club of Kiev pushed the cave to −340 m by breaking through several critically tight meanders between the shafts. During this time the cave received its alternative name Voronja (Crow's Cave), owing to the number of crows nesting in the entrance shaft. Meanwhile, other deeper caves of the Ortobalagan Valley diverted the main effort, and the exploration of Krubera Cave was suspended. In August 1999 the Ukrainian Speleological Association expedition, led by Yury Kasjan, recommenced work in Krubera Cave and made a major breakthrough by finding a deep continuation, explored to −750 m, from a window in the wall of a pitch at −220 m. Further expeditions explored the new branch to −1410 m in 2000 and to −1710 m in 2001 (see profile).

The cave is developed in the thickly bedded and massive Upper Jurassic limestones, in the fold zone of the Berchil’sky



Krubera Cave, Georgia: Vertical profile through the Krubera Cave.

anticline entrenched by the Ortobalagan trough valley. The main branch descends steeply in vertical pitches, separated by short meanders, while shifting slightly towards the southern slope of the anticline. Apart from the "non-Kujbyshevskaja" branch, which stretches for almost 500 m to the northwest, the cave develops within quite a small area (400 m by 400 m), remaining within a small tectonic block and not extending beyond the southern margin of the trough valley. There is a strong tectonic control of cave development in plan view. Some segments of the major caves stretch along faults, other sections twist within major tectonic blocks and reflect back inside the blocks when intercepted by a fault. The main branch of the Krubera Cave turns many times and drops steeply via vertical pits, separated by short meanders. Through both the degree of morphological development and its hydrological system, the cave seems to be a tributary to the adjacent Kujbyshevskaja Cave. A small water flow (up to 1 s^{-1}) appears in the cave at a depth of about 340 m. This flow disappears and reappears at various levels, but never increases significantly.

Major karst springs with individual average discharges of 1 to 4 $m^3 s^{-1}$ are located along the fringes of the massif at altitudes above sea level ranging from 1 m (Reproa Spring) to 540 m (Gegsky Vodopad). Submarine springs are also known, emerging from the floor of the Black Sea at depths of 20–40 m (and probably greater). Some boreholes located along the shore of the Black Sea yield karstic groundwater from depths of 40–280 m below sea level. An outline of the hydrogeological structure of the massif and its true speleological potential were revealed in the 1980s, when spectacular progress was made in deep cave exploration. Two dye-tracing tests during 1984 and 1985 proved connections between the major caves and springs. In particular, tracers injected in the Kujbyshevskaja Cave were de tected in Kholodnaja Rechka (1.5 $m^3 s^{-1}$, 50 m above sea level) and Reproa (2.5 $m^3 s^{-1}$; 1 m above sea level) springs along the seashore. Tracer was also detected in a borehole which yields groundwater at a depth of 40 m below sea level, located between these two springs. This gave a reason to identify the major karst hydrological system as being potentially the deepest in the world at that time, with a vertical range greater than 2300 m. The system comprises the majority of the southeastern flank of the major Arabika anticline.

At its present lowest explored point of −1710 m (530 m above sea level) Krubera Cave neither enters a master river passage nor shows any signs of major flooding (which could indicate close proximity to the base-level of a main collector). These features, together with the proven connection of the Arabikskaja caves to large springs on the shore of the Black Sea, suggest a good potential for further deepening the cave system of the Ortobalagan valley. Equally realistic is the possibility of connecting caves with entrances at higher elevations into the Krubera or Kujbyshevskaja caves. The best prospects can be found in the nearby Berchil'skaja Cave (−500 m), the entrance of which is some 150 m above, and Martel's Cave, located some 80 m higher up. Hence the future possibility of locating a 2000 m+system in the area is exceptionally good.

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See also **Caucasus, Georgia**

Further Reading

Klimchouk, A. & Kasjan, Ju. 2001. Krubera (Voronja): The deepest cave in the world. In a search of −2000 m in the Arabika Massif, Western Caucasus. *Caves & Caving,* 91:34–41. The same article is also published in *Spelunca,* 82:15–24 and *NSS News,* 59(9):252–57

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LIMESTONE AS A MINERAL RESOURCE

Limestones have been worked for many thousands of years—initially for building stone and, more recently, for a wide range of constructional and industrial uses. In Europe and North America, the industrial revolution of the 19th century led to a rapid increase in the demand for limestone, which was one of the main commodities (together with coal) carried by the early canals and railways. More recently there has been a global increase in the demand for limestone for use in cement making. In some countries, such as Great Britain and the United States, it is also of major importance as an aggregate. Indeed, 70% of the stone produced in the United States is limestone. Limestone has a very large range of uses that may be grouped under seven main headings.

Aggregate: The principal uses of aggregate are as roadstone (which is often coated with asphalt), as a component of concrete, and as ballast (large material, e.g. railways). The suitability of a particular limestone for use as an aggregate is governed by its physical properties, most notably density and porosity, and its mechanical properties. Density should be >2.65 g cm^{-3}; hence chalk is not suitable. Porosity controls water absorption which should be low (<1%) so as to minimize damage from frost and from salt crystallization. In addition, a porous limestone will absorb more bitumen in the coating process, thereby increasing costs. Dolomites tend to have higher porosity and hence are less suitable as roadstones. The mechanical properties control the response of limestone to external stimuli such as shear stress or compressive impact.

Cement: Cement is strictly a manufactured product, made by blending different natural and synthetic materials, in order to achieve rather precise chemical proportions of lime, silica, alumina, iron, and sulfate in the finished product. Over 80% of the raw material is limestone and the manufacture of cement is the main user of limestone in many countries, and is second only to aggregates in others. Low magnesium limestones (<3% $MgCO_3$) are necessary and specific cements may have more stringent requirements. The limestone and other raw materials are finely ground and blended to an exact chemical specification prior to being fed into large rotary kilns for conversion into cement "clinker". The clinker is then cooled and ground, and at this stage a small amount of gypsum ($CaSO_4$) is added to control the setting time.

Lime (quicklime): Lime is made by burning (calcining) limestone or dolostone in a furnace, thereby driving off CO_2. Lime has been manufactured for several hundred years, initially in small wood-fuelled kilns, through a series of increasingly sophisticated designs to the large modern rotary kilns. The initial stimulus was the need for agricultural lime, which is applied directly to the soil. Non-agricultural uses of lime include the manufacture of mortar, plaster, calcium silicate brick, aerated insulation blocks, lime washes, and a variety of external renderings. It is also reacted with water to produce hydrated (slaked) lime which has a variety of chemical and industrial uses.

Chemical processing: Limestones and lime are used in many chemical-processing industries. For example, in the making of glass, limestone or lime may be used to flux silica sand, to form chemically fused calcium silicates. They also render the glass less soluble, reduce its brittleness, and improve its appearance by enhancing its lustre. High calcium stone is preferred for window glass and high magnesium stone for glass containers and tumblers, as the magnesium oxide provides greater resistance to etching by chemical solvents and acids. Limestone is also important in papermaking, as hydrated lime is reacted with SO_2 to form calcium bisulfite, which is heated as a liquor in which wood pulp is digested, to dissolve all constituents, except those which are cellulose based. The end product is then refined and pressed as the initial basis for papermaking. A high calcium limestone is required but there is an increasing trend to replace limestone by magnesia, ammonia, or soda ash as the alkaline agent to react with SO_2. Finely ground limestone fillers are used in the manufacture of paint, ceramics, rubber, plastics, and a variety of floor-covering materials. Whiting is a specific category of fine-grained filler derived by fine grinding such that >95% is <44 µm. Chalk is a particularly good source material.

Limestone as a Mineral Resource: Production of limestone (including dolomite and chalk) in Great Britain by end use (data from British Geological Survey Annual Mineral Statistics)

	1981		1988		1992		1996	
	Mt	**%**	**Mt**	**%**	**Mt**	**%**	**Mt**	**%**
Roadstone	30.0	42.5	52.1	43.5	52.9	49.0	37.1	38.6
Other aggregate	27.0	38.3	49.4	41.3	36.8	34.1	40.1	41.7
Cement	8.8	12.4	10.3	8.6	8.9	8.3	9.7	10.1
Agriculture	1.4	2.0	1.3	1.1	1.4	1.3	1.4	1.5
Iron and steel	0.9	1.3	2.2	1.9	2.2	2.0	3.0	3.1
Fillers	0.8	1.1	1.1	0.9	1.3	1.2	1.6	1.7
Glass making	0.3	0.5	0.3	0.2	0.2	0.2	0.0	0.0
Building stone	0.1	0.1	0.2	0.2	1.4	1.3	0.2	0.2
Other uses	1.1	1.7	2.8	2.3	2.8	2.6	3.0	3.1
TOTAL	70.4		119.7		107.8		96.1	

Ferrous and non-ferrous metal processing: Limestone is used as a flux in the processing of a variety of metals including copper, lead, zinc, and most notably iron. Limestone is added to the blast furnace where it reacts with the fuel and impurities in the ore and forms a molten slag that is removed gravimetrically.

Building/dimensional stone: Not all limestones are suitable for building, only those that have a high mechanical strength. Where the rock is to be used outside, or in other wet applications, it must also have a high durability (soundness), that is an ability to resist wetting/drying and freezing/thawing cycles. Marble has long been prized for statuary and ornamental uses (see Ornamental Use of Limestone), but in the dimensional stone trade the term is commonly applied to those limestones that will take a polish, whether or not they have actually been metamorphosed.

Environmental protection: An increasingly important use of limestone is in the removal of pollutants from air and water. Limestone aggregate is used in sewage works, where it provides a surface upon which colonies of bacteria can become established. These bacteria feed upon the bacteria already present in the sewage. Hydrated lime is used to balance the pH of domestic water from surface sources, which are often quite acidic. However, groundwater from limestone aquifers in general, and chalk in particular, may need to have its pH reduced to avoid build up in pipes. Problems associated with "acid rain" became a major issue during the 1980s and one proposed solution was the fitting of flue gas desulfurization (FGD) equipment to power stations and other major consumers of fossil fuels. There are over 200 methods of FGD but one of the most popular uses limestone, which is reacted with sulfur dioxide to produce gypsum.

The proportion of limestone used for each of these purposes varies from country to country, but in general the greatest use of limestone is as an aggregate in those countries where there is a shortage of easily exploitable hard rocks or gravels. However, in those countries where there are alternative sources of aggregate, the greatest use of limestone is in the production of cement. An exception would be the United States, where limestone is commonly preferred as an aggregate, even where other rocks are available. The table shows the production of limestone by end use in Great Britain over the period 1981–1996.

JOHN GUNN

Further Reading

Carr, D.D., Rooney, L.F. & Freas, R.C. 1994. Limestone and dolomite. In *Industrial Minerals and Rocks,* edited by D.D.Carr, 6th edition, Littleton, Colorado: Society for Mining, Metallurgy, and Exploration

A very good general reference that gets about as non-technical as a technical reference can get!

North, F.J. 1930. *Limestones, Their Origins, Distribution, and Uses,* New York: Van Nostrand, and London: Thomas Murphy

Prentice, J.E., 1990. *Geology of Construction Materials,* London and New York: Chapman and Hall

This book does not refer only to limestone but it does have a good overview of the dimension stone and aggregate industries—including limestone.

Raymond, F. (editor) 1994. *Mendip: Limestone Quarrying, A Conflict of Interests,* Tiverton: Somerset Books

Proceedings of a seminar to discuss aspects of quarrying on Mendip. Includes discussion of uses of limestone, minerals planning policy, and environmental impacts.

Smith, M.R. (editor) 1999. *Stone: Building Stone, Rock Fill and Armourstone in Construction,* London: Geological Society

(Geological Society Engineering Geology Special Publication No. 16)

Smith, M.R. & Collis, L. (editors); revised by Fookes, P.J., Lay, J., Sims, I. & West, G. 2001. *Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes,* 3rd edition, Bath: Geological Society (Geological Society Engineering Geology Special Publication No. 17; originally published 1985)

Stanier, P. 1985. *Quarries and Quarrying,* Shire Publications Discussion of the history of quarrying in the UK. Includes 7 pages related to limestone and a list of 20 books for further reading.

LITTORAL CAVES

Littoral caves, more commonly known as sea caves, are found throughout the world, actively forming along present coastlines and as relict sea caves on former coastlines. Some of the bestknown sea caves are European. Fingal's Cave, on the Scottish island of Staffa, is a spacious cave some 70 m long, formed in columnar basalt. The Blue Grotto of Capri, although smaller, is famous for the apparent luminescent quality of its water, imparted by light passing through openings underwater (see picture in colour insert and entry Art Showing Caves). The Romans built a stairway in its rear and a now-collapsed tunnel to the surface. The Greek islands are also noted for the variety and beauty of their sea caves. Numerous sea caves have been surveyed in England, Scotland, and in France, particularly on the Normandy coast. The largest sea caves are found along the west coast of the United States and in the Hawaiian islands.

True littoral caves are those formed by processes other than dissolution. They should not be confused with dissolutional caves that pre-dated the wave action but were then intersected and revealed as the cliff line was eroded back, or with the dissolutional voids formed in the littoral zone on tropical islands (see Speleogenesis: Coastal and Oceanic Settings). In some regions, such as Ha-Long Bay, Vietnam (see separate entry), caves in carbonate rocks are found in littoral zones but were formed by dissolution. Littoral caves may be found in a wide variety of host rocks, ranging from sedimentary to metamorphic to igneous, but caves in the latter tend to be larger due to the greater strength of the host rock.

In order to form a sea cave, the host rock must first contain a zone of relative weakness. In metamorphic or igneous rock, this is typically either a fault (Figure 1), as in the caves of California's Channel Islands, or a dyke, as in the large sea caves of Kauai's Na Pali Coast (Hawaii). In sedimentary rocks, this may be a bedding-plane parting or a contact between layers of different

Littoral Caves: Figure 1. Lady's Harbor Cave, Santa Cruz Island, California, is formed on a prominent fault visible along the right wall. (Photo by Dave Bunnell)

hardness (Figure 2). The latter may also occur in igneous rocks, such as in the caves on Santa Cruz Island (California), where waves have attacked the contact between the andesitic basalt and the agglomerate.

The driving force in littoral cave development is wave action. Erosion is ongoing anywhere that waves batter rocky coasts, but where sea cliffs contain zones of weakness, rock is removed at greater rate along these zones. As the sea reaches into the fissures thus formed, they begin to widen and deepen due to the tremendous force exerted within a confined space, not only by direct action of the surf and any rock particles that it bears, but also by compression of air within. Blowholes (partially submerged caves that eject large sprays of sea water as waves retreat and allow rapid re-expansion of air compressed within), attest to this process. Adding to the hydraulic power of the waves is the abrasive force of suspended sand and rock. Most sea-cave walls are irregular and chunky, reflecting an erosional process where the rock is fractured piece by piece. However, some caves have portions where the walls are rounded and smoothed, typically floored with cobbles, and result from the swirling motion of these cobbles in the surf zone.

Rainwater may also influence sea-cave formation. Carbonic and organic acids leached from the soil may assist in weakening rock within fissures. As in solutional caves, small speleothems may develop in sea caves. The largest that the author has seen are stalactites and sheets of flowstone in sea caves formed in calcareous sandstone.

Life within sea caves may assist in their enlargement as well. For example, sea urchins drill their way into the rock, and over successive generations may remove considerable bedrock from the floors and lower walls.

Sea-cave chambers sometimes collapse leaving a "littoral sinkhole". These may be quite large, such as Oregon's Devil's Punchbowl or the "Queen's Bath" on the Na Pali coast. Small peninsulas or headlands often have caves that cut completely through them, since they are subject to attack from both sides, and collapses of sea-cave tunnels often leave free-standing "sea stacks"

Littoral Caves: Figure 2. Littoral caves below the vertical cliffs of South Wales; the rock is limestone but there is almost no karstification and the caves have been excavated by wave action on the bedding planes and joints. (Photo by Tony Waltham)

Littoral Caves: Long sea caves of the world (compiled by D.Bunnell and C.Self).

Rank	Cave Name	Location	Region	Country	Length (m)
1	Painted Cave	Santa Cruz Island	California	USA	374
2	Waiahuakua Cave	Kauai	Hawaii	USA	352
3	Cueva Tres Pisos	Baja California	California	USA	316

4	Waiwaipuhi Cave	Kauai, Hawaii	Hawaii	USA	290
5	Sunbeam-by-the-Sea Cave	Punta Banda, Baja	Baja	Mexico	270
6	Catacombs Cave	Anacapa Island	California	USA	246
7	Cathedral Cave	Anacapa Island	California	USA	241
8	Forbidden Fissures	Santa Cruz County	California	USA	241
9	Sandside Head Cave #2	Thurso, Highlands	Scotland	UK	230
10	Sea Maze	San Luis Obispo County	California	USA	229
11	Waialoha Cave	Kauai, Hawaii	Hawaii	USA	225
12	Virgin's Spring	Lundy Island, Devon	England	UK	225
13	Sand Hill Bluff Cave	Santa Cruz Co.	California	USA	206
14	Jumbo Gumbo	Santa Rosa Island	California	USA	205
15	Parallel Tunnels	Punta Banda, Baja	Baja	Mexico	204

along the coast. The Californian island of Anacapa is thought to have been split into three islets by such a process.

Most sea caves are small in relation to other cave types. A compilation of sea-cave surveys by the author showed three over 300 metres, 15 over 200 metres, and 86 over 100 metres in length. The Table presents details of the 15 caves with surveyed lengths exceeding 200 metres. In Norway, several apparently relict sea caves exceed 300 metres in length, but are not included in the above compilation of actively forming sea caves. There is no doubt that many other large sea caves exist but are unsurveyed due to their remote locations and hostile sea conditions.

Several factors contribute to the development of relatively large sea caves. The nature of the zone of weakness itself is surely a factor, although difficult to quantify. A more readily observed factor is the situation of the cave's entrance relative to prevailing sea conditions. At Santa Cruz Island, the largest caves face into the prevailing northwest/west swell conditions—a factor which also makes them more difficult to survey. Caves in well-protected bays sheltered from prevailing seas and winds tend to be smaller, as are caves in areas where the seas tend to be calmer.

The type of host rock is important as well. All of the largest sea caves are in basalt, a relatively strong host rock compared to say, sedimentary rock. Basaltic caves can penetrate far into cliffs where most of the surface erodes relatively slowly. In weaker rock, erosion along a relative zone of weakness may not greatly outstrip that of the cliff face.

Time itself is another factor—i.e. the length of time that a cave has been actively enlarging. The active littoral zone changes throughout geological time by an interplay between sea-level change and regional uplift. Recurrent ice ages during the Pleistocene have changed sea levels within a vertical range of some 200 metres. Significant sea caves have formed in the Californian Channel Islands that are now totally submerged by the rise in sea levels over the last 12000 years. In regions of steady uplift, continual littoral erosion may produce sea caves of great height—Painted Cave is almost 40 m high at its entrance.

Finally, caves that are larger tend to be more complex, as discussed below. By far the majority of sea caves consist of a single passage or chamber. Those formed on faults tend to have canyon-like or angled passages that are very straight. In Seal Canyon Cave on Santa Cruz Island, entrance light is still visible from the back of the cave 189 m from the entrance. By contrast, caves formed along horizontal bedding planes tend to be wider with lower ceiling heights. In some areas, sea caves may have dry upper levels, lifted above the active littoral zone by regional uplift.

Sea caves can prove surprisingly complex where numerous zones of weakness—often faults—converge. In Catacombs Cave on Anacapa Island (California), at least six faults intersect. In several caves of the Californian Channel Islands, long fissure passages open up into large chambers beyond. This is invariably associated with intersection of a second fault oriented almost perpendicularly to that along the entrance passage.

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Further Reading

Bunnell, D. 1983. The amazing caves of Santa Cruz Island. *NSS News,* 41(2):86–91

Bunnell, D. 1988a. *Sea Caves of Santa Cruz Island,* Santa Barbara, California: McNally and Loftin

Bunnell, D. 1988b. The 1987 Na Pali Coast Sea Caves Expedition. *NSS News,* 46(2):446–53

Bunnell, D. 1993a. *Sea Caves of Anacapa Island,* Santa Barbara, California: McNally and Loftin

Bunnell, D. 1993b. Sea caving in the Channel Islands. *NSS News,* 51(6):150–59

Bunnell, D. 1995. Preliminary list of the long (>100m) sea caves of the world. *Geo*^{2}*,* 21:38–39

Bunnell, D. 1998. California's coastal sea caves. *NSS News,* 56(10): 292–300

MacCulloch, D.B. 1975. *Staffa,* 4th edition, North Pomfret, Vermont: David and Charles

Moore, D.G. 1954. Origin and development of sea caves. *National Spekological Society Bulletin,* 16:71–76

Petrocheilou, A. 1984. *The Greek Caves,* Athens: Ekdotike Athenon

Rodet, J. 1983. Karst et littoral du Bec de Caux. *Karstologia,* 2:23–32

Sjöberg, R. 1981. Tunnel caves in Swedish Archean rocks. *Tramactions of the BCRA,* 8(3):159–67

http://www.pipeline.com/-caverbob/seacave.html Long Sea Caves of the World

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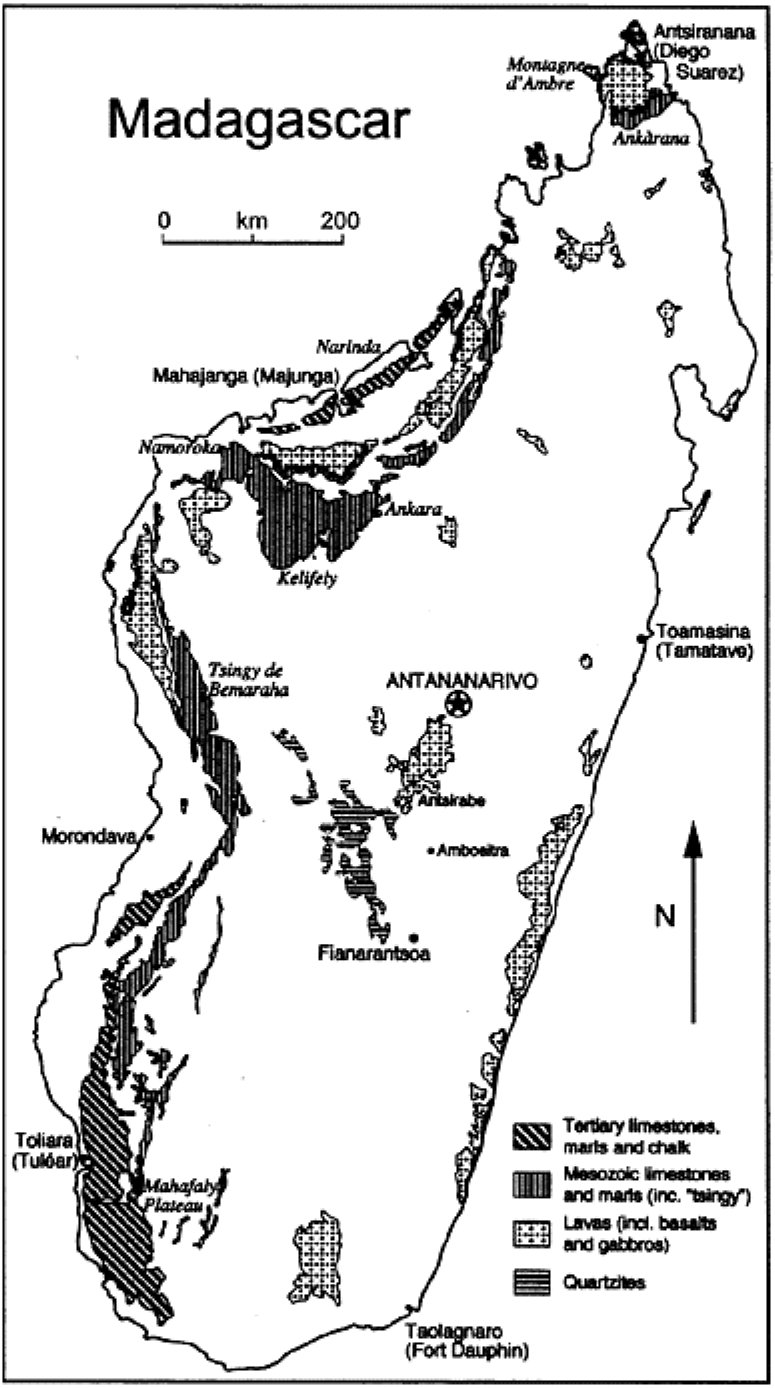
MADAGASCAR

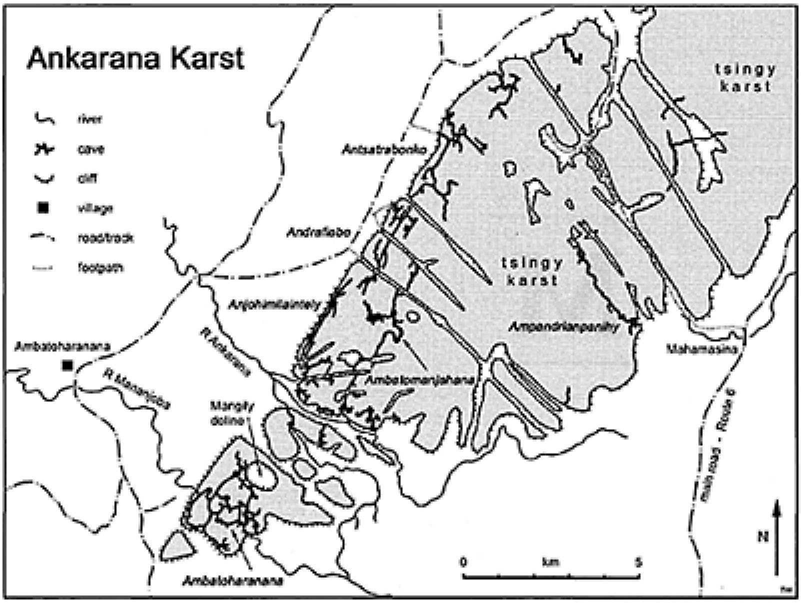
The island of Madagascar lies in the Indian Ocean, about 500 km from Mozambique. The fourth largest island in the world at 594000 km^2, it is of continental origin, having broken away from the African mainland *c.* 160 million years ago. It stretches 1600 km north to south and rises to an altitude of 2876 m. While much of the surface is lateritic sandstone over crystalline bedrock, there are extensive belts of karst, especially in the west, besides smaller areas of cave-bearing lava, quartzite, and granite (Figure 1). There was sporadic cave exploration during the French colonial period, particularly from the 1930s to 1960s, but major international interest in Madagascar's karst dates from the easing of restrictions on access to the country in the early 1980s, since when a number of British, French, and German expeditions and cavers from the United States, Australia, and Italy have documented many caves. The principal karst areas from north to south are as follows.

Ankarana

This area of some 200 km^2 of highly karstified Jurassic limestone lies about 70 km south of the northern city of Antsiranana (Diego Suarez). Initial exploration and documentation was undertaken, virtually single-handedly, by Jean Radofilao, but the area was really placed on the map by British expeditions in 1981 and 1986 (Wilson, 1990). The limestone, which rises up to 200 m in sheer walls on the west, has been deeply eroded under a strongly seasonal tropical climate, giving rise to a distinctive landscape of small pinnacle karst fretted by rillenkarren (see separate entry, Karren) and known locally as "tsingy" (derived from the ringing sound emitted when struck). The karst is split by a series of deep, narrow fault-controlled canyons, some of which give access to caves (Figure 2). These sheltered canyons are inhabited by many endemic species of lemur, while the tsingy plateaus are sparsely colonized by succulent xerophytic plant species. The caves are perhaps best known for their watercourses and as one of the few places where crocodiles *(Crocodylus niloticus)* can be found underground; large eels are also present and probably provide the crocodiles' main food source. Bats include


Madagascar
0 km 200
Antsiranana (Diego Suarez)
Montagne d'Ambre
Ankàrana
Narinda
Mahajanga (Majunga)
Namoroka
Ankara
Kelifely
Tsingy de Bemaraha
ANTANANARIVO
Toamasina (Tamatave)
Antsirabe
Ambositra
Morondava
Fianarantsoa
N
Toliara (Tuléar)
Mahafaly Plateau
Taolagnaro (Fort Dauphin)
Tertiary limestones, marls and chalk
Mesozoic limestones and marls (inc. "tsingy")
Lavas (incl. basalts and gabbros)
Quartzites

Madagascar: Figure 1. The main karst areas in Madagascar.



Madagascar: Figure 2. Outline map of the main caves within the Ankarana karst, Madagascar.

both the insectivorous microchiroptera and the large fruit-eating species, *Eidolon dupraenum* and *Rousettus madagascariensis*. The more significant caves are Ambatoharanana (Grotte des Crocodiles) >18000 m (longest in Madagascar), Ambatomanjahana (Grottes des Rois) 2200 m, Andrafiabe 11460 m, Antsatrabonko 10400 m, Antsiroandoa 1100 m, Lavaka Fanihy (Grotte des Chauve-Souris) 4460 m, and Milaintety 8300 m. Most of the limestone is within the Ankarana Special Reserve, under the management of Assoc. Nationale pour la Gestion des Aires Protegées (ANGAP); an entry fee is payable and permits are required for scientific collecting. Some caves have been used as tombs and access to these by foreigners is normally restricted.

Narinda

Tertiary limestone and dolomite is found northeast of Majunga on the west coast. The topography is largely cone karst with rounded hills rising 20 to 40 m above a palm savannah. Caves are not known to be numerous, but Anjohibe (place of the big cave), previously known as Grotte de Andranoboka, with a length of over 5.3 km (Laumanns & Gebauer, 1993), was developed as a show cave during the colonial period (probably in the 1940s). Only a few rusty ladders and electrical insulators remain. Nearby is Anjohikely (place of the small cave), that is over 2.1 km long, well decorated and less trafficked than Anjohibe. To the west of Majunga, the karst continues as a plain with caves beneath.

Namoroka

This area comprises ~180 km^2 of Jurassic limestone, south of the Betsiboka estuary and the Andranomavo River. This area is very remote and has seldom been visited by cavers (Laumanns & Gebauer, 1993; Middleton, 1998b). The largest known cave is the complex maze of Anjohiambovonomby (Zebu Well Cave, 4630 m). The karst is similar to Ankarana, but has less relief and is more broken by canyons. Notable are some large bogaz that are flooded for several months each year and remain dry and bleached white for the other months.

Kelifely

Even though this area is contiguous with Namoroka and Ankara, the Kelifely Plateau—about 50×70 km—is treated separately. It is approached from the north or east and in the south rises in a 400–500 m escarpment and is bisected by the Mahavavy River. Access problems and threat of bandits have limited speleological investigation in recent years. Notable are Abadie's work in the 1940s (Abadie, 1950), Rossi's detailed geomorphological studies in the 1970s (Rossi, 1986), and Peyre's attempt in 1982 (Peyre, 1983). The plateau exhibits a variety of karst landscapes, with canyons, dolines, poljes, fluviokarst, cockpit karst, tsingy, and areas of volcano-karstic interaction. Some streams have part of their course underground; the Tondraka sinks and rises a number of times, flowing about 12 km underground before rising in the bed of the Mahavavy (Abadie, 1950). Peyre (1983) describes the main sink as "needing a rope" (he did not enter). Abadie reported three caves in the Kassijie Forest (Peyre's guides were too frightened of a local tribe to take him to them), one at the foot of Doany Hill and one (Anjohibe) near Ambararata village.

Tsingy de Bemaraha

This large, forested tropical karst extends for ~100 km northsouth and up to 15 km east-west in the central west of Madagascar, 150 km north of Morondava. The natural values of the region were recognized as early as 1927, when the Reserve Naturelle Integrale was established over a large part of the karst. This was expanded in 1966, to cover all of the karst north of the Manambolo River; at 152000 ha, it is the largest protected area in Madagascar. In 1990, the area was the first in Madagascar to be inscribed on the World Heritage List (Bosquet & Rabetaliana, 1992) and it is now managed with assistance from UNESCO. It was listed on account of both its superlative natural phenomena—particularly the spectacular pinnacle karst known as tsingy (Figure 3) and areas of exceptional beauty, and because it contains important natural habitats for conservation of biological diversity. Caves have been documented along the Manambolo Gorge, the river providing the only easy access into the area, and in less accessible parts of the karst (e.g. Dobrilla & Wolozan, 1994; Middleton, 1996, 1998a). North of the river, the caves consist of networks of joint-controlled passages that may be very extensive. Very old pottery may be encountered in the caves, which hopefully will not be disturbed.

Madagascar: Figure 3. Well-developed tsingy of karren-fluted pinnacles in the Tsingy de Bemaraha. (Photo by John Middleton)

Tulear Region

This is the most southerly extension of the western limestone belts, extending from ~300 km north of Tuléar (Toliara) to about 200 km south. The major feature in the north is the Mickoboka Plateau (where there are reports of pits—locally termed "avens"—up to 165 m deep) and, in the south, the Mahafaly Plateau, where there are numerous small caves and large pits up to 100 m in depth (Middleton, 1999). Underground waters in the region are inhabited by an endemic, eyeless white fish, *Typhleotris madagascariensis.*

The main documented region of lava tubes is around Montagne d'Ambre, just south of Antsiranana, and particularly to its west, south of Andranofanjava (Middleton, 2000). Caves have also been reported in quartzite at Mt Ibity (or Ibinty) in the central highlands (152 m long Grotte Albert) at an altitude of 1900 m, the highest cave in Madagascar.

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Works Cited

Abadie, Ch. 1950. Note sur la région du Kelifely. *Bulletin de l'Académie Malgache,* new series 28 (for 1947–48):12–16

Bosquet, B. & Rabetaliana, H. 1992. *Site du patrimoine mondial des Tsingy de Bemaraha et autres sites d'intérêt biologique et écologique du fivondronana d'Antsalova,* Paris: Unesco

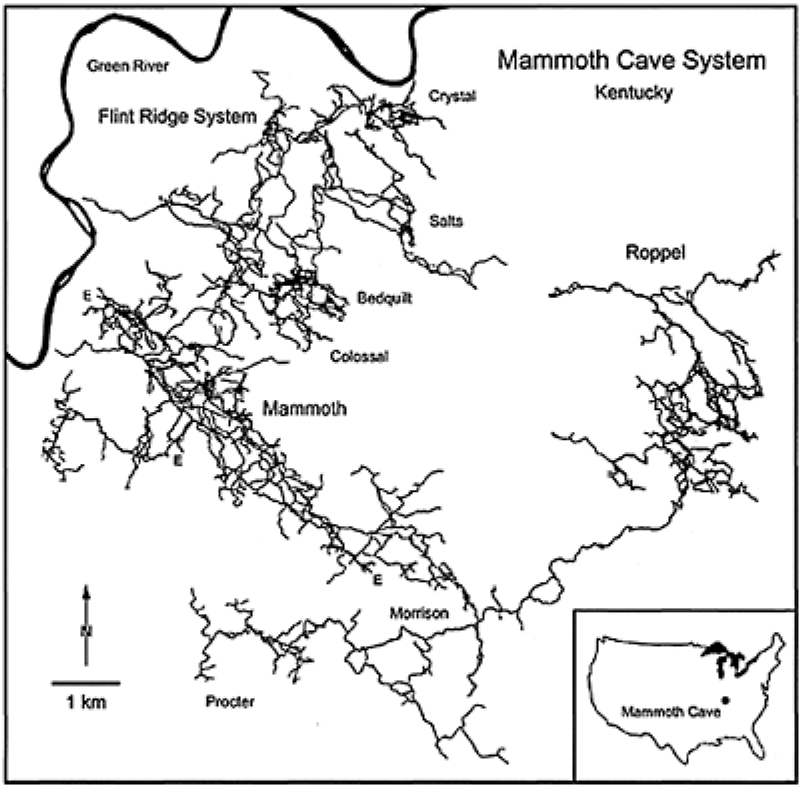
Dobrilla, J.-C. & Wolozan, D. 1994. Spéléologie sous les Tsingy de Bemaraha, Madagascar 1993. *Etudes et Documents de l'ADEKS,* 4 (1994):1–62
Laumanns, M. & Gebauer, H.D. 1993. Namoroka 1992: Expedition to the karst of Namoroka and Narinda, Madagascar. *The International Caver,* 6:30–36
Middleton, G. 1996. The 1995 Australo-Anglo-Malagasy SpeleoOrnitho-Malacological Expedition: Tsingy de Bemaraha, Western Madagascar. *Journal of the Sydney Speleological Society,* 40(9): 141–58
Middleton, G. 1998a. The 1996 International Speleo-Ornitho-Geo-Malaco-logical Expedition: Northern Tsingy de Bermaraha, Western Madagascar. *Journal of the Sydney Speleological Society,* 42(1):3–18
Middleton, G. 1998b. Narinda and Namoroka Karst Areas: Madagascar 1997. *Journal of the Sydney Speleological Society,* 42(10):231–43
Middleton, G. 1999. Mahafaly Plasteau and Onilahy Valley Expedition: Tulear Karst Region: Madagascar 1998. *Journal of the Sydney Speleological Society,* 43(7):157–67
Middleton, G. 2000. Madagascar 1999: A preliminary reconnaissance of the lava caves of Andranofanjava region. *Journal of the Sydney Speleological Society,* 44(10):335–42
Peyre, J-C. 1983. Au bout de la paperasse et des demarches administratives: encore 1'aventure. *Spéléologie,* 122:14–18
Rossi, G. 1986. Aspects morphologiques du karst du Kelifely (Madagascar). In *New Directions in Karst: Proceedings of the Anglo-French Karst Symposium September 1983,* edited by K. Paterson & M.M. Sweeting, Norwich: Geo Books
Wilson, J. 1990. *Lemurs of the Lost World: Exploring the Forests and Crocodile Caves of Madagascar,* London: Impact

Further Reading

Decary, R. & Kiener, A. 1971. Inventaire schématique des cavités de Madagascar. *Annales de Spéléologie,* 26:31–46
De Saint Ors, J. 1959. Les phénomens karstiques a Madagascar. *Annales de Spéléologie,* 14:275–91
Middleton, J. & Middleton, V. 2002. Karst and caves of Madagascar. Cave and Karst Science, 29(1):13–20.
Rushin-Bell, C.J. 1998. Caving in Madagascar. *NSS News,* 56(9): 260–61
Protected Areas Programme
http://www.wcmc.org.uk/protected-areas/data/wh/bemaraha.html

MAMMOTH CAVE REGION, UNITED STATES

Mammoth Cave (Kentucky, United States) is the longest cave in the world, with about 557 km of mapped passages. The cave consists of several large sections, explored separately through various entrances and connected by later discoveries (Figure 1). It is located mainly within Mammoth Cave National Park, estab lished in 1941, and is administered by the National Park Service. The Park, which encompasses 214 km^2, was designated a World Heritage Site in 1981, on the basis of its geological, archaeological, and biological significance. It was designated an International Biosphere Reserve in 1990. The Park receives an average



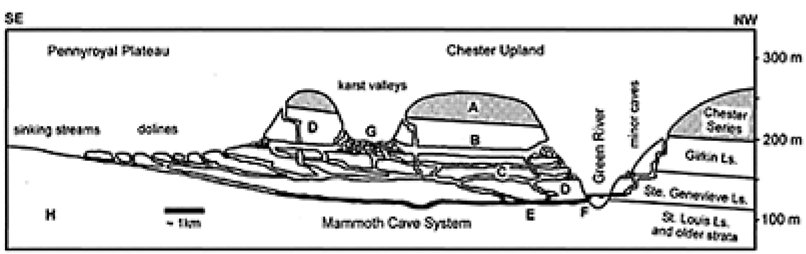
Mammoth Cave Region, United States: Figure 1: Map of the Mammoth Cave System, Kentucky (based on surveys by the Cave Research Foundation and Central Kentucky Karst Coalition). Names are shown for caves explored separately but connected by later discoveries. E=entrances to tour routes in the main part of Mammoth Cave.

of 1.7 million visitors per year. About 15 km of trails in the cave are open to the public, through 13 different guided tours. Other parts of the cave, which lie within the Park, are accessible only under permit for research or mapping. Mammoth Cave extends beyond the Park boundaries, but access to these sections is restricted. Exploration and surveying of the system are carried out by the Cave Research Foundation and the Central Kentucky Karst Coalition (White & White, 1989).

The cave is located in a low-relief plateau of Mississippian (lower Carboniferous) limestones and dolomites, locally capped by low-permeability sandstones and shales (Figure 2). The climate is temperate and humid, with a mean annual rainfall of ~1300 mm, and both surface and subsurface karst processes are very active. The average stratal dip is about 0.3° toward the northwest. The capped region (Chester Upland) rises to an altitude of *c.* 250 m. Stream erosion has breached the caprock, forming irregular flat-topped ridges separated by karst valleys. Most recharge to the system is through dolines in the valley floors, and from the adjacent Pennyroyal Plateau, a vast karst plain to the southeast, where the clastic rocks have been completely removed by erosion. Its surface lies about 45–60 m below the ridge crests of the Chester Upland. The karst area of the Pennyroyal Plateau and Chester Upland covers thousands of square kilometres, extending through western Kentucky and into adjacent Indiana and Illinois. All explored passages of the Mammoth Cave System lie in the Chester Upland, but dye traces show considerable subsurface inflow from ponors and dolines up to 10 km away in the Pennyroyal (Quinlan & Ewers, 1989).

Throughout the erosional history of the region (since the late Carboniferous, with few interruptions), the karst landscape has gradually migrated northwestward toward the centre of the Illinois Basin, as the overlying clastic rocks have been stripped away. Superimposed on this broad trend are irregular fluctuations in stream entrenchment rate, interspersed with occasional aggradation. A simplified review of the landscape evolution with time can be obtained simply by traversing the region from northwest to southeast, i.e. from downdip regions, where the caprock is still intact, to updip regions where the limestone is completely exposed and ultimately removed entirely by erosion.

In most places, the Pennyroyal is dimpled by an almost continuous array of dolines, but the overall surface has very little relief. Along the foot of the Chester Upland the surface is partly buried by thick colluvial, alluvial, and residual sediment. Remnants of alluvial gravel and sand persist at high elevations. Karst is also subdued in the far updip regions, because the carbonates are shaly and less deeply dissected. Surface drainage from this area sinks where it encounters purer carbonates or greater erosional relief. The Pennyroyal surface is a stratally discordant erosion surface formed during a period of rather stable base level (Miotke & Palmer, 1972).



Mammoth Cave Region, United States: Figure 2: Geologic cross section through the Mammoth Cave region. A=caprock composed mainly of sandstone and shale, with minor limestone units (late Mississippian-mid-Carboniferous age); B=large upper-level canyons and tubes of late Tertiary age; C=tubular passage levels of Pleistocene age; D=vadose infeeders of various ages; E=passages flooded by late Pleistocene rise in base level; F=springs partly blocked by alluvium; G=truncation of upper-level passages by karst valleys; H=impure limestones that support surface drainage.

The Green River, one of the few permanent surface rivers in the region, is the local base level for cave development at Mammoth Cave. The river now lies only 100 m below the ridge crests, but late Pleistocene alluvial fill has raised its level about 15 m. The Green River is a tributary to the extensive Ohio River, and so the passage layout and sediments of Mammoth Cave hold clues to the erosional history of the entire east-central United States.

Typical passages in Mammoth Cave consist of narrow vadose canyons that change downstream to tubular phreatic conduits. Canyons are fed by, or alternate with, vertical shafts up to 45 m deep. The local carbonate rocks are prominently bedded, with few conspicuous faults and joints, and so nearly all passages follow the bedding. Canyons have nearly flat ceilings and are almost invariably oriented directly down the local dip, following local irregularities in the partings along which cave inception took place (Palmer, 1981). Most canyons are only 1–3 m wide and highly sinuous, as the result of local variations in dip direction, which in turn are caused by minor irregularities (mainly depositional) in bedding-plane partings. Canyons in the uppermost levels of the cave are large, up to 20 m wide and 30 m high, and are generally far less sinuous than their narrower counterparts (Figure 3). Most vadose entrenchment involves headward retreat of waterfalls and rapids, imposed by massive or relatively insoluble beds.

Tubular passages have lenticular cross sections elongated along the bedding (Figure 4). They are not as sinuous as the typical narrow canyon, because their greater width engulfs all but the largest bedding irregularities. Most tubes form at or below the water table, although some minor ones (usually having rather flat ceilings) are perched vadose conduits. Fissure passages and linear passage segments are rare.

Shafts are generally round or oval in horizontal cross section and nearly all have developed in stages by successive downward dissolution from bed to bed, as shown by sequential drains at many elevations in their walls. Very few shafts descend in single drops along major fractures. Each drain leads to narrow canyons

Mammoth Cave Region, United States: Figure 3: Dyer Avenue, a remnant of the 183–189 m level of late Pliocene age in the Crystal Cave section of the Mammoth Cave System. Remnants of a former tourist trail are visible. (Photo by Art Palmer)

Mammoth Cave Region, United States: Figure 4: Turner Avenue, a tubular passage at the 168 m level of early Pleistocene age in the Flint Ridge section of the Mammoth Cave System. (Photo by Art Palmer)

or small stratally perched tubes that interconnect in tangled complexes. The abundance of sequential shaft drains is partly responsible for the great interconnectivity between various parts of the cave. Most shafts are clustered around ridge boundaries, where they receive diffuse seepage through the thin eroded edge of the clastic caprock.

Passages in Mammoth Cave are scattered over a vertical range of ~120 m. Vadose canyons can form anywhere above base level, and roughly half of them are still active today. But tubular passages cluster at only a few elevations, which indicate significant pauses in base-level lowering. Vertical sinuosity in the tubes indicates that while forming, they extended as much as 23 m below the water table. Former base levels, that controlled the vertical positions of the tubes, can be determined by the elevations of points where there is a change in the original downflow direction from downdip vadose canyons to tubes with irregular, low gradients and no systematic relation to the dip. Many tubes are oriented almost along the strike of the beds, following shallow routes along the same beds that guide the incoming vadose canyons. These vadose-phreatic transition points cluster at elevations of 210, 183–189, 168, and 152 m. These four levels were roughly dated from geomorphic evidence (Miotke & Palmer, 1972; Palmer, 1989) and by paleomagnetic analysis of sediment (Schmidt, 1982). Since then, much more precise dates have been obtained from $^{26}A1/^{10}Be$ ratios in quartz sediment (Granger, Fabel & Palmer, 2001). While the sediment is at the surface, these two isotopes are produced in tiny quantities by cosmic radiation. When the sediment is carried underground, the isotopes decay at different rates, and their ratio indicates the duration of burial.

The two upper levels (above 168 m) are wide canyons and tubes, filled to various depths with stream-borne quartz silt, sand, and gravel. Some are completely filled, but in others, most of the sediment has been removed by stream erosion. The greatest sediment thickness is about 20 m. Passages at these levels have sediment dates of 2.3–3.5 million years ago and, of course, the passage origins predate the sediment. These passages represent slow fluvial entrenchment during the late Tertiary, which was interrupted by periodic aggradation, probably in response to climate changes. The rather flat Pennyroyal Plateau surface formed at this time. At 2.3 million years ago, there was widespread aggradation to as much as 30 m, which filled all upperlevel passages, some partially and others completely. Aggradation also took place on the Pennyroyal surface. This event appears to coincide with the first major North American glaciation.

The two lower levels contain smaller passages, partly because groundwater recharge had been fragmented into many sub-basins by that time, and also because pauses in base level were shorter. They represent fairly rapid Pleistocene entrenchment of the Green River. Prior to that time, karst was probably sparse on the Pennyroyal, because of limited entrenchment. The rapid drop in base level during the Pleistocene caused nearly all surface drainage on the Pennyroyal to be diverted underground, and the extensive doline-pocked surface of today began to form. Cave levels at 168 and 152 m are well-developed tubes with little sediment fill. Sediments at these levels are, respectively, about 1.5 and 1.2 million years old. Passages at different elevations are mainly shafts, small canyons, and crawlways, mostly of vadose origin. Some large tubes have formed below the 152 m level, but their elevations are not consistent. They include local tube segments fed by many vadose infeeders, as well as passages perched on relatively insoluble beds.

The sudden abandonment of the large upper-level passages and development of many small passages at lower levels, apparently resulted from major changes in the patterns of surface drainage (see Palmer, 1981). Until the early Pleistocene, the Ohio River was rather small, not significantly larger than the Green River. Most of the drainage from the east followed a more northerly route (the so-called Teays River), which drained directly into the Mississippi River. The first major glacial advance into the region blocked the Teays and diverted its flow into the Ohio. Suddenly the Ohio became the largest river in the eastern United States. It began to entrench its valley rapidly and, as a tributary of the Ohio, the Green River did the same. Minor adjustments in drainage pattern may account for the periodic pauses in valley incision that resulted in the tubular passage levels. Diversion of the Teays drainage into the Ohio took place about 1.5 million years ago, accounting for the rapid entrenchment below the upper two cave levels.

At any time during the evolution of the cave, the pattern of active passages has been crudely dendritic. On cave maps, this pattern is obscured in several ways. For example, there are many superimposed levels of old, abandoned passages overlying more recent active ones. Even many active vadose passages cross over active or abandoned passages at lower levels. Post-glacial alluvial fill in the valley has flooded the lowest 15 m or so of the cave, reactivating many formerly abandoned passages.

Secondary mineral deposits in Mammoth Cave are highly varied. Calcite is rare because of the rather low caprock permeability, but evaporite minerals, such as gypsum and epsomite, are abundant in the driest passages.

The Mammoth Cave region contains hundreds of smaller caves, some of which are huge in their own right. Fisher Ridge Cave consists of 161 km of mapped passages northeast of Mammoth Cave, and there is almost certainly, as yet undiscovered, a connection between them. The Martin Ridge Cave System, to the southwest, contains more than 53 km of mapped passages. The Pennyroyal Plateau also contains many caves with one or two levels of passages. Some are very large, and most are highly flood-prone. An example is the Hidden River Cave System, east of Fisher Ridge Cave, which contains several tens of kilometres of explored passages.

The astonishing length of Mammoth Cave results from several coinciding factors. Its drainage basin is large, nearly 300 km^2. Prominent bedding, with many lithologic contrasts, allows diversion of vadose water along many successively lower partings. The resistant caprock has protected many of the uppermost passages from erosional destruction. Finally, the many small but discrete adjustments in base level have fostered the development of numerous, independent cave levels.

Mammoth Cave is also of great archeological, biological, and historical interest. As early as 4000 years ago, native humans ranged through many kilometres of the cave on a quest for minerals or adventure, using only reed torches for light. Artefacts, paleofaeces, and several mummified bodies have been discovered in the cave (see America, North: Archaeological Caves). Cave biota include the rare Kentucky cave shrimp and eyeless fish (see Mammoth Cave: Biospeleology). Sediment in the main passage of Mammoth Cave was mined for nitrates to make gunpowder during the “War of 1812” (see Gunpowder). Since then the cave has been more or less continually open to the public, first by a series of private owners, and later by the National Park Service.

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See also **Speleogenesis: Unconfined Settings**

Works Cited

Granger, D.E., Fabel, D. & Palmer, A.N. 2001. Pliocene-Pleistocene incision of the Green River, Kentucky, determined from radioactive decay of ^{26}Al and ^{10}Be in Mammoth Cave sediments. *Geological Society of America Bulletin,* 113(7):825–36

Miotke, F.-D. & Palmer, A.N. 1972. *Genetic Relationship among Caves and Landforms in the Mammoth Cave National Park Area,* Würtzburg: Böhler

Palmer, A.N. 1981. *A Geological Guide to Mammoth Cave National Park,* Teaneck, New Jersey: Zephyrus Press

Palmer, A.N. 1989. Geomorphic history of the Mammoth Cave System. In *Karst Hydrology: Concepts from the Mammoth Cave Area,* edited by W.B.White & E.L.White, New York: Van Nostrand Reinhold

Quinlan, J.F. & Ewers, R.O. 1989. Subsurface drainage in the Mammoth Cave area. In *Karst Hydrology: Concepts from the Mammoth Cave Area,* edited by W.B.White & E.L.White, New York: Van Nostrand Reinhold

Schmidt, V.A. 1982. Magnetostratigraphy of Sediments in Mammoth Cave, Kentucky. *Science,* 217:827–29

Thornbury, W.D. 1965. *Regional Geomorphology of the United States,* New York: Wiley

White, W.B. & White, E.L. (editors) 1989. *Karst Hydrology: Concepts from the Mammoth Cave Area,* New York: Van Nostrand Reinhold

Further Reading

Harmon, R.S., Schwarcz, H.P. & Ford, D.C. 1978. Stable-isotope geochemistry of speleothems and cave waters from the Flint Ridge—Mammoth Cave system, Kentucky: implications for terrestrial climate change during the period 230,000 to 100,000 years B.P. *Journal of Geology,* 86:373–84

Hess, J.W. & White, W.B. 1993. Groundwater geochemistry of the carbonate karst aquifer, south-central Kentucky, USA. *Applied Geochemistry,* 8:189–204

Palmer, A.N. 1987. Cave levels and Their interpretation. *National Speleological Society Bulletin,* 49:50–66

White, W.B., Watson, R.A., Pohl, E.R. & Brucker, R.W. 1970. The central Kentucky karst. *Geographical Review,* 60:88–115

MAMMOTH CAVE, UNITED STATES: BIOSPELEOLOGY

Introduction

In order to understand the biospeleology of Mammoth Cave, it must be viewed in the context of the South-Central Kentucky Karst, where there are two historical and four functioning ecosystems. In pre-settlement times, prairie and savannah maintained by fire were prevalent. These ecosystems were converted to agriculture over the past two centuries, but forest, river, and cave ecosystems are relatively intact. Mammoth Cave biota is among the most diverse in the world (Culver *et al.*, 1999), with approximately 130 regularly occurring species, roughly divided among troglobites, troglophiles, and trogloxenes (Barr, 1967; Poulson, 1992).

Interconnections and Habitats

Functionally, since sinking streams and cave streams are tributaries of base-level rivers by way of springs, they are all part of the river continuum, with the important distinction that the middle section is underground. These distinct but connected aquatic ecosystems are energetically supported by in-washed organic debris from the forest and former prairie/savannah ecosystems. Food transport is usually down gradient, but natural backflooding from the river into cave streams is also important.

Cave aquatic habitats can be roughly divided on the basis of water quantity. Ephemeral pools occur in rimstone dams, near terminal breakdowns, in passages rarely flooded, and in shafts. These may feed nearby shallow streams, tributaries to master shaft drains grading into base-level streams, which feed springs on Green River. As the river lowers its channel, cave streams follow and leave dry upper levels.

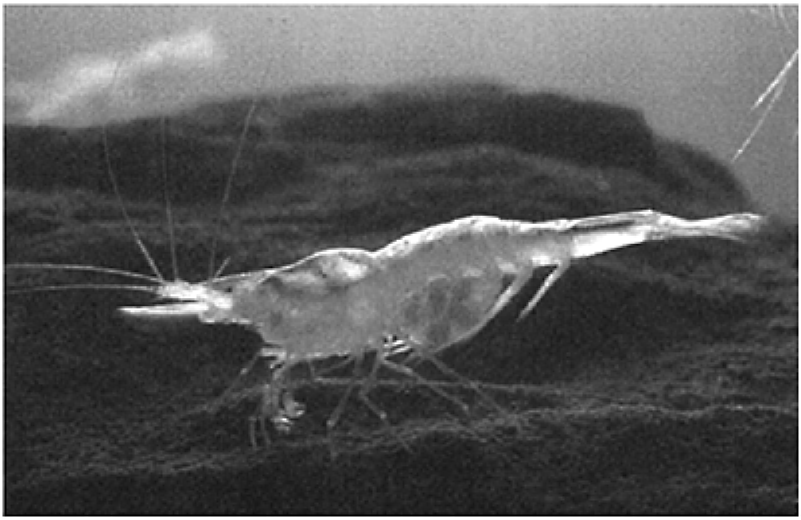
These upper levels are habitat for the terrestrial cave ecosystem, also dependent upon forest and agricultural land for food. The import of food is mostly accomplished by cave crickets, and to a lesser degree, by wood rats *(Neotoma magister)*. Also bats, which feed in the forest, use caves for refuge, depositing guano. Crickets' eggs within caves also support separate communities. Raccoons, entering caves to feed on bats and cave crickets, may leave significant quantities of scat. Habitats here are determined by proximity to entrances with variable temperature and humidity, which in turn determines the species depositing guano. Leaf litter falling into entrances, and flood debris deposited on passage surfaces, are also locally important to the terrestrial cave ecosystem.

The Biota and Their Interactions

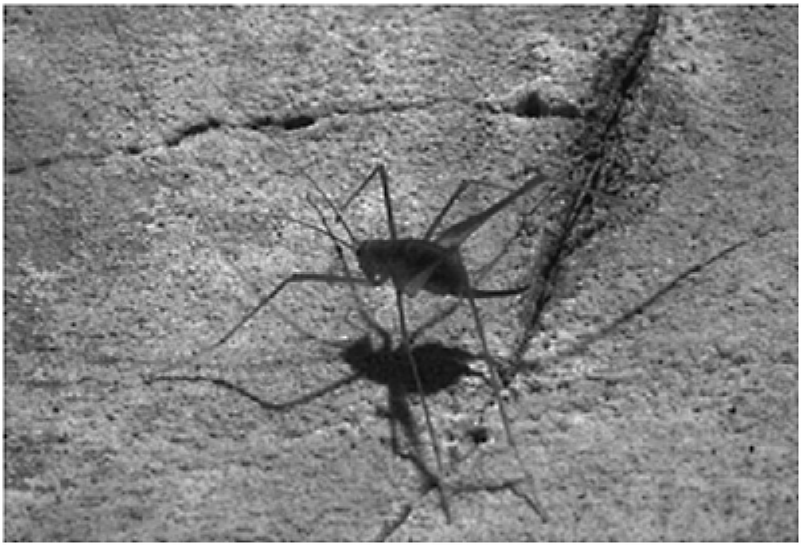
One prevalent aspect of aquatic life in the Mammoth Cave System is habitat partitioning by similar species within a taxonomic group. Two stygobitic species each of planaria *(Sphalloplana percocea* and *S. buchanani*), amphipods (*Stygobromus vitreus* and *S. exilis*), isopods (*Caecidotea stygius* and *C. bicrenata*), and fish (*Typhlichthys subterraneus* and *Amblyopsis spelaea*) occupy up-stream and downstream habitats, respectively. Stygobites found only in base-level streams include a snail *(Antroselates spiralis),* and the endangered Kentucky Cave Shrimp (*Palaemonias ganteri,* see Figure 1). The more adaptable cave crayfish *(Orconectes pellucidus)* occupies habitats ranging from base level to tiny streams, and can travel out of water if necessary. The stygophilic amphipod *Crangonyx packardi,* crayfish *Cambarus tenebrosus,* the sculpin *Cottus carolinae,* and the spring fish *Chologaster agassizi* often occur in organically rich situations. With the exception of sculpin, fish and crayfish are predators and the remaining species are primarily grazers.

Common organisms living within the sediments of Mammoth Cave streams are nematodes (undescribed), copepods *(Maraenobiotus, Moraria, Nitocra,* and *Parastenocaris),* tardigrades *(Macrobiotus),* and oligochaete worms *(Aeolosoma)*. Worm casts and tracks are also visible on mud banks of cave streams, and these organisms are preyed upon by troglobitic beetles, e.g. *Pseudanophthalmus striatus, P. menetriesii,* and *Neaphaenops tellkampfi.This* zone forms an ecotone between aquatic and terrestrial cave ecosystems. As part of the community dependent upon flood-deposited organic films, the springtails *Folsomia candida* and *Pseudosinella* are preyed upon by the troglobitic harvestman, *Phalangodes armata.* Another major ecotone exists at cave entrances, where litter from surface vegetation accumulates via gravity and wood rats. The collembolans *Tomocerus, Hypogastrura, Sinella,* and *Arrhopalites* are found in the entrance zone. Predators include the beetle, *Pseudanophthalmus,* and a rhagidid mite (Poulson, 1992).

The cave cricket (*Hadenoecus subterraneus,* Figure 2) buries its eggs in sandy passages with moderate moisture in the constant temperature zone, and *Neaphaenops tellkampfi* is especially skilled at finding those eggs. After cave crickets, this beetle has the highest density of any species in Mammoth Cave, and a small community subsists on beetle faeces (Poulson, 1992). The springtail *Arrhopalites* and the dipluran *Litocampa* are consumers, which are preyed upon by the mite *Arctoseius,* the spider *Anthrobia,* and the pseudoscorpion *Kleptochthonius*. These latter two are in turn preyed upon by *N. tellkampfi*.



Mammoth Cave, United States: Biospeleology: Figure 1. The Kentucky Cave Shrimp *(Palaemonias ganteri)* is an endangered species found only in the Mammoth Cave area. (Photo by Chip Clark).



Mammoth Cave, United States: Biospeleology: Figure 2. The Cave Cricket *Hadenoecus Subterraneus* is a keystone species in the terrestrial cave ecosystem due to many species dependent on its eggs and guano. (Photo by Rick Olson)

In addition to their eggs, *Hadenoecus* guano is also important as a food source. Crickets feed in surface habitats at night and return to the cave to roost. Here their guano supports the millipedes *Scoterpes* and *Antriadesmus*, the springtails *Hypogastrura, Arrhopalites, Pseudosinella, Tomocerus,* and *Lepidocyrtus* plus the bristletail *Litocampa,* the beetles *Ptomophagus hirtus* and *Batrisodes henroti,* the snail *Carychium stygius,* and the mites *Ceratozetes* and *Belba.* These in turn are preyed upon by the pseudoscorpion *Kleptochthonius,* the beetle *Pseudanophthalmus menetriesii,* the larval dipteran *Macrocera nobilis,* and the spider *Phanetta.* The spider *Meta ovalis* and the cave salamander *Eurycea lucifuga* are also present and prey upon crickets.

Woodrats and raccoons were formerly abundant in Mammoth Cave, and though today reduced, their faeces support specialized communities. Latrines of the Eastern Wood Rat *Neotoma magister* sustain larva of the fly *Psychoda* and fungus gnat *Bradysia,* and the beetle *Ptomaphagus hirtus,* which are preyed upon by the rove beetle *Quedius* (Richards, 1990). Raccoon faeces support a similar community, with the exception that cave crickets may preempt fly larvae, most notably *Spelobia* and *Amoebelaria*.

Due to low populations, bat guano in Mammoth Cave is today negligible as an energy source, but would have been highly significant during pre-settlement times, since Mammoth Cave was formerly one of the largest bat hibernation sites in the world. Indiana Bats *(Myotis sodalis)* and to a lesser extent Gray Bats *(M.grisescens)* were prominent species in Mammoth Cave only 150 years ago, but are today listed as endangered. Little Brown Bats *(M. lucifugus)* were also abundant, with the Big Brown Bat *(Eptesicus fuscus)* and Eastern Pipistrelle *(Pipistrellus subflavus)* being less common (Toomey *et al.*, 1998). These, and more rare bat species, such as *M. leibii* and *M. septentrionalis,* have been estimated to have had a total population of 9–12 million just in the Historic Section (Tuttle, 1997). Ecological restoration of this portion of Mammoth Cave, and the facilitation of the return of bats is an ongoing effort (Olson, 1996).

Major Conservation Issues

In addition to correcting major ecological distortions to the Historic Section of Mammoth Cave, lamp flora are a problem as in all show caves, and elimination via wavelength selection has been achieved on a small scale (Olson, 2002). On a karst landscape scale, contamination of groundwater recharge is a major issue, especially from Interstate Highway 65 (Olson & Schaefer, 2002). A problem also exists downstream on Green River in the form of Lock and Dam Number 6, which ponds water up into Mammoth Cave and degrades the habitat for the endangered Kentucky Cave Shrimp (Olson & Leibfreid, 1999).

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Works Cited

Barr, T. 1967. Ecological studies in the Mammoth Cave System of Kentucky, I. The Biota. *International Journal of Speleology,* 3: 147–203

Culver, D., Master, L., Christman, M. & Hobbs, H. 1999. Obligate cave fauna of the 48 contiguous United States. *Conservation Biology,* 14:386–401

Olson, R. 1996. This old cave: The ecological restoration of the historic entrance ecotone of Mammoth Cave, and mitigation of visitor impact. *Proceedings of the Fifth Annual Mammoth Cave National Park Science Conference,* Mammoth Cave National Park, Kentucky: National Park Service

Olson, R. 2002. Control of lamp flora in Mammoth Cave National Park. In *Proceedings of the International Conference on Cave Lighting, November 2000, Budapest, Hungary,* edited by T. Hazslinszsky, Budapest: Hungarian Speleological Society: 131–33

Olson, R. & Leibfreid, T. 1999. The importance of inventory and monitoring data sets in resolving ecosystem management problems at Mammoth Cave National Park. In *On the Frontiers of Conservation: Proceedings of the 10th Conference on Research and Resources Management in Parks and on Public Lands,* edited by D. Harmon, Hancock, Michigan: George Wright Society

Olson, R. & Schafer, J. 2002. Planned spill retention and runoff filtration structures on Interstate 65 in the South-Central Kentucky Karst. *Proceedings of the 2001 National Cave and Karst Management Symposium, Tucson, Arizona,* edited by T.Rea, Tucson, Arizona: US Department of Agriculture, Forest Service

Poulson, T. 1992. The Mammoth Cave ecosystem. In *The Natural History of Biospeleology,* edited by A.I.Camancho, Madrid: Museo Nacional de Ciencias Naturales

Richards, P. 1990. The effects of predation on invertebrate community structure in the cave rat fecal latrine. Cedar Falls, Iowa: Cave Research Foundation (Cave Research Foundation 1990 Annual Report)

Toomey, R., Colburn, M., Schubert, B. & Olson, R. 1998. Vertebrate paleontological projects at Mammoth Cave National Park. In *Proceedings of Mammoth Cave National Parks Seventh Science Conference,* Mammoth Cave National Park, Kentucky: National Park Service

Tuttle, M.D. 1997. A Mammoth discovery. *Bat Conservation International,* 15(4):3–5

Further Reading

Barr, T. 1985. Cave life of Kentucky. In *Caves and Karst of Kentucky,* edited by P.H.Dougherty, Lexington: Kentucky Geological Survey

MARINE CAVE HABITATS

Marine (or littoral) caves form special environments within rocky shores. Although their walls and ceiling are of hard substrate, the bottom substrate can be either soft or hard. Marine caves can be as large as many cubic metres; however small voids and crevices of several cubic centimetres are also included in this habitat, which can ecologically be termed as the mesolithial. The biocenosis (or community of living creatures) in the mesolithion is comparable to that in the marine mesopsammon (sandy-bottomed habitats) including the interstitial fauna between grains of sand. Therefore, when considering the mesolithion the fauna between or under boulders and pebbles should be included.

The larger sea caves which lie at the water surface and therefore include air domes are called grottos and passages, and those which lie below the water surface are called bag caves (if they have only one entrance; from the German *Sackhöhle*) or tunnels (Riedl, 1966). All these kinds of sea caves have a constant euhaline salinity level, in contrast to anchialine caves where salinities decrease from their sea entrance, to a brackish or freshwater environment (see Anchialine Habitats). Holes or crevices within sea caves form caves within caves. They may shelter mobile animals from being visible if they are very narrow; piddock holes can completely contain the inhabitants (Abel, 1959).

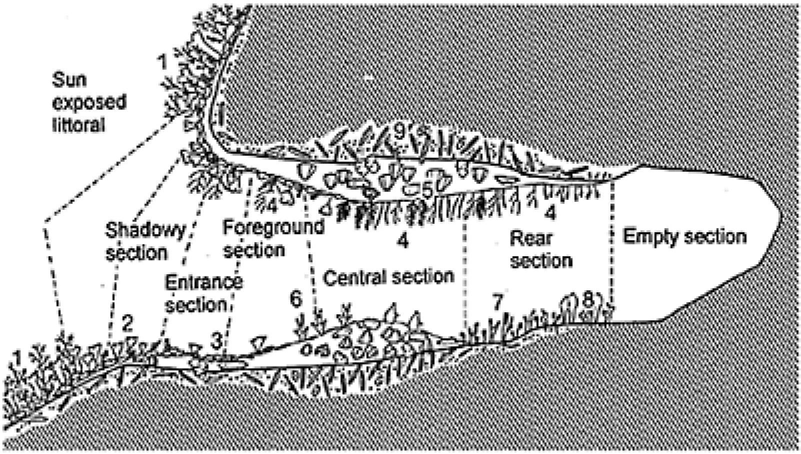
Three main abiotic parameters influence the composition of the biocenosis of sea caves: light, currents, and constancy of substrate. Light decreases to 10% of surface illumination in cave entrances (reflected light zone), and to 1% and lower (scattered light zone) in the inner cave sections (Riedl, 1966). This reduction is caused by distance from the entrance, by substrate inclination, and, most importantly, by absorption of light with depth. The important consequence is that photosynthesis, and therefore the existence of plants, ceases in this habitat. The greater the depth of sea caves, where light absorption can attain lower values than 1 % of surface light on the open substrate, the less significant they are ecologically.

Currents of at least 2–10% of the strength of surface currents are needed in order to guarantee a constant influx of plankton into sea caves; these are then prey for the many sessile filter feeders. With increasing distance from the cave entrance, the number of passive filter feeders increasingly exceeds the number of active ones. Where currents are absent or weak, plankton cannot penetrate the boundary layer of the substrate and “empty sections”, where sessile fauna cannot exist, are found (Gili, Riera & Zabala, 1984).

The mobility of the substrate is of importance when considering small voids such as the holes and crevices between boulders and pebbles. The latter must be heavy enough to remain in position for at least two months in order to give colonizing animals the chance to grow and mature. Where voids change in size or location with a periodicity of less than two months they provide shelter only for mobile fauna.

Sea caves characteristically consist of five sections (Riedl, 1966; see Figure):

1. Entrance section, where crusted red algae may still have a chance of existence.
2. Foreground section, where hydroids and bryozoans dominate.
3. Central section, where the densest populations of sponges, oysters, barnacles, zoantharians, and corals occur, partially overlain by higher bryozoans and hydroids, gorgonians, and finger-shaped sponges.



Marine Cave Habitats: A characteristic bag cave and its five sections, and the zones outside the cave. 1: light-exposed algae; 2: shadow-flora; 3: crusted flora; 4: hydroids; 5: sponges, oysters, barnacles; 6: bryozoans; 7: gorgonarians; 8: finger-like sponges; 9: boring mussels and sponges. (According to Ott, 1996)

4. Rear section, where the density of organisms, which are predominantly sponges, decreases.
5. Empty section, where no sessile organisms can exist.

Generally, the biocenosis of sea caves is characterized by species which prefer currents (rheophilic) but avoid light (photophobic). These are predominantly sessile, filter-feeding groups such as sponges, barnacles, mussels, ascidians, and polychaetes, but also comprise anthozoans and hydrozoans. These groups make up to 80–90% of the total population. The remaining 10–20% are mobile animals which are animal grazers, deposit feeders, or predators such as gastropods, crustaceans, also apparently decapods, and fish. Blenniid fish (blennies) prey on sponges and other "aufwuchs" (the plants and animals that are attached to or move about on the surfaces of submerged plants or debris) (Zander, 1990). There are no troglobitic species found exclusively in sea caves, but many troglophilic species exist which search for prey during the day and can even leave caves. Several shrimp and fish species hide in caves during the day, but leave them and become active at night.

Some special adaptations are characteristic of cave-dwelling organisms. Many species are conspicuous by their red or bright yellow colouring. This is true of many sponges, anthozoans which can dominate in the central section, crustaceans, ascidians, and fish.

The red colour is advantageous because of its invisibility in the scattered light zone (below 1% of surface light). Redcoloured fish of Mediterranean caves include, for example, the suprabenthic *Anthias anthias* (Serranidae) and *Apogon imberbis* (Apogonidae), as well as the epibenthic *Lipophrys nigriceps* (Blenniidae) and *Tripterygion melanurus* (Tripterygiidae) (Zander & Heymer, 1976). *Parablennius zvonimiri* (Blenniidae) changes from red in the cave to chocolate brown outside (Zander, 1990). It is apparent that these species are diurnally active, in contrast to dusty-coloured species like *Oligopus ater* (Bythitidae) or *Phycis phycis* (Gadidae) which are active nocturnally.

Diurnally active troglophilic fish have enlarged eyes which enable them to use the reduced light. The epibenthic *Lipophrys nigriceps* additionally possess bigger lenses and cones, as well as a more advantageous relation of rods and cones than related species from the free littoral (Zander, 1982). In contrast, nocturnally active fish have rather reduced eyes.

The adaptation of sessile organisms to life in caves are short planktonic periods: the parenchymula larvae of sponges, planula of cnidarians, and cyphonautes of bryozoans settle out and become sessile within hours in order to use the substrate as quickly as possible. Mobile cave-dwellers such as crustaceans or echinoderms have relatively long larval periods with durations of several months. Life-spans of one year or longer are an adaptation of sessile animals to prolong the period of distribution (e.g. Cnidaria, Echinodermata; Riedl, 1966).

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See also **Anchialine Habitats**

Works Cited

Abel, E.F. 1959. Zur Kenntnis der Beziehungen der Fische zu Höhlen im Mittelmeer. *Pubblicatione della Stazione Zoologia Napoli,* 30 (Suppl.): 519–28

Gili, J.M., Riera, T. & Zabala, M. 1984. Physical and biological gradients in a submarine cave in the western Mediterranean coast (north-east Spain). *Marine Biology,* 90:291–98

Ott, J. 1996. *Meereskunde: Einführung in die Geographie und Biologie der Ozeane,* Stuttgart: Ulmer

Riedl, R. 1966. *Biologie der Meereshöhlen: Topographie, Faunistik und Ökologie eines unterseeischen Lebensraumes,* Hamburg: Parey

Zander, C.D. 1982. Morphological and ecological investigations on sympatric *Lipophrys* species (Blenniidae, Pisces). *Helgoländer Meeresunter-suchungen,* 34:91 − 110

Zander, C.D. 1990. Benthic fishes of sea caves as component of the mesolithion in the Mediterranean Sea. *Mémoires de Biospéologie,* 17:57–64

Zander, C.D. & Heymer, A. 1976. Morphologische und ökologische Untersuchungen an den speleophilen Schleimfischartigen *Tripterygion melanurus Guichenot, 1850 und T. minor* Kolombatovic, 1892 (Perciformes, Blennioidei, Tripterygiidae). *Zeitschrift für Zoologische Systematik und Evolutionsforschung,* 14: 41–59

MENDIP HILLS, ENGLAND

The smallest of the four main karst areas in Britain, the Mendip Hills of southwest England, are of special interest because of the unusual complexity of their geological structure, history of erosion, burial and exhumation, and the occurrence of periglacial features. Although there are only about 200 known caves, with an aggregate length of no more than 60 km, these systems display many classic geomorphological features, and are often cited as the type examples for cave development in geologically unconfined settings (Ford & Ewers, 1978) (see also Speleogenesis: Unconfined Settings).

The Mendips form an elongate plateau 40 km long and 8 km wide, rising abruptly to a maximum of 250 m above the surrounding lowlands at or close to modern sea-level. Structurally they consist of four *en echelon* asymmetrical periclines, each with a central core of Devonian sandstone flanked by Carboniferous limestone. Marginal dips are high, mostly between 20° and 70°; the steepest dips occur on the northern limbs, which in places are overturned. The Carboniferous limestone sequence comprises about one kilometre thickness of regular, medium- to thick-bedded platform carbonates, with a thin but hydrologically important sequence of calcareous shales (the Lower Limestone Shale) at the base (Waltham *et al.,* 1997). In deep structural basins either side of the Mendips, these strata are overlain by sandstones and Coal Measures, themselves partially buried by Mesozoic strata. Folding and thrusting have created complex joint and fault patterns in the rocks.

Permian uplift and erosion created a rugged desert topography incised by many ravines. The sandstone core of the western pericline was breached and gutted, leaving the limestones as cuestas. Regional extension and karst solution created numerous fissures. The Hills then began to subside. Ravines were filled with scree and fan deposits, creating a cemented calcareous breccia known locally as the “Dolomitic Conglomerate”. The rugged crest was subject to planation. Fissures were infilled with terrestrial Triassic and marine Jurassic deposits, and the Mendips became buried under thick Jurassic and Cretaceous deposits. There was extensive lead and zinc mineralization during the burial. Paleokarst features are now exposed in quarries, including marine surfaces with borings, filled caves, and collapses, but they do not appear to have influenced modern karst development to a significant extent.

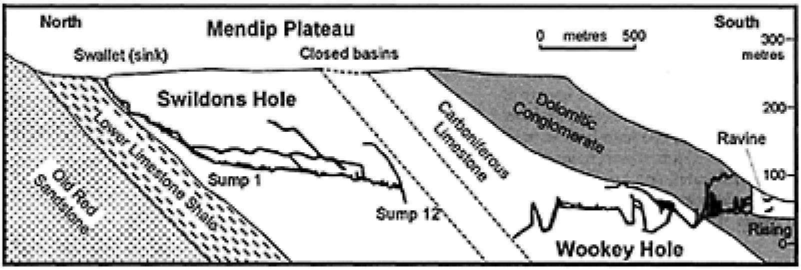
Tertiary and Quaternary erosion by eastward scarp retreat has partially exhumed the former Triassic landscape beneath, exposing the limestone and allowing the development of cave and karst systems, initially in the west and then progressively eastwards during the past two million years or more. The Hills were never glaciated, but ice reached their northern margins and there were severe periglacial conditions periodically. During this time, base-level continued to fall, permitting multiphase caves to form. The largest of these are found in central Mendip, because cave development has been active there for a long period but surface lowering and dissection have not yet destroyed them. Caves on western Mendip are generally older truncated fragments of relict phreatic systems, many of which are important archaeological sites. Conversely, eastern Mendip is characterized by numerous immature sinks and springs but generally few caves. Exceptions are the extremely well-decorated caves intersected by Fairy Cave Quarry and the Stoke Lane Slocker system with its active streamway and large relict chambers.

The principal surface karst landforms are dolines, dry valleys, and gorges (Ford &: Stanton, 1968). The central plateau is indented with regular dendritic patterns of dry valleys that deepen into the gorges of Cheddar, Ebbor, and Burrington Coombe as the steep flanks of the Hills are approached. Cheddar is the largest limestone gorge in Britain. The origin of the valleys is attributed to inheritance from the non-karstic cover rocks, which was succeeded by episodic entrenchment during periglacial stages or when surface runoff could be generated during very severe storms. The longer dry valleys are all indented by dolines, but local runoff can flow along them during the most severe storms.

The Hills contain numerous solution dolines. These are generally small, but can be up to 20 m in depth and 100 m in diameter. Stream-sink dolines have allogenic stream-flow from the Limestone Shales or cover rocks. Dolines are also scattered along dry-valley floors, and on slopes and interfluves, but there is never the complete colonization required to form polygonal karst. Larger, shallow closed basins drain to one or more central small dolines. They are infilled with clays, loessic or thermoclastic deposits, with modern suffosion dolines draining through them. Most have an overflow outlet in the perimeter, indicating that they filled episodically as lakes; one has a lake-edge corrosion platform 25 m wide, with a low limestone cliff at its back (Ford & Stanton, 1968). These basins are taken as evidence of effective permafrost blockage of the smaller catchments; larger catchments supplied by allogenic streams maintained groundwater intake through the most severe cold. There are collapse dolines through thin covers of Liassic limestones or marls resting on the Carboniferous limestones.

The steeply dipping limestone has produced a characteristic style of cave development, with most influent caves developed at the stratigraphic base of the limestone. Typically, an "invasion" vadose streamway descends rapidly down dip to the local baselevel, whereupon the passage continues as an undulating phreatic tube, ultimately reaching the resurgence after rising stratigraphically through the limestone sequence. Depending on its orientation, the phreatic passage takes on either a looping profile following bedding planes down dip and ascending stratigraphically up joint or fault risers, or develops along strike as a series of shallower loops or quasi-horizontal elliptical tubes along bedding partings. Most systems display a mixture of both. The deepest loop so far explored is 60 m deep in Wookey Hole. Due to the depth that the active phreatic conduits reach, and the sediment that accumulates in them to obstruct the loops, no Mendip cave has been explored completely from sink to spring. Most known caves are either vadose influent systems, resurgence systems, or relict fragments truncated by surface entrenchment or lowering. The study of these caves has stimulated development of the "four-state model" for cave long section genesis and also modern understanding of the network-linking rules that govern the plan patterns of a majority of caves forming where there is unconfined groundwater circulation (Ford, 2000).

There are substantial deposits of clastic sediments in all but the youngest caves, ranging from pebble and cobble sizes down to sand, silt, and clay. Most relict passages become blocked by them, and elsewhere they have aided the development of paragenetic features. Many of these clastic fillings are interbedded with speleothem layers that have been dated to the warm phases of the past 350000 years. This suggests that the clastics were deposited chiefly during colder phases when forest cover was reduced or eliminated.



Mendip Hills: Figure 1. Profile of the known passages in Swildons and Wookey caves, beneath the Mendip Hills. The vertical scale is exaggerated by 5, and there is a gap of 2300 m between the nearest points in the two caves.

At 9.1 km in length, the longest cave on Mendip is Swildons Hole, a classic influent cave system (Figure 1). The streamway initially cascades steeply down a small vadose canyon to a siphon, “Sump 1”, the location in 1935 for a pioneering diving attempt using a home-made respirator. Beyond it the passage gradient slackens and the streamway changes to a series of phreatic loops. The troughs are marked by ten further siphons before becoming impassable at a twelfth. Between the sumps, the stream flows through vadose canyons entrenched into the loop crests. Above lie series of abandoned passages at several levels, representing former courses of the stream that demonstrate a complex sequence of passage captures.

St Cuthbert’s Swallet nearby is a similar influent cave, with numerous vadose canyons developed either side of a plunging anticline uniting at depth into a single phreatic looping streamway. Extensive collapse, coupled with major sediment influxes and paragenetic development, have modified much of the original system, which is further disturbed by the influx of tailings from lead-mining operations.

Both caves have been traced to Wookey Hole, a resurgence which has been known since Roman times, a show-cave, and the site of many pioneering cave dives. Here, the River Axe flows through a series of deep phreatic loops within the Carboniferous Limestone, before reaching daylight via a channel with shallower sumps developed in the overlying Triassic Dolomitic Conglomerate.

To the west, the Charterhouse Caves (GB Cavern, Charterhouse, Manor Farm, and Longwood Swallets) are further classic examples of complex influent caves all draining to Cheddar Gorge. Relative to their size, this group of caves, especially GB Cavern (Figure 2), is one of the most intensively studied in the world, with much pioneering work on geomorphology (Ford, 1964; Atkinson, 1967; Smart *et al.*, 1984), landscape evolution, and paleoclimate (Atkinson *et al.*, 1978). All four major caves have similar morphology: vadose streamways with up to four vertically stacked abandoned phreatic conduits which occur at the same elevations in each cave, suggesting that they experienced a uniform response to base-level changes. Complex sequences of thick clastic sediments interbedded with stalagmites have been dated using U-series, ESR, and paleomagnetic methods.

The Charterhouse waters resurge at springs at the mouth of Cheddar Gorge, the lowest place at which limestone is exposed along the southern front of the main plateau. There is a series of abandoned conduits above them. The largest is Gough's Cave, which intercepts the active conduit. Discovered in 1898, this show cave is also one of Europe's most important Upper Paleolithic sites and the home of "Cheddar Man", one of several skeletons found in the cave. Mitochondrial DNA from this skele-

Mendip Hills: Figure 2. Very white calcite dripstone in the old high level of Bat Chamber in GB Cavern. (Photo by Tony Waltham)

ton was found/to match that of a schoolteacher living nearby today.

Quarrying has had a major impact, especially on eastern Mendip, where much of the outcrop has been quarried away or has planning permission for quarrying. Some quarries are now subwater-table operations and have intercepted groundwater conduits between the sinks and resurgences. The sub-water-table quarrying may affect the Bath Hot Springs 20 km to the northeast.

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See also **Speleothems: Carbonate for photo from Shatter Cave**

Works Cited

Atkinson, T.C. 1967. The geomorphology of Longwood Swallet, Charterhouse-on-Mendip. *Proceedings of the University of Bristol Spelaeological Society,* 11:161–85

Atkinson, T.C., Harmon, R.S., Smart, P.L. & Waltham, A.C. 1978. Paleoclimatic and geomorphic implications of ^{230}Th/^{234}U dates on speleothems from Britain. *Nature,* 272:24–28

Ford, D.C. 1964. On the geomorphic history of GB Cave, Charterhouse-on-Mendip, Somerset. *Proceedings of the University of Bristol Spelaeological Society,* 10:149–88

Ford, D.C. 2000. Speleogenesis under unconfined settings. In *Speleogenesis, Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Ford, D.C. & Ewers, R.O. 1978. The development of cave systems in the dimensions of length and breadth. *Canadian Journal of Earth Sciences,* 15:1783–98

Ford, D.C., & Stanton, W.I. 1968. Geomorphology of the southcentral Mendip Hills, *Proceedings of the Geologists' Association,* 79(4):401–27

Smart, P.L., Moody, P.D., Moody, A.A.D. & Chapman, P.R.J. 1984. Charterhouse Cave: Exploration, geomorphology and fauna. *Proceedings of the University of Bristol Spelaeological Society,* 17:5–27

Waltham, A.C., Simms, M.J., Farrant, A.R. & Goldie, H.S. 1997. *Karst and Caves of Great Britain,* London and New York: Chapman and Hall

Further Reading

Barrington, N. & Stanton, W.I. 1977. *Mendip, the Complete Caves and a View of the Hills,* Cheddar: Cheddar Valley Press

A very thorough guidebook, indispensable for anyone interested in Mendip caves and the karst landscape

Farrant, A.R. 1999. *Walks around the Caves and Karst of the Mendip Hills,* London: British Cave Research Association (BCRA Cave Studies, 8)

Friederich, H. & Smart, P.L. 1982. The classification of autogenic percolation waters in karst aquifers: A Study in GB Cave, Mendip Hills, Somerset. *Proceedings of the University of Bristol Spelaeological Society,* 16:143–60

Gunn, J. (editor) 1994. *An Introduction to British Limestone Karst Environments,* London: British Cave Research Association

Halstead, L.B. & Nicoll, P.G. 1971. Fossilized caves of Mendip. *Studia Speleologica,* 2(3):93–102

Hanwell, J.D. & Newson, M.D. 1970. The great storms and floods of July 1968 on Mendip. *Wessex Cave Club Occasional Paper,* 2(2)

Describes the events and aftermath of the 1968 floods.

MICROBIAL PROCESSES IN CAVES

Microorganisms are the most widespread form of life on Earth and represent the largest biomass grouping of organisms. They are adapted to many modes of life, unfamiliar to us as dwellers on the planet's surface. In common with ourselves, some microorganisms use atmospheric oxygen to respire an organic substrate (food) to generate energy for vital processes. However, many are adapted to life in the subsurface, where oxygen is usually absent (i.e. conditions are anoxic). These utilize other types of respiration, most commonly reduction of nitrate, or oxidized forms of iron and manganese or sulfate; processes which are less energyefficient than oxygen respiration, but allow bacteria to colonize and thrive in a wide range of environments. All of these bacteria are heterotrophs—that is, they require an organic substrate for respiration, and cell growth and division. Other bacteria are chemotrophs and can gain energy from the oxidation of inorganic substrates, such as sulfide and methane. Some bacteria are also autotrophs, having the ability to convert inorganic forms of carbon (such as carbon dioxide or bicarbonate dissolved in karst groundwaters) into organic carbon for cell growth.

The range of subsurface environments colonized by bacteria is huge. In soils, microbes play a central role in the degradation of plant and other organic material, under both oxic and anoxic conditions. Microbes and their activity have been identified at depths of hundreds of metres, in deeply buried aquifer sediments (Krumholtz, *et al.* 1997). In deep marine sediments, active bacteria have been identified at depths >700 m below the sea floor and the frequent recovery of biodegraded oil from reservoirs of even greater depth indicates that microorganisms are active deeper still.

Microbial activity is crucial to the origin and development of most "normal" limestone caves. Carbon dioxide, which forms the carbonic acid that corrodes limestone, is derived principally from respiration of soil microorganisms (and plant roots). The atmosphere contains only 0.035% CO_2, which provides minimal corrosive power via carbonic acid formation, whereas soil gases contain 0.1 to over 1% CO_2. The influence of soil bacteria in this respect is clear from the distribution of the world's largest limestone cave passages (in the tropics where the warmer soils are more productive) to seasonal differences in karst spring-water chemistry in temperate zones, due to differing seasonal rates of soil microbial activity.

In cave sediments, microbial activity has been shown to degrade organic matter in detrital sediments washed into cave systems (Humphreys, 1991; Bottrell, 1996). The nature and rates of these processes are similar to surface soils (Bottrell, 1996) and the microbial populations are presumably introduced with the surface-derived sediment. These microbes are, however, important in their ability to break down the complex surface-derived organic material in the sediment and thus form the basis of subterranean food chains.

Microbial reduction and oxidation of nitrogen species is implicated in the origin of nitrate deposits and nitrate-rich waters in caves. Sources of nitrogen may be indigenous guano or ammonium ions leached in by percolation from soil horizons overlying the caves (Hill, 1981). Bacteria such as *Nitrosomonas* spp. oxidize ammonium to nitrite, and then *Nitrobacter* spp. carry out the final stage of nitrification, the oxidation of nitrite to nitrate. These nitrates can crystallize as a variety of mineral forms in dry caves. An alternative view (Lewis, 1992) suggests that nitrogenfixing microorganisms may exist in cave sediments, but to date only nitrifying bacteria have been identified from caves (Fliermans & Schmidt, 1977).

Iron and manganese are the two metallic elements that most commonly undergo redox transitions in natural environments, which can be microbiologically mediated. Whilst reactions involving iron are likely prevalent, the distinctive black/purple colourations associated with manganese oxide deposits often make them a focus for study. Most iron and manganese formations and deposits in caves result from the microbiological oxidation of soluble Mn(II) and Fe(II) species in inflowing water to precipitate insoluble Mn(IV) and Fe(III) hydroxides (e.g. Peck, 1986; Manolache & Onac, 2000). Microorganisms, capable of such reactions, have also been found in cave clay deposits (Morehouse, 1968).

The microbial system that has received the most attention in caves and karst is that involving reduction and oxidation of sulfur species. The stable sulfur species under earth surface conditions is sulfate, but in anoxic environments a wide range of microbes are able to gain energy by using sulfate to oxidize organic matter (anaerobic respiration), usually reducing the sulfate to hydrogen sulfide. This process has been documented from several cave environments (e.g. Bottrell, *et al.,* 1991; Lauritzen & Bottrell, 1994). A larger variety of studies describe sulfidic waters entering the shallow, oxidized zone of karst aquifers, where hydrogen sulfide can be oxidized. This reaction represents a very significant energy source and again, a wide range of sulfur-oxidizing microbes are adapted to make use of it. The oxidative part of this cycle also has the ability to produce acidity that could be involved in development of significant secondary porosity and cave development (e.g. Morehouse, 1968; Hill, 1990). One example is Cueva de Villa Luz, Mexico (see Villa Luz entry). A particularly interesting case is the discovery of a previously closed cave system in Romania (Movile Cave, see separate entry), where a whole ecosystem has developed, based on chemoautotrophic microbial mats. These mats gained energy by oxidation of sulfide from thermal waters and could fix inorganic carbon for growth. This ecosystem was thus truly subterranean, completely independent of surface-derived photosynthetic organic matter.

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See also **Biofilms; Guano; Microorganisms in Caves; Sediments: Biogenic**

Works Cited

Bottrell, S.H., Smart, P.L., Whitaker, F. & Raiswell, R. 1991. Geochemistry and isotope systematics of sulphur in the mixing zone of Bahamian blue holes. *Applied Geochemistry,* 6:97–103

Bottrell, S.H. 1996. Organic carbon concentration profiles in recent cave sediments: Records of agricultural pollution or diagenesis? *Environmental Pollution,* 91:325–32

Fliermans, C.B. & Schmidt, E.L. 1977. *Nitrobacter* in Mammoth Cave. *International Journal of Speleology,* 9:1–19

Hill, C.A. 1981. Origin of cave saltpeter. *National Speleological Society Bulletin,* 43:110–26

Hill, C.A. 1990. Sulphuric acid speleogenesis of Carlsbad Cavern and its relation to hydrocarbons, Delaware Basin, New Mexico and Texas. *American Association of Petroleum Geologists Bulletin,* 74:1685–94

Humphreys, W.F. 1991. Experimental re-establishment of pulsedriven populations in a terrestrial troglobite community. *Journal of Animal Ecology,* 60:609–23
Krumholz, L.R., McKinley, J.P., Ulrich, G.A. & Suflita, J.M. 1997. Confined subsurface microbial communities in Cretaceous rock. *Nature,* 386:64–66
Lauritzen, S.-E. & Bottrell, S.H. 1994. Microbiological activity in thermoglacial karst springs, south Spitzbergen. *Geomicrobiology Journal,* 12:161–73
Lewis, W.C. 1992. On the origin of cave saltpeter: A second opinion. *National Speleological Society Bulletin,* 54:28–30
Manolache, E. & Onac, B.P. 2000. Geomicrobiology of black sediments in Vantului Cave (Romania): Preliminary results. *Cave and Karst Science,* 27:109–12
Morehouse, D.F. 1968. Cave development via the sulphuric acid reaction. *National Speleological Society Bulletin,* 30:1–10
Peck, S.B. 1986. Bacterial deposition of iron and manganese oxides in North American caves. *National Speleological Society Bulletin,* 48:26–30

MICROORGANISMS IN CAVES

Microbiologists study five main groups of organisms: bacteria, fungi, algae, protozoa, and viruses. The property that unites all microorganisms is their minute size. Prokaryotic microorganisms can be as small as 0.2 µm in diameter and as big as 750 µm in diameter in the newly discovered colourless sulfur bacterium, but the average bacterium is 1 by 3 µm. Eukaryotic cells are usually much larger, ranging from 2 µm to more than 200 µm in diameter. Typical bacterial shapes are cocci (spherical), rods, filaments, and spirals, but one can see bacteria that resemble braided or twisted rope-like shapes, stars, beads-on-a-string, etc. and fungal spores take on many unusual shapes, including some that look like ancient urns. The calcifying and silicifying algae take on intricate shapes with highly ornamented structures. Protista (algae and protozoa) and fungi are eukaryotic cells, similar to human cells in having a "true nucleus" ("eu" = true, "karyon"=nucleus). Bacteria and Archaea are prokaryotic ("pro"=before) and lack a true membrane-bound nucleus. Viruses are not even cells, just genetic material surrounded by a protein coat, and are incapable of independent existence. We know almost nothing about viruses in caves, with the exception of the rabies virus associated with bats.

Within caves, microbes cycle nutrients such as carbon and nitrogen, provide nutrition to invertebrates, and participate in the formation of secondary minerals (speleothems). Microbes may also produce some growth factors, such as vitamins, needed by higher organisms. Microorganisms in caves worldwide have been studied since the end of the 19th century, with many pioneering studies done in Europe (Caumartin, 1963; Juberthie & Decu, 1994).

Like all organisms, microorganisms require water, an energy source, and nutrients such as carbon and nitrogen, in order to grow. There is a broad range of physical conditions that microbes can tolerate, allowing them to occur in many habitats, including those hostile to humans. Microorganisms, particularly bacteria, are metabolically very diverse in what they can use for energy sources. Microbes can be divided into metabolic classes relating to the sources of energy they use. The three groups are heterotrophs, which utilize organic substrates as an energy source (these are also called chemoheterotrophs); photoautotrophs, which obtain energy from light; and chemolithotrophs, which obtain energy from inorganic compounds. Carbon for cell synthesis is obtained from organic substrates; however some microbes, including the photoautotrophs, fix CO_2. Some microorganisms in cave entrances and twilight zones use sunlight for energy, but most use chemical energy sources. In general, chemoheterotrophs are found where there is sufficient organic matter, and chemolithotrophs are found in the absence of organic matter where inorganic sources of chemical energy exist, such as manganese and iron.

Microorganisms can enter caves by flowing water, gravity, or on air currents, travelling through fissures, porous rocks, and tiny voids in the overlying rock, and can be carried in on humans or animals entering caves. Studies of microbes in caves have identified a wide variety of different microorganisms present; how they interact with and adapt to the cave environment; and their role in creating and destroying secondary mineral deposits. A new area of study is the broad field of geomicrobiology. Microbes are also seen as important in food-limited cave environments because they recycle organic material into microbial biomass as the first step in the food chain, or as primary producers (see Food Resources). Other microbes can be agents of disease, such as the fungus causing histoplasmosis.

Microbiological Methods

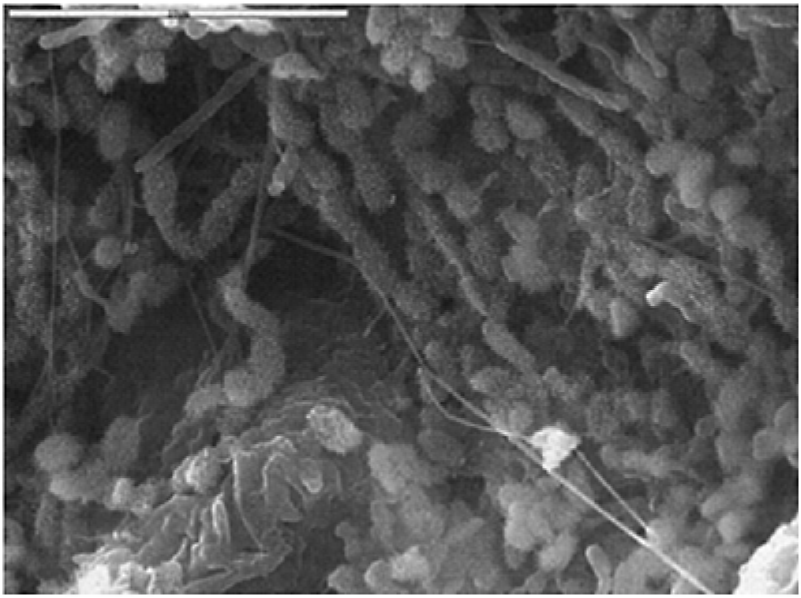
Basic microbiological techniques can be used to study karst microbes. Typically, we want to find out which microbes are present, their abundance, and what they are doing. Light microscopy with appropriate staining techniques (e.g. Gram's Stain) can be used to observe microorganisms and for enumeration. Staining with metabolic dyes such as INT has been used to indicate respiratory activity. Electron microscopy (e.g. scanning or transmission, see Figure 1) allows greater magnification and examination of the interaction of microbes with their environment.

Traditional methods of culturing microorganisms from the environment (e.g. spread plating) can be useful, although it has been estimated that only 0.1% can be cultured using standard techniques. Pure cultures of one kind of organism can be tested for biochemical and physiological characteristics for identification. The types and proportion of fatty acids (lipids) in cell membranes of microorganisms can be used to provide a "fingerprint" for identification. Newer applications do not require the microbes to be cultured. For example, fluorescent monoclonal antibodies are being developed for identification, but have had limited applications to cave microbes. Methods based on the microbial genetic sequences of DNA and RNA are being employed to identify cave microorganisms and to evaluate microbial diversity. Stable isotopic ratios are very useful in determining the contribution of microbes to the cave food-chain and their role in the production of secondary mineral deposits.

Major Groups of Microorganisms

Bacteria and Archaea

We are only now becoming aware of the complex range of prokaryotic microbes found in caves, and a tremendous amount of



Microorganisms in Caves: Figure 1. Scanning electron microscopy reveals the diversity of microorganisms present on the wall of a lava tube in the Cape Verde Islands. (Photomicrograph by M.Spilde, D. Northup, and P.Boston)

work remains to be done. Archaea, including those that produce methane, are just beginning to be studied in caves.

One of the most visible groups of bacteria seen in caves are colonies of actinomycete bacteria. They are evident as reflective white (sometimes pink or gold) dots on moist limestone or lava. These actinomycetes are responsible for the distinctive odour of caves and soils. Filamentous in nature, actinomycetes may be widespread in caves due to lower temperatures and high humidity. They have been implicated in the biodeterioration of cave paintings studied extensively in Altamira and other Spanish caves (Groth & Saiz-Jimenez, 1999). Two of the more commonly reported genera are *Streptomyces* and *Nocardia*. Actinomycetes are often very dense on the walls and ceilings of lava tube caves.

Bacteria are involved in all phases of the nitrogen cycle in caves. Studies have concentrated on the role of nitrifying bacteria, such as *Nitrosomonas* and *Nitrobacter,* in the generation of saltpetre, a component of gunpowder. The former oxidizes ammonia to nitrite and the latter oxidizes nitrite to nitrate. Bacteria that fix atmospheric nitrogen are also found in caves. Thus, the processes of ammonification, nitrification, denitrification, and nitrogen fixation have all been documented in caves.

Studies of sulfur bacteria have rapidly expanded in the last decade as several new sulfur-containing caves have been discovered, including Movile Cave (see separate entry), whose food web is based on chemolithotrophic processes involving sulfur and other compounds (Sarbu, Kane & Kinkle, 1996). Isotopic studies have established a microbial role in the production of sulfur compounds and in the enlargement of passages in caves (reviewed in Northup & Lavoie, 2001). Both sulfide/sulfur oxidizers (*Thiobacillus, Beggiatoa,* and *Thiothrix*) and sulfate-reducers are found in caves.

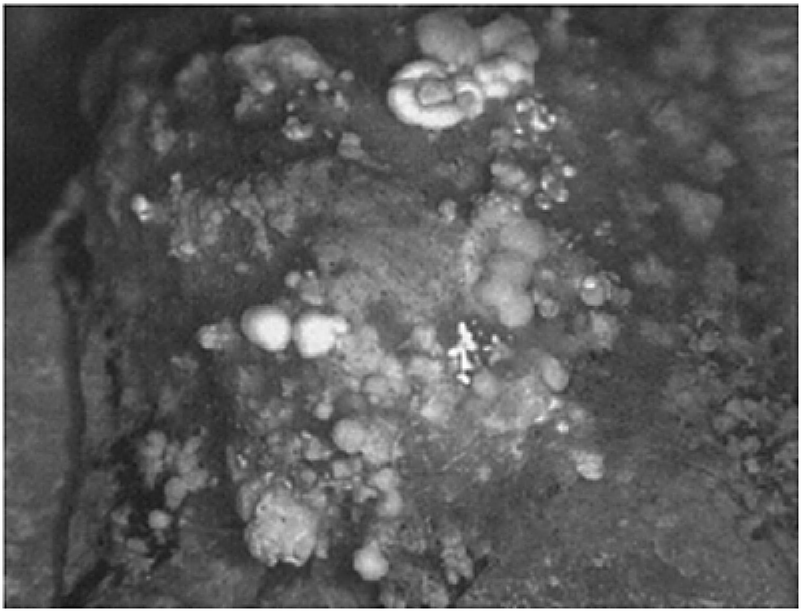
Several studies have proposed microbial participation in the formation of cave manganese and iron deposits. Manganese- and iron-oxidizing bacteria have been reported from caves, including the genera *Leptothrix, Gallionella,* and *Clonothrix*. Most studies have reported only on the presence of these bacteria, but some studies have established the production of manganese and iron oxides in cultures of organisms from caves. Cyanobacteria, formerly classified as algae (i.e. blue-green algae), are photosynthetic bacteria that produce oxygen. They are frequently found in the entrance and twilight zones of caves, alone, or as one partner in the lichen symbiosis with fungi. Some are adapted to very low-light conditions, and some have the ability to fix atmospheric nitrogen, allowing them to colonize low-nitrogen areas. Two cyanobacteria described from caves, *Geitleria calcarea* and *Scytonema julianum,* can be encrusted by calcium carbonate. Genera most often noted include *Oscillatoria, Phormidium, Gleocapsa,* and *Lyngbya*.

Algae

Algae are a diverse group of phototrophic, eukaryotic organisms that contain chlorophyll. Several algae are adapted to the low light levels of cave entrances, and may produce chlorophyll in darkness. Some algae may grow chemoheterotrophically in total darkness. Green algae (Chlorophyta) and diatoms (Bacillariophyceae) have been extensively reported from caves. Along with cyanobacteria, algae can be significant nuisance organisms in areas of artificial lighting in caves. Both groups can also figure prominently in studies of speleothem formation in entrance and twilight regions, and in studies of the biodeterioration of rock. Both groups also serve as food sources for other organisms, acting as locally important primary producers in cave entrances.

Fungi

A wide variety of fungi have been documented from caves (Dickson & Kirk, 1976; Rutherford & Huang, 1994), but studies of their activities have been limited. Caumartin (1963) believed there were no true indigenous cave fungi in the typical low-food cave; however, the richness of the media generally used to isolate fungi may prevent the discovery of cave-adapted (oligotrophic) forms. In caves, fungi are found on any source of organic material, such as wood, carcasses, and guano, often as large mycelial mats, or growths with bright colours (Figure 2). Fungi are important decomposers in caves and produce a variety of extracellular enzymes (lipases, proteinases, and chitinases) that degrade organic detritus. Most fungi found in caves are moulds (filamentous fungi) in the Zygomycetes (bread moulds such as *Mucor*) or



Microorganisms in Caves: Figure 2. Yellow mould covers a bat carcass in Carlsbad Cavern, Carlsbad Caverns National Park, New Mexico. (see also in colour insert; photo by D.Northup)

Deuteromycetes (fungi imperfecti, including, most commonly, *Penicillium, Aspergillus, Fusarium,* and *Trichoderma*). Mushrooms (Basidiomycetes) are also found in caves on dead matter, and mycorrhizal fungi have been documented from rootlets in a cave stream. Besides their decomposer role, fungi may be pathogens. The causative agent of histoplasmosis, *Histoplasma capsulatum,* grows on bat guano. Filamentous fungi have been implicated in the formation of micritic laminae in speleothems, and can serve as nucleation sites (Went, 1969).

Slime Moulds

Slime moulds are eukaryotes that share characteristics with both fungi and protozoa. They produce spores, feed on bacteria, and can move across surfaces fairly rapidly. Perhaps the least-studied microorganisms in caves, cellular slime moulds in the genera *Dictyostelium* and *Polysphondylium* have been documented in caves, where they may be most active in bacteria-rich soils.

Protozoa

Protozoa are mobile, one-celled eukaryotic microorganisms that do not have cell walls. They are all chemoheterotrophs. Some protozoa are parasitic on cave vertebrates and invertebrates, while others are free-living on organic matter, bacteria, and other protozoa. They, in turn, serve as food for other cave biota. When protozoa find conditions unfavourable for growth they may form a dormant cyst. The first paper on cave protozoa appeared in 1845 and since that time more than 350 species have been identified from aquatic habitats and from cave biota (Gittleson & Hoover, 1969). Cave protozoans correspond well with those found in forest litter, and most are considered to be troglophilic. Protozoans that are parasitic on troglobitic cave fauna are themselves considered troglobitic.

Microbes as Agents of Destruction

Microorganisms have been shown to be significant agents of dissolution of rock (Northup & Lavoie, 2001) and destruction of paintings in caves. For example, some sulfur-oxidizing bacteria produce sulfuric acid as a waste product, which reacts with limestone to form gypsum, a mineral that is highly soluble in water. An example of the destruction wrought on prehistoric cave paintings by microorganisms is the “Maladie Verte” of Lascaux, where human-transported microorganisms contaminated cave paintings and human activities raised the temperature in the cave, increasing microbial growth (see also Tourist Caves: Algae and Lampenflora).

Human Impacts on Microbes

Human activities can have a major impact on microbes. The input of human faecal pollution brings in organic matter that stops the growth of native microbes adapted to normal lowfood conditions in caves. Polluting bacteria may pose a threat of infection to cavers. Faecal contamination in the Red Lake area of Lechuguilla Cave in New Mexico has persisted for at least five years. Northup and Boston have advocated low-impact caving such as wearing clean caving clothes, packing out all wastes, and leaving areas undisturbed as microbial nature preserves, as ways for us to minimize our impact on cave microorganisms.

Microbes and Caver Health

Water in caves may be heavily polluted from farmland grazed by sheep or cattle, or from leaking septic tanks, and may contain high concentrations of faecal indicator bacteria, posing a risk to caver health. For example, Gunn *et al.* (1998) report faecal coliform concentrations of up to 14400 CFU/100 ml and faecal streptococci concentrations up to 440 CFU/100 ml in springs draining recreational cave systems at Castleton, England. Polluted water in caves may exceed standards for water quality for recreational uses, and it is not advisable to drink any cave waters. Other microbial dangers to cavers are the Histoplasmosis fungi, usually encountered growing on deposits of bat guano. Often a whole group of cavers is infected from the same exposure. Rabies from bats is a potential source of risk to cayers, although no cases are known. (See also Disease.)

Future Studies

Many microbes identified from deep caves are similar to surface forms, being non-residents transported into caves by water, air, sediment, and animals. However, most microbiological studies have focused on typical heterotrophic microbes known from surface studies and have missed microorganisms that are difficult to culture. Culture-independent, molecular phylogenetic techniques that compare genetic sequences of organisms have since shown that many novel organisms can be found in caves (Angert *et al.,* 1998). Multidisciplinary studies and the application of techniques from surface studies are now greatly expanding our knowledge of the roles of cave microorganisms.

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See also **Biofilms; Microbial Processes in Caves**

Works Cited

Angert, E.R., Northup, D.E., Reysenbach, A.-L, Peek, A.S., Goebel, B.M. & Pace, N.R. 1998. Molecular phylogenetic analysis of a bacterial community in Sulphur River, Parker Cave, Kentucky. *American Mineralogist,* 83:1583–92

Caumartin, V. 1963. Review of the microbiology of underground environments. *National Speleological Society Bulletin,* 25:1−14

Dickson, G.W. & Kirk, P.W. 1976. Distribution of heterotrophic microorganisms in relation to detritivores in Virginia caves (with supplemental bibliography on cave microbiology and mycology). In *The Distributional History of the Biota of the Southern Appalachians,* edited by B.C.Parker & M.K.Roane, vol. 4: Algae and Fungi, Charlottesville, Virginia: University Press of Virginia

Gittleson, S.M. & Hoover, R.L. 1969. Cavernicolous protozoa: Review of the literature and new studies in Mammoth Cave Kentucky. *Annales de Spéléologie,* 24(4):737–76

Groth, I. & Saiz-Jimenez, C. 1999. Actinomycetes in hypogean environments. *Geomicrobiology Journal,* 16(1):1–8

Gunn, J., Tranter, J., Perkins, J. & Hunter, C. 1998. Sanitary bacterial dynamics in a mixed karst aquifer. In *Karst Hydrology,* edited by C.Leibundgut, J.Gunn & A.Dassargues, Wallingford, Oxfordshire: International Association of Hydrological Sciences (IAHS Publication no. 247)

Juberthie C. & Decu, V. (editors) 1994. *Encyclopedia Biospeologica*, vol. 1, Moulis and Bucharest: Société de Biospéleologie

Northup, D.E. & Lavoie, K.H. 2001. Geomicrobiology of caves: a review. *Geomicrobiology Journal,* 18(3):199–222

Rutherford, J.M. & Huang, L.H. 1994. A study of fungi of remote sediments in West Virginia caves and a comparison with reported species in the literature. *National Speleological Society Bulletin,* 56(1):38–45

Sarbu, S.M., Kane, T.C. & Kinkle, B.K. 1996. A chemoautotrophically based cave ecosystem. *Science,* 272:1953–54

Went, F.W. 1969. Fungi associated with stalactite growth. *Science,* 166:385–86

MILITARY USES OF CAVES

Throughout human history, caves have been used in military situations, and many karst landscapes have been arenas for significant military conflict. The nature of karstlands, particularly the irregular topography, restricted surface water supply, and the suitability of caves for refuge and ambush, affords strategic offensive and defensive advantages to native combatants familiar with the surface and underground terrain and poses tactical problems for unfamiliar foreign forces. Caves and karstlands are especially well suited to guerrilla warfare by small, mobile local units, and partisans have hidden and lived in caves since time immemorial (Kempe, 1988).

Caves have been employed historically for a multitude of specific military purposes, both offensive and defensive. Aggressive activities include planned ambushes and strategic entrapment, troop concealment, training and deployment, munitions storage, weapons testing, command and communications facilitation, imprisonment, and execution. Caves have been important sources of military materials including lead and other metals used to manufacture ammunition, saltpetre, which is a principal component of gunpowder, and even flint, from which were crafted early knives, arrowheads, flintlocks, and other weapons.

Defensive strategies include troops and civilians seeking refuge from conflict, both from land invasion and from air raids, establishing armed defensive positions, and caching essential sur vival supplies and potential spoils of war such as precious metals, jewelry, rare books, priceless artwork, and secret documents. Caves have also been used as medical facilities for treatment of military and civilian casualties, and as military burial grounds.

The impacts of military activities in caves and karstlands may be profound and long lasting. Many caves have been extensively modified or expanded for military purposes, their resources exploited and their ecosystems disrupted or destroyed. Karst groundwaters have been contaminated, both deliberately and by accident, and surface landforms disfigured or obliterated by tunnelling, heavy equipment use, or bombardment. Indigenous flora and fauna likewise have been devastated. Notwithstanding, military impact on karstlands has received relatively little attention.

Prehistoric conflict involving caves is speculative, although it seems reasonable to envision early hominids hiding from aggressors in caves and seeking underground flint for weapon making. Reliable documentation of military use of caves increases through human history, with the best-known examples from the 20th century. An early example is from China, where the emperor Sun Quan (222–252 AD) ordered a cave in Jiangsu Province to be explored as a potential route for the invasion of neighbouring provinces (LaMoreaux, 1999). Even earlier, during the first century BC, the Indian King Kharavela recorded his military exploits by means of inscription in the monastic caves of Orissa.

Caves may serve as useful refuges, but equally they can represent deathtraps. In 1577 nearly 400 members of the Clan Ranald, a scion of the MacDonalds, were suffocated in the Cave of Francis (or St Francis' Cave) on the Scottish Hebridean island of Eigg when they were found and trapped there by a force of their enemies, the MacLeods, who lit a large fire in the cave entrance (Kempe, 1988). Such tactics are not always successful, as in a 1923 incident in which Free State troops tried to dislodge seven IRA men from the Clashmealcon Caves in County Kerry, Ireland. Examples of fortified cave entrances include the Erasmus Castle at the entrance to Predjama Cave in Slovenia and the Covolvo del Butistone in the Venetian Prealps (Gams *et al.,* 1993). During the Middle Ages the caves beneath Buda, now incorporated into Budapest, were enlarged and connected for military purposes; in the 1930s the labyrinth was converted into a shelter large enough to accommodate 10000 people, and during the Cold War it served as a secret military installation. The Veterani Cave in Romania was extensively fortified by troops of the Austro-Hungarian Empire in the 17th and 18th centuries during conflicts with Turkish forces (Patay, 1997). Caves, both natural and man-made, also featured as military installations during the Crimean War (1853–56).

Cave use for military storage, construction, training, and testing is also well documented. During World War I, the Bethlehem Steel Company used one of the Reddington Caves, Pennsylvania, as an artillery firing range (Folsom, 1956). An aircraft assembly plant was set up in the Bedeilhac Cave in France in 1940 (Nicod *et al.*, 1996), and during 1944 a Heinkel aircraft factory was established in a cave near Vienna. Also during World War II a German ammunition dump in Postojna Cave (Slovenia) was blown up by Yugoslav partisans (Kempe, 1988). Nuclear missiles are said to have been stored in Cuban caves during the Cuban missile crisis, and in Russia and China during the Cold War.

Perhaps the most bizarre military operation involving caves was the World War II "Bat bomb" project, in which a US military scientist proposed attaching small incendiary devices to Mexican free-tailed bats that were to be dropped over Japan. Thousands of bats were collected from caves in Texas and stored under conditions resembling hibernation, guarded by US Marines. The project was ultimately abandoned in favour of the atomic bomb (Folsom, 1956; Couffer, 1992).

Caves have played a significant role in the military history of several islands, including Gibraltar. In 1704 Spanish troops concealed themselves overnight in St Michael's Cave while preparing unsuccessfully to attack the British and Dutch defenders. The island's cave systems, extensively modified, were used as civilian air raid shelters and hospitals during World War II. Similarly, caves played important roles during the 1690–1796 Maroon Wars in Jamaica.

World War I saw extensive military activity in caves and karst throughout Europe. Northeastern Italy was affected particularly (Sauro, 1987). Over 100 Slovenian caves were modified for military use (Kepa, 2001); in Postojna Cave Russian prisoners were used to build the famous "chasm footbridge", which is still used by tourists. Examples of caves being used as military hospitals and burial sites are legion. In 1769 Russian soldiers and sailors apparently were both hospitalized and buried in caves in Mi norca following battles with the Turks. Similar underground hospitals have been reported in caves ranging from Gibralter to Eritrea.

Caves have been used as military execution sites and for the disposal of executed victims. Large numbers of Armenians reportedly were asphyxiated in caves by Turkish troops during 1915, repeating an earlier Turkish action in the Melidoni Cave in Crete in 1822 (Nicod *et al.*, 1996). During World War II Yugoslav partisans are reputed to have thrown thousands of Italians and others to their deaths in karst chasms known as *foibes* (Pizzi, 1998). In March 1944, in reprisal for partisan actions, German troops massacred 335 Italian civilians in the Ardeatine Caves near Rome. In 1997 some 300 victims were recovered from a cave near Hrgar, in Bosnia.

Some of the most bloody military actions involving caves took place in the Pacific during World War II when advancing Allied troops encountered tenacious Japanese defenders entrenched in heavily fortified cave entrances and passages. Intense conflict in 1943–45 consumed caves and karst on Tarawa, Okinawa, Iwo Jima, Guam, and Peleliu, among others, with the flame-thrower playing a pivotal role in clearing the caves. The battle for Iwo Jima resulted in the deaths of 22000 Japanese defenders and nearly 6000 US Marines. Thousands of Japanese soldiers were trapped by US Marines in the Biak

Caves of Irian Jaya in 1944; in Japan itself the Akiyoshi caves were extensively fortified and heavily defended.

There are numerous other instances of caves being used temporarily during battle, for example in South Africa's Transvaal and Zululand, on the Northwest Frontier of India, and during the American Civil War in the 1800s. In February 1944, during the Allied landings on the Anzio beachhead, there occurred a decisive but costly action known as the Battle of the Caves. On a more permanent basis, various guerrilla forces have used caves as military bases and sanctuaries. The Sohoton caves and the surrounding karst were a stronghold of native partisans during the Philippine-American war until they were subdued in 1901. Mao Tse-tung and his revolutionary forces made extensive use of caves prior to and during the Long March of 1934, and Fidel Castro and his followers, including Che Guevera, based their 1959 Cuban Revolution around caves (Núñez Jimínez, 1986). The caves of Cao Bang were the initial military headquarters and training grounds for Ho Chi Minh's Viet Minh during the 1940s. During World War II Tito's partisans were headquartered in caves at Drvar, Bosnia, and during the Vietnam War (1961–75) Viet Cong forces made offensive and defensive use of both natural and man-made caves and tunnels, in which fierce hand-to-hand fighting subsequently occurred.

Most recently, caves have figured prominently in wars in Afghanistan. Mujaheddin fighting Russian occupying troops between 1979 and 1989 used caves, particularly in the Zhawar region, as bases for guerrilla activities and proved impossible to defeat. In 2001–02 these same artifically enlarged "caves", including the Tora Bora cave and tunnel complex in the White Mountains, were used by the Al-Qaeda network to evade and resist Allied military forces.

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See also **Gunpowder**

Works Cited

Couffer, J. 1992. *Bat Bomb: World War II's Other Secret Weapon,* Austin: University of Texas Press

Folsom, F. 1956. *Exploring American Caves: Their History, Geology, Lore, and Location: A Spelunker's Guide,* New York: Crown Publishers

Gams, I., Nicod, J., Julian, M., Anthony, E. & Sauro, U. 1993. Environmental change and human impacts on the Mediterranean karsts of France, Italy and the Dinaric Region. In *Karst Terrains: Environmental Changes and Human Impacts,* edited by P.W. Williams, Cremlingen: Catena

Kempe, D.R.C. 1988. *Living Underground: A History of Cave and Cliff Dwelling,* London: Herbert Press

Kepa, T. 2001. Karst conservation in Slovenia. *Acta Carsologica,* 30(1):143–64

LaMoreaux, P.E. 1999. The historical perspective. In *Karst Hydrology and Human Activities: Impacts, Consequences and Implications,* edited by D.Drew & H.Hötzl, Rotterdam: Balkema

Nicod, J., Julian, M. & Anthony, E. 1996. A historical review of man-karst relationships: Miscellaneous uses of karst and their impacts. *Rivista Geografica Italiana,* 103:289–338

Núñez Jimínez, A. 1987. *Geografia y Espeleologia en Revolucion,* La Habana: Imprenta Central de las Fuerzas Armadas Revolucionarias

Patay, K. 1997. Abbildungen der Veterani-Hohle aus dem 17–18 Jahrhundert. *Acta Carsologica,* 26(2):149–57

Pizzi, K. 1998. Silentes Loquimur: Foibe and border anxiety in post-war literature from Trieste. *Journal of European Studies,* 28(3): 217–29
Sauro, U. 1987. The impact of Man in the karstic environments of the Venetian Prealps. In *Karst and Man: Proceedings of the International Symposium on Human Influence in Karst,* edited by J.Kunaver, Ljubljana: Department of Geography, University E. Kardelj

Further Reading

Collins, J.M. 1998. *Military Geography for Professionals and the Public,* Washington, D.C.: National Defense University Press
Peltier, L.C. & Pearcy, G.E. 1966. *Military Geography,* Princeton, New Jersey: Van Nostrand
O'Sullivan, P. & Miller, J.W. 1983. *The Geography of Warfare,* London: Croom Helm and New York: St Martins Press
Winters, H.A., Galloway, G.E., Reynolds, W.J. & Rhyne, D.W. 1998. *Battling the Elements: Weather and Terrain in the Conduct of War,* Baltimore: Johns Hopkins University Press

MINERALS IN CAVES

A cave mineral is any secondary mineral formed within a natural subterranean cavity, fissure, or tube that is human-size or larger and that extends past the twilight zone. A "secondary" mineral is derived by a physicochemical reaction from a primary mineral in bedrock or detritus, and is deposited because of a unique set of conditions within a cave (i.e. the cave environment has influenced the mineral's deposition). Secondary mineral deposits formed in this way in caves are called speleothems. However, a "cave mineral" is definitely not the same as a "speleothem", although speleothems are composed of cave minerals. The term "speleothem" refers to the mode of occurrence of a mineral in a cave (i.e. its morphology, or how it looks), not to its composition. For example, calcite is not a speleothem, but a calcite stalactite in a cave is a speleothem. The speleothem type "stalactite" can be composed of many minerals besides calcite (e.g. aragonite, gypsum, halite, ice, etc.). While only about 40 speleothem types have been recognized worldwide, a total of 255 "official" secondary minerals are known to occur in caves (Hill & Forti, 1997). Cave minerals can have a number of different origins and depositional settings. Figure 1 shows a generalized depositional scheme for all the different classes of cave minerals discussed in this section.

Cave minerals, like minerals in the outside world, can be organized according to the classification scheme *of Dana's System of Mineralogy* (Gaines *et al.,* 1997), where grouping is by chemical class.

Native elements: Sulfur (S) is the only native element known to have a secondary origin in caves. Sulfur forms in "abnormal" cave situations where: (1) fumarole activity exists in volcanic caves; (2) primary pyrite and/or marcasite are oxidized in mine caves; or (3) reduced sulfur (H_2S) is oxidized in sulfuric acid caves. This last mechanism is responsible for most large cave sulfur deposits, e.g. those in Lechuguilla Cave, New Mexico, United States.

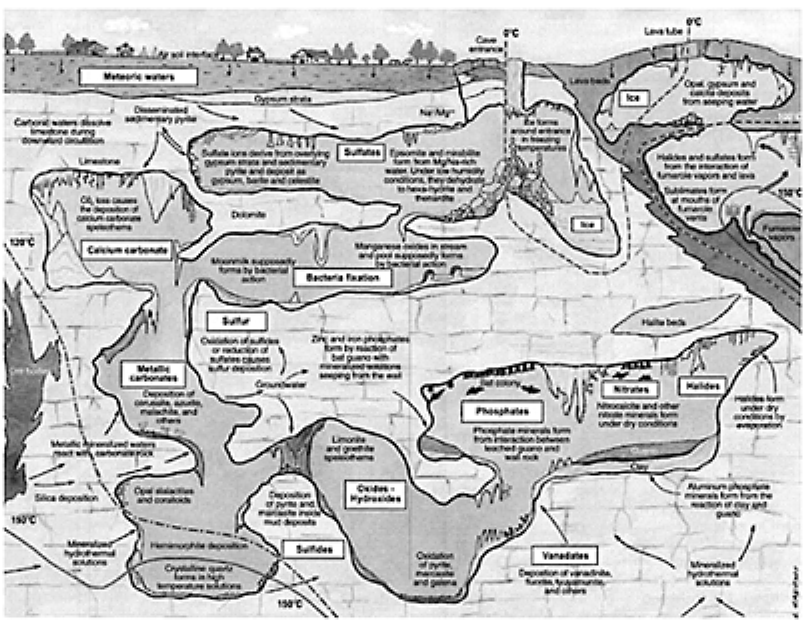
Sulfides: Sulfide minerals in caves almost always have a primary origin (i.e. they pre-date the cave and are only exposed by the cave), but in rare circumstances they can form as secondary mineral deposits—usually either as sulfide inclusions within hydrothermal calcite or as sulfide minerals produced by the anaerobic bacterial reduction of iron sulfates within cave clay. For more information on this topic refer to Sulfide Minerals in Karst.

Oxides and hydroxides: Common oxide-hydroxide cave minerals fall into three categories: ice (H_2O), manganese oxides, and iron oxides. Caves with ice speleothems in them can be limestone or gypsum caves with an average or seasonal temperature that falls below freezing, lava tube caves where the insulating effect of lava rock enhances the survival of ice, and caves within glacial ice itself (see Ice in Caves). The most famous caves containing ice speleothems are those in the limestone mountains of Europe (e.g. Eisriesenwelt and Rieseneishöhle of the Austrian Alps).

Manganese oxides are introduced into caves by stream water and, less frequently, by dripping water or associated with ore mineralization. The soluble Mn^{2+} in water is oxidized to the insoluble Mn^{4+}, thus causing the precipitation of manganese oxide minerals, a process probably aided by bacteria. Manganese minerals, such as birnessite [$(NaCa)Mn_7O_{14}\cdot 3H_2O$], usually occur as black layers coating stream cobbles.

The most common iron oxide-hydroxide mineral is goethite [FeO(OH)], often referred to by the catch-all term "limonite". Goethite usually occurs within cave sediment, but it can also take the form of dripstone and flowstone. Goethite in caves is also probably related to the activity of bacteria.

Halides: Halide minerals are relatively rare in caves, with halite (NaCl) being the most common, but only where halite evaporite rock exists in the overburden and where the climate is (or has been) arid. Halite is known to form seeping water



Minerals in Caves: Figure 1. Different depositional settings for different classes of cave minerals. From *Cave Minerals of the World,* Hill & Forti, 2nd edition. © 1997, National Speleological Society, Inc. Used with permission. Drawing by Luciano Casoni.

speleothems such as crusts, hair, cotton, and flowers, and dripping water speleothems such as stalactites and stalagmites. It also forms as euhedral spar crystals. Halide minerals usually form by the simple mechanism of groundwater dissolution of halite bedrock and reprecipitation in an underlying cave, but they can also derive from bat guano. Some, such as fluorite, can have a hydrothermal origin. A classic example of caves formed in halite rock, and containing halite minerals and speleothems, are the Mount Sedom caves of Israel (see Sedom Salt Karst).

Arsenates: Arsenate minerals are very rare in caves, and where they do occur are usually associated with arsenic-rich ore.

Borates: Only one borate mineral is known from a cave occurrence, associated with the borax deposits of the Mojave Desert, California, United States.

Carbonates: By far the most important class of cave minerals are the carbonates, with the two most common cave minerals, calcite ($CaCO_3$) and aragonite ($CaCO_3$), making up >95% of all speleothem deposits. Carbonate speleothems are abundant because most caves are formed in limestone rock, which readily supplies the necessary calcium and carbonate. Since this is such an important class of cave minerals, a separate Encyclopedia entry has been written on this topic (see Speleothems: Carbonate for a more in-depth discussion). In summary, the deposition of carbonate minerals begins when rainwater picks up carbon dioxide in the air and soil zone above a cave to form a weak carbonic acid. This acid dissolves limestone bedrock as groundwater percolates downward toward a cave; in this way, the water can become saturated with calcium carbonate. The precipitation of carbonate minerals happens when this carbonate-bearing groundwater reaches a cave: the exchange of carbon dioxide in the water with the cave atmosphere causes the precipitation of calcite (and other carbonate minerals). Carbon dioxide exchange is the primary cause of carbonate mineral precipitation in caves, but less often it can be caused by evaporation, the common-ion effect, and/or pressure-temperature changes.

Besides calcite and aragonite, a number of other carbonate minerals also exist in caves. Usually these minerals are either ore-related (e.g. azurite, cerussite, hydrozincite, malachite), or related to the evolution of cave waters with respect to magnesium content, evaporation, and/or carbon dioxide loss (e.g. hydro-magnesite, huntite, nesquehonite, monohydrocalcite). In dolostone caves, where there is a general trend of increasing magnesium in solution with precipitation of carbonate species, the deposition of calcite, and then aragonite, huntite, and hydromagnesite is a common sequence. Dolomite also occurs as a secondary mineral in some caves, but primarily as a replacement of other carbonate minerals.

Nitrates: Nitrate minerals are not common in caves, but they do occur where cave conditions are dry enough, and the relative humidity low enough, for these very soluble minerals to crystallize. Nitrate minerals are both hygroscopic (they can absorb moisture from the air) and deliquescent (they can dissolve in that moisture). Thus, as the relative humidity of a cave seasonally oscillates, these minerals can alternately disappear (become deliquescent and sink into cave sediment or walls) and reappear (effloresce).

Nitrocalcite [$Ca(NO_3)_2 \cdot 4H_2O$] is historically interesting in that it is the nitrate constituent of “saltpetre earth”, which was mined as an ingredient for gunpowder in the Revolutionary War, the War of 1812, and the Civil War in the eastern United States (e.g. Mammoth Cave, Kentucky; see Gunpowder). The source of nitrate to the saltpetre earth is groundwater seeping into a cave from the surface: dry caves act as receptacles where the soluble nitrate can accumulate rather than being leached away. In addition, bat guano can supply nitrate for cave mineralization (see entries on Guano and Sediments: Biogenic). Nitrocalcite, nitrammite, nitre, and nitromagnesite are all derived directly from bat guano in the caves of southern Africa (e.g. Chaos Cave, South Africa), where these minerals can form as crusts, flowers, and small stalactites.

Phosphates: Over 50 different phosphate minerals are known to form in caves, and almost all of these derive from bat guano. Bat guano is rich in both nitrogen and phosphorus; decomposition by leaching involves a process by which the very soluble nitrogen is first removed, leaving the relatively insoluble phosphate. This process often creates a complex stratified suite of phosphate minerals within the guano. In limestone caves, the most common phosphate minerals are brushite, carbonatehydroxylapatite, and hydroxylapatite. All of these minerals contain Ca^{2+}, which is derived from limestone bedrock in contact with the bat guano.

Phosphate minerals are not usually recognizable because they form mainly as indistinct fine-grained powders within or near bat guano. However, rarely phosphates can also form as dripstone or flowstone deposits, or they can be associated with ore deposits. An unusual occurrence of brushite ($CaHPO_4 \cdot 2H_2O$) exists in Kartchner Caverns, Arizona (United States): a 2 m long, ivory-yellow deposit of moonmilk-flowstone can be seen on the side of a breakdown block covered on top with fresh bat guano.

Silicates: Silicate minerals in caves fall into three categories: opal/quartz; clay minerals; and ore minerals. Opal ($SiO_2 \cdot nH_2O$) is the most common non-clay silicate mineral in caves, and can be locally abundant in lava tubes where basaltic rock supplies the silica. Clay minerals (e.g. montmorillonite) usually reconstitute within the cave from detrital (residual) sediment washed into the cave by surface streams.

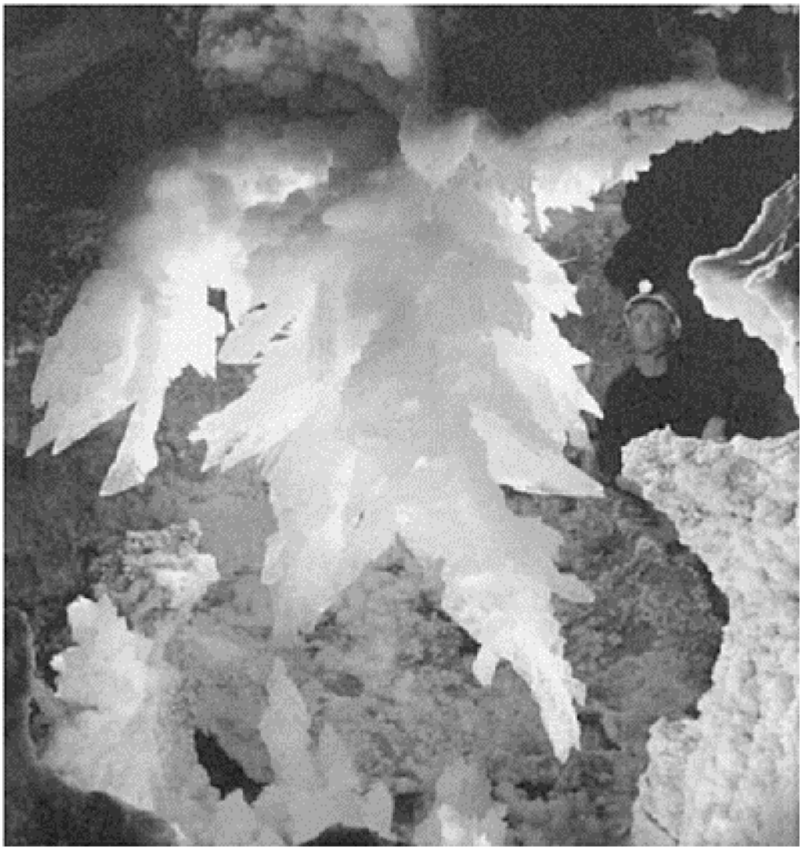
Some silicate minerals are useful indicators of precipitation conditions within a cave. Opal forms under low-temperature conditions, whereas quartz (SiO_2) forms under high-tempera ture conditions (hydrothermal waters). Endellite—a colourful, waxy, hydrated halloysite; $Al_2Si_2O_5(OH)4 \cdot 2H_2O$—has been used as an indicator mineral for sulfuric-acid cave development in the Guadalupe Mountains, New Mexico, United States. Endellite is a mineral that is known to form in low pH, sulfuricacid rich waters.

Sulfates: The second most important class of cave minerals, after the carbonates, is the sulfates. The third most common cave mineral, gypsum ($CaSO_4 \cdot 2H_2O$), is in this class, as are two other fairly common minerals, epsomite ($MgSO_4 \cdot 7H_2O$) and mirabilite ($NaSO_4 \cdot 10H_2O$). Like the carbonates, a separate entry has been written about this important class: Speleothems: Evaporite.

Sulfate cave minerals fall into five general categories depending on origin: (1) those that form in a "normal" limestone or gypsum rock setting (e.g. gypsum); (2) those that form in lava tubes (e.g. thenardite); (3) those that derive from bat guano (e.g. arcanite); (4) those that derive from ore bodies (e.g. chalcantite); and (5) those that are associated with fumarole activity (e.g. voltaite). Because of this variety of possible origins, more different sulfate minerals are known to exist in caves than any other crystal class (Hill & Forti, 1997, list 64 different sulfate cave minerals). Gypsum can occur in all five settings.

Sulfate speleothems can assume many of the same forms as carbonate speleothems (e.g. stalactites, stalagmites), but more frequently they display a fibrous habit (e.g. crusts, flowers, cotton). A spectacular form of gypsum is "chandelier" stalactites, such as those that occur in Lechuguilla Cave, New Mexico (Figure 2). Epsomite and mirabilite (like the nitrates) are deliquescent and effloresce only under relatively low-humidity cave conditions.

Vanadates: Like the arsenates, vanadates are rare in caves and occur mostly in ore settings. However, the vanadate mineral



Minerals in Caves: Figure 2. Crystal chandelier, Lechuguilla Cave. (Photo by David Harris)

tyuyamunite [$Ca(UO_2)_2(VO_4)2 \cdot nH_2O$] can be an indicator mineral for sulfuric-acid cave development. Hydrogen sulfide (which oxidizes to sulfuric acid) precipitates uranium (and vanadium) in groundwater. When these constituents are remobilized in the vadose zone, bright-yellow tyuyamunite crystals form as crusts, such as in Carlsbad Cavern, New Mexico, United States.

Many cave minerals are rare or fragile. Others may be unique to a single cave or location within a cave. Therefore, the collection of cave minerals and speleothems is almost never justified, and even scientific sampling should be kept to a minimum or avoided if sampling will cause the complete destruction of a unique mineral occurrence. Cave minerals belong in, and should stay in, caves!

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See also **Speleothems**

Works Cited

Gaines, R.V. *et al.* 1997. *Dana's New Mineralogy: The System of Mineralogy of James Dwight,* 8th edition, Chichester and New York: Wiley, 3 vols

Hill, C.A. & Forti, P. 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society

Further Reading

Hill, C.A. & Forti, P. 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society The authors recommend their book for further reading because it is the only extensive book available on this subject. Colour photographs of many cave minerals and of each major speleothem type and subtype are included, as are over 5000 references to cave minerals worldwide.

MINERAL DEPOSITS IN KARST

A variety of different mineral deposits are found in the infilling of paleokarst and neokarst. Karst-related mineral placer deposits are divided into four genetic types: sedimentary deposits, weathering deposits, hydrothermal deposits, and fluids. The metallic ore deposits include gold, tin, wolframite, columbite, and tantalite placers, bauxites (see separate entry), iron, manganese, leadzinc, copper, uranium, mercury, and vanadium. Non-metallic ore deposits include phosphorites, diamond, ruby, sapphire, and spinel placers, barite, antimony, fluorite, onyx marble, clays, clay pigments, sands, coal, and peat. The fluid deposits are oil, gas, water, and brines.

Karst mineral deposits can also be divided by the source of the useful components as follows: (1) autochthonous deposits, where the components are formed due to destruction of the host rocks; (2) allochthonous deposits, where the components were brought from outside; and (3) parautochthonous deposits, where the components are foreign to the host rocks, but the same as their close surroundings (Zuffardi, 1976). The karst-related placers are divided into alluvial, deluvial, proluvial, and eluvial types by their genesis. Karstified surfaces of carbonate rocks act as traps for heavy minerals and also protect the placers from erosional destruction. Karst depressions and pockets create extremely favourable conditions for weathering of ore-bearing rocks, and for extraction of valuable components.

Diamond placers in a karst environment are known from the Siberian Platform, Russia. Quaternary alluvial placer deposits, occurring on Cambrian karstified dolomites with pockets and depressions, have been mined since 1997 in the Ebelyakh River basin. Neogene and Cretaceous alluvial placers in paleokarst depressions are also known there. A collapse karst placer, filling a deep karst hollow in Silurian and Ordovician carbonate rocks near the Aikhal kimberlite pipe, was exhausted in the 1960s. Buried middle Carboniferous alluvial placers in paleokarst depressions in Ordovician carbonate rocks have been explored in the Morkoka River basin. Buried alluvial and residual placers of upper Triassic-lower Jurassic Age were prospected in paleokarst depressions in lower Ordovician carbonate rocks near the Nakynskaya and Botuobynskaya kimberlite pipes. Quaternary alluvial diamond placers in karst erosional depressions have been exploited during the last 40 years in the Koyva and Vishera river basins in the Ural Mountains, Russia. They formed by rewashing of ancient placers.

Deluvial diamond karst-associated placers were mined in Bakwanga, Congo Republic. These placers formed due to destruction of the nearby kimberlite pipes. Diamondiferous material was redeposited downslope and accumulated in karst dolines up to 80 m deep. Breccia 20–80 m thick, containing 60% sandstones, dolomites, and weathered kimberlites, filled the lowest parts of the dolines. Deluvial karst diamond placer was also mined in the Lichtenburg area, South Africa. The placer developed due to rewashing of Precambrian and Cretaceous diamondiferous deposits. Diamond-bearing deluvium had accumulated up to 45 m deep within the karst depressions.

There are three types of gold placers in karst: (1) polygenetic placers in karst erosional depressions; (2) alluvial placers, which occur on karstified carbonate rock with rugged relief; and (3) eluvial chemical weathering crusts, which develop in contact zones of sulfidized ore occurrences and carbonate rocks (Kropachev, 1972). The first and the last are numerous in the Urals, Russia. Gold-bearing layers occur in karst erosional depressions, which are a few kilometres in length and 50–60 m deep. Alluvial placers have been mined recently in the Tommot, Yakokit, Seligdar, and Maly Yllymakh river basins (Yakutia), and in the Birusa River basin, East Sayan (Russia).

Mineral Deposits in Karst: Working a ruby mine in Mogok, Burma. The miners are digging the sediment from between the limestone pinnacles of rockhead that they have exposed, as the best stones are usually found at the bottom of the fissures. (Photo by Tony Waltham)

Tin and wolframite alluvial karst placers are mined in Malaysia and Laos in the Nam-Phatene River basin, and in Vietnam at Tin-Tac polje. Kinta Valley within the Malayan peninsula is the world's most productive area. It lies between the Main and Kledang ranges, which consist of granite masses, while the bedrock of the valley floor is generally limestone. The tin-bearing alluvium lies on karstified limestone with a highly irregular surface of pinnacles and depressions. These act as ripples to concentrate the cassiterite brought down by rivers. The alluvium varies from 1–2 m to over 60 m thick.

Sapphire and ruby are extracted from karst placers in Sri Lanka (the Pelmadulla deposit). Ruby and spinel are obtained from alluvial and deluvial karst-associated placers in Burma (Myanmar, the Mogok deposit; see Figure).

It is thought that the Mississippi Valley-type deposits, the world's largest productive lead-zinc resources, are of hydrothermal karst genesis (Dźulyński & Sass-Gutkiewicz, 1989). They are known in Upper Silesia (Poland), in the southern Appalachians (US), and in the eastern Alps (see Sulfide Minerals in Karst).

Iron ore deposits in karst and paleokarst depressions are numerous. They accumulated as weathering residua. Currently mined deposits include the Qui-Xa (Vietnam), Alapaevskoye and Akkermanovskoye (Urals, Russia), and deposits in northeast Bavaria (Germany). Nickel deposits were formed in the karst pockets, developed along the contact between carbonate and ultrabasic rocks in the Urals, Russia. Nickel, iron, manganese, and chromium, the weathering products of ultrabasic rocks, migrate into karst pockets where they form compound precipitates. Low-temperature hydrothermal barite deposits in karst cavities have been exhausted in the Tyuya Muyun (Kirgizstan). Residual barite accumulations in karst depressions are known from Strawczynek and the Holy Cross Mountains (Poland), and from Missouri (US). The Missouri deposit yielded barite from weathered barite veins and leached limestones. Paleokarst-related uranium deposits have been exploited in Tyuya Muyun (Kirgizstan), Orphan Mine (Arizona, US), Bakouma (Central African Republic), Le Vigan (France), and in the Vise region (Belgium).

Phosphorites of infiltrational metasomatic genesis often fill large depressions and pockets in karstified rocks. Numerous de posits were prospected in East Sayan (Russia), in Tennessee and Florida (US), and in Liège (Belgium). Phosphatic cover deposits exist in the high carbonate islands (such as Nairu) in the Pacific Ocean. The ores are trapped on and within karst.

Approximately one-half of the world production and reserves of reservoir oil and gas are contained in carbonate rocks (see Hydrocarbons in Karst). Remarkable resources of hydromineral raw materials, connected with deep salt karst, are accumulated within the Siberian Platform. In addition to common macro-elements and microelements such as strontium, rubidium, caesium, and lithium, the unique concentrated brines of deep horizons contain rare elements (yttrium, tantalum, niobium, europium, cerium, thorium, zirconium, molybdenum, and tungsten).

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Works Cited

Dźulyński, S. & Sass-Gutkiewicz, M. 1989. Pb-Zn ores. In *Paleokarst: A Systematic and Regional Review,* edited by P.Bosák, D.C.Ford, J.Glazek & J.Horácek, Amsterdam and New York: Elsevier

Kropachev, A.M. 1972. K geneticheskoy klassifikatsii otlozheniy v karstovykh polostyakh i depressiyakh [Genetic classification of deposits in karst cavities and depressions]. In *Karst Sredney Azii i gornykh stran* [Karst of Central Asia and mountainous regions], Tashkent: Uzbekgidrogeologiya

Zuffardi, P. 1976. Karst and economic mineral deposits. In *Handbook of Strata-Bound and Stratiform Ore Deposits,* vol. 5, edited by K.H.Wolf, Amsterdam and New York: Elsevier

Further Reading

Amstutz, G.C., El Goresy, A., Frenzel, G., Kluth, C., Moh, G., Wauschkuhn, A. & Zimmermann, R.A. (editors) 1982. *Ore Genesis. The State of the Art,* Berlin and New York: Springer

Bosák, P., Ford, D.C., Glazek, J. & Horácek, I. (editors) 1989. *Paleokarst: A Systematic and Regional Review,* Amsterdam and New York: Elsevier

Kutyrev, E.I. & Lyakhnitsky, U.S. 1982. Rol’ karsta v formirovanii mestorozheniy medi, svintsa, zinka, sur’my, rtuti i flyuorita [Role of karst in the origin of lead, zinc, antimony, mercury, and fluorite deposits]. *Litologiya i Poleznie Iskopaemie,* 2:54–69

Laznicka, P. 1985. *Empirical Metallogeny: Depositional Environments, Lithologic Associations and Metallic Ores,* vol. 1: *Phanerozoic Environments, Associations and Deposits,* Amsterdam and New York: Elsevier
Prokopchuk, B.I., Metelkina, M.P. & Shofman, I.L. 1985. *Drevniy karst i ego rossypnaya minerageniya* [Ancient karst and its placer metallogeny], Moscow: Nauka
Quinlan, J.F. 1972. Karst-related mineral deposits and possible criteria for the recognition of paleokarsts: A review of preservable characteristics of Holocene and older karst terraines. In *Proceedings of the 24th International Geological Congress, Montreal,* vol. 6
Tsykin, R.A. 1985. *Otlozheniya i poleznye iskopaemye karsta* [Deposits and raw materials in karst], Novosibirsk: Nauka

MOLLUSCA

Subterranean habitats worldwide are permanently inhabited by several hundred molluscan species. Most terrestrial species belong to the Gastropoda: Pulmonata (snails and slugs), whereas aquatic species primarily belong to the operculate Gastropoda: Prosobranchia (freshwater snails), and a few to the Bivalvia (mussels).

Approximatively 100 species of terrestrial troglophilic and troglobitic snails are known. The entrance zone of caves, being mostly dark, cool, wet, and rich in organic debris, is a common habitat for terrestrial molluscs inhabiting similar surface habitats in (troglophiles). In the deeper cave zones we find some mollusc species unique to hypogean habitats (troglobites). These may be relicts from early climatic changes, for example some molluscs known from European caves are survivors of a subtropical fauna, still found today in the subtropics and tropics but extinct in surface habitats in Europe; other molluscs survived the Quaternary glaciations beneath ice-free “massifs de refuge”. Often these relicts possess an adaptation to subterranean life, for example no or little pigmentation, loss of eyes, a specialized radula for carnivorous feeding, or a respiratory system allowing an amphibious life. The diet of troglobitic species may contain a higher proportion of organic matter from invertebrates and their secretions and a lower proportion of vegetal organic matter than that of surface-dwelling species.

More than 100 species of snails live in subterranean waters, mostly in phreatic aquifers. Living specimens are occasionally found in cave streams, but usually they are only accessible at wells, in groundwater outlets (artesian and karstic springs), by drilling and pumping, or when trapped in water pools deep in caves after violent flooding. Aquatic subterranean snails (stygobites) are depigmented, eyeless, and particularly small. They normally live in fresh water, although certain species are also known from brackish underground waters (such as Movile Cave, Romania). Certain aquatic snails that live only in springs (crenobionts) can penetrate and live underground; other aquatic snails live in interstitial habitats.

The first cavernicolous mollusc, *Carychium spelaeum* (now known as *Zospeum),* was discovered in Adelsberger Grotte (now Postojnska Jama) in 1839. *Zospeum schaufussi* from caves in the Spanish Pyrenees and *Carychium stygium* from Mammoth Cave, Kentucky, were described in 1862 and 1897 respectively. Many stygobitic genera and species were discovered during the 19th century in alluvial sediments, in wells (for example, *Avenionia* in 1882 in France), and in springs. A few discoveries were made inside caves: e.g. *Hydrobia quenstedti* in 1873 (southern Germany), *Vitrella tschapecki* in 1878 (southern Austria), and *Lartetia virei in* 1903 (northern Italy) (these are now all incorporated in the genus *Bythiospeum*). In the early 1900s, zoologists such as Wagner, Kuscer, and Sturany described many new species and genera from caves and karstic springs in the Dinaric karst (see Dinaric Karst: Biospeleology). In the second half of the 20th century, numerous subterranean snails were discovered worldwide in subterranean waters as well as in caves (in Europe, North and South America, New Zealand, Australia, Japan, China, Caucasus, and North Africa).

The correct taxonomic classification of molluscs needs knowledge of their anatomy. The shells, particularly of the aquatic Hydrobiidae, often show great variability in shape, so efforts were made to find living subterranean snails in order to examine their anatomical structures. On this basis, our knowledge about taxonomic classification and biogeographical relationships has greatly improved.

The majority of subterranean snails are found in the western Palearctic zone, particularly in the Balkan Peninsula. The tropical and subtropical zones have fewer troglobitic and stygobitic snails. Some genera living in hypogean habitats in the Balkan Peninsula represent relicts of a molluscan fauna which has otherwise been extinct in Europe since the Tertiary. Examples are *Pholeoteras euthrix* in Herzegovina and Croatia, and *Pholeoteras zilchi* in Greece (Prosobranchia: Cyclophoridae); *Hydrocena cattaroensis* (Prosobranchia: Hydrocenidae) in Montenegro, Croatia, and Albania; *Sciocochlea collasi* and *Sciocochlea nordsiecki* (Pulmonata: Clausiliidae) in Greece; and *Congeria kusceri* (Bivalvia: Dreissenidae) from cave streams in Croatia.

Most terrestrial snails found in tropical and subtropical caves belong to the following Prosobranch families: Hydrocenidae (e.g. *Georissa papuana* from Papua New Guinea, *Georissa pangianensis* from Sumatra); Assimineidae (e.g. *Cavernacmella kuzuuensis* from Japan, *Anaglyphula minutissima* from Sumatra); and Cyclophoridae (e.g. *Opisthostoma mirabilis* from Borneo). Most terrestrial subterranean snails in the western Palearctic are Pulmonata, belonging primarily to the Zonitidae family (genera: *Oxychilus*, *Spelaeopatula*, *Gyralina*, *Lindbergia*, and others). Monotypic troglobitic species are *Meledella werneri* (Mljet Island, Croatia), *Troglaegopis mosorensis* (Croatia), and *Troglovitrea argintarui* (Romania). A few single genera or monotypic species of Pupillidae, Orculidae (e.g. *Speleodentorcula beroni* from Greece), Clausiliidae, and Cochlicopidae are restricted to the caves of the Balkan Peninsula, particularly the Dinaric karst. *Cryptazeca spelaea* and C. *elongata* (Subulinidae) are known only from Cantabrian caves. In the Carychiidae family, cavernicolous snails belong to the genus *Zospeum*—all species being blind (*Z. spelaeum* and related species in the Dinaric karst, northeastern Italy, and southern Austria; *Z. schaufussi* and related species in the French—Spanish Pyrenees). *Carychium stygium* and *C. exile* are widespread in subterranean habitats throughout the southeastern United States. An interesting representative of a troglobitic slug is *Troglolestes sokolovi* (Trigonochlamydia) from Caucasian caves.

Aquatic snails belong mostly to the Prosobranch rissoacean family Hydrobiidae. Aquatic snails restricted to phreatic habitats are widespread. Species and genera found and described from cave waters (streams or pools) include, for example, *Catapyrgus spelaeus* and *Opacuincola coeca* (New Zealand); *Pseudotricula eberhardi* (Tasmania); *Selmistomia beroni* (Papua New Guinea); *Akiyoshia uenoi* (Japan); *Antroselates spiralis*, *Antrobia culveri,* and *Holsingeria unthanksensis* (all from the United States); *Andesipyrgus sketi* (Colombia and Ecuador); *Bythiospeum [Paladilhiopsis] grobbeni* (Slovenia); *Heleobia [Semisalsa] dobrogica* (Movile Cave, Romania); *Alzoniella feneriensis* (Italy); *Paladilhia umbilicata, Palacanthilhiopsis vervierii, Moitessieria lescherae, Alzoniella pyrenaica,* and *Palaospeum bessoni* (all from France).

The majority of stygobitic snails have been discovered in karstic springs or by drilling wells, for example the remarkable molluscan fauna of Texan aquifers *(Phreatodrobia, Balconorbis, Phreatoceras, Stygopyrgus,* and *Texapyrgus* genera). Recent new discoveries of stygobites include, *Alzoniella cornucopia* and *Plagigeyeria stochi* (Italy); *Sardopaladilhia plagigeyerica* and *Sardohoratia sulcata* (Sardinia); *Kerkia brezicensis* (Slovenia); *Atebbania bernasconii* and *Heideella makhfamanensis* (southern Morocco).

RENO BERNASCONI

Further Reading

Bernasconi, R. 1995. Two new cave prosobranch snails from Papua New Guinea: *Selmistomia beroni* n.gen. n.sp. (Caenogastropoda: Hydrobiidae) and *Georissa papuana* n.sp. (Archaeogastropoda: Hydrocenidae) (Zoological results of the British Speleological Expedition to Papua New Guinea 1975). *Revue Suisse de Zoologie,* 102(2):373–86

Bodon, M., Cianfanelli, S., Manganelli, G., Girardi, H. & Giusti, F. 2000. The genus *Avenionia* Nicolas, 1882, redefined (Gastropoda, Prosobranchia, Hydrobiidae). *Basteria,* 64:187–98

Gittenberger, E. & Maassen, W.J.M. 1980. *Hydrocena (H.) cattaroensis* (L.Pfeiffer, 1841) (Prosobranchia Neritacea) und ihre Lebensbedingungen [*H. cattaroensis* and its conditions of life]. *Basteria,* 44:9–10

Haase, M. 1995. The stygobiont genus *Bythiospeum* in Austria: A basic revision and anatomical description of *B. cf. geyeri* from Vienna (Caenogastropoda: Hydrobiidae). *American Malacological Bulletin,* 11(2):123–37

Hershler, R. & Holsinger, J.R. 1990. Zoogeography of North American hydrobiid cavesnails. *Stygology,* 5(1):5–16

Hershler, R. & Thompson, F.G. 1992. A review of the aquatic gastropod subfamily Cochliopinae (Prosobranchia: Hydrobiidae). *Malacological Review, Supplement* 5:1–140

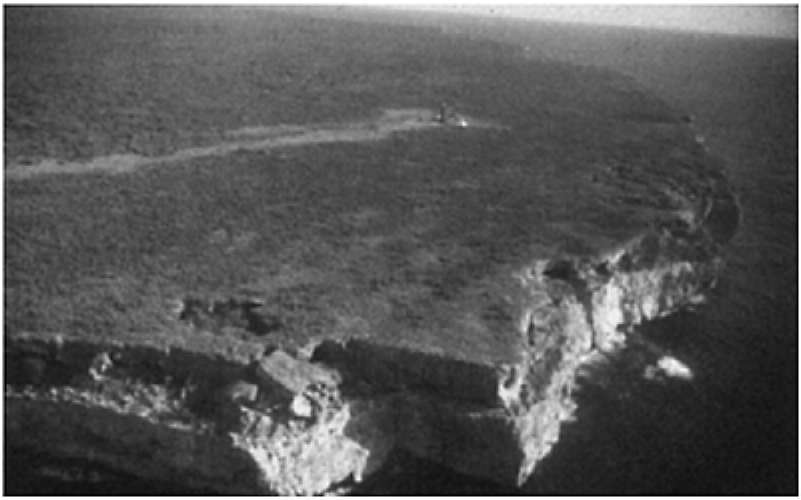
Manganelli, G., Bodon, M. & Giusti, F. 1995. The taxonomic status of *Lartetia cornucopia* De Stefani, 1880 (Gastropoda, Prosobranchia, *Hydrobiidae*). *Journal of Molluscan Studies,* 61: 173–84

Morton, B., Velkovrh, F. & Sket, B. 1998. Biology and anatomy of the “living fossil” *Congeria kusceri* (Bivalvia: Dreissenidae) from subterranean rivers and caves in the Dinaric karst of the former *Yugoslavia*. *Journal of Zoology,* 245:147–74

Saul, M. 1966; Shell collecting in the limestone caves of Borneo. *Conchologist’s Newsletter, London,* 19:128–30

MONA, PUERTO RICO

Isla de Mona is a carbonate island some 55 km^2 in area, located midway between Puerto Rico and Hispaniola. Part of the Commonwealth of Puerto Rico, it is a National Park and the largest uninhabited island in the Caribbean. The island has been tectonically uplifted to a maximum elevation of 90 m, and consists of the Mio-Pliocene Lirio Limestone and underlying Mona Dolomite, with a small Pleistocene limestone coastal plain along the southwest coast. Sheer cliffs plunge 40–80 m from a flat "mesata" or plateau surface directly to the sea on all sides, except where the Pleistocene coastal plain is located. The cliffs contain numerous cave openings, which are concentrated at the contact of the Lirio Limestone and the Mona Dolomite (Figure 1). The caves are the world's largest known examples of "flank-margin caves", a type of cave that develops in carbonate coastlines as a



Mona, Puerto Rico: Figure 1. Southeast corner of Isla de Mona. Lirio limestone is dark upper layer, Mona dolomite is the lighter lower layer. Note cave entrances at the contact, cave collapse entrances on the mesata surface, and the lighthouse in the distance for scale. All visible cave entrances are part of the 19.1 km Sistema del Faro.

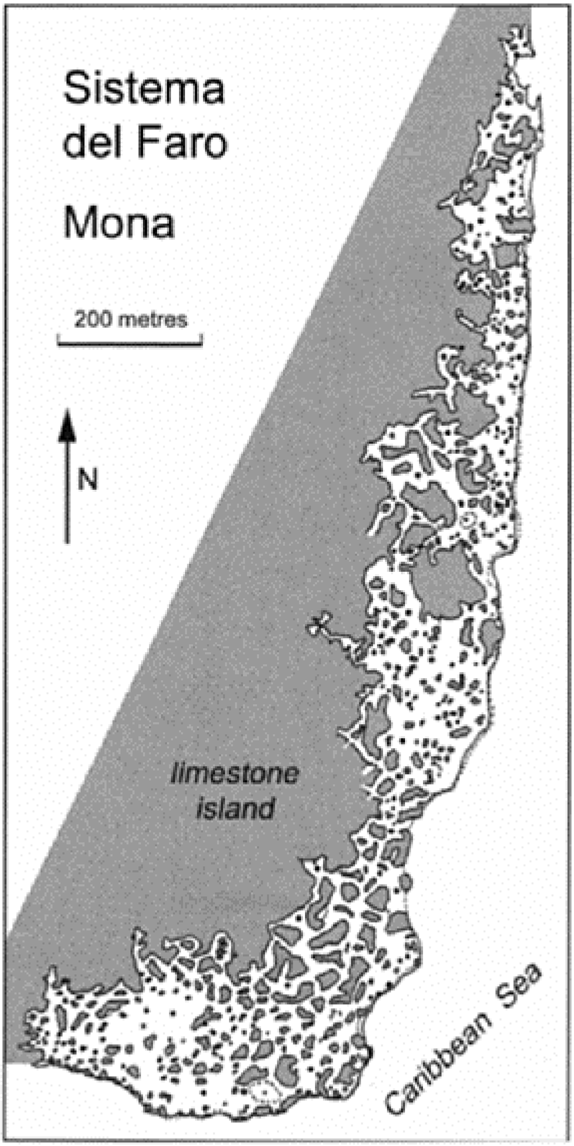
result of sea-water and freshwater mixing inside the coastline (see also Speleogenesis: Coastal and Oceanic Settings).

The interior of the island contains very few horizontal caves. There are, however, numerous pits with a depth range of 5–20 m, in concentrations of several hundred per square kilometre (Frank *et al.*, 1998). These pits commonly lead to a single chamber, but no extensive horizontal cave. The mesata contains a few large closed depressions. The central depression, Bajura de los Cerezos, shows evidence that sinking streams occur during high rainfall. Other depressions, such as Cuevas del Centro and Los Corrales de los Indios, contain short caves in the walls of the depression. A few large collapse chambers are known on the mesata, but none leads to significant lateral cave passages.

Isla de Mona's flank-margin caves are spectacular. They are extensive, with spacious, well-decorated chambers and complex passage configurations. The largest system, Sistema del Faro, is located at the southeastern end of the island, and links the caves of Lirio, Faro, and las Losetas into a continuous series of passages with 19.1 km of survey (Figure 2). The cave has a very maze-like quality, and numerous entrances exist where it has been intersected by the retreat of the cliffs. Because the cave developed by mixing of sea water, and fresh water from within the island, the cave is extensive parallel to the coast, over a range of 2.5 km, but penetrates into the island a maximum distance of only 220 m. The cave has many large chambers adjacent to each other, such that there are numerous connections between them. This complexity gives the cave its maze-like character, and 19.1 km surveyed does not mean 19.1 km of continuous passage, because surveying the numerous chambers has required a large number of survey lines.

North from Sistema del Faro along the east coast, and west along the north coast, the caves become smaller and less frequent, as the north coast is the more elevated side of the island, and the Lirio Limestone has been thinned by erosion. Where small patches of Lirio Limestone remain, the entire patch is commonly underlain by a single cave, such as Cueva de Frio. West from Sistema del Faro along the south coast, many caves exist where the Lirio Limestone is thicker. Cueva de los Parajos, 2 km southwest of Sistema del Faro, is another extensive cave with over 10 km of passages and several large chambers (50 m across and 15 m high). Numerous caves with survey lengths of roughly 1 km or more are known along the southwest coast, where the coastal plain makes access to the cliffs possible. Where the island cliffs swing north along the west coast, there are a number of large caves, including Cueva del Diamante, Cueva del Esqueleto, and Ceuva del Capitan, each with several kilometres of passages.

The flank-margin caves commonly have several levels, which are believed to reflect different sea-level positions while the cave was forming. The caves also have many subaerial calcite speleothems, which show evidence of being subjected to phreatic dissolution. Again, changes in sea level, and therefore the position of the water table, are thought to have caused this dissolutional attack on the speleothems. Paleomagnetic analysis has shown one cave to be at least 1.6 million years old. The large size of the Isla de Mona flank-margin caves is due to fact that they were formed initially before the onset of glacial changes in sea level at the start of the Pleistocene (Frank *et al.*, 1998). Therefore, sea level stayed constant for a long period of time, and the caves grew very large. Then the caves were uplifted and drained by tectonic activity, so that subaerial speleothems could grow. Glacial sea-level changes began, which allowed water to re-enter the caves, enlarging them and also dissolving the speleothems. Tectonic uplift of the island, and its caves, has continued, so that today most of the caves are far above any interaction with the sea, regardless of how sea-level changes due to glaciation-deglaciation cycles. The caves are dry and dusty much of the year, but during major rainfall events, such as tropical storms, the caves gather large amounts of water, which drips from the ceilings.



Mona, Puerto Rico: Figure 2. Outline map of Sistema del Faro, the largest coastal cave on Isla de Mona. Based on a survey made in 1998–2000, from a map drawn up by Marc Ohms. The cave is laterally extensive but penetrates inland no more than 220 m, which is consistent with the flank-margin model.

The caves of Isla de Mona were mined for guano fertilizer from 1887 to 1927. Most of the cave earth was removed, and elaborate trails and causeways were built by the miners to move the earth to the cave entrances. Ore carts, iron track, and other relicts from mining are common in some of the caves. It is interesting to note that the miners took care to avoid damaging the cave speleothem formations, even though it meant more work to lay the trails. The mining operation resulted in clearcutting of the native forest for fuel and building material, upsetting the hydrological balance of the island. Visited by Columbus in 1493 for water, and listed on old British naval charts as a watering locality, visitors must now bring all their fresh water with them.

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See also **Blue Holes of Bahamas; Caribbean Islands; Speleogenesis: Coastal and Oceanic Settings**

Works Cited

Frank, E.F., Mylroie, J., Troester, J., Alexander, E.C., & Carew, J.L. 1998. Karst development and speleogenesis, Isla de Mona, Puerto Rico. *Journal of Cave and Karst Studies,* 60(2):73–83

Further Reading

Briggs, R.P. & Seiders, V.M. 1972. *Geologic Map of the Isla de Mona Quadrangle, Puerto Rico,* Reston, Virginia: US Geological Survey
(US Geological Survey Miscellaneous Geological Investigations, Map 1–718)
Frank, E.F. 1998. History of the guano mining industry, Isla de Mona, Puerto Rico, *Journal of Cave and Karst Studies,* 60(2): 121–25
Gonzalez, L.A., Ruiz, H.M., Taggart, B.E., Budd, A.F. & Monell, V. 1997. Geology of Isla de Mona, Puerto Rico. In *Geology and Hydrogeology of Carbonate Islands,* edited by H.L.Vacher & T.M. Quinn, Amsterdam and New York: Elsevier
Journal of Cave and Karst Studies, 60(2):1998 is a special issue dedicated to the caves of Isla de Mona
Mylroie, J.E., Carew, J.L., Frank, E.F., Panuska, B.C., Taggart, B.E., Troester, J.W. & Carrasquillo, R. 1995. Comparison of flank margin cave development: San Salvador Island, Bahamas and Isla de Mona, Puerto Rico. In *Proceedings of the Seventh Symposium on the Geology of the Bahamas,* edited by M.R. Boardman, San Salvador Island: Bahamian Field Station

MONITORING

Human use and interaction with cave and karst systems can readily lead to adverse impacts on the quality and integrity of both the environment and visitor experience. Monitoring involves the systematic sampling, measurement, and recording of characteristics reflecting environmental and social conditions. It is a management tool that identifies actual and emerging problems related to impacts. Monitoring also assists planning and priority setting, and provides a means to evaluate the effectiveness of management actions in preventing or reducing impacts. This entry briefly reviews the monitoring process and its applications in cave and karst management. The main steps involved in developing a monitoring programme are given in the Table.

In cave and karst systems, impacts can be generated internally, or on adjacent non-karst lands, and it is difficult to predict the pathways that impacts will follow. This is due to the complex and variable conduit system linking surface and subterranean areas. The integrity of the karst system depends on the interrelationship among bedrock, soils, water, gases, landforms and biota, and damage to any one of these can affect the entire system. Hence, karst managers need to develop a holistic understanding of this web of linkages and incorporate this knowledge into the design of monitoring programmes.

Traditionally, monitoring programmes in caves and karst have focused on accumulated visitor impacts in show caves, and in the surface areas immediately adjacent. Accordingly, most karst monitoring programmes have been based on visitor impact management approaches. These include the Recreational Opportunity Spectrum (Clark & Stankey, 1979), Visitor Activities Management Process (Parks Canada, 1985), Limits of Acceptable Change (Stankey *et al.*, 1985), Visitor Impact Management (VIM: Kuss, Graefe & Vaske, 1990), and Visitor Experience and Resource Protection (Belnap *et al.,* 1997). Monitoring programmes, using these approaches, describe en vironmental and social conditions, identify visitor impacts, measure and assess condition, and develop management actions to reduce impacts.

At Jenolan Caves, New South Wales (Australia), the VIM approach has been modified into the Social and Environmental Monitoring (SEM) programme (Hamilton-Smith, 2000). This programme recently moved away from a purely visitor impact approach, to consider any process that may cause impact. This is more akin to sustainability models that consider the resource as a whole rather than starting from the issue of specific impacts. The SEM programme now includes consideration of impacts and issues not directly related to visitors, such as exotic species invasion or wildfire. Given that karst systems are highly interconnected, a holistic approach is a more suitable basis for future monitoring programmes than impact management approaches.

In keeping with a holistic approach, monitoring of both show caves and wild caves must be considered. Unfortunately, impacts in wild caves are poorly documented as they are difficult to quantify, consequently monitoring efforts have been limited. Recent research in New Zealand caves successfully developed and tested techniques for monitoring indicators of impacts, such as sediment erosion, compaction, and tracking (Bunting, 1998). A higher priority for similar research will ensure that wild caves are included in future monitoring programmes.

The identification of indicators is an important consideration for karst monitoring programmes (see Table). For any given issue, more than one indicator may be required, and indicators developed for the same issue in one karst area will not necessarily be appropriate for other karst areas. Some indicators, such as variables relating to air and water quality, are well established and relatively easy to measure.

Identifying indicators for other aspects of the karst system are more problematic. For example, selection of indicator species in subterranean invertebrate faunas is very difficult, as they are

Monitoring: Summary of main steps in the monitoring process.

Step	Notes
1. Identify issues and/or objectives	Issues may be identified from a range of sources including plans of management, legislation, management experience, or stakeholder concerns. This step enables the monitoring programme to stay focused.
2. Identify indicators	Key indicators are specific, measurable environmental, or social variables that reflect overall condition. Indicators should be relevant and specific to prominent environmental or social issues, and sensitive to changes in condition.
3. Establish standards	A standard is the minimum acceptable condition for each indicator. Setting of standards is intrinsically subjective, and their selection needs to consider the degree of rigour and reliability required for assessing condition.
4. Develop monitoring plan	Planning should include identifying the location, methods, frequency, and timing of measurements, analysis and reporting procedures, and management strategies for dealing with impacts.
5. Compare existing conditions with standards	Standards provide a baseline against which existing conditions can be compared. When indicators approach or exceed a standard, this signals a problem requiring management attention.
6. Identify causes of impact	Causes of impact may be complicated and should not rely on guesswork, but should be based on monitoring results to avoid making decisions based on false assumptions.
7. Develop management strategies	The collection of monitoring data is meaningless if data cannot be translated into actions to prevent violation of standards or to address indicators that are out of compliance with standards.
8. Continue ongoing monitoring and regularly review	Monitoring programmes need to be dynamic. Analysis of results may require readjustments in the methods, frequency, and location of data collection, or the revision or rejection of indicators.

generally cryptic, patchily distributed, and often occur in low numbers. To address this problem, researchers at Mammoth Cave, United States, developed an Index of Biological Integrity (IBI) for monitoring purposes (Poulson, 1992). This index combines habitat data with population and community data, using information on all species and habitats present. Instead of assessing the response of individual indicator species, the IBI develops cave community “signatures” for different classes of impacts. This example demonstrates that detailed research and innovative thinking are required before indicators can be selected for use in karst monitoring.

Conditions in karst can change rapidly, so the timing and frequency of data collection is an important consideration, and will vary for each indicator. Diurnal, seasonal, or annual changes in indicators occur regardless of impacts, and baseline data should be collected to determine these patterns. However, event-based monitoring should also be undertaken, as impacts related to events may not be detected when regular sampling intervals are used. Where events, such as periods of high visitation, are predictable, continuous sampling before, during, and after an event will give the most reliable information on the movement of impacts through a karst system. Unpredictable events, such as chemical spills, should be continuously monitored immediately after the event has occurred.

Current environmental and social conditions in a karst area are determined by comparing indicators against standards. Some standards have been formalized as part of best-practice management, or may be set within legislation. For example, national and international health authorities have established standards for acceptable levels of many pollutants, while occupational health and safety legislation in many countries establishes standards for acceptable exposure levels of workers.

Published research and expert opinion may also be the source of standards for a wide range of issues, including visitor perceptions of crowding or the quality of habitat required to sustain endemic or endangered species. Such standards may only apply to the country or region in which the research occurred, and may need to be modified to suit local conditions. For many site-specific issues, established standards may not be appropriate or may be lacking, and on-site research, coupled with management and stakeholder input, may be required to develop appropriate standards.

Monitoring programmes are now well established in many cave and karst areas across the world. The information provided by these programmes is an important tool for identifying impacts and developing management actions to maintain social and environmental conditions. Given the important social, economic, scientific, and environmental values of karst areas and their susceptibility to impact, continued improvement of the monitoring process should remain a high priority well into the future.

MIA THURGATE

See also **Tourist Caves entries**

Works Cited

Belnap, J., Freimund, W.A., Hammett, J., Harris, J., Hof, M., Johnson, G., Lime, D.W., Manning, R.E., McCool, S.F. & Rees, M. 1997. *VERP: The Visitor Experience and Resource Protection Framework: A Handbook for Planners and Managers,* Denver: National Park Service

Bunting, B. 1998. The physical impacts of recreational users in caves: Methods currently in use for assessing recreational impacts in two New Zealand caves. In *Cave and Karst Management in Australia XII,* edited by D.W.Smith, Carlton South, Victoria: Australasian Cave and Karst Management Association

Clark, R.N. & Stankey, G.H. 1979. *The Recreation Opportunity Spectrum: A Framework for Planning, Management and Research,* Experiment Station (General Technical Report PNW-98) Portland, Oregon: Pacific Northwest Forest and Range

Kuss, F.R., Graefe, A.R. & Vaske, J.J. 1990. *Visitor Impact Management,* vol. 2: *The Planning Framework,* Washington, DC: National Parks and Conservation Association

Hamilton-Smith, E. 2000. Managing for Environmental and Social Sustainability at Jenolan Caves, New South Wales, Australia. *Acta Geographica Szegedensis,* 36:144–52

Parks Canada. 1985. *The Management Process for Visitor Activities,* Ottawa, Ontario: National Parks Directorate, Visitor Activities Branch

Poulson, T.L. 1992. Assessing groundwater quality in caves using indices of biological integrity. *Proceedings of the Third Conference on Hydrogeology, Ecology, Monitoring and Management of Ground Water in Karst Terranes*. Dublin, Ohio: National Ground Water Association

Stankey, G.H., Cole, D.N., Lucas, R.C., Petersen, M.E. & Frissell, S.S. 1985. *The Limits of Acceptable Change (LAC) System for Wilderness Planning,* Ogden, Utah: Intermountain Forest and Range Experiment Station (General Technical Report INT-176)

Further Reading

Acta Carsologica 31(1), 2002:5–177 is a special issue in which papers from an international workshop on monitoring karst caves are published

Drew, D. & Hötzl, H. (editors). 1999. *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* Rotterdam: Balkema

Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwell

Nilson, P. & Tayler, G. 1997. A comparative analysis of protected area planning and management frameworks. In *Proceedings—Limits of Acceptable Change and Related Planning Processes: Progress and Future Directions,* edited by S.McCool & D.N. Cole, Ogden, Utah: Rocky Mountain Research Station (General Technical Report INT-GTR-371)

Watson, J., Hamilton-Smith, E., Gillieson, D. & Kiernan, K. (editors) 1997. *Guidelines for Cave and Karst Protection,* Cambridge: International Union for Conservation of Nature and Natural Resources

Williams, P.W. (editor) 1993. *Karst Terrains: Environmental Changes, Human Impact,* Cremlingen, Germany: Catena

MORPHOLOGY OF CAVES

Caves are formed as three-dimensional features. Their morphology can be described by their plan patterns or vertical sections. The principal plan patterns that develop within a given phase (level) are angular or sinuous branchworks and reticulate or anastomosing mazes. The patterns become more complex where there are sequences of such passages at different levels, complexly interconnected, for example in Mammoth Cave, Kentucky. Ford (2000) outlined a conceptual model that describes four stages of the vertical development and morphology of caves according to the fractures available where the caves formed (see Speleogenesis: Unconfined). There can be many combinations of these cave types, and with development of the karst they can be further modified. The principal types of modification are vadose entrenchment, paragenesis (see separate entry), and bypass galleries. Entrenchment occurs in the upper parts of phreatic loops if the piezometric level lowers. Paragenetic passages develop when sediments protect the lower part of the passage by directing the flow and dissolution between the fill and the ceiling under phreatic conditions. If the entire ceiling is lifted, a paragenetic canyon develops. Bypasses form new pathways for water near obstructions or deep phreatic loops.

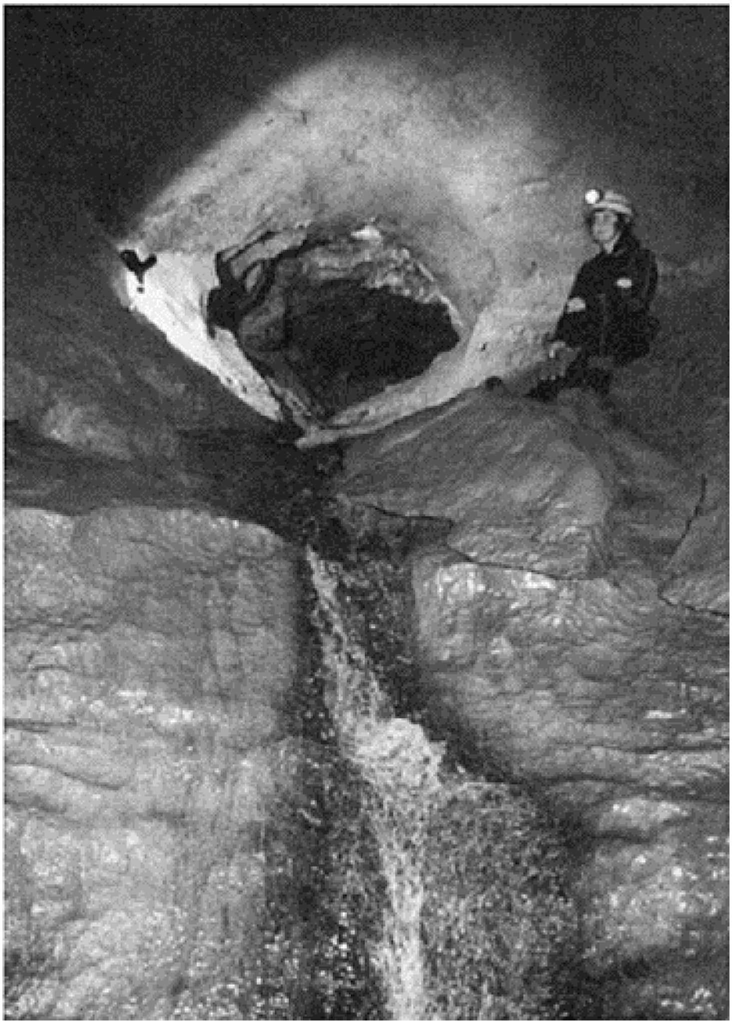
In the vadose zone, drawdown caves develop when the effective porosity of the karst increases, thus lowering the piezometric level. Early conduits drain towards the lowered water table forming drawdown caves. The original phreatic forms may still be preserved, but the majority of the passage has been shaped in the vadose conditions. Invasion vadose caves form when a new stream, or water collected within the rock, invades a cave that was formed in a previous phase of speleogenesis. They develop where the effective porosity is high or where the resistance in fissures is low. This is usually connected with young mountain systems. Most alpine caves are of this type, consisting of fluted shafts connected by short meandering canyons.

Passage Cross-Section Morphology

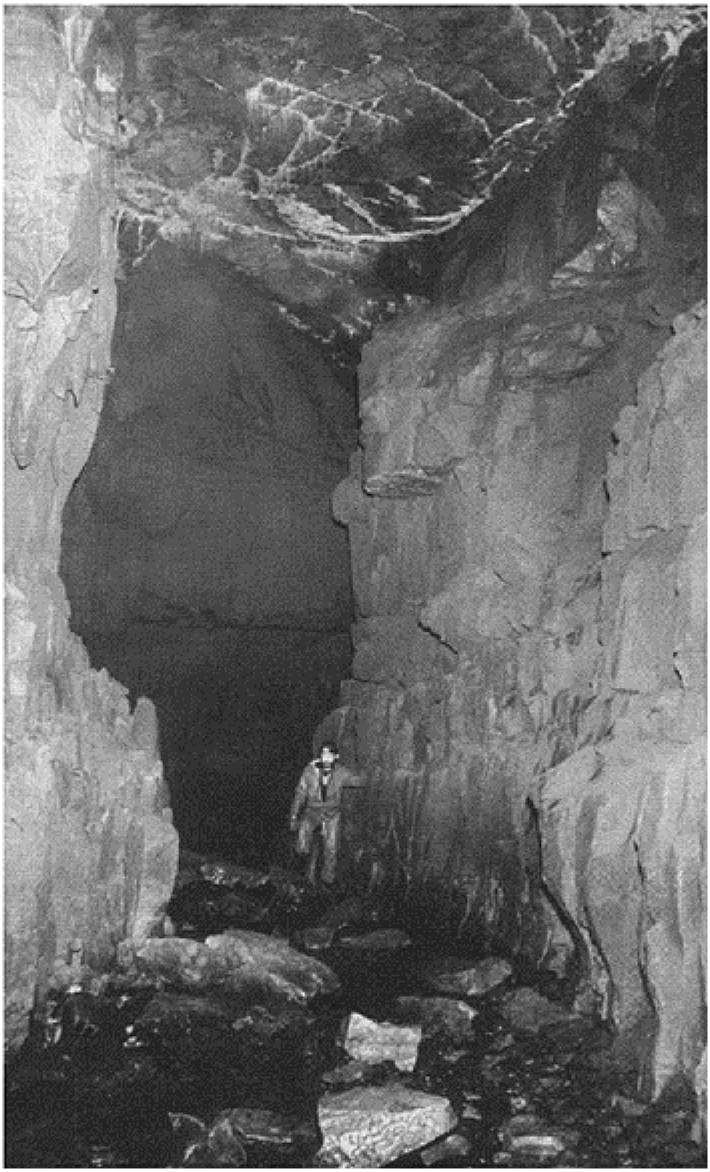
The morphology of cave passages is best described by their cross sections which result from the activity of dissolutional and mechanical erosion processes during the development of the cave system. Some cross sections can be explained by geological structures and the solubility of the rock, but most are polygenetic. The geological setting influences morphology by providing secondary porosity, rock strength, and susceptibility to dissolution and erosion (Lauritzen & Lundberg, 2000). Fractures and bedding plane surfaces or their intersections are the most important structures for the initiation and shaping of passages. Symmetric profiles develop along horizontal bedding planes or vertical joints; dipping strata or joints produce asymmetric cross sections. Rock strength influences the size of the gallery. Most carbonate rocks can support large cave galleries, but this is not the case with some evaporite rocks. In homogeneous rock, the hydrodynamic factors of the water flow determine the form of the passage. If the solubility varies through a stratigraphic column, less soluble parts or insoluble particles, nodules, or layers can protrude from the walls and become significant features in the cave profile.

Passage shape is influenced by the hydrologic zone in which it is situated and so by the flow properties. The profile may be phreatic (Figure 1) or vadose (Figure 2) or a combination of the two. Phreatic passages are, or were originally, completely filled with water such that dissolutional processes could act evenly on all cave walls. In these conditions passages with rounded cross sections develop. Elliptical passage profiles are common due to development along guiding bedding planes or joints. Passages in homogeneous rock or passages with changing flow conditions can have irregular profiles but they retain characteristic smooth circular forms. The profiles of phreatic passages can reach dimensions of several tens of metres. In the unsaturated (vadose) zone dissolution only occurs in that part of the cave that contains water. Passage enlargement is downwards and forms underground canyons. These canyons are often sinuous and like surface rivers form cave meanders. Vadose passages vary from small features to large underground canyons such as the 95 m high and 10–20 m wide canyon in the Škocjan Cave, Slovenia (see photo in Škocjan entry). Narrow vadose canyons have often developed at the bottom of phreatic passages. The characteristic combined profile with a phreatic tube in the upper part and a vadose canyon is called a "keyhole" profile. A combined profile can be the result of the draining of the phreatic zone due to a change in the external base level, the developing conductivity of the karst and the subsequent lowering of the piezometric level in it, or a drop in the quantity of the water in the passage.

Vadose shafts are vertical or nearly vertical passages formed by falling water originating from sinks on the surface, from the



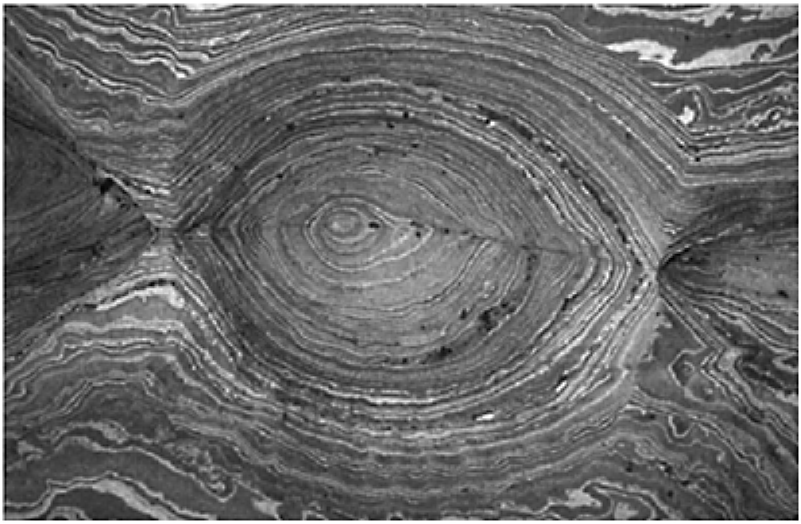
Morphology of Caves: Figure 1. Peak Cavern, Derbyshire, England. The phreatic tube has been drained by a large vadose canyon into which the present misfit stream drains. (Photo by John Gunn)



Morphology of Caves: Figure 2. One of the larger vadose canyons in the

Yorkshire Dales caves, Hensler's Main Drain in the Gaping Gill System. (Photo by Tony Waltham)

epikarst, or at drops from one cave level to another. Most of the falling water does not touch the walls, corroding mostly at the bottom and deepening the shaft. Shafts often show a lenticular cross section in their upper parts and a more rounded cross section at the bottom due to the spray of the water (see Figure 3 in United States of America entry). The largest shafts are



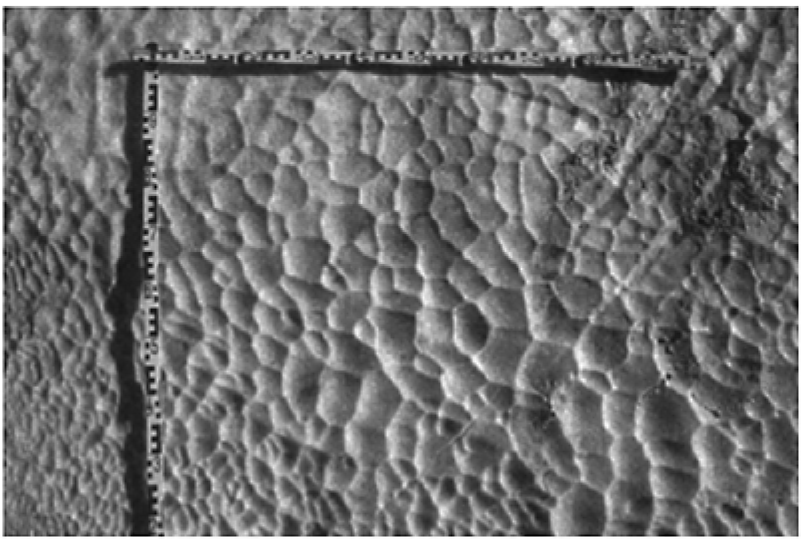
Morphology of Caves: Figure 3. A fine example of a solution pocket developed along a joint in the ceiling of Grutta de Torrinha, Brazil. (Photo by John Gunn)

several hundred metres deep and most of the deepest caves in the world consist of a series of shafts connected by short sections of vadose canyons.

Cave sediments are important for cave morphology. They can fill and modify the profile of a passage, and they can also influence cave formation. Fluvial sediments transported by underground rivers can contribute to the erosion of passages in vadose conditions or can fill phreatic channels causing the paragenetic development of the passage (see Paragenesis).

Erosional Sculpture Within Passages (Rock Relief)

Bedrock features that dissect the walls of caves are combined under the term "cave rock relief" (Slabe, 1995). They are smaller than the wall (lateral surface) of a cave. According to their shapes, which frequently reflect the mode of their formation, such features may be classified as: channels and groups of flutings; depressions (scallops, pockets (Figure 3), bell holes, potholes, and cups); notches and bevels; and protuberances (pendants, rock knives, spikes, and crags). They may occur as isolated individuals, linked together in networks, or packed together and overlapping, reflecting many factors operating simultaneously or contributing to their formation in sequence. The texture and composition of the rock often have a decisive influence on the origin and shape of these features (Slabe, 1995). Standard "scallops" (Figure 4) form due to accelerated dissolution where the chemically saturated boundary layer of the water is locally detached by fixed eddies in the flow along the rough surface of the rock. The form of scallops (spoon-shaped depressions of various sizes with steepened upstream surfaces, overlapping each other in dense patterns) reflects the shape and hydraulic conditions in passages (Knez & Slabe, 1999). Length and breadth reflect primarily the velocity of the water; the faster the flow the shorter the scallop (Curl, 1974). Bedrock composition also influences their shape and size, and scallops form best on homogeneous, fine-grained rocks. Flutes (*sensu* Curl, 1966) are a rare form that exhibit scallop asymmetry but are elongated across the direction of flow and represent very stable conditions of detachment. Paleohydraulic conditions can be reconstructed from scallop measurements in passages long abandoned by flowing water. Scalloping by sublimation in flowing air is common



Morphology of Caves: Figure 4.
Scallops in marble. Surface stream channel, Svartisen, North Norway. (Photo by Stein-Erik Lauritzen)

in ice and snow caves, the scallops being much longer than in water at the same velocity due to the lower viscosity of air.

Ceiling and wall pockets reveal a great diversity of dissolutional forms. Their origin and varied shapes are consequences of eddies in flow caused by the characteristics of the rock, the shape of the passages, and/or by hydrodynamic conditions. Eddies may form around the entire circumference of a passage but their effects are preserved primarily on their ceilings and upper walls. Isolated individual ceiling pockets may form due to mixing corrosion where tributary water enters from a fissure, the mixing of fresh and salt water, differing temperatures of water and rock driving cellular convection, particularly in hydrothermal caves (Forti, 1996), and air trapped under ceilings in flooding caves (Mücke, Völker & Wadevitz, 1983). One particular type of pocket is the result of convectional cellular circulation established in very slowly flowing waters due to solute density differences and is particularly evident in gypsum caves due to their greater solubility (Kempe *et al.*, 1975).

Where vadose channel gradients are steep and the rock is hard, stream potholes (French—"marmites") may develop. These are circular in cross section and may have a depth up to several times their diameter. They occur in all strong rocks, being drilled when grinder boulders are trapped and spun (rock mills) in any small hole in the channel bed. However, they are most frequent and display the most regular form in soluble rocks because dissolution in the swirling water reinforces the grinding and may replace it entirely (Ford, 1964). Diameters range from a few centimetres to several metres.

Wall and ceiling flutings are characteristic on the sloping surfaces of doline shafts through which large quantities of water may flow. In caves formed in gypsum, ceiling channels may be carved by fresh water with a lower specific density. Underfit floor channels form due to the flow of small quantities of water across the floors of passages that are largely abandoned by their formative flow. Rock pillars form due to the eddying of water in vertical fissures dissecting walls. Knife-like blades or spikes occur where the rock is fisssured more densely. Residual pinnnacles are frequently found on the floors of passages. Horizontal notches carved into walls or irregular ceilings and planar, horizontal dissolutional bevels in ceilings form where the water surface is stable for a long period and flow is slow. Cellular density currents are established that remove denser, solute-rich water from the surface, replacing it with lighter, chemically aggressive water (Ford, 1989).

Distinctive cave rock features occur along the contacts with fine-grained sediments. Paragenetic above-sediment channels and anastomoses are formed by water flowing over sediments and dissolving upwards into the ceilings of nearly-filled passages; if later dissolution reshapes them, only pendants may remain. Small, cup-like solutional pits form at the contact with wet sediments, and scallops may develop where water flows along a permeable contact with overhanging walls. Pockets occur due to water flowing through fissures at the contact point with sediment. Sub-sediment dissolutional sculpture is characteristic of periodically flooded passages in which water deposits smaller quantities of fine-grained sediments. Flutes are formed on sloping walls where water trickles from the sediment. Small notches are characteristic of vertical and overhanging walls, as are small pendants on ceilings (Slabe, 1995). Pits also occur on sloping walls and deep niches may be carved into the rock walls where water flows in meandering channels over fine-grained sediments (Bretz, 1942).

Where there is frequent percolation of water from the surface, flutes may form along slopes, isolated scallops on vertical and overhanging walls, and small pendants on ceilings (Slabe, 1995). Small channels, single or parallel in groups, that are frequently found descending from slightly opened bedding planes and fissures are the result of small, acidic discharges of water from them, often during floodwater recession. Ceiling pockets form due to the dispersion of water that reaches the ceiling through fissures (Dreybrodt & Franke, 1994). Dripping water carves cup-like pits. Ceiling pockets, large and shallow scallops, and ceiling channels form due to the condensation of moisture from the air onto the rock (see Condensation Corrosion). Some bell holes may have formed in a similar fashion (Tarhule-Lips & Ford, 1999). Unusual cave condensation forms are found in thermal caves (Cigna & Forti, 1986) and condensed moisture often etches the surfaces of the rock in cave entrance zones in all climates. Dissolutional notches and pits form under ice masses accumulating in cold caves.

Biokarstic processes most frequently pit or dissect the rock at much smaller scales. Tiny pits and pendants form under lichen; exposure to light particularly influences their shapes. Larger animals can also leave their traces on the rock. Rock can be weathered several centimetres deep by sediments, condensing moisture, trickling water, freezing, and microorganisms (Zupan Hajna, 2001). Such small-scale sculpture is a frequent and significant clue to the formation and development of karst caves. Distinctive features appear in every type of cave, and the traces of a variety of processes can be interwoven in them. The processes may operate simultaneously to create the diversity, or they can be distributed over various periods of development, where younger traces more or less distinctly cover the older.

Breakdown

Breakdown is the term for the collapse of caves and the debris it produces (see Sediments: Autochthonous). Breakdown plays a role in the evolution and enlargement of many cave passages. It can occur at any time during the evolutionary history of a cave but is most frequent during the enlargement and decay phases. Geological control is apparent in the process of breakdown where the original hydrodynamically created form is modified by mechanical degradation. In most karst rocks, it is the bedding planes and joints that fail under mechanical stress, so the spacing of joints and bedding planes dictates the occurrence and form of breakdown. The stable form for a breakdown passage is a dome. The most stable symmetric domes occur in well-bedded and horizontally bedded rocks. Asymmetric and less stable domes develop where beds dip. Within the bedrock, breakdown is most likely to lie at passages where prominent joint sets intersect. The main reason for all collapses is mechanical breakdown inside a bedding plane, between bedding planes, or between fissured blocks. Some breakdowns can be triggered by earthquakes but this is probably a rare occurrence. The largest known collapse chamber in the world is Sarawak chamber in Borneo, which developed at the axis of an anticline and a thrust fault and along the contact between the impermeable Mulu Formation and the Melinau Limestone (see Mulu Karst and Caves).

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Works Cited

Bretz, J.H. 1942. Vadose and phreatic features of limestone caverns. *Journal of Geology,* 6(2):675–811

Cigna, A.A. & Forti, P. 1986. The speleogenetic role of air flow caused by convection. *International Journal of Speleology,* 15:41–52

Curl, R.L. 1966. Scallops and flutes. *Transactions of the Cave Research Group of Great Britain,* 7(2):121–160

Curl, R.L. 1974. Deducing flow velocity in cave conduits from scallops. *NSS Bulletin,* 36(2):1–5

Dreybrodt, W. & Franke, H.W. 1994. Joint controlled pockets (Laugungskolke) in ceilings of limestone caves: A model of their genesis, growth rates and diameters. *Zeitschrift für Geomorphologie N.F.,* 38:239–45

Ford, D.C. 1964. Stream potholes as indicators of erosion phases in caves. *NSS Bulletin,* 26(4):67–74

Ford, D.C. 1989. Characteristic of dissolutional cave system in carbonate rocks. In *Paleokarst: A Systematic and Regional Review,* edited by P.Bosák, D.C.Ford, J.Glazek & I.Horácek, Amsterdam: Elsevier

Ford, D.C. 2000. Speleogenesis under unconfined settings. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama National Speleological Society, 319–324

Forti, P. 1996. Thermal karst systems. *Acta Carsologica,* 25:99–117

Kempe, S., Brandt, A., Seeger, M. & Vladi, F. 1975. “Facetten” and “Laugdecken”, the typical morphological elements of caves developing in standing waters. *Annales de Spéléologie,* 30(4):705–08

Knez, T. & Slabe, T. 1999. Škocjanske jame, Slovenia: Development of caves related to rock characteristic and rock relief. In *Contribución del estudio científico de las cavidades kársticas al conocimiento geológico* [The scientific study of karstic cavities as a contribution to geological knowledge], edited by B. Andreo, F.Carrasco, & J.J.Durán, Málaga: Patronato de la Cueva de Nerja, Instituto de Investigación

Lauritzen, S-E. & Lundberg, J. 2000. Solutional and erosional morphology. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Mücke, B., Völker, R. & Wadevitz, S. 1983. Cupola formation in occasionally inundated cave roofs. *Proceedings of the European Regional Conference on Speleology,* vol. 2, Sofia: Bulgarian Federation of Speleology

Slabe, T. 1995. *Cave Rocky Relief and its Speleogenetical Significance,* Ljubljana: Zbirka ZRC 107

Tarhule-Lips, R. & Ford, D.C. 1999. Morphometric studies of bellhole development an Cayman Brac. *Cave and Karst Science,* 25(3):119–307

Zupan Hajna, N. 2001. Weathering of cave walls in Martinska jama, SW Slovenia. *Proceedings of the 13th International Congress of Speleology,* Brasilia: Sociedade Brasiliera de Espeleologia (CD-ROM)

MORPHOMETRY OF CAVES

A number of parameters may be used to characterize and compare dimensions and shapes of caves and their patterns. They are derived from data reduction of cave surveys or from resultant cave maps. The pattern of the cave can be represented and measured by building a traverse framework, comprising a combination of traverse (centre) lines for each individual passage, based on tape, compass, and clinometer readings. The cave shape may be represented by a complex surface in three dimensions, to characterize which additional measurements are made, tied to the framework.

Caves are generally compared by their length and depth. The length of a cave is the combined length of all the centreline segments that constitute a framework of the entire integrated passage system. It is necessary to distinguish between the plan length, that is the length of passage projections on the horizontal plane, and the true length. The difference can be substantial for inclined caves, and can be very large for a system in which pitches and vertical shafts predominate. In the extreme case of a single vertical shaft, it will have no plan length but the true length will be equal to the depth. The distribution of caves by length varies between regions, due to both the variable degrees of exploration and differing local geological and hydrogeological conditions. Smooth distributions are characteristic for well-studied regions with a large number of explored caves. All populations are truncated at the short end, commonly at 10 or 30 m, because of the lower limits of documentation and inventory. Extremely long caves are not common. By March 2003, there were 13 caves in the world with lengths exceeding 100 km (Table 1) and 44 caves with lengths exceeding 50 km. The listing of the longest caves is rather conservative as their growth relies on systematic explora tion and mapping over many decades. The number of caves of lesser lengths increases dramatically.

The majority of those caves that have a substantial vertical component were explored "top-down" from an upper entrance or entrances. Their depth may be defined as the vertical range between the altitudes of the entrance (the highest entrance if there is more than one) and the lowermost point reached in the cave. Less commonly, a cave may be explored upwards from a low entrance or entrances without any connection being made to a higher point on the surface. In this case it is more appropriate (from an exploratory perspective) to define the "height" of the cave as the vertical range between the altitude of the lowest entrance and the highest point reached in the cave. If a cave has sections that extend higher than the highest entrance (or lower than the lowest entrance in a "bottom-up" system), then the total vertical range of the cave is measured by the amplitude between the altitudes of the extreme upper and lower points. Depth may be represented by "−" and height by "+", but is often taken as the vertical range, since the positions of the accessible entrances are not significant to the total morphology of the cave. For example, in Table 2, the depth (vertical range) of Boj Boluk is 1415 m, of which 1158 m is below the highest entrance and 257 m is above. As the depth potential for direct cave exploration is limited by the vertical extent of continuous carbonate rocks, deep caves are concentrated in the mountain regions. Most of the world's deepest caves (Table 2) are in the young mountain belt that stretches across Europe from the Pyrenees (Spain) in the west to the Caucasus (Georgia) in the east. This reflects a bias in exploration efforts and the last two decades of the 20th century witnessed a rapid increase in deep cave explora-

Morphometry of Caves: Table 1: The longest caves of the world (as of March 2003)

	Cave	Country	Length (km)
1	Mammoth Cave System	USA, Kentucky	556.9
2	Optymistychna (in gypsum)	Ukraine	214.0
3	Jewel Cave	USA, South Dakota	205.6
4	Hölloch	Switzerland	186.0
5	Lechuguilla Cave	USA, New Mexico	180.0
6	Wind Cave	USA, South Dakota	173.3
7	Fisher Ridge Cave System	USA, Kentucky	169.1
8	Siebenhengste-Hohgant	Switzerland	145.0
9	Ozernaja	Ukraine	117.0
10	Gua Air Jernih	Malaysia Sarawak	111.0
11	Ox Bel Ha (under water)	Mexico	107.1
12	Toca de Boa Vista	Brazil	102.0
13	Réseau Felix Trombe	France	101.0
14	Ojo Guarena	Spain	99.3
15	Sistema Purificacion	Mexico	94.3
16	Zoloushka (in gypsum)	Moldavia-Ukraine	92.0
17	Hirlatzhöhle	Austria	86.6
18	Bullita Cave System	Australia	81.9
19	Raucherkarhöhle	Austria	78.6
20	Ease Gill Cave System	Great Britain	75.0
21	Friar’s Hole Cave	USA, West Virginia	73.3
22	Ogof Draenen	Great Britain	70.0
23	Kazumura Cave (in lava)	USA, Hawaii	65.5
24	Organ Cave	USA, West Virginia	63.6
25	Nohoch Nah Chich (under water)	Mexico	61.0
26	Réseau de 1’Alpe	France	60.2
27	Red del Silencio	Spain	60.0

Morphometry of Caves: Table 2: The deepest caves of the world (as of March 2003)

	Name	Country	Depth (m)
1	Gouffre Mirolda	France	1733
2	Krubera (Voronja)	Georgia	1710
3	Lamprechstofen	Austria	1632
4	Réseau Jean-Bernard	France	1602
5	Torca del Cerro	Spain	1589
6	Cehi 2 “la Vendetta”	Slovenia	1533
7	Sarma	Georgia	1530
8	Vjacheslava Pantjukhina	Georgia	1508
9	Sistema Cheve	Mexico	1484
10	Sistema Huautla	Mexico	1475
11	Sistema del Trave	Spain	1441
12	Boj Bulok	Uzbekistan	1415
13	Puertas de Illamina	Spain	1408
14	Lukina Jama	Croatia	1392
15	Evren Gunay düdeni (Peynirlikönü)	Turkey	1377
16	Sneznaja—Mezhennogo	Georgia	1370
17	Réseau de la Pierre Saint-Martin	France—Spain	1342
18	Siebenhengste	Switzerland	1340
19	Slovacka jama	Croatia	1320
20	Cosa Nostra Loch	Austria	1291
21	Gouffre Berger	France	1271
22	Gouffre Muruk	Papua New Guinea	1258
23	Pozo del Madejuno	Spain	1255
24	Torca de los Rebecos	Spain	1255
25	Abisso Paolo Roversi	Italy	1249
26	Iljukhina	Georgia	1240
27	Sotano Akemati	Mexico	1226
28	Kijahe Xontjoa	Mexico	1223
29	Schwersystem	Austria	1219

30	Abisso Olivifer	Italy	1215
31	Gouffre Gorgothakas	Greece, Crete	1208

tion in other regions of the world. Table 2 lists the deepest caves known at March 2003. However, the fast pace of exploration changes the list substantially within periods of a few years. Frequent changes in ranking of caves occur due to small differences, and new deepest caves may appear quite often. All the deepest caves are combinations of vertical shafts and inclined passages, some constituting very complicated three-dimensional systems. The deepest single pits explored so far are in the Slovenian side of the Monte Kanin massif (see separate entry): Vrtiglavica (643 m deep) and Brezno pod velbom (501 m deep).

Caves can also be compared by the area occupied by passages and chambers, and by their combined volume. The former parameter can be measured from cave maps, whereas to determine volume, it is necessary to sum up volumes of individual elements of the cave, determined from original survey measurements of lengths, widths, and heights. If this was not done routinely throughout all the mapping history of a complex cave, then its volume can be only roughly evaluated. Data on cave areas and volumes in the literature are scarce. Areas of the largest caves are of an order of hundreds of thousands of square metres and rarely exceed one million square metres. Volumes of some longest caves can be as large as several millions of cubic metres. It is noteworthy that the volume of some of the largest individual underground chambers, such as Sarawak Chamber in the Mulu karst in Malaysia (12 million m^3), is greater than the volumes of some of the longest caves that integrate tens or hundreds of kilometres of passages. Even greater are volumes of some huge and deep dolines or pits, such as Luse (50 million m^3) and Minye (26 million m^3), in the Nakanai karst of Papua New Guinea.

Caves are also characterized by the area of cave fields, which is the area of a polygon that reasonably closely delineates a plan array of mapped passages, and by the volume of cave block, which is the volume of rock that contains a cave. The latter parameter can be obtained by multiplying the area of the cave field by the vertical amplitude of a cave.

For the purposes of speleogenetic analysis and hydrogeological and engineering characterization of karstified rocks, some specific parameters that can be derived from basic cave measures and from cave field and block measures are used. Specific volume (the cave volume/length ratio) characterizes an average size of cave passage in the cave system. Passage network density is characterized conveniently by using the ratio of the cave length to the area of the cave field (km km^{-2}). Areal coverage is the area of the cave itself divided by the area of the cave field, expressed as a percentage. It refers to plan-view cave porosity density, which is equivalent to the probability of a drill hole encountering the cave. Cave porosity is a fraction of the volume of a cave block occupied by mapped cavities. It is the volume of the cave divided by the volume of cave block, expressed as a percentage.

Morphometric analysis of caves or their particular components (form) includes various exercises aimed at determining their characteristics and the relationship between cave morphology and structural, lithological, and hydrogeological factors. This can shed more light on the origin of caves or their particular forms. Recent studies suggest that at least some of the above specific parameters can be indicative of whether the caves evolved under an unconfined setting or a confined setting. Analysis of samples of typical caves formed in the respective settings shows that average passage network density for unconfined settings is 16.6 km km^{-2} while this parameter for confined settings is 177.6 km km^{-2}. Average areal coverage for unconfined speleogenesis is 6.16%, while it is 32.8% for confined speleogenesis. Cave porosity for unconfined speleogenesis is 0.54% but it is an order of magnitude greater for confined speleogenesis (5.4%).

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See also **Morphology of Caves; Patterns of Caves; Speleogenesis**

Further Reading

Courbon, P., Chabert, C., Bosted, P. & Lindsley, K. 1989. *Atlas of the Great Caves of the World,* St. Louis, Missouri: Cave Books

MORPHOMETRY OF KARST

Morphometry is the measurement and analysis of form (shape). In the context of geomorphology, defined as the study of earth surface processes and landforms, morphometry may be utilized in the quantitative analysis of individual landforms and their landscape assemblages. In this context, general geomorphometry is "the measurement and analysis of those characteristics of landform which are applicable to any continuous rough surface. This is distinguished from "specific geomorphometry", the measurement and analysis of specific landforms" (Evans, 1972, p.18).

Morphometric studies in karst terrains have a long history, beginning with the doline shape analyses conducted by Cvijić (1893). Other, sporadic, morphometry was applied to karst in the first half of the 20th century, notably by Cramer (1941), who made a detailed worldwide inventory of thousands of dolines, their numbers, sizes, and densities, and by Meyerhoff (1933), who examined doline size and distribution using measures of relief and spacing. However, it was not until the "quantitative revolution" of the 1960s that morphometry became widely utilized in karst studies.

Although karst morphometry has focused on surface landforms and landscapes, it has also been applied to caves (see Morphometry of Caves), where quantitative data on shapes and sizes of cave passages, specific erosional and depositional features, and even entire systems are valuable evidence of speleogenic origins. Geometric analyses have been conducted on cave passage crosssections, passage meanders, and scallops, but quantitative treatments of cave morphology in general are sparse.

Pioneering work on karst morphometry, initially evolving from fluvial drainage basin studies, was carried out by Williams (1969), who treated swallets (stream-sinks), and later enclosed karst depressions (dolines) as discrete catchment areas, and conducted quantitative analyses of their shapes, sizes, and drainage components, concluding that fluvial morphometric relationships also applied in the karst landscape. Williams (1971; 1972a,b) and others subsequently extended these analyses to tropical karst terrains, which had previously been regarded as chaotic assemblages of depressions, hills, and valleys. Williams showed that these were, in fact, organized landscapes with distinct landscape patterns reflecting predictable modes of closed depression development. In particular, he identified so-called polygonal karst, in which enclosed depressions are surrounded by residual hills whose summits could be connected by lines to produce a polygonal pattern. Focusing on the enclosed depressions, Williams revealed that they could be considered viably as individual drainage basins, and that their dispersion pattern tended towards uniformity, reflecting general slope and structural controls.

Morphometric analyses of dolines have been legion. A large number of studies have focused on spatial distribution, pattern, and density, correlating doline density, for example, with carbonate lithology, mantle thickness, and limestone purity. Lavalle (1968) employed doline parameters as a measure of landscape dissection, and several studies have used doline numbers and sizes to assess degree of karstification, for example employing an index of pitting. Other studies have attempted to illuminate doline evolution, for example using spatial relations, historical sequences, or using space-time substitution. Clustering of "daughter" dolines around individual "mothers" apparently occurs in some areas, although not others. Some dolines elongate through time, and Day (1983) showed that, on the raised reef terraces of Barbados, doline numbers increased through time until they attained a density that was structurally controlled. Depth/diameter ratios have also been employed, for example to illuminate differences between doline populations.

Other workers have expanded morphometric analysis to other landscape components, including regional valley systems. Again following prior studies in fluvial landscapes, morphometry of karstic valley systems has focused on such issues as valley ordering, density, pattern, and orientation. Several studies have examined the relationships between valley systems and karst depressions, which are, in a sense, "competitive". Other studies have employed morphometry at a smaller scale, focusing, for example on the components of limestone pavements (e.g. Goldie & Cox, 2000).

Morphometry has also been applied to residual carbonate hills (cones or towers), which are of variable morphology and which have been classified on the basis of such dimensions as their heights and diameters. This approach was extended by Day (1981) to incorporate both enclosed depressions and residual hills into an overall classification of tropical karst landscape styles. This approach produced a simple tripartite framework as follows: in type I landscape enclosed depressions are dominant, and interspersed with subdued hills; in type II landscape enclosed depressions and residual hills attain approximately equal prominence; and in type III landscape isolated residual hills dominate intervening near-planar surfaces. Morphometric approaches to karst landscapes are relatively straightforward where individual landforms are clearly defined, but are far more problematic where landforms coalesce or intersect.

Field measurement of karst landscape is arduous and time-consuming, but maps, air photographs, and satellite imagery generally do not provide sufficiently detailed information at a suitable scale to be acceptable substitutes. Comparative data on the density and spacing of individual landforms is relatively easily assembled, but meaningful measurements of height and three-dimensional shape, for example, are far more problematic. Where field data are available, usually for relatively restricted areas, a variety of approaches to measurement and classification have been employed.

Other studies have gone beyond individual landforms to consider general karst landscape morphometry, which should provide overall indices of landscape morphology, although this has until recently been less fruitful than might be hoped. McConnell and Horn (1972) employed quadrat analysis to analyse doline density, revealing patterns suggestive of other than single random processes or contagion, but suggestive of multiple random processes, such as dissolution and collapse. Surface roughness has also been utilized as a discriminator of tropical karst landscape styles by Day (1979) and, with greater sophistication, by Brook and Hanson (1991) who used double Fourier series analysis to analyse landscape wavelength variance within doline and cockpit karst landscapes in Jamaica. They were able to demonstrate statistically the greater complexity and roughness in the latter, and illuminated the differing roles of fracture sets on landscape development. More recently, GIS modelling has been applied to karst landscapes, an approach that holds great promise.

One incentive for morphometric studies in karst geomorphology has been the hope that they would reveal explicit linkages between karst landforms and landscape assemblages on the one hand and suites of karst process variations on the other; that they would serve to forge a link between disparate information about forms and processes, especially in differing climatic zones. In this context morphometry has not proven to be as useful a tool as had been hoped. Nevertheless, quantification of form has made inter-regional comparison more rigorous. It has also helped in the development of meaningful indices of landscape morphology and it has clarified the role of lithological, structural, and other factors in influencing karst landform development. Development of more rigorous mathematical modelling techniques and the employment of digital elevation models and related landscape data in geographic information systems (GIS) may be expected to contribute to more productive mathematical analysis of karst landscapes.

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See also **Cone Karst; Dolines; Morphometry of Caves; Tower Karst**

Works Cited

Brook, G.A. & Hanson, M. 1991. Double Fourier series analysis of cockpit and doline karst near Browns Town, Jamaica. *Physical Geography,* 12(1):37–54

Cramer, H. 1941. Die Systematik der Karstdolinen. *Neues Jahrbuch für Mineralogie, Geologie und Paleontologie,* Beilage-Band, Abt B 85:293–382

Cvijić, J. 1893. Das Karstphänomen. *Geographische Abhandlungen Wien,* 5(3):218–329

Day, M.J. 1979. Surface roughness as a discriminator of tropical karst styles. *Zeitschrift für Geomorphologie N.F., Supplementbande,* 32:1–8

Day, M.J. 1981. Towards numerical categorization of tropical karst terrains. *Proceedings of the 8th International Congress of Speleology,* vol. 1, edited by B.F.Beck, Huntsville, Alabama: National Speleological Society

Day, M.J. 1983. Doline morphology and development in Barbados. *Annals of the Association of American Geographers,* 73:206–19
Evans, I.S. 1972. General geomorphometry, derivatives of altitude, and descriptive statistics. In *Spatial Analysis in Geomorphology,* edited by R.J.Chorley, London: Methuen
Goldie, H.S. & Cox, N.J. 2000. Comparative morphometry of limestone pavements in Switzerland, Britain and Ireland. *Zeitschrift für Geomorphologie N.F., Supplementbande,* 122:85–112
Lavalle, P. 1968. Karst morphology in south central Kentucky. *Geografiska Annaler,* 50:94–108
McConnell, H. & Horn, J.M. 1972. Probabilities of surface karst. In *Spatial Analysis in Geomorphology,* edited by R.J.Chorley, London: Methuen
Meyerhoff, H.A. 1933. Texture of karst topography. *Journal of Geomorphology,* 1(4):279–95
Williams, P.W. 1969. The geomorphic effects of groundwater. In *Water, Earth and Man,* edited by R.J.Chorley, London: Methuen
Williams, P.W. 1971. Illustrating morphometric analysis of karst with examples from New Guinea. *Zeitschrift für Geomorphologie N.F.,* 15:40–61
Williams, P.W. 1972a. Morphometric analysis of polygonal karst in New Guinea. *Bulletin of the Geological Society of America,* 83: 761–96
Williams, P.W. 1972b. The analysis of spatial characteristics of karst terrains. In *Spatial Analysis in Geomorphology,* edited by R.J. Chorley, London: Methuen

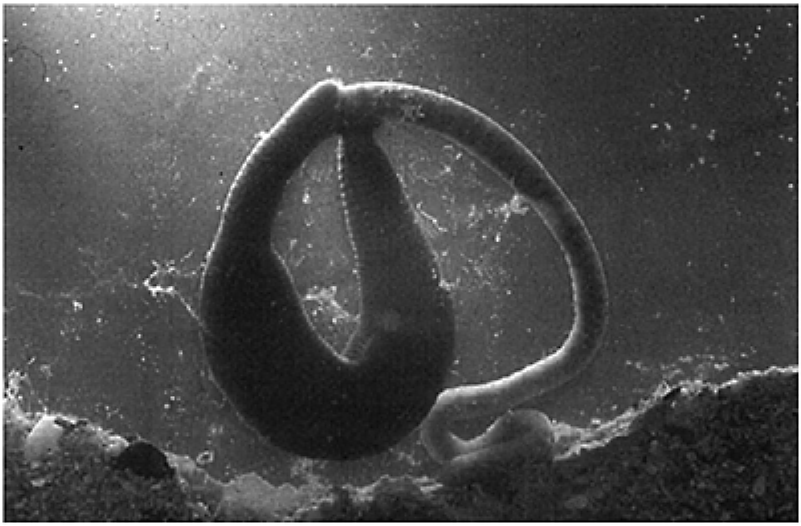
Further Reading

Goudie, A.S. (editor) 1990. *Geomorphological Techniques,* 2nd edition, London and Boston: Unwin Hyman
MacGillivray, C.M.I. 1997. A review of quantitative techniques for measuring karst terrain, with examples from the Caribbean. *Caribbean Geography,* 8(2):81–95

MOVILE CAVE, ROMANIA

An artificial shaft dug in 1986 near the Black Sea, in the limestone platform of the Romanian Dobrogea, intercepted a cave with thermal sulfurous water. Movile Cave, which has no natural entrance, connects to a short groundwater system and shelters a rich biological community with 48 species of aquatic and terrestrial invertebrates, many of which are new taxa and 34 are endemic to this ecosystem. Stable isotope data shows that the Movile Cave ecosystem derives its organic carbon solely from *in situ* chemoautotrophic production, the cave being the first terrestrial ecosystem known to be independent of solar energy (Sârbu, Kane & Kinkle, 1996); mineral-rich deep-sea hydrothermal vents are the only other known non-photosynthetic ecosystems on Earth. The Movile discovery supports the Deep Hot Biosphere theory and the expectation of exobiologists that chemoautotrophic (also known as chemolithoautotrophic) life forms may be found beneath the surface of Mars, in volcanic caves.

Movile Cave is located near the city of Mangalia in southeastern Romania, 3 km from the Black Sea coast, at the eastern border of the Dobrogea Plateau. The upper part of the plateau consists of fossiliferous, oolitic limestones *c.* 12.5 Ma in age. The plateau is locally disturbed by solutional karstic features, such as dolines, dry valleys, and cliffs (in Romanian, "Movile" means



Movile Cave: Figure 1. *Haemopsis caeca* devouring a worm.

hillocks). Except for Limanu, a 4 km long maze cave, the area previously offered little interest for cave explorers. However, in 1986, a power-plant construction project began near Mangalia and Cristian Lascu, a speleologist at the "Emil Racoviță" Institute in Bucharest, suggested that the proposed location should be investigated with a few drill holes, in order to avoid possible karstic collapses. During the survey of an exploratory shaft he found the cave at a depth of 18 m beneath the surface.

Movile Cave is a horizontal maze cave 240 m long, with two levels. The upper level is dry, with a phreatic morphology including rounded and elliptical sections, 1–2 m in diameter. Red and yellowish fine clay is abundant. There are no speleothems and the only secondary mineral deposits are a few calcite crusts associated with millimetric aragonite needles and gypsum (Diaconu & Morar, 1993). The lower level has a clastic morphology that indicates a more recent origin. It consists of a 25 m succession of four underwater passages, 0.5–2 m wide and 1–3 m deep, separated by three small airbells. A very soft, grey, organic sediment lies on the bottom. Secondary gypsum needles are present on the walls above the water table. A 5 m shaft from a pool connects the two cave levels.

Cave Environment

Movile is a low-grade thermal cave. The air temperature is 20°C and humidity is 100%. There is no detectable air movement (Boghean & Racoviță, 1989). The upper level's atmosphere contains *c*. 20% oxygen and around 1% carbon dioxide, and the atmosphere in the airbells becomes progressively poorer in oxygen (19–16–7%) and enriched in carbon dioxide (1.5–2–3.5%) due to biological activity (Sârbu, 2000). The airbells also contain small amounts of hydrogen sulfide and methane. Moisture on the walls has a pH of 3.5–4. The groundwater contains 30 mg l^{-1} H_2S, with a pH of 7.2 at a constant temperature of 21°C. Although the water contains dissolved oxygen in a 1 mm layer at the air-water interface it is anoxic below this layer. The water contains no organic compounds from the surface and is probably derived from a deep (180–600 m) thermomineral aquifer in the Mesozoic limestones. A slight current was detected in the underwater passages.

Cave Life

The lower level of Movile Cave hosts a rich and diverse biological community. On the walls of airbells it is possible to see simul-taneously tens of spiders, Isopoda, centipedes, and Coleoptera. Near the water level, every square decimetre contains nearly 100 specimens of the gastropods *Semisalsa* and *Paladilchia,* 1–3 mm long snails. The water surface in the airbells is covered with a layer of white, cream-like organic matter. This mat is a mixture of fungi and sulfide-oxidizing micro-organisms including *Thiomicrospira* sp., *Beggiatoa* sp., and *Thiobacillus thioparus* (Ylăsceanu, Popa & Kinkle, 1997; see also Biofilms entry). The terrestrial fauna is composed of 30 species of cave-dwelling invertebrates, including 23 endemic species (Sârbu, 2000; Sârbu & Popa, 1992). Of particular interest are species of pseudoscorpions, spiders, and centipedes that are new to science. *Agroecina cristiani,* a 20 mm long arachnid that is a close relative of a cave spider found inhabiting lava tubes in the Canary Islands, is very abundant. There are also numerous specimens of *Criptops anomalans,* a voracious centipede that reaches up to 100 mm in length. Its favourite prey are the isopods *Trachelipus and Armadillidium* and the coleopterans *Glivina, Medon,* and *Tychobitinus.*

The aquatic fauna is represented by 18 species that are new to science, with 11 endemics. Here there are even more peculiar creatures. The water scorpion *Nepa anophthalma,* which grows up to 25 mm long, is the first cave-adapted aquatic hemipteran known in the world. Hidden below the surface it extends two pincer-like front legs, probing the water for signs of shrimps or worms. To breathe, the water scorpion arches its hollow tail upwards into the air, drawing air through this built-in snorkel. A new species of the predatory leech, *Haemopis caeca,* the only species of cave leech known, preys on worms and *Niphargus,* a common amphipod. *H.caeca* also grazes the organic mats of bacteria and fungi.

The cave fauna generally displays morphological features typical for species with a long evolutionary history of isolation in caves, and there is paleogeographical evidence to suggest that the ancestors of some species may have invaded the subterranean system as early as the late Miocene (5.5 million years ago), when the climate was much warmer. Most of the cave's invertebrate species show a reduction or loss of eyes. In compensation they present an enlargement of appendages and extraoptic sensitive structures. Another troglomorphic adaptation is the loss or reduction of pigmentation and some of the cave fauna are white or translucent.

Movile Cave: Figure 2. The spider *Agroecina cristiani* (new endemic species), a 20 mm long arachnid.

Energetics of the Movile Ecosystem

In most instances life in caves is based on food that originated from the surface. Vegetal detritus and animal excreta, such as bat guano, represent rich food resources and percolation water brings small amounts of organic matter along limestone cracks. However, at Movile Cave a deposit of clay overlying the limestone seals the cracks and pores and several different experiments have proved that the subterranean community can receive little, if any, organic input from the surface. In particular, whereas the soil, plants, surface sediments, and other caves in the area contain the radionuclides ^{137}Cs and ^{90}Sr as a result of the Chernobyl nuclear accident, no trace of them has been detected in Movile Cave sediments. The dehydrogenase (a bacterial enzyme) activity in samples of sediment from the limestone strata overlying the Movile passages is very low, proving the scarcity of external microbes and organic compounds (Sârbu, 2000).

The presence in Movile Cave of a large population of invertebrate species and abundant predators, with a high metabolic activity, suggests a large energy base for the ecosystem. Studies of stable isotope ratios indicate that the community is totally dependent on *in situ* chemoautotrophic production within the bacterial mat. Carbon and nitrogen stable isotopes are fractionated by organisms during metabolic processes, the lighter isotopes being preferentially selected. All forms of inorganic carbon in the cave are isotopically light. The Movile Cave atmosphere contains CO2 as a mixture of heavier CO2 from limestone sulfuric corrosion and lighter CO2 presumably from endogenetic methane oxidation. The nitrogen in the bacterial mat in the cave is enriched in the lighter nitrogen isotope. The organisms in Movile Cave consuming these mats are isotopically lighter both in carbon and nitrogen when compared with similar organisms sampled from the nearby Limanu cave and some other surface locations. If the Movile Cave ecosystem were dependent on allochthonous input of organic material from the surface, the organism would be isotopically heavier, for both carbon and nitrogen. The stable isotope analyses demonstrate the absence of photosynthetically derived carbon in the cave but also suggest that the carbon of the microbial mat is solely of chemoautotrophic origin (Sârbu, Kane & Kinkle, 1996). Since the reduced carbon in organic molecules metabolized by Movile microbiota does not take part in the external carbon cycle, the energy used by microorganisms to fix inorganic carbon both from atmospheric CO_2 and from methane must result from an internal source, the oxidation of hydrogen sulfide from the thermomineral groundwater:

$$H_2S + 2O_2 = SO_4 + 2H + 798.2\ \mathrm{kJ\ mol}^{-1}$$

Chemical energy resulting from the oxidation of reduced compounds such as sulfide, methane, iron, or ammonium is the alternative source to photosynthesis for manufacture of carbohydrates and cells in aphotic habitats such as sulfurous caves, deepsea vents, and underground thermomineral waters.

Although most of the oxygen in the cave probably comes from the surface atmosphere, part of it may be produced by iron reduction bacteria in a sulfidic environment. An alternative

Movile Cave: Figure 3. Phreatic tunnel in the upper level of Movile Cave.

source for oxygen in the cave could be hyperoxidized iron compounds from the red clay. The results are fine grains of pyrothine and greigite: iron sulfide compounds that form spheroidal aggregates resembling a blackberry. Such features and associated magnetic bacteria have been detected in Movile Cave.

Origin of Movile Cave and the Mangalia Karst

Movile Cave is a recent, shallow, and limited segment of the extensive and deep karstic system of southern Dobrogea. The Dobrogea Platform consists of Mesozoic and Cenozoic limestones up to 800 m thick, and is bordered by the Danube to the west and by the Black Sea to the east. This large limestone body experienced several karstification periods related to oscillations in the level of the Black Sea which have favoured the formation of large karstic networks. A study based on analysis of 52 boreholes has proved that at least three different karstic levels were formed. The deepest level is located at an average depth of 200 m and was formed during the Upper Miocene, 5.5 million years ago. At that time, the Black Sea, as throughout the Mediterranean Basin, experienced a dramatic hydrological and climatic event known as the Messinian Crisis. Due to a northward movement of the African plate, the Gibraltar Strait closed, separating the Mediterranean Basin from the Atlantic Ocean. In a few millennia the Mediterranean Sea lost nearly all of its water by evaporation, leaving a few hypersaline lakes. Consequently, the satellite seas of the former Tethys, climatically and hydrologically dependent on the mother-sea, experienced a drop in their levels of several hundred metres (Hsu, 1978). The study of shallow-water deposits in boreholes in the Danube Delta has shown that the Black Sea level was probably 200 m lower (Lascu, Popa & Sârbu, 1994). At this stage, the Dacian Lake, another remnant basin located in the west of Dobrogea, drained towards the Black Sea through large karstic passages carved in the Dobrogea carbonate platform. Some of these karst conduits seem to be still active, circulating huge amounts of water from the Danube River towards the Black Sea (up to 10×10^6 l s^{-1}). Several 200 m deep submarine canyons in the Black Sea are thought to be remnants of the Messinian karstic development. Six hydrogeological boreholes which penetrate this level provide large amounts of water ranging between 110 and 225 l s^{-1}; the water is sulfidic, low- grade thermal (24–25°C), at a pressure of some 1.7 atm.

Later oscillations of the Black Sea level led to several other karstification periods. A middle-Quaternary speleogenetic episode may be responsible for the formation of the upper level of Movile Cave. Another karstification episode was contemporary with the Würm II glacial, *c.* 15000 years ago, when the Black Sea level was about 50–60 m lower. This initiated collapse processes that produced large dolines in this area. The Movile doline collapse cut the pre-existing phreatic conduits and water drainage was lowered to its present level.

Speleogenesis of the modern cave may have been influenced by microbial activity as the presence of sulfide-oxidizing bacteria could have generated small amounts of H_2SO_4, increasing the rate of carbonate dissolution. According to the mechanism proposed by Egemeier (1981), the acid environment of Movile Cave, which includes gypsum deposits, is actively undergoing enlargement.

CRISTIAN LASCU

Works Cited

Boghean, V. & Racoviță, G. 1989. Données préliminaires sur le topoclimat de la Grotte “Peştera de la Movile” (Mangalia-Dobrogea de Sud-Roumanie). *Miscellanea Speologica Romanica,* 1:19–31

Diaconu, G. & Morar, M. 1993. Analyses mineralogiques dans la grotte “Pestera de la Movile” (Mangalia-Dobrogea de Sud). *Karstologia,* 22:15–20

Egemeier, S.J. 1981. Cavern development by thermal waters. *National Speleological Society Bulletin,* 43:31–51

Hsu, K.J. 1978. When the Black Sea was drained. *Scientific American,* 238:52–63

Lascu, C., Popa, R. & Sârbu, Ş. 1994. Le Karst de Movile (Dobrogea de Sud) (I). *Revue roumaine de géographie,* 38:85–94

Sârbu, Ș.M. 2000. Movile Cave: A chemoautotrophically based groundwater ecosystem. In *Subterranean Ecosystems,* edited by H. Wilkens, D.C.Culver & W.F.Humphreys, Amsterdam and New York: Elsevier

Sârbu, Ș.M., Kane, T.C. & Kinkle, B.K. 1996. A chemoautotrophically based groundwater ecosystem. *Science,* 272: 1953–55

Sârbu, Ș.M. & Popa, R. 1992. A unique chemoautotrophically based cave ecosystem. In *The Natural History of Biospeleology,* edited by A.I.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Vlăsceanu, L., Popa, R. & Kinkle, B.K. 1997. Characterization of *Thiobacillus thioparus* LV43 and its distribution in a chemoautotrophically based groundwater ecosystem. *Applied and Environmental Microbiology,* 63:3112–27

Further Reading

Sârbu, Ș.M. & Kane, T.C. 1995. A subterranean chemoautotrophically based ecosystem. *National Speleological Society Bulletin,* 57:91–98

MULU, SARAWAK

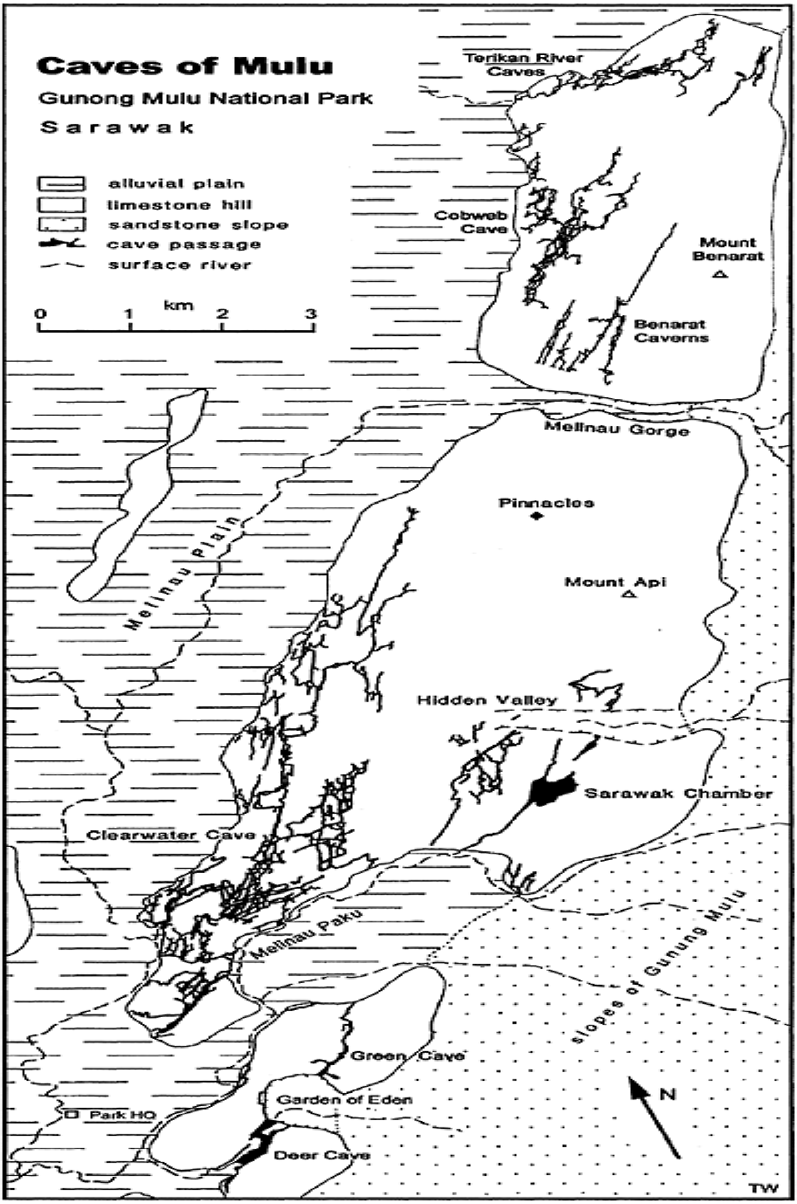
The Gunung Mulu National Park covers a large slice of preserved rain forest in the northeast corner of Sarawak, Malaysia. Within its boundaries, the mountains of Api and Benarat are formed of steeply dipping, very massive, Miocene Melinau Limestone. Annual rainfall of 5000–10000 mm, and temperatures rarely outside 20–30°C, create the classic hothouse environment, where karst matures most rapidly. Drainage from the sandstone mountain of Gunung Mulu feeds onto the Api-Benarat limestone outcrop—which therefore contains some of the world’s largest caves—and through to a terraced alluviated plain, eroded into the limestone and overlying shales. Serious cave exploration started in 1978, since when a series of British expeditions have mapped over 320 km of passages within the Park.

Gunung Api is the largest limestone block (Figure 1). It is largely drained by Gua Air Jernih (Clearwater Cave), over 110 km long. Its large passages give the southern end of Api a cavernous permeability close to 3%, an unusually high figure and one that takes no account of further caves not yet explored. The lowest level carries the river (Figure 2), whose base flow of 0.1 $m^3 s^{-1}$ rises to about 5 $m^3 s^{-1}$ on many afternoons, in response to daily rainstorms. Its upstream section has lengths of canyon separated by flooded loops, but the downstream 2000 m forms a singularly impressive, clean canyon out to the resurgence boulder choke. It once carried all the Melinau River from sinks in its gorge, but these are now buried and almost sealed.

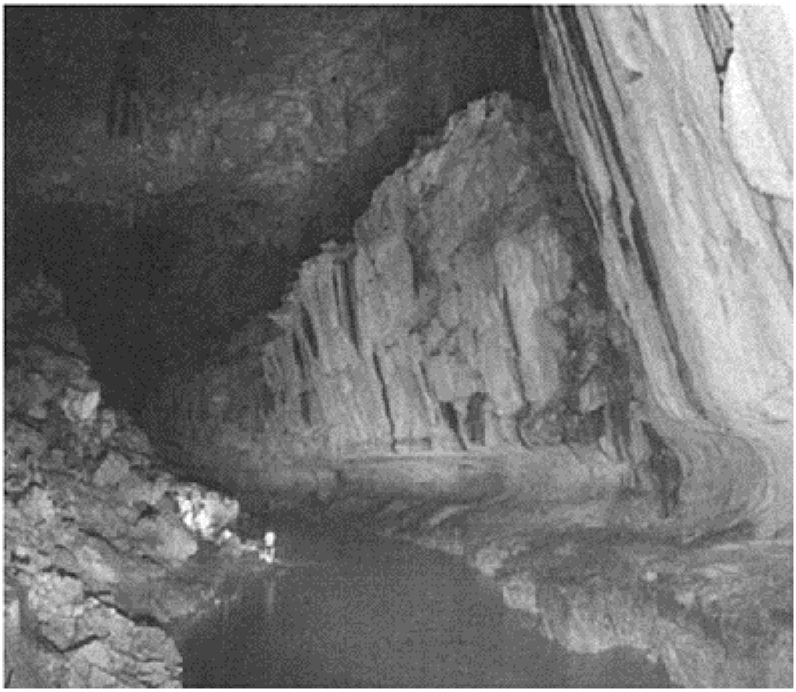
The abandoned high-level passages of Air Jernih are huge tunnels along the strike, forming a sequence at successive levels on just a few major dipping bedding planes. Dip-oriented inlets include phreatic risers more than 100 m deep, now abandoned as dry shafts. Many of these mature passages are graded to their contemporary outlet levels. They originated as phreatic routes with varying extents of switchback looping, guided by joints across their host bedding planes. Downloops were removed by paragenetic roof dissolution associated with massive sedimentation, while canyons were cut through the uploops. Huge thicknesses of clastic sediments survive in many passages. The pattern of stream sinks around Api has changed over time, as alluvial fans from the sandstone of Gunung Mulu have built up against the limestone, with streams shifting easily across their convex surfaces. The caves have evolved in response, with complete reversals of flow in some of the strike-oriented passages that lie across the regional drainage direction.

Wall notches, typically 2 m high and cut 4–5 m into vertical walls, are a feature of the Mulu caves; a few are active, most are abandoned. They are formed by dissolutional undercutting at river levels, which are controlled by the resurgences onto the alluvial plain. The cave rivers rise and fall by the notch height, with the almost daily flood events. The main notches form downstream of large sinks at the alluvial plain base level, and the finest active examples are in the Cave of the Winds along the large streamway from the Melinau Paku to the Melinau.

A sequence of 20 notch levels in Gua Air Jernih, spread over 300 m of altitude and dated by their associated stalagmite and clastic sediments, records a base level that has fallen at a mean rate of 0.19 m per 1000 years, for 700000 years (Farrant *et al.*, 1995). Phases of interglacial gravel aggradation alternated with base-level lowering during Pleistocene cold stages. Over about 10 Ma, the limestone hills of Mulu have evolved by remaining almost uneroded, while the adjacent plains and non-carbonate slopes have been intermittently lowered. Combined with steady tectonic uplift, this has had the effect of the limestone hills rising slowly from an almost stationary plain.



Mulu, Sarawak: Figure 1. Mapped cave passages in the limestone hills of the Gunung Mulu National Park, Sarawak (compiled from surveys by the British expeditions 1978–2001).



Mulu, Sarawak: Figure 2. The main river passage in Gua Air Jernih (Clearwater Cave) in Gunung Api. (Photo by Tony Waltham)

In the east side of Api, Lubang Nasib Bagus carries a second river underground, from Hidden Valley south to a resurgence beside the Melinau Paku. It drains through the base of Sarawak Chamber, which is 700 m long and 300–400 m wide, with an arched roof 100 m high. By far the world's largest cave chamber, this only survives due to the very massive nature of the Melinau Limestone. It appears to have originated as a wide inclined slot cut along a major dipping bedding plane by a powerful river; this migrated laterally, probably in part by waterfall retreat, and was matched by roof blockfall to create a single stable arch above.

South of Api, a smaller hill is breached by Deer Cave, with a passage 100 m high and wide for more than a kilometre of length—making it the world's largest cave passage (Figure 3). It is one of a series of larger, older caves that lie close to the eastern edge of the limestone. Between it and Green Cave, the Garden of Eden is an asymmetrical doline, 800 m across, with an inlet stream off the sandstone. The doline has grown as the stream sink has shifted its course off its own alluvial fan; wall scallops indicate that it flowed out through Green Cave at one stage. There is debate over how much the doline originated by collapse of a cave passage or chamber, but there is no evidence for the scale of individual collapse events within a progressive process. The concept of a single very large collapse does become real when the doline's size is compared to that of Sarawak Chamber, not far to the north.

North of Api, Gunung Benarat contains more very large caves. Cobweb Cave (30 km long) has a complex of old high levels, but with few long graded passages, unlike the layered, more mature tunnels of Benarat Caverns (8 km long) and the various caves of the Terikan River. North of Benarat, Gunung Buda is another smaller limestone hill, containing another 30 km of caves, explored mainly by American groups; they include Gua Kulit Siput, whose phreatic ramps reach 470 m above the entrances at plain level.

Mulu, Sarawak: Figure 3. The largely abandoned tunnel that is the main passage of Deer Cave, probably the largest passage in the world. The roof is more than 100 m above the show-cave path that winds across the floor. (Photo by Tony Waltham)

The surface karst of Mulu is dominated by forested pinnacles. Very steep slopes and high cliffs form the perimeter of the limestone mountains, whose high ridges are scored by deep dolines. All surfaces, steep and gentle, are fretted into pinnacles and blades each 1–10 m high, now shrouded in forest vegetation. The Pinnacles on Gunung Api are up to 50 m tall and rise clear of the forest canopy (Figure 4), but they are just the largest and best known of a widespread landform. Most pinnacles are razorsharp subaerial forms, but rounded versions are evolving beneath

Mulu, Sarawak: Figure 4. The Pinnacles on Gunung Api with blades of limestone rising clear of the forest canopy. (Photo by Tony Waltham)

the thicker organic soils. The Melinau River carries the largest single flow off Gunung Mulu, and has maintained a surface course across the limestone outcrop between Api and Benarat; its gorge has vertical cliffs up to 500 m high, which cleanly truncate the ancient phreatic tubes of Benarat Caverns.

In addition to its extraordinary karst geomorphology, the Gunung Mulu National Park hosts an amazing variety of fauna and flora, both above and below ground. Deer Cave has over two million bats that roost on its high roof every day, and emerge most evenings in one of the world's most spectacular bat flights. In most of the Mulu caves, bats and swifts provide the guano that supports a pyramid of cave fauna, topped by large spiders and centipedes.

The Gunung Mulu National Park was established in 1975, to preserve a sample of Borneo's rain forest. The caves were intended to provide some visitor interest and financial support, but their sheer scale has turned them into a major tourist attraction. In 2001, the Park was designated as a World Heritage Site, on the strength of both its surface and underground features, which should support appropriate management and conservation of this magnificent karst.

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Works Cited

Farrant, A.R., Smart, P.L., Whitaker, F.F. & Tarling D.H. 1995. Long-term Quaternary uplift rates inferred from limestone caves in Sarawak, Malaysia. *Geology,* 23:357–60

Further Reading

Eavis, A.J. 1985. *Caves of Mulu '84,* Bridgewater: British Cave Research Association
Smart, P.L. & Willis, R.G. (editors) 1982. Mulu '80 expedition. *Cave Science,* 9:55–164
Waltham, A.C. & Brook, D.B. (editors) 1978. *Caves of Mulu,* London: Royal Geographical Society
Waltham, T. 1997. Mulu—the ultimate in cavernous karst. *Geology Today,* 13:216–22
Wilford, G.E. 1964. The geology of Sarawak and Sabah caves. *Bulletin of Geological Survey of Borneo Region, Malaysia,* 6:1–181

MUSIC IN AND ABOUT CAVES

The amazing sonority and acoustic qualities of certain cave chambers have appealed to musicians since prehistoric times when footprints of dancers circling clay sculptures were made on the floor of caves in the French Pyrenees. Later religious ceremonies accompanied with instruments and chant were performed in Mayan caves of Central America and in Buddhist temple caves of Southeast Asia.

In historic times the earliest known performances of secular music in caves date to the end of the 18th century. In Peak Cavern (Derbyshire, England) around 1778, choral groups would climb around to the niche overlooking Roger Rain's House and sing for famous and wealthy travellers (Bray, 1778). Somewhat earlier in the Franche-Comté region of France, the provincial royal intendant organized a very successful festive banquet in the Grotte d'Osselle, involving music and dancing illuminated with hundreds of torches (Minvielle, 1970).

In 1822, dances were being held in the world-famous Postojnska Jama (then known as Adelsberger Grotte). Here on Whit Monday the Tournier Platz (now Congress Hall) was lit with rustic chandeliers and the locals would dance to traditional music (Russell, 1828). These dances continued annually throughout the 19th century. Farther back in a magnificent chamber the management later installed a stage and seating area where symphony concerts are still held occasionally.

In the latter half of the 20th century the idea of holding concerts in show caves during the summer caught on in several countries. In France there are jazz and folk concerts in the Aven Armand, Lozère and pan flute concerts in the Grotte de Lombrives, Ariège. In St Michael’s Cave, Gibraltar, band concerts predominate. Once a year in Romania musicians hike for an hour carrying their instruments to Peştera Româneşti in the Poiana Rusca mountains to play classical concerts. On the isle of Kephalonia in Greece, classical and choral music are performed in Drogarati Cave. Contemporary and *concrete* music concerts were held in a relict gallery of Jeïta Cave in Lebanon before the outbreak of the war there. There are also winter venues such as the annual Christmas carol concert in the entrance chamber of Peak Cavern, England, which is attended by several hundred people.

Some show caves hold regular yearly festivals where worldclass ballet troupes, symphony orchestras, and famous soloists come to perform. Theatre, choral groups, and jazz musicians have performed in the Balver Höhle in the Sauerland, Germany since 1949 (Allhoff-Cramer, 1996). Starting in 1960, the Cueva de Nerja near Malaga, Spain set up a large stage beneath a splendid speleothem display where many prestigious ballet troupes and soloists have performed (Ortega, 1970). The Baradla Barlang in northeastern Hungary has also hosted many fine concerts every summer (see photograph) and in South Africa the Cango Caves have been staging choral concerts for 40 years.

The European practice of holding concerts in caves was not carried over to North America. Instead, during the hot summer months there, the early colonists would take to their local caves

Music in and about Caves: Concert of cave-inspired classical and contemporary music in Baradla Barlang, Hungary, in July 1996.

and dance to live music. In 1839 hundreds of candles lit Weyer's Cave (now Grand Caverns) in Virginia and a band played for square dancing on the clay floor of the Ball Room. Then in 1878, with the opening of Luray Caverns, Virginia, a wooden floor was laid down, a band played, and anyone who wished to dance was charged 25 cents (Gurnee, 1978). As in many other caves worldwide, the cave guides would play simple tunes on a row of stalactites. This inspired Leland Sprinkle to create a "stalacpipe organ" in Luray Caverns by harnessing an organ console to various cave formations which when struck by rubber-tipped plungers would sound the desired notes. However, this entailed some damage to the cave where a few stalactites had to be ground down to achieve the proper pitch. The first concert where the cave itself became a musical instrument was in 1957.

During the 1920s and 1930s some caves in the southern United States proved ideally suitable for establishing speakeasy nightclubs with ballroom dancing. At Lost River Cave in Bowling Green, Kentucky; at Bangor Cave in Alabama; at Longhorn Caverns in Burnet, Texas; and at Wonderland Cave in Bella Vista, Arkansas, the customers danced to the music of name orchestras, but all these cave clubs had closed by the 1950s. Today nightclub-discotheque caves with recorded or live dance music can be found in Bermuda at Prospero's Cave, in Cuba at the Cueva del Pirate in Varadero, and in the Dominican Republic at Meson de la Cava in Santo Domingo.

Damage to the cave environment due to sustained use by nightclubs and discotheques is deplorable. However, the occasional use of cave spaces for concerts or dancing has been found acceptable in most cases. Hearing a great concert with the superb acoustics and surroundings of a natural cave chamber is a truly memorable experience surpassing imagination.

This special sonority combined with the emotions of wonder and mystery experienced in caves have inspired many musicians to compose music about caves. This music inspired by specific, actual caves around the world ranges through many categories including classical, contemporary, folk, country, jazz, and New Age. One of the first cave musical works and certainly the best known worldwide was the "Fingal's Cave Overture", a masterpiece of early Romantic music composed by Felix Mendelssohn Bartholdy following his visit in 1829 to this celebrated cave in the Hebrides of Scotland. Later in the 19th century two cave pieces for classical guitar were written: one by a Czech composer, Johann Mertz, entitled "Fingals Höhle", and the other by a French composer, Napoléon Coste, "La Source du Lyson (sic)", dedicated to the famous resurgence cave in the Doubs department.

Works of contemporary art music in the 20th century paid homage to various caves. In 1968, Zsolt Durkó composed a piece for concert orchestra and choir celebrating the renowned Altamira Cave in Spain. The *concrète* music composer, François Bayle, wrote an electro-acoustical work for the spectacular Jeïta Cave in Lebanon where sounds recorded in the cave were modified electronically and mixed with synthesizer music. In the realm of experimental music, Mariolina Zitta recently improvised a series of unusual pieces by tapping (without damaging) on the formations in caves of Sardinia and Liguria, Italy.

In the folk music field many short traditional works were inspired by Scottish caves: a bagpipe chant for the Cave of Gold at Harlosh, Isle of Skye, a march for the ubiquitous Piper's Cave, and another march for Huntley's Cave near Grantown. In the United States, following the tragic death of Floyd Collins in Sand Cave, Kentucky in 1925, six different event ballads were written and recorded in his honour. Jazz cave music seldom appears but in 1956 Raymond Scott composed, “Blue Grotto in Capri”, and in the 1980s Kristian Blak wrote two long works, “Concerto Grotto” and “Antifonale”, for two caves in the Faroe Islands. Recently New Age music composers have been finding caves very inspiring. Mathias Grassow set down three pieces dedicated to the famous lava tube caves on Lanzarote, Canary Islands. The British caver, Steve Thomas, composed a collection of synthesizer pieces all revolving around the cave diving experience (“More people have been to the Moon”, 1997).

The timeless, magical surroundings of caves continue to provide ideal venues for musical performances and, hopefully, the awesome beauty of caves will inspire many more compositions.

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Works Cited

Allhoff-Cramer, A. 1996. *Die Festspiele Balver Höhle,* Balve: Festspiele Balve Höhle

Bray, W. 1778. Cited in Woodall, B. 1976. *Peak Cavern,* Buxton: Brian Woodall

Gurnee, R.H. 1978. *Discovery of Luray Caverns, Virginia,* Closter, New Jersey: Gurnee

Minvielle, P. 1970. *Guide de la France Souterraine,* Paris: Tchou

Ortega, E.Rodriquez. 1970. *La Cave de Nerja,* Nerja: Patronato de la Cueva de Nerja

Russell, J. 1828. *A Tour in Germany and Some of the Southern Provinces of the Austrian Empire in 1820, 1821, 1822,* Edinburgh: Constable; cited in Shaw, T.R. 1980. British and American travellers in the Cave of Postojna before 1865, *Naše Jame,* 22: 101

Further Reading

Brison, D. 1966. Caves on phonograph records, *York Grotto Newsletter,* 7(5):65–71, 7(6):79–84

Brison, D. 1997. Les grottes dans la musique et la chanson enregistrées, *Grottes et Gouffres,* 144:19–28; see also same text in English: Caves celebrated in recorded music and song, *Al-Ouat'Ouate,* 11, 1997–1998:96–107

Brison, D. 2001. The early Floyd Collins ballads. *Journal of Spelean History,* 34 (3):3–24

Mills, M. 1986–1989. Caves in music, *Shepton Mallet Caving Club Journal,* 8(1):22–37, 8(4):145–68, 8(6):244–84

MYRIAPODA (CENTIPEDES AND MILLIPEDES)

Myriapoda is an artificial superclass of about 15000 species, containing all terrestrial Arthropods having antenna, mandibles, and above all more than ten pairs of legs (terrestrial Isopoda, Arachnida, and Insecta have respectively seven, four, and three pairs). The two subclasses centipedes (Chilopoda) and millipedes (Diplopoda) are the best represented in the subterranean world. Others (Pauropoda, Symphyla, and Penicillata) are microscopic edaphic (soil-dwelling) myriapods that are occasionally cave-dwelling but rarely true troglobites.

Centipedes (about 2500 species distributed in 4 orders) have a flattened body, with a supple leathery integument, only one pair of legs per segment, and three pairs of mouth parts. Most (except the worm-like Geophilomorpha) are very agile and all are predators in which the first pair of legs is modified into poison-claws. Only about 50 species (mostly Lithobiomorpha) can be considered as troglobitic. Geophilomorpha (more than 25 pairs of legs) inhabit leaf litter or soil fissures, and are rarely cavernicolous (though there are examples from Cuba, France, and Movile Cave, Romania).

Within the Scolopendromorpha order (21 pairs of legs), only one family (Cryptopidae) has a few species showing adaptations such as depigmentation or elongated appendages (Cuba, United States) or species known only from caves (Cuba, Italy, and Yugoslavia). Scutigeromorpha (antenna and 15 pairs of considerably elongated legs) has some species inhabiting caves in Mediterranean countries (e.g. the trogloxene *Scutigera coleoptrata*). Lithobiomorpha (15 pairs of legs, usually elongated) are mostly represented in European and circum-Mediterranean caves by about 40 species belonging to the genus *Lithobius*. The majority of these species are endemic having a very limited geographical distribution, and are dispersed from the Pyrenees to the Carpathians and Balkans. Only two cave-dwelling species are known from the Far East, and none in the New World. Of the characteristics usually associated with adaptation to subterranean habitats, loss of eyes and pigmentation are the most frequent expression. Less frequent is the elongation of appendages, which gives an unusual "scutigeroid" (or Scutigera-like) aspect in some Lithobius, such *L. drescoi* (Spanish Basque province). An increase in the number of antennal articles is even more rare, though *L. sbordonii* (Sardinia) has 111.

Millipedes (about 10000 species distributed in 12 orders) have two pairs of legs per segment and only two pairs of mouth parts. Segments are usually cylindrical, often bearing paranota (lateral projections), each one concealing a pair of repugnatorial glands. Generally slow-moving and eating dead plant material, their relatively permeable integument confines them to hygrophilous and cryptophilous habitats. A large number are accidental inhabitants of caves (trogloxene), and although the number of troglobites is greater than in centipedes (about 300–400 species), only five orders have true cavernicolous forms.

If the classic adaptive characteristics such as depigmentation, loss of eyes, and decalcification of integuments are frequent, other characteristics such as elongation of appendages or increased body size, are not the rule. In orders having a variable number of segments (such Iulida and Lysiopetalida), this number increases, but it stays unchanged (or rarely decreases) in orders having a fixed number of segments (such as Glomerida, Polydesmida, and Chordeumida). A special adaptation concerns the mouth parts (enlarged lamellae which act as a filter) in various millipedes inhabiting waterlogged caves.

Glomerida are characterized by their small number of segments (11−12) and their ability to roll up in a sphere. Cavernicolous species are generally smaller than epigean ones, and are blind and unpigmented. The true troglobites are distributed in a dozen endemic genera (such as *Speleoglomeris*) which are all European, distributed from the Pyrenees to the Caucasus and Balkans. The genus *Trachysphaera* (previously *Gervaisia*), while not exclusively troglobitic, is remarkable for its decorative integument and its distribution from the Cantabric Mountains to the Caucasus.

Polydesmida are remarkable for their segments (usually numbering about 20) having usually strong lateral projections, and containing glands that often secrete cyanide. All are blind and many species are troglophilic or troglobitic. These last are divided into two categories: those whose epigean close relatives are sympatric, such as the poorly modified European *Polydesmus (=Brachydesmus)* and the Japanese *Epanerchodus;* and those (all small or microscopic forms in size) whose epigean close relatives are allopatric and are relics of a former tropical fauna—they are distributed in eight small genera in Europe (e.g. *Trichopolydesmus*), and five in North America (e.g. *Speodesmus*).

Chordeumida (=Craspedosomida) are relatively agile millipedes living in the temperate countries of the world. Small or moderate in size, their segments (usually numbering about 30), without repugnatorial glands, always bear three pairs of dorsal hairs. They possess preanal spinnerets secreting silk. The endemism rate is very important in this order, and thus troglophilic and troglobitic forms are particularly numerous. Some genera contain both epigean and troglobitic species; the latter show only poor morphological adaptations (e.g. the European *Nanogona* and US *Cleidogona*), modifications in the sense of reduction of size and number of ocelli (e.g. *Opisthocheiron* in southern France), or more important modifications in the sense of elongation of appendages (e.g. *Psychrosoma* from Spain). But usually species having the full range of adaptations to the subterranean habitat are distributed in some small endemic genera scattered in all karstic countries of Europe, North America, and the Far East.

The body of Iulida is usually very elongated in shape, composed of numerous cylindrical segments, and their repugnatorial glands secrete quinones. Palearctic species are represented by numerous troglophilic and troglobitic taxa that are mainly members of two families: the rather eastern Iulidae and the rather western Blaniulidae. All have a similar shape caused by the loss of pigmentation and elongation of body and appendages. Four genera have a relatively large area of distribution, such as *Mesoiulus* (discontinuous area from Turkey to Spain), *Blaniulus* (= *Typhloblaniulus,* common in caves of southern France), and *Metaiulus* (terricole or soil-inhabiting in Great Britain, troglophilic in south France). The latter, and also a dozen endemic small genera having restricted distribution (in western Europe and North Africa) have affinities with their epigean (and sympatric) homologues. But some of them (such as the Spanish *Paratyphloiulus)* belong to a line that possesses allopatric epigean homologues living in Nepal and Southeast Asia. Cave-dwelling species are rarer in palearctic Asia and in North America: they belong to other families (Paraiulidae and Mongoliulidae). In tropical and subtropical countries, the family Glyphiulidae, remarkable for its multicarenate segments, inhabits numerous caves from south of China, India, and Southeast Asia. In Central America, the genus *Jarmilka* (from Belize) has a number of segments particularly low for Iulida (18). In South America, only the genus *Pseudonannolene* has some species presumed troglobitic (in Brazil).

Callipodida (=Lysiopetalida) are iulida-like in shape (but slightly compressed laterally) and have preanal spinnerets producing silk and repugnatorial glands secreting phenols. Many are carnivorous and live in the hottest of the temperate zones of the northern Hemisphere, often in hypogean habitats. There are no notable modifications to the external morphology of the European cave-dwelling genera, such as *Apfelbeckia* (former Yugoslavia) or *Callipus foetidissimus* (cryptophilous in southern France, troglobitic in the catacombs of Paris). However, *Tetracion* (United States) and

Paracortinus (China and Vietnam) are unpigmented, and show elongated appendages and reduced eyes.

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Further Reading

Ginet, R. & Decou, V. 1977. *Initiation a la Biologie et a l'écologie souterraines.* Paris: Delage

Hopkin, S.P. & Read, H.J. 1992. *The Biology of Millipedes,* Oxford and New York: Oxford University Press

Juberthie, C. & Decu, V. (editors) 1994. *Encyclopaedia Biospeologica,* vol. 1, Moulis and Bucharest: Société de Biospéologie For Myriapodes, see pages 249–66, which includes a bibliography of 128 titles, 12 figures, and 3 maps (in French)

Lewis, J.G.E. 1981. *The Biology of Centipedes,* Cambridge and New York: Cambridge University Press

Shear, W.A. 1969. A synopsis of the cave Millipeds of the United States, with an illustrated key to genera. *Psyche,* 76(2):126–43

N

NAHANNI KARST, CANADA

Nahanni National Park (the first UNESCO World Heritage Site) extends 230 km along the South Nahanni River, where it crosses the central and eastern ranges of the remote Mackenzie Mountains in northern Canada (see Canada Karst and Caves, Figure 1, for location). Valley to summit elevations range from 200 to 2600 m. The history of glaciation is complex—the western half experienced repeated alpine glaciation and the eastern quarter continental glaciation, but a central corridor was always ice-free, due to its aridity. The modern climate is subarctic, mean annual temperatures being −4° to −12°C and precipitation 400–600 mm, roughly half of which falls as snow.

In the western park, a granitic batholith of Cretaceous age is intruded into mixed carbonate and clastic strata, deforming them. At the contact are Rabbitkettle Hotsprings, calcite travertine deposits, which are the largest in Canada. “North Mound”

Nahanni Karst: Raven Lake, a doline within a karst corridor, Nahanni Karst.

The doline is 300 m in length. Cliffs rise 150 m above the waterline, which itself may rise a further 50m. The lake drains dry in winter. (Photo by Derek Ford)

is a classic tiered wedding-cake structure, Holocene in age, 250 m in basal diameter and very colourful. The springs are perennial, with temperatures ~21.5°C and total hardness of 475–550 mg l^{-1} as $CaCO_3$. Nearby (and at Yohin Lake downstream) are dozens of large piping sinkholes (see Pseudokarst entry) in river terrace silts resting on coarse gravels.

The principal karst is in the eastern park, on 140–180 m of thick, massively bedded Devonian limestones and >1000 m of weaker, banded dolostones beneath them. The limestone is overlain by black shales. The strata are folded into broad, anticline domes rising to an altitude of 1500–1600 m. The South Nahanni and its tributaries have carved meandering, antecedent canyons through them, with walls as high as 1200 m (Ford, 1991). The karst forms a belt up to 20 km wide between the South Nahanni River First Canyon dome and Ram Canyon dome 50 km further north. Waters flow into it from the crests of the domes and from flanking shale lowlands. The underground drainage appears to be relatively simple. Groundwater flows south to perennial springs in First Canyon that are *c.* 520 m below the stratigraphic top of the dolostones, or north to springs emerging where the limestone dips under the shale cover. The active cave channels are inaccessible but dye tracing suggests flow rates of 20–30 m h^{-1} along major routes. The systems are very dynamic, floodwaters quickly rising 50 m in some big dolines. The waters have a bicarbonate composition, with a total hardness of 100–200 mg l^{-1} at the springs and the estimated regional dissolution rates are equivalent to 18–27 mm of lowering per 1000 years (Brook & Ford, 1982).

The outstanding landforms are dissolutional corridors (“streets”) in the limestone that follow major vertical fractures created by the doming (Brook & Ford, 1978). Individual corridors are 30–100 m deep, 15–100 m wide, and up to 6 km in length. For a distance of 13 km they intersect to form a natural labyrinth. The walls recede from frost shattering, causing some parallel corridors to amalgamate into broader closed depressions, like squares in a pattern of city streets; the greatest measures 800 ×400 m. Isolated towers are preserved within them. Floor profiles of corridors and squares are highly irregular, with local streams sinking into depressions between talus accumulations or into bedrock shafts.

At the north end of the labyrinth the shale cover and glacifluvial sands encroach to reduce the limestone outcrop to a narrow spillway with three small (<2.5 km^2) but elegant poljes developed in it. There are many collapse and suffosion dolines in the shales and sands. In the labyrinth and elsewhere on the limestone are large, vertical-walled dolines (see photo) and smaller, elliptical dissolutional shafts. Many trap the water of successive melt seasons, depth increasing slowly until pressure bursts an ice plug below and the feature drains with catastrophic rapidity.

Flanks of the domes are incised by consequent streams, creating canyons up to 800 m deep. Ancient glacial moraines blocked the downstream ends of seven of these streams, which now drain underground into the limestone or dolostone. Lafferty Canyon, 24 km in length, is an intermediate case; all waters sink into the dolostone except during occasional summer flash floods, when overflow into South Nahanni River rolls 50-tonne boulders along the bed.

More than 200 relict caves are known but most are sealed off by ground ice or permafrozen silts within a few metres. Grotte Louise-Grotte Mickey (*c.* 3 km long) is a multilevel series of phreatic passages exposed in limestone cliffs at the junction of First Canyon and Lafferty Canyon, 200 m above the South Nahanni River: it has complex clastic fills, seasonal and perennial ice (Schroeder, 1977). Grotte Valerie (*c.* 2 km long) opens in south-facing cliffs 300 m above the river. It was created by influents from the surface 60 m overhead draining to a major bedding plane where a sequence of shapely arched phreatic passages developed. In summer, cold air drains from a low exit, drawing in warm air to replace it through an entry 40 m higher. This creates (1) a "warm entrance cave" (+6 to+1°C) with active speleothem growth, supplying moist air to (2) a "cool exit cave" (0 to −1.5°C) covered with ice and hoar frost: behind and below both is (3) a "permafrost cave" (−2.5°C) receiving only the cold air of winter, dry and dusty, without speleothems or ice and preserving the remains of 80 or more wild sheep. It is a spectacular example of cave climatic zonation.

The Nahanni is the most accentuated periglacial karst yet reported from the Arctic or Subarctic. Its development in a cold, rather dry climate is attributed to the young domal fracturing and the fact that the main belt has not been over-ridden by glaciers recently, perhaps not for 350000 years or more.

DEREK FORD

See also **Alpine Karst; Glacierized and Glaciated Karst**

Works Cited

Brook, G.A. & Ford, D.C. 1978. The nature of labyrinth karst and its implications for climaspecific models of tower karst. *Nature,* 275:493–96

Brook, G.A. & Ford, D.C. 1982. Hydrologic and geologic controls of carbonate water chemistry in the sub-Arctic Nahanni karst, Canada. *Earth Surface Processes and Landforms,* 7(1):1–16

Ford, D.C. 1991. Antecedent canyons of the South Nahanni River. *The Canadian Geographer,* 35(4):426–31

Schroeder, J. 1977. Les formes de glaces des grottes de la Nahanni, T.N.O. *Canadian Journal of Earth Sciences,* 14(5):1179–85

Further Reading

Ford, D.C. 1984. Geology; geomorphology; hydrology. In *Nahanni National Park Reserve: Resource Description and Analysis,* Winnipeg, Manitoba: Parks Canada

Hartling, R.N. 1993. *Nahanni: River of Gold, River of Dreams,* Hyde Park, Ontario: Canadian Recreational Canoeing Association

NAKANAI CAVES, PAPUA NEW GUINEA

The Nakanai mountains are located on the island of New Britain, east of Papua New Guinea (see the map in the Asia, Southeast Islands entry). They are world famous for their megadolines, which carry huge underground streams (Table), in the middle of one of the world's last tropical rain forests. The island's Miocene limestone platform lies on an old paleogene volcanic arc located along the south coast. An active volcanic arc lies along the northeast coast, and the limestones were covered by a thick Pliocene volcano-sedimentary series.

The Nakanai mountains include a large plateau (5000 km^2 in area), with a high point at an altitude of 2185 m in the north, which descends to the south coast and is cut by canyons more

Nakanai Caves, Papua New Guinea: Major caves and dolines of Nakanai

Cave	Depth	Exploration team	Observations	Low-water discharge
Muruk	−1178m	France (1985, 1995, 1998)	Through-cave to Berenice, 17 km long,	$2 m^3 s^{-1}$
Gamvo	−478m	United Kingdom (1985)	Stream-sink cave	$5 m^3 s^{-1}$
Arcturus	−475m	France (1988)	Muruk system (not connected)	
Minye	−468m	Australia (1968), France (1978, 1985)	Megadoline 26 M m^3, 410 m shaft	$20 m^3 s^{-1}$
Ka2	−414m	France (1978, 1980)	Kavakuna system (not connected)	$20 m^3 s^{-1}$
Bikbik Vuvu	−414m	France (1978, 1980)	Megadoline 141 m shaft	
Nare	−415m	France (1978, 1980), United Kingdom (1985)	Megadoline 4.7 M m^3, 238 m shaft	$20 m^3 s^{-1}$
Kavakuna	−392m	France (1978, 1980)	Megadoline	$7 m^3 s^{-1}$
Ora	−270m	Australia (1972–1973)	Megadoline	
Luse	−224m	France (1980)	Megadoline 61 M m^3	

Nakanai Caves, Papua New Guinea: Figure 1. Nare megadoline (300 m), with the Vaisseau Fantôme river flowing at the bottom (15–20 $m^3 s^{-1}$). (Photo by J.-P.Sounier) than 1000 m deep (e.g. Galowe, Wunung, and Bairaman). Since the beginning of the late Pliocene uplift, the volcano-sedimentary deposits have been weathered and eroded, bringing the Yalam limestones to the surface and allowing karst processes to take place. The clay sediments presently exist as a covering of detritus, only a few metres thick, overlying the karst relief. This combination results in the formation of rounded hills and deep depressions, connected by small valleys.

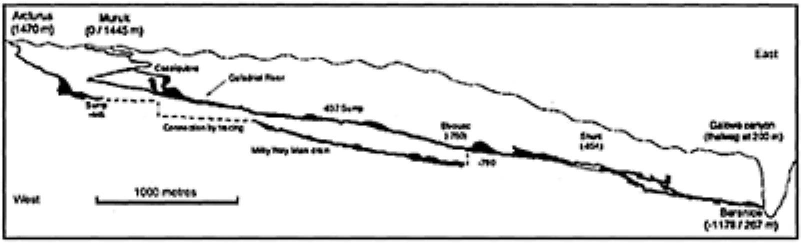
The mountains have an oceanic monsoon climate, with considerable rainfall (6 m per year on the coast, 10 to 12m per year in the mountains). This significant and continuous humidity, combined with high temperatures all year round, allows the growth of rain forest.

The underground karst benefits from three types of hydrological input. Diffuse drainage across thick soils and tiny fissures allows saturation and gives rise to calcite deposition in shallow caves (upstream, Muruk Cave). Rapid drainage into larger fissures causes flow-path enlargement at moderate depths. Allogenic aggressive drainage first concentrates in thalwegs or canyons (such as Kavakuna) during high water and is then absorbed into stream sinks. High water is permanent during the rainy season and frequent during the “dry” season, so solution can easily occur in the deep and remote parts of the caves.

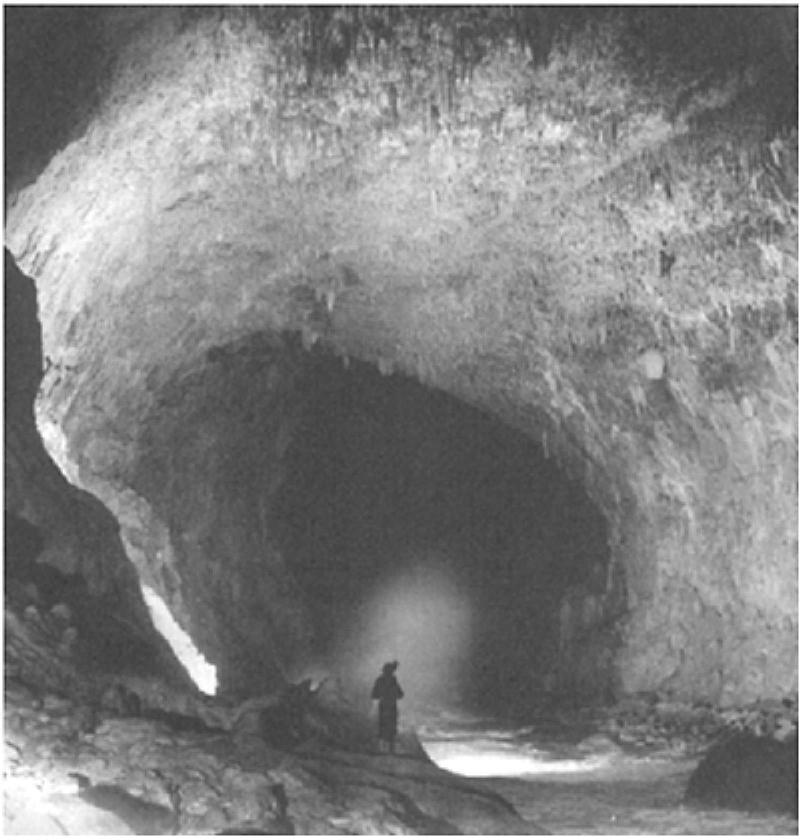
In the “dry” season the karst is fed essentially by diffuse drainage, with occasional episodes of turbid runoff entering via the surface gully system, but these are limited in both time and volume (two to three times the low-water discharge). The forest/ soil system plays a remarkable role. Just one or two days without rain are enough to drain the soils, which are then able to absorb up to 50 mm of rain without causing any runoff. But if the soil is saturated from previous rainfall, 20 mm of rain are sufficient to produce runoff. During heavy rainfall, in some large catchments, discharge can reach several $m^3 s^{-1}$ (10 times the low-water discharge), probably up to 100 $m^3 s^{-1}$ during the highest water, and 1000 $m^3 s^{-1}$ during exceptional flooding (50 times the low water discharge in the Kavakuna Matali system).

Karst processes are influenced by exceptional conditions, with pure limestones being subjected to solution. The high rainfall supplies large amounts of water, which is concentrated on the clay floors of valleys before being injected into the karst, and the rain forest, with a highly productive biomass, provides abundant carbon dioxide and humic acids. In addition there is a steep topographic gradient due to the high tectonic activity. For these reasons, karstic denudation is estimated at a world record of 400 $m3km^{-2}a^{-1}$ (Audra, 2001; Maire, 1990). Nakanai can be considered as a “hyperkarst”, since so many factors favouring karst processes are pushed to their extreme. The Nakanai caves are therefore on a dramatic and very large scale, and 80 km of conduits have been surveyed by 11 expeditions.

The formation of the megadolines is due to the upward stoping of the ceilings of large passages (up to 150 m high) below the floors of dolines (up to 150 m deep). If the drains are at a depth of around 350 m (e.g. Nare, Minye), the thickness of rock in the roof can be quite thin. If it collapses, it can form



Nakanai Caves, Papua New Guinea:
Figure 2. Profile of Muruk system.



Nakanai Caves Papua New Guinea:
Figure 3. The main passage in Nare.
(Photo by Dave Gill)

open windows to the subterranean rivers below (Maire, 1981; Figure 1). Where the depth of the drain is deeper (>450 m in Muruk), collapses do not exist (Audra, 1999). Such large passages develop in soft chalky limestone, by downcutting linked to a high flow rate.

The Muruk system began as a tube sloping gently from a stream-sink to a spring (Figure 2). It evolved by entrenchment into a canyon hollowed out by giant potholes, and downstream into large passages (>50 m in diameter). It is a monophase system, which is exceptional in a mountain environment, with no perched passages except in the vicinity of the spring. The Berenice resurgence is perched 50 m above the Galowe river, which is mainly fed by the Mayang spring (flowing at 20 $m^3 s^{-1}$). This shows the lag time between karst processes as compared with fluvial entrenchment, which is the result of the rapid uplift. The morphology is typical of a juvenile karst system.

Paleomagnetic dating of fluvial sediments originating from reworked soils shows normal polarities (i.e. an age of <780 ka). Uranium-series dating on speleothems has only provided ages younger than 50 ka. The Muruk system was probably initiated around 100 to 200 ka, as shown by the Berenice perched spring at 50 m above base-level. The efficiency of the karst processes, which led to such extraordinary dimensions, is peculiar to the Nakanai mountains.

Cave genesis starts with water flowing over the clay cap and entering the limestone through the stream-sinks. It then follows a nearly straight line to the springs through limestone that was not karstified in its deeper parts. Subsequently, the cave system evolved by entrenchment and enlargement caused by torrential flows, mainly in the vadose zone. The initial cave outline was not greatly changed by subsequent evolution. This differs greatly from the common karst model, where shafts drop vertically through the vadose zone and horizontal galleries are located near the water table. Muruk can be regarded as a juvenile system model. As a case study it can aid in the understanding of other more ancient and generally more complex systems with similar profiles.

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Works Cited

Audra, P. 1999. Genèse des grands vides souterrains du réseau de Muruk, influence des séismes sur le karst (Montagnes Nakanai', Nouvelle-Bretagne, Papouasie-Nouvelle-Guinée). *Etudes de géographie physique,* 28 (suppl.):37–42

Audra, P. 2001. Karst solution and denudation assessment in Nakanai mountains. In *Nakanai, 20 Years of Exploration,* Antibes: Hemisphere Sud

Maire, R. (editor) 1981. Papouasie-Nouvelle Guinée. *Spelunca,* 3 (suppl.)

Maire, R. 1990. *La haute montagne calcaire.* Thesis, Paris: Fédération française de spéléologie and Bordeaux: Association française de karstologie (Karstologia Mémoires, 3)

Further Reading

Audra, P., Lauritzen, S.E. & Rochette, P. 1999. Datation de sediments (U/Th et paléomagnétisme) d'un hyperkarst de Papouasie-Nouvelle-Guinée (Montagnes Nakanaï, Nouvelle-Bretagne). *Etudes de géographie physique,* 28 (suppl.):43–48

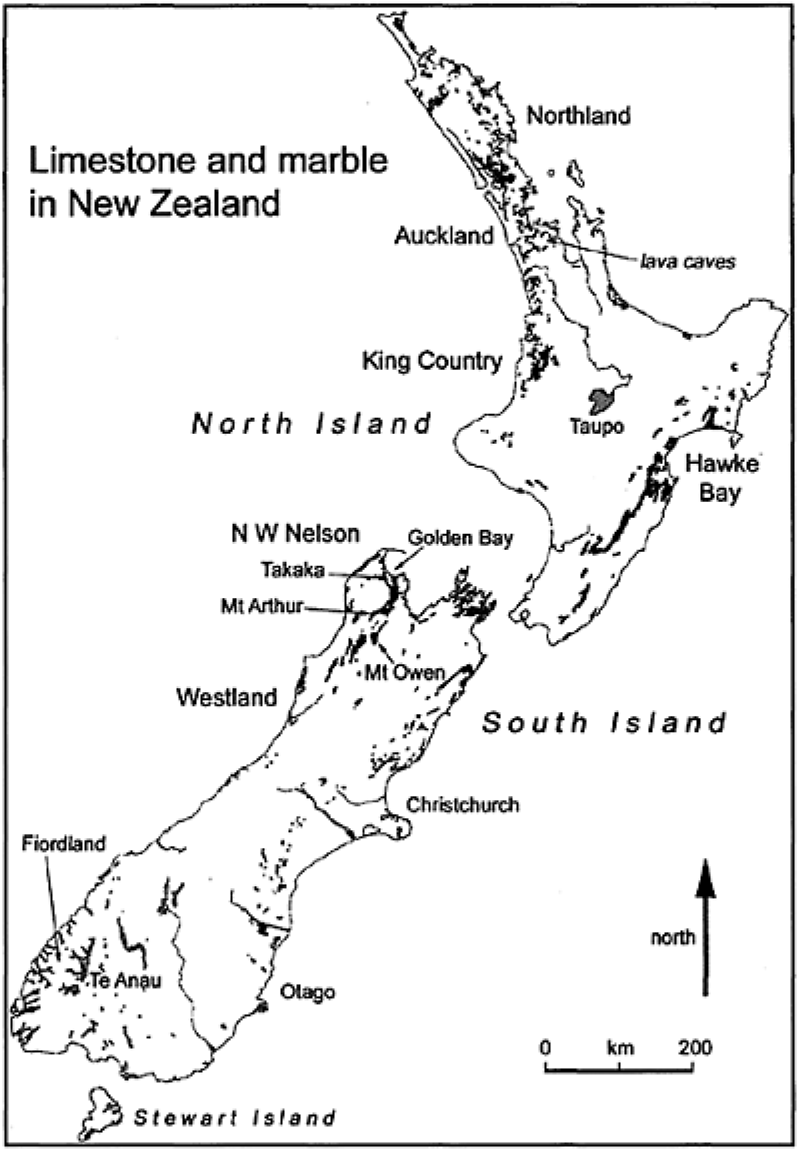
Audra, P., de Coninck, P. & Sounier, J.-P. 2001. *Nakanai, 20 Years of Exploration,* Antibes: Hemisphere Sud
Gill, D.W. (editor) 1988. *The Untamed River Expedition 1985,* Stockport: Gill
Hache, P., Hobla, F., Philips, M., Sessegolo, D. & Sounier, J.-P. 1995. Muruk, hemisphere sud, premier–1000. *Spelunca,* 60, 35–54
Pernette, J.-F. 1981. *L'abîme sous la jungle,* Grenoble: Glénat
Sounier, J.-P. 1995. *Nakanaï: Dans les gouffres géants de Papouasie,* Marseille: Spelunca Librairie
Sounier, J.-P. 1996. Muruk: the Southern Hemisphere's first–1000. *International Caver,* 17:17–25
Sounier, J.-P. 2000. Muruk: l'épilogue? *Spelunca,* 77:15–22

NEW ZEALAND

The main rocks supporting karst in New Zealand are Oligocene limestones and Ordovician marble (Figure 1). During the mid-Oligocene limestones were deposited over most of the Northland peninsula and along the east and west coasts of what are now both North and South Islands. However, plate tectonic deformation along the Pacific-Australian plate boundary, associated uplift since the Miocene, and considerable erosion has reduced the outcrop to discontinuous patches widely distributed throughout the length of the country. Miocene to Plio-Pleistocene limestones also occur, especially along the east coast of North Island, although they tend to be poorly cemented coquina limestones (limestones composed mainly of fossil debris) with high porosity and little karstification beyond widened fissures. Ordovician marble is found mainly in the northwest of the South Island (northwest Nelson). Caves are also found in Quaternary basalts, especially in the vicinity of the city of Auckland in North Island, where there are about 60 short lava tube caves (see photo in Pseudokarst entry).

North Island

The Northland peninsula has many small limestone outcrops (Figure 1), some with caves, although much is too argillaceous to support well-developed karst. The most important karst is near Waipu, about 100 km north of Auckland, where doline karst with karren fluted outcrops covers a few square kilometres. The limestones exceed 100 m in stratigraphic thickness and are pure but thinly bedded. Two Tone Cave is developed at the unconformable contact of the Oligocene limestone and underlying Mesozoic greywacke.



New Zealand: Figure 1. Map of outcrops of limestone and marble in New Zealand. Most carbonate rocks have karst development, especially in their groundwater systems, although surface karst landforms and caves are best developed on marble and dense crystalline limestones. Occurrences of lava caves near Auckland are also indicated. Marble outcrops at Takaka, Mt Arthur, and Mt Owen.

The main karst area in North Island is in the west between Kawhia and Aria, in a district referred to locally as the King Country (Figure 1). The karst occurs at altitudes below 400 m and currently experiences a moist, warm temperate climate. The mean annual temperature of caves and mean annual rainfall range from 13°C and 1600 mm at 100 m above sea level, to about 11.5°C and over 2300 mm in the hills at around 350 m. About 20% of the original podocarp-hardwood evergreen rainforest remains, usually in reserves. Carbon dioxide production in volcanic soils overlying the karst has been investigated by Gunn and Trudgill (1982).

Karst is developed in 100 m thick, step-faulted, Oligocene limestones blanketed by thick volcanic ash. Prominent northsouth faulting results in the limestones ascending from Waitomo towards the west. As a result of Upper Tertiary and Quaternary tectonic and erosional processes, the limestone outcrops and subcrops now present a fragmented mosaic and in total cover about 800 km^2 of the region. Dips are gentle, seldom exceeding 10–15°. The limestones are part of the Te Kuiti Group (White & Waterhouse, 1993), which comprises calcareous siltstones and sandstones near its base and thinly bedded limestones above. Occasionally the lower clastic formations are underlain by coal measures, but sometimes both are absent and the limestones rest directly and unconformably on Mesozoic greywackes. The limestones are divided into a lower Orahiri Limestone and an upper Otorohanga Limestone, in places separated by the calcareous Waitomo Sandstone. The limestones are particularly notable for their thinly bedded flagginess, which is partly a consequence of pseudo-bedding along stylolites, and most beds are of the order of only decimetres in thickness, just occasionally exceeding a metre. Associated with this thin bedding is closely spaced jointing. Thus the limestones have a very high fissure frequency, which is exploited by hydrogeological processes.

Karstification commenced in the upper Tertiary prior to the burial of many dolines by mid-Pleistocene ignimbrites, many of which have since been exhumed. The southern shore of Kawhia Harbour along the edge of the Rakaunui Peninsula has karst that descends below sea level, with partly drowned dolines containing remnants of ignimbrite fill. There are also well-developed intertidal karren and, in places, shallow multiple solution notches reflecting the position of former sea levels. These reach up to about 2 m above sea level. In the larger patches of limestone around Waitomo, the landscape is notable for very good examples of polygonal karst, with doline densities of 55 per km^2. Most are solution dolines, although impressive collapse dolines in bedrock and suffosion dolines (usually in tephra infills within solution dolines) also occur. Hydrological processes in solution dolines have been described by Gunn (1981b).

There are numerous caves in the King Country, the longest being Gardners Gut Cave (>12 km; Figure 2), a totally vadose dendritic river cave that can be traversed from stream-sinks to resurgence beside the Waitomo Stream. It probably commenced to form about 250000 years ago as the overlying cap of Miocene mudstone was eroded to reveal inliers of underlying limestone. The rate of incision of the Gardners Gut cave stream has been estimated by Williams (1991) as 0.13 m ka^{-1} by dating the basal calcite of a flowstone (118 ka BP) and speleothems (12 ka BP) at various heights above the modern cave stream. This is of the same order as the rate of uplift of the region. Rates of karst denudation in the uplands of the district have been measured by Gunn (1981a) as $69^{+18}_{-7}\ \mathrm{m\ km^{-2}\ a^{-1}}$ (or mm $\mathrm{ka^{-1}}$), which is about half the rate of uplift.

Many caves in the region have spectacular glowworm displays (Pugsley, 1984). Some are of international significance and of importance to the tourist industry, especially in the Waitomo

New Zealand: Figure 2. Calcite speleothems in Gardner's Gut Cave in the King Country Karst. (Photo by Andy Eavis)

Glowworm Cave, the climate of which has been studied by de Freitas *et al.* (1982) and de Freitas and Littlejohn (1987). Waitomo is also the original home of Blackwater Rafting, which commenced as a tourist venture in Ruakuri Cave.

Extensive limestone outcrops occur in a discontinuous belt over about 450 km along the East Coast of North Island. The limestones rise to 1300 m in places and form distinctive scarps. The carbonates are mainly Upper Tertiary to early Pleistocene in age, and vary in composition from dense crystalline limestone to friable coquina. Particularly important from the point of view of karst development is the Whakapunake Limestone, of mid-Pliocene age, a cream-coloured, well-bedded, hard barnacle plate coquina up to 300 m thick. Despite the young age of many limestones and the recent uplift, there is significant karstification including cave development and active groundwater networks, especially in the more indurated limestones. The most significant caves are in the Wairoa district of northern Hawke Bay. Especially important is the Te Reinga Cave system (4 km long, 134 m deep) developed in Whakapunake Limestone. However, thick sandstone coverbeds over the limestones inhibit the development of solution dolines, most closed depressions originating by progressive collapse of clastic sediments into developing caves.

The Te Aute Limestone south of Hawke Bay is often less well cemented and more porous than at Te Reinga, so karstification is less advanced. For example the Te Mata Peak, Maraetotara Plateau, and Kahuranaki uplands are composed of a soft friable coquina limestone that varies from 30–330 m thick. Early stages of karstification are evident along joints and there are occasional closed depressions, springs, and calcareous tufa deposits. The groundwater circulation is unstudied, but probably mainly diffuse.

South Island

Extensive areas of cavernous karst occur in the northwest corner of the South Island, in northwest Nelson, and northern Westland (Figure 1). Tertiary limestones occur as a discontinuous strip for over 250 km along the northwest coast, and in places extend inland where they have sometimes been uplifted to 1000–1500 m, for example in The Haystack and Thousand Acre Plateau of the Matiri Range north of the Buller Gorge. The limestones are very variable in thickness and in lithology, from thin and sandy to thick and crystalline. In the Paturau district the Takaka Limestone is 25–50 m thick, whereas at Tarakohe it is 80 m thick but sandy in its lower half. Near Charleston and Punakaiki in north Westland, the Tertiary carbonate sequence is highly variable in thickness but in places exceeds 700 m. The Potikohuna Limestone is particularly important for karst development, being a dense polyzoan biosparite. It is stylobedded and has a platy appearance in weathered outcrop, giving rise to the Pancake Rocks where an uplifted last interglacial marine platform (34–36 m) has been partly stripped of gravelly beach sediments by surf and spray. The flaggy layering appears related to the differential exploitation of insoluble clays and micas formed along stylolites by pressure solution. Inland from the coast at Punakaiki, the limestones underlie a plateau at 300–400 m that is heavily dissected by solution dolines, forming the southernmost polygonal karst in New Zealand. Dolines, karren, stream-sinks, springs, and gorges are well developed. Because of the copious rainfall (up to 3 m annually), there is a high density of caves, some of which have rich fossil avifauna deposits of international significance, Honeycomb Hill Cave being a particularly important site (Worthy & Mildenhall, 1989). The area also contains excellent examples of underground river capture, Bullock Creek-Cave Creek being the most well-known case (Figure 3). The capacity of the stream-sink zone is 15–20 m^3s^{-1} and the combined peak discharge of outflow springs is of the order of 30–40 m3s^{-1}, the largest flood flow from any karst system in New Zealand. Most of the area is rugged and covered in dense evergreen rainforest with essentially intact natural vegetation making it virtually impenetrable. This is important for the conservation of many endemic species of plants and invertebrates.

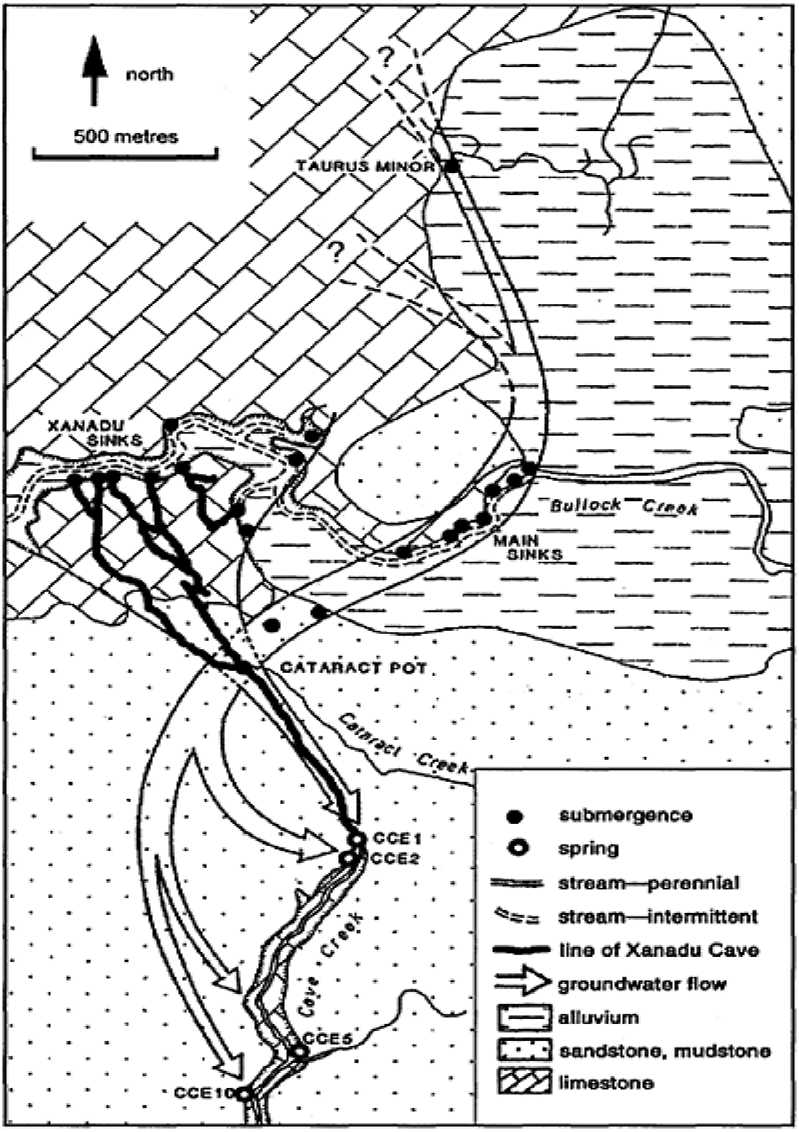
A greater diversity of karst features is found in the Arthur Marble, which crops out extensively in northwest Nelson (Figure 1). It is found mainly in the mountains to 1875 m, but extends below sea level in Golden Bay. The marble is Ordovician in age, about 1000 m thick, and occurs in a discontinuous belt for about 90 km. It is largely covered by undisturbed natural vegetation, some in the alpine zone, and is mostly within two National Parks. Mt Arthur and Mt Owen were both glaciated in the Pleistocene and provide the best examples of glacio-karst in the Southern Hemisphere with dry cirque basins, karrenfeld, and limestone pavements (Williams, 1992a). They contain the five deepest caves in the country and the three longest (see Table). Nettlebed Cave, the deepest (889 m), and Bulmer Cave, the longest (50.1 km), both have a development history that is likely to exceed 1 million years. The Takaka valley contains New Zealand's largest spring, the Waikoropupu Spring, with an average discharge of *c.* 15 $m^3 s^{-1}$ and an age spectrum of outflowing waters of 2–20 years (Williams, 1992b). Water clarity measurements have shown it to have the third clearest water yet recorded in the world and the aquatic ecology of the spring has international significance. The spring also has local cultural significance to the Maori people. However, much of the catchment area is under farmland with intensifying landuse and is not protected.

The Riwaka River catchment in northwest Nelson has an average rainfall of 2518 mm and the solution denudation was calculated as 100±24 $m^3 km^{-2} a^{-1}$ by Williams and Dowling

New Zealand: The five deepest and six longest caves in New Zealand. All but Gardner's Gut Cave are in northwest Nelson in the South Island.

Cave	Area	Depth (m)	Length (m)	Rock
Nettlebed Cave	Mt Arthur	889	24252	Ordovician marble
Ellis Basin System	Mt Arthur	775	28730	Ordovician marble
Bulmer Cavern	Mt Owen	749	50125	Ordovician marble
Bohemia Cave	Mt Owen	713	9300	Ordovician marble
HH Cave	Mt Arthur	710	1906	Ordovician marble
Megamania Cave	NW Nelson	<200	14800	Oligocene limestone
Honeycomb Hill Cave	NW Nelson	<200	13712	Oligocene limestone
Gardner's Gut Cave	Waitomo	<70	12197	Oligocene limestone

(1979) who estimated that ~80% of the solution was accomplished by rain falling directly onto the marble outcrop with most corrosion occurring in the uppermost 10–30 m of the rock beneath the soil. The remaining 20% comes mainly from conduit (cave) enlargement by allogenic streams that originate



New Zealand: Figure 3. Subterranean river capture of Bullock Creek, near Punakaiki, northern Westland, South Island (from Williams, 1992a after Crawford, 1994).

on neighbouring non-carbonate rocks. Thus the overall rate of surface lowering in the marble catchment is about 80 mm ka^{-1} under present conditions. Within the estimated error terms, the solution denudation rate for Ordovician marble in the Riwaka basin is about the same as that calculated by Gunn (1981a) for Oligocene limestones at Waitomo, despite the entirely different carbonate lithologies. These solutional denudation rates are moderately rapid on a world scale.

Rates of downcutting of cave streams may also be compared. Basal ages of stalagmites in Metro Cave in northern Westland indicate an incision of Tertiary limestones by the cave stream at a rate of about 0.27 m ka^{-1} (Williams, 1982). This is twice as rapid as the rate determined for Waitomo, but less than that calculated for Nettlebed Cave beneath Mt Arthur, where the rate of water-table lowering in the marble was estimated by the same means as about 0.44 m ka^{-1}. Whereas the rate of solutional denudation is determined principally by the annual rainfall, the rate of cave stream incision is determined by at least two factors: (1) the erosive power of the stream (sum of mechanical and chemical erosion) and (2) the rate of uplift of the land (which increases potential energy). If the erosive power of the stream is high, the rate of cave passage downcutting can equal the uplift rate. This is probably the case for the caves investigated. At each site the rate of tectonic uplift is probably <1 m ka^{-1}.

Fiordland is part of the Te Wahipounamu-South West New Zealand World Heritage site. It is an exceptionally rugged and inaccessible area with mountains to over 2200 m and deeply glaciated valleys and fiords. The vegetation of the region is largely thick Southern Beech forest, which gives way to alpine herbfield above the treeline at about 1100 m. Mean temperatures at sea level range between 18° (summer) and 2°C (winter) and annual precipitation on windward west-facing slopes sometimes exceeds 10m. Although caves, dolines, and karrenfeld are known, these areas are little explored. Karst occurs in narrow bands of marble in Paleozoic metamorphic rocks. Very steeply dipping Permian limestones to 750 m thick have been mapped near the Hollyford valley, but have not been investigated for karst features. Patches of Oligocene limestones also occur in the region and are known to contain caves, the best investigated being Aurora Cave on the shore of Lake Te Anau, which is 6.4 km long and 267 m deep and contains an excellent dated record of glacial and interstadial deposits (Williams, 1996).

PAUL WILLIAMS

See also **Speleothems: Evaporite** (photo from Puketiti Flower Cave, King County Karst)

Works Cited

de Freitas, C.R., Littlejohn, R.N., Clarkson, T.S. & Kristament, I.S. 1982. Cave climate: Assessment of airflow and ventilation. *Journal of Climatology,* 2:383–97

de Freitas, C.R. & Littlejohn, R.N. 1987. Cave climate: Assessment of heat and moisture exchange. *International Journal of Climatology,* 7:553–69

Gunn, J. 1981a. Limestone solution rates and processes in the Waitomo district, New Zealand. *Earth Surface Processes and Landforms,* 6:427–45

Gunn, J. 1981b. Hydrological processes in karst depressions. *Zeitschrift für Geomorphologie,* 25(3):313–31

Gunn, J. & Trudgill, S.T. 1982. Carbon dioxide production and concentrations in the soil atmosphere: A case study from New Zealand volcanic ash soils. *Catena,* 9:81–94

Pugsley, C. 1984. Ecology of the New Zealand Glowworm, *Arachnocampa luminosa* (Diptera: Keroplatidae), in the Glowworm Cave, Waitomo. *Journal of the Royal Society of New Zealand,* 14(4):387–407

White, P.J. & Waterhouse, B.C. 1983. Lithostratigraphy of the Ke Tuiti group: A revision. *New Zealand Journal of Geology and Geophysics,* 36:255–66

Williams, P.W. 1982. Speleothem dates, Quaternary terraces and uplift rates in New Zealand. *Nature*, 298:257–60

Williams, P.W. 1991. Tectonic geomorphology, uplift rates and geomorphic response in New Zealand. *Catena*, 18:439–52

Williams, P.W. 1992a. Karst in New Zealand. In *Landforms of New Zealand,* 2nd edition, edited by J.M.Soons & M.J.Selby, Auckland: Longman Paul

Williams, P.W. 1992b. Karst hydrology. In *Waters of New Zealand,* edited by M.P.Mosley, Wellington: New Zealand Hydrological Society

Williams, P.W. 1996. A 230 ka record of glacial and interglacial events from Aurora Cave, Fiordland, New Zealand. *New Zealand Journal of Geology and Geophysics,* 39:225–41

Williams, P.W. & Dowling, R.K. 1979. Solution of marble in the karst of the Pikikiruna Range, northwest Nelson, New Zealand. *Earth Surface Processes,* 4:15–36

Worthy, T.H. & Mildenhall, D.C. 1989. A late Otiran-Holocene palaeoenvironment reconstruction based on cave excavations in Northwest Nelson, New Zealand. *New Zealand Journal of Geology and Geophysics,* 32:243–53

Further Reading

Crossley, P. (compiler) 1988. *The New Zealand Cave Atlas: North Island,* New Zealand Speleological Society

Main, L. (editor) 1993. *The New Zealand Cave Atlas, vol 2: South Island,* 2nd edition, New Zealand Speleological Society www.massey.ac.nz/~sglasgow/nzss/the NZ Speleological Society web site

NULLARBOR PLAIN, AUSTRALIA

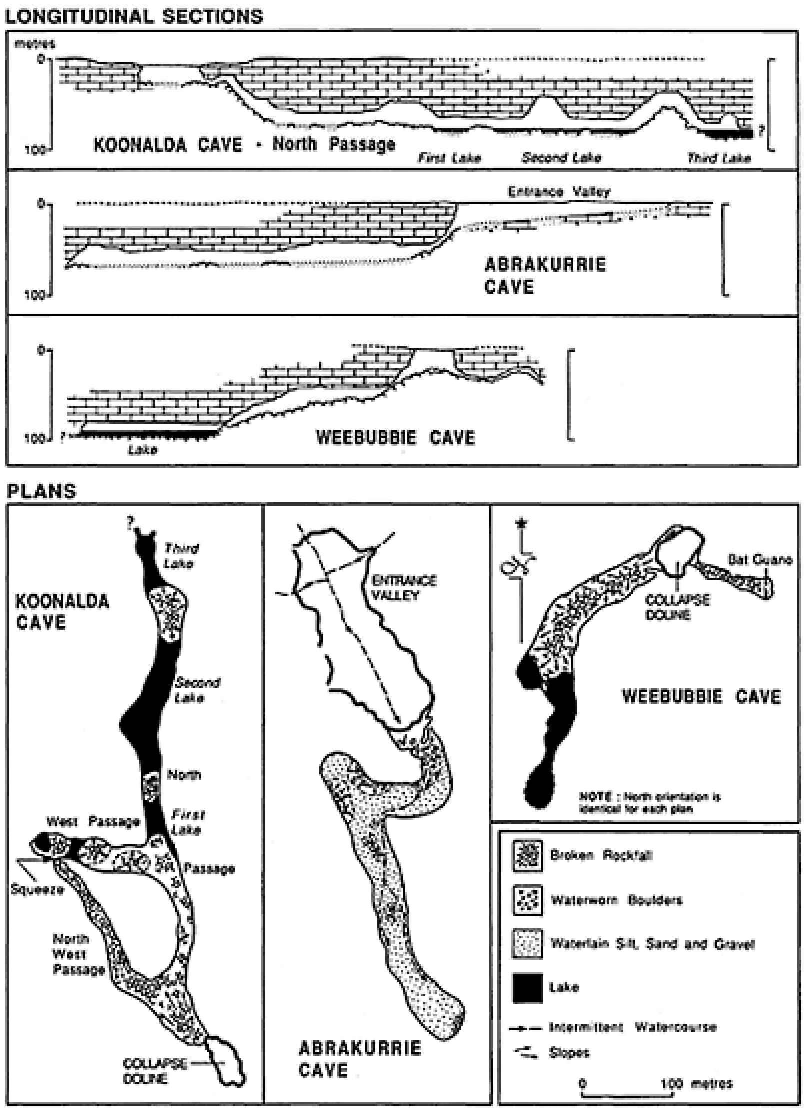
The Nullarbor Plain is a remarkably flat, nearly treeless arid karst plain developed on the Tertiary limestones of the Eucla Basin. It lies on the southern border of the continent between the states of Western and South Australia, and forms a biogeographical barrier between west and east (see map in Australia entry). This is Australia's largest karst (200000 km^2) and perhaps the most intensively studied. The region has an arid to semi-arid climate with annual rainfall between 150 and 250 mm, with a maximum in the winter months. Annual potential evaporation is 1250–2500 mm. Relief is low, less than 5 m, with slope angles of 1°–3°. The Nullarbor Plain has no surface drainage, but relict stream channels are found on the northern and western flanks of the plain. These have meandering traces and are infilled with alluvium and eolian deposits. Elsewhere

Nullarbor Plain, Australia: Figure 1. Collapse doline on the northeastern part of the Nullarbor Plain, South Australia. The depression leads into Koonalda Cave. (Photo by John Gunn)

there are many aligned depressions with clay pans; these are of structural origin (Lowry &: Jennings, 1974). These clay pans, locally termed "dongas", act to channel the slight runoff and direct it into dolines and blowholes. Dolines are sparse, steep sided, and show evidence of collapse into underlying cavities (Figure 1). Blowholes are very numerous, fed by deep solution pipes of complex origin. The caves are extensive, much modified by salt wedging and collapse processes, and commonly descend gently to near-static pools and lakes of brackish to saline water. A low-gradient water table underlies the plain and its depth ranges from 30 m in the north to 120 m in the south. The flooded tunnels of Cocklebiddy Cave are more than 6 km long but most of them can only be explored by divers. Withdrawal of hydrostatic support at times of lower sea level has led to collapse into these water table caves, allowing entry into large caverns such as Koonalda (Figure 2), Abrakurrie, Mullamullang, and Weebubbie Caves (Figure 3). All of these caves are characterized by having spectacularly grand old trunk passages that retain a 20–40 m diameter for several kilometres.

These deeper caves of the Nullarbor may intersect the water table, producing underground lakes, as at Weebubbie, Koonalda, and Tommy Graham's caves. These lakes are remarkable for their exceptional clarity, depth, and high salinity. The large

Nullarbor Plain: Figure 2. Looking out of Koonalda Cave into the collapse doline. Passage continues at this size for some 500 m. (Photo by John Gunn)



Nullarbor Plain, Australia: Figure 3. Plans and sections of three deeper caves on the Nullarbor Plain, Australia.

cave passages are typically flattened collapse arches with extensive breakdown blocks on the floor. Individual collapse events have been recorded on a time-scale of decades, especially near entrances. Cones and ridges of coarse sandy weathering debris are found in many caves, one of the best known being "The Dune" in Mullamullang Cave.

However, the majority of the caves on the Nullarbor Plain are shallow and contain a variety of passage forms, dominated by breakdown and also including phreatic passages, e.g. Old Homestead Cave. Many of these shallow caves are entered via cylindrical blowholes up to 30 m deep. Networks of anastomosing half-tubes are common in the upper zone of the limestone and create a large air volume, producing strong air movements in response to variations in atmospheric pressure. Stream-cut passages are uncommon in Nullarbor caves, and running water is absent except during flash flooding into cave entrances. In several caves the exceptionally dry microclimate has produced mummified wallabies, and, in one, the preserved remains of a Tasmanian tiger *(Thylacinus cynocephalus),* dating from 3500 years BP. A particular feature of the Nullarbor caves is the abundance of halite, which produces both speleothems (see photo in Speleothems: Evaporite) and many weathering forms through wedging during recrystallization. Gypsum speleothems are also abundant, with calcite speleothems less obvious, largely because of destruction through salt wedging. In Kelly Cave basal calcite speleothems are overlain by gypsum speleothems, and these in turn by halite. Speleothem history has much to contribute to the study of past climates and the history of the caves, which is at present unknown (Lowry & Jennings, 1974).

When the long-term operation of karst processes in the arid zone is considered, a fundamental dilemma emerges: are the present features the product of slow, low-intensity processes in a variable but essentially arid climate, or do they reflect inheritance from a past, wetter climate under which processes operated at a faster rate? There is some evidence for wetter conditions on the Nullarbor Plain in the distant past: first, the speleothem sequences mentioned previously; second, the dark-brown to black colours of calcite speleothems which have been demonstrated (Caldwell *et al.,* 1983) to be due to organic compounds such as humic acids, fulvic acids, and phenolics, suggesting more effective leaching of soil organic matter; and third, the presence of relict solution tubes and spongework in Thampanna and Old Homestead caves and the presence of solution scallops (spoonshaped hollows) in the flooded tunnels of Weebubbie and Cocklebiddy caves (Grodzicki, 1985) suggest a more vigorous fluvial regime in the geological past. Thus the cave systems of the Nullarbor Plain may have originated in a more humid climate phase, and probably span the entire Quaternary and part of the Tertiary. Since the onset of the present arid climate, these features have been heavily modified by salt wedging and collapse processes (Lowry & Jennings, 1974).

Under present climatic conditions, exposed outcrops are merely pitted by raindrops, and no solution rills are present. Some solution of limestone does occur in the coastal fringe of the Nullarbor Plain, and mixing corrosion may be important in this context (James, Rogers & Spate, 1990). The large caves of the Nullarbor may have been formed initially by enhanced solution at the mixing zone of fresh and saline waters. The groundwater of the Eucla Basin has a high salinity and some solution may also be occurring at great depth in the limestone. Inland periodic low-intensity rainfall may cause some solution on the margins of clay pans, and calcretes are forming, but overall rates of solution must be very low. Of more significance are the intrusions of rain depressions of tropical origin, which occur twice or three times per decade. These have the capacity to dump large amounts of water on the western Nullarbor, flooding clay pans and dolines, and perhaps maintaining epiphreatic passage forms in several caves such as Thampanna and Old Homestead.

During the last interglacial—glacial cycle the sea level dropped at least twice, steepening hydraulic gradients. This prompted a shift in the isohyets, allowing the saltbush shrubland of the interior plain to extend across terrain which today lies closer to the coast and supports eucalypt woodland. Conversely, during the last interglacial, eucalypt woodland would have extended farther inland than it does today and this may have enhanced solutional processes. These changes in the vegetation cover may have acted to destabilize the continental dunefields to the north of the Nullarbor and so allowed reddened quartz sands to accumulate downwind in caves and dolines on the eastern portion of the plain. Cave and doline infills on the eastern margin of the Nullarbor are dominantly red eolian quartz sand with well-developed silica skins from pedogenesis. At least three different pedogenic cycles are involved, with some loessic additions. These sands have their origin in the Great Victoria Desert and suggest a wind regime different to the present predominantly southerly to southwesterly airflow. The distribution of these sands, in a narrow belt around the Diprose Caves, suggests that they may have moved as sand streaks across the gravelly plain. The most recent disturbance of these sands, dated by thermoluminescence at <360 years BP, may reflect the increased fire frequency consequent on pastoralism and the spread of rabbits across the Nullarbor Plain. Recent environmental impacts on the Nullarbor and other arid karsts are reviewed by Gillieson (1993).

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Works Cited

Caldwell, J.R., Davey, A.G., Jennings, J.N. & Spate, A.P. 1983. Colour in some Nullarbor Plain speleothems. *Helictite,* 20:3–10

Gillieson, D. 1993. Environmental change and human impact on arid and semi-arid karsts of Australia. In *Karst Terrains: Environmental Changes and Human Impact,* edited by P.W. Williams, Cremlingen: Catena

Grodzicki, J. 1985. Genesis of the Nullarbor Plain caves in Southern Australia, *Zeitschrift für Geomorphologie,* 29:37–49

James, J.M., Rogers, P. & Spate, A.P. 1990. The role of mixing corrosion in the genesis of the caves of the Nullarbor Plain, Australia. *Proceedings of the 10th International Congress of Speleology,* edited by A.Kosà Budapest Hungarian Speleological Society: 263–65

Lowry, D.C. & Jennings, J.N. 1974. The Nullarbor karst, Australia. *Zeitschrift für Geomorphologie,* 18:35–81

Further Reading

Gillieson, D.S. & Spate, A.P. 1992. The Nullarbor karst. In *Geology, Climate, Hydrology and Karst Formation: IGCP 299 Field Symposium in Australia,* edited by D.S.Gillieson, Canberra: Department of Geography and Oceanography, Australian Defence Force Academy

Gillieson, D.S., Wallbrink, P., Murray, A. & Cochrane, A. 1996. Estimation of wind erosion using GIS modelling and caesium137 on the Nullarbor Plain karst, Australia. *Zeitschrift für Geomorphologie Supplement,* 105:73–90

Jennings, J.N. 1983. The disregarded karst of the arid and semiarid domain. *Karstologia,* 1:61–73

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ORGANIC RESOURCES IN CAVES

A wide range of organic materials is commonly found in caves. Some of these enter caves by being washed or blown into the cave, seeping through cracks in the bedrock, or simply by falling into an entrance. The living fauna and flora within or visiting caves is a further significant contributor. Tree roots and other vascular plant materials, algae, fungi, mosses and bryophytes (particularly in the twilight zone), birds, bats, and other vertebrates all make up a significant biomass. In turn the biota provide their excreta and their dead remains. All of these sources may interact with each other and with the rocks and minerals of the cave to produce a range of both further organic compounds and minerals. Many organic deposits have been mined or excavated as economic resources, and these are the subject of this entry. Hydrocarbons in karst are the subject of a separate entry.

Probably the greatest total of organic deposits are provided by the accumulated guano deposited by bats or birds (see Guano entry). These deposits provide an immensely rich food resource for other species, particularly invertebrates, and a substrate for the growth of fungi. They are often the basis for the genesis and development of special suites of minerals and in many regions their spontaneous combustion at intervals provides a still further source of chemical reactions. Guano, most commonly that from insectivorous bats, was mined extensively from caves in the 19th and early 20th centuries in Puerto Rico, the Bahamas, Mexico, and the southern United States for use as fertilizer (being rich in nitrogen and phosphate). The invention of chemical fertilizers has dramatically reduced the need for guano, and bat conservation measures have closed some operations. However, smallscale mining continues in a number of tropical caves, e.g. in Malaysia, the Caribbean, and Latin America, and there is a "cottage industry" level of extraction for the home garden market even in modern industrialized countries. Bone deposits in caves are also rich in phosphates and mining was carried out at the extensive vertebrate fossil deposits at Wellington Caves (New South Wales) from 1913–19.

Until the end of the 19th century nitrate deposits (saltpetre), formed largely as a result of seepage from the surface above the cave but often enriched by bat or rat guano, were commonly mined in order to manufacture gunpowder or other explosives (see Gunpowder entry).

Although the organic mineral guanine, which provides luminescence to liquid cosmetics, was originally found in bird guano in 1846, it has never been commercially produced from guano of any kind. Other organic minerals, occurring as a component of stalactites and crusts on the walls of caves containing bat guano deposits such as at Murra-el-elevyn Cave, Nullarbor Plain, Western Australia, appear to have no commercial value.

The nests of *Collocalia* and *Aerodramus* swiftlets are without doubt the most economically important cave products. These nests are comprised largely of dried saliva, and cemented to the cave walls. They are collected, cleaned and processed, then used to make bird's-nest soup. The processed nests command a very high price in the (Asian) gourmet market, now ranging up to $US 4000 per kilogram (Vermuelen & Whitten, 1999:32–35, 59–60). The management of the industry varies from one country to another. Traditional family harvesting had, for many centuries, ensured the sustainability of the industry, but with disruption of indigenous cultures and rising profitability, violent takeovers of some areas have occurred and poaching is becoming widespread (Valli & Summers, 1990). There is now an increasing demand for governmental or other regulation to re-establish sustainability (Casellini, Foster & Hien, 1999).

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See also **Sediments: Biogenic**

Works Cited

Casellini, N., Foster, K. & Bui Thi Thu Hien. 1999. *The "White Gold" of the Sea: A Case Study of Sustainable Harvesting of Swiftlet Nests in Coastal Vietnam,* Hanoi: IUCN Vietnam Programme

Valli, E. & Summers, D. 1990. *The Nest Gatherers of Tiger Cave,* London: Thames and Hudson, and Charlottesville, Virginia: Eastman Kodak

Vermeulen, J. & Whitten, T. 1999. *Biodiversity and Cultural Property in the Management of Limestone Resources,* Washington, DC: World Bank

Further Reading

Chapman, P. 1993. *Caves and Cave Life,* London: Harper Collins

Francis, C. 1987. *The Management of Edible Bird's Nest Caves in Sabah,* Kota Kinabalu, Malaysia: Wildlife section, Sabah Forest Department

ORGANISMS: CLASSIFICATION

All classifications are somewhat arbitrary. Furthermore, the groups that are proposed necessarily reflect the views of the classifier, since the latter chooses both the discriminative characteristics and the methodology used for the formation and the ordering of groups. The classification of living creatures is a well-known example that illustrates this. Classifications of organisms were successively utilitarian and anthropomorphic, typological, evolutionary, and more recently phenetic (based on global similarity) and finally phylogenetic, aiming for greater objectivity. Subterranean organisms include representatives of most large groups of the animal kingdom plus some groups of bacteria, fungi, and plants. These organisms live in a great variety of subterranean habitats and any reasonable classification of them must necessarily be based on ecological criteria that reflect the wide variety of habitats and life histories utilized. Several different classifications have been proposed, although they cannot always be easily compared because the authors frequently use similar names but employ different definitions.

Terrestrial *versus* aquatic species: The diversity of subterranean habitats results in a great diversity of potential niches suitable for terrestrial animal species using mainly atmospheric oxygen, as well as for aquatic species using dissolved oxygen for respiration. There is presently no common term referring to the whole terrestrial subterranean fauna, whereas the aquatic subterranean fauna is known as the stygofauna (Botosaneanu, 1988), the Styx being the main subterranean river of Hades in Greek mythology. The stygofauna includes all subterranean aquatic fauna, whether continental or marine, living in open water, in caves and crevices, or in interstitial water within sediments. As the prefix "troglo" (from the Greek word *troglé*) means hole, cavity, or cave, all kinds of animal species observed in caves or other subterranean cavities form the troglofauna, and this includes both terrestrial and aquatic species. However, since the introduction of the prefix stygo for aquatic subterranean organisms, the prefix troglo- has increasingly been used specifically for terrestrial cave fauna.

Organisms within caves may occur on the ground or in scree, on the walls and stalagmites, or on the roof and on stalactites. Others, the stygobites, occur in subterranean lakes or rivers utilizing open water biotopes in the dark environment of caves. When considering the terrestrial and aquatic fauna within caves, most speleobiologists recognize three different types of inhabitants: troglobites, troglophiles, and trogloxenes.

Troglobites are species permanently and exclusively living in caves or other subterranean cavities such as that of the "superficial underground compartment" (Camacho, 1992; Humphreys, 2000), also called the MSS (mesovoid shallow substratum; Juberthie, 2000), or in fissures or interstices providing large spaces compared to the animal body size. They are sometimes considered as the true cave-dwelling organisms and are often called troglobites (Holsinger & Culver, 1988). The adjectives "troglobiontic" or "troglobitic" are used, but compound names including troglobite are generally preferred by many authors. Troglobites generally present troglomorphic (or "troglobiomorphic") characteristics *sensu* Christiansen (1962), including morphological traits such as reduction or loss of eyes and tegument pigmentation, thinning of cuticle, and elongation of appendages, especially antennae, in arthropods. In addition, they frequently have biological, ecological, or behavioural traits such as a low metabolism and fecundity associated with a K-reproductive strategy, and a tendency to the loss of circadian and seasonal rhythms. This set of characteristics is called "troglomorphy" (or "troglobiomorphy") and is considered an adaptation to subterranean environments (see the entries on Adaptation). Troglobites exhibiting marked troglomorphic traits are generally considered as "paleotroglobites" as their ancestors colonized subterranean habitats in ancient times, from millions to hundreds of million years ago. When the ancestral group has disappeared from all surface habitats, the paleotroglobites, being the sole representative of the group, are often called "living fossils" or relict species. Other troglobites are genuinely limited to caves and differ from all closely related surface (epigean) species in respect to some specific traits but may exhibit few or no troglomorphic traits. These species are called “neotroglobites”, having relatively recently colonized the subterranean habitat. Conversely, some epigean organisms may appear to possess troglomorphic characteristics even though they do not inhabit subterranean environments.

Troglophiles are species that can establish and maintain subterranean populations but also occur in surface habitats that may have little similarity with the cave environment. They are able to support viable reproductive hypogean populations and may be common in caves, but are not obligate subterranean inhabitants. They may exhibit only some troglomorphic traits but these are generally less marked than in troglobites. They often look very similar to closely related surface species. Sometimes their status is uncertain, such as when they are theoretically able to live in surface habitats but are unknown outside of caves.

Trogloxenes are species that sometimes occur in caves but belong to surface communities, usually living and feeding in epigean habitats. They have sometimes been called “xenocaval” and as some are found in caves only by chance they have also been called “tychocaval” organisms or “accidentals” (Holsinger & Culver, 1988). However, the term trogloxene is by far the most commonly used and following Racovitza (1907) it is usual to distinguish the “regular trogloxenes” (such as the bats that usually reside in caves but feed outside of the cave) and the accidental or “occasional trogloxenes”, corresponding to the tychocaval or accidentals, including many surface forms exceptionally and passively drawn into some caves (surface fishes or aquatic invertebrates) or temporarily resting in caves (snakes, birds, rodents, or many terrestrial invertebrates).

Some authors have proposed other categories. For example, Ginet and Decou (1977) added a fourth category to the three categories discussed above, the “subtroglophiles”, for animal species such as bats that frequent caves only during one part of their life cycle such as the diapause period (a form of hibernation). These taxa do not feed in the cave whereas the troglophiles are able to feed and spend their entire life cycle within cave habitats. This distinction has not been widely adopted and most authors would consider bats to be trogloxenes. Christiansen (1962) focused more attention on the level of adaptations to subterranean life than to the different habitats; he considered four categories of cave animals: the “trogloxenes” (*sensu* accidental trogloxenes), the “troglomorphs” (ancient and well-adapted troglobites exhibiting most troglomorphic traits), the “ambimorphs” which exhibit only some traits related to caves or other subterranean habitats (probably some recent troglobites and some troglophiles), and the “epigiomorphs” which live in caves but have a phenotype still similar to that of surface animals (many guanobitic species, and some troglophiles or recent troglobites).

Aquatic fauna living in groundwater within caves, fractured rocks, and pores can be placed in all the categories proposed above. Thus the stygofauna *sensu lato* includes “stygobites”, “stygophiles”, and “stygoxenes” with definitions similar to those for the three main troglofauna categories but limited to aquatic organisms.

Some classifications result from the utility of defining some particular communities. For example, bat, or sometimes swiftlet, guano is often a major source of food for terrestrial cave species that are termed guanophages. Some authors also recognize “guanobites”, “guanophiles”, and “guanoxenes” (see Humphreys, 2000) but such categories cannot be the basis for a rational classification because it is not always possible to identify definite feeding groups of species. Moreover, many subterranean species are polyphagous, with complex variations of diet and habitat use in the same cave. Other tentative classifications are based on the spatial and abiotic characteristics of different parts of the subterranean ecosystems (see Hypogean Habitats). Some cave biologists have distinguished between the entrance (cave threshold) communities, the wall (or parietal) communities, and the deep and clayey soil communities, but it is impossible to recognize a finite number of clearly defined communities.

More interesting is the separation of stygobites into "troglostygobites" (mainly karstostygobites) and "phreatostygobites". The first live in open water of cave rivers and lakes whereas the latter live in the groundwaters of alluvial sediments, i.e. in interstitial waters, where the space available for animals is limited (see Interstitial Habitats entries). In each habitat, the selective pressure of the environment acting on the evolution of the body size and morphology is quite different as are the resulting stygobites: larger animals (cave fishes, amphibians, or crayfishes) with hypertelic appendages (e.g. some cave shrimps with very long antennae) only occur as troglostygobites, but very small species, with more elongated shapes, short antennae and appendages, and phreatomorphic traits (Coineau, 2000) mainly occur as phreatostygobites (see comparative figures of different kinds of stygobitic isopods in Crustacea: Isopoda Aquatica). Similar differences in morphological traits have been observed in terrestrial invertebrates between cave terrestrial troglobites and deep soil "edaphobites" (Humphreys, 2000). The latter generally have a smaller and thinner body, with shorter appendages than the closely related troglobitic species.

Other classifications of stygobites have been proposed that are from an evolutionary and biogeographical perspective: "limnostygobites" inhabit fresh continental subterranean waters, whilst "thalassostygobites" inhabit either marine sediments or marine caves, or coastal biotopes with a marine influence. Some groups of Crustacea (for example the micro-isopod crustaceans *Microcharon* spp. and *Microcerberus* spp.) have interstitial species belonging to the same genus in the two groups of stygobites and both exhibit a clear phreatomorphy. The thalassostygobites include many troglobitic species living either in marine caves (marine troglobitic species) or in anchialine caves—littoral caves always in connection with marine water but displaying some continental influence, and characterized by spatial variation of ecological factors, especially salinity (Sket, 1986; see also Anchialine Habitats). There is a great variety of anchialine habitats and a rich anchialine fauna including three categories of stygobites. Some taxa belong to groups usually continental and limnostygobitic (e.g. the numerous species of the cirolanid isopod genus *Typhlocirolana* discovered first in brackish waters of Balearic caves), whereas others belong to marine groups (e.g. the galatheid crab *Munidopsis polymorpha* from an anchialine lava tube in the Canary Islands). A third kind of taxa occur solely in anchialine caves and thus are characteristic of this habitat in all locations, for example, *Speleonectes* spp. and other genera of Remipedia, a group discovered only 20 years ago. They have a very plesiomorphic trunk, but very apomorphic head appendages and are generally considered to be one of the most primitive classes of Crustacea.

Some limnostygobites (such as the above micro-isopods) have no closely related species in surface freshwaters. They are clearly related to marine groups and are derived from marine ancestors that have directly colonized the coastal and continental groundwaters and are called "thalassoid" limnostygobites. Other limnostygobites, originating from surface freshwater ancestors which colonized groundwaters and interstices in alluvial sediments or the subterranean waters of caves, are called “limnicoid” limnostygobites (Coineau & Boutin, 1992; Notenboom, 1991). Groundwater cirolanid isopods are thalassoid limnostygobites whereas the subterranean isopods Asellidae or the cave amphipods *Gammarus* (Culver, Kane & Fong, 1995) are limnicoid limnostygobites.

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Works Cited

Botosaneanu, L. (editor) 1986. *Stygofauna Mundi, A Faunistic, Distributional, and Ecological Synthesis of the World Fauna Inhabiting Subterranean Waters (Including the Marine Interstitial),* Leiden: Brill

Camacho, A.I. 1992. A Classification of the aquatic and terrestrial environments and their associated fauna. In *The Natural History of Biospeleology,* edited by A.I.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Christiansen, K. 1962. Proposition for the classification of cave animals. *Spelunca,* 2:76–78

Coineau, N. 2000. Adaptations to interstitial groundwater life. In *Subterranean Ecosystems,* edited by H.K.Wilkens, D.C.Culver & W.F.Humphreys, Amsterdam and New York: Elsevier

Coineau, N. & Boutin, C. 1992. Biological processes in space and time: Colonization, evolution and speciation in interstitial stygobionts. In *The Natural History of Biospeleology,* edited by A.I. Camacho, Madrid: Museo Nacional de Ciencias Naturales

Culver, D.C., Kane, T.C. & Fong, D.W. 1995. *Adaptation and Natural Selection in Caves: The Evolution of Gammarus minus*. Cambridge, Massachusetts: Harvard University Press

Holsinger, J.R. & Culver, D.C. 1988. The invertebrate cave fauna of Virginia and a part of Eastern Tennessee: Zoogeography and ecology. *Brimleyana, Journal of the North Carolina State Museum,* 14:1–163

Humphreys, W.F. 2000. Background and glossary. In *Subterranean Ecosystems,* edited by H.K.Wilkens, D.C.Culver & W.F. Humphreys, Amsterdam and New York: Elsevier

Juberthie, C. 2000. The diversity of the karstic and pseudokarstic hypogean habitats in the world. In *Subterranean Ecosystems,* edited by H.K.Wilkens, D.C.Culver & W.F.Humphreys, Amsterdam and New York: Elsevier

Notenboom, J. 1991. Marine regressions and the evolution of groundwater dwelling amphipods (Crustacea). *Journal of Biogeogmphy,* 18:437–54

Racovitza, E.G. 1907. Essai sur les problèmes biospéologiques. *Archives de Zoologie Expérimentale et Générale,* 6:371–478

Sket, B. 1986. Ecology of the mixohaline hypogean fauna along the Yugoslav coasts. *Stygologia,* 2(4):317–38

Further Reading

Gibert, J., Danielopol, D.L. & Sanford, J.A. (editors) 2000. *Groundwater Ecology,* San Diego: Academic Press

Ginet, R. & Decou, V. 1977. *Initiation a la Biologie et a l’écologie souterraines,* Paris: Delarge

Juberthie, C. & Decu, V. (editors) 1994, 1998, 2001. *Encyclopaedia Biospeologica,* 3 vols, Moulis and Bucharest: Société de Biospéologie

Vandel, A. 1964. Biospéologie: La Biologre des animaux cavernicoles, Paris: Gauthier-Villars

Wilkens, H., Culver, D.C. & Humphreys, W.F. (editors) 2000. *Subterranean Ecosystems,* Amsterdam and New York: Elsevier

ORNAMENTAL USE OF LIMESTONE

Limestone has great value as a resource for many types of construction, and depending on the specific properties and characteristics of the particular rock, its use can be interpreted as ornamental. There are many popular uses of cut (dimensional) quarried limestones, including exterior and interior building surfaces and monuments. Limestones may be used ornamentally in both their weathered and unweathered states. Many unweathered limestones, freshly cut, are extremely attractive and interesting by virtue of their rich and varied textures and constituents, often involving visible fossil content. Polishing enhances this attraction but can also be a source of confusion in that the building trade uses the term "marble" to describe any limestone, and sometimes non-limestone, rocks that can be polished whereas strictly it should be applied only to metacarbonates.

In addition to cut or dimensional stone, blocks of natural weathered rock from surface limestone outcrops are very attractive to many people for ornamental purposes, providing a sculptured appearance which can appear very dramatic and "modern". Such weathered limestone blocks, with their wide variety of attractive karren features, have been used ornamentally in various ways for several centuries. In Great Britain, solutionally sculpted limestone pavement blocks have been used in garden rockeries since the mid-19th century, and in gateways and wall toppings for even longer. Unfortunately, due to the popularity of these blocks a very high proportion of the pavement in the country has been quarried, and the extraction has caused considerable environmental damage to surface limestone outcrops. The clash between landscape conservation and resource exploitation has been the focus of considerable discussion and action, including legislation, to prevent the damage and to conserve the remaining natural limestone landscape features. In particular, the Wildlife and Countryside Act passed by the UK Parliament in 1981 provided a mechanism on which to base protection of the limestone pavements. This is the only case in the UK where a specific landform has been protected, as opposed to protection for areas or sites of special scientific interest.

There are many cases around the world of similar ornamental use of weathered limestone blocks, for example features taking advantage of attractive patterns of runnels are used in gardens in China, Slovenia, and Switzerland. Large intact Flachkarren, or clints, which have been scrubbed clean are sold as "sculpture" in the Jura area of Switzerland, and near to Mammoth Cave in Kentucky, United States, clints have been modified and in some cases painted to form a "sculpture park". The striking solutional sculpture of humid tropical areas (e.g. southern China) is also naturally ornamental and has been copied in artificial materials in Disneyland, Florida, as well as being used in its natural state in China, for example, in the Imperial Palace in Beijing.

Quarrying of limestones for ornamental use has a very important impact on the visual environment. This may be adverse at

Ornamental Use of Limestone: Dimensional stone quarry, Borba, Portugal. Blocks of limestone are cut with a diamond saw providing a cross section through the karst. (Photo by John Gunn)

the point of extraction, although some dimensional stone quarries provide fascinating cross sections through the karst (see photo in Quarrying of Limestone entry), but is usually positive in the case of the construct using the stone. Most dimensional stone quarries are smaller in both scale and extent than quarries producing aggregates.

Many of the world's most famous buildings use some type of limestone or marble in their construction. Examples include the Taj Mahal, in which Makrana marble from Rajasthan is used, and many 17th-century buildings in Rome constructed from, or decorated with, a marl limestone named the Cottanello "marble". Another famous limestone is Portland Stone, extracted from quarries on the Isle of Portland on the south coast of England. This is a Jurassic oolitic limestone in which the texture is very even, which means that it can be sculpted or cut in any direction. It became famous in the 17th century after Wren chose it for the reconstruction of St Paul's Cathedral in London. Many famous buildings have been constructed from it since, including the United Nations building in New York. The Indiana Limestone of Lawrence County, Indiana, has also been used in the construction of well-known buildings including the Empire State

Building and the Pentagon in the United States. This limestone is very easily worked, has an attractive pale buff colour, and makes up about 80% of the dimensional limestone used in the United States.

Limestones from France have been very widely used for ornamental purposes, the most well-known examples being in the great Gothic cathedrals of the north, more modern examples including the extensive and widely marketed use for tiling, especially of floors. Greece and Portugal are two other sources of such materials. In Greece limestone has been used ornamentally since Classical times and is seen in many of the famous buildings such as the Parthenon in Athens. Many other famous structures of the ancient civilizations of the Middle East and Mediterranean are composed of limestones, for example the Sphinx in Egypt. Another very striking example of a limestone used ornamentally is the Globigerina Limestone of Malta. This is a relatively soft yellow limestone which hardens on exposure to the atmosphere, and its softness renders it easy to carve into shapes before hardening occurs. It is worked in this way for both public buildings and private residences on both Malta and Gozo, and the ornamentation is very varied.

In Central America, a further example of the ornamental use of quarried limestone in buildings from an old civilization comes from the Mayan city of Nakbe in Guatemala. The limestone used in the most impressive buildings was quarried at Nakbe, and excavations in these quarries were important for understanding Mayan culture.

A final example of a particularly striking ornamental use is of redeposited limestone, or tufa. Pieces of this material are used in grottoes and gardens, in the former case to create a rough, pocked, or bony surface, deemed attractive in the 18th and 19th centuries in England and copying the contemporary ideas of the appearance of cave interiors (see Art Showing Caves). In horticulture, pieces of tufa are used to provide a microhabitat for lime-loving plants, creating a mini-rock garden such as in an extensive tufa rockery at the Lakeland Horticultural Society gardens at Holehird in Cumbria, United Kingdom. Harder tufas and travertines are used ornamentally in buildings, for example in the Tubingen area of southwest Germany and at the Bagni di Tivoli and other sites in and near Rome, including the colonnades around St Peter's Square. More recent applications include the Basilica of the National Shrine of the Immaculate Conception in Washington, DC, where the South Vestibule and Narthex (passageway) are being clad with travertine and marble following the installation of a new marble relief sculpture believed to be the largest of its type in the world.

Thus, ornamental use of limestones is widespread, varied, and sometimes curious, exploiting the attractiveness and interest of the weathered and unweathered, cut and uncut, polished and unpolished sufaces of the endlessly varied rocktype.

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Further Reading

Smith, M.R. (editor) 1999. *Stone: Building Stone, Rock Fill and Armourstone in Construction,* London: Geological Society (Engineering Geology Special Publication No. 16)

Useful websites

www.swgfl.org.uk/jurassic/pordand.htm provides details on the uses and quarrying of Portland stone.
www.limestonecountry.com/Limestone.html provides details of Indiana stone.
http://www.imiweb.org/stonemagazine/dimston1.htm is the website of *Stone,* the trade magazine for specifiers, fabricators, and suppliers of dimensional stone.

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PALEOENVIRONMENTS: CLASTIC CAVE SEDIMENTS

Caves make excellent sediment traps, with nearly all caves having some form of clastic sediment within them. These deposits, and any fossils or artefacts they contain, are often preferentially preserved compared to surface deposits and can provide valuable clues to the genesis and evolution of the cave system and to the changing environment outside. Furthermore, many cave sediments can be dated, allowing this information to be put into a chronological context. However, clastic cave sediments are often overlooked, even though they are an essential part of the evolutionary history of the host cave.

Clastic sediments can occur throughout a cave system, but an important distinction can be made between cave entrance and interior facies. Cave entrance deposits are generally much more complex and often contain valuable archaeological deposits. Archaeological artefacts or fossils may be dated using radiocarbon, thermoluminescence, or amino acid racemization dating techniques, providing information on the confining clastic sediments (see Dating Methods: Archaeological). Interior deposits may be devoid of significant archaeological material but often provide valuable information about the genesis and evolution of the cave system.

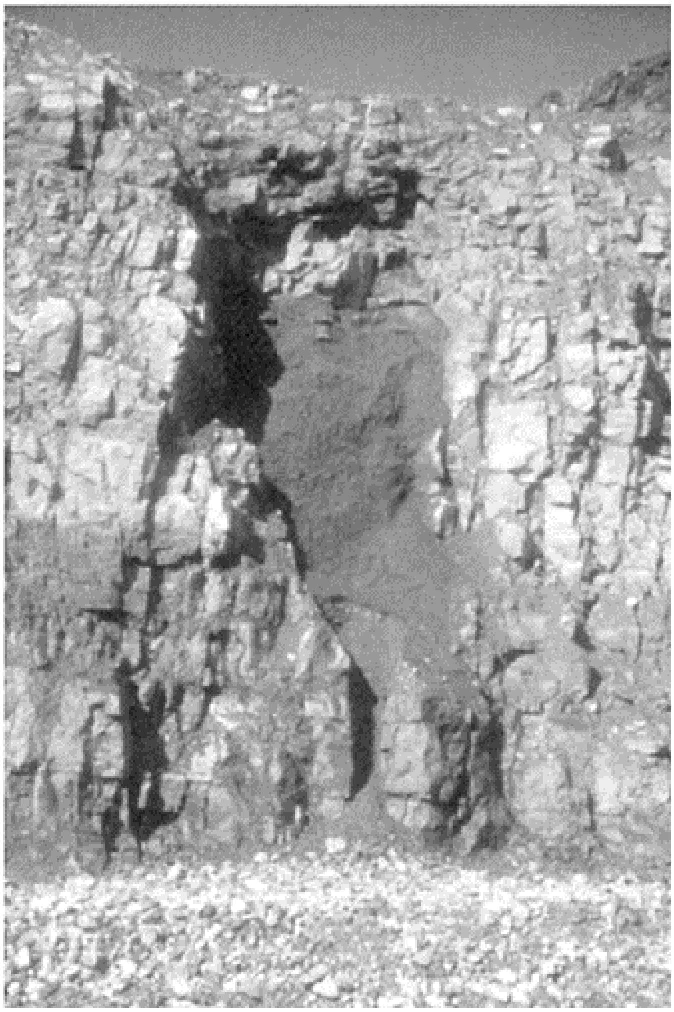
Clastic cave sediments fall into two main categories: autochthonous and allochthonous. Autochthonous clastic sediments are generated within the cave by endogenetic processes operating at the site of deposition, although such sediments may be subsequently transported further into the cave. The commonest sediments of this type are the products of roof collapse and breakdown. Most clastic cave sediments, however, are allochthonous; generated outside caves and transported into them. Two main transport pathways into caves occur: either vertically by collapse, slumping, and translocation (gravitational fills); or laterally by fluvial action, mudflows, solifluction, or more rarely by ice and wind, although water is by far the dominant transport agent. Aeolian deposits are rare in caves, usually only occurring in entrance passage, but reworked loess is a common component of cave sediments in northern Europe and America. Similarly, gla cial deposits rarely penetrate far underground, even where cave systems extend under ice caps such as Castleguard Cave, Canada. However, glacially derived sediments are often transported long distances underground by meltwater.

Many of the processes, bedforms, and deposits found in caves are identical to those seen in surface fluvial environments. As with surface clastic sediments, the range of depositional environments is immense, although in general cave sediments are often very chaotic with rapid lateral facies changes and complex stratigraphic relationships. This is partially because underground the normal laws of superposition do not apply. Although sediments in a particular passage normally young upwards, sediments in overlying passages are normally older. Furthermore, within single sediment sequences, repeated cut and fill episodes, collapse, subsidence, and re-sedimentation can generate very complex stratigraphies. Additional complexities arise when sediments cemented by flowstone are subsequently partially eroded, leaving false floors. Moreover, several unusual transport mechanisms occur in caves. Under pipe-full conditions during flood or mass movement events, sediment may be emplaced as a single, fluidized, self-perpetuating sliding mass of sediment similar to that proposed for esker formation. This “sliding bed” facies enables sediment bodies to penetrate far into a cave system (Gillieson, 1986). At the other extreme, Bull (1981) suggested that translocation of mud down joints and fissures can accumulate to create “cap mud” deposits, often infilling caves to roof level.

Influxes of large amounts of clastic sediment can also affect cave development by protecting passages, floors, and walls from further dissolution, concentrating any erosion upwards (see Paragenesis entry) and modifying passage morphology. This is a fundamental process that is vastly underestimated in cave development. Many caves show at least some evidence of modification in this way, especially in low-gradient systems with an allochthonous sediment source.

Clastic cave sediments and the sedimentary structures they contain can provide clues on the paleoenvironment and paleohy- drology at the time of deposition. Furthermore, clast lithology, surface texture, chemistry, and mineralogy may give clues as to the sediment source area, catchment area, transport mechanism, relative age, and transport distance. Many caves in temperate latitudes contain enormous quantities of coarse, poorly sorted, gravelly allochthonous sediment. Analysis of such sediments in South Wales using clast analysis and examination of their microscopic surface textures, demonstrated that these were not deposited under current interglacial conditions, but are consistent with a fluvioglacial origin (Bull, 1981). Analysis of sediments in the Peak District, England, demonstrated that sediments exhibited distinctive mineralogical and chemical characteristics dependent on age and source (Bottrell, Hardwick & Gunn, 1999). In Clearwater Cave, Sarawak, systematic changes in clast lithology downstream give an indication of transport distance underground.

Crucially, clastic cave sediments can be dated in various ways, permitting any paleoenvironmental or sedimentological inferences to be put into a chronological context. Indirectly, paleontological or archaeological dating methods can be applied if fossils or artefacts are present within the sediment, although most bones and artefacts often occur near cave entrances. Morevover, they can be reworked and do not necessarily date the cave or the host sediment. Pollen grains and phytoliths can occur widely in sediments (see Palynology). The abundance, type, and preservation of pollen grains can indicate surface environments at the time of deposition and potentially constrain the age of the sediment



Paleoenvironments: Clastic Cave Sediments: Figure 1. Clastic sediments infilling a cave in Eldon Hill Quarry, Castleton, Derbyshire, England. These sediments consist of coarse sandstone and shale derived from the adjacent Namurian Millstone Grit and Edale Shales (see Peak District entry). Some of the clasts have chatter marks suggestive of a glacial origin. Paleomagnetic dating of the fine-grained cap muds and U-series dating of intercalated speleothem deposits suggest these sediments may be up to 900000 years old. (Photo by John Gunn)

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Paleomagnetism is the most widely used method for directly dating clastic sediments, although only clays and silts can be reliably dated, often only as far back as the first few polarity reversals. Records of secular magnetic variation can be obtained from caves and compared to other dated sections such as lake sediments, although curve matching can prove problematic in older sediments. Alternatively, samples can be obtained throughout a vertically stacked series of cave passages to identify periods of reversed polarity sediments. Such an approach has been undertaken in many caves, including Mammoth Cave, Kentucky (Schmidt, 1982) and the Mulu Caves, Sarawak (Farrant *et al.*, 1995). From this technique, rates of base-level lowering can be estimated. However, without independent dating control, the correlation between observed sediment polarity and the paleomagnetic timescale becomes increasingly tenuous beyond the first few reversals. Other paleomagnetic techniques such as susceptibility and anisotropy have not been extensively used on cave sediments.

Absolute dates can be obtained using radiometric methods. Although clastic cave sediments cannot be dated using U-series or Electron Spin Resonance methods, speleothem deposits interbedded within clastic sediment sequences can. Studies in many caves have utilized this method to constrain the age of sediment sequences. Examples are the studies of Quinif and Maire (1998) in the Gouffre de Pierre Saint-Martin and of Williams (1996) in Aurora Cave on the slopes above Lake Te Anau in Fiordland, New Zealand. The latter cave descends steeply from a formerly glaciated valley and drains to the Te Anau tourist cave on the lakeshore. Sequences of glaciofluvial sediments interbedded with speleothems in the cave are evidence of the number and timing of glacial advances and the status of intervals between them. Twenty-six U-series dates on speleothems underpin a chronology of seven glacial advances in the last 230000 years, with the peak of the late Otira glaciation (Last Ice Age) at *c.* 19000 years BP. With five advances in the Otiran, the last glaciation is more complex than previously recognized. Comparison of the record from the Aurora Cave sequence with that interpreted from other onshore deposits is very convincing. Glacial deposits on slopes above the cave may be evidence of “missing” glacial events in the mid to early Pleistocene that are not preserved at other sites due to their obliteration by successive glacial advances.

Paleoenvironments: Clastic Cave Sediments: Figure 2. Extensive gravels of glaciofluvial origin were deposited in Crag Cave, County Kerry, Ireland between *c.* 114000 and 65000 years ago. (Photo by John Gunn)

Recent advances in the use of terrestrial cosmogenic isotopes as dating tools provide another promising method of dating clastic cave sediments. Cosmic ray reactions in the uppermost few metres of the Earth's crust produce minute quantities of the rare isotopes ^{26}A1, ^{10}Be, and ^{36}Cl, whose accumulation can be used to determine surface exposure ages, measure erosion rates, and trace sediment production and dispersal. As these elements are only produced near the ground surface, the isotope ratios can be used to date the burial age of surface-derived allogenic sediments. Such methods have been used to date fluvial sediments in the upper levels of Mammoth Cave, Kentucky and hence determine the rates of incision of the Green River during the last 3.5 million years (Granger, Fabel & Palmer, 2001). However, the technique is in its infancy and problems determining the rate of terrestrial cosmogenic nuclide production arise as their production varies spatially and temporally due to the shielding influence of the Earth's atmosphere and with changes in geomagnetic field intensity.

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See also **Sediments: Allochthonous Clastic; Sediments: Autochthonous Clastic**

Works Cited

Bottrell, S., Hardwick, P. & Gunn, J. 1999. Sediment dynamics in the Castleton Karst, Derbyshire, UK. *Earth Surface Processes and Landforms,* 24:745–59

Bull, P.A. 1981. Some fine grained sedimentation phenomena in caves. *Earth Surface Processes and Landforms,* 6:11–22

Farrant, A.R., Smart, P.L., Whitaker, F.F. & Tarling, D.H. 1995. Long term Quaternary uplift rates inferred from limestone caves in Sarawak, Malaysia. *Geology,* 23:357–60

Gillieson, D. 1986. Cave sedimentation in the New Guinea Highlands. *Earth Surface Processes and Landforms,* 11:533–43

Granger, D.E., Fabel, D. & Palmer, AN. 2001. Pliocene-Pleistocene incision of the Green River, Kentucky, determined from radioactive decay of cosmogenic ^{26}A1 and ^{10}Be in Mammoth Cave sediments. *Geological Society of America Bulletin,* 113:825–36

Quinif, Y. & Maire, R. 1998. Pleistocene deposits in Pierre Saint-Martin Cave, French Pyrenees. *Quaternary Research,* 49:37–50

Schmidt, V.A. 1982. Magnetostratigraphy of sediments in Mammoth Cave, Kentucky. *Science,* 217:827–29

Williams, P.W. 1996. A 230 ka record of glacial and interglacial events from Aurora Cave, Fiordland, New Zealand. *New Zealand Journal of Geology and Geophysics,* 39:225–41

Further Reading

Bosák, P. (editor) 1989. *Paleokarst: A Systematic and Regional Review,* Amsterdam: Elsevier

Bull, P.A. 1980. Towards a reconstruction of timescales and paleoenvironments from cave sediment studies. In *Timescales in Geomorphology,* edited by R.A.Cullingford, D.A.Davidson & J. Lewin, Chichester and New York: Wiley

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Ford, T.D. 2001. *Sediments in Caves,* London: British Cave Research Association (BCRA Cave Studies Series, 9)

A short introduction to cave sediments for the educated caver.

Karstologia Memoires No. 2: Quinif, Y. 1990 *Remplissages karstiques et paleoclimats,* Paris: Fédération française de spéléologie and Bordeaux: Association française de karstologie

Karstologia Memoires No. 5: Audra, P. 1994. *Karsts alpins,* Paris: Fédération française de spéléologie and Bordeaux: Association française de karstologie

These provide a good introduction to much previous work published in French.

Kranjc, A. 1989. *Recent Fluvial Cave Sediments, Their Origin and Role in Speleogenesis,* Ljubljana: SAZU, ZRC

Smart, P.L. & Francis, P.D. (editors) 1991. *Quaternary Dating Methods: A User's Guide,* Cambridge: Quaternary Research Association

A specialist technical guide to dating methods.

White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

PALEOENVIRONMENTS: SPELEOTHEMS

Caves are amongst the longest-lived components of landscapes, surviving for millions of years, or longer where preserved as paleokarst. They function as giant sediment traps, sampling all rock, chemical, and organic waste products that are mobile in the outside environment. They are important in many types of paleoenvironmental research (Ford, 1997). A stalagmite may be likened to a stone tree that can grow for many thousands of years. Calcite stalagmites, plus flowstones and underwater crystal linings, are now being studied intensively. Aragonite and gypsum speleothems attract less attention because of their rarity and comparative instability.

Dating Speleothems

Speleothems are dated by several different methods. They are among the most important deposits for establishing precise ages of events during the last 500000 years.

^{14}*C method:* Carbon-14 is created by cosmic radiation in the atmosphere and has a half-life of 5730 years. It is precipitated together with the stable isotopes, ^{12}C and ^{13}C, in most types of speleothem calcite and can be detected by mass spectrometry for 8–10 half-lives, i.e. 45000–57000 years Before Present (BP). Unfortunately, the proportion of "dead" carbon (dissolved from ancient rock in which all ^{14}C has decayed in the speleothem can range 5–38% or more. This uncertainty, plus the short time range, limits the utility of the method.

U-series methods: These are the most important at the present time. Uranium isotopes are common trace components in rocks, especially shales. They weather readily, forming $UO_2(xCO_3)$ ions in solution that contribute U atoms to precipitating speleothems. The U decays by emitting ^{4}He nuclei, electrons, and X-rays, until stable as ^{206}Pb or ^{207}Pb. The early decay products, ^{230}Th and ^{231}Pa, are insoluble in waters of normal pH and thus will not be precipitated (Ivanovich & Harmon, 1992).

The decay of ^{234}U (half-life=245000 years) to ^{230}Th (halflife=75700 years) is the principal method. Figure 1 gives the graph of the dating equation, which is complex because decay of ^{238}U must also be considered. With modern mass spectrometer techniques it is possible to date a sample 500000 years in age with an analytical error of only±15000 years (2 standard deviations). Decay of ^{235}U (half-life=713 million years) to ^{231}Pa (half-life=34000 years) is a similar method but with a range of only ~200000 years: it is little used because of the scarcity of these isotopes.

The chief problems encountered with these methods are:

1. insufficient uranium. Acceptable results can be obtained with as little as 0.02 ppm U but >0.1 ppm is preferred. Most calcite speleothems have 0.02–2.0 ppm U; aragonite is often much richer;
2. presence of ^{230}Th carried on detritus (chiefly clay particles) in the calcite. This produces too great an age and affects many speleothems, particularly at archaeological sites. ^{232}Th can derive only from detritus, thus where ^{230}Th/^{232}Th >20. the sample is considered "clean". Dirty calcites can often be tackled by repeated extractions or datings;

3. high porosity, which permits leaching of uranium. It is a serious difficulty in evaporitic calcite but can be avoided in other types.

Despite these problems, several thousand speleothem $^{230}Th/^{234}U$ dates of high analytical quality have been published.

Decay of ^{238}U to ^{234}U permits dating back to ~1500000 years. However, these isotopes precipitate together in calcite and their initial ratio cannot be calculated where ^{230}Th is in equilibrium (>600000 years). In Figure 1, one speleothem has an initial ratio always close to 3.35 and might be used for a reasonable $^{234}U/^{238}U$ estimate beyond 600000 years. The other sample in the figure has a widely varying ratio and could not be used.

Uranium-Lead dating: The half-life of ^{238}U is 4.7 billion years, similar to the age of the Earth itself. Its decay to stable ^{206}Pb is the principal means of dating the oldest rocks on the planet. Most speleothems are much younger and thus contain little ^{206}Pb derived from decay, making it difficult to differentiate from background concentrations of non-radiogenic ^{206}Pb present in all speleothems. Samples with large variations of ^{238}U concentration within them are required in order to construct a $^{238}U/^{204}Pb$ v $^{206}Pb/^{204}Pb$ linear trend ("isochron") that estimates the age: such speleothems appear to be rare (Richards *et al.,* 1998).

Paleomagnetism: Most speleothems contain small quantities of precipitated or detrital grains of magnetite, which is common in all environments. When deposited, the grains orient (declination) and tilt (inclination) towards the Earth's magnetic poles and become locked in position by subsequent calcite accumulation. The declination, inclination, and intensity of the Earth's magnetic field change continuously by small amounts and sometimes shift abruptly or reverse. This behaviour has been dated using quick-setting lavas. In principle, the age of a speleothem may be determined by comparing its paleomagnetic record to the lava record. The method requires large volumes of calcite; in speleothems it is used chiefly to detect the Brunhes/Matuyama reversal at ~780000 years and some older excursions and reversals (Latham & Ford, 1993).

Amino acid racemization: Many speleothems contain trace quantities of soil organic matter (see below). The protein amino acids in them decay slowly from an L to a D configuration, at a rate that is constant where the temperature is constant. Lauritzen *et al.* (1994) measured the decay in extracts from an ancient Norwegian speleothem, obtaining a fair correlation with its U-series ages and suggesting that racemization might be used to extend dating a little beyond the $^{230}Th/^{234}U$ dating range.

Environmental Isotope Records

Many stable elements, including hydrogen, oxygen, carbon, and sulphur involved in the dissolution and deposition of calcite, aragonite, and gypsum, occur in two or more isotopic configurations, where the "heavier" isotope has one or more extra neutrons in its nucleus. When vapour condenses or a solid is precipitated, the heavy isotope is slightly more abundant ("enriched") in the denser phase. The amount of enrichment may be controlled entirely by the ambient temperature ("equilibrium fractionation") or determined by dynamic mechanisms such as evaporation ("kinetic fractionation"). These eflfects are potent tracers of environmental processes (Clark & Fritz, 1997) that become locked into a speleothem when its $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ are precipitated.

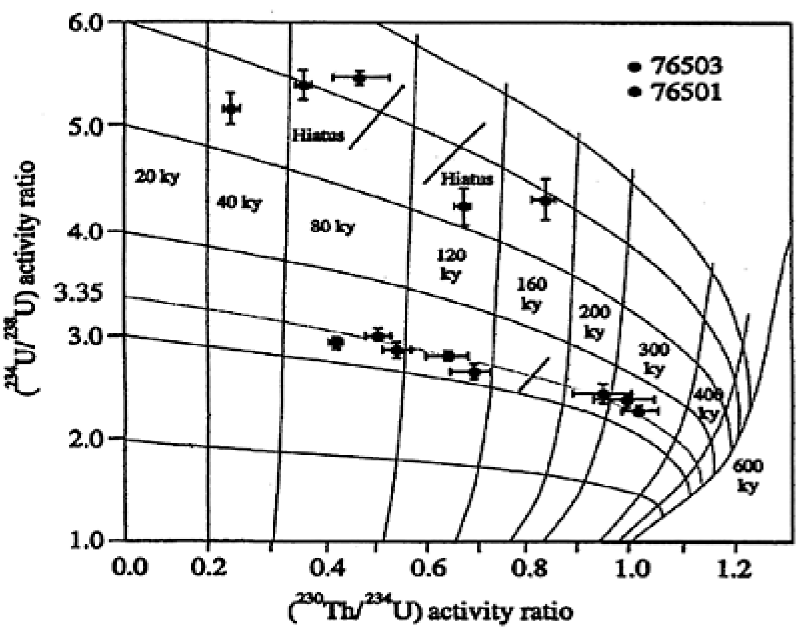
The fractionation of ^{18}O:^{16}O is the most used. There are three competing controls:

1. because of ice sheet growth during the Quaternary Ice Ages the oceans become slightly enriched in ^{18}O (one part per thousand, or “permil”);
2. cave interior temperatures are close to mean annual values outside; ^{18}O of calcite, etc. increases 0.24 permil per degree C (°C) of cooling; but
3. less ^{18}O is evaporated from the oceans during cold periods and it precipitates out of the clouds after shorter distances, reducing the proportion of ^{18}O falling as inland rains.

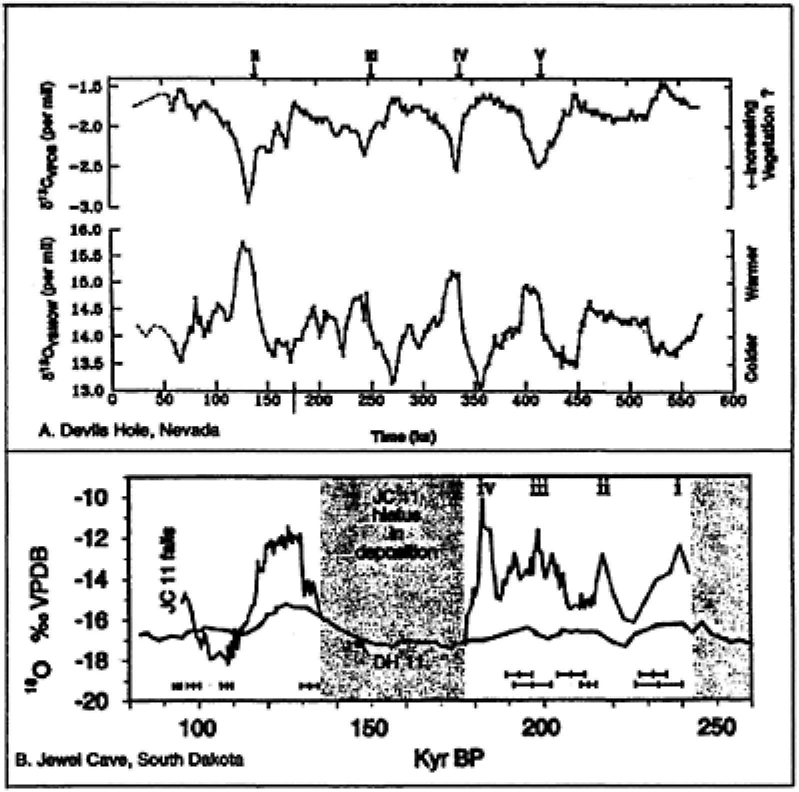
Many published studies have shown that effect 3 most often predominates, i.e. speleothems are a little depleted in ^{18}O during cold periods (Figure 2), but there may be enrichment in coastal areas or the effects may cancel each other elsewhere. All such signals may be negated where there is strong evaporation during deposition.

Measurement of the ^{18}O:^{16}O ratio in calcite, aragonite, or gypsum can only show whether any temperature change was “warmer” or “cooler”. The actual change (°C) requires that the water of precipitation (trapped in microscopic fluid inclusions in speleothems) also be measured. ^{1}H:^{2}H (the D/H ratio) is preferred because oxygen ratios may be disturbed by interacting with the calcite, etc. Work on the problem continues (Dennis, Rowe & Atkinson, 2001).

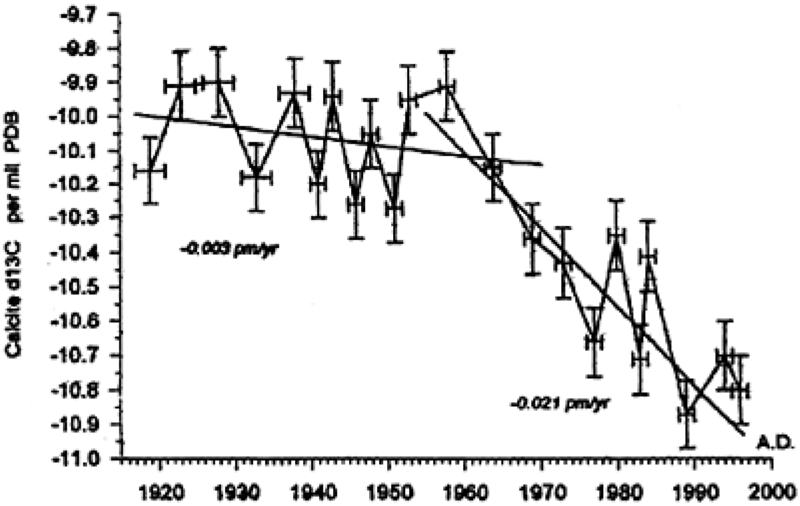
Part of the carbon in a speleothem derives from dissolution of limestone and other rocks, where ^{13}C:^{12}C=0±5 permil compared to VPDB (a global standard), and part from



Paleoenvironments: Speleothems: Figure 1. Graphical form of the $^{230Th/}$234U dating equation. Ages may be obtained back to 600000 years, when the decay ratio of the two isotopes attains secular equilibrium. Ages for two different speleothems from Tumbling Creek Cave, Missouri, are shown with their one standard deviation error bars. The $^{234}U/^{238}U$ activity ratio at time of calcite deposition (vertical axis) can vary substantially; Sample 76501 (lower sample) was nearly constant at 3.35, making it suitable for extended dating ($^{234}U/^{238}U$ method) but Sample 67503 shows erratic behaviour. From Ivanovich & Harmon, 1992. These results were obtained by alpha spectrometry; modern mass spectrometric methods reduce errors by a factor of ten or more.



Paleoenvironments: Speleothems: Figure 2. A. The δ^{13}C and δ ^{18}O records of Sample DH11, Devil's Hole, Nevada. The sample is a 36 cm core from a thermal water calcite spar coating in the cave, which is part of the spring outlet of a major regional aquifer. Dating control is by 21 mass spectrometer ^{230}Th/^{234}U and ^{234}U/^{238}U ages obtained at regular intervals along the core. From Coplen *et al.*, 1994. B. For comparison, the δ ^{18}O record from the upper part of a vadose speleothem, JC11, that grew in Jewel Cave, South Dakota, until it fell about 90000 years ago. Dating control by ten mass spectrometer $^{230}Th/^{234}U$ ages is shown, with two standard deviation error bars. This location is colder than the Devil's Hole region. The local vadose zone feedwater is vulnerable to cold, as indicated here, where speleothem deposition ceases during the coldest periods. Note that the amplitude of ^{18}O cyclic variation is much greater than in the Devil's Hole thermal water, where the climatic signal is muted by effects of mixing and slow groundwater circulation.



Paleoenvironments: Speleothems: Figure 3. An example of current studies exploiting annual depositional bands detected in some speleothems. The speleothem is from southern France. Two trends in the $^{13}C/^{12}C$ ratio can be seen: (1) between 1920 and the 1950s, the "Suess Effect", the slow dilution of ^{13}C in the atmosphere caused by the burning of fossil fuels;

(2) the "Bomb Effect", rapid dilution caused by detonation of nuclear bombs in the atmosphere (Genty *et al.*, 1998).

atmospheric CO_2 ^{13}C:^{12}C is approximately −7 permil in CO_2 in the open air, reducing to around −14 permil in soil air under rich grasslands, and to −26 permil under dense forest. As a consequence, ^{13}C:^{12}C ratios may record processes in vegetation and soil above a cave or aquifer. In Figure 2A, it is seen that the carbon signal is negatively correlated with the oxygen signal in the DH11 phreatic calcite spar, suggesting slight increase in vegetal activity during interglacials in this desert setting: the amplitude of the speleothem ^{13}C:^{12}C oscillation here is about 1.4 permil. The forest-grassland-desert transition shifts back and forth across Jerusalem during a glacial climatic cycle, where the amplitude in vadose zone speleothems has been found to be as great as 12 permil (Frumkin, Ford & Schwarcz, 2000).

Organic and Other Cyclic Traces in Speleothems

Under magnification, many speleothems display micrometric layering of apparently cyclic kinds. This includes growth microterminations (with or without some dissolution) that suggest seasonal flooding or drying up of the feedwater, and even seasonal alternation of calcite and aragonite deposition. The most widespread, however, is probably colour banding in calcite without growth terminations. The banding usually has a couplet form-lighter to darker-with a colour range between yellow and dark brown. This is caused by variation in trace concentrations of fulvic acids (chiefly), plus humic acids, and fine particulate organic matter, incorporated in the crystal lattice (van Beynen *et al.*, 2001). Shopov (1987) showed that the banding is best seen when fluoresced with ultraviolet light and suggested that, in many instances, each couplet represents one climatic year of deposition (see Speleothems: Luminescence). This has now been confirmed by many studies where the annual accumulation can be checked by field measurement, historic records, etc. (Baker *et al.*, 1993). In temperate climates, the darker component is usually deposited in winter, or during the spring thaw if the ground freezes (Genty & Quinif, 1996). There are sometimes correlative variations in the abundance of common trace elements such as Ba, Mg, and Sr deposited in speleothems (Fairchild *et al.*, 2000).

Speleothems may also incorporate pollen grains, enhancing paleovegetal information (see Palynology). However, their abundance is generally too low for conventional palynological ecologic reconstructions. Bacteria, fungi, algae, and mites (chiefly arthropods) have also been found in trace amounts.

This work is opening up a fruitful field for very high-resolution paleoenvironmental studies, similar to that of tree rings but extending much further back in Quaternary time. Investigations are expanding geographically to speleothems in hot desert and alpine regions. The stable isotopic composition of annual banding of known age is permitting precise tracking of human impacts on the environment, as shown in the example in Figure 3.

DEREK FORD

See also **Dating of Karst Landforms**

Works Cited

Baker, A., Smart, P.L., Edwards, R.L. & Richards, D.A. 1993. Annual growth banding in a cave stalagmite. *Nature,* 304:518–20

Clark, I.D. & Fritz, P. 1997. *Environmental Isotopes in Hydrogeology,* Boca Raton, Florida: CRC Press

Coplen, T.B., Winograd, I.J., Landwehr, J.M. & Riggs, A.C. 1994. 500000-year stable carbon isotope record from Devil's Hole,Nevada. *Science,* 26; 361–65

Dennis, P.F., Rowe, P.J. & Atkinson, T.C. 2001 The recovery and isotopic measurement of water from fluid inclusions in speleothems. *Geochimica et Cosmochimica Acta,* 65(6):871–84

Fairchild, I., Borsato, A., Tooth, A.F., Frisia, S., Hawkesworth, C.J., Huang, Y., McDermott, F. & Spiro, B. 2000. Controls on trace element (Sr-Mg) compositions of carbonate cave waters: Implications for speleothem climatic records. *Chemical Geology,* 166; 255–69

Ford, D.C. 1997. Dating and paleo-environmental studies of speleothems. In *Cave Minerals of the World,* 2nd edition, C.A. Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Frumkin, A, Ford, D.C. & Schwarcz, H.P. 2000. Paleoclimate and vegetation of the last glacial cycles in Jerusalem from a speleothem record. *Global Biogeochemical Cycles,* 14(3):863–70

Genty, D. & Quinif, Y. 1996. Annually laminated sequences in the internal structure of some Belgian stalagmites—importance for paleoclimatology. *Journal of Sedimentary Research,* 66(1): 275–88

Genty, D., Vokal, B., Obelic, B. & Massault, M. 1998. Bomb ^{14}C time history recorded in two modern stalagmites. *Earth and Planetary Science Letters,* 160:795–809

Ivanovich, M. & Harmon, R.S. 1992. *Uranium-series Disequilibrium: Applications to Earth, Marine and Environmental Sciences,* 2nd edition, Oxford: Oxford University Press

Latham, A.G. & Ford, D.C. 1993. The paleomagnetism and rock magnetism of cave and karst deposits. In *Applications of Paleomagnetism to Sedimentary Geology,* edited by D.M.Aissaoni, D.F.McNeill & N.F.Hurley, Tulsa, Oklahoma: Society of Economic Paleontologists and Mineralogists

Lauritzen, S.-E., Haugen, J.E., Lovlie, R. & Gilje-Nielsen, H. 1994. Geochronological potential of isoleucine epimerization in calcite speleothems. *Quaternary Research,* 41:52–58

Richards, D.A., Bottrell, S.H., Cliff, R.A., Strohle, K.-D. & Rowe, P.J. 1998. U-Pb dating of a Quaternary-aged speleothem. *Geochimica et Cosmochimica Acta,* 62(23–24):3683–88

Shopov, Y.Y. 1987. Laser luminescent microzonal analysis: A new method for investigation of the alterations of climate and solar activity during the Quaternary. In *Problems of Karst Study in Mountainous Countries,* edited by T.Kiknadze, Tbilisi, Georgia: Metsniereba

Van Beynen, P.E., Bourbonniere, R., Ford, D.C. & Schwarcz, H.P. 2001. Causes of color and fluorescence in speleothems. *Chemical Geology,* 175(3–4):319–41

Further Reading

Bradley, R.S. 1999. *Paleoclimatology: Reconstructing Climates of the Quaternary,* 2nd edition, London and New York, Academic Press

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

PALEOKARST

Although a great range of geological structures and landform features of variable ages have been described as paleokarst, the term is difficult to define. The most inclusive definition is to say that paleokarst is evidence for karst processes acting in the past. This definition intentionally includes both karst landforms formed in the past and the deposits that fill them. The essential characteristic of paleokarst is that it is inert, i.e. there is no longer any significant gain or loss of matter in it as a result of karst processes. Every feature of karst that we recognize today, from towers and giant maze caves to microkarren and helictites, existed in the past and may be preserved in the geological record by burial or may have survived in the surface or underground landscape through isolation from weathering and erosion.

As paleokarst *sensu stricto* is inert it should be distinguished from fossil karst and relict karst. Fossil karst is correctly used to describe karst features that are not in equilibrium with modern landscape process, but are not inert from a karst perspective. Relict karst is isolated from the karst excavation processes that formed it, but still is subject to modification for example by weathering, breakdown, and speleothem deposition. However, the terms paleokarst and fossil karst are often used interchangeably, while cavers frequently, and erroneously, refer to "fossil passage" when they are actually describing relict passage that is above the present zone of active erosion by running water.

Paleokarst is a worldwide phenomenon that is found on all continents, including Antarctica, and in the geological record from the early Proterozoic to the Holocene. Very young paleokarst, including filled caves, occurs in raised coral reefs on the north shore of Oahu, Hawaii. Paleokarst has been reported in a range of soluble rocks including limestone, dolostone, chalk (England), gypsum (Ukraine and Canada), salt (Canada), and carbonatites (Canada).

Diagenetic Settings

For many limestones the process of diagenesis, which converts sediments into rock, begins with a period of subaerial exposure and karst development (see Syngenetic Karst). Consequently many karsts have undergone at least one previous period of karstification. Large filled caves and dolines preserved at grand unconformities are the most outstanding forms of paleokarst, but the most frequent type of paleokarst occurs when epikarst (ectogenetic karst) is preserved. This often occurs at minor disconformities in carbonate sequences when short periods of subaerial exposure are followed by a marine transgression and further carbonate sedimentation. For this reason some carbonate petrologists consider paleokarst to be a facies. Karst can develop in lithified soluble rocks (telogenetic karst) wherever and whenever they are exposed to karst processes. This can occur at or near the Earth's surface and deep underground where hydrothermal, thermal, or artesian processes can dissolve the rock, producing endogenous karst. This means that most karsts, particularly those in Mesozoic or older rocks, have been subjected to more than one period, and often many periods, of karstification. Multiple or polycyclic karstification is more often the rule than the exception. Some karst features, such as caves and dolines, may be buried and exhumed a number of times. For this reason paleokarst should not be thought of as "dead" karst. The real death of karst comes when the rock mass is completely removed by solution. It is caves without roofs, not filled caves, that are really on their deathbed (see photo).

Preservation of Paleokarst

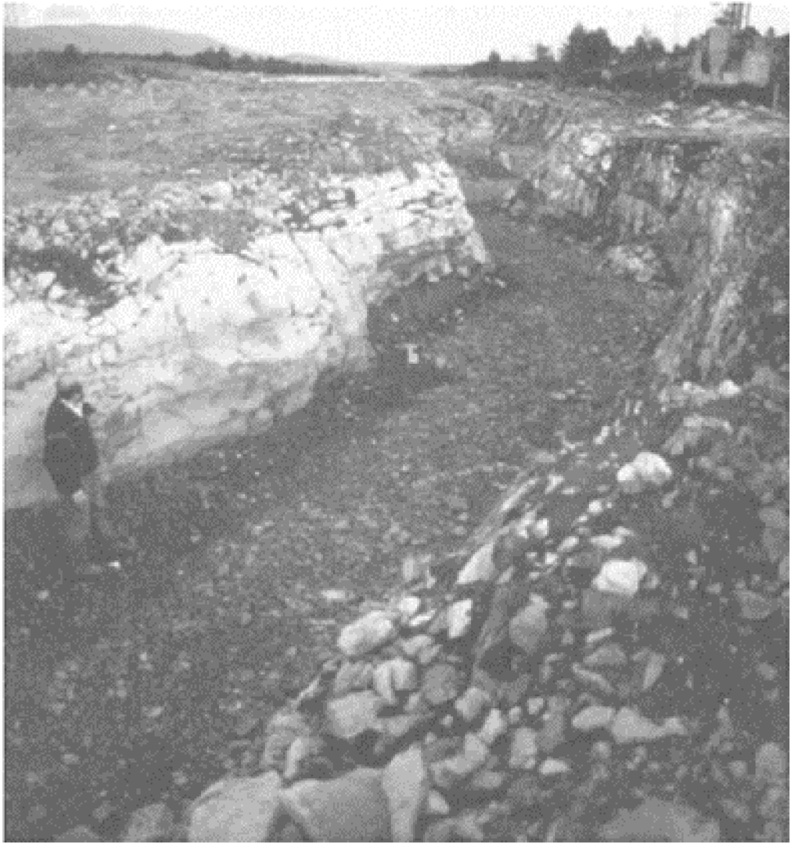
There are three main ways in which paleokarst can be preserved: burial, isolation, and cessation of process. When karst landscapes are covered by sediment, buried karsts are produced. Depressions in the karst surface, and caves, are filled, or partially filled, with sediment. The degree of preservation of surface solution features depends on the energy with which the sediment is deposited. Buried karsts are protected from surface karst processes while they remain isolated from the surface groundwater system. Subjacent karst may develop in buried karst rocks if they are close to the surface. However, buried karsts are not protected from *per ascensum* karst processes. Many karsts remain buried, their presence being discovered only by drilling or geophysical investigation. In other cases, natural processes of uplift and erosion have exposed buried karst rocks at the Earth's surface revealing, and/or exhuming, the paleokarst. When karst landforms, particularly caves, become isolated from karst processes, ancient karst features may survive as relict karst. This can occur, for example, when caves become disconnected from the local hydrological system in regions with low erosion rates or where climatic changes convert wet tropics to deserts. Relict caves can also be preserved after *per ascensum* processes cease. Thermal caves, formed at depth in localities where there is no longer rising warm water, and the giant gypsum caves of the Ukraine, from which artesian waters have now drained, belong to this category.

Rises in sea level can flood both surface karst and caves, causing karst processes to cease. As a result paleokarst is an important feature of limestone coastlines. Caves below sea level may still carry fresh water to the sea, producing submarine springs. The Sea Mills of Argostoli, Kephallonia, Greece are a curious flooded-karst feature. Sea water sinks into a doline on one side of the limestone island, only to rise, slightly diluted, just above sea level on the other side of the island, ten kilometres away.

Plate tectonics is significant when thinking about all types of paleokarst: buried, relict, and exhumed. In parts of the world where the present landscape has ancient origins, such as Australia and South Africa, relict karst forms, including caves, may have formed in the ancient continent of Gondwana, within the Antarctic Circle. Similarly, relict karst landforms in Europe may have formed under tropical conditions.

Caves without roofs are an important paleokarst landform which has only recently attracted scientific attention. Caves without roofs are produced when lowering of the karst surface intersects, and removes the roof of a cave. A cave without a roof may be a cave floor or a depression consisting of cave walls and floor, exposed at the surface. They can be considered as paleokarst because they are now under the influence of surface lowering, rather than karst processes. Often caves without roofs are filled with, or contain a considerable quantity of, cave sediments. Interest in caves without roofs arose when motorway construction in the Kras (Slovenia) intersected a considerable number of these features (see photo).

In geologically active parts of the world, a mass of soluble rock can subside, become buried, and then be uplifted again on a number of occasions. Each time the rock is at the surface it



Paleokarst: Roofless cave discovered during construction of an expressway through the Classical Karst of Slovenia. (Photo by John Gunn)

is possible for karst to develop. The same rock mass may also be intruded by igneous rocks resulting in hydrothermal or thermal karst, or may form part of an artesian basin resulting in artesian karstification. At some localities, four, six, and ten periods of karstification have been recognized. With increased scientific interest in this field, it is likely that recognition of many periods of karstification will become more common. Multiple karstification can effect the whole range of paleokarst features, from large caves and dolines to cases where modern epikarst is invading and re-activating ancient epikarst.

Economic Deposits

Paleokarst is of great economic significance: large lead-zinc ore bodies, oil resources, bauxite, uranium, iron, and clay deposits occur in paleokarst. Paleokarst aquifers are important sources of water and can present a significant flooding hazard to underground mining operations. Mississippi Valley-type ore bodies are one of the most significant forms of paleokarst ore deposits. These consist of large bodies of galena and sphalerite emplaced in limestone (see Sulfide Minerals in Karst). Many of these bodies have plan shapes similar to those of caves and some ore occurs as speleothems. The three-kilometre long zinc-lead ore body at Nanisivik, Baffin Island, Canada has been interpreted as a large keyhole-shaped cave passage in which sulfide ores were emplaced. Ancient karst surfaces, paleokarst unconformities, and cavernous zones in limestone are significant traps and reservoirs for petroleum (see Hydrocarbons in Karst). Paleokarst is important in the great areas of carbonate-hosted petroleum such as the Middle East and Texas. Paleokarst bauxites account for 10% of the world's resources of aluminium. They develop in deeply weathered sediments filling ancient karst depressions and in some cases caves. Karst bauxites include large deposits in Jamaica and the majority of bauxite deposits in Europe, such as those of Greece and Hungary (see Bauxite Deposits in Karst). The phosphate deposits of Pacific islands such as Nauru have developed in and on karst surfaces. The complex shape of karst surfaces makes them ideal traps for dense minerals forming placer deposits (see Mineral Deposits in Karst). Some filled dolines and caves contain economic concentrations of alluvial gold, diamonds, cassiterite (tin ore), rare earths, and precious stones. Paleokarst aquifers and submarine springs can both be significant resources for water supply.

Scientific Significance

Paleokarst can be an important source of scientific information. It can preserve information about events and environmental conditions in the past which is not preserved elsewhere in the geological record. This is particularly important in areas where there are significant gaps in the stratigraphic record. In some cases the only record of a particular event, or the only means of dating an event, is provided by paleokarst. Evidence for a marine transgression in the Czech Republic during the Miocene is provided by a tiny deposit of fossil-bearing limestone, adhering to the wall of Zbrašovské Aragonite Cave. Paleokarst exposed in a small quarry in Tasmania provides the principal evidence for the age of a major Devonian folding event in eastern Australia. With continuing improvements in dating techniques, paleokarst has great potential for providing a window into times in the past about which we presently have little or no information. Palaeokarsts, including caves without roofs, are a rich source of vertebrate fossils. Examples include the hominid sites of the Transvaal, South Africa and the Tertiary marsupial deposits of Riversleigh, Queensland, Australia. Dinosaur fossils have been found in paleokarst in Belgium, Romania, and Slovenia. Modern caves are complex sedimentary environments in which many different types of sediments (e.g. sand, mud, bone, guano) and minerals are deposited. These are preserved in paleokarst, and frequently become transformed into rock. Paleokarst deposits are complex and present petrologists and sedimentologists with a fascinating range of unusual rock types and sedimentary structures to study. The variety of their economic and scientific significance means that scientists from a range of backgrounds are interested in paleokarst. As a consequence, information about paleokarst is published in a great range of literature.

Finding and Recognizing Paleokarst

Evidence for karst processes in the past occurs in two main forms, morphological and material. Morphological evidence includes surface and underground karst structures (buried, exhumed, or preserved) which are indicative of past processes, while material evidence includes earth materials (minerals, sediments, and rocks) deposited in, on, or over karst. Paleokarst is most easily recognized where large (but not too large) buried or filled karst features are intersected and exposed. Sections through filled cave passages in cliffs or quarry faces, such as those in Czatkowice Quarry, Poland, are quite compelling. For this reason, much paleokarst research has focussed on filled caves and dolines exposed in quarries (see photo in Paleoenvironments: Clastic Sediments). However, it is doubtful whether researchers would recognize some of the world's largest caverns as paleokarst if they were filled with sediments and then exposed in section (e.g. Sarawak Chamber, Mulu, Sarawak: 700 m long, 400 m wide, and 280 m high). On a different scale, oil and mining geologists tend to see paleokarst exposed in drill cores. Their work often centres on the microfabrics produced in carbonate rocks by karst processes.

In some areas, such as the Kras of Slovenia, where paleokarst deposits are exposed at the surface, paleokarst has not yet been found in caves. Paleokarst deposits are most likely to be intersected by younger caves in steeply bedded impounded karsts where there are a limited number of flow paths through the limestone, or where recent caves have developed from below *(per ascensum)* by thermal or artesian processes. Recognizing paleokarst in caves can be difficult. Some caves, such as those in the Peak District, England, intersect ancient open cavities (see photo in Peak District entry), while others, such as Jenolan Caves, New South Wales, Australia and Beremend Crystal Cave, Hungary, intersect ancient sediment-filled caves. In addition, some caves that are now open and accessible were once filled with sediments or ore bodies. These exhumed caves can sometimes be recognized because their morphology is unrelated to modern hydrological conditions, or because they contain tiny remnants of the material that once filled them but many probably go unrecognized. Modern caves may contain passages, chambers, and speleogens that are remnants of older cave systems. A modern stream cave may intersect cupolas that were part of an ancient thermal cave. If polycyclic karst is common, it must be common for caves to be made up of sections of differing ages, formed by different processes. Recognizing the different paleokarst elements and unravelling the history of complex caves is a challenging, four-dimensional, puzzle.

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Further Reading

Bosák, P., Ford, D.C., Glazek, J. & Horácek, I. (editors) 1989. *Paleokarst: A Systematic and Regional Review,* Amsterdam: Elsevier

Ford, D.C. 1986. Genesis of paleokarst and strata-bound zinc-lead sulfide deposits in a Proterozoic dolostone, northern Baffin Island, Canada—a discussion. *Economic Geology,* 81:1562–66

Ford, D.C. 1995. Paleokarst as a target for modern karstification. *Carbonates and Evaporites,* 10(2):138–47

James, N.P. & Choquette, P.W. (editors) 1988. *Paleokarst,* New York and London: Springer

Jones, B. & Smith, D.S. 1988. Open and filled features on the Cayman Islands: Implications for the recognition of paleokarst. *Canadian Journal of Earth Sciences,* 25:1277–91

Korpas, L. 1998. Paleokarst studies in Hungary. *Occasional Papers of the Geological Institute of Hungary*, 195:1–139
Kranjc, A. (editor) 1999. Papers presented at the 7th International Karstological School "Roofless Caves." Postojna, 1999. *Acta Carsologica*, 28(2):15–210
Olson, R.A. 1984. Genesis of paleokarst and strata-bound zinc-lead sulfide deposits in a Proterozoic dolostone, northern Baffin Island, Canada. *Economic Geology,* 70:1056–1103
Osborne, R.A.L. 2000. Paleokarst and its significance for speleogenesis. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society
Osborne, R.A.L., 2002. Paleokarst: cessation and rebirth. In *Evolution of Karst: From Prekarst to Cessation,* edited by F. Gabrovsek, Ljubljana: Zalozba ZRC
Quinlan, J.F. 1972. Karst-related mineral deposits and possible criteria for the recognition of paleokarsts: A review of preservable characteristics of Holocene and older karst terranes. In *Proceedings of the 24th International Geological Congress, 1972:* Section 6:156–68
Wrenrich, K.J. & Sutphin, H.B. 1994. Grand Canyon caves, breccia pipes and mineral deposits. *Geology Today,* May-June 1994:97–104
Wright, V.P. (editor) 1991. *Palaeokarsts and Palaeokarstic Reservoirs,* Reading: Postgraduate Research Institute for Sedimentology, University of Reading (Occasional Publication Series, 2)

PALEONTOLOGY: ANIMAL REMAINS IN CAVES

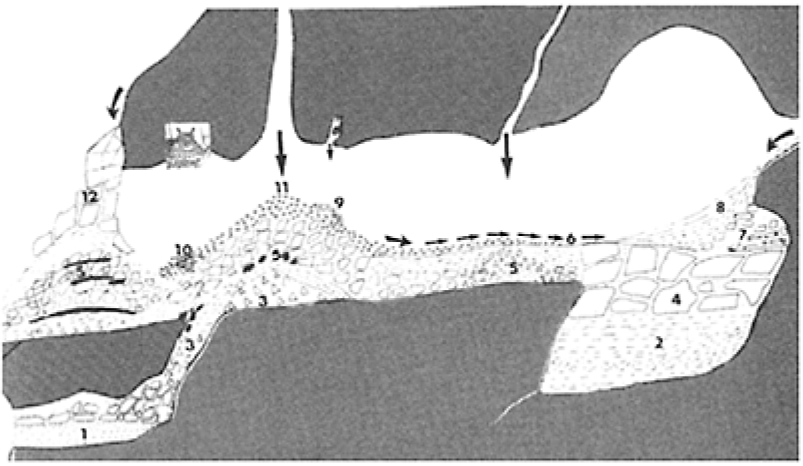
Deprived of the life-giving energy of the sun, caves are an environment that, in principle, is hostile to life. Few mammals regularly use the deeper areas of the cave, exceptions being bats that can find their way in total darkness, and cave bears, now extinct (Pinto & Andrews, 2003). On the other hand, many animals dwell near the entrances of caves, making use of the shelter provided. However, the majority of animal remains that are found in caves have been introduced by other means, human agency being one of them. This is an account of the ways that animal bones come to be in caves and how they may be interpreted in the archaeological record to take account of the biases introduced by these different processes.

Bone Accumulation in Caves

Animal remains accumulate in caves in four basic ways: the animals live and die in the cave; they fall in by accident and cannot get out again; they are taken in by predators; or their bones are transported in after death by other means (Figure 1). Cave size and shape, altitude, and relation to water determines its usefulness for animal occupation and whether animals may be trapped, carried in, or washed in.

Common dwellers of caves include bats, porcupines, and many species of mammalian and avian predator. Some tropical caves have large accumulations of bat remains mixed with the deep layers of bat guano. Large mammals may seek shelter in caves and may be trapped, for example, by heavy snowfalls. Caves in England have been observed to be home to foxes and badgers, and in Africa, leopards have been found living in caves, e.g. the Mount Suswa caves in Kenya (Brain, 1981). The lair of the well-known man-eating lions of Tsavo was eventually located in a nearby cave. In the past, human beings and their ancestors frequently lived in caves, not only in temperate regions but in Africa as well (Balch, 1914; Klein, 1975; Deacon, 1979). It has been inferred that many fossil animal assemblages found in caves were derived from animals actually living in the caves. For example, it is probable that the bats found in some abundance in one unit of the caves at Westbury-sub-Mendip, Somerset (England), were living in the cave, for where the bats occurred there were few other mammals (Andrews, 1990). Similarly, extremely rich amphibian remains were found in wet clay deposits in a cave at Draycott, Somerset, and again these were the only animals present. In the past also, there is good evidence that cave bears occupied and died in large numbers in caves, and this has been documented for the Westbury caves. Occupation over thousands of years has resulted in huge quantities of bones being accumulated in some European caves.

The second way animals get into caves is by accident, trapped in a pit fall chamber or in the soft mud of the bottom of a pit,



Paleontology: Animal Remains in Caves: Figure 1. Generalized section of a cave. The numbers indicate different forms of accumulation of bones and sediment: **1.** Accumulation of cave in a closed chamber; **2.** Waterlain silts; **3. & 11.** Breccia formation beneath an the, and secondary transport into the lower chamber; **4.** Roof fall; **5.** Cave entrance breccias with bone; **6.** Breccias flattened by trampling of large animals; **7.** Den accumulation of bones; **8.** Watertransported muds from further inside the cave; **9.** Accumulation of bat remains beneath roosting area in the cave roof; **10.** Accumulation of small mammals beneath owl roosting/nesting area in the cave roof; **12.** Closing of cave entrance by collapse of the cliffspace.

from where they cannot escape. Usually the structure of the cave provides an indication, if this is the case. For example, the Sima de los Huesos accumulation of human and cave bear bones in Spain may have been a natural trap, at least for the cave bears, and the bears found in the deep pit of Somiedo cave likewise (Pinto & Andrews, 2003). Both these caves are in Spain, but there is also the famous Natural rap cave in Wyoming, United enter caves seeking water in karstic crevices, and mineral salts. States (White *et al.*, 1984). Elephants and rhinoceroses may Remains of these animals have been found in caves on Mount Elgon, Uganda, after meeting with accidents inside the caves (Andrews, 1990). Rodents have been found living (and dying) at the bottom of cave (and mine) shafts, where they are able to have been found at the bottom of a 30 m vertical shaft in the survive for a time on food debris blown in. For example, rodents Eastwater Cave, Somerset. Finally, animals may be trapped in caves, not by the cave formation itself, but by inclement weather such as heavy snowfalls (Sutcliffe, 1955). A feature of such bone accumulations is that animals are represented by whole skeletons, as there is no way for the animals to be removed, dead or alive. Carnivores are sometimes attracted into such caves, if not too deep, but their meals are dearly bought when they cannot get out again.

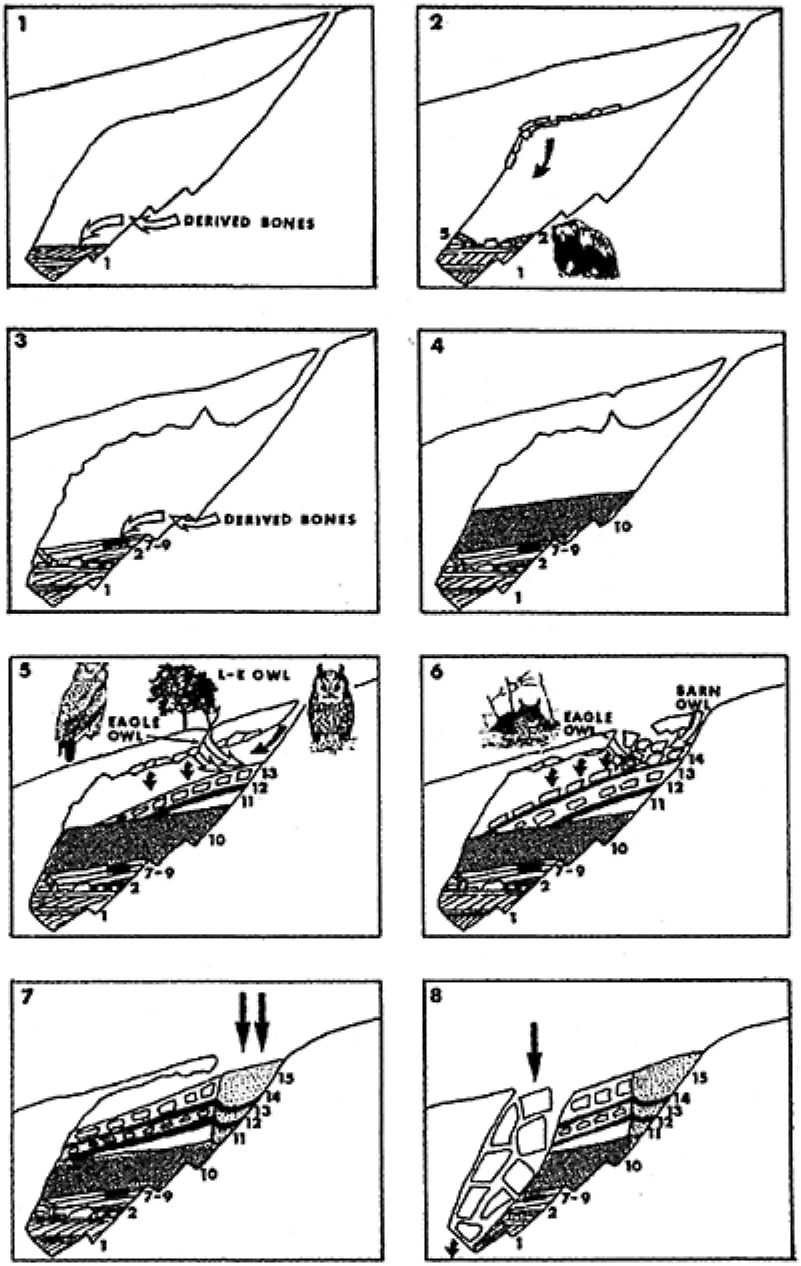
The third way of entry of bones into caves is when transported by predators. The predators either live in the caves and accumulate prey remains in their pellets or scats, carry prey individuals into the cave and discard bones uneaten, or they may live just outside the cave and their prey remains either fall in or are carried in by another process. For example, partly eaten remains of bovids have been found in African caves, left over from leopard kills and rabbit remains have been found in Devon caves, brought in by foxes. In one unusual case, the abundant remains of porpoises were found in a cave formerly inhabited by striped hyenas in Qatar (Andrews & Whybrow, 2003). Some species of owl and diurnal raptors also shelter in caves, and their droppings contain extremely rich remains of their small mammal prey. The remains of the predators themselves may be present in the caves in which they lived, but their absence cannot be taken as evi dence for absence of these predators. For example, several different predators have been identified as living at different times in the caves at Westbury-sub-Mendip, Somerset, by analysis of their prey remains (Andrews & Ghaleb, 2000).

The fourth way of entry is transport by water, gravity, etc. A model for this was provided for Swildons Hole, a modern cave in Somerset (Andrews, 1990). Bones from a bovid were found in a blind chamber on top of a talus cone in the process of accumulation beneath an which communicated to the surface above through a narrow crack. On the surface was a deep doline, caused by the gradual movement of soil down into the chamber below, and it is inferred that the bones were carried with the soil over a period of 850 years. Movement can be much more rapid, as in the cavern collapse at GB cave, Somerset, when heavy rain caused the collapse of about 4000 m^3 of surface sediment and soil into an underground chamber. Water transport of sediment and bone into caves has also been documented for several levels in the Westbury sequence.

Bone Modification in Caves

The method of entry into caves clearly affects the degree to which bones may be modified. In the first case listed above, of animals living and dying in caves, it is apparent that initially they will be preserved as whole skeletons. Where there is free access to the cave, however, scavengers may enter the cave (some may even live there) and they may destroy much of the material. This is generally the case with large mammals dying in caves; for example, hyenas scavenged the leopard kills in the East African caves at Mount Suswa, but the mammals brought into the South African caves by leopards were still intact, since no scavenger had found them. Smaller animals may be scavenged as well, and even in the case of the large bat accumulations mentioned above, some of the bones may be modified, even destroyed, by insect action and fungal/bacterial decay. For small mammals, however, it remains the case that natural accumulations such as this may be distinguished from predator assemblages by. their greater completeness and relative lack of modification. For example, in Wookey Cave, Somerset, a barn owl assemblage or-dispersed rodent bones, some showing evidence of digestion (see below), was found with some incomplete but still articulated bat skeletons which showed no evidence of digestion. The latter were clearly derived from bats living in the cave and dropping to the floor of the cave when they died and their bones becoming mixed with the owl prey bones (Andrews, 1990).

There may be other factors operating as well to disperse or otherwise modify the bones from natural deaths in caves. By their very nature, caves have restricted areas compared with land surfaces above, and animals moving about the cave, whether scavengers or later entrants into the cave, trample, break, and scatter the bones of earlier deaths. Rock falls and sediment



Paleontology: Animal Remains in Caves: Figure 2. Summary of the taphonomy of one of the caves at

Westbury-sub-Mendip, shown in 8 stages from bottom to top, numbered 1 to 8 top left of each figure. **1.** Deposition of water-transported sands and gravels, generally lacking fossils. **2.** Major collapse of roof-fall blocks onto the surface of the eroding sands; occupation of the chamber by all-male groups of cave bears in units 2 and 5. **3.** Further accumulation of water-transported sediments with local pockets of water-transported fossils in unit 8. **4.** Silts and sands of unit 10, with dispersed fauna throughout and concentration of bat remains at the top, derived from bats living in the cave. **5.** Formation of cave breccias of units 11 to 13, with multiple sources of sediments (black arrows) and fossils (open arrows); large mammals may have been transported into the cave along with the sediment, but the small mammals were the product of eagle owl and long-eared owl predation. **6.** Formation of cave breccias of unit 14 and lower subunits of unit 15 infilling space between roof fall blocks; origin of sediments and fossils as before, with the predators being barn owls and eagle owls; at this time the roof of the chamber was largely destroyed. **7.** Formation of the upper subunits of unit 15, now probably exposed to the open air, so that the fossil accumulations cover a greater area. **8.** The final stage came with the collapse of the sediments along one side of the cave, down into a chamber below, and the infill of the void thus left by loosely consolidated infill breccias, indicated by the vertical arrow. The numbers refer to unit numbers, the black arrows indicate source and direction of the sediments and the open arrows indicate source and direction of the fossil bones.

pressure may also produce breakage, and the result is that most bones in caves become broken and scattered, even if originally they were present in the cave as entire animals. The very high humidity within caves and its changes, the acidity or alkalinity of water, and dripping water may also further corrode the bones.

Animals trapped by pitfalls also enter the cave entire, and in this case they more often remain in one piece since the structure of the cave prevents entry by scavengers. This is not always the case, however, for scavengers may be tempted in and then cannot get out again, and in this case the damage to bones may be extreme as the scavengers are driven by hunger to consume as much of the skeleton as they can. The other factors mentioned above come into play as well: trampling, sediment movement, and corrosion.

Predation is both the most important cause of death in mammal faunas and the cause of their greatest modifications. Many predators live in caves, and numerous examples are known of owls roosting in caves (Andrews, 1990, Avery, 2001), and larger predators such as hyenas and leopards living and hiding their prey in caves (Maguire *et al.*, 1980). The amount of bone present and the species representation in prey assemblages vary from predator to predator but are always biased with respect to the community from which they came. The important issue is how to identify the predator and hence the probable bias, but the relationship of prey to predators is highly complex and is dependent on several unrelated factors. Predator size, for example, is related to prey size, but it varies with seasonal and annual cycles of climate, habitat, and prey populations, but predator adaptability and ability to learn may offset the impact of these cycles. Independent of these factors is the potential difference in activity patterns between predator and prey, so that nocturnal and diurnal predators hunting the same area may produce completely different prey assemblages. Because of these variations in predator/ prey relationships, neither the size of the prey nor the species preyed upon are diagnostic of any single predator species.

The biases produced by predators as a result of their hunting and selective behaviour can be interpreted and allowed for if the identity of the predator is known (Andrews, 1990). It has been found that different predators produce specific patterns of bone modification of their prey, so that it is sometimes possible to predict predator species from the consideration of modifications to the bones making up faunal assemblages. Bone breakage in prey assemblages may be diagnostic of certain predators but not of others; but bone digestion is the most diagnostic feature, although here too it is not possible to distinguish all predator species. Degree of digestion also varies between predators according to their state of hunger and their maturity.

Several Pleistocene cave faunas have been analysed based on these criteria, in order to identify their modes of accumulation (Figure 2). The long cave sequence at Westbury-sub-Mendip has been shown to have faunas accumulated by barn owls, eagle owls, and long-eared owls (Andrews, 1990). The equally good sequence at Dolina cave, one of the Atapuerca caves in Spain, has similarly been shown to have faunas accumulated by an eagle owl, tawny owl, and an unidentified species of small mammalian carnivore (Fernandez-Jalvo & Andrews, 1992). In both cases there were additional modifications that went some way towards obscuring these patterns, but despite additional breakage, extensive cave corrosion, and in one case weathering (at the top of the Westbury sequence where the roof had fallen in), the original evidence of the predator damage was still apparent.

In the final method of entry of bones into caves, the association of bones with water-lain sediments and the presence of abrasion of bone surfaces, provide evidence of transport. Large mammal bones have been found deep inside caves in Wales and in Swildon's Hole, Somerset, where they were washed in by streams flowing through the caves. An example from the fossil record comes from the Westbury cave again (Andrews, 1990). Two of the major units were formed as part of a series of mudflows brought into the cave from outside, and the mammal fossils are dispersed in it. Some of the bones entered the cave with the mudflow, and some were the result of cave bear occupation in or near this part of the chamber. Carnivore damage is moderately common, with some of the bones being highly modified. The bone is rounded and extremely broken. Human presence is indicated by cut marks on a few of the bones.

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Works Cited

Andrews, P. 1990. *Owls, Caves and Fossils: Predation, Preservation, and Accumulation of Small Mammal Bones in Caves, with an Analysis of the Pleistocene Cave Faunas from Westbury-sub-Mendip, Somerset, UK,* Chicago: Chicago University Press

Andrews, P. & Ghaleb, B. 2000. Taphonomy of the Westbury Cave bone assemblages. In *Westbury Cave,* edited by P.Andrews, J. Cook, A.Currant & C.Stringer, Bristol: Western Academic and Specialist Press

Andrews, P. & Whybrow, P. 2003. A striped hyaena den site in Qatar, United Arab Emirates. *Préhistorie, Anthropologic Méditerranéenes*

Avery, D.M. 2001. The PlioPleistocene vegetation and climate of Sterkfontein and Swartkrans, South Africa, based on micromammals. *Journal of Human Evolution,* 41:113–32

Balch, H.E. 1914. *Wookey Hole, its Caves and Cave Dwellers,* London and New York: Oxford University Press

Brain, C.K. 1981. *The Hunters of the Hunted? An Introduction to African Cave Taphonomy,* Chicago: University of Chicago Press

Deacon, H.H. 1979. Excavations at Boomplaas Cave: A sequence through the Upper Pleistocene and Holocene in South Africa. *World Archaeology,* 10:241–57

Fernandez-Jalvo, Y. & Andrews, P. 1992. Small mammal taphonomy of Gran Dolina, Atapuerca (Burgos) Spain. *Journal of Archaeological Science,* 19:407–28

Klein, R.G. 1975. Middle Stone Age man-animal relationships in southern Africa: Evidence from Die Kelders and Klasies River Mouth. *Science,* 190:265–67

Maguire, J., Pemberton, D. & Collett, N.H. 1980. The Makapansgat limeworks grey breccia: Hominids, hyaenas, hystricids or hillwash. *Palaeontologia Africana,* 23:75–98

Pinto, A.C. & Andrews, P. 2003. *Taphonomy and Palaeoecology of Bears from N.Spain,* Oviedo, Spain: Fundacion Oso de Asturias

Sutcliffe, A.J. 1955. A preliminary report on the reindeer remains from Banwell Bone Cave. *Journal of the Axbridge Cave Group Archaeological Society,* 2:36–40
White, J.A., McDonald, H.G., Anderson, E. & Soiset, J.M. 1984. Lava blisters as carnivore traps. In *Contributions in Quaternary Vertebrate Paleontology: A Volume in Memorial to John E. Guilday,* edited by H.H.Genoways and M.R.Dawson, Pittsburgh: Carnegie Museum of Natural History

Further Reading

Stiner, M.C. 1994. *Honor Among Thieves: A Zooarchaeological Study of Neandertal Ecology,* Princeton, New Jersey: Princeton University Press
Kurtén, B. 1976 *The Cave Bear Story: Life and Death of a Vanished Animal,* New York: Columbia University Press

PALEOTECTONICS FROM SPELEOTHEMS

Over the last few decades, seismotectonic studies of speleothems have proved that broken speleothems and actively growing stalagmites are the most powerful tools for the quantitative and chronological reconstruction of seismotectonic events over the last 500000 years (Forti, 1999). The first person to suggest that speleothems may record earthquake activity was Becker (1929), who proposed the idea after studies of Bing Cave in Germany. Nevertheless, until the 1980s, geophysicists did not give serious consideration to the method because it was impossible to discriminate between the fracturing of speleothems by earthquakeinduced effects and that caused by other mechanisms. However, improvements in sampling and statistical analysis now allow the paleotectonics of karst areas to be reconstructed, using not only broken speleothems but also actively growing stalagmites. They may be used as a tool for the detection of ancient earthquakes, and the relative and absolute dating of seismotectonic activity, the determination of its magnitude, and for improving general seismic hazard evaluation. The dating of speleothems is described in Paleoenvironments: Speleothems.

Detection of Ancient Earthquakes using Broken Speleothems

Caves in seismically active areas may contain broken and collapsed speleothems, but before it can be determined that broken speleothems are really related to earthquakes, all other factors must be discounted. The more common natural causes of speleothem breakage are: (1) An increase in the weight loading of stalactites growing from porous or highly fractured ceilings; (2) Sliding of stalagmites, columns, and flowstones along unconsolidated walls and floors; and (3) The presence of ice tongues during glaciation.

The morphology of the breakages can help to determine their cause: several types of breakage are caused only by tectonic stresses (Figure 1), the most characteristic being the perfect breakage of stalagmites along subhorizontal planes. This unusual type of breakage can be explained by the resonance induced by high-frequency seismic waves. Another sign of seismic activity is the presence of consistent speleothem breakage in certain directions. The preferential azimuths of the collapsed stalagmites normally coincide with the main structural directions in the cave area. However, it is often difficult to use this type of analysis, because it is virtually impossible to be sure that broken speleothems still retain their pre-earthquake orientation. Breakages resulting from seismic activity may also be distinguished from non-seismic breakages by a statistical analysis of their ages as the dates of earthquake-induced breakages tend to be grouped together at around the same time.

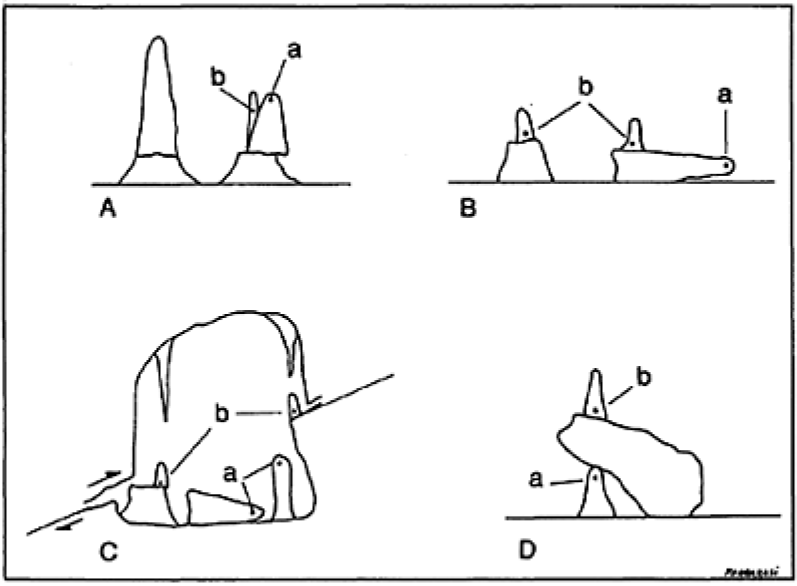
Estimating Earthquake Magnitude

Some seismic-induced breakages (e.g. A and B of Figure 1) may also provide data for evaluating earthquake accelerations, thus making it possible to define both the epicentre and the magnitude of the event. The method is similar to that used by geophysicists studying the effect of earthquakes on tombstones (Post-pischl *et al.*, 1991). The stalagmite itself is considered to be a homogeneous cylinder, perfectly connected to the floor, with its breakage being caused by resonance induced by the earthquake, and with the ratio of the diameter/height of the broken stalag mite being related to the horizontal acceleration of the seismic waves (which, in turn, is affected by the distance from the epicentre and the magnitude). Although this appears to be simple from a theoretical point of view, performing such a study is very complex because real stalagmites are very different from the model of a homogeneous cylinder, perfectly attached to the floor of the cave.

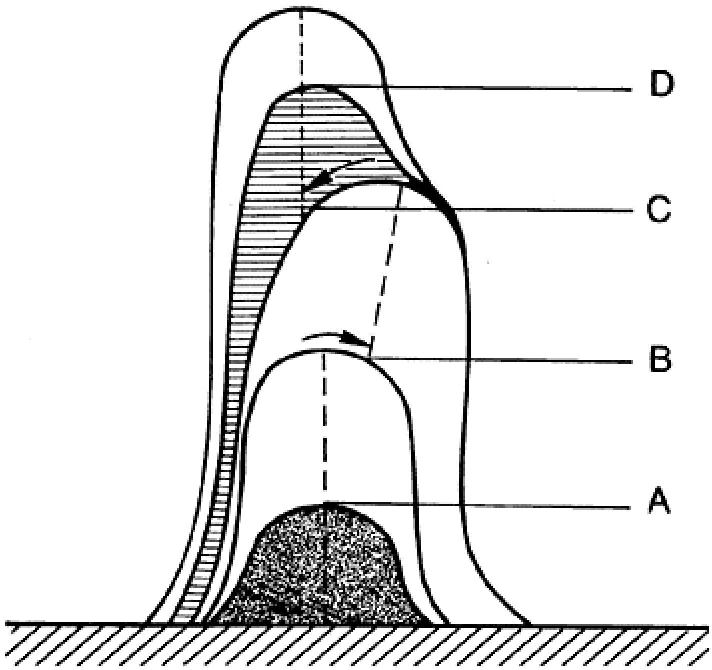
Actively Growing Stalagmites

Seismotectonic information may also be extracted from stalagmites that are still being deposited. Schillat (1977) considered the stalactite-drip-stalagmite system to be a "recording pendulum", in which the stalagmite, with its successive growth layers, acts as a recorder of the "actual verticality". A polished section along the growing axis of a stalagmite normally shows well-marked, symmetrical growth layers. Ideally, this axis records the vertical direction, which, if stable over time, should be a rectilinear segment. In reality, progressive and/or sudden variations in the growth axis can be found in many stalagmites, associated with environmental conditions in the cave itself, or associated with tectonic events. However, there are also many speleological factors which may affect the orientation of the stalagmite growth axis, for example: (1) permanent air currents; (2) migration of the dripping point along a fracture; and (3) gravity sliding of the stalagmite over unstable material.

In order to rule out these local effects, it is necessary to perform a statistical analysis of a large number of stalagmites. A three-dimensional analysis of the stalagmite growth axis enables the reconstruction of the tectonic movements experienced by



Paleotectonics from Speleothems: Figure 1. Characteristic breakage of speleothems, induced by seismic stress. Resonance-induced stalagmite fractured along a subhorizontal plane: (A) the upper part is still standing on its base, being only slightly translated and/or rotated from its original position; (B) the broken upper part lies on the floor close to its base; (C) stalagmite collapse caused by the displacement of the adjacent wall; (D) new stalagmite growing over a fallen rock, which covered an older stalagmite. Positions (a) and (b) indicate characteristic sampling points for absolute (U/Th and/ or ^{14}C) dating of deposits which occurred just before (a) or after (b) the seismic event.



Paleotectonics from Speleothems: Figure 2. Evidence of earthquakes as seen in the inner structure of a stalagmite: i.e. sudden and sharp vertical changes in the stalagmite axis (B & C) and abrupt variations in the texture, colour, and chemical composition of the growing layers (A, C, & D) may be induced by seismic shocks.

the speleothem, and the order in which they occurred. This may be converted into a chronology using absolute dating.

The above-mentioned data on tectonic movements are not the only information that can be obtained from stalagmites—they may also provide records of the major earthquakes that hit the cave area. In many cases the vertical polished section of a stalagmite shows some clear discontinuities in the growth axis (Figure 2). Such discontinuities may be abrupt vertical variations and/or sharp changes in colour or texture, both of which can reveal the occurrence of an earthquake if local factors are excluded. By applying this method to two different gypsum caves, Forti & Postpischl (1986) reconstructed the seismic history of Bologna (Italy) over the last 1200 years with an average error of±11 years.

Seismic Hazard

The evaluation of the seismic hazard for a given area is normally based on its seismic history, which can rarely be known for more than two thousand years. Clearly this span of time is too short to determine the possible magnitude of the strongest earthquake that might hit a particular region in future. By using seismic analyses of speleothems it is possible to recognize and date strong paleo-earthquakes up to the limits of radiometric dating methods, which presently exceed 500000 years.

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Works Cited

Becker, H.K. 1929. Höhle und Erdbeben. *Mitteilungen Über Höhlen- und Karstforschung,* 14:130–33

Forti, P. 1999. Evidencias tectónicas y sísmicas a partir del estudio de espeleotemas: conocimiento actual y desarrollo futuro. In *The Scientific Study of Karstic Cavities as a Contribution to Geological Knowledge, Proceedings of the Geology Symposium Nerja Cave (Malaga, Spain), June 17–20,* edited by B.Andreo, F.Carrasco & J.J.Durán, Nerja, Malaga: Patronato de la Cueva de Nerja, Instituto de Investigación

Forti, P. & Postpischl, D. 1986. May the growth axes of stalagmites be considered as recorders of historic and prehistoric earthquakes? Preliminary results from the Bologna karst area. *Proceedings of the International Symposium on Engineering Problems in Seismic Areas,* vol. 1, Bari, Italy: Istituto di geologia applicata e geotecnica, Università di Bari

Postpischl, D., Agostini, S., Forti, P. & Quinif, Y. 1991. Palaeoseismicity from karst sediments: the “Grotta del Cervi” cave case study. *Tectonophysics,* 193:33–44

Schillat, B. 1977. Conservation of tectonic waves in the axes of stalagmites over long periods. *Proceedings of the 7th International Speleological Congress,* edited by T.Ford, Sheffield: BCRA

Further Reading

Quinif, Y. (editor) 1998. Karst & Tectonics: Proceedings of the International Symposium—Han’98, *Spéléochronos* hors-série, Fac. Polytecnique de Mons, Belgium

PALYNOLOGY

Palynology, the study of microscopic organic matter known as palynomorphs (Traverse, 1988), offers enormous potential in karst research since it can provide important evidence about ancient environments. The most commonly studied palynomorphs are pollen and spores, but also important are algal microfossils, dinoflagellate cysts, fungal spores, cyanophyte phycomas, amoeboid cysts, and a variety of other remains which can be lumped under the general name of kerogen and analysed using palynofacies analysis. Apart from the limestones and evaporites themselves, which sometimes contain palynomorphs coeval with their deposition, two important types of sites are available for palynological study in karst terrains: closed depression fills and cave fills.

Understanding of taphonomy (the production, transport, deposition, and preservation of fossils) in karst depositional systems is still developing. Sediments in karst systems may be highly oxidized and/or subject to repeated wetting and drying. These are inimical to the preservation of organic matter. Organic matter in karst depositional systems is therefore often poorly preserved. However, good to adequate preservation of organic matter will occur where the oxygen supply is limited through rapid burial or waterlogging, or where desiccation prevents bacterial activity.

Closed depression (doline, uvala, or polje) fills offer what is often the only available evidence for past vegetation patterns in many karst areas. Often the closed depression contains, or has contained, permanent water, thus enabling palynomorphs to be preserved by waterlogging and anoxia. Palynological studies of doline fills have been carried out for many karst areas, for instance in Ireland (Coxon & Flegg, 1987). These doline fills provide virtually the only evidence for late Tertiary and early Pleistocene vegetation in Ireland and hence are of enormous importance. In arid countries, for instance in the Libyan desert, pollen was preserved by desiccation in a closed depression fill at Grerat-es-Salam (Gilbertson *et al.,* 1994).

Palynomorphs enter caves in a diversity of ways. The flora in cave mouths is usually distinctive and of low diversity, often dominated by ferns, and this flora has an impact on cave pollen assemblages. In the entrance facies of most caves and throughout those caves where there is a vigorous circulation of air, much pollen arrives through the air (Genty, Diot & Oyl, 2002). In caves where there is a diurnal circulation, fern spores, which are shed nocturnally, are carried into the cave at night by air currents entering the cave at low level. This, plus the dominance of ferns in many cave entrance floras, may account for the high incidence of fern spores in many cave deposits (Coles *et al.,* 1990). Palynomorphs may also be recycled by wind, for instance as a component in loess; they may be recognized as having been reworked by being ecologically and chronologically mixed.

Other mechanisms are also important. Some percolation water is reputed to carry significant amounts of pollen into caves, although rigorous experiments by a number of authors (e.g. Genty, Diot & Oyl, 2002) has shown that this is comparatively unusual. Pollen has been documented to have been carried over 5 km in streamways and it is also likely that pollen sometimes enters caves via mudflows. Pollen may be carried by mammals and birds on their fur/feathers or in their gut contents. For example, a single vole may carry several thousand pollen grains in its fur during the flowering season. Pollen has been found in animal dung in a number of caves, for instance in the American Midwest and Libya. Insects may also carry significant amounts of pollen into caves. Ground-nesting bees carry significant amounts of Compositae pollen into some southern European cave fills and in Sarawak burrowing wasps introduce enormous quantities of pollen into some cave deposits.

Once it is within the cave system, pollen may be preserved in clastic sediments and flowstones. Very often rapid deposition of clastics or flowstone dilutes the pollen so that it is extremely sparse, often no more than five pollen grains per gram. It is clear from a number of studies that, once the effects of entrance floras have been allowed for, cave pollen assemblages are similar to those of the immediately adjacent local pollen rain or to Quaternary deposits of equivalent age (e.g. Coles *et al.,* 1990).

The first palynological study of cave sediments was undertaken by Schutrumpf (1939). Subsequently, cave pollen studies have been carried out in many karst regions. Many of the early studies, including Schutrumpf's, were undertaken to correlate cave sediments with external sequences and thus provide a measure of dating. With the rise of radiometric dating, the objective of many studies became explicitly paleoenvironmental, although correlation using palynology is still undertaken where datable materials are absent, chronological resolution is poor, or the sediments are beyond the range of radiometric tools. A good example is the use of palynology to date paleokarst fills in southwest England as being Rhaetian in age. Notable research on pollen in speleothems, with complementary dating by radiomet ric methods, has been carried out in Belgium by Bastin (1990). Palynology is an integral part of many archaeological investigations in caves, since it provides a picture of the flora close to the cave and thus enables environmental and climatic reconstruction. Occasionally, palynology provides important behavioural evidence. The most famous case of this is still Arlette Leroi-Gourhan's (1975) palynological evidence for the burial of bunches of flowers with the body of a young Neanderthal girl in Shanidar Cave, Iraq, around 70000 years ago (see Shanidar Cave: Archaeology).

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Works Cited

Bastin, B. 1990. L'analyse pollinique des concretions stalagmitiques: méthodologie et résultats en provenance des grottes belges. *Karstologia Mémoires,* 2:3–10

Coles, G.M., Gilbertson, D.D., Hunt, C.O. & Jenkinson, R.D. 1990. Pollen taphonomy in caves. *Cave Science,* 16:83–89

Coxon, P. & Flegg, A. 1987. A Late Pliocene/Early Pleistocene deposit at Pollnahallia, near Headford, Co. Galway. *Proceedings, Royal Irish Academy,* 87B:15–42

Genty, D., Diot, M.-F. & Oyl, W. 2002. Sources of pollen in stalactite dip water in two caves in southwest France. *Cave and Karst Science,* 28(2):59–66

Gilbertson, D.D., Hunt, C.O., Feiller, N.R.J. & Barker, G.W.W. 1994. The environmental consequences and context of ancient floodwater farming in the Tripolitanian pre-desert. In *Environmental Change in Drylands: Biogeographical and Geomorphological Perspectives,* edited by A.C.Millington & K. Pye, Chichester and New York: Wiley: 229–51

Leroi-Gourhan, A. 1975. The flowers found with Shanidar IV, a Neanderthal burial in Iraq. *Science,* 190:562–64

Schutrumpf, R. 1939. Die pollenanalytische Datierung der Altsteinzeitlichen Funde von Mauren. *Das Ahnenerbe, bericht über die Kieler Tagung 1939 der Forschungs und Lehgemeinschaft*

Traverse, A. 1988. *Paleopalynology,* Boston: Unwin Hyman

Further Reading

Baker, A, Caseldine, C.J., Hatton, J., Hawkesworth, C.J. & Latham, A. 1997. A Cromerian complex stalagmite from the Mendip Hills, England. *Journal of Quaternary Science,* 12(6): 533–37

Bastin, B. 1978. L'analyse pollinique des stalagmites: une nouvelle possibilité d'approche des fluctuations climatiques du Quaternaire. *Annales de la Société Géologique de Belgique,* 101: 13–19
Carrión, J.S., Munuera, M., Navarro, C., Burjachs, F., Dupré, M. & Walker, M.J. 1999. The palaeoecological potential of pollen records in caves: The case of Mediterranean Spain. *Quaternary Science Reviews,* 18(8–9):1061–73
Hunt, C.O. & Gale, S.J. 1986. Palynology: A neglected tool in British cave studies. In *New Directions in Karst,* edited by K. Paterson & M.M.Sweeting, Norwich: GeoBooks: 323–32
Navarro, C., Carrión, J.S., Navarro, J., Munuera, M. & Prieto, A.R. 2000. An experimental approach to the palynology of cave deposits. *Journal of Quaternary Science,* 15(6):603–19
Marshall, J.E.A. & Whiteside, D.I. 1980. Marine influence in the Triassic "uplands". *Nature,* 287:627–28

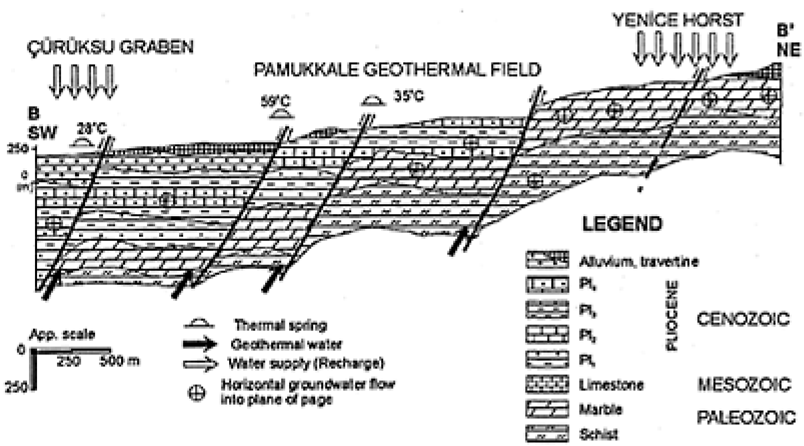
PAMUKKALE, TURKEY

The Pamukkale hydrothermal field is located in western Turkey, a region of intense vertical tectonism that commenced in the Upper Miocene with the formation of horst and graben structures (see map in Turkey entry for location). Since later tectonic movements have modified the fracture patterns and enhanced the anisotropic permeability, there are four reservoirs in the Pamukkale hydrothermal system: Paleozoic marble, Mesozoic crystallized limestone, Pliocene limestone, and Quaternary travertine. Pliocene units of claystone, siltstone, marl, and sandstone act as an impermeable caprock in the system (see Figure).

The drainage area of the Pamukkale thermal springs is about 102 km^2 and the annual mean rainfall has been estimated to be 881 mm using rainfall-altitude relationships. The isotopic characteristics of the thermal waters show that they possess almost the same deuterium composition as that of local meteoric water. Hence, the water constituting the thermal fluid is of a predominantly meteoric origin. The cold fluid, circulating through faults and fractures, is heated by magmatic intrusions at great depth, and ascends from deep reservoirs to the surface. Discharge takes place along fault systems that appear to follow the northern margin of the Çürüksu graben, but some thermal springs are also present in the Çürüksu valley. Hydrochemical surveys have shown that the chemical and physical characteristics of the thermal waters are affected by cooling, dilution, and mineral deposition as they ascend, because the interaction with relatively cold groundwater becomes prominent in the near-surface zone (Figure). The combined discharge of the Pamukkale thermal springs is about 385 $1\ s^{-1}$. However, recession curve analysis indicates an estimated active annual reservoir capacity of 16 x 10^6 m^3 and this corresponds to a discharge rate of 510 $l\ s^{-1}$. Günay *et al.* (1997) suggested that the excess (125 $l\ s^{-1}$) could be abstracted from the aquifer for recreational purposes at the site or to enhance travertine formation.

The thermal springs are issued at 35°C and a pH of 5.6. They exhibit a calcium-bicarbonate-sulfate composition with total dissolved ions of 2300 mg l^{-1}. The temperature and chemistry of individual thermal springs are more or less constant through time, indicating that thermal systems develop chemical compositions in equilibrium with the reservoir rocks. The thermal springs have very high carbon dioxide concentrations and the source of this gas is thought to be the decomposition of marine carbonate rocks. Experiments on calcium carbonate precipitation kinetics at the travertine site show that as the thermal water runs over the surface rapid carbon dioxide outgassing occurs, and as a result the water becomes highly supersaturated with respect to calcium carbonate, which then precipitates as the travertine terraces for which Pamukkale is famous. Age estimations show that travertine deposition started during the late Pleistocene.

The five principal morphological types of travertine formation at Pamukkale are (1) terraced mounded travertine, (2) fissure-ridge travertine, (3) range-front travertine, (4) eroded-sheet travertine, and (5) self-built channel travertine (Altunel & Hancock, 1994). The total area of these travertine types is about 10 km^2. The beautifully ornate architecture of the travertine terraces consists of a curving and steeply raked, or overhanging, ramp of overlapping cup-shaped pools on all scales from a few centimetres to a few metres. Small-scale terraces tend to be initially constructed where thermal water becomes turbulent as it flows over or around the obstructions, such as at breaks of slope, leaves,



Pamukkale, Turkey:
Hydrogeological cross-section of the Pamukkale geothermal field (vertical scale bar represents the topographic relief).

twigs, pebbles, or wall-like self-built channels. As long as water continues to flow over the terraces they grow higher and their maximum development occurs where there is a series of pools separated by rims of travertine (Altunel & Hancock, 1994). The morphology of the rimstone pools was studied by Ekmekçi *et al.* (1995) who found that flow regime strongly affects the grading from micro-terraces to flowstone.

The oxygen-18 and deuterium stable isotope values of the thermal waters range from −9.42 to −8.65 ‰ and −59.7 to −57.1 ‰, respectively. The tritium concentration varies between 0.8 and 4.5 tritium units (TU) because of mixing with shallow cold groundwater. Since all the thermal waters are immature, an indication of the reservoir temperature is provided by the solubility of silica minerals. Chalcedony solubility gives an equilibrium temperature in the range 63–93°C.

The existence of the thermal springs and white travertine terraces, together with the cultural ruins of the ancient city of Hierapolis, attract many visitors to Pamukkale and in 1988 UNESCO declared the area a Natural and Cultural World Heritage Site and inscribed it on the World Heritage list. Unfortunately, with the increasing numbers of tourists, and the development of tourist facilities, serious environmental problems became apparent. The main causes of damage were uncontrolled walking over the delicate travertine surface; swimming in thermal springs; intensive and uncontrolled excavations including wells; vehicle entry to the site; sewage leaking from non-isolated cesspools; and waste storage in karstic features. In an attempt to reduce the damage the Pamukkale Preservation and Development Plan was published in 1992 by the Governorship of Denizli, Ministry of Culture, and UNESCO. The scope of this plan was to create more suitable protection activities for the natural and archaeological assets (Dilsiz, 2002).

The main objectives of this ongoing project are to determine the nature of the hydrologic and thermal flow systems; to describe the hydrochemical characteristics of the springs; to identify carbonate mineral dissolution and precipitation reactions; to perform environmental studies to prevent pollution in and around the thermal springs and travertine area; and to increase both the yield of the thermal waters and the area of white travertine. Covered concrete channels were constructed to prevent the loss of thermal water and further pollution along the water path, and water outlets in the thermal spring zone were protected by concrete structures. A series of concrete terraces, imitating the natural morphology, were constructed through the old asphalt road with the aim of encouraging new deposition of travertine (Dilsiz, 2002). Despite the many studies that have been conducted or are still in progress, the site is still at risk. Hence, it is essential that special regulations and laws should be enacted soon to ensure permanent protection of the natural assets in Pamukkale.

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See also **Travertine**

Works Cited

Altunel, E. & Hancock, P.L. 1994. Morphology and structural setting of Quaternary travertines at Pamukkale, Turkey. *Geological Journal,* 28:335–46

Dilsiz, C. 2002. Environmental issues concerning natural resources at Pamukkale protected site, southwest Turkey. *Environmental Geology,* 41:776–84

Ekmekçi, M., Günay, G. & Şimşek, Ş. 1995. Morphology of rimstone pools at Pammukale, western Turkey. *Cave and Karst Science,* 22:103–06

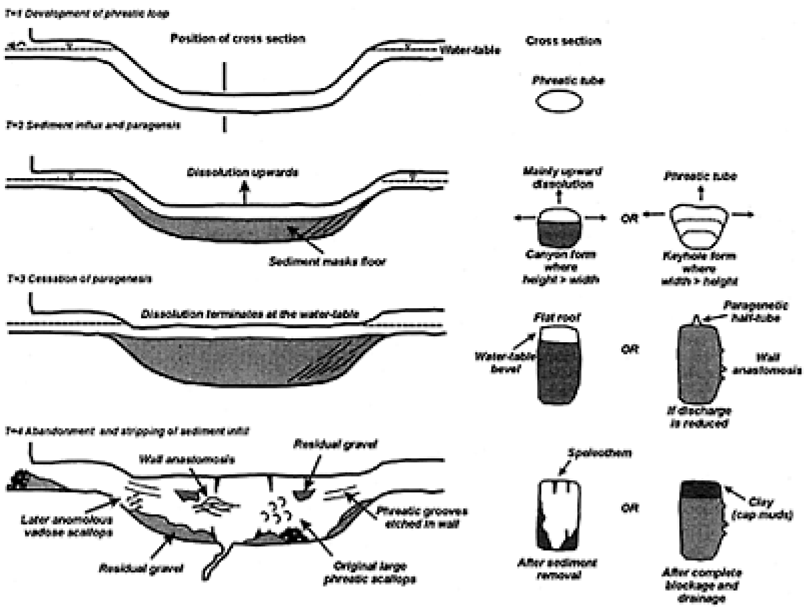
Günay, G., Şimşek, Ş., Ekmekçij. M., Elhatip, H., Yeşertener, C., Dilsiz, G. & Çetiner, Z. 1997. Karst hydrogeology and environmental impacts of Pamukkale thermal springs. In *Karst Waters & Environmental Impacts,* edited by G.Günay & A.I. Johnson, Rotterdam: Balkema

PARAGENESIS

Paragenesis is the term introduced by Renault (1968) to describe the processes by which cave genesis within the phreatic zone is modified by influxes of sediment. True paragenesis occurs in the phreatic zone when influxes of sediment armour the floor and lower walls of a passage, concentrating dissolution upwards and thereby creating a distinctive passage morphology.

In the absence of any clastic sediment, the process of dissolution will produce a continuous increase in the cross-sectional area of a cave passage; unlike a surface stream excavated in sediment in. which the channel will expand in area to some limit (normally the "bankfull flood" stage) and then stabilize. Paragenesis is, in a sense, the equivalent happening in a phreatic conduit after it has undergone the basic expansion needed to handle flow up to "bankfull equivalent". As a phreatic passage enlarges by dissolution, the cross-sectional area increases and the average flow velocity decreases, favouring deposition of any transported sediment. Thus the average flow velocity is held constant at the threshold of sediment transport. Since sediment deposition generally occurs on the passage floor, the passage enlarges upwards (and often migrates laterally) over time; creating a high phreatic canyon, terminating only at the water table (Ford & Ewers, 1978). Although most dissolution occurs upwards, Groves, Vaughan & Meiman (1998) demonstrated that acidic water and dissolution still occur within the saturated sediment, although the total solute flux is much reduced. Dissolution takes place within the sediment and on the bedrock floor and walls, but it is very small in comparison with that in unshielded flow!

A clear distinction should be made between paragenesis *sensu stricto* and vadose entrenchment followed by alluviation. Both processes may result in sediment-filled canyon passages but the geomorphic and hydrological implications of these two possible origins are radically different. Palmer (2000) argues the case for vadose incision followed by aggradation in Mammoth Cave (Kentucky), as many of the passages observed do not fit the criteria for true paragenesis. However, even alluviated passages often display some minor paragenetic modification, including small anastomosing half-tubes cut into passage walls and ceilings by water flow within the saturated sediment. Indeed, some passages may originate as vadose canyons, become alluviated, and continue to evolve paragenetically, creating a two-phase passage. Where such passages can be observed it is because the sediment



Paragenesis: Schematic paragenetic evolution of a phreatic conduit (elevation and cross section) under conditions of high sediment flux and on abandonment. T=1: Development of a phreatic loop prior to sediment aggradation. T=2: Sediment influx and the initiation of alluviation and paragenetic erosion. T=3: Continued sediment influx and termination of upwards paragenetic erosion at the water table. T=4: Abandonment and subsequent stripping of sediment by vadose dripwaters, revealing passage morphology.

was subsequently flushed out to render the passage accessible. The downstream portion of Thomas Avenue in the Mammoth Cave system is an excellent example where canyon infilling terminated, with the stream carving very regular meanders into bedrock at a new water-table level. Several cycles of sediment aggradation, paragenesis, and sediment flushing may occur in a given cave, in response to base-level or climatic fluctuations, or to avulsions in stream channels on clastic rocks upstream of the caves.

Paragenetic passages can be recognized by a characteristic suite of features which distinguish them from either vadose canyons or more classic phreatic (i.e. "syngenetic") passages. In particular, paragenetic canyons may superficially resemble vadose canyons. However, they are morphologically and genetically distinct and can be distinguished from vadose canyons by several criteria. Vadose canyons often form part of a keyhole profile where the initial phreatic opening along a bedding plane is at roof level. In paragenetic canyons the opposite is true; the guiding fracture is at floor level. Paragenetic canyons meander in a similar fashion to vadose canyons except that the axis of the meander shifts progressively *upstream* against the direction of flow (Lauritzen & Lauritsen, 1995). Furthermore, there is often evidence for a complete sediment fill, with pockets of sediment preserved in alcoves or cemented by speleothem deposits. In addition, there are many instances where bedrock passage roofs rise and fall in synch with sediment bars on the floors underneath, the passage enlarging upwards to match the surface of the sediment profile beneath to maintain cross-sectional area.

As well as the gross passage form, several erosional morphological features can be identified, including paragenetic anastomoses, pendants, and half-tubes. Morphologically and genetically different from bedding plane anastomoses, these dissolutional features are formed by water flowing along the sediment—rock interface. Unlike bedding plane anastomoses they are not confined to a single bedding plane and can occur on vertical passage walls and ceilings. Paragenetic pendants result from an extreme form of anastamosis where the sediment carrying stream becomes braided and flow becomes confined into a series of channels etched into the roof, leaving isolated pendants between the channels. Paragenetic wall notches form at the level of the sediment floor and have the same gradient as the passage, and can either form in the vadose zone as a result of alluviation, or in the phreatic zone during true paragenesis. The latter often display a looping profile, mimicking the looping profile of the sediment floor, governed by the local channel bedload dynamics (Allen, 1970). In some passages, several vertically stacked grooves may be etched in the side of a single passage, marking successive positions of the sediment floor. 'Examples of vadose notches can be seen in many caves. Excellent examples occur in the Caves Branch caves of Belize (Ford, 2000b) and the Mulu caves, Sarawak. Here, notches relate to lateral incision following sediment deposition controlled by external alluvial fan aggradation at the resurgence (Farrant *et al.*, 1995). Another superb example occurs in the Nanisivik zinc-lead mine, Baffin Island (Ford, 1986; Olson, 1984) where a horizontal paragenetic notch 1 m high, 400 m wide, and 800 m long is host to sulfide ore deposits.

As described above, paragenesis can modify the internal passage morphology (Lauritzen & Lundberg, 2000), but can also modify cave patterns (Palmer, 2000), and long section geometry (Ford, 2000a). In looping cave systems, sediment accumulates in the base of phreatic loops where paragenetic dissolution of the ceiling erodes the passage upwards. This process combined with vadose incision over loop crests work together above and below the base level to reduce passage amplitude and create a water-table cave as the ultimate end product. Ford (2000a) described a classic example of this in the Swildons Hole streamway (see Mendip Caves). Bypass passages or anastomotic mazes can develop where downward loops become choked, increasing the hydraulic head across the obstruction, enabling otherwise insignificant fissures to be opened up.

The causes for sediment influx are varied and depend on the geomorphic, tectonic, and climatic location of the cave. Moreover, caves are dynamic features and many display evidence of one or more phases of sediment infilling. Sediment accumulation may be caused by a rapid decrease in stream transport capacity as a stream enters a low gradient cave; ponding in phreatic loops; external aggradation at the resurgence; or increased sediment flux into the cave following climatic change (or simply upstream channel avulsion, as noted above). In temperate caves, especially in northern Europe, massive sediment influxes are typically associated with a climatic deterioration at the beginning of a glacial stade and the onset of periglacial conditions. Interglacial weathering products are quickly stripped off and washed underground. Glacial deposition may block the outlets of preglacial caves, causing sediment aggradation and abandonment. In tropical regions, aggradation may be a result of climatic fluctuations, for example creating increased rainfall, increased erosion, and alluvial fan build up. Even slight rises in base level may cause alluviation and ultimately paragenesis of cave passage.

Clearly, the ability to observe these features requires the sediment fill to be partially or totally removed, either by natural geomorphic processes or by human actions such as quarrying or excavation in the search for new passage. Many caves display some evidence of either paragenetic development or subsequent modification. Its recognition is crucial as vadose and paragenetic passages have very different geomorphic and paleoclimatic implications, yet the true extent and significance of paragenesis and alluviation in speleogenesis and development is probably underestimated. This is partially because by their very nature, most paragenetic caves are flooded or choked with sediment and thus remain unexplored.

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See also **Morphology of Caves**

Works Cited

Allen, J.R.L. 1970. *Physical Processes of Sedimentation,* London: Allen and Unwin and New York: Elsevier

Farrant, A.R., Smart, P.L., Whitaker, F.F. & Tarling, D.H. 1995. Long term Quaternary uplift rates inferred from limestone caves in Sarawak, Malaysia. *Geology,* 23:357–60

Ford, D.C. 1986. Genesis of paleokarst and strata-bound zinc/lead sulfide deposits in a Proterozoic dolostone, Northern Baffin Island—a discussion. *Economic Geology,* 81(6):1562–63

Ford, D.C. 2000a. Speleogenesis under unconfined settings. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Ford, D.C. 2000b. Caves branch, Belize and the Baradla-Domica system, Hungary and Slovakia. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Ford, D.C. & Ewers, R.O. 1978. The development of limestone caves in the dimensions of length and depth. *Canadian Journal of Earth Sciences*, 15:1783–98

Groves, C.G., Vaughan, K. & Meiman, J. 1998. Carbonate chemistry of interstitial fluids within cave stream sediments. *Proceedings of the International Meeting of the International Geological Correlation Program, Project 379: "Karst Processes and the Global Carbon Cycle"*, Bowling Green, Kentucky

Lauritzen, S.-E. & Lauritsen, A, 1995. Differential diagnosis of paragenetic and vadose canyons. *Cave and Karst Science*, 21:55–59

Lauritzen, S.-E. & Lundberg, J. 2000. Solutional and erosional morphology. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W Dreybrodt, Huntsville, Alabama: National Speleological Society

Olson, R.A. 1984. Genesis of paleokarst and strata-bound zinc-lead sulphide deposits in a Proterozoic dolostone, northern Baffin Island Canada. *Economic Geology,* 70:1056–1103

Palmer, A. 2000. Speleogenesis of the Mammoth Cave system, Kentucky, USA. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Renault, P. 1967–68. Contribution a 1'étude des cations méchaniques et sédimentologiques dans la spéléogenese. *Annales de Spéleologie,* 22:5–21 & 209–67; 23:259–307 & 529–96; 24:317–37

Further Reading

Pasini, G. 1975. Sull'importanza speleogentica dell' "erosione antigravitativa". *Le Grotte d'Italia,* 4:297–326

Simms, M.J. 2001. *Exploring the Limestone Landscapes of the Burren and the Gort Lowlands,* Belfast: Burrenkarst.com

PATAGONIA MARBLE KARST, CHILE

The karsts of the Chilean Patagonia archipelago are the most southerly (50–52°S) and the most inhospitable on the planet, due to the extreme rainfall and strong winds. Alpine karst is well developed on the islands of Madre de Dios and Diego de Almagro, in the province of Ultima Esperanza (see America, South map). The archipelago is uninhabited except near Guarello Quarry (which has exploited lime since 1948 for the steel works at Talcahuano). Pure limestones are rare in Chile, and these partly calcareous islands were recognized in 1930–50 within an inventory of mineral resources (Biese, 1956). Cave and karst exploration, however, only began in 1995, with further expeditions in 1997 and 2000 (Maire, 1999).

The sedimentary rocks of the archipelago form part of the pre-Jurassic basement of the Andean cordillera. The limestones are bounded to the west by the Pacific Ocean and to the east by the Patagonian granite batholiths dating from the early Cretaceous, and are interbedded with volcanic sediments. The limestones and marbles of the Tarlton Formation, which is more than 500 m thick, date from the Carboniferous and Permian. They were formed as coral reefs, which settled on underwater volcanic intraoceanic mounts, forming atolls surrounded by bioclastic limestone formations.

The archipelago has an isothermic subpolar climate. The confrontation between the tropical anticyclones and the southern low pressures accounts for the climate of the "roaring forties". Precipitation reaches 7330 mm per year (80% rain, 20% snow) at the Guarello station, with an average of 611 mm per month. In the shelter of rock dolines and at the bottom of the cliffs, the magellanic forest of *Nothofagus,* inhabited by hummingbirds, constitutes one of the last primary forests in the world. It is similar to the equatorial cloud forests of New Guinea at altitudes of 3000–4000 m. The combination of wind and rain is the origin of a widespread hydro-aeolian karren not previously described. Tapered, parallel ridges 1–4 m long and 10–30 cm high, formed in the shelter of volcanic blocks deposited by glaciers (Figure 1).

Patagonia Marble Karst, Chile: Figure 1. Hydro-aeolian karren on Madre de Dios island. These aeolian ridges of limestone occur on the leeward sides of glacial volcanic rock fragments due to erosion by high-velocity wind and heavy rain. (Photo by R.Maire)

These forms of lateral differential dissolution are located on cols that are exposed to the northwesterly winds, where horizontal karren grooves are cut between them by dissolution in surface water pushed by the wind.

On the rock slopes, rillenkarren form small catchment areas with small deep canyons from 5 to 10 m deep, a true natural laboratory for studying regressive erosion by dissolution related to the slope and flow of water. Each stream leads to a streamsink cave, whose exploration is hazardous due to the frequent flood events. Littoral karren are very well developed, and there are remarkable staged notches of erosion, corresponding to glacio-isostatic uplift; 10–12 m on Diego de Almagro, and 4–8 m on Madre de Dios.

The rate of surface dissolution is 3 mm in 50 years (60 m^3 km^{-2} a^{-1}). It has been calculated with precision on Guarello Island, which was exploited for lime. Traces of paint dating back to 1948 show a raised relief of 3 mm. Elsewhere, small dykes of basalt and lamprophyre are highlighted by dissolution, and stand proud by 600–1000 mm. On the col of Madre de Dios, an inclined marble pillar, protected by a piece of basalt, measures more than 1.5 m high. A 10 m broad dyke projects by 4–6 m, due to differential dissolution of the surrounding marble which was weakened by contact metamorphism. The underground karst is very developed, but explorations are still in a preliminary phase. In the western part of Madre de Dios, an important karst system was reached through two stream-sinks. La Perte du Futur (376 m deep) is a cave with an alpine morphology, fed by a sink, and constituting the upstream part of the system. La Perte du Temps, 2.65 km long, forms the intermediate part of the system; it is fed by another large sink (estimated 2 m^3 s^{-1}) located at the contact between the limestone and the volcanic tuffs. The resurgence is to the west on the Pacific coast. This active karstic system shows some older parts with a few eroded concretion formations.

On the island of Diego de Almagro, la Perte de 1'Avenir (130m deep, 1.2 km long) constitutes a young cave system, probably formed during and after the melting of the glaciers within the last 20000 years (Figure 2). It is located at the contact between the marble and volcanic sediments, at the lip of a glacial cirque occupied by two lakes. The lakes are drained by a 50-m waterfall (0.2–3 m^3 s^{-1}) into the cave, which continues as an underground canyon through a marble dome, and then continues on the surface as a roofless canyon. Above the canyon, an abandoned meltwater canyon can be observed. Between the underground canyon and the glacial canyon, a network of phreatic tubes has developed by subglacial and proglacial meltwater erosion.

Bordering the sea, dry caves with glacial infill and massive stalagmites have been observed. Older caves, truncated by glacial erosion on the side of certain valleys, indicate the existence of several generations of karst. Resurgences are all located at the coast or below sea level. The most significant resurgence known from diving is the siphon of Lobos (49 m deep, discharge 2 m^3 s^{-1}) on Madre de Dios. On the archaeological side, the 2000 expedition for the first time highlighted the cave burials of the Alakalufs, a maritime people, whose bones have been carbon-dated as nearly 4000 years old.

RICHARD MAIRE

Patagonia Marble Karst, Chile: Figure 2. The Avenir Sinkhole is a 50 m waterfall at the contact of volcanoclastic rocks and marbles, located on Diego de Almagro Island. (Photo by R.Maire)

Works Cited

Biese, W.B. 1956. Uber Karstvorkommen in Chile. *Die Höhle,* Dezember 1956:91–96
Maire, R. 1999. Les “glaciers de marbre” de Patagonie, Chili: un karst subpolaire de la zone australe. *Karstologia,* 33:25–40

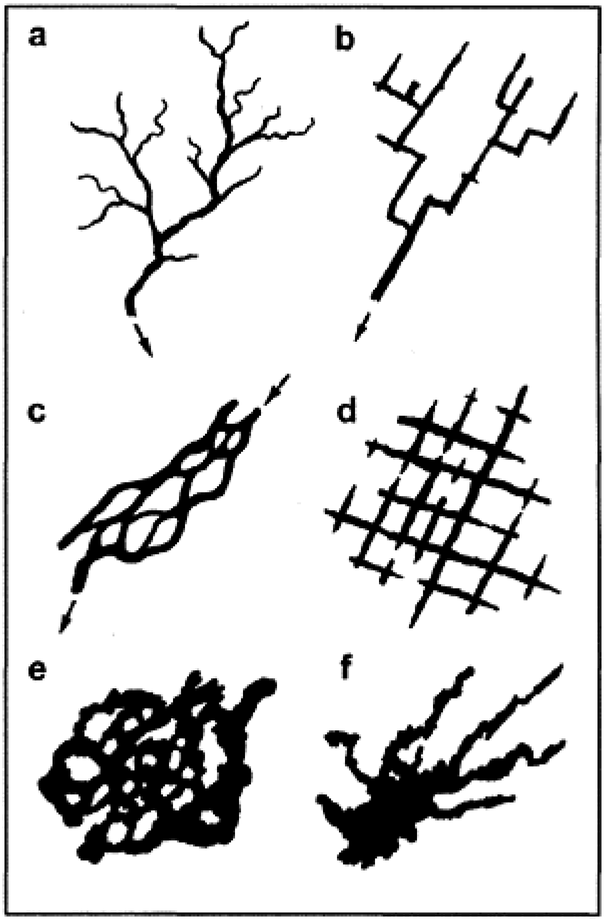
Further Reading

Fage, L.-H., Maire, R. & Pernette, J.-F. 1997. L’expédition Ultima Esperanza en Patagonie chilienne: les karsts de 1’extrême. *Proceedings of the 12th International Congress of Speleology,* vol. 6, La-Chaux-de-Fonds, Switzerland: International Union of Speleology/Swiss Speleological Society
Hobléa, F., Jaillet, S. & Maire, R. 2001. Erosion et ruissellement sur karst nu: les îleś subpolaires de la Patagonie chilienne. Karstologia, 38:13–18

PATTERNS OF CAVES

Solutional caves exhibit several distinct patterns (Figure 1). “Branchwork caves” consist of converging tributaries that merge downstream into fewer but generally larger passages. They are the most common type, representing >60% of all solutional caves. “Maze caves”, in contrast, contain many closed loops in which the passages form simultaneously. “Network mazes” are angular grids of intersecting fissures guided by fractures. “Anastomotic mazes” consist of curvilinear tubes that intersect in a braided pattern and usually follow bedding-plane partings. “Spongework mazes” are irregular cavities enlarged from primary pores, which interconnect in a three-dimensional array like the holes in a sponge. “Ramiform mazes” resemble inkblots in map view, with branches extending outward from irregular central rooms. Some caves include a combination of patterns. For example, most ramiform caves contain zones of spongework or network mazes. Many small caves have only single passages, or are erosionally dissected fragments of larger caves, but they share the origins of the types described above.

Cave patterns reflect the local hydrogeologic setting (Palmer, 1975; 1991). Branchwork caves are formed by groundwater recharge through many discrete inputs, particularly dolines. Each source contributes a small amount of water, capable of forming a passage, or at least an incipient passage. Where bedding is prominent, passages are sinuous and curvilinear. Where fractures are prominent, passages are rectilinear and meet at sharp angles. Branchworks usually possess more than one tier or storey, and the combination of active and relict passages can mask or confuse the branching pattern on maps. Among many examples described in separate entries are Mammoth Cave (United States), Friar’s Hole Cave (see Appalachian Mountains entry), caves in the Mendip Hills (England), and Ogof Draenen (see Draenen, Ogof Draenen, Wales).



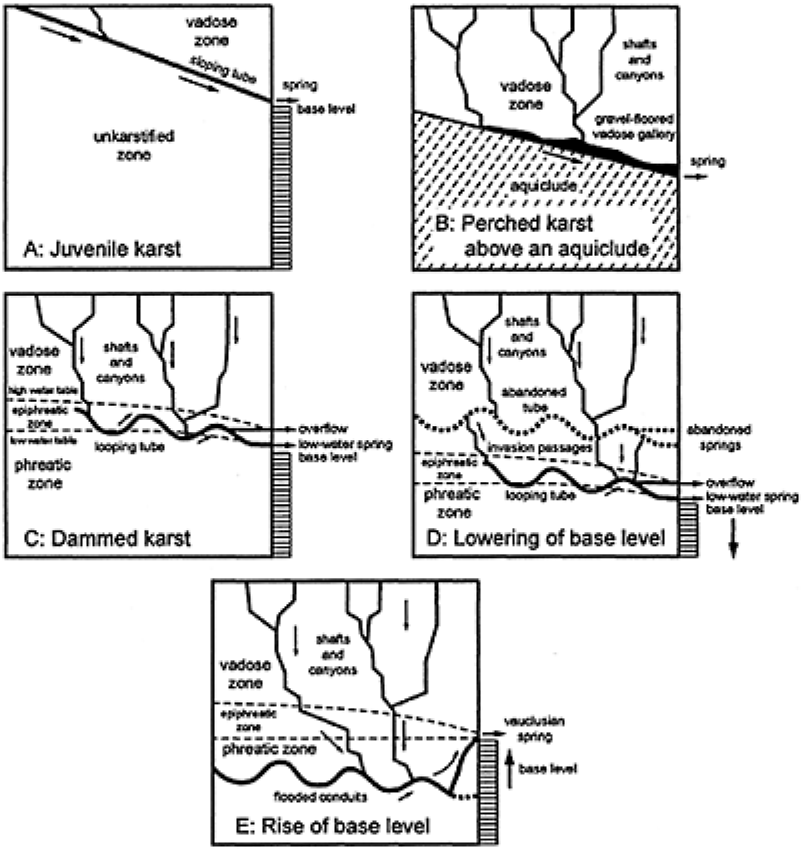
Patterns of Caves: Figure 1. Cave patterns in plan view (adapted from Palmer, 1991). **a**=branchwork in prominently bedded strata; **b**=branchwork in prominently fractured strata; **c**=anastomotic maze; **d**=network maze; **e**=spongework maze; **f**=ramiform pattern. Arrows show dominant flow direction. In many caves, the pattern is obscured by rudimentary development, multiple levels, or superposition of more than one pattern.

Maze caves require simultaneous enlargement of many competing paths. This is achieved by water with a steep hydraulic gradient and/or short flow paths from where the solutionally aggressive water first encounters the soluble rock (Palmer, 1991). Their specific patterns are controlled by the mode of groundwater recharge and by local structural conditions.

Periodic floodwaters delivered by allogenic recharge (e.g. sinking streams) pond in the caves under great pressure, injecting aggressive water into surrounding openings and enlarging them all simultaneously (see Hydraulics of Caves). Where fractures are prominent, local networks and blind fissures are superposed on the initial cave pattern (e.g. see Sof Omar Cave, Ethiopia entry). Where low-angle bedding planes or thrust faults are prominent, anastomotic mazes form (e.g. parts of Hölloch, in Switzerland, see separate entry). In massive rocks with intergranular pores, local spongework mazes can form (Palmer, 1975). Where fractured soluble rock receives uniform aggressive seepage through an overlying or underlying insoluble formation, two-dimensional network caves are formed (e.g. see Ukrainian Gypsum Caves entry). Three-dimensional network mazes are usually formed by the mixing of two waters of contrasting chemistry, for example high-CO_2 water rising from depth mixing with shallow low-CO_2 water. Wind and Jewel Caves (United States, see separate entry) may have formed in a combination of these two ways. Speleogenesis by sulfuric acid, generated by oxidation of hydrogen sulfide, can produce either network or ramiform patterns. The latter tends to develop along major flow routes where generation of sulfuric acid is intense (e.g. Carlsbad Cavern and Lechuguilla Cave (United States), and Cupp-Coutunn Cave, Turkmenistan, see separate entries). It is also theoretically feasible for three-dimensional networks to be formed by cooling of thermal water ascending along multiple fractures (Palmer, 1991), but most examples in the literature seem instead to have formed by mixing. Many spongework mazes are products of mixing of fresh water and saline water along seacoasts, in young limestones of high primary porosity (see Speleogenesis: Coastal and Oceanic Settings).

Artesian conditions are commonly thought to produce maze caves. However, there is no inherent tendency for this to happen. Although many mazes formerly experienced artesian conditions, their patterns result instead from one of the above processes.

The vertical profile of a cave depends on a combination of geologic conditions and geomorphic history. Ford (1971) explained the evolution of cave profiles with time (see Figure in



Patterns of Caves: Figure 2.
Evolution of cave profiles, based on concepts in Audra (1994). See text for details.

Speleogenesis: Unconfined Settings entry). Early in an aquifer's history, fissure frequency is low. Caves contain deep phreatic loops that descend to considerable depth below the water table (piezometric surface). With time, fissure frequency increases due to stress release, and later passages (often successively lower levels) have a greater number of phreatic loops but with lower amplitude. Where the fissure frequency is great enough, cave passages follow the water table with no significant phreatic loops. From empirical evidence, Worthington (2001) suggested that the depth of initial phreatic cave development in cave systems >3 km long is determined by decreasing viscosity of water as temperature rises with depth. Flow depth is proportional to flowpath length and stratal dip.

Audra (1994) presented an alternate view. "Juvenile karst" (Figure 2a) prevails when soluble rocks are first exposed by uplift and removal of any impermeable cover. Because of sparse fracturing, the water table is steep and located high above fluvial base level. Phreatic paths are later entrenched by vadose water as the water table drops. These are common in young, rapidly developing karst (e.g. see entry on Nakanai, Papua New Guinea). Geologic structure determines the aquifer development in several ways. Where the aquifer is perched above base level on an underlying aquiclude, there is no significant phreatic cave development (Figure 2b). Shafts and canyons converge on conduits at the aquiclude top and feed springs along hill slopes (e.g. see entry on Dent de Crolles System, France). Mechanical erosion, aided by detrital sediment, quickly enlarges the main routes. Major springs open into the heads of blind valleys. In "dammed karst" (Figure 2c) the karst aquifer extends below the spring outlet, which is determined by a fluvial or structural base level. Major passages either follow the water table or loop below it. During high flow, water rises in phreatic lift tubes and emerges at overflow springs (as in Castleguard Cave, Canada, see separate entry). In this model, high-amplitude looping passages form in the epiphreatic zone and are enlarged by aggressive high flows. Their amplitudes can exceed 200 m. During low flow the water follows lesser openings at lower elevations.

As fluvial base level drops with time, successively lower phreatic passages develop (Figure 2d). Pauses in base-level lowering produce cave levels that correlate with river terraces (see Mam moth Cave Region). Vadose development extends down to the new water table. Former conduits and springs are abandoned and partly filled with floodwater sediments and secondary minerals. Perched in the vadose zone, old phreatic conduits are cut by new shafts and canyons that feed active conduits. Base-level rises (Figure 2e) cause flooding of conduits, although they often preserve their original morphology. Some become sediment-filled, but the main flow lines remain active. New ascending routes, or reactivation of relict conduits, may form vauclusian springs (e.g. Fontaine de Vaucluse, France).

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See also **Morphology of Caves; Speleogenesis**

Works Cited

Audra, P. 1994. *Karsts alpins. Genèse de grands réseaux souterrains. Examples: le Tennengebirge (Autriche), l'Ile de Crémieu, la Chartreuse et le Vercors (France), Thesis,* Paris: Fédération française de spéléologie and Bordeaux: Association française de karstologie (Karstologia Mémoires, 5)

Ford, D.C. 1971. Geologic structure and a new explanation of limestone cavern genesis. *Transactions of the Cave Research Group of Great Britain,* 13(2):81–94

Ford, D.C. & Ewers, R.O. 1978. The development of limestone cave systems in the dimensions of length and depth. *Canadian Journal of Earth Sciences,* 15:1783–98

Palmer, A.N. 1975. The origin of maze caves. *National Speleological Society Bulletin,* 37:56–76

Palmer, A.N. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin,* 103:1–21

Worthington, S.R.H. 2001. Depth of conduit flow in unconfined carbonate aquifers. *Geology,* 29(4):335–38

Further Reading

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

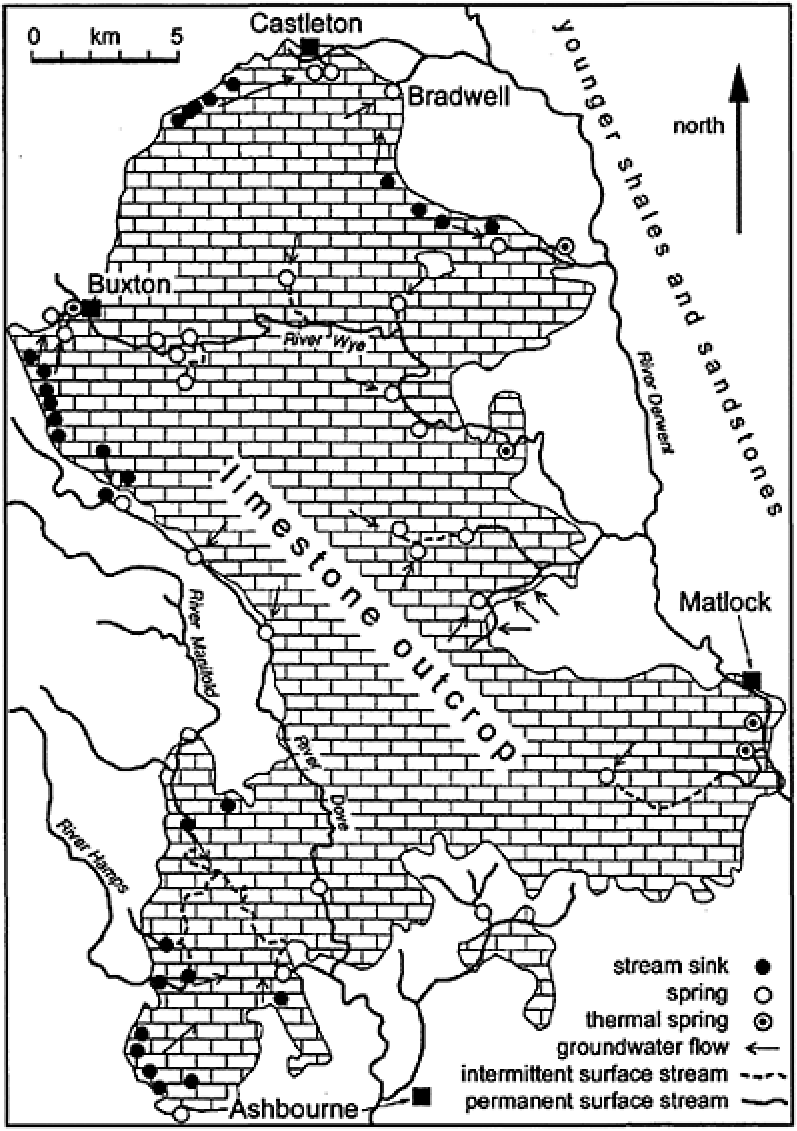
Gillieson, D. 1996. *Caves: Processes, Development, and Management,* Oxford and Cambridge, Massachusetts: Blackwell

Klimchouk, A, Ford, D.C., Palmer, AN. & Dreybrodt, W. (editors) 2000. *Speleogenesis: Evolution of Karst Aquifers,* Huntsville, Alabama: National Speleological Society

PEAK DISTRICT, ENGLAND

The Peak District is situated in the centre of England, and is one of four main caving regions in Britain (see map in Europe, Northern). Lower Carboniferous (Dinantian) limestones crop out over an area of some 520 km^2, which is known as the "White Peak" and forms *c.* 30% of the Peak District National Park. The largest unbroken karst area in Britain, it measures 40 km north—south and up to 20 km west—east (Figure 1). The surrounding Triassic sandstones (in the south) and the Namurian rocks of Millstone Grit facies support surface drainage, but only in the northern half of the area are these topographically higher than the limestones. The limestones, ranging from a few hundred metres to over 1800 m in thickness, were deposited in three main environments: lagoonal, reefal, and basinal. Subsequent folding has produced dips of up to 20° in lagoonal facies rocks, with much steeper dips in reefal rocks. Bedding planes are rare in the reef limestones but common elsewhere, with individual beds from 0.5 m to over 5 m thick. Three types of bedding discontinuity are recognized: contrasts in limestone lithology that reflect relatively rapid changes in carbonate deposition; pyriterich shale bands that mark short episodes of dominantly terrestrial sedimentation; and 1 mm^{-1} m thick green clay bands, known locally as "wayboards", that originated as falls of volcanic dust. Dinantian vulcanism also produced basaltic lavas and tuffs, locally interbedded with the limestones, and intrusive dolerites ("toadstones") also occur. Wayboards, toadstones, and volcanic rocks have influenced subsequent conduit/cave development.

Locally preserved paleokarstic features indicate at least one period of subaerial conditions during the Carboniferous (Ford, 1984). Following burial beneath later sediments, some paleokarstic voids were exploited as migration routes for hydrothermal fluids, becoming infilled by mineral deposits, mostly during the late Carboniferous. Mineralization is a key feature of the Peak



Peak District: Figure 1. Location of the White Peak, showing regional geological setting.

District karst, which is traversed by hundreds of veins. Most known veins were mined for lead between Roman times and the mid-20th century and some are still exploited for fluorspar. One form of fluorspar, Blue John, which is of high value as an ornamental stone, occurs only within paleokarstic voids on Treak Cliff, near Castleton, in the north of the White Peak.

Drainage always presented a problem to lead miners, and increasingly so as time progressed. Pumps were employed in many mines, but a later widespread solution was the construction of drainage adits (“soughs”), to dewater the mines. Soughs were driven from river level to lower the natural water levels and drain the phreatic zone. This was so successful that around Matlock, in the south of the limestone outcrop, no significant natural springs remain, and the whole area drains via a few major soughs. Lead miners encountered large, isolated dissolution cavities within mineral veins, faults, and fractures. Some cavities carried torrents of water and were described as “Great Swallows”, whereas others were termed “Large Opens”. In the Castleton area a notable concentration of these “vein-related cavities” is thought to represent a primitive phase of phreatic karst development. They provided inception routes for early water movement through the limestone, thereby stimulating later phreatic and vadose, bedding-related cave development (Ford, 1984, 2000).

There are over 210 caves in the Peak District, with a total length of *c.* 50 km, but only nine individual systems are over 1 km long (Gunn, Lowe & Waltham 1998). Most of the caves, and all those over 1 km long, are located where escarpments of Namurian Millstone Grit strata are close enough to the karst, and high enough, for surface streams to cross the shale and sink into the limestone. Castleton’s Peak-Speedwell cave system is the longest (*c.* 15 km) and has both the greatest vertical range (*c.* 290 m) and the deepest explored sump (Speedwell Main Rising, 70 m and continuing) in England. The system has a 8.4 km^2 autogenic catchment with dispersed recharge and a 5 km^2 allogenic catchment, within which 13 streams flow across solifluction debris-covered slopes and sink in marginal reef limestones. Eight of the stream sinks are associated with accessible influent caves, including the Giants-Oxlow system (5 km long; 240 m deep). The influent caves consist primarily of narrow meandering vadose streamways that drain to sumps, the deepest of which are at a similar altitude to the input sumps in Speedwell Cavern. Within Peak-Speedwell, the majority of the passage length consists of long phreatic tubes developed on three horizons within the gently dipping limestones and modified to varying degrees by vadose trenching and collapse. However, the most unusual feature of the cave system is the number, and vertical extent, of its mineral vein related cavities. At least 57 have been identified, with a cumulative vertical extent of over 2600 m and a volume of about 185000 m^3. Most spectacular is the recently discovered Titan, Britain’s largest natural shaft, with a vertical range of some 219 m, including a free-hanging drop of 142 m (Figure 2). At the top of the cavity the east-west extent is *c.* 100 m and the north-south width is 15–20 m. A surface dig is in progress to connect with the shaft via a passage near the top that is presently blocked by a boulder choke.

Eldon Hole, south of, and connected hydrologically to, the Peak-Speedwell cave system, is the largest open pothole in the Peak District, being 34 m long and 6 m wide at the surface and over 60 m deep. It was first explored around 1600 (Shaw, 1992), but the first properly documented descent was by Lloyd (1772), who also provided a survey. The nearby Eldon Hill Quarry exposes several narrow dissolutional passages up to 10 m high, apparently aligned along north-south joints. Their relationship to the vein-related cavities remains uncertain, but paleomagnetic dating of glaciofluvial infill (see photo in

Paleoenvironments: Clastic Cave Sediments entry) indicates ages of around 900000 years (Ford, 2000). Glaciofluvial sediment sequences older than 730000 years have also been found near Matlock, where some cave segments follow mineral veins, and mining has re-exposed paleokarstic features. These sediments are the earliest evidence of Quaternary glaciation in Britain outside East Anglia. Evidence for even earlier cave development is provided by Early Pleistocene bones recovered from Victory Quarry Fissure near Buxton (Bramwell, 1977) and speleothem dating from the Olduvai event (1.67–1.87 Ma) at Elderbush Cave in the Manifold Valley (Rowe, Austin & Atkinson, 1989). It is generally assumed that the first significant breaching of the clastic cover took place in the Early Pleistocene and marked the beginning of significant cave development. However, limestone was exposed in the south of the region during Permo-Triassic times, when cavities were enlarged in the Brassington area (Walsh *et al.*, 1972) and conduit inception must have been ongoing for millions of years beneath the "impermeable" cover. Evidence for deep circulation of meteoric water in hydrothermal convection systems that are thought to be primarily within the carbonate sequence, is provided by the warm springs that issue at Buxton, Stoney Middleton, Bakewell, and Matlock. Water-tracing experiments in the central White Peak also suggest that there is a large body of slow-moving groundwater, in contrast to the margins where the water from sinking streams moves very rapidly through the conduit systems.

A notable feature of the Peak District caves in general, and the Castleton caves in particular, is the high concentration of radon gas. Ventilation systems have been installed in each of the four show caves in the Castleton area to ensure the safety of visitors and employees, but Giants Hole is thought to have the highest measured radon gas concentration of any natural limestone cave in the world.

Some cave deposits confirm that the Peak was ice-covered during at least one early glaciation, but Quaternary glaciers are not thought to have influenced major river valley incision significantly, and the area lies outside the most recent (Devensian) ice limits. Consequently there is virtually no bare limestone, although soils are generally thin (*c.* 1m) and developed largely from loessic material rather than from weathered limestone. Virtually no surface drainage exists on the limestone, and only two allogenic-fed rivers, the Dove and the Wye, maintain perennial flow across the karst. However, the most notable feature of the limestone plateau is that it is dissected by a dendritic system of valleys ("dales") that are dry for all, or most, of the year. Thus, the Peak District is an internationally important example of a relict fluviokarst (see Photo in Valleys in Karst).

The valleys are thought to have been inherited by the limestone after originating on an impermeable clastic cover. Their desiccation largely reflects gradual karstification of drainage, aided by regional water table lowering in response to downcutting by major rivers. However, not all the desiccation was natural, as dewatering via mine soughs affects some rivers, most notably the Lathkill's middle reaches, which dry up every summer. Dry valleys might have been active again under Pleistocene periglacial conditions when the ground froze and extensive screes developed. Solution dolines, subsidence dolines, and a few small collapse dolines pit the limestone surface, but they are mere details within the dominantly fluviokarstic landscape. Additionally, the courses of most lead veins are marked by depressions that were either modified or created by lead miners. Quarrying, a major local industry, has also impacted on the natural landforms and more limestone was removed by quarrying during the 20th century than by natural solutional processes acting over the whole of the Holocene (the last 10 000 years).

JOHN GUNN

See also **Europe: North; Fluviokarst; Quarrying in Limestone; Radon in Caves; Sulfide Minerals in Karst**

Peak District: Figure 2. Looking up the Titan Shaft, in the inner reaches of the Peak-Speedwell cave system, Castleton, Derbyshire. (Photo by Paul Deakin)

Works Cited

Bramwell, D. 1977. Archaeology and paleontology. In *Limestones and Caves of the Peak District,* edited by T.D.Ford, Norwich: Geo Abstracts

Ford, T.D. 1984. Palaeokarst in Britain. *Cave Science,* 11(4):246–64

Ford, T.D. 2000. Vein cavities: an early stage in the evolution of the Castleton Caves, Derbyshire, UK. *Cave and Karst Science,* 27(1): 5–14

Gunn, J., Lowe, D.J. & Waltham, A.C. 1998. The karst geomorphology and hydrogeology of Great Britain. In *Global Karst Correlation,* edited by Yuan Daoxian & Liu Zaihua, New York: Science Press

Lloyd, J. 1772. An account of Elden Hole in Derbyshire. *Philosophical Transactions of the Royal Society,* 61(1):250–56

Rowe, P.J., Austin, T.J. & Atkinson, T.C. 1989. The Quaternary evolution of the south Pennines. *Cave Science,* 16(3):117–21

Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society

Walsh, P.T., Boulter, M.C., Ijtaba, M. & Urbani, D.M. 1972. The preservation of the Neogene Brassington Formation of the southern Pennines and its bearing on the evolution of upland Britain. *Quarterly Journal of the Geological Society of London,* 128: 519–59

Further Reading

Cave Science, 18(1), 1991 is a special issue on the Peak-Speedwell Cave System

Ford, T.D. (editor) 1977. *Limestones and Caves of the Peak District,* Norwich: Geo Abstracts

Ford, T.D. & Gunn, J. 1992. *Caves and Karst of the Peak District: An Excursion Guidebook to the Karst Landforms and Some Accessible Caves within the Peak District,* London: British Cave Research Association

Ford, T.D. & Rieuwerts, J.H. (editors) 2000. *Lead Mining in the Peak District,* 4th edition, Ashbourne: Landmark Publishing

Gill, D.W. & Beck, J.S. 1991. *Caves of the Peak District,* Clapham: Dalesman

Gunn, J. 1985. Pennine karst areas and their Quaternary history. In *The Geomorphology of North-west England,* edited by R.H.Johnson, Manchester: Manchester University Press

Harrison, D.J. & Adlam, K.A.McL. 1985. *Limestones of the Peak: A Guide to the Limestone and Dolomite Resources of the Peak District,* London: HMSO (British Geological Survey Mineral Assessment Report 144

PHOTOGRAPHING CAVES

The history and development of cave photography is closely linked to two factors: technology and motivation. When the invention of photography was announced in 1839 it brought widespread excitement, but the early process required a cumbersome camera and tripod, and also that the sensitized materials were prepared, exposed, and developed within a few minutes. Restrictions such as these and the long exposure times required meant that few photographers—who were, in the main, motivated by commercial portraiture—ventured far from their studios. Of those that did, John Dillwyn Llewelyn photographed cave entrances in South Wales between 1852 and 1856, but photography in darkness awaited better light sources than the prevalent candles, gas lamps, and oil lamps.

The turning point came with the commercial preparation of magnesium in 1863. When burned, the metal produces light which is rich in the actinic (blue) part of the spectrum that photographic plates were sensitive to. To illustrate its photographic power, on 27 January 1865 Alfred Brothers, a professional photographer of Manchester, England, photographed a chamber in the Blue John Caverns in Derbyshire—the first successful underground cave photograph.

Following the American Civil War there was a perceived need to attract tourists to Kentucky's Mammoth Cave. A Belgian immigrant, Charles L.Waldack, was employed to take stereo photographs for sale to an avid public. Stereo pictures were taken using a double-lensed camera, simulating the slightly different views seen by each eye and giving an impression of depth—such pictures were a popular commodity. By 24 June 1866 Waldack had produced seven good images—returning for a second, three-month-long expedition in July. Spending up to 35 hours underground, he echoed Brothers by burning strips of magnesium bound into a taper—up to 120 tapers were used for each picture. Subsequently, a set of 42 images was placed on sale.

Waldack's meticulous techniques and pictures were widely reported and brought universal acclaim. The photographic press exclaimed that: "It is a greater triumph of photography than anything yet accomplished…Mr. Waldack deserves the thanks of the world of science and art." (Edward L.Wilson, "Photography in the Mammoth Cave", 1866; reproduced in Howes, 1989, pp. 68–69)

During his experiments, Waldack found that light sources close to the camera produced uninteresting pictures which lacked relief or shadows and, in addition, the cave air was so humid that light reflected back into the lens, degrading the image. He surmounted these problems by placing the magnesium burners to one side of the camera, producing greater detail in his pictures. Waldack frequently had no room to manoeuvre in narrow passages, so for the second expedition he chose a wider-angle lens, conferring more freedom to compose his picture and placing him closer to the subject. Basic tenets such as these—using a wide-angle lens with separate lighting positions—remain true today.

This commercial motivation—benefiting both the photographer and the cave owners—remained the controlling factor behind cave photography for much of the 19th century. Under- ground photography increased alongside tourism, fuelled in the United States by the spread of the railroad which, in some cases, was deliberately laid near commercial caves. The rail companies frequently funded cave photography for advertising (typified by the work of W.R.Cross and W.F.Sesser during the 1880s), to encourage tourists to use their services.

Photographing Caves: Figure 1. Waldack's 1866 stereo photograph of the Deserted Chamber in Mammoth Cave clearly shows clouds of magnesium fumes drifting overhead. (Photo by Charles L. Waldrack)

However, technology did not stand still. Glass plates were improved and exposure times were reduced, and the "wet" process gave way to dry plates, which removed the need to prepare these in the field. Recording red colours in black and white tones remained difficult, producing virtually black areas, but no solution to this was found until panchromatic film was introduced in 1906. For now, cave photographers avoided taking pictures containing ochre-rich mud or iron-stained formations.

Experiments were made with alternative light sources to magnesium, such as limelight (used by A.Veeder around 1877 at Howe's Cave near New York) and electricity (used in 1881 by C.H.James in Luray Caverns, Virginia). These pictures were characterized by their bland lighting and static nature: exposure times were too lengthy to include people in the scene as they could not stand still for the duration of the exposure. Magnesium ribbon remained the only realistic choice, although it was less than perfect because of the copious clouds of magnesium oxide ash that obscured the scene within seconds and prevented a second exposure.

In 1887 the invention of flashpowder was announced and the new compound (consisting of finely ground magnesium mixed with an oxidizing agent—potassium chlorate) was soon used underground when, in 1888, Max Müller built and deployed a "magnesium blitzlicht" lamp in the Hermannshöhle in Germany. His techniques were explained in a monograph, published with 20 prints. Flashpowder offered cave photographers a valuable new tool, which "instantaneously" illuminated the scene—the powder was both powerful and portable. The problem of fumes remained, but pictures could be taken with far greater ease, and subtly the nature of artificial light photography changed. The inclusion of people within the scene became more common as the likelihood of blurring was reduced by the shorter exposure times, while shadows became harsher.

With flashpowder in widespread use, by the 1890s cave photography was well served by established techniques, but a change in emphasis was under way. Cave exploration for its own sake began, and photographers such as Ben Hains in the United States and Charles Henry Kerry in Australia recorded the caves that they explored. In France, Édouard Alfred Martel required photographs to support his explorations, and encouraged his companions to develop new photographic techniques and equipment, writing the first book on the subject in 1903: *La Photographie souterraine* (Underground Photography). As a motivating force, depicting the cave as a place of exploration had at last outstripped commercial interests, although, in France, Martel's dictum that lighting should simulate daylight from behind, above, and to one side of the lens, restrained the discipline from reaching maturity.

As part of the rise in cave exploration during the closing years of the 19th century and the first decades of the 20th, many amateur and professional photographers worked underground, but they were outshone by one man: James Henry Savory (universally known as Harry Savory). A professional photographer, between 1910 and the mid-1920s Savory produced an outstanding series of pictures from the caves of the Mendip hills of south west England. By the time that Savory concluded his work the change in emphasis was complete: cave photography now belonged to dedicated photographers who held a genuine interest in the underground world.

Cave photography also had a profound effect during the 1920s. At Carlsbad, New Mexico, Ray V.Davis had solved many of the difficulties in photographing the immense and beautiful chambers in the nearby Bat Cave (today known as Carlsbad Caverns). The pictures were influential in persuading President Coolidge to inaugurate the caves as a national monument (later to become a national park). Davis was keenly involved with preserving the cave for posterity and his photographs are perhaps some of the most important tools ever used to support conservation.

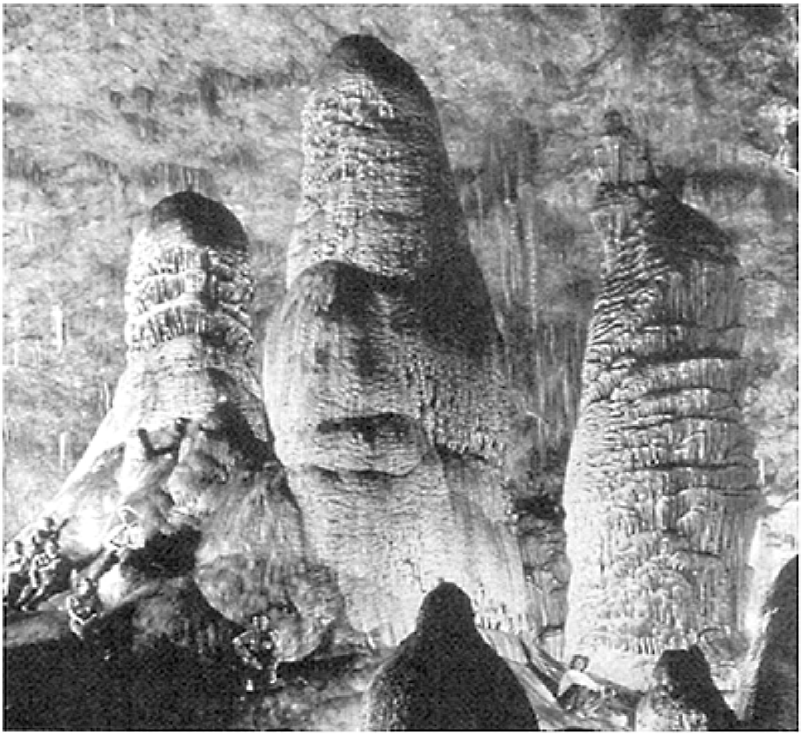
Photographers such as Savory and Davis produced stunning pictures because, in part, they were so skilful in lighting their subjects. Light behind a subject produces a silhouette; with light to one side there is strong relief which is suited to showing texture. By combining more than one flash, the effects are often startling.

In 1929 the flashbulb (aluminium burned in oxygen sealed within a glass globe) removed the problem of magnesium fumes, but, initially, flashbulbs were large and expensive. Just as Brothers and Waldack had helped popularize magnesium, in 1952 it fell to Ennis Creed "Tex" Helm to use 2400 flashbulbs in a single exposure in Carlsbad Caverns, thus helping his sponsor—Sylvania Electric Products—to produce a new and appealing advertisement. Flashbulbs, being waterproof, also enabled Luke Devenish to make the first stumbling attempts at photography in sumps at Wookey Hole, England in 1955, by which time cave photographic techniques were well known. Even so, it was not until smaller and cheaper bulbs became available that cave photographers finally turned away from flashpowder in the late 1950s and early 1960s.

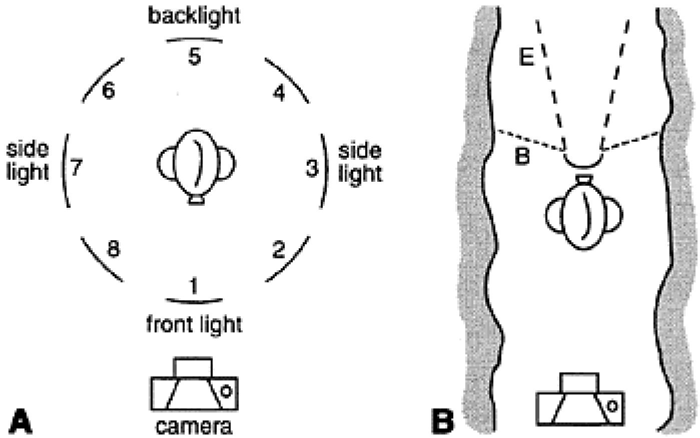
Other advances in cave photography during the latter half of the 20th century relied on better and cheaper electronic components, resulting in the proliferation of electronic flashguns. These differ from bulbs in that they have a shorter duration of flash and typically emit light over a narrower angle. The effect is striking. Moving water lit with a bulb is blurred and appears to flow, while an electronic flash "freezes" movement and produces harder shadows. Cavers, then as now, mixed the light sources to obtain the results that they required. All flash sources can be assigned a guide number, which is relative to the sensitivity of the film; higher numbers indicate a more powerful flash. Using the guide number and the formula: Guide Number=Distance from flash to subject multiplied by the lens Aperture *(GN= D×A)* it is relatively easy, even with multiple flash situations, to determine the correct settings to use on the camera.

Despite advances in cameras, film, and lighting, techniques had changed little for many years. Typically, the camera was mounted on a tripod and, with all lights extinguished and the shutter open to admit light to the film, single, or multiple flashes were manually fired by the photographer or assistants. As long as the camera remained steady and everyone stayed still, the ensuing picture was sharp. Therein lay the difficulty: if the camera or subject moved, the picture was blurred. The unwieldy tripod did not fit in well with modern exploration into remote areas of new caves, and the restrictions produced very static, staid poses.

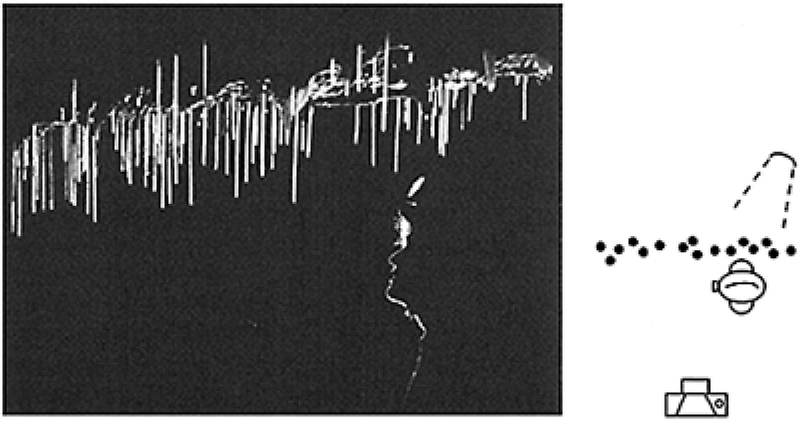
The answer lay with caver-designed slave units, which have become widely used since the late 1970s. Slave units are attached



Photographing Caves: Figure 2. Pictures by R.V.Davis, such as this one taken in The Big Room in Carlsbad Caverns, influenced the decision to inaugurate the national park. (Photo by R.V.Davis)



Photographing Caves: Figure 3. A: Lighting details can be recorded using a simple code system, where the letters E and B represent an electronic or bulb flash and a number indicates the direction of flash relative to the camera. A sidelit photograph taken with a single flashbulb would be designated B3 or B7, for example. Other photographs in this section are coded in this manner. **B:** A caver firing a flashgun away from the camera but from within the picture area produces a silhouette. A flashbulb (B) can have an advantage in some situations, as the more directional light from an electronic flash (E) may not illuminate the nearby passage walls.



Photographing Caves: Figure 4. Back-lighting—as with these straw stalactites in Dan yr Ogof, Wales (E5)—produces dramatic results characterized by strong highlights and dense shadows. In the diagram the caver is placed between the flash and the camera, ensuring that no direct light reaches the lens. (Photo by Chris Howes)

Photographing Caves: Figure 5. Cave photographers use the characteristic long-duration light from a flashbulb—about l/30th second rather than the 1/10000th second duration of electronic flash—to simulate flowing water by allowing it to blur. (Arête Chamber, Ogof Ffynnon Ddu, Wales, B6; Photo by Chris Howes)

to a flashgun and detect a pulse of light to act as an electronic switch. By firing a master flash attached to the camera the photographer can therefore trigger any additional number of flashes without using intervening cables. Because all the flashes fire together, the camera can be hand-held and subjects are able to move—the short-duration flash of modern flashguns prevents blurring.

In addition, most caver-built slave units use infrared wavelengths. Film is insensitive to infrared light, so by using an appropriate filter over the master flash no light from the camera position is recorded in the picture. This further increases the photographer's creative control as pictures with strong back-or side-lighting can readily be taken. These slave units are often sensitive at distances in excess of one kilometre which, although this is greater than required, is a major advantage because weaker pulses of reflected light can be detected in shadow areas and around passage corners. Slave units confer the freedom to com pose a picture exactly as the photographer envisages—a tremendous advantage in that cavers can be more easily and quickly photographed in action.

In the latest technological advances, digital cameras are further revolutionizing cave photography. Less light is required to record an image, which is immediately viewable on an LCD screen so that errors in lighting and exposure can be corrected and the picture retaken. An age-old photographic technique is to build up a cave picture using separate flashes to fill in different portions of the scene, but digital techniques can extend this theme. By taking a series of pictures from the same viewpoint with different camera settings or lighting positions, portions of each can be assembled on a computer using graphic-editing software. The requirement that everything is perfectly exposed in a single shot is no longer valid.

Purists might grumble as pictures produced using this technique become more prevalent. Perhaps the early pioneers would wince with displeasure—they struggled with heavy and unmanageable equipment, preparing and developing their glass-plate negatives underground. In comparison, using highly sensitive films, digital cameras and light-weight, small yet powerful flashguns which can be placed and fired at will, today's cave photographers have an easy time indeed.

Yet cave photography is not totally encapsulated and controlled by technology—it is a creative discipline conducted within a harsh, unyielding environment. In 1866 Charles Waldack wrote that: "You will agree with me that photographing in a cave is photographing under the worst conditions" (Charles L. Waldrack, "Photographing in the Mammoth Cave", 1866; reproduced in Howes, 1989, p.66). His statement was true then and, arguably, is more so now that explorers penetrate ever further into the Earth. Technology may ease aspects of the challenge, but the impetus to produce an outstanding picture remains one that is very personal to the photographer. Ultimately, motivation and creativity remain more important than technology.

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Further Reading

Howes, C.J. 1989. *To Photograph Darkness: The History of Underground and Flash Photography,* Gloucester: Sutton and Carbondale: Southern Illinois University Press

Howes, C.J. 1997. *Images Below: A Manual of Underground and Flash Photography,* Cardiff: Wild Places

Martel, É.A. 1903. *La Photographie souterraine,* Paris: Gauthier-Villars; reprinted Marseille: Laffitte, 1989

PHYTOKARST

Phytokarst encompasses a range of small-scale landforms, produced by the action of plants on limestone surfaces. Such landforms have been identified since the early 1970s, when Folk, Roberts & Moore (1973) published observations from a site at Hell, Grand Cayman Island. Most phytokarst features reported in the literature are thought to be erosional features, produced through dissolution of limestone by organic acids, although depositional features produced by the reprecipitation of calcium carbonate, encouraged by plant activity, could also be defined as phytokarst. The term phytokarst is rather restrictive as it implies plant action only, and biokarst is a better, broader term for organically-influenced karst features (see Biokarstification). Phytokarren and photokarren are other terms which have been used to described plant-influenced landforms in karst areas.

Most phytokarst features, described in the literature, are centimetres to metres in scale and consist of a series of pits and upstanding areas. In some cases they form fields of pinnacles oriented towards a source of light, and in other cases they form randomly orientated spongework nested on larger-scale topography. Notable examples of light-oriented pinnacles have been reported from tropical cave entrances (e.g. as recorded by Waltham & Brook (1980) and Bull & Laverty (1982) from Mulu, Borneo), and temperate coastal caves (as discovered by Simms (1990) along the Burren coast, Co. Clare, Ireland). Random spongework forms were first identified by Folk, Roberts & Moore (1973) from near-coastal limestone terrain in Grand Cayman Island in the Caribbean, received more detailed study by Jones (1989) and are common on young limestone deposits on many tropical islands. Other examples of phytokarst forms include algal and lichen-induced pitting, observed on many coastal and terrestrial limestone surfaces, in tropical and temperate areas. The term phytokarst has also been applied to the constructional role of plants and micro-organisms growing on speleothems on vertical slopes and cave entrances (such as tower karst foot caves) in tropical karst. Such speleothems are sometimes orientated away from the vertical wall or cave entrance, and have been given the term "aussen stalactiten" by some authors (e.g. Viles, 1984). Their spongy, plant-covered and often tufa-like appearance marks them out from other, less organically influenced stalactites.

Despite the dramatic appearance of many phytokarst forms, it has proved difficult to determine the exact role of biological agents in their formation. Using scanning electron microscopy, it is possible to show that micro-organisms and plant roots are boring into limestone surfaces at the micron to millimetre scale. However, the challenge remains to try and link such microscale processes with the production of landforms at the centimetre to metre scale.

HEATHER VILES

See also **Biokarstification; Coastal Karst; Tourist Caves: Algae and Lampenflora**

Works Cited

Bull, P.A. & Laverty, M. 1982. Observations on phytokarst. *Zeitschrift für Geomorphologie,* 26:437–57

Folk, R.L., Roberts, H.H. & Moore, C.H. 1973. Black phytokarst from Hell, Cayman Islands, British West Indies. *Bulletin of the Geological Society of America,* 84:2351–60

Jones, B. 1989. The role of microorganisms in phytokarst development on dolostones and limestones, Grand Cayman, British West Indies. *Canadian Journal of Earth Sciences,* 26: 2204–13

Simms, M.J. 1990. Phytokarst and photokarren in Ireland. *Cave Science,* 17:131–33

Viles, H.A. 1984. Biokarst: Review and prospect. *Progress in Physical Geography,* 8:523–43

Waltham, A.C. & Brook, D.B. 1980. Cave development in the Melinau limestone of the Gunung Mulu National Park. *Geographical Journal,* 146:258–66

Further Reading

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

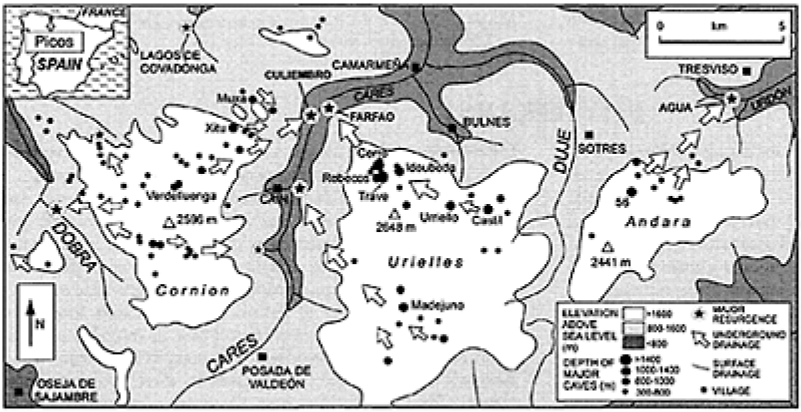
Jennings, J.N. 1985. *Karst Geomorphology,* 2nd edition, Oxford and New York: Blackwell

PICOS DE EUROPA, SPAIN

The Picos de Europa, in northwest Spain, hosts the largest concentration of deep caves in the world. Covering an area of *c.* 500 km^2, the Picos are located on the northern flank of the Cantabrian Mountains and contain the highest peaks in this range, rising to an altitude of over 2500 m. The Picos are dissected from north to south by the spectacular gorges of the Cares and Duje rivers, which, flowing at altitudes of from 300 to 400 m, divide the Picos into three sub-massifs (Figure 1). Declared in 1918, the Picos de Europa was the first national park in Spain and one of the first in Europe.

Geological Background

The Picos are composed almost exclusively of a 1500 m thick sequence of Carboniferous (Visean to Moscovian) marine limestones. This sequence starts with the nodular limestones and radiolarites of the Alba Formation (50 m) and the dark, thinbedded limestones of the Barcaliente Formation (250–300 m). Both formations were deposited in a deep platform setting over most of the Cantabrian zone. In the Picos de Europa, overlying the Barcaliente, are the deposits of a large steep-margined carbonate platform, dominated by the massive limestones of the



Picos de Europa, Spain: Figure 1. Outline map of the three massifs of the Picos de Europa, with sites of the main caves and known underground drainage patterns.

Valdeteja (300 m) and Picos de Europa Formations (up to 1000 m). In areas surrounding the Picos, deposits coeval to this carbonate platform mainly consist of siliciclastics.

During the late Carboniferous, the Cantabrian zone was incorporated into the Variscan orogeny and the Picos limestones were deformed into an imbricate system of thrust sheets. The strike of the thrusts is roughly east-west, and their dip increases from south to north. Although pre-Carboniferous siliciclastics are found locally at the base of some thrust sheets, most are formed almost exclusively of limestones. As a consequence, the stacking of thrusts has produced a huge vertical accumulation of limestone.

In the Picos de Europa and adjacent areas, a Permo-Mesozoic, siliciclastic-dominated sedimentary cover was deposited over the Hercynian basement. The current relief of the Cantabrian Mountains, including the Picos de Europa, is related to Alpine uplift during the Eocene to Miocene. As a consequence, the Permo-Mesozoic cover was eroded from the western Cantabrian Mountains, including the Picos de Europa. The fluvial gorges dissecting the Picos run perpendicular to the structures, suggesting that the present drainage was inherited from the cover and superimposed onto the Carboniferous basement during the Tertiary.

Quaternary glaciation extensively affected the Picos de Europa (Smart, 1986). Glaciers covered most of the highlands and occasionally, the Cares and Duje valleys. The largest ice cap developed on the Western Massif, covering an area of *c.* 50 km^2 and locally reaching 300 m in thickness. Gale & Hoare (1997) have recognized five glacial phases, the most extensive probably being latest Tertiary.

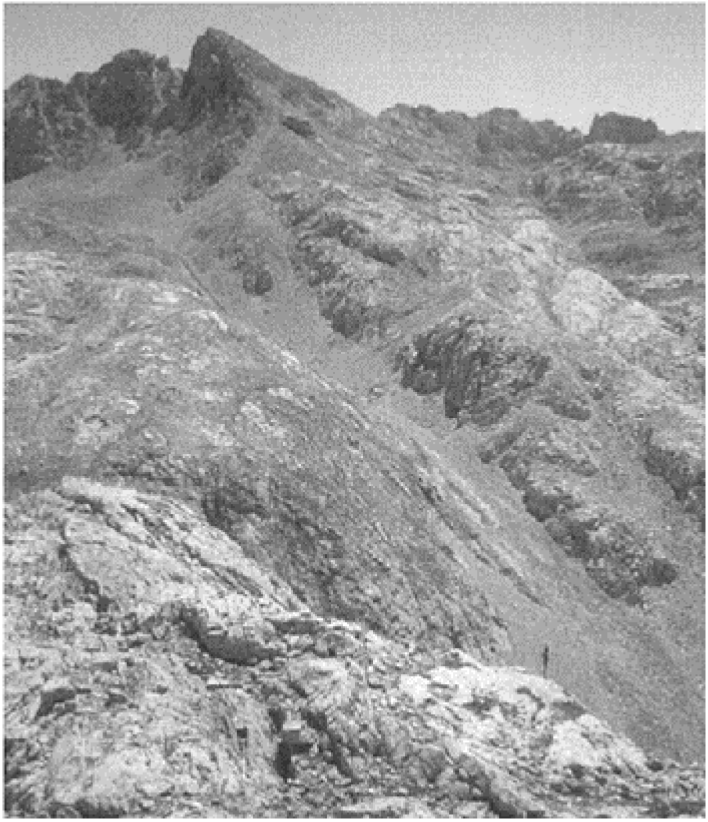
The rugged Picos highlands are composed of plateaus, usually at altitudes ranging from 1500 to 2000 m, and ridges and horns that typically rise *c.* 500 m above the plateaus. The plateaus have no surface drainage and their bare bedrock surfaces are covered by karren and dolines (Figure 2). However, the most notable feature is the presence of closed depressions up to 1000 m across, which are glacial modifications of pre-Quaternary karst depressions (Smart, 1986).

Thousands of caves are known in the Picos, and hundreds are explored every summer. Caves are predominantly vertical vadose systems located in the highlands. The majority are small shafts that become impenetrable or blocked at depths of a few tens of metres. However, a significant number of caves attain considerable depths: 96 caves exceed 300 m and 9 caves exceed 1000 m in depth (see Table). Such a concentration of deep caves is related to the paucity of non-carbonate lithologies and the large differences in elevation between the highlands and the valley floors, resulting in an exceptionally thick vadose zone.

Most of the deep vadose Picos caves consist of shafts systems interconnected by narrow canyons. Shafts are guided by Alpine faults or Variscan thrusts. An impressive example of the latter is the Trave system which, between −500 and −1000 m of depth, has several series of shafts following the dip of a major thrust (Vidal, 1990). Where shafts are developed in massive limestones (Valdeteja and Picos de Europa Formations) they can reach spectacular proportions, and four single pitches exceeding 300 m of depth are known.

Many of the large vadose Picos caves are partially subglacial in origin. Glaciers provided large catchments and concentrated meltwater into certain sinks, explaining large shafts at points which currently receive little modern drainage (Smart, 1986). Additionally, some cave morphologies, particularly the “pitch-ramp” systems, are best explained by the action of glacial meltwater (Senior, 1987). The pitch-ramp systems, characteristic of many Picos canyons, are inclined bedrock terraces ascending from the base of each pitch to the head of the next, and are vadose features that are formed by pitch retreat (Senior, 1987).

Except in the case of the resurgence caves, only the deepest caves reach the water table, which is defined by segments of low-gradient streams interrupted by inundated phreatic passages. Overall, horizontal water-table passages are uncommon, particularly in the resurgence caves such as Culiembro and Cueva del Agua. Instead, these caves consist of active and relict looping phreatic tubes, suggesting that a significant part of the present drainage is through phreatic caves.



Picos de Europa, Spain: Figure 2: Typical landscape of the Picos highlands, showing the bare bedrock surfaces of the Vega Huerta Plateau (to the left) and Canal de la Duernona (to the right) on the Western Massif. Glacial rounding and karren are common. The area shown in the lower part of the image contains abundant shafts, including the 949 m deep Pozo del Llastral and the 420 m deep Pozo de la Garita Cimera. (Photo by Carlos Rossi)

Relict phreatic conduits are uncommon in the influent Picos caves. However, some deep caves intersect large, looping, strike-oriented phreatic tubes in their lower sections (typically up to 100–150 m above the present water table). Excellent examples are found in the M2 cave, Pozu Jultayu, Sil de Oliseda, and Asopladeru de la Texa (Western Massif), and in the Torcas Urriellu, Castil, del Cerro, and Idoúbeda (Central Massif). At higher elevations, relict phreatic conduits are scarcer and smaller, and most have been invaded by vadose streams, resulting in deep canyons. Some phreatic tubes are found at altitudes as high as 1000 m above the water table. Based on the rate of base-level lowering deduced from uranium-series dates of speleothems, some of these high-level phreatic conduits may be as old as 3 million years (Smart, 1986). In caves of the Western and Eastern Massifs, some relict phreatic conduits preserved siliciclastic

Picos de Europa, Spain: Caves in the Picos de Europa more than 900 m deep.

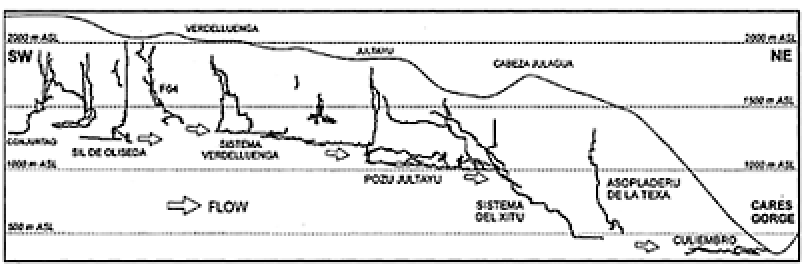
Cave	Depth (metres)	entrance altitude (m)	massif	resurgence name	gorge	altitude (m)
Torca del Cerro del Cuevón (T–33)	1589	2019	Central	Farfao	Cares	320
Sistema del Trave	1441	2042	Central	Farfao	Cares	320
Torca de los Rebecos (T27)	1255	2083	Central	Farfao	Cares	320
Pozu Madejuno (Omega 45)	1255	2425	Central	Molinos	Cares	450
Sima 56	1169	1975	Eastern	Agua*	Urdón	465
Torca Idoúbeda	1168	1856	Central	Farfao	Cares	320
Sistema del Xitu	1148	1652	Western	Culiembro*	Cares	390
Torca Urriello	1022	1860	Central	Farfao	Cares	320
Torca Castil (PC-15)	1028	2000	Central	Farfao*	Cares	320
M2 (Pozo de Cuetalbo)	972	1990	Western	Capozo*	Cares	900
Pozo del Llastral (Beta 3)	949	1950	Western	Reo Molin*	Dobra	930
Torca Tortorios (CT-1)	943	?	Central	Farfao	Cares	320
Pozu Cabeza Muxa	939	1504	Western	Culiembro*	Cares	390
Torca del Jou de Cerredo	910	2325	Central	Farfao	Cares	320
Sima del Jou de la Canal Parda	903	2215	Western	?	?	?

* indicates that the resurgence has been dye traced from the sink cave.

sediments related to the erosion of the Permo-Triassic cover (Smart, 1986; Fernández *et al.*, 2000).

The water drained by the caves resurges in a few springs at the bottom of the gorges. Underground drainage is in a broadly east-west direction, following the strike of beds, thrusts, and post-Hercynian faults. Because the dip is towards the north, no resurgences exist in the southern front. In the Western Massif, the most important resurgences are Culiembro in the Cares gorge (see below) and Reo Molín in the Dobra gorge (Figure 1). In the Central Massif, underground drainage is predominantly towards the west—northwest, and the Farfao and Molinos springs at the Cares gorge drain the southern and northern parts of the massif, respectively. In the Eastern Massif, the most important resurgence is Cueva del Agua, located in the Urdón gorge.

The Culiembro and Farfao systems are examples of important and relatively well-known underground drainage systems. The Cueva de Culiembro, located at an altitude of 390 m, in the Cares gorge, and with a summer discharge of 1 $m^3 s^{-1}$, drains the northeastern part of the Western Massif (Figure 3). The Culiembro drainage system has two branches (Figure 1). The north branch drains to the southeast, following the strike of a series of thrust sheets. In this area, three caves (Pozu les Cuerries, 545 m deep, Cabeza Muxa, 906 m deep, and Asopladeru de la Texa, 837 m deep) descend to segments of a low-gradient streamway, interrupted by sumps up to 28 m deep, that has been dye traced to Culiembro. The altitude of these sumps decreases towards Culiembro, defining the water table. To the south, a second drainage branch is developed within a series of northeast-oriented thrust sheets, draining to the northeast, and containing several major caves, including the 1148 m deep Sistema del Xitu. Its terminal sump has been dye traced to Culiembro, 1 km distant from and 115m below the Xitu sump. The nearby Pozu Jultayu (820 m deep, *c.* 12 km long) contains a large horizontal streamway, which has been also dye traced to Culiembro, 2 km



Picos de Europa, Spain: Figure 3: Profile through the major caves in the northern sector of the Cornion Massif, the western part of the Picos de Europa. Survey data from Oxford University Cave Club home page.

distant from and 600 m below the downstream end of Jultayu. Upstream, the Jultayu river is fed by the low-gradient streamways found at the bottoms of the 644 m deep, 8 km long

Sistema Verdelluenga and the 806 m deep Sil de Oilseda. Other major caves, located 1–2 km further to the west, may be also related to the Culiembro system. They are the Canal Parda (903 m deep), Porru la Capilla (863 m deep) Conjurtao (658 m deep), Jorcada Blanca (590 m deep), and F20 (582 m deep) systems, all developed along a common fault plane and ending in sumps located at similar altitude (1300–1350 m). This altitude is similar to those of the low gradient streams and sumps of Verdelluenga, Sil de Oliseda, and Jultayu, suggesting a hydrologic connection and that the water table in this sector is 600–800 m higher than elsewhere in the Culiembro drainage area (Figure 3; Roberts, 1986).

The Farfao resurgence, located at an altitude of 320 m, in the Cares gorge, drains the northern Central Massif (Figure 1), producing 3 m^3 s s^{-1} in summer. The area drained by Farfao consists of two major thrust sheets, and contains six caves exceeding 1000 m in depth, including the 1589 m deep Torca del Cerro, one of the deepest in the world. Four of these caves (Trave, Cerro, Urriellu, and Castil) have low-gradient streams at their bottoms, interrupted and/or ending in sumps. The coincidence in elevation of streams and sumps indicates that they are at the water table. The elevation of the terminal sumps decreases progressively to the northwest, indicating general drainage towards Farfao. This has been further confirmed by dye tracing in Torca Castil, which is 8 km distant from Farfao.

CARLOS Rossi

Works Cited

Fernández, E., Calaforra, J.M. & Rossi, C. 2000. Karst in the Picos de Europa massif (North Spain). In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N. Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Gale, S.J., & Hoare, P.G. 1997. The glacial history of the northwest Picos de Europa of northern Spain. *Zeitschrift fur Geomorpkologie,* 41(1):81–91

Roberts, S. 1986. Combined survey of the top camp caves. *Proceedings of the Oxford University Cave Club,* 12:55

Senior, K.J. 1987. Geology and speleogenesis of the M–2 Cave System, Western Massif, Picos de Europa, Northern Spain. *Cave Science,* 14(3):93–103

Smart, P.L. 1986. Origin and development of glacio-karst closed depressions in the Picos de Europa, Spain. *Zeitschrift fur Geomorphologie,* 30(4):423–43

Vidal, B. 1990. Picos de Europa. Sistema del Trave:–1441; T–31: *–570. L'Aven,* 50:63–87

Further Reading

Alonso, V. 1998. Covadonga National Park (Western Massif of Picos de Europa, NW Spain): A calcareous deglaciated area. *Trabajos de Geología,* 20:167–81

Beniot, P. (editor) 1985. *Les Picos de Europa. Spelunca* supplement, 19, 64 pp

Maragliano, D., Muñoz, J. and Estévez, J.A. 1998. Record de España en la Torca del Cerro del Cuevón (Macizo Central de los Picos de Europa, Asturias). *Subterránea,* 10:20–29

Marquínez, J. & Adrados, L. 2000. La geología y el relieve de los Picos de Europa. *Naturalia Cantabricae,* 1:3–10

Sánchez, J. & Cerdeño, R. 1999. Resumen de las exploraciones de la Torca de la Nieve—estudio del nivel freático. *Subterránea,* 11: 36–41

Sefton, M. 1984. Cave explorations around Tresviso, Picos de Europa, Northern Spain. 1975–1983. *Cave Science,* 11(4):199–237

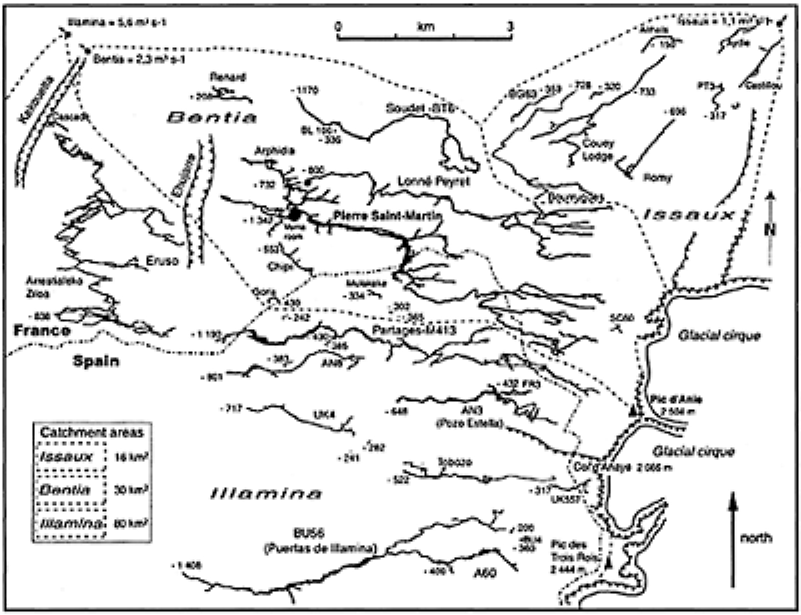
Smart, P.L. 1984. The geology, geomorphology and speleogenesis of the Eastern Massifs, Picos de Europa, Spain. *Cave Science,* 11(4): 238–45

PIERRE SAINT-MARTIN, FRANCE-SPAIN

The French—Spanish Pyrenean massif of Pierre Saint-Martin is of interest both historically, and for its superb geology and speleology. Situated 50 km southwest of Pau, this alpine karst area of 140 km^2, at altitudes between 430 m (Illamina and Bentia springs) and 2504 m (Pic d'Anie), is affected by a montane climate—temperate and marine and very humid (with a rainfall of 2500 mm a^{-1}). The area is characterized by typical alpine topography: rillenkarren and lapiés, rock benches, snow shafts, and underground glaciers, depressions, small valleys, and dolines of glaciokarstic origin. The first speleological investigations known in the area (of the Napia Cave) go back to 1818. Towards 1880, some local naturalists began to explore the shafts beneath Sainte-Engrâce and towards the col of Pierre Saint-Martin. They were joined from 1892 to 1909 by Édouard Alfred Martel, Eugene Fournier, and their companions, who carried out several reconnaissances and explored the canyons of Kakouetta, Holzarté, and Olhadubie.

Between 1930 and 1949, Max Cosyns and Norbert Casteret undertook many descents and explorations of canyons and shafts in the area. In 1950, Georges Lépineux discovered the entrance of the Pierre Saint-Martin cave. More than 320 m deep, the Lépineux shaft was descended for the first time in 1951, but in 1952 exploration was halted by the death of Marcel Loubens in an accident caused by a faulty winch. In 1953, the bottom of La Verna chamber was reached at −734 m. This was the world depth record at the time, and it was the largest underground chamber then known (4.5 million cubic metres).

From 1951 to 2002, more than 350 km of shafts and passages were explored and surveyed and in 1996 the Association pour la Recherche Spéléologique Internationale a la Pierre Saint-Martin (ARSIP) was formed to coordinate research. At the end of 2001, the number of caves explored is impressive: 49 deeper than 300 m, and four deeper than 1000 m (Table 1). The regional map of the caves shows a remarkable density of underground systems (Figure 1). Thanks to underground tracings with fluorescein indicating the hydrological relations between the networks, three large drainage basins are recognized. Two karstic systems drain northwest. The Bentia Basin (2.37 $m^3 s^{-1}$ mean flow, 30 km^2 in area) includes the Pierre Saint-Martin, Lonné Peyret, and Soudet. The Illamina Basin (5.64 $m^3 s^{-1}$, 80 km^2) lies to the south, largely in Spain, with the Partages and BU56 caves draining to the d'Arrestialeko (58 km long). The third basin is Issaux



Pierre Saint-Martin France-Spain: Figure 1. Outline map of the cave passages in the Pierre St Martin and adjacent cave systems, beneath the France-Spain border. The numbers indicate the depths in metres of each cave below its own top entrance.

(1.15 $m^3 s^{-1}$, 16 km^2), to the northeast, which drains the Bourrugues, BG 63, Couey Lodge, and Romy caves. A fourth basin to the east, not indicated on the map, is Lees Athas (1.2 $m^3 s^{-1}$, 17 km^2), but it has few known caves of importance.

The underground and surface karstification is due to favourable geological and geomorphological conditions. Upper Creta ceous limestones −350 m thick and very fractured—directly overlie Paleozoic basement in the axis zone of the Pyrenees. Since the major Miocene uplift, erosion of the overlying impermeable flysch and shales made it possible for karstification to begin in the underlying limestones. Between 20 and 6 million years ago, under subtropical climate conditions, the sedimentary cover was

Pierre Saint-Martin, France-Spain: Table. The deepest caves of Pierre Saint-Martin Massif (in 2002).

Cave	Depth (m)	Length (km)	Location
Las Puertas de Illamina (BU56)	1408	14.5	Isaba (Spain)
Gouffre de la Pierre Saint-Martin	1342	52.5	Arette et Sainte-Engrâce (France), Isaba (Spain)
Réseau de Soudet (BT6)	1170	10.3	Arette et Sainte-Engrâce (France)
Gouffre des Partages (M413)	1097	23.9	Arette (France), Isaba (Spain)
Arresteliako Ziloa	838	58.1	Sainte-Engrâce (France)
Gouffre AN8	810	7.2	Isaba (Spain)
Gouffre Lonné Peyret	807	24.3	Arette et Sainte-Engrâce (France)
Gouffre du Couey Lotdge	733	8.7	Arette et Osse-en-Aspe (France)
Gouffre des Bourrugues (B3)	728	7.5	Arette et Osse-en-Aspe (France)
Sima de Ukerdi Abajo (UK4)	717	4.6	Isaba (Spain)
Grotte d'Arphidia	712	22.3	Sainte-Engrâce (France)

subjected to intense weathering, indicated by the pockets of red earth (with micaceous clays, smectite, chlorite, and goethite) eroded by the modern karst drainage.

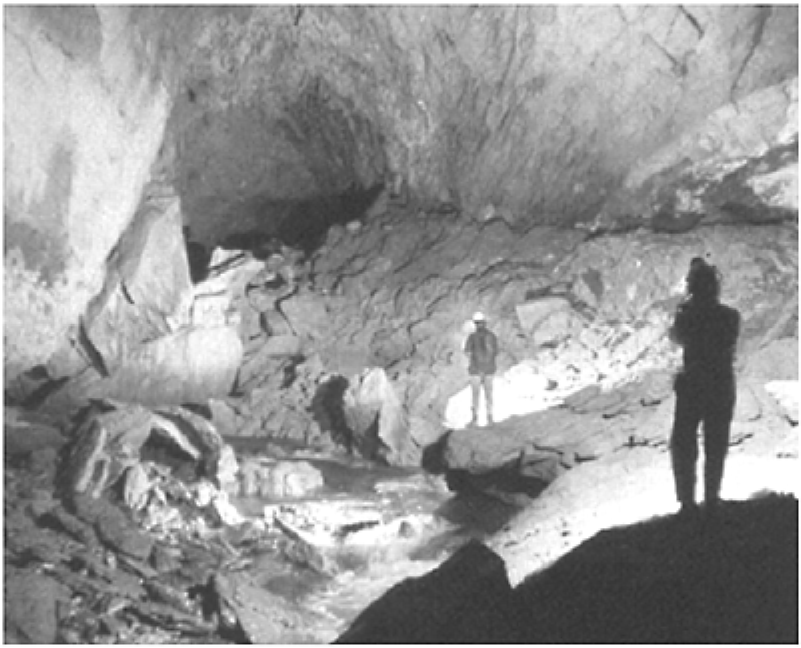
The evidence of lowering of limestone surfaces and of the erosion of karstic closed basins is numerous. The upstream edge of the massif exposes cavities in walls, relict unroofed caves, and large surface stalagmitic masses. However, the calcite deposits are not currently being formed at this altitude, in the absence of soil and vegetation. These old speleothems exposed by erosion are probably pre-Quaternary, and were formed at a time when the massif was less high and the vegetation and soil were more abundant. U-Th dating puts the age at more than 350 ka. These paleo-cavities lost their catchment areas when Pleistocene glacial erosion destroyed the higher cirques.

There are also inactive caves within the limestones, 80–120 m above the Paleozoic basement, but at different altitudes, such as in the caves SC60 (length 1930 m), UK4 (1600 m), AN8 (1500 m), and Chipi Joseteko (1300 m). These dry horizontal conduits, with phreatic morphology, were intersected by more recent caves, and they formed in relation to old base levels which progressively changed with deepening of the valleys. The current base level ranges between 435 and 445 m altitude at the height of the Illamina and Bentia springs. At the downstream end of the Bentia karstic system, 22 km of passages in the Arphidia Cave have five levels between 1100 and 600 m altitude. This situation, low down in the system, is due to a combination of two factors: Pleistocene uplift and the presence of Devonian limestones in the Paleozoic basement. These basement limestones enabled the formation of drains beneath the Cretaceous limestones, due to lowering of the base level. The sediments in the Aranzadi passages—passages which are perched 100m above La Verna chamber—indicate that the underground river formerly flowed in this gallery, but a collapse captured the river in the Paleozoic basement. Significant voids were formed by infiltration in the Devonian floor, and the chamber there evolved by collapse. La Verna chamber (255×245×180 m) is thus related to a hydrological capture by an underground version of a collapse doline.

The Aranzadi passage is accessible by the old EDF (Electricité de France) tunnel, constructed between 1956 and 1960 with the aim of capturing the underground river, but, because of the variability of the flow (from 0.05 $m^3 s^{-1}$ up to an estimated 5–15 $m^3 s^{-1}$), the project was abandoned. This passage contains a sequence of sediments over 20 m in thickness, the most important known in the alpine karst environment (Maire, 1990; Quinif & Maire, 1998). Three unmatched detrital assemblages are observed: a lower ensemble of blocks and scree; a main sequence of silts and calcareous varved clays (Figure 3); a series of fluvial terraces encased in the lower and main sequence. About 50 U-Th dates have been determined on the speleothems. The lower unit probably dates from a former cold period before 330 ka (isotope stage 10). The principal sequence, which ranges from 225000 to 300000 years BP, is allotted to glacial stage 8, from which the external moraine deposits have disappeared. The fluvial terraces are covered with uneroded stalagmites, of which the oldest is 190000 years BP. The oldest stalagmite from La Verna is older than 210000 years; it is located at the same level as the Aranzadi passage and was eroded by the old river. Consequently, the abandonment of the Aranzadi passage corresponds with the evolution of La Verna between 194000 and 211000 years BP. Seismotectonic indicators are widespread in the caves. In BU56, the walls of the meandering passage between 380 m and 450 m depths are broken by a series of tear faults, related to the reactivation of a major east—west fault after the cave passage was formed. Within the Pierre Saint-Martin caves there are numerous collapses on faults, which are evidence of seismotectonic activity due to the compression of the Iberian plate against the European plate.

The massif of Pierre Saint-Martin appears to be a natural laboratory for further detailed study, in space and time, of the different karstification parameters and their complex interactions in an alpine karst situation. The construction of a ski station during the 1960s caused a degradation of the surface karst and pollution of the caves in the Issaux basin, but a project to open La Verna chamber for tourism could become a reality in the future.

RICHARD MAIRE



Pierre Saint-Martin, France-Spain: Figure 2. The underfit streams in the main passage of Gouffre Pierre Saint-Martin between Puits Lépineux and Salle de la Verna. (Photo by Tony Waltham)

Works Cited

Maire, R. 1990. *La haute montagne calcaire,* Paris: Fédération française de spéléologie and Association française de karstologie (Karstologia Mémoires, 3)

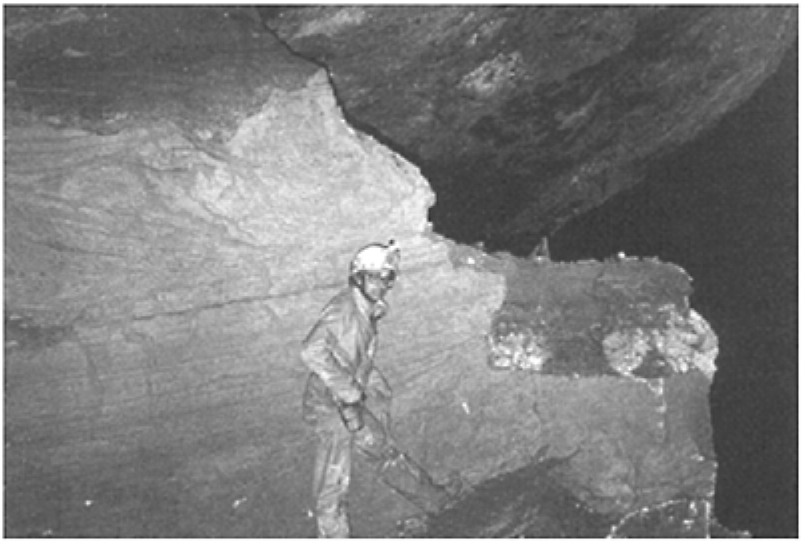
Quinif, Y. & Maire, R. 1998. Pleistocene deposits in Pierre Saint-Martin Cave, French Pyrenees. *Quaternary Research,* 49: 37–50

Further Reading

Douat, M. (editor) 2002. *Bulletin n.17 de l'ARSIP*: 1–250

Pernette, J.-F. 1983. *Rivières sous la Pierre,* Paris: Fernand Nathan

Tazieff, H. 1952. *Le gouffre de la Pierre Saint-Martin,* Paris: Arthaud



Pierre Saint-Martin, France-Spain: Figure 3. The fluvioglacial deposits in Aranzadi gallery (Pierre Saint-Martin Cave). The main unit of laminated clay, with carbonate-rich varves devoid of pollen, correlates with stage 8. The river terraces inset into this unit formed during stage 7 before collapse of Verna Room between 194000 and 211000 years BP. (Photo by Yves Quinif)

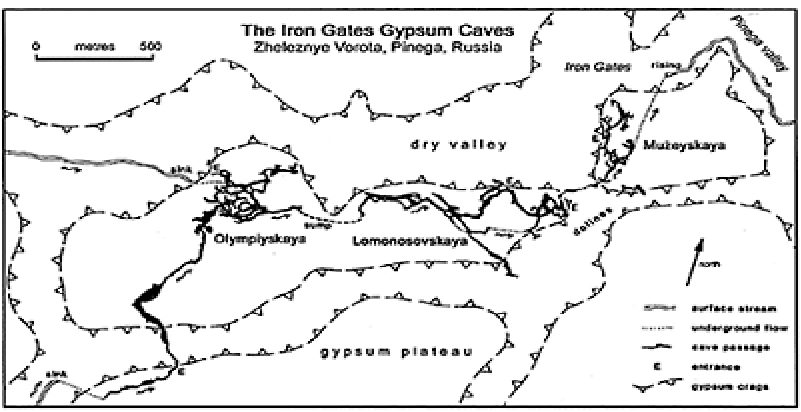
PINEGA GYPSUM CAVES, RUSSIA

Permian gypsum forms a long north-south outcrop west of the Urals, in northern Russia. The main bed of soluble evaporites is a complex of gypsum and anhydrite, that thickens to ~50 m around the small town of Pinega, due east of Arkhangelsk (see area map in Russia and Ukraine). Low plateaux in the almost horizontal gypsum are dissected by the Pinega River and its tributaries. The rugged karst landscape is overgrown with taiga forest of birch and spruce. It is broken by rocky dolines, and large areas are surfaced in spectacular schlottenkarst, with funnel-shaped dolines spaced on 3–4 m centres, tapering into vertical shafts, that are usually plugged with vegetation, snow, or soil just a few metres down. These features are larger than those that are common on gypsum elsewhere, and they constitute an excellent form of polygonal karst. In addition, scattered vertical shafts drop into bedding plane caves.

The plateau edges drop 50 m to the intervening valley floors, and many are broken by long scars and crags of bare gypsum, with some separated pinnacles, sharpened up from the tops of schlotten divides, so that they resemble a small-scale pinnacle karst. Perennial streams flow along many of the valley floors, but some thalwegs are dry—mostly where their streams have invaded older cave passages. There are many sinks, karst lakes, and resurgences, mainly where the thalwegs with more irregular profiles are almost broken into chains of dolines.

Numerous caves are truncated in the valley walls, but most cave entrances are choked by rock debris. New caves, both in the crags and in the doline floors, are often only found when they are exposed by collapse. Some of the new collapses are formed by inwashing of soil and debris, but others are due to rapid dissolution of the gypsum by snowmelt water. Face retreat of the gypsum has been measured at 20 mm a^{-1}, where it is subject to a constant flow of unsaturated surface water. Over 50 km of cave passages have been mapped in the Pinega gypsum, and 22 caves are each longer than 1 km.

A notable feature of the Pinega caves is that a large proportion have dendritic passages that carry, or have carried, significant underground streams. The finest group of caves is at Zheleznye Vorota (Iron Gates), just northeast of Pinega (see Figure 1). The two main caves of Olympyskaya and Lomonosovskaya are connected by a sump, which has been dived to establish a single system with over 9 km of passages. A stream can be followed through the length of the system. Part of it is in shallow vadose canyons, part is in drained phreatic tubes with almost no entrenchment, and it follows a shallow phreatic loop between the



Pinega Gypsum Caves, Russia:
Figure 1. Outline map of the gypsum caves in the Iron Gates Nature Reserve, just above Pinega, Russia

(after surveys by Arkhangelsk Geologia).

Pinega Gypsum Caves, Russia: Figure 2. The main tunnel in Lomonosovskaya, an elliptical phreatic tube in the gypsum, liberally decorated with ice that forms every winter and largely melts away each summer. (Photo by Tony Waltham)

two drier cave systems. The main passages have very low gradients. They were initiated on bedding planes, of which some are clay-bearing paleokarst horizons and others are on thin interbeds of solutionally-resistant dolomite. Many of the largest phreatic tubes are within white gypsum but have ceilings of beautiful, pale blue anhydrite.

At least two higher levels of passages can be recognized. These also follow the bedding, but are now heavily collapsed. Some have thick curved slabs that are slowly peeling away from the ceiling by plastic deformation, which is aided by the hydration of anhydrite to gypsum. Kulogorskaya is another dendritic system with multiple levels close to the main river just northeast of Pinega; it has over 16 km of mapped passages.

Other caves are drained phreatic mazes of joint-controlled passages. Symphoniskaya (3.2 km long) and Golubinskaya (1.6 km long) are both maze caves that carry no modern streams and lie abandoned at higher levels in the gypsum plateaux. Their long, narrow, fissure passages locally widen, and some link into bedding-guided chambers. The mazes are comparable in appearance to those in the gypsum caves of the Ukraine; it is unclear if they were formed in similar conditions of slow, rising phreatic flow, or at a river-level water table beneath multiple drainage inputs from the schlotten fissures.

In contrast, the larger passages in the main dendritic cave systems have acted as major karst conduits. Phreatic tubes 10–20 m wide and 3 m high, have carried streams much larger than those that now occupy some of them as underfits. The segments of large old passage, now abandoned above the modern streams, may have been formed by subglacial meltwater during the Pleistocene. The braided system of surface valleys, cut with irregular profiles into the gypsum plateau at the Iron Gates (see Figure 1), is also characteristic of subglacial phreatic drainage.

Pinega lies just outside the Arctic zone of permafrost. The ground never freezes to depths of more than a few metres, and the larger cave streams continue to flow through the winter, beneath a landscape with a thick blanket of snow for nearly half the year. However, freezing air blows through the caves that have multiple entrances, or just sinks into those with single entrances. All percolation seepage, therefore, freezes as it enters the caves, and creates huge ice cascades and spectacular icicles (Figure 2). Lakes freeze over to form underground skating rinks, even where water continues to flow beneath. In addition, water vapour freezes into giant hoarfrost of ice crystals that are plastered over the walls and ceilings of all passages near the entrances. The total effect is very beautiful, and nearly all the ice displays disappear each summer and form anew every winter. Only below some of the larger open entrances, does blown-in snow accumulate beyond what can melt, so that some small cave glaciers are created; the oldest ice yet found has been dated to 3000 years ago.

The finest of the gypsum karst landforms, and many of the longer caves, now lie protected within the Pinega National Park and the Iron Gates Nature Reserve. Both these sites are primarily known for their populations of deer, moose, and black bears that roam unmolested through the taiga-covered karst.

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Further Reading

Malkov, V.N., Nikolaev, J.I. & Kuznetsova, V.A. 1986. Regionalisation of the Pinega and Kuloj basins according to settings and intensity of exogenous geological processes. In *Geologija i poleznye iskopaemye Arkhangelskoj oblasti,* Moscow: 154–74

Malkov, V.N., Nikolaev, J.I. & Luskan, V.F. 1988. Types of karst caves of the Piezhje. In *Peschery: peschery v gipsakh i angidritakh*, Perm University Publishing: 46–50

Waltham, T. 1994. Gypsum caves of Pinega. *International Caver,* 10:15–22

Waltham, T. & Cooper, A. 1998. Features of gypsum caves and karst at Pinega (Russia) and Ripon (England). *Cave and Karst Science,* 25:131–40

PIPING CAVES AND BADLANDS PSEUDOKARST

Introduction

Grain-by-grain removal of particles by groundwater flow produces caves and smaller conduits in some poorly soluble rocks and unconsolidated material. Nonkarstic hydrologists and engineering geologists consider these phenomena on the basis of mindsets with radically different terminologies and methodologies. If read carefully, however, their literatures are perceived to achieve largely similar conclusions.

The traditional engineering geology mindset is expressed especially by Parker *et al.* (1990), and the general viewpoint of academic nonkarstic hydrologists is explicated elegantly by Dunne (1990). Dunne seems more concerned with movement of water through micropores and intergranular and interpedal voids than with depressions, caves, and smaller conduits, but includes them in his overall construct. The editors of the authoritative volume which brought together these divergent papers deliberately avoided attempting to arbitrate these semantic and conceptual conflicts (Higgins & Coates, 1990, p. vii). An additional European terminology of suffosion pseudokarst has not been widely accepted elsewhere.

Parker's concepts and terminology are congruent with those of the current mainstream of English-language speleology. Consequently, Parker's terminology and concepts are employed in this entry, and extended to more consolidated rocks than those he studied. For details of the inception stage of piping, interested readers are referred to Dunne (1990) and numerous references cited therein.

Definitions: Piping Caves

Piping caves are natural underground spaces; large enough to enter and investigate; extending beyond daylight; formed by grain-by-grain subterranean removal of particles by channelled flow of groundwater; primarily from poorly soluble rock or granular material; and with little or no dissolution. Other than the cited human module, no clearcut line of differentiation can be specified between large pipes and small piping caves, and an interface or continuum exists between piping caves and dissolutional caves in rocks of various solubilities. Terms used in the literature for piping caves include clay caves, claystone caves, gully caves, loess caves, mud caves, mudstone caves, peat caves, shale caves, slutch caves, suffosion caves, tunnel caves, and tunnels.

Definitions: Badlands

This term is not the equivalent of the Spanish-language "malpais" which generally is applied to rough flowfields of lava. Badlands topography consists of a complex of bare, moderately steep slopes intricately dissected by intermittent stream runoff, with narrow interfluves and generally with a resistant caprock. Its type locality is Badlands National Park, South Dakota (United States). Especially notable examples also are exhibited in Petrified Forest National Park, Arizona (United States). Here, expansion and contraction of clays with rainfall and drought repeatedly roof and unroof many small closed conduits (Mears, 1968). Badlands topography develops especially in shales, mudstones, claystones, and siltstones, but also occurs in some thin-bedded calcareous and arenaceous rocks, and in volcanic ash. Mears and Parker *et al.* (1990) (Figure 2) and others have neatly depicted mechanisms which produce piping and other pseudokarstic landforms in such topography. The terms avalanche pseudokarst, loess pseudokarst, mudflow pseudokarst, piping pseudokarst, and suffosion pseudokarst have been used to describe badlands pseudokarst.

Significance

Some planetary geologists (e.g. Malin & Edgett, 2000) have suggested that certain landforms on Mars are piping features. Thus the possibility of extraterrestrial piping caves must be given serious consideration as potential sources of subterranean ice (see also Extraterrestrial Caves). On Earth, however, piping caves are primarily of interest as geological curiosities and recreational sites. Piping itself is a serious, often overlooked cause of engineering problems.

Types of Piping

Piping appears in different physical forms and originates in different ways, depending on climatic and geological conditions. Basically, it is accomplished by one of two specific mechanisms. One is a form of mass fluidization of soil with failure of lithostatic resistance. This produces "heave", "sand boils", and the like, without any well-defined conduit and hence is not considered further in this entry. The other mechanism is an enclosed process forming more or less stable "pipes" in poorly soluble rocks and unconsolidated materials. These intergrade into dissolution conduits in karstifiable rocks. This process occurs through eluviation, sapping, seepage face erosion, "tunnel scour", and other erosive mechanisms. Primarily it occurs in drylands settings, especially in granular media and in rocks predisposed to slake, e.g. mudstones and claystones. Large examples tend to occur in these rocks where shattered in avalanches and mudslides. In humid regions, this form of piping is said to occur only in soils and peat (e.g. Jones, 1990), but this fails to consider recent speleological literature including that on caves in quartzose rocks.

Classical Piping in Diylands

Mostly relying on English-language sources, Parker *et al.* (1990) have provided a global overview of more than a century of studies of drylands piping and the pseudokarstic features which it produces, including subsurface drainage with caves and smaller conduits, funnel-shaped sinks and swallets, dry valleys, natural bridges, and shallow circular lakes. Some of these features resemble karstic and other pseudokarstic landforms (e.g. thaw lakes on permafrost pseudokarsts). Classically, the process begins with laminar transport of fine particles through sand or gravel, or through tiny cracks in coherent rocks. A limited amount of solution of matrix or of particles may occur (Striebel & Schäferjohann, 1997). Once a continuous channel is established, transport becomes turbulent and scour and other erosive mechanisms enlarge it. As the pipe grows larger, the volume of flow increases. Slumping and local roof collapse may permit entry of additional volumes of runoff, enlarging it further, or may dam it with surface debris, leading to development of a tortuous conduit pattern. The resulting pipes may propagate vertically or at grade, upslope or downslope. Some develop braided or dendritic networks. Perhaps in many cases, the incipient pipes develop at the bottom of shrinkage or other crevices rather than de novo between sand- or gravel-sized particles. This occurs especially in clayey shales and other rocks whose physical properties change with their state of hydration. Alternating swelling and shrinkage repeatedly form large and small cracks.

Some clays are especially slippery when wet, with formation of dislocation blocks, large and small block slippages and rotation, extensive spalling and even underground slides, all of which contribute materially to erosion and pipe enlargement. Numerous authors cited by Dunne report that a high exchangeable sodium content deflocculates such clays, concentrating flow of water in crevices and thus providing additional lubrication. Piping is not restricted to such rocks, however. It also occurs in quartzose rocks. Here, corrosion and limited dissolution may modify crevice features into multiprocess caverns with features typical of karst (see entries on Pseudokarst and Crevice Caves). Further, the superficial parts of some pyroclastic flows and ash fall deposits lose cohesiveness when wet, and fracture in large blocks (some of which form the roof of fractures). Further, they also tend to become slurries of wet sand which flow through newly-formed streamway pipes one to a few metres below the surface at the bottom of roofed fractures (Halliday, 1986).

Badlands Pseudokarst

Some badlands topography is riddled with pipes, piping caves, funnel-shaped dolines, dry valleys, and other features of centripetal subsurface drainage, commonly observed in karstic terrain. Locally, these form specific landscapes. Because their bedrock tends not to be notably coherent, most individual forms are short-lived, but the general landscape evidently persists throughout long periods of scarp retreat. Some features in Triassic shales or claystones in Arizona's Petrified Forest National Park (United States) seem to be especially stable, but elsewhere, each storm may replace old features with new examples.

Piping Caves

Because they are short-lived, only a few classical pipes in poorly consolidated material persist long enough to reach the size of caves as defined in this volume. Perhaps simplest are the muchvisited caves in claystones and mudstones in Southern California's arid Arroyo Tapiado area. Rainfall here is rare and scant, but is sufficient to cause numerous piping caves in narrow gorges in Pliocene lake deposits through the mechanisms of block slumping, disaggregation, and outwash. Except where they are partially or completely filled with disaggregated slump, the gorges are deep, narrow meandering stream slots with vertical walls. Most of the caves are unitary. Blind valleys leading to pipe swallets are common. Crumbly slumped blocks form the roofs of caves as much as 110m long. Multiple cave levels and collapse entrances to caves are not uncommon. Cave rooms are up to 25 m high and 10m wide. In normal weather, the caves are dry and dusty and "dry waterfalls" up to 15 m high have been reported. Apparently similar caves are present in Saskatchewan's Big Muddy Valley (Canada).

Disruption of structural stability during avalanching evidently facilitates piping speleogenesis in claystones and mudstones. Officers Cave in Eastern Oregon (United States) is especially well known (Parker, 1964). The 345 m cave is in a rotated landslide mass of Oligocene/Miocene John Day siltstone which contains montmorillonite and ash, and is slippery when wet. Desiccation cracks are numerous, with innumerable small fracture sets, slickensides on the sides of small blocks, extensive spalling, and block fracturing. A dendritic drainage conducts disaggregated sand-sized and smaller particles to an intermittent streamway into which the cave sags with headward erosion of its scarp. Small vertical pipes perforate nearby hillsides.

In semi-arid western Colorado (United States), more than 100 claystone and mudstone caves have been found, especially near the town of Grand Junction. Most of these also are in landslide and slump masses. The largest is the Anvil Points Claystone Cave, where 620 m of passages have been mapped (Davis, 2001). Here, a chaotic mixture of clay, silt, sand, and angular blocks of sandstone sags intermittently into another dendritic stream network. The upper part of the rectilinear Catarina-Confusion Cave System in Texas' Palo Duro Canyon (United States) also is in a landslide mass. Large pseudokarstic sinks are reported elsewhere in this canyon, and approximately 50 smaller piping caves have been noted. In Cameron County, Texas (United States), Model T Cave was formed by runoff of irrigation water which cut a short subterranean passage through an old trashpile and the surrounding soil. Its small central room was roofed by the hood of a Model T Ford; the walls and floor are soil. Archaeological discoveries included a steering wheel and a sparkplug.

Loess Caves

Loess pseudokarst is a special case. The study of loess is an active subscience, with international symposia and an extensive literature entirely separate from speleology. Numerous pseudokarstic features form in loess and loess-like silt, especially in vast areas of China. Although Jakucs (1977) attributed much of such piping to decalcification accompanied by pedological alteration, caves as defined in this volume are perhaps the least of these features. Cavernous features have been described, but the vast majority in China are artificial habitations and shelters. Some of these are artificially enlarged pipes and a few such pipes evidently are large enough to qualify as caves.

Piping in Humid Lands

Jones (1990) has provided a limited global overview of piping in humid lands. Such piping tends to occur in or at the top of thick, saturated soils rather than in bedrock or alluvium as in drylands. Such pipes are generated by high through-flow discharges (Jones, 1990) but rarely remain open long enough to form caves.

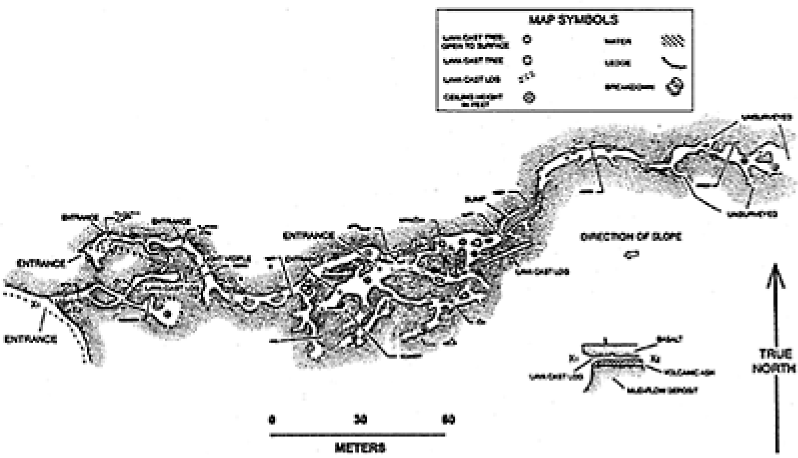
In the United States, wetlands piping occurs in badlands topography in humid eastern Oklahoma and a variety of other settings. The 804 m long Christmas Canyon Cave (Washington state), is a low (<0.5 m), braided channel in volcanic ash atop a mudflow deposit beneath a recent lava flow in Mount St Helens National Volcanic Monument (Figure 1). In the 1980 blast zone on the other side of Mount St Helens, extensive but very shortlived pseudokarsts developed in thick ash-cloud pyroclastic accumulations. Much of their volume was soon piped through crevices, some of which were in parallel groups (Figure 2).

In quartzites in tropical rainforests, groundwater flow through pipes has removed enormous volumes of clastic particles, forming conduits indistinguishable from karstic dissolution conduits. This is one extreme of the limestone-quartzite dissolutional spectrum. In New Zealand, the 8 km Bohemia Cave was largely formed by groundwater erosion in phyllites underlying marble.

Peatlands, and particularly upland blanket bogs, are very susceptible to piping erosion and pseudokarst landscapes with stream-sinks, closed depressions and risings are common. Small pipes (<10 cm diameter) occur at different depths through the profile but larger pipes may form by upwards erosion at the interface with the underlying bedrock. These pipes often reach accessible dimensions but are only rarely long enough to qualify as true caves. Pipes are common in all areas of upland blanket bog in Britain and Ireland, and caves have been explored in the Derbyshire Peak District (where they are known as slutch caves and are up to 50 m long), on the slopes of Kippure outside Dublin, and on Cuilcagh Mountain in County Fermanagh, Northern Ireland, where Poll na Mona has a length of 150 m. “Soil caves” in tropical Ecuador (Funkhowser, 1951) may have had a similar origin in leached lateritic soil.

Interfaces and Multiprocess Caves

Concomitant rockfall and piping form caves up to 300 m long in clean, friable, and poorly cemented sandstones in Arkansas (United States). In Minnesota (United States), low, wide maze caves and tubular caves up to 350 m long exist in the similar St



Piping Caves and Badlands Pseudokarst: Figure 1. Map of Christmas Canyon Cave, a long piping cave in volcanic ash beneath a basalt flow, Washington state (United States). Courtesy Larry King.

Peter sandstone. One maze cave under downtown Minneapolis underlies an entire city block.

In central Kenya, Gigglers Caves appear to fall within an interface between crevice caves, dissolutional caves, and piping, much like multiprocess caves in quartzite, discussed in the entries on Pseudokarst and Crevice Caves. They are developed along a series of small crevices in a hard granular tuff. Their passages

Piping Caves and Badlands Pseudokarst: Figure 2. 18 May 1980 pyroclastic deposits in the Spirit Lake pseudokarst, Mt St Helens, Washington state (United States). Pits are along crevices that are intermittently roofed by slumped blocks, with piping at the bottom of the crevices. (Photo by William Halliday)

appear primarily phreatic, with rounded conduits and small rounded chambers which fill in flood season. Bedding plane development is prominent, and only a few linear crevice passages are present. In northwestern Kenya, voluminous Kitum Cave, Makningen Cave, and some others on Mt Elgon appear to be large multiprocess caves formed primarily by removal of enormous quantities of particulates by disaggregation and periodic stream transport. Other processes include considerable dissolution of complex bedrock. Makningen Cave is primarily a deadend borehole passage up to 70 m wide and 10 to 20 m high, but it also has a high, rounded chimney more than 5 m in diameter. These caves were formed in little-studied lakebed deposits quite unlike those in the Arroyo Tapiado area. The Mt Elgon lakebed complex contains agglomerate, tuff, organic components, and evaporites. Soluble salts provide underground salt licks for both wild and domestic animals.

Extraterrestrial Piping and Piping Caves

Malin and Edgett (2000) have observed several types of Martian terrain which may be analogous to various badlands and piping pseudokarst features (see also Extraterrestrial Caves). Especially intriguing evidence of conduits exists in two or three specific terrains: alcoves associated with resistant layers in cliffs, landslide or slumped material, and “perhaps colluvium”. On Earth, piping occurs in all three such terrains, and piping caves in at least two of them. Characteristically, Martian channel heads and interiors appear not to be clogged with clastic debris, implying efficient transport through conduits. Present-day conditions on Mars are hyper-arid beyond any conditions on earth, but some hyper-

Piping Caves and Badlands Pseudokarst: Figure 3. Makningen Cave, Kenya, a voluminous piping cave in partially soluble lakebed deposits. Note the large chimney above the caver. (Photo by William Halliday) arid terrestrial regions may have piping caves that may be useful as models for Mars. Limited photodocumentation of the Oumou Caves in the Republic of Chad (Dossal, n.d., *c.* 1995) suggests such a possibility. The Cave of Swimmers and others in sandstone on Gilf Kebir in Egypt also may be analogs but are even less known geologically.

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Works Cited

Davis, D. 2001. Anvil Points Claystone Cave Complex: An exceptionally large "mud cave" system. *NSS News,* 59(11):331–34

Dossal, D. (photographer) n.d. (*c.* 1995) Untitled photograph. In *Expedition 1994 "Tibesti—Terre Interdite",* edited by P.Courbon *et al.,* Carcassonne: Imp. Gabrielle, p.36

Dunne, T. 1990. Hydrology, mechanics, and geomorphological implications of erosion by subsurface flow. In *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms,* edited by C.G.Higgins & D.R.Coates

Funkhowser, J. 1951. Soil caves in tropical Ecuador. *NSS News,* 9:4

Halliday, W. 1986. Caves and other pseudokarstic features of Mount St. Helens: 1980–1985 observations. In *Mount St Helens: Five Years Later,* edited by S.A.C.Keller, Cheney,Washington: Eastern Washington University Press

Higgins, C.G. & Coates, D.R. (editors) 1990. *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms,* Boulder, Colorado: Geological Society of America (GSA Special Paper 252)

Jakucs, L. 1977. *Morphogenetics of Karst Regions,* New York: Wiley

Jones, J. 1990. Piping effects in humid lands. In *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms,* edited by C.G.Higgins & D.R.Coates

Malin, M. & Edgett, K. 2000. Evidence for recent groundwater seepage and surface runoff on Mars. *Science,* 288:2330–35

Mears, B. 1968. Piping. In *Encyclopedia of Geomorphology,* edited by R.W.Fairbridge, New York: Reinhold

Parker, G. 1964. Officers Cave, a pseudokarstic feature in altered tuff and volcanic ash of the John Day Formation in Eastern Oregon. *Bulletin of the Geological Society of America,* 75:393–407

Parker, G. *et al.* 1990. Piping and pseudokarst in drylands. In *Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms,* edited by C.G.Higgins & D.R.Coates, Boulder, Colorado: Geological Society of America

Striebel, T. & Schäferjohann, V. 1997. Karstification of sandstone in central Europe: Attempts to validate chemical solution by analysis of water and precipitates. In *Proceedings of the 12th International Congress of Speleology,* vol. 1, edited by J.Bauchle *et al..,* Basel, Switzerland: Speleo Project

Further Reading

Péwé, T., Liu Tungsheng, Slatt, R.M. & Li Bingyuan. 1995. *Origin and Character of Loesslike Silt in the Southern Qinghai-Xizang (Tibet) Plateau, China,* Washington DC: US Government Printing Office (US Geological Survey Professional Paper 1549)

Rideau, D. & Hansen, A. (editors) 1993. *Disorder and Granular Media,* New York: North Holland

PISCES (FISHES)

A Chinese account from 1541 was probably the first record of a”blind, white fish”, the description given of the depigmented, often eyeless, fishes which are found in caves and other subterranean habitats. Although this stygobitic species, and others, were already known, the first formally described species was *Amblyopsis spelaea* from Mammoth Cave, Kentucky (United States) in 1842. By 1969, when the seminal work by Georges Thinès *(L’Evolution regressive des poissons cavernicoles et abyssaux)* was published, the total number of stygobitic fish described was about 50. Since this date, due to a large increase in cave exploration, particularly in China, Southeast Asia, and Mexico, the total has nearly tripled to 92 described species. Five countries alone (China, Mexico, Brazil, United States, and Thailand) contain almost 50% of the total, although subterranean fishes have been recorded in 30 countries. The trend of description fits an exponential curve and it is possible to predict that there could be 250 known species by 2050. Stygobitic fishes seem to be restricted to tropical and subtropical regions with limits of 40°N and 25°S. Many species of fishes are known from caves outside this range but none are obligate. Two hypotheses may explain this: (1) glaciation in the northern hemisphere in Pleistocene times rendered extinct any pre-existing stygobitic fishes and there has been insufficient time for more to evolve; (2) the lower temperature in temperate regions leads to a reduced food supply so that stygobitic fish cannot evolve.

Nearly three-quarters of all hypogean fishes belong to the Superorder Ostariophysi, but as this group comprises over 60% of all freshwater fishes this is not surprising. The principal families containing hypogean fish are the Cyprinidae and Balitoridae (with 37 species) and various siluriform (catfish) families (with 24 species). Eighteen families have stygobitic representatives and only a few species are of marine origin. The genera *Lucifuga*, with five species (all restricted to hypogean waters in the Caribbean), *Ogilbia* (two species, both Bythitidae), and *Milyeringa* (Gobiidae) are the main marine invaders. In 17 cases two or three species exist in the same hydrological system. Stygobitic fishes account for only 0.3% of all Teleosts (the large group of fishes with bony skeletons).

Most species live in vadose streams (e.g. *Ancistrus cryptophthalmus* in Brazil) but some are known only from phreatic regions. Perhaps the most extreme hypogean environment is that within the Edwards Aquifer, San Antonio, Texas, United States (see Edwards Aquifer: Biospeleology). This aquifer exists to a depth of at least 600 m and has a very diverse fauna including two fishes, *Satan eurystomus* and *Trogloglanis pattersoni* (both Ictaluridae). These fishes show adaptations to the extreme hydrostatic pressure (Langecker & Longley, 1993). Other fishes live in shallow phreatic aquifers and the aberrant, and probably ancient, *Phreatobius cisternarum* (Pimelodidae) appears to inhabit water sheets underlying the mouth of the Amazon River.

Hypogean fishes are very restricted in distribution and 50 are known from only one site each. Even where species are known from more than one site, they may exist as sub-populations between which there is little, if any, demographic or genetic exchange. Only two species are widely distributed, *Typhlichthys subterraneus* in the United States and *Lucifuga spelaeotes* in the Bahamas, and both may consist of several, genetically distinct, sibling species.

Very few of the known species have been properly studied. The best known is the cave form of *Astyanax fasciatus* from Mexico. Since its discovery in 1936, and the important observation that the troglomorphic cave form and the normal epigean form can interbreed, many observations and experiments have been undertaken (Wilkens, 1988). It is likely that the troglomorphic populations are actually a separate species, and they were once considered as a separate genus *(Anoptichthys)*. The four stygobitic species from the family Amblyopsidae are also relatively well known (see Pisces: Amblyopsidae). Other species which have been relatively well studied are *Pimelodella kronei* (Pimelodidae) (e.g. Trajano, 1991), *Caecobarbus geertsii* (Cyprinidae) (e.g. Heuts & Leleup, 1954), the cave form of *Poecilia mexicana* (Poeciliidae) (e.g. Parzefall, 2001) and *Milyeringa veritas* (Gobiidae) (e.g. Humphreys, 2001).

Typical troglomorphic features include absence of eyes and melanin pigment; elaboration of extra-ocular sensory structures such as lateral line organs and canal neuromasts; behavioural changes (slowing of swimming speed, loss of aggressive behaviour); and extreme K-selection with lower growth rate, increased longevity, delayed reproduction, and fewer and bigger eggs with more yolk. The lost characters are termed “regressive” characters, the others are termed “constructive” since they allow the fishes to exist in the usually exacting cave environment (see Evolution of Hypogean Fauna). The most advanced regressive and constructive features are found in phylogenetically old fishes, those evolving longest in the subterranean environment (e.g. Wilkens, 1988).

Many other species of fishes have been recorded from hypogean habitats (see e.g. Poly & Boucher, 1996). Most of these are accidentally present and will not be able to support viable populations within the cave/subterranean environment. While in the cave they may function as predators or prey, or when dead, as a substrate for decomposition thereby providing potential food for other cave animals. Some species can feed and reproduce successfully underground (stygophilic species). Very few of these have been studied but they could provide information on the mechanisms of cave colonization and the acquisition of troglomorphy. One species from China *(Varicorhinus macrolepsis)* appears to be a habitual trogloxene. It migrates into the warmer cave water in winter, existing on stored fat, but leaves the caves in summer to feed and breed (Zhang, 1986). There are also a number of species in the Dinaric karst which behave as habitual trogloxenes.

Most subterranean fishes are opportunistic feeders, taking whatever food they can obtain. Some are generalist predators but only a few are thought to be the top predators in a system (possibly *Satan eurystomus* and *Ogilbia pearsei*). Given the sporadic nature of food supplies within caves these animals are adapted to withstand long periods without food and build up large, to massive, deposits of fat and adipose tissues within the body.

Subterranean fishes are among the world’s most endangered animals. Since around 50 taxa are known from one location only, they are susceptible to extinction following anthropogenic disturbances, e.g. a toxic spill. The international “Red List” contains three subterranean fishes on the critically endangered category and two Chinese species, *Sinocyclocheilus hyalinus* (the fish recorded in 1541 above) and *Triplophysa gejiuensis* have been described as “nearly extinct” by Chinese workers. Many other species are probably vulnerable and require special consideration.

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Works Cited

Heuts, M.J. & Leleup, N. 1954. La géographie et 1'ecologie des grottes du Bas- Congo: les habitats de *Caecobarbus geertsii* Blgr. *Annales Musée Royale du Congo Belge,* 35:1–71

Humphreys, W.F. 2001. *Milyeringa veritas* (Eleotridae), a remarkably versatile cave fish from the arid tropics of northwestern Australia. *Environmental Biology of Fishes,* 62:297–313

Langecker, T. & Longley, G. 1993. Morphological adaptations of the Texas blind catfishes *Trogloglanis pattersoni* and *Satan eurystomus* (Siluriformes, Ictaluridae) to their underground environment. *Copeia,* 1993:976–86

Parzefall, J. 2001. A review of morphological and behavioural changes in the cave molly, *Poecilia mexicana,* from Tabasco, Mexico. *Environmental Biology of Fishes,* 62:263–75

Poly,W.J. & Boucher, C.E.. 1996. Nontroglobitic fishes in caves: Their abnormalities, ecological classification and importance. *American Midland Naturalist,* 136:187–98

Trajano, E. 1991. Population ecology of *Pimelodella kronei,* troglobitic catfish from southeastern Brazil (Siluriformes, Pimelodidae). *Environmental Biology of Fishes,* 30:407–21

Wilkens, H. 1988. Evolution and genetics of epigean and cave *Astyanax fasciatus* (Characidae, Pisces). Support for the neutral mutation theory. *Evolutionary Biology,* 23:271–367

Zhang, C. 1986. On the ecological adaptation and geographical distribution of the barbine fish *Varicorhinus macrolepis* (Bleeker). *Acta Zoologica Sinica,* 32:266–72

Further Reading

Environmental Biology of Fishes 62(1–3), 2001 is a special issue on hypogean fishes.

Many papers providing a modern perspective on cave fish biology.

Parzefall, J. 1998. Behavioural adaptations of cave fishes. In *Encyclopaedia Biospeologica,* vol. 2, edited by C.Juberthie & V. Decu, Moulis and Bucharest: Société Internationale de Biospéologie

Describes the various behaviour changes that subterranean fishes have undergone during their adaptation.

Proudlove, G.S. 2001. The conservation status of hypogean fishes. *Environmental Biology of Fishes,* 62:201–13

Describes why cave fishes are so vulnerable and provides an IUCN threat category for 85 species.

Thinès, G. 1969. *L'évolution rǵressive des poissons cavernicoles et abyssaux* [The regressive evolution of cave and deep sea fishes], Paris: Masson

The best review of the biology of cave fishes.

Thinés, G. & Proudlove, G.S. 1986. Pisces. In *Stygofauna Mundi,* edited by L.Botosaneanu, Leiden: Brill

Lists all troglomorphic species, including those from non-cave habitats (e.g. river rapids).

Weber, A., Proudlove, G.S. & Nalbant, T.T. 1998. Morphology, systematic diversity, distribution, and ecology of stygobitic fishes. In *Encyclopaedia Biospeologica,* vol. 2, edited by C.Juberthie & V.Decu, Moulis and Bucharest: Société Internationale de Biospéologie

Contains a list of subterranean fishes and some details of their biology.

PISCES (FISHES): AMBLYOPSIDAE

This freshwater family, in the Order Percopsiformes, is distributed in the southern and eastern (unglaciated) United States. It is characterized by the presence of a flattened head, a strongly protruding lower jaw, a jugular vent (anus), and small embedded cycloid scales, except on the head, which is naked. Individuals have rows of sensory papillae on the head, body, and tail. Their eyes range from small (microphthalmic) in the epigean and stygophilic species, to vestigial (remnant eye tissue under the skin) in the stygobitic ones. Stygobitic species are also characterized by: (1) depigmentation (they have a pinkish colour due to the blood vessels showing through the translucent skin, with only a few, mostly nonfunctional, melanophores); (2) low metabolism; (3) low fecundity; and (4) increased swimming efficiency, tactile receptivity, and longevity. The systematics of this family need revision since genetic studies have shown that they are much more complex that previously believed (Bergström *et al.*, 1995). The six species of this family demonstrate the transition from epigean (surface) to hypogean waters: *Chologaster cornuta* is epigean, *Forbesichthys agassizi* is a stygophile or facultative cavernicole, and *Typhlichthys subterraneus, Amblyopsis spelaea, Amblyopsis rosae,* and *Speoplatyrhinus poulsoni* are all stygobites, with increasing troglomorphy from *T. subterraneus* through to *S. poulsoni* in the sequence above (see Figure). Comparative characteristics are summarized in the Table. The family is most closely related to another Percopsiform, *Aphredoderus,* but it may merit its own order, the Amblyopsiformes.

Swamp fish, *Chologaster cornuta*. This species is characterized by being dorsally brown and ventrally creamy white, with three dark stripes on each side. It is found in swamps, ponds, ditches, and slow streams in the Atlantic Coastal Plain from southeast Virginia to central Georgia. It feeds mostly at night, on small crustaceans and aquatic insects. It spawns in March and April and may live up to two years. Although locally common, individuals are hard to spot because they are largely nocturnal and found in heavily vegetated waters.

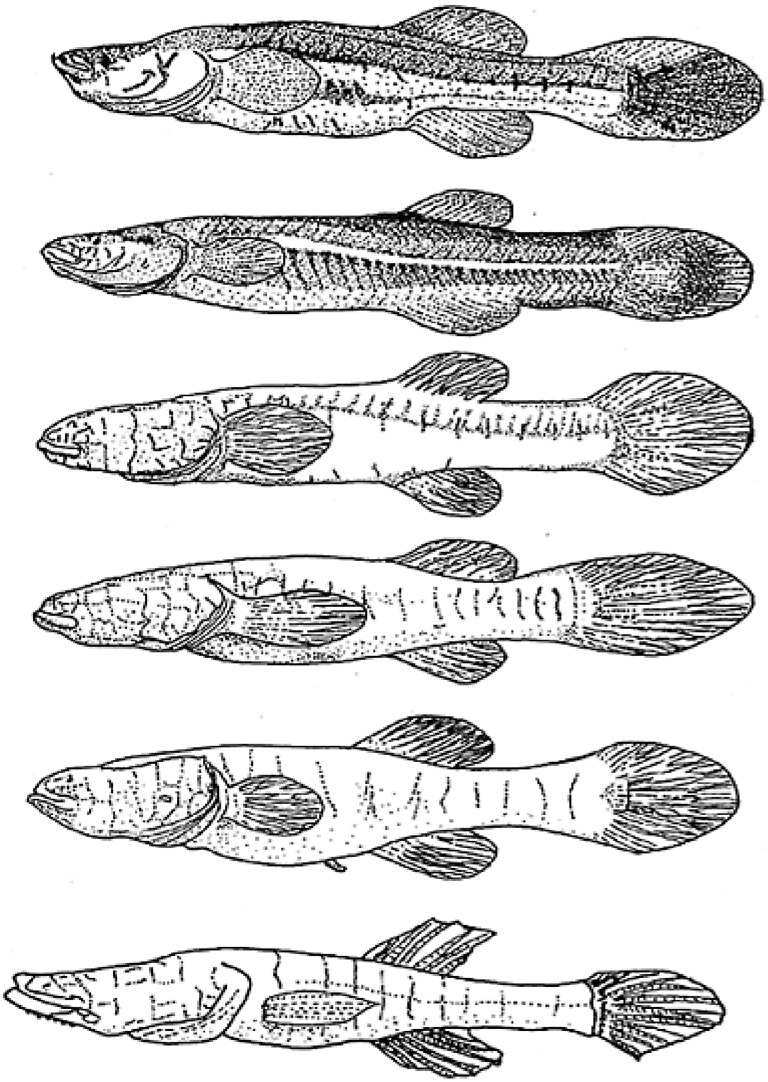
Spring cavefish, *Forbesichthys agassizi*. This species is characterized by being dorsally dark brown to nearly black, grading to lighter brown laterally. It is ventrally cream-yellow, often with a thin yellow stripe along each side. It is found in central and western Kentucky (west to the Tennessee River) to southern central Tennessee and west across southern Illinois to southeastern Missouri. The Missouri population may have been isolated from the others for 2000 years when the Mississippi River changed its course. Individuals are active in springs at night (feeding on crustacea, insect larvae, and oligochaetes) and they usually retreat underground during the day. The few individuals which venture into the spring portions of their habitat hide under rocks or debris. They prefer highly oxygenated water, and show scotophilia (i.e. they respond to light by moving away from it), thigmotaxis (orienting themselves using clues in the substrate), and a wide range of temperature tolerance. Little is known of their breeding habits, but spawning probably takes place underground in the winter.

Southern cavefish, *Typhlichthys subterraneus*. This species is probably a mosaic of unrelated (paraphyletic) populations (Bergström *et al.*, 1995). It is found in the subterranean waters of two major disjunct ranges separated by the Mississippi River: the Ozark Plateau of central and southeastern Missouri and northeastern Arkansas, and the

Cumberland and Interior Low plateaux of northwest Alabama, northwest Georgia, central Tennessee and Kentucky, and southern Indiana. It inhabits deep pools and streams, where individuals feed mostly on copepods. Breeding probably occurs in late spring in association with rising water levels and individuals are long-lived, slow-growing, and

Pisces (Fishes): Amblyopsidae: Summary information for amblyopsid species.

Species	Maximum size (standard length, SL, mm)	Eyes	Pigmentation	Number of rays in fins			Pelvic fins	Number of rows of papillae in the caudal fin
				Dorsal	Anal	Caudal		
C. cornuta	68	Microphthalmic	Yes	9–12	9–10	9–11	Absent	0–2 (branched)
F. agassizii	75	Microphthalmic	Yes	9–11	9–11	11–16	Absent	0–2 (branched)
T. subterraneus	75	Vestigial	No	7–10	7–10	10–15	Absent	0–2 (branched)
A. spelaea	110	Vestigial	No	9–11	8–11	11–13	Absent /reduced	4–6 (branched)
A. rosae	65	Vestigial	No	7–9	8	9–11	Absent	4–6 (branched)
S. poulsoni	72	No vestiges?	No	9–10	8–9	21–22	Absent	4 (unbranched)



Pisces (Fishes): Amblyopsidae: Drawings of (a) *Chologaster cornuta*, (b) *Forbesichthys agassizi*, (c) *Typhlichthys subterraneus*, (d) *Amblyopsis rosae*, (e) *Amblyopsis spelaea*, and (f) *Speoplatyrhinus poulsoni*. Drawing by John Ellis.

do not respond to light. It is classified as "Vulnerable" in the Red List of the International Union for the Conservation of Nature and Natural Resources (IUCN) (Romero, 1998b).

Ozark cavefish, *Amblyopsis rosae*. This species is made up of at least four genetically distinct populations (Bergström *et al.,* 1995), and is found in 41 sites occurring on the Springfield Plateau, in seven counties of three states: southwest Missouri (20 sites), northwest Arkansas (10 sites), and northeast Oklahoma (11 sites). The verified historic range was larger (Willis & Brown, 1985). Individuals are found mostly in small cave streams with chert or rubble sediments, in pools over silt and sand sediments, and in karst windows or wells. Most of their diet is copepods but they also eat small salamanders, crayfish, isopods, amphipods, and young of their own species. Their breeding habits are not well understood, but they have an extended spawning season with a peak in late summer. They are classified as "Vulnerable" by IUCN and "Threatened" by the US Fish & Wildlife Service (USFWS) (Romero, 1998a),

Northern cavefish, *Amblyopsis spelaea*. This species is found in about 45 caves in Kentucky and about 17 caves in southern Indiana (Keith, 1988). The distribution may be limited by competition from the Southern Cavefish. Typical habitats are caves and subterranean passages in well-developed karst terrain where it is a top predator in both habitats (Poulson, 1963). Breeding occurs during high water from February to April. Females carry eggs in their gill cavities until hatching and then carry young until they lose their yolk sacs—a total period of four to five months. Young appear in late summer and early fall. They are scotophilic. This was the first stygobitic species of fish described in the scientific literature. It is classified as "Vulnerable" by the IUCN (Romero & Bennis, 1998).

Alabama cavefish, *Speoplatyrhinus poulsoni*. This species is characterized by its extremely elongated and anteriorly depressed head, which comprises one-third of the standard length in adults, with a laterally compressed snout and terminal mouth. It is found only in Key Cave, Lauderdale County, Alabama, on the north bank of the Tennessee River. Its habitat is not well understood but probably consists of phreatic groundwater. Its total population size is estimated to be less than 100 individuals, which would make it one of the most endangered fish species in the world. It is classified as "Critically Endangered" by the IUCN and "Endangered" by the USFWS (Romero, 1998c).

The classic studies of Poulson and co-workers have elucidated many aspects of the biology of this unique family, but much remains to be learned. However, all of the stygobitic species are threatened to some degree and it is vitally important that the need for conservation is taken into account in future studies.

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See also **Adaptation: Morphological**

Works Cited

Bergström, D.E., Noltie, D.B. & Holtsford, T.P. 1995. Ozark Cavefish genetics: the phylogeny of Missouri's Ozark Cavefish *(Amblyopsis rosae)* and Southern Cavefish *(Typhlichthys subterraneus),* Missouri: Missouri Department of Conservation

Keith, J.H. 1988. Distribution of Northern Cavefish, *Amblyopsis spelaea* Dekay, in Indiana and Kentucky and recommendations for its protection. *Natural Areas Journal*, 8:69–79

Poulson, T.L. 1963. Cave adaptation in Amblyopsid fishes. *American Midland Naturalist,* 70:257–90
Romero, A. 1998a. Threatened fishes of the world: *Amblyopsis rosae* (Eigenmann, 1842) (Amblyopsidae). *Environmental Biology of Fishes,* 52:434
Romero, A. 1998b. Threatened fishes of the world: *Typhlichthys subterraneus* (Girard, 1860) (Amblyopsidae). *Environmental Biology of Fishes,* 53:74
Romero, A. 1998c. Threatened fishes of the world: *Speoplatyrhinus poulsoni* Cooper and Kuehne, 1974 (Amblyopsidae). *Environmental Biology of Fishes,* 53:293–94
Romero, A. & Bennis, L. 1998. Threatened fishes of the world: *Amblyopsis spelaea* De Kay, 1842 (Amblyopsidae). *Environmental Biology of Fishes,* 51:420
Willis, L.D. & Brown, A.V. 1985. Distribution and habitat requirements of the Ozark cavefish, *Amblyopsis rosae*. *American Midland Naturalist,* 114:311–17

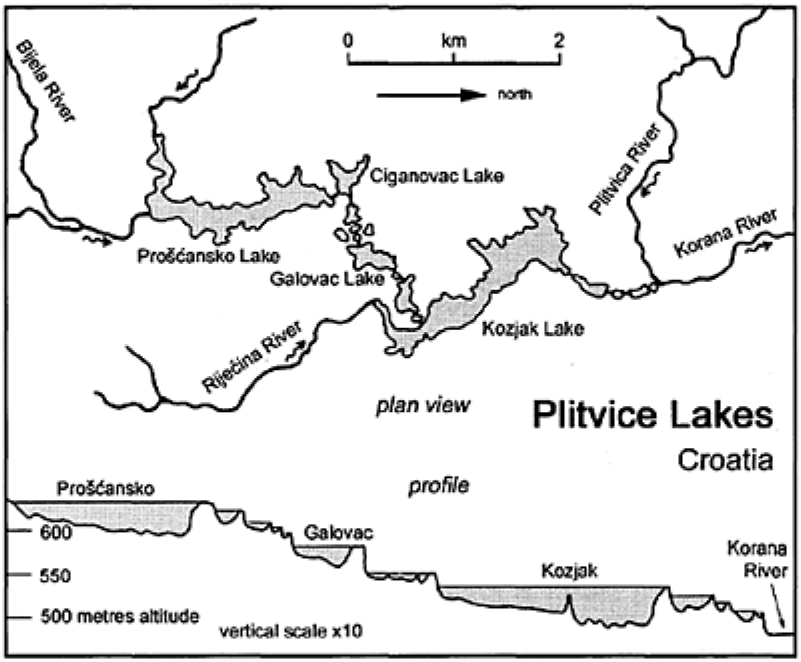
Further Reading

Environmental Biology of Fishes, 62 (2001) is a special issue on hypogean fishes and contains a number of papers on the Amblyopsidae. Many of the recent studies described in the essay text are included in this volume.
Bechler, D.L. 1983. The evolution of agonistic behavior in Amblyopsid fishes. *Behavioral Ecology and Sociobiology,* 12:35–42
Eigenmann, C.H. 1909. *Cave Vertebrates of America: A Study in Degenerative Evolution,* Washington DC: Carnegie Institute of Washington.
This is a major work, which still gives the best description of the eyes of this family; it is beautifully illustrated.
Poulson, T.L. 1961. *Cave Adaptation in Amblyopsid fishes,* Ph.D. Dissertation. Ann Arbor: University of Michigan
Rosen, D.E. 1962. Comments on the relationships of the North American cave fishes of the family Amblyopsidae. *American Museum Novitates,* 2109:1–35
Smith, P.W. & Welch, N.M. 1978. A summary of the life history and distribution of the Spring Cavefish, *Chologaster agassizi,* Putnam, with population estimates for the species in southern Illinois. *Illinois Natural History Survey, Biological Notes,* 104
US Fish and Wildlife Service 1989. *Ozark Cavefish Recovery Plan,* Atlanta: US Fish and Wildlife Service
US Fish and Wildlife Service 1990. *Alabama Cavefish, Speoplatyrhinus poulsoni Cooper and Kuehne 1974, Recovery Plan,* Jackson, Mississippi: US Fish and Wildlife Service
Woods, L.P. & Inger, R.F. 1957. The cave, spring, and swamp fishes of the family Amblyopsidae of central and eastern United States. *American Midland Naturalist,* 58:232–56

PLITVICE LAKES, CROATIA

The Plitvice Lakes are located in the Dinaric karst region of Croatia, between the mountain massifs of Mala Kapela in the southwest and Plješivica in the east. In the late 19th century they were described as the “only cataract lakes in Europe”. The natural dams that separate the lakes form waterfalls, for which the lakes are justly famous. The dams themselves are constructed of travertine or calcareous tufa (porous hard limestone), precipitated from the lake water. This process is still going on, with new travertine barriers, curtains, stalactites, stalagmites, channels, and cascades being formed and existing ones altered. The water continues to breach the travertine barriers at different locations, creating new lakes and barriers (Srdoč *et al.*, 1985; Plenković, Marčenko & Srdoč, 1989).

In the hard waters of the Plitvice Lakes, in areas of strong aeration and under favourable temperature conditions, calcium carbonate ($CaCO_3$) precipitates in considerable quantities. Some hydrobionts (bacteria, algae, and mosses) retain the particles of calcite, and in this way gradually form tufa barriers (Matoničkin & Pavletić, 1967). The precipitation of calcium carbonate from lake water requires the interaction of abiotic and biotic factors, along with the interglacial climatic conditions that prevail at the present day. The basic abiotic factors are: pH between 8.2 and 8.4, $CaCO_3$ saturation index over 3.0, and dissolved organic matter concentration less than 10 mg 1^{-1}. Biotic factors influencing precipitation include the presence of bacteria and algae on the aquatic plants growing in the waterfalls. Phyto-



Plitvice Lakes, Croatia: Plan and profile of the tufa-dammed lakes of Plitvice in Croatia. Note that the vertical scale is greatly exaggerated.

plankton and periphyton are also important in the formation of lacustrine sediment. Furthermore, as tufa is deposited, it coats the bottoms and sides of the watercourses, petrifying everything in the water—fallen trees, stones, and even entire beaches (Stilinović & Božičević, 1998).

The natural beauty and ecological importance of the Plitvice Lakes led to their designation as the first National Park in Croatia, in 1949. In 1979 they were added to the UNESCO list of World Heritage Sites (WHS). The National Park is 29 482 ha in area, of which 22 300 ha (75%) is covered by forests. The surface area of the 16 lakes is only 192 ha. The remainder of the park is grassland and other vegetation. There are a total of 16 lakes (Riđtanović & Božičević, 1996), which are geographically an integral part of the Korana River (Figure 1). The distance between the first lake (Prošćansko, at an altitude of 637 m) and the last lake (Novakovića Brod, at an altitude of 503 m) is 8300 m. Eleven of the lakes have surface areas of more than 1 ha. The two deepest and largest lakes are Prošćansko (area 682 720 m^2, depth 37 m) and Kozjak (815 060 m^2 in area, 46 m deep). In total, the lakes store about forty million cubic metres of high-quality fresh water. The lakes can be divided into two subsystems: the Upper Lakes (12 lakes) which lie on dolomite bedrock, and the Lower Lakes (4 lakes) which lie on limestone bedrock. At the end of the last lake, the Novakovića Brod, the Plitvica River flows out through a magnificent waterfall with a height of 28 m.

The Upper Triassic strata in this area comprise 400 to 600 m of predominantly dolomite rocks underlain by shales whose presence was essential in the formation of the lakes. The Jurassic strata comprise alternating well-bedded limestones of varying thickness, containing irregular dolomite intercalations.

The Cainozoic biogenic calcareous tufa deposits have been badly damaged by human activity. In the Lower Lakes, unconsolidated muddy sediments have covered the lake bottoms, making the bedrock impermeable. The estimated thickness of calcar eous tufa varies from 30 to more than 50 m, covering a zone several hundred metres in width in the Upper Lakes section (Božičević, 1990).

The exact hydrological catchment area and boundaries of the Plitvice Lakes are not known, although numerous investigations have been carried out. Determination of the exact catchment area is problematical, due to strong, direct, complex, and unpredictable interactions between groundwater and surface water flowing from the different karst subregions. The average annual temperature in the lake area is 8–9°C and the annual rainfall varies from 1100 to 1700 mm, with an average of about 1400 mm. The climate is continental.

The annual mean inflow into the first Prošćansko Lake varies from 1.8 to 2.9 $m^3 s^{-1}$. Outflow from the last Novakovića Brod Lake varies from 2.4 to 2.8 $m^3 s^{-1}$. Minimum inflow is 0.579 $m^3 s^{-1}$ and minimum outflow is 0.605 $m^3 s^{-1}$, while maximum inflow is 12.5 $m^3 s^{-1}$. Since 1980 there has been a general decrease in discharges.

Scores of algae and non-vertebrate species have been found in the lakes, indicating that the water quality is oligotrophic or mesotrophic. However, some other species indicate a continuous increase in the trophic state values (towards eutrophication) of the water in the lakes. Of the fish species, the autochtonous lake trout *(Salmo trutta lacustri)* and the river trout *(Salmo trutta fario)* are worthy of note. The river crayfish disappeared entirely from the lakes in 1958, but reappeared in the Lower Lakes in October 1995.

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Works Cited

Božičević, S. 1990. Hidrogeološke zanimljivosti Plitvićkih jezera [Hydrogeological characteristics of the Plitvice Lakes], *Ekološki glasnik* 7–8:28–33

Matoničkin, I. & Pavletić, Z. 1967. Hidrologija protočnog sistema Plitvičkih jezera i njegove ekološko biocenološke značajke (Hydrology of the Plitvice Lakes flow system and its ecological biocenological characteristics), *Krš Jugoslavije—Carsus Iugoslavie,* 5:83–126

Plenković, A., Marčenko, E. & Srdoč, D. 1989. Periphyton on glass slides in aquatic ecosystems of the National Park Plitvice Lakes. *Periodica Biologica,* 91(1):88

Riđanović, J. & Božičević, S. 1996. Geographic-physical conditions of runoff and hydrogeological characteristics of the Plitvice Lakes. *Acta Geographica Croatica*, 31:7–26

Srdoč, D., Horvatinčić, N., Obelić, B., Krajcar, I. & Sliepčević, A. 1985. Procesi taloženja kalcita u krškim vodama s posebnim osvrtom na Plitvička jezera (Calcite deposition processes in karst waters with special emphasis on the Plitvice Lakes). *Krš Jugoslavije—Carsus Iugoslavie,* 11(4–6):101–204

Stilinović, B. & Božičević, S. 1998. The Plitvica Lakes—a natural phenomenon in the middle of the Dinaric Karst in Croatia. *European Water Management*, 1(1):15–25

Further Reading

Chafetz, H.S. & Folk, R.L. 1984. Travertines: depositional morphology and the bacterially constructed constituents. *Journal of Sedimentary Petrology,* 54(1):289–316

Lorah, M.M. & Herman, J.S. 1988. The chemical evolution of a travertine depositing stream: geochemical processes and mass transfer reactions. *Water Resources Research,* 24(9):1541–52

Ford, T.D. 1989. Tufa—the whole dam story. *Cave Science,* 16(2):39–49

Plitvice National Park, http://www.archaeology.net/plitvice/

POLJES

In a strict sense, poljes can be defined as depressions in limestone karst. They are generally elliptical, with bottoms that slope relatively gently from the inflow (spring) zone to the outflow (often swallow hole) zone (Bonacci, 1987b). They are the largest and most conspicuous type of surface depression found in carbonate rock megarelief. Poljes are frequently aligned along tectonic and fold axes, often forming flat alluvial valleys bordered by relatively steep, bare limestone ridges, ranging from almost a kilometre to several kilometres in width (see photo in Dinaride Poljes entry). They are somewhat elongated, often with surface streams flowing along the longer axis. Poljes vary in size from less than 0.5 km^2 to more than 500 km^2 in area.

The formation of depressions in karst terrain results from the successive and simultaneous action of a number of environmental factors, including underlying geology and paleoclimate. According to Trudgill (1985), there are two important factors that affect the formation of poljes: surface lateral planation at the average height of water-table levels in the sediment, and the accumulation of the sediments themselves. In the case of poljes, the erosion is lateral (Sweeting, 1972)—where sediments and water come in contact with the limestone massif. Neogene and Quaternary superficial deposits such as terra rossa often tend to accumulate on the floors of poljes. Poljes show complex hydrological and hydrogeological features and characteristics, such as permanent and temporary springs, permanent and lost rivers, swallow holes and estavelles (openings that may function as either a sink or a spring).

Karst poljes can be found in various parts of the world, but are particularly common in the Mediterranean countries (Greece, Italy, France, Spain, Morocco, Tunisia, Slovenia, Croatia, Bosnia and Herzegovina, and Montenegro). There are a few in Asia (China), a large number in Cuba, Jamaica, Canada (in the Nahanni area), and at least one (Bögli, 1980) in the United States in Tennessee (Grassy Cove). The Dinaric karst of Slovenia probably contains the highest concentration of classic poljes (see Cerknica Polje, Slovenia: History), but they also occur in Croatia, Bosnia and Herzegovina (see Dinaride Poljes) and Montenegro. Thus, the term has passed from Croatian, Serbian, and Slovenian into other languages, and is now used internationally. As Sweeting (1972) pointed out, over time "polje" has acquired a more specific scientific meaning than simply a flat overgrown or cultivated area—firstly to indicate a surface karst landform and secondly to mean all such extensive karst plains surrounded by limestone hills.

In the Dinaric karst (and similarly elsewhere), poljes represent the only areas with conditions favourable for human habitation. Surrounded by bare rocky terrain, they tend to be covered with arable soil and have either permanent or temporary springs and rivers. Although relatively small in size, they are thus significant from an economic and social standpoint.

From the hydrological point of view, a polje is only part of a wider system. It cannot and should not be treated as a complete system, but only as a subsystem in the process of surface and groundwater flow through and over the karst massif. Consequently, poljes cannot be studied adequately without establishing measurement points within the surrounding karst mass, and in the poljes of higher and lower groundwater horizons that connect to the subsystem being analysed.

Karst poljes flood regularly in the cold and wet periods of the year (in Dinaric karst from October to April) and in summer they have a tendency to dry up (Bonacci, 1985; Bonacci & Plantić, 1997). According to their hydrological regime, inflows, and outflows, they can be classified into four basic types: (1) closed poljes; (2) upstream open poljes; (3) downstream open poljes; and (4) upstream and downstream open poljes. Flooding is caused by the limited capacity of outlet structures and/or by a high groundwater level in the surrounding area. Poljes thus play an important role in the hydrological balance of karst areas.

Some anthropogenic changes have already been made to improve the hydrological regimes of polje areas, and more will be done in the future. However, some environmental damage has also been done and in some cases this has exceeded the benefits. From a hydrotechnical standpoint, it should be borne in mind that karst poljes are often linked to other adjacent upstream and downstream poljes—this being especially true for the Dinaric karst. Anthropogenic influences on the hydrological regimes of poljes can be divided into four categories: water storage, an increase in the capacity of outlet structures, surface hydrotechnical work, and the pumping of groundwater (Bonacci, 1987a).

Water storage in karst is not just affected by water retention in the poljes themselves—most water storage schemes involve damming river sections, in some cases either permanently flooding adjacent parts of the poljes or raising water table levels. Often human activity makes it necessary to preserve the fertile parts of the poljes as oases, only permanently flooding the less valuable areas of the karst. Building reservoirs in karst has a major influence on hydrotechnical relations in the poljes, and this effect is often difficult to assess (see Dams and Reservoirs on Karst). Spring discharges tend to increase in downstream areas, but there may be some additional negative consequences that cannot be amended easily. In upstream areas, drainage systems formerly inactivated by downward karstification may be reactivated (Milanović, 1986).

To prevent the flooding of karst poljes, attempts have been made to enlarge the capacities of ponors (see Ponors). These have usually failed because the capacities of ponors depend to some degree upon the size of inflows. In the last hundred years, it has been necessary to drill relief tunnels, and the connections between adjacent poljes have had to be enlarged.

In general, surface hydrotechnical construction work in poljes involves hydrological regulatory work in open streams, construction of channels for surface drainage, large land reclamation projects, and other measures. It is generally assumed that surface drainage does not have a great influence on the underground water level, which essentially governs outflow processes in karst. However, some forms of construction work may adversely affect the hydrological regime.

The pumping of groundwater from a karst aquifer for irrigation is a common practice, and since the 1980s it has been gaining prominence as a method of supplying water in karst areas. When groundwater is abruptly extracted, this can lead to fracturing of the upper layers of unstable lithologies, because of the presence of interlinked fissures within the karst mass. This can create new ponors and activate existing ones. Pumping groundwater from the karst also significantly lowers the local water table.

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See also **Cerknica Polje, Slovenia: History; Dinaride Poljes**

Works Cited

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)

Bonacci, O. 1985. Flooding of the poljes in karst. In *Papers Presented at the 2nd International Conference on the Hydraulics of. Floods and Flood Control, Cambridge, 24–26 September 1985),* Cranfield: BHRA

Bonacci, O. 1987a. Karst hydrology and water resources—past, present and future. In *Water for the Future: Hydrology in Perspective,* edited by J.C.Rodda & N.C.Matalas, Wallingford: International Association of Hydrological Sciences

Bonacci, O. 1987b. *Karst Hydrology with Special Reference to the Dinaric Karst,* Berlin and New York: Springer

Bonacci, O. & Plantić, K. 1997. Hydrology of the Drežničko Polje in the karst (Croatia). In *Karst Waters and Environmental Impacts: Proceedings of the 5th International Symposium and Field Seminar on Karst Waters and Environmental Impacts, Antalya, Turkey, 10–20 September 1995,* edited by G.Günay & A.Johnson, Rotterdam: Balkema

Milanović, P. 1986. Influence of the karst spring submergence on the karst aquifer regime. *Journal of Hydrology,* 84:141–56
Sweeting, M.M. 1972. *Karst Landforms,* London: Macmillan and New York: Columbia University Press
Trudgill, S. 1985. *Limestone Geomorphology,* London and New York: Longman

Further Reading

Breznik, M. 1998. *Storage Reservoirs and Deep Wells in Karst Regions,* Rotterdam: Balkema
Drew, D. & Hötzl, H. (editors) 1999. *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* Rotterdam: Balkema
Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman
Milanović, P.T. 1981. *Karst Hydrogeology,* Littleton, Colorado: Water Resources Publications
Yuan D. 1991. *Karst of China,* Beijing: Geological Publishing House

PONORS

Ponors or swallow holes are fissures in the karst mass through which water sinks underground. Field (1999) cites two definitions:

1. A hole or opening in the bottom or side of a depression where a surface stream or lake flows either partially or completely underground into the karst groundwater system. A sea ponor is where sea water flows or is drawn into an opening by a vacuum in karstified rock;
2. A hole in the bottom or side of a closed depression, through which water passes to or from an underground channel.

Ponors play an important role from the hydrological—hydrogeological standpoint of water circulation in karst. According to their hydrological function, ponors can swallow water permanently or can function partly as ponors and partly as springs, i.e. as estavelles. Very often ponors are situated close to the margins of the floor of a polje while estavelles are more central (see Poljes; Cerknica Polje; and Dinaride Poljes). Water circulation in karst terrain is characterized by the existence of a strong inflow-outflow relationship. Ponors generally serve as the main inflow networks.

From the morphological standpoint (Milanović, 1981) ponors can include: large pits and caves; large fissures and caverns; systems of narrow fissures; or alluvial ponors. Jamas (vertical or steeply inclined shafts) most frequently function as ponors and present paths for the direct contact of surface water with the underground water in the karst mass. Ponors often provide entry points to the underground karst for cavers, and their investigation can reveal the positions, dimensions, and interactions of surface and underground karst features and water flow in the karst and on its surface.

Marine (sea) ponors are a rare phenomenon in karst. Most sea ponors are short-lived and actually represent the functioning of a vrulja (submarine spring) immediately after it dries up. The only permanent sea ponor in the world is the sea mill of Argostoli, located on Kefalonia Island in the Ionian Sea (Greece) (Glanz, 1965).

When an open stream flows through a karst terrain, the surface water frequently sinks underground and water losses occur through small ponors, which are found in karst fissures. In some karst regions, rivers sink underground through huge ponors or a well-developed ponor zone, and reappear at a large resurgence.

The capacity of a ponor to swallow water depends only upon the water level in the pre-ponor retention if the flow in the main karst conduit is not under pressure. A pre-ponor retention is a temporary water accumulation in the surface depression just above the ponor. The dimensions of these pre-ponor retentions vary greatly, and are a function of surface morphology. When the flow comes under pressure the ponor swallow capacity depends exclusively upon the difference between the level of water in the pre-ponor retention and the average level of the spring exit. When the groundwater level in the surrounding karst mass is higher than the water level in the pre-ponor retention, the ponor acts as an estavelle (Bonacci, 1987). In order to determine the swallow capacity of independent, large ponors, it is possible to use specially designated measurement devices based upon the principle of measuring velocities and/or pressure changes at a few points. More frequently there are numerous ponor zones with several large and a great number of small ponors in one area, and particularly in poljes. In that case, in order to define the swallow capacity of each ponor zone, it is necessary to carry out measurements of the groundwater levels in an appropriate part of the karst mass, since they influence the swallow capacity of that ponor zone.

With the objective of flood prevention in karst areas, particularly in poljes, attempts have been made to increase the capacities of ponors. Such attempts have usually failed because the capacity of ponors depends on the conduit system to which they drain as well as upon their size. Where the ponors do not have sufficient capacity as outlet structures, other hydrotechnical structures are often built to deliver water from the flooded areas.

Sometimes occasionally flooded karst areas are transformed into permanent storage basins (see Dams and Reservoirs in Karst). To prevent water losses the bottom and the sides of the new storage basin must be rendered impermeable but this is problematic where the reservoir is located on a permeable karst terrain with many ponors (Breznik, 1998). There have been more unsuccessful attempts to isolate or surface seal ponors than successful ones and water losses from a reservoir can result in large increases in the discharge of karst springs (Bonacci & Jelin, 1988).

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See also **Dams and Reservoirs on Karst; Hydraulics of Caves for Photo; Poljes**

Works Cited

Bonacci, O. 1987. *Karst Hydrology with Special Reference to the Dinaric Karst*, Berlin and New York: Springer

Bonacci, O. & Jelin, J. 1988. Identification of a karst hydrological system in the Dinaric karst (Yugoslavia). *Hydrological Sciences Journal*, 33(5):483–97

Breznik, M. 1998. *Storage Reservoir and Deep Wells in Karst Regions*, Rotterdam: Balkema

Field, M.S. 1999. *A Lexicon of Cave and Karst Terminology with Special Reference to Environmental Karst Hydrology*, Washington DC: US Environmental Protection Agency

Glanz, T. 1965: Das Phänomen der Meermühlen von Argostolion [Phenomenon of the sea mills of Argostoli], *Steierische Beiträge zur Hydrologie*, 17:113–27
Milanović, P. 1981. *Karst Hydrogeology,* Littleton, Colorado: Water Resources Publications

Further Reading

Drew, D. & Hötzl, H. (editors) 1999. *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* Rotterdam: Balkema
Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman
Kogovšek, J. 1996. Sinking rivers quality—the Pivka case study. *Acta Carsologica,* 25:145–56

POSTOJNA-PLANINA CAVE SYSTEM, SLOVENIA

Postojnska Jama (Postojna Cave) is the longest known cave system in Slovenia (20 570 m in length, 115m deep). Between Postojna Cave and the Planina Cave system there is still about 500 m of unexplored passages. If both caves are connected, the cave system will be about 30 km long. Postojnska cave system has several entrances and consists of: Postojnska Jama, Črna Jama, Pivka Jama, Magdalenska Jama, and Otoška Jama (Figure 1).

People have lived in the entrance parts of the cave system for at least 10 000 years. The oldest inscriptions on cave walls date from the 13th and 14th centuries. The Slovenian historian and naturalist Baron Valvasor described Postojnska Jama in 1689 as one of the most spectacular caves in the world that was known at the time, even though just a small part of today's cave systems was then known. In 1748 Joseph Nagel made the first map of the cave, and in 1781 Tobias Gruber inferred the underground water connection between Postojnska Jama and Planina Cave system (see entry, Cerknica Polje, Slovenia: History). The Post-ojnska cave system was also important for the development of biospeleology, being the location of the first cave fauna specimens described scientifically (see Postojna-Planina Cave system: Biospeleology).

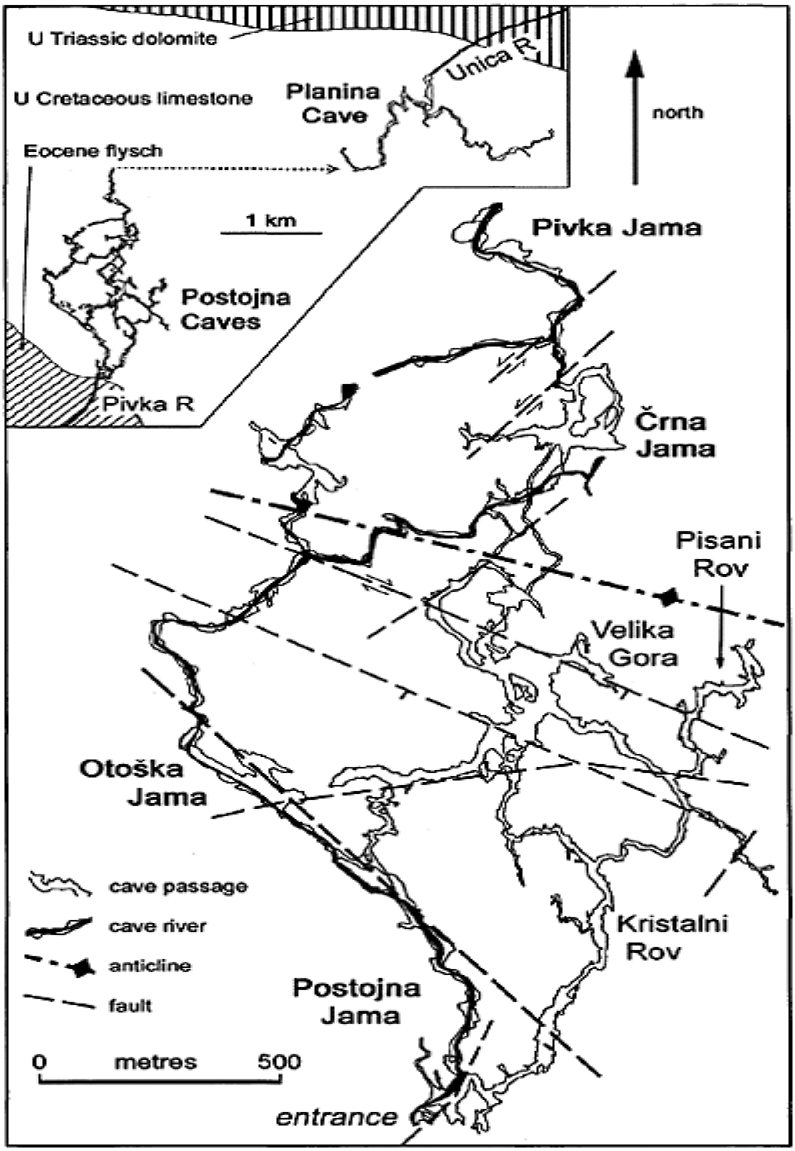
On 14th April 1818; the discovery by cave guide Luka Čeč of extensive new parts of the cave marked the beginning of official cave tourism Postojnska Jama and 5 km has now been opened as a show cave. In 1997, the caves were visited by about 400 000 tourists. Between the years 1818 and 1992 Postojnska Jama were visited by 26 million people, the highest number in a single year being over 900 000 in 1985. Postojnska Jama has one of the oldest tradition in guidebooks; from 1821 to the present, 110 guidebooks have been published. The first printed guidebook was-written by Girolamo Agapito in 1823.

The River Pivka sinks into Postojnska Jama at 511 m altitude from the impermeable Eocene flysch of its basin, and resurges from the Planina Cave system (Figure 1) as a spring of the Unica River. The Pivka is an interesting river in that the main drainage is to the Black Sea, but part of the river before entering the Postojnska system flows to the Adriatic (Habič, 1989).

The Postojnska caves are developed on two principal levels. The higher level starts at an altitude of 529 m and comprises dry passages which are partly filled with cave sediments, flowstone, and collapse blocks. A great number of these passages have been reshaped through collapses, with many of the largest chambers being formed by collapse. The lower level comprises the active underground channels of the Pivka River which are situated west of the higher levels. The two levels are connected by side passages.

The caves are developed in the *c.* 800 m thick Upper Cretaceous bedded limestones. The Cenomanian and Turonian limestones are more thinly bedded and include chert lenses or beds while the Senonian limestones are thick bedded to massive. The caves are situated between two regionally important Dinaric-trending faults, the Idrija fault to the north and Predjama fault to the south. The principal folding deformation in Postojnska Jama is the Postojna anticline. Cave passages are developed in both flanks of the anticline, and follow strike and dip of the bedding planes, especially those with interbedded slips. Sections of the underground River Pivka between Otoška Jama and Pivka Jama follow the dip of bedding planes and the northeast-southwest fault zones.

Sediments from Postojnska Jama were studied by Gospodarič (1976) who determined 10 principal development stages of the cave system by absolute dating of flowstone and by the relative age of cave sediments; according to Gospodarič (1976) the oldest sediments originate from an interglacial period (Mindel-Riss). In 1999 sediments from Postojnska Jama were studied by paleomagnetic analyses (Šebela & Sasowsky, 1999) and it was found that most were deposited during the Brunhes Normal Epoch (younger than 0.73 Ma). However, samples from a small natural



Postojna-Planina Cave System, Slovenia: Figure 1. Main elements of the structural geology of the limestones containing the Postojna caves, Slovenia; the inset shows the relationship of the Postojna and Planina caves.

passage which is accessible from the tunnel between Postojna and Crna caves showed reverse polarity and are at least 0.73–0.90 million years old. These cave sediments are cut by a younger cross-Dinaric fault zone with horizontal displacement. This is the best example of neotectonic activity in Postojnska caves.

The average annual temperature in Postojna is 8.4°C and most of the average annual rainfall of 1579 mm infiltrates directly into the karstified limestone. This water appears in the caves as permanent or seasonal trickles that contain up to 250 mg l^{-1} $CaCO_3$. Measurements over several years have shown that the precipitation amount is among the most important factors for dissolving limestone and consecutive karstification. The percolation water is oversaturated and deposits flowstone. Permanent trickles in Pisani rov (Gams & Kogovšek, 1998) with discharge of about 100 ml min^{-1} deposit carbonate up to 18–39 g m^{-3} in one year.

Postojna-Planina Cave System, Slovenia: Figure 2. Calcite deposits in a high-level gallery of Planina Jama. (Photo by Tony Waltham)

Monitoring of discharge and water tracing tests with fluorescent dyes (Kogovšek, 2000) has shown that water percolating from the surface through the 100m thick roof into

Kristalni rov reaches a velocity of 4.5 m h^{-1} through the main, most permeable conduit (maximum discharge through the conduit, Q_{max}=1.5 l min^{-1}) and 0.7 m h^{-1} through less permeable ones (Q_{max}<0.18 l min^{-1}). To determine what would happen if a pollutant was accidentally discharged on the surface above the cave, 6 m^3 of water containing Uranin dye was poured on the surface and gave a flow velocity of 80 m h^{-1} through the most permeable conduit (almost 20 times faster than under natural conditions) and 0.05 m h^{-1} through the less permeable fissure.

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Works Cited

Gams, I. & Kogovšek, J. 1998. The dynamics of flowstone deposition in the caves Postojnska, Planinska, Taborska and Škocjanske, Slovenia. *Acta Carsologica,* 27(1):299–324

Gospodarič, R. 1976. The Quaternary cave development between the Pivka basin and polje of Planina. *Acta Carsologica,* 7:8–135

Habič, P. 1989. Pivka karst bifurcation on Adriatic-Black Sea watershed. *Acta Carsologica,* 18:233–64

Kogovšek, J. 2000. How to determine the way of percolation and transport of substances by water tracing test in natural conditions. *Annales: Annals for Istrian and Mediterranean Studies,* 10:133–42

Šebela, S. & Sasowsky, I.D. 1999. Age and magnetism of cave sediments from Postojnska jama cave system and Planinska jama cave, Slovenia. *Acta Carsologica,* 28(2):293–305

Further Reading

Čar, J. & Gospodarič, R. 1984. About geology of karst among Postojna, Planina and Cerknica. *Acta Carsologica,* 12:91–106

Gams, I. 1965. H kvartarni geomorfogenezi ozemlja med Postojnskim, Planinskim in Cerkniškim poljem. *Geografski Vestnik,* 37:61–101

Gams, I. 1966. Factors and dynamics of corrosion of the carbonatic rocks in Dinaric and Alpine karst of Slovenia. *Geografski Vestnik,* 38:11–68 (In Slovenian, with an English summary)

Habe, F. 1986. *The Postojna Caves,* 4th edition, Ljubljana: Tone Tomšič

Sebela, S. 1998. *Tectonic Structure of Postojnska Jama Cave System,* Ljubljana: Založba ZRC (In Slovenian and English)

Kogovšek, J. 1999. New knowledge about the underground water drainage in the northern part of Javorniki Mountains (High Karst). *Acta Carsologica,* 28(1):161–200

Shaw, T.R. & Čuk, A. 2002. Royal and other notable visitors to Postojnska jama 1819–1945. *Acta Carsologica,* 31(1) supplement 1:1–107

Vokal, B., Obelić, B., Genty, D. & Kobal, I. 1999. Chemistry measurements of dripping water in Postojna Cave. *Acta Carsologica,* 28(1):305–20

POSTOJNA-PLANINA CAVE SYSTEM: BIOSPELEOLOGY

The Postojna-Planina Cave System (Postojnsko-planinski jamski sistem, or PPCS) comprises the hypogean bed of the river Pivka, between its sink at Postojna and its resurgence at Planina, along with the adjacent relict cave corridors. Upstream passages more than 20 km in length (Postojnska jama, Otoška jama, Magdalenska jama, Črna jama, Pivka jama, and Lekinka) include approximately 4 km of river sections. Most of the 6 km of the downstream section (Planinska jama) is hydrologically active, and includes more than 2 km of the Pivka River in addition to its confluences. A phreatic section, so far unexplored, with a length of 500 m (measured in a straight line), connects both sections.

Since 1818, more than 5 km of relict passages in Postojnska jama have been utilized as tourist caves. The River Pivka is now being polluted by effluents from the town of Postojna. A biospeleological station was installed in Postojnska jama and has been intermittently active since the 1930s.

Scientific Importance of the Cave System

These caves are sometimes referred to as “the cradle of speleo biology”, since they are the type localities of some of the first cave animals described scientifically, in the 19th century. In 1797 the cave salamander *(Proteus anguinus)* was first seen here in its primary cave environment. The caves are also the type locality of the first troglobitic beetles discovered *(Leptodirus hochenwartii),* pseudoscorpions *(Neobisium spelaeum),* spiders *(Stalita taenaria),* cnidarians *(Velkovrhia enigmatica),* and even of the trogloxene crickets (e.g. *Troglophilus cavicola*). In fact the cave system is the type locality for more than 60 invertebrate species. It is faunistically by far the richest cave system in the world, with 49 stygobitic and 35 troglobitic species (Culver & Sket, 2000). A high number of troglophilic and accidental terrestrial and aquatic species have also been recorded. The scientifically most interesting are populations of those stygophilic species, which exhibit clines (i.e. a gradual increase) in their degree of troglomorphism between the sink and the resurgence. Along the hypogean part of the Pivka River, for example, the sponge *Ephydatia muelleri,* the snail *Ancylus fluviatilis,* the leech *Dina krasensis,* the amphipod *Synurella ambulans,* and the isopod *Asellus aquaticus* all show this type of variation.

The relatively intensive ecological studies of this cave system have resulted in the discovery of a characteristic relationship between specialized (starvation-resistant but less active) stygobites and generalist stygophilic (more active but more fooddemanding) species. When organic pollution increases, the surface species gain a competitive edge, pushing the stygobites further underground (Sket, 1973). Postojnska jama was also the site of a detailed study of “Lampenflora” (see Tourist Caves: Algae and Lampenflora).

Ecological Conditions

The normal cave temperature of the system varies between 9 and 10°C; the monthly mean temperature of the hypogean Pivka varies between 2 and 17°C in Postojnska jama and between 6 and 12°C in Planinska jama; daily variations may exceptionally reach 3°C in Planinska jama, but only during high water discharges. The discharge of the Pivka River varies between negligible values and in excess of 40 $m^3 s^{-1}$. At high discharges, water takes only seven hours to pass through the 9 km of cave corridors between the sink and the resurgence, but five days or more in dry periods. Being influenced by the river to a large degree, the air temperatures in the system are dependent on the precipitation/discharge fluctuations and the regional air temperature regime in a particular year. Therefore, the mean yearly temperature within the cave may deviate slightly from the mean air temperature outside the cave.

Aquatic Fauna

The benthic fauna of Pivka River in Postojnska jama consists largely of epigean animals. Some of them are restricted to the sink region, while others inhabit the entire hypogean river bed. These include, in addition to those clinally variable populations outlined above, the water-flea *Chydorus sphaericus,* stonefly larvae *Nemoura* sp. and *Brachyptera tristis,* and some mayfly larvae (family Leptophlebiidae). The isopod *Asellus aquaticus* is represented in Postojnska jama by pigmented or slightly depigmented specimens of the type subspecies *A. aquaticus*. With increasing distance from the sink, more troglomorphic subpopulations of stygophiles and some stygobitic species prevail. Examples include tiny hydrobioid snails, which may reach densities of more than 10000 specimens per square metre. The amphipod *Niphargus spoeckeri* is among the most common species on the riverbed surface, while the smaller *N. aquilex dobati* is present within deeper interstitial layers in Planinska jama. The cave shrimp *Troglocaris anophthalmus,* and the highly troglomorphic isopod *Asellus aquaticus cavernicolus* (which may be a separate species) are present in pools. The amphibian *Proteus* is rare in the Tartarus in Postojnska jama, while it may be seen regularly in the bed of the Pivka River in Planinska jama. However, no very young or very old specimens have been found there, forcing Briegleb (1962) to consider the hypogean river as a marginal ecotope for this animal.

During periods of increased organic pollution (in the 1950s to 1980s) the less troglomorphic species or subpopulations increased in density, even in the remote parts of the hypogean stream. Prior to 1950, and following the construction of a purification plant in Postojna in the 1980s, the stygobites were and have become more abundant.

The fauna of the Rak branch in Planinska jama includes a greater proportion of stygobitic fauna. In addition to *Proteus,* cave shrimps and troglomorphic asellids, and a larger number of tiny stygobitic snail species *(Neohoratia subpiscinalis and Acroloxus tetensi)* are common. The tiny sessile cnidarian *Velkovrhia enigmatica* may also reach high densities.

The fauna of the percolation waters are distinctive. *Niphargus stygius* is the characteristic amphipod species in pools, accompanied by a number of copepod species. Some harpacticoid copepods (e.g. *Elaphoidella* spp.) have been found within drips of percolating waters from the crevicular system in the ceiling. Amphipods are represented by the small *Niphargus wolfi* and *Niphargobates orophobata;* the latter was filtered out from only one such drip in Planinska jama, and its only known relative was later discovered on Kriti Island (Greece).

Terrestrial Fauna

The fauna in the non-modified entrance areas of the caves is characteristic of most of the Slovenian Dinaric karst. On the walls, resting specimens of the moths *Triphosa dubitata* and *Scoliopteryx libathrix* may be seen. Trogloxene crickets, *Troglophilus* spp., may be present deeper within caves, particularly during the winter. In the organic debris on the cave floor there may be numerous edaphic—troglophilic animals such as the millipede *Brachydesmus subterraneus*, the troglophile beetle *Laemostenes cavicola*, and Collembola. Among the troglobites, the large amphibious isopod *Titanethes albus* may be particularly numerous. Occasionally, tiny snails (two *Zospeum* spp.) may be found on the damp walls. Spiders and pseudoscorpions are even rarer, while troglobitic beetles, including *Leptodirus*, three *Anophthalmus* species and others, are the species most regularly caught using bait.

BORIS SKET

See also **Dinaric Karst: Biospeleology**

Works Cited

Briegleb, W. 1962. Zür Biologie und Oekologie des Grottenolms (*Proteus anguinus* Laur. 1768). *Zeitschrift fuer Morphologie und Oekologie der Tiere*, 51:271–334

Culver D.C. & Sket, B. 2000. Hotspots of subterranean biodiversity in caves and wells. *Journal of Cave and Karst Studies*, 62(1):11–17

Sket, B. 1973. Gegenseitige Beeinflussung der Wasserpollution und des Hoehlenmilieus. In *Proceedings of the 6th International Congress of Speleology*, vol. 5, Olomouc: International Union of Speleology

Further Reading

Brancelj, A. 1986. Rare and lesser known harpacticoids (Copepoda Harpacticoida) from the Postojna—Planina Cave System (Slovenia). *Biološki Vestnik*, 34(2):13–36

Brancelj, A. 1987. Cyclopoida and Calanoida (Crustacea, Copepoda) from the Postojna-Planina Cave System (Slovenia). *Biološki Vestnik* 35(1):1–16

Kranjc, A. & Malečkar, F. 1988. *Postojnska jama: 170 let odkrivanja, raziskovanja in turističnega razvoja* [Postojna Cave: 170 years of discovery, research, and tourist development], Postojna: Kraška muzejska zbirka pri IZRK ZRC SAZU

Turk, S., Sket, B. & Sarbu, S. 1996. Comparison of some epigean and hypogean populations of *Asellus aquaticus* (Crustacea: Isopoda: Asellidae). *Hydrobiologia*, 337:161–70

PSEUDOKARST

Introduction

Large areas of the Earth's land surface are characterized by concentrated subsurface drainage, or by interconnected voids caused by processes other than dissolution. Where these processes occur in loess, lava flows, glaciers, permafrost regions and elsewhere in poorly soluble rocks, terrains characterized by dolines, caves, sinking streams and/or other features commonly observed in karst are termed pseudokarst.

Definitions

A working session of the 1997 12th International Congress of Speleology concluded that "pseudokarsts are landscapes with morphologies resembling karst, and/or may have a predominance of subsurface drainage through conduit-type voids, but lack the element of long-term evolution by solution and physical erosion" (Kempe & Halliday, 1997). Watson Monroe and many others have said it more simply: karst-like morphology produced by some process other than solution. Pseudokarstic caves are natural underground spaces, large enough to enter and investigate, extending beyond daylight, and produced by some process other than dissolution.

Among especially common types of pseudokarstic caves are lava tube caves, talus caves ("boulder caves") on mountainsides and in stream gorges (called purgatory caves in some parts of the United States), crevice caves, glacier caves, and littoral caves ("sea caves"), each of which has a separate entry in this Encyclopedia. Few stream-cut voids are large enough to meet the basic definition of "cave", and by this definition, rock shelters and tafoni are not considered caves in this volume.

Significance of Pseudokarst

Resources and values of pseudokarsts are dependent on the processes which formed them, their features, and their extents. Their geological values differ considerably from those of karsts. They provide access for study of a wide range of geological features, some of which are of special interest to planetary geologists (see Extraterrestrial Caves). They contain a wider range of minerals than do karstic caves. Their archaeological and paleontological values largely depend on their age and location. Their biological resources vary widely. Because pseudokarsts tend to be smaller than karsts, development of troglobitic species tends to be limited. Some in Hawaii and the Canary Islands, however, are so large and so fortuitously located that these have developed nonetheless (see Hawaiian Islands: Biospeleology and Canary Islands: Biospeleology).

Just as in karsts, educational, recreational, wilderness, and other cultural resources and values are highly site-specific. Recreational caving in some stream-smoothed granite talus caves is exceptionally enjoyable. While comparatively few show caves have been developed in pseudokarsts, their educational values are at least as great as those of their karstic counterparts. Some (e.g. parts of Hawaii's Kazumura Cave) are as aesthetically pleasing as all but the greatest karstic caves. During much of the 20th century, the Paradise Ice Caves of Mount Rainier were among the most noted visitor attractions of the United States' Pacific Northwest states.

Hazards

Outburst floods from normothermic or hyperthermic glacier caves are perhaps the most spectacular hazard of pseudokarst. A large literature exists on engineering problems caused by crevice pseudokarsts, isolated crevice caves, piping, and piping caves (see entries on Crevice Caves and Piping Caves). Sudden collapse of overloaded cave roofs is especially a hazard of pseudokarsts containing lava tube caves. Public health hazards exist where such caves function jointly as floodwater or perennial conduits and unlawful disposal sites. In a few pseudokarstic caves, the water flow is formidable; an alpine torrent in a talus cave caused the recent death of an experienced, well-equipped Colorado caver (see entries on Talus Caves and Volcanic Caves).

History

Pseudokarstic forms were observed in loess, perhaps 2300 years ago (Liu *et al.*, cited by Péwé *et al.*, 1995). These became known outside China late in the 19th century; a 1879 description by von Richthofen is often cited. Roman writings mentioned lava tube caves on Mt Etna. The presence of large caves in or beneath some glaciers also must have been known locally from early times. During the early 20th century, the specific terms "pseudokarst" and "pseudokarstification" originated several times, in several languages, and for several types of features. Reports accumulated from a wide variety of terrains. Most of them described features remote from centres of learning and their writers were not academics. Commonly they were in obscure publications and many were in languages that were not widely read. Locally invented terminologies baffled "outsiders", even of the same nationality. Especially confusing were diligent efforts to apply karstic concepts and terminology to phenomena which only looked karstic. Yet an impressive body of knowledge gradually accumulated.

The German geologist von Knebel (1908, p.171) apparently was the first to use any of these terms. Seeing Icelandic streams disappear into fractured basalt, he recorded that "in many lava areas, rivers are features of the subsurface, but it is proper to consider this only as pseudokarstification ("pseudoverkarstung" in his German-language account).

Beginning around 1927, Russian scientists pioneered the study of karst-like features in permafrost and poorly soluble rocks. In 1931 and 1935, F.P. Savarensky wrote about karstlike phenomena in clayey sediments and loess, calling them "clay karst" and "loess karst". In 1947, N.A. Gvozdetskij recommended qualified use of the term "pseudokarst", correctly pointing out that the processes are real, not "pseudo".

Especially after World War II, these papers became known in the portion of Europe under Soviet domination, and elsewhere to a lesser degree. Meanwhile, a significant paper was published in Italy, specifically referring to "A pseudokarstic phenomenon ('fenomeno pseudocarsico') in clay" (Floridia, 1941), and Malaurie used the term in the title of a short geological note in French in 1948. These reports, however, were not in widely read journals.

In the 1950s, English began to be a common scientific language. In 1950, Kukla appended an English summary to a report on sizeable sandstone caves in Bohemia and Kunský (1957) discussed types of pseudokarstic caves in a notable English-language paper. Innumerable reports have appeared since, but many continue to be in little-read languages and/or journals. Proceedings volumes of international symposia on pseudokarst, however, tend to unify central European concepts.

Controversies

In part because of its divergent origins, the concept of pseudokarst is not universally accepted, and agreement on what should be included is less than complete. Several leading dissenters did not attend the 1997 IUS working session which agreed upon the cited definition (Kempe & Halliday, 1997). William B. White specifically considered glacier caves and related features to be "karst-like" rather than either pseudokarst or karst; Eraso and Pulina (1992) and some others consider them to be karstic despite the lack of dissolution. Jennings and some others have accepted the term “volcanokarst” for volcanic pseudokarst, but Grimes pointed out that this term previously was established for a dissolutional form in volcanic ash. A similar controversy exists about the term “thermokarst”. Even in 1972, Marjorie Sweeting noted that “to include such forms is to make the definition of karst too wide and thus to lose much precision”. Other controversies have arisen because of misunderstanding. In the 1950s and 1960s, William E. Davies repeatedly identified certain American closed depressions as pseudokarstic; these were shown as such in the 1970 US National Atlas. Subsequently it was found that these were caused by karstification at depth. Ervin Otvos, a coastal geologist, correctly pointed out (1976) that these are karstic phenomena, not pseudokarstic, and Otvos also proposed restricting the term “pseudokarst” to “only processes and forms involving predominantly piping and thermokarst”. The conclusions of the IUS 1997 working session, however, reflect broad agreement that this proposed limitation was too narrow. Controversies about quartzite karst and pseudokarst have diminished as a result of recent increased emphasis on specific features and processes evident in various tropical areas of quartzite and other poorly soluble rocks (see entry on Silicate Karst).

Classification of Pseudokarst

Pseudokarsts may be classified by morphology, by process, and by lithology. Most classifications have been morphological, or a combination of morphology with other factors. Nearly all have been regionally oriented (e.g. central Europe, western United States, north-central Sweden, etc.) or limited to specific terrains (e.g. volcanic, glacier, etc.). On a global basis, the 1997 IUS working session specifically identified “pseudokarst on lava”, “pseudokarst on ice”, “pseudokarst on permafrost”, “pseudokarst on talus”, and “pseudokarst on unconsolidated sediments and volcanic ash”. At least two additional types were mentioned but not discussed. Based largely on that working session, the following classification is used in this entry:

1. rheogenic pseudokarsts (pseudokarsts on lava flows);
2. glacier pseudokarsts;
3. badlands and piping pseudokarsts;
4. crevice pseudokarsts including littoral pseudokarsts;
5. talus pseudokarsts;
6. permafrost pseudokarsts;
7. consequent pseudokarsts.

Rheogenic Pseudokarsts and Their Caves

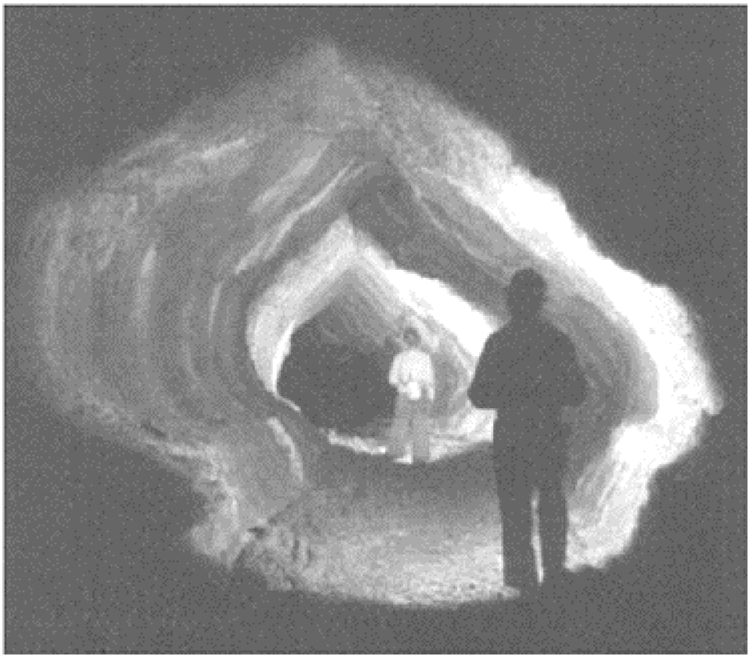
Rheogenic pseudokarsts are features of certain types of lava flows, primarily pahoehoe basalts. In these flows, individual caves up to 65.6 km long have been explored. In addition to specific rheogenic features, many have cross sections (Figure 1), speleothems (see photo in Volcanic Caves entry), speleogens and petromorphs comparable to those of karstic caves. Many have multiple entrances. Some of these occur in patterns reflecting braided cavern passages within the flows. Patterns consistent with extraterrestrial lava tube caves have been identified on Mars, Venus, and Io, and a NASA-funded world database on lava tube caves is maintained at Arizona State University (United States).

Pseudokarst in other volcanic terrains is discussed as crevice pseudokarst and badlands pseudokarst (q.v.).

Glacier Pseudokarsts and Their Caves

Glacier caves provide unique observation points for study of features and mechanics of glacial flows. Until recently, however, their values and their hazards commonly were overlooked. The devastating 1892 outburst flood from Switzerland's Tête Rousse Glacier may have been the first which was recognized immediately as having come from a previously unknown glacier cave.

Glacier caves vary greatly in size. The world's largest water-filled cavern chamber is probably the enormous space beneath Antarctica's Ross Ice Shelf, although some have proposed the Antarctic cavern which contains Lake Vostok. At least until recent ablation of its piedmont lobe, one of the world's longest



Pseudokarst: Figure 1. A drained lava tube showing cross section similar to phreatic tube in limestone. Wiri Cave, Auckland, New Zealand. (Photo by John Gunn)

subterranean rivers ran (or runs) beneath part of Alaska's Malaspina Glacier, a distance of some 50 km. More than 19 km of passages were mapped in the Paradise Ice Caves of Mount Rainier (Washington state, United States) before its glacier melted completely.

This large system and most other large glacier snout caves were largely formed by modification of small subglacial and intraglacial conduits by sublimation and evaporation. Fountain and Wilder (1998) have provided an excellent overview of this process. Other glacier caves are formed by plastic arching of ice in the lee of rocky obstructions and by snow bridging of crevasses. Still others (moulin caves) form by meltwater enlargement of crevasses. To date, moulin caves have been explored to depths of nearly 200 metres. This permits sampling of ice nearly 100 000 years old. The enormous, much-depicted moulin of New Zealand's Fox Glacier is believed to remain unexplored because of the formidable cliffside waterfall which created it.

Crevice Pseudokarst and Its Caves

Crevice pseudokarst and its caves reach their maximum expression in four terrains: volcanic and other terrains which have undergone extensive fracturing; littoral pseudokarst; cliff and mass movement terrains; and glaciers. Mass movement terrains often are not recognized as such, but locally cause serious engineering problems due to gravity-driven sliding or tilting. Most of the island of Hawaii (the "Big Island" of the Hawaiian Archipelago) consists of crevice pseudokarst, but only a few of its crevices are caves (the remainder of the pseudokarst of the island consists of rheogenic pseudokarst). Perhaps most visible of all crevice forms are crevasses in glaciers. A few crevice caves have commercial value as show caves. Only rarely are cavernous littoral areas extensive enough to comprise a landscape, but at least one exists: at Ballybunion, on the west coast of Ireland.

Talus Caves and Their Pseudokarsts

In Sweden and some other areas where granitic and metamorphic rocks predominate, talus caves are as important as karstic caves. Most of these caves are in talus accumulations too small to be considered landscapes. However, Colorado's Lost Creek Pseudokarst (United States), formed in granite, is comparable in features and size to sections of Puerto Rico's famous karst (Hose, 1996). In the northeastern United States, large blockfields (boulder fields) contain lengthy, tortuous maze caves. Boulder accumulations large enough to contain caves have been identified on Mars (Malin & Edgett, 2000).

Badlands (Piping) Pseudokarst and Its Caves

Badlands and other forms of piping pseudokarst are best known for causing serious engineering problems but several sizeable piping caves are important individual features (e.g. Officers Cave, Oregon, Anvil Points Claystone Cave, Colorado, and Christmas Canyon Cave, Washington state, United States). While piping originally was described in loess, it occurs in many forms of poorly consolidated material and some rocks, including quartzite, where it transports some of the clastic debris generated in the development of multiprocess caves. Some small-scale features on Mars suggest recent piping on that planet (Malin & Edgett, 2000).

Permafrost Pseudokarst and Its Caves

Permafrost pseudokarst is formed by a combination of thawing and piping in areas of tundra and taiga where permafrost under-lies the ground surface. Such terrains occupy more than 10% of the Earth's surface. In summer, parts of these terrains are conspicuous for circular to oval thaw ponds and drained, steepwalled depressions up to 10 km in diameter and 1 to 40 m deep, with flat bottoms. Locally they may occupy as much as half of the surface, pockmarking the landscape much as in the case of some karstic plateaux. These depressions are formed by local collapse of thawing soil layers which contain ice wedges and permafrost polygons, with subsequent piping. Related karst-like features include funnel-shaped pits, ponors, and dry valleys. Small caves form by melting of ice veins in subsurface polygons and by piping in earthy walls of depressions. Especially in Europe, the term "thermokarst" has been applied to these terrains, but there is nothing dissolutional in the process which formed them. Sweeting has decried the term, pointing out its confusing similarity to the established term "thermal karst".

Consequent Pseudokarsts and Their Caves

Istvan Eszterhas has developed the concept of consequent pseudokarst: karst-like terrains formed by the action of natural processes interacting with mines, underground quarries, and other subsurface works of mankind. Their surface features tend to be rectilinear, and commonly reflect serious engineering problems (Figure 2). Some consequent collapse areas contain extensive caverns formed by natural stoping. These are bounded on all sides by talus or fracture surfaces, much as in the case of karstic or lava tube caves in which breakdown has filled the original space and the present-day cave is entirely above the original cave.

Interfaces and Multiprocess Caves

Because of the variety of processes and lithologies that form pseudokarsts, numerous interfaces and multiprocess caves exist. In Brazil, "canga caves" have been identified beneath limonitecemented, haematite-rich surface debris. Some are believed to be solutional, others corrasional, and perhaps some are a combination of these processes. More study is needed. Several geologists have discussed small closed depressions caused by dissolution on horizontal or gently sloping surfaces of poorly soluble rocks. While large quantities of insoluble particles are removed by piping or streamflow, this phenomenon generally is considered to be karstic. Similarly, karren (lapiès) also are found on a variety of soluble and poorly soluble rocks. Examples of the latter are the much-photographed granite boulders of the Seychelles Islands. Most lapiès are karstic, but some in lava tube caves clearly are the result of thermal erosion and are pseudokarstic phenomena. Dolines penetrating thin mantles of loess and other poorly soluble material overlying karstified bedrock are also karstic, not pseudokarstic. Because dissolution of calcareous materials in loess is part of the process forming its karst-like features, some geologists have considered them also to be karstic. This, however, is so minor a part of the process that, in this entry, loess features are considered part of badlands pseudokarst. Grimes has differentiated between laterite karst (in which silicate minerals are removed in solution from within a deep weathering profile) and laterite caves in western Australia which appear to have been caused by piping.

Pseudokarst: Figure 2. Consequent pseudokarst atop an abandoned coal mine in Wyoming (United States). US Geological Survey aerial photo by C.R.Dunrud published in US Geological Survey Circular 876. Scale is shown by roads.

Karstic and Pseudokarstic Processes in Quartzite Caves

The role of dissolution in speleogenesis and karstification of poorly soluble quartzites and related rocks has been much debated in recent years. The spectacularly pitted Sarisarinana and other rainforest quartzite plateaus of Venezuela, the gentler Chimanimani area of Zimbabwe, and some regions of South Africa have received especially intensive consideration (see Silicate Karst). Somewhat similar features in ferruginous metamorphic rocks also have been discussed.

In calcareous rocks, karstification requires both dissolution and physical removal of varying amounts of clastic debris originally present in the bedrock. Even in very pure limestones, laminar or turbulent flow must carry small loads of insoluble residue freed from bedrock by dissolution, with karstic conduits acting as pipes. Other cavernous limestones contain horizons of sand, gravel, and even large boulders of poorly soluble material (e.g. Espluga de Francoli, Tarragona, Spain). These similarly are freed by dissolution, and choke incipient conduits if not actively removed by stream transport. Further, some caves in limy sandstones and conglomerates (e.g. Cova de Salnitre, Catalunya, Spain) also have features characteristic of phreatic speleogenesis despite an even greater proportion of clastic material. Thus, it appears that there is a continuum between piping and dissolution caves in carbonate rocks, including rocks with a mere carbonate matrix.

In clastic rocks with siliceous and ferric matrices, such a continuum is not as clear. However, dissolution of these non-carbonate binders has been documented in some quartzose localities (e.g. Striebel & Schäferjohann, 1997). Such dissolution permits similar transport of siliceous particles by piping and stream flow.

Some but not all caves in quartzites in the humid tropics contain dissolutional speleogens, and appear to be part of this continuum. Photodocumentation of passages in these caves shows patterns typical of phreatic conduits. But comparatively enormous volumes of clastic material must have been removed so that the pits and conduits were not choked by their own debris. In such a multiprocess continuum, no specific percentage of processes can be said to separate karstic, interface, and pseudokarstic caves. It is of some interest that colloidal silica speleothems have been documented in Brazilian and Venezuelan caves, but actual laminar transport of colloidal silica as an inception mechanism apparently has not been studied. On the other hand, published maps, descriptions, and photographs of the quartzite Chimanimani Caves of Zimbabwe and some in South Africa do not document similar evidence of dissolution. Like caves near Ellenville, New York (United States), the Chimanimani Caves appear to be rectilinear crevice caves with chambers developed vertically, without evidence of significant dissolution or piping. It therefore appears that some major caves in quartzose rocks are largely or entirely pseudokarstic crevice caves while others are multiprocess caves that have become predominantly karstic.

Martian Analogues of Terrestrial Pseudokarsts

Malin and Edgett (2000) have reported several Martian features which may be analogous to terrestrial pseudokarsts (see also Extraterrestrial Caves). One consists of talus accumulations where alcoves are “littered” with boulders “several metres to several decimetres” in diameter. These are directly downslope from egresses of recent outbursts of water, some of which evidently entered the talus. On Earth, talus accumulations with these parameters commonly contain talus caves, and terrestrial talus acts as a baffle to subsurface atmospheric movement. As a result, some talus caves function as natural deep-freezes, and contain unseasonal snow and ice. On Mars, they may protect recent spelean ice accumulations from ablation. In addition, the open conduits above these Martian talus accumulations may be analogous to terrestrial piping caves. Malin and Edgett merely referred to badlands topography in polar pits, without explanation. But they presented detailed evidence of piping or other open conduits in perhaps three specific Martian terrains: alcoves associated with resistant layers in cliffs, in landslide or slumped material, and “perhaps in colluvium”. On Earth, piping caves occur in all three types of terrain.

Present-day Martian terrains are hyper-arid beyond any conditions now present on Earth. Some extremely hyper-arid terrestrial terrains, however, may sufficiently approach Martian conditions that their piping caves may serve as useful models of Martian conduits. Speleological observations are largely lacking in such forbidding parts of the Earth. But a published photograph of the Oumou Caves, Republic of Chad, suggests that they should be investigated as possible terrestrial equivalents in clastic sedimentary rock. The Cave of Swimmers and other sandstone caves reported on Egypt’s Gilf Kebir also may be equivalents, but except for archaeological features, little is known of these. In a humid region, Christmas Canyon Cave (Washington state, United States) is a low but extensive piping cave in volcanic ash beneath a resistant layer of basalt, seemingly replicating the Martian stratigraphy. Major piping caves (e.g. Officers Cave, Oregon and Anvil Points Claystone Cave, Colorado, United States) also may have features usefully analogous to Martian conduits in landslide or slumped material (see Piping Caves and Badlands Pseudokarst).

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See also **Crevice Caves; Glacier Caves and Glacier Pseudokarst; Littoral Caves; Piping Caves; Talus Caves**

Works Cited

Eraso, A. & Pulina, M. 1992. *Cuevas en Hielo y Rios Bajo los Glaciares,* Madrid: McGraw-Hill

Floridia, G. 1941. Un particolare fenomeno pseudocarsico manifestato da algune argile. *Bolletino della Societa di Sciencio Naturale ed Economiche di Palermo,* 23:10–19

Fountain, A. & Wilder, J. 1998. Water flow through temperate glaciers. *Reviews of Geophysics,* 36(3):299

Hose, L. 1996. The Lost Park Reservoir Project, Park County, Colorado. In *The Caves and Karst of Colorado, 1996 NSS Convention Guidebook,* edited by R.Kolstad, Huntsville, Alabama: National Speleological Society

Kempe, S. & Halliday, W. 1997. Report of the discussion on pseudokarst. In *Proceedings of the 12th International Congress of Speleology,* vol. 6, Basel, Switzerland: Speleo Projects: 107

Knebel, W. von 1908. *Höhlenkunde mit Berücksichtigung der Karstphänomene,* Braunschweig: Friederich Vieweg und Sohn

Malin, M. & Edgett, K. 2000. Evidence for recent groundwater seepage and surface runoff on Mars. *Science,* 288:2330–35

Otvos, E. 1976. "Pseudokarst" and "pseudokarstic terrains": Problems of terminology. *Geological Society of America Bulletin,* 87:1021–22

Péwé, T., Liu Tungsheng, Slatt, R.M. & Li Bingyuan. 1995. *Origin and Character of Loess-like Silt in the Southern Qinghai-Xizang (Tibet) Plateau, China,* Washington: Government Printing Office (US Geological Survey Professional Paper 1549)

Striebel, T. & V.Schäferjohann. 1997. Karstification of sandstone in Central Europe: attempts to validate chemical solution by analyses of water and precipitates. In *Proceedings of the 12th International Congress of Speleology,* vol. 1, Basel, Switzerland: Speleo Projects: 473–76

Further Reading

Proceedings volumes of international symposia on pseudokarst, most recent volume being *Proceedings of the 6th International Symposium on Pseudokarst,* Galyatető Hungary, 1996, edited by I. Eszterhás & S.Sárkozi

Newsletter of the Commission for Pseudokarst, International Union of Speleology. (bilingual), edited by Istvan Eszterhás (www.clubs.privateweb.at/speleoaustria/pseudokarst.htm)

Halliday, W. 1974. *American Caves and Caving: Techniques, Pleasures, and Safeguards of Modern Cave Exploration,* New York: Harper and Row, pp.46–70

Kosack, H.-P. 1952. Die Verbreitung der Karst- und Pseudokarsterscheinungen über die Erde. *Petermanns Geographische Mitteilungen,* 96 Jahr, 1st Q.: 1ff.

Kunský, J. 1957. Thermomineral karst and caves of Zbrašov, northern Moravia. Sbor. Čs. Spol. zeměpis., 62, 4:306–351.
Parker, G. & Higgins, C. 1990. Piping and pseudokarst in drylands. In *Groundwater Geomorphology: The Role of Subsurface Water in Earth-surface Processes and Landforms,* edited by C.Higgins and D.Coates, Boulder, Colorado: Geological Society of America
White, W., Jefferson, G. & Haman, J. 1966. Quartzite karst in southeastern Venezuela. *International Journal of Speleology,* 2: 309–14

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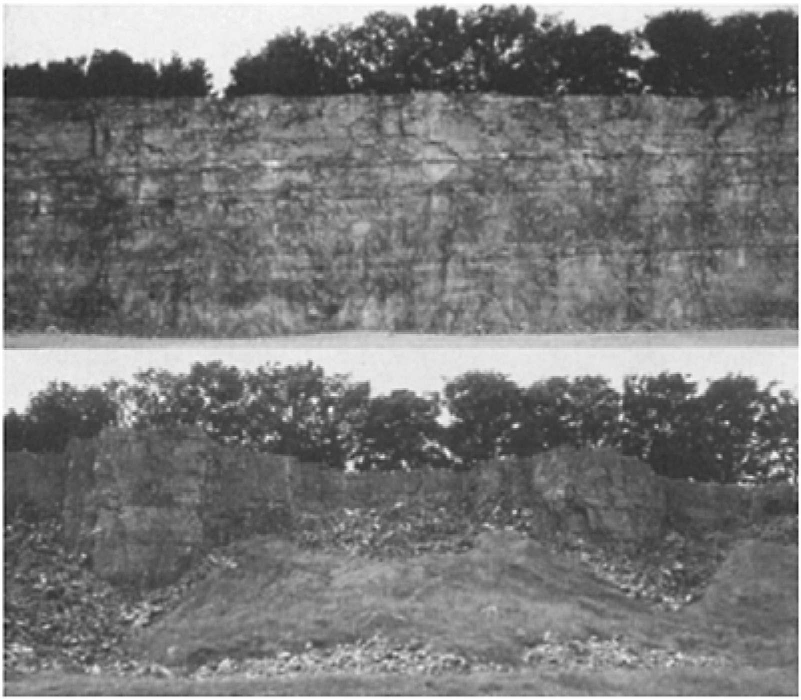
QUARRYING OF LIMESTONE

The extraction of limestone has a long history, going back quite literally to the Stone Age. Three primary groups of extraction techniques may be identified: mechanical techniques; techniques that use low explosives (blackpowder); and modern techniques that use high explosives, often in combination with ANFO (Ammonium Nitrate and Fuel Oil). In general terms, there is a technological progression, but non-explosive and low-explosive techniques are still used for the extraction of dimensional (building) stone.

The earliest forms of quarrying utilized human muscle to remove limestone from free faces. For example, drawings of early English quarries show labourers suspended from ropes prising loose stones from valley sides. Large blocks were reduced by labourers with sledgehammers. Similar techniques are still practised in some developing countries where there is an abundance of labour. There are various modern non-explosive techniques, including the use of drilling, feathers and wedges, mechanical shovels on weaker limestones, and diamond saws to cut dimensional stone, particularly marble (Figure 1).

Explosives were introduced into quarrying in the 19th century. The essential property of any explosive is that, on detonation, it is converted as rapidly as possible into gases which occupy many times the original volume of the explosive. In high explosives the gases are produced almost instantaneously at very high temperatures and pressures and are accompanied by an intense shock wave. Blackpowder (gunpowder) is slower in action and the gases are released at much lower pressures. This difference in explosive property determines the amount of rock liberated on detonation, together with the resulting end-form of the blasted face.

Blackpowder was the primary explosive used in quarrying limestone until the mid-20th century when it was largely replaced by high explosives. It is only rarely used in modern quarrying, usually where there is a need to minimize fracture damage to the rock, as in the extraction of dimensional stone. In the older quarries the ground above the face was cleared of overburden prior to blasting, so as to reduce the amount of washing needed to clean the stone. Initially this was done by teams of quarrymen, a process known as piking (hand picking). Piking located suitable fractures and joints into which black powder could be poured and fired almost at random. These blasts were sometimes augmented by header tunnels, which were excavated beneath the face and packed with explosives. Teams of men with sledgehammers were employed to break down oversized rocks and to remove loose or overhanging rocks from the face, a process known as face-dressing. Blackpowder was replaced



Quarrying of Limestone: Figure 1. Tunstead Quarry, Derbyshire, England showing a typical rock face blasted using ANFO/emulsion explosives (top) and the same face after restoration blasting and habitat reconstruction (bottom).

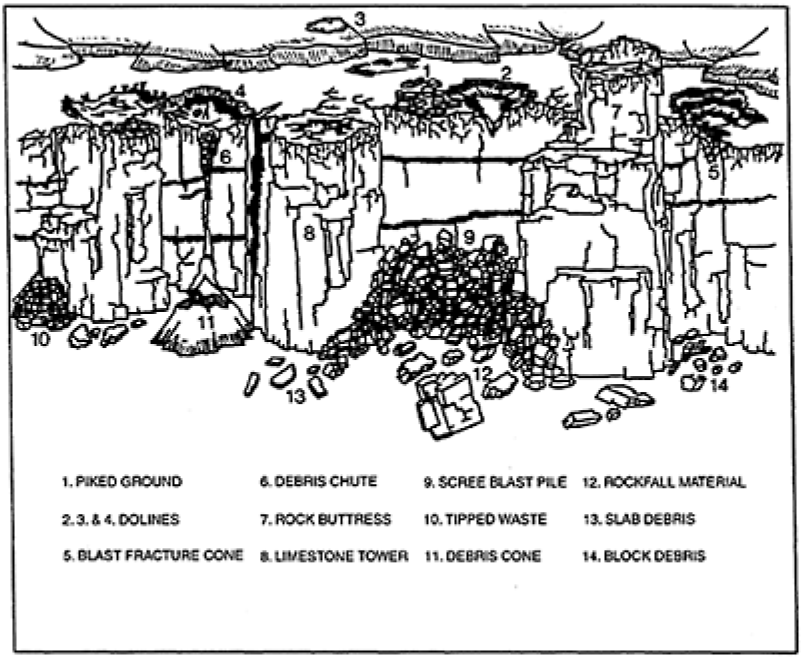
firstly by high explosives such as TNT and nitro-glycerine and then by a combination of high explosives and ANFO. To accommodate the new explosives and take advantage of new technologies there were also changes to drilling and blasting designs. The aim of the drilling and blasting design is to excavate safely the maximum amount of stone of the desired fragmentation into an easily removed blast pile, while leaving the rock face in a condition suitable for further blasts to take place.

Limestone quarrying has three main environmental impacts: aesthetic, geomorphological, and hydrogeological. The aesthetic impacts are obvious, and to most people quarrying represents a visual intrusion into the landscape, although it has been argued that quarry faces provide features of interest in areas otherwise devoid of natural cliffs. In the past, dust was a major associated problem but in most countries this has been much reduced by the imposition of stringent controls.

Geomorphologically, quarrying represents the most dramatic impact of human activity on karst landscapes. It is initially erosional, through the removal of materials from the ground, but may also include depositional components such as spoil heaps and tailings lagoons. In process terms quarrying represents an extremely potent erosive agent. For example, during the 20th century, quarrying removed more limestone from the English Peak District than had been removed by natural processes during the entire Holocene period, some 10 000 years. This process activity results in the destruction and modification of surface and underground landforms including hills, valley sides, dolines, and cave systems. The latter has been a cause of particular concern, where the caves contain deposits of archaeological, paleoenvironmental or paleontological interest, or where there is a rich subterranean fauna.

When extraction ceases, a hole remains and, unless it is infilled, the perimeter slopes will begin to evolve under the influence of natural processes. Ultimately it may become virtually indistinguishable from the surrounding landscape, the time involved being a function of the excavation processes, geology (structure and strength), and the intensity of natural processes. In the English Peak District, a characteristic sequence of landforms develops in abandoned blackpowder quarries (Figure 2). In contrast to blackpowder quarries, there are just two primary landforms on faces in high explosive/ANFO quarries: blast fracture cones and buttresses. Blast fracture cones are doline-like features with a lateral extent of 3–5 m, while rock buttresses accord with the position of drilled shot holes and are easily identified on recently blasted faces by the prominent explosives scorch marks. They project out from the quarry face and increase in size and lateral extent towards the quarry or bench floor. Their vertical extent is half to two-thirds of the face height, in contrast to the buttresses produced by blackpowder blasting, which are frequently full face height.

Quarrying is often associated with groundwater pollution, principally by fine material and also, in some cases, by fuel oil. In some quarries, pumping of groundwater allows working to extend sub-water table but this may result in the drying up of springs and surface streams. Hence it is important that any new quarries are located in areas where potential impacts may be minimized.



Quarrying of Limestone: Figure 2. Typical landform assemblage in an abandoned quarry in the English Peak District excavated by blackpowder blasting.

A principal concern, in areas where limestone is extracted, is the restoration of sites once quarrying has ceased. The small scale and extent of the blackpowder blasted quarries, together with the manner in which their margins evolve under the influence of natural processes, mean that they will eventually be assimilated into the natural landscape, over periods of tens to hundreds of years. By contrast, the scale of modern quarries and the methods used in their excavation are such that they will continue to intrude upon the natural landscape for many centuries. In order to speed up the process of assimilation a new technique, Landform Replication, was developed in Britain. The first step is to identify the key elements in a natural limestone landform sequence. These are then replicated using restoration blasting and habitat reconstruction. In the Peak District, restoration blasting aims to replace the engineered appearance of a production blasted quarry face by a sequence of constructed landforms, whose scale and extent mimics that of a natural limestone valley side. Habitat reconstruction aims to establish vegetation, similar to that on natural valley sides, on the constructed landforms. Landform replication techniques have been applied on the Niagara escarpment in Canada and other techniques for quarry reclamation, particularly of the quarry floor, have been pioneered at the Banburi Quarry near Mombasa, Kenya and at the Lune River Quarry in Tasmania.

JOHN GUNN

See also **Limestone as a Mineral Resource**

Further Reading

Brashaw, P. (editor) 2002. *Reclamation of Limestone Quarries by Landform Simulation: Summary of Lessons Learnt from Trial Sites,* London: Department for Transport, Local Government and the Regions

Drew, D. & Hötzl, H. (editors) *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* Rotterdam: Balkema. (Section 6 contains a number of papers on the Impacts of extractive industries).

Ekmekci, M. 1993. Impact of quarries on karst groundwater systems. In *Hydrogeological Processes in Karst Terrains,* edited by G.Günay, International Association of Hydrological Sciences Publication no. 207

Gillieson, D. & Houshold, I. 1999. Rehabilitation of the Lone River Quarry, Tasmanian Wilderness World Heritage Area, Austrialia. In *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* edited by D.Drew & H.Hötzl, Rotterdam: Balkema

Gunn, J. 1993. The geomorphological impacts of limestone quarrying. In *Karst Terrains: Environmental Changes & Human Impact,* edited by P.W.Williams, Cremlingen-Destedt: Catena

Gunn, J. & Bailey, D. 1993. Limestone quarrying and quarry reclamation in Britain. *Environmental Geology,* 21(3):167–72

Gunn, J., Bailey, D. & Handley, J. 1997. *The Reclamation of Limestone Quarries using Landform Replication,* London: Department of the Environment, Transport and the Regions

Harrison, D.J., Buckley, D.K., & Marks, R.J. 1992. *Limestone Resources and Hydrogeology of the Mendip Hills,* Keyworth: British Geological Survey (BGS Technical Report WA/92/19)

Hobbs, S.L. & Gunn, J. 1998. The hydrogeological impacts of quarrying karstified limestone, options for prediction and mitigation. *Quarterly Journal of Engineering Geology,* 31:147–57

Mineral Planning, 2001–2002. Three papers entitled Limestone landform simulation in quarry restoration were published in issues 89 (pp.28–32), 90 (pp.13–17) and 91 (pp.16–19). The journal publishes many short papers on aspects of limestone quarrying and quarry restoration.

Walton, G. & Allington, R. 1994. Landform replication in quarrying. *Transactions of the Institute of Mining and Metallurgy* (Section A: Mining industry), 103:A55–66

QUARTZITE CAVES OF SOUTH AMERICA

While not well endowed with carbonate karst South America hosts the world's best-developed quartzite karst. Extensive quartzite outcrops (see map in America, South), in varied climatic and geomorphic settings, allow the existence of a large number of caves of impressive extent and depth. Although exploration and research in quartzite areas is still in its early stages, there are now at least 11 caves over 1 km in length (Table 1), and 16 over 200 m in depth (Table 2), including the deepest and longest quartzite caves in the world.

The study of quartzite caves and karst is a relatively recent field of karst science (see separate entry, Silicate Karst). The model for formation of caves in quartzite was initially based on the quartzite caves of South Africa (Martini, 1979), but has found wider applicability on the quartzite caves of South

Quartzite Caves of South America: Table 1. The longest quartzite caves of South America.

Cave	Location	Country	Length (m)
1. Gruta do Centenário	Inficionado Peak	Brazil	3790
2. Gruta da Bocaina	Inficionado Peak	Brazil	3220
3. Sima Auyán-tepui Noroeste	Auyán-tepui	Venezuela	2950
4. Gruta das Bromélias	Ibitipoca	Brazil	2750
5. Sima Aonda Superior	Auyán-tepui	Venezuela	2128
6. Sima Aonda	Auyán-tepui	Venezuela	1690
7. Lapão	Chapada Diamantina	Brazil	1600
8. Sima Acopán 1	Acopán	Venezuela	1376
9. Sima de la Lluvia	Sarisariñama	Venezuela	1352
10. Sima Menor de Sarisariñama	Sarisariñama	Venezuela	1179

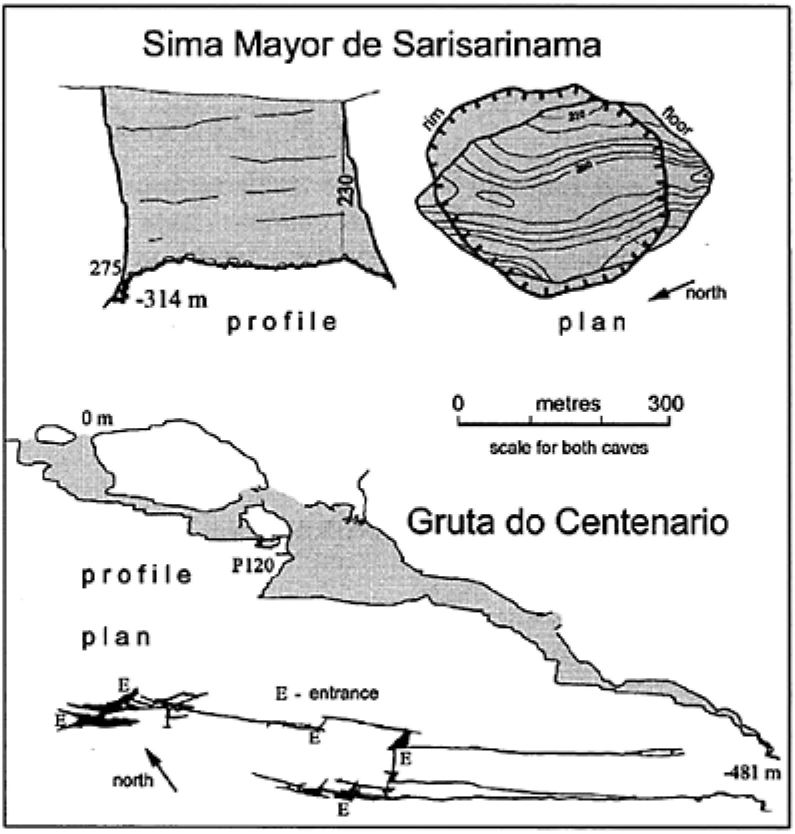
Quartzite Caves of South America: Table 2. The deepest quartzite caves of South America.

Cave	Location	Country	Depth (m)
1. Gruta do Centenário	Inficionado Peak	Brazil	481
2. Gruta da Bocaina	Inficionado Peak	Brazil	404
3. Sima Aonda	Auyán-tepui	Venezuela	383
4. Sima Auyán-tepui Noroeste	Auyán-tepui	Venezuela	370
5. Sima Aonda 3	Auyán-tepui	Venezuela	335
6. Sima Aonda 2	Auyán-tepui	Venezuela	325
7. Sima Auyán-tepui Norte	Auyán-tepui	Venezuela	320
8. Sima Mayor de Sarisariñama	Sarisariñama	Venezuela	314
9. Sima Auyán-tepui Norte 2	Auyán-tepui	Venezuela	297
10. Sima Aonda Este 2	Auyán-tepui	Venezuela	295

America. Current knowledge of quartzite karst in South America allows the recognition of at least two major types of caves: (1) vertical, fissure-like caves related to high plateaux; and (2) horizontal or gently sloping caves in flat lying areas of "cuesta" landscape.

Fissure vertical caves were recognized initially in the Precambrian quartzites of the Roraima Group, in the Gran Sabana area of southern Venezuela. In this ever wet region, where precipitation can reach as much as 4000 mm a^{-1}, a number of isolated flat-topped towers, known locally as tepuis, some over 1 km high, rise abruptly from the dense rainforest. The tops of the tepuis are criss-crossed with joints, some of them (mainly the ones close to the scarps) opening into vertical shafts over 100 m deep, that give access to joint-controlled passages at the bottom. Many of these passages contain underground streams, although it has not been possible to connect the passages to resurgences observed at the scarps. The difficulty of access has acted as a major limitation to exploration in this area. To date, some of the most visited plateaux are Sarisariñama, Auyán-tepui, Roraima, Autana and Kukenan, but there is still much work to be done in these areas, while many other tepuis await exploration. The Sarisariñama plateau contains massive open shafts, the largest, Sima Mayor, reaching as much as 350 m in diameter and 314 m in depth, holding an internal volume of *c.* 12 million m^3 (Figure 1). The deepest caves to date have been explored at the Auyántepui. Sima Aonda and Sima Auyán-tepui Noroeste are, respectively, 383 m and 370 m deep. The latter is also the longest cave in the area, reaching 2950 m in length. The proximity of these caves to the tepui scarp has led to the suggestion that pressure relief has aided in the enlargement of the joints (Galán, 1991). Surface karst features include swallets, resurgences, pinnacles, towers, and solution basins (kamenitza). A small portion of the Roraima quartzite karst has been included in the National Park of Cainama, established in 1962 and now a World Heritage Site. The National Park protects mainly the Auyán-tepui, including its main attraction, the 970 m high Angel Falls.

In south-central Brazil, recent research has yielded another area of outstanding potential. The Inficionado Peak is one of a series of peaks in the Caraça Range, composed of Precambrian quartzites of the Caraça Group. Although not a plateau like the Venezuelan tepuis, it rises abruptly over the surrounding lower area, possessing a 1 km high scarp in its southeast-facing slope. The top of the Inficionado Peak covers only 0.9 km^2, but it presents a number of joints, some of them opening into deep and narrow crevasses that lead into rectilinear passages containing streams. The general character of the Inficionado karst resembles those of the tepuis, with the exception that there is no surface drainage, and it is sometimes possible to traverse the caves to entrances situated at the face of the scarp. The deepest and longest quartzite cave in the world, and currently the deepest cave in South America, is the 481m deep and 3790 m long Gruta do Centenário (Figure 1). Gruta da Bocaina (404 m deep and 3220 m long) is another significant cave. Surface karst features are poorly developed, except for large collapse dolines and resurgences. Due to its small area, the potential at the Inficionado Peak appears limited, although there are still many open joints awaiting exploration. Other high quartzite peaks elsewhere in Brazil may hold similar potential for deep and long quartzite caves.



Quartzite Caves of South America: Figure 1. Plans and profiles of two major caves in South American quartzite: Sima Mayor de Sarisariñama and Gruta do Centenário (courtesy of Grupo Bambuí de Pesquisas Espeleológicas).

Quartzite Caves of South America: Figure 2. Typical passage morphology in Lapão Cave (Lencóis) showing breakdown modification of vadose canyon. The 1.6 km cave is developed in metasandstones and conglomerates of the Tombador Formation and is the fourth longest cave in sandstones and quartzites in Brazil. (Photo by John Gunn)

The second type of quartzite cave, commonly found in South America, comprises caves occurring in the gently rolling cuestatype of relief typical of the Andrelândia Group rocks of southern Minas Gerais state, Brazil (Corrêa Neto, 2000). These caves tend to follow favourable quartzite horizons (parallel to the cuesta gentler slope) and develop along active passages with frequent tributary junctions. Many of these caves end in restrictions, due to the accumulation of sand, although some can be followed to another entrance. The largest concentration of this type of cave occurs at the Ibitipoca State Park, where the Gruta das Bromélias, with 2750 m of mapped passages, is the longest cave known. Other areas, with a large number of caves, are the Luminárias and Carrancas areas, also in southern Minas Gerais State, and the Espinhaço Range, extending across the states of Minas Gerais and Bahia. The Chapada Diamantina in central Bahia State is the northern extension of the Espinhaço orographic system. Here, Lapão Cave is the fourth largest cave in sandstones and quartzites in Brazil. Along the 1600 m of passage the dominant morphology is of breakdown modification of vadose conyons but in some parts the remnant elliptical passage cross sections suggest modification of phreatic conduits (Figure 2). The cave is also notable for opan speleothems.

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See also **America, South; Silicate Karst**

Works Cited

Corrêa Neto, A.V. 2000. Speleogenesis in quartzite in southeastern Minas Gerais, Brazil. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Galán, C. 1991. Disolución y genesis del karst en rocas carbonáticas y rocas silíceas: Un estudio comparado [Dissolution and genesis of karst in carbonate and siliceous rocks. A comparative study]. *Munibe,* 43:43–72

Martini, J.E.J. 1979. Karst in Black Reef quartzite near Kaapsehoop, eastern Transvaal. *Annals of the Geological Survey of South Africa,* 13:115–28

Further Reading

Chalcraft, D. & Pye, K. 1984. Humid tropical weathering of quartzite in southeastern Venezuela. *Zeitschrift für Geomorphologie,* 28(3):321–32

Galán, C. & Lagarde, J. 1988. Morphologie et evolution des cavernes et formes superficielles dans les quartzites du Roraima (Venezuela) [Morphology and evolution of caves and surface forms in the Roraima quartzites (Venezuela)]. *Karstologia,* 11–12: 49–60

Martini, J.E.J. 2000. Dissolution of quartz and silicate minerals. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Szczerban, E. & Urbani, F. 1974. Carsos de Venezuela. Parte 4: Formas carsicas en areniscas precambricas del Territorio Federal Amazonas y Estado Bolivar [Venezuelan Karst. Part 4. Karst forms in Precambrian sandstones in Amazonas Federal Territory and Bolivar State]. *Boletin de la Sociedad Venezolana de Espeleologia,* 5(1):27–54

Urbani, F. 1978. Les karsts gréseux du Venezuela. Une spéléologie entre ciel et terre [The Venezuelan sandstone karst. A speleology between the sky and Earth]. *Spelunca,* 18(1):24–8

Urbani, F. 1986. Notas sobre el origen de las cavidades en rocas cuarciferas precambricas del Grupo Roraima, Venezuela [A note on the origin of caves in precambrian quartzite of the Roraima Group, Venezuela]. *Interciências,* 11(6):298–300

Wray, R.A.L. 1997. A global review of solutional weathering forms on quartz sandstones. *Earth Science Reviews,* 42:137–60

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RADIOLOCATION

Radiolocation, in the speleological context, is the procedure of determining the position and depth of an underground radio transmitter beacon, by making measurements on the surface using a radio receiver. The name is perhaps a misnomer, because the underlying physical principle owes more to the phenomenon of magnetic induction than to “true” radio. Using radiolocation, an underground aven or choked inlet passage can be correlated with a surface feature quicker than by conventional cave surveying methods (see Surveying Caves). Such fixes are useful, not only for exploration, but as an aid to cave communication using induction radios, which generally require the shortest possible communications path (see entry, Communications in Caves). Rescue teams maintain maps showing the location of these surface and underground stations, thus allowing communications to be set up swiftly in the event of an incident. Radiolocation is also used to verify underground surveys—the point on the surface immediately above a survey station is radiolocated and its position measured by an accurate surface survey or GPS reading.

Radiolocation in its present form dates from the mid-1950s, when transistorized equipment started to become readily available to experimenters and the mid-1960s also saw a spate of research by the US Bureau of Mines. The method of radio-location used by cavers has changed little since its inception. A transmitter antenna, consisting of many turns of wire on a loop of typically 500 mm diameter, is placed horizontally underground with the aid of a spirit level (Figure 1). An amplifier drives the antenna with a very low frequency (VLF) signal, causing it to generate an alternating magnetic field. Typically, a power of 10 W is used at 1–3 kHz. At such low frequencies there is virtually no electromagnetic radiation—the power is dissipated as heat in the antenna. The magnetic field induces a signal in a receiver antenna, which is usually of similar construction to the transmitter. If the receiver loop is orientated such that no magnetic field lines pass through it, then it will not detect any signal. Establishing this “null” orientation at several locations allows the operator to triangulate a “ground zero” point directly above the underground transmitter, at which location the field lines are vertical (Figure 2). The method is described by Glover (1976) and France (2001).

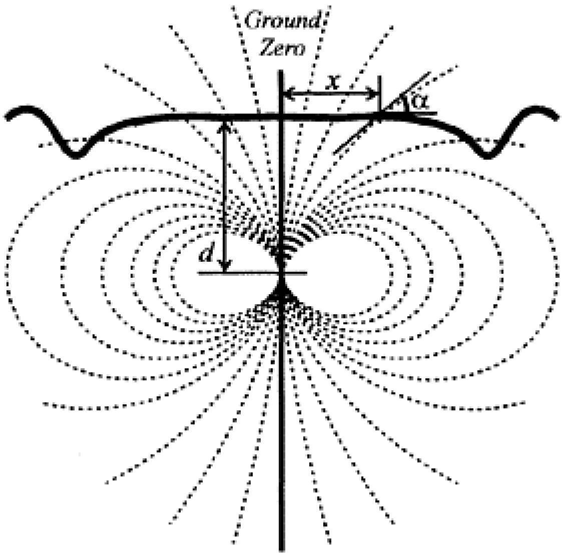
With ground zero (GZ) fixed, there are several methods of determining the depth. The simplest, and one that has been used by the mining industry and for commercial pipe and sewer location, is to measure the field strength using calibrated equipment and to calculate the depth from the knowledge that the field strength decays as the inverse cube of distance. Cavers normally use a different method that does not depend on accurate measurement of signal strength. At a measured distance *x* from GZ, the angle a of the field line to the horizontal is determined using the "nulling" procedure outlined above (Figure 3). The depth d below GZ is then given (Glover, 1973) by

$$\frac{x}{d} = \frac{\sqrt{(8 + 9 \tan^2 \alpha)} - 3 \tan \alpha}{2}$$

The careful surveyor will take several readings at different distances, plot a graph, find a best-fit curve and thereby arrive at a good approximation to the depth. In practice, a couple of rough-and-ready approximations are adequate—for the field line at 45°, we have, $x/d \approx 0.562$, so the depth is approximately twice the distance *x* and, when $x/d=1$, the field angle is $\alpha \approx 18.4°$.

The formula assumes that the field lines are in a "bar magnet" pattern. Obvious exceptions are if a magnetic ore body distorts the field or if the transmitter is tilted (Gibson, 1998). With a levelled antenna, an experienced operator can achieve an accuracy for GZ of 1 m for a 50 m depth (2%) and a depth accuracy of perhaps 5%. With a 5° tilt, geometry dictates additional errors of 3%. If the surface terrain is uneven, this must be taken into account or further errors will result. If the transmitter is grossly tilted, then the technique described here will not work. However, the methods of radiolocation used by the mining industry do allow for this situation, where body-worn transmitters can allow prone or unconscious miners to be located. An adaptation

Radiolocation: Figure 1. Levelling a radiolocation transmitter loop prior to use, in Valley Entrance, Kingsdale Master Cave, North Yorkshire. (Photo by Mike Bedford)



Radiolocation: Figure 2. The magnetic field lines from an underground transmitter form the familiar “bar magnet” pattern. Measurements of field angle (*α*) and distance from Ground Zero (*x*) on the surface allow the depth (*d*) to be calculated.

of the technique using vertical antennas allows cave-to-cave location.

Derivations of depth from measurements on different bearings from GZ will sometimes differ markedly, especially if the transmitter is deeply buried, or if $x>>d$. If the transmitter is known to be level, and if the presence of ore bodies can also be discounted, then the likely cause is that the ground is anisotropic with respect to electrical conductivity—which is only to be expected for a bedded and jointed rock such as limestone. Indeed, an adaptation of this radiolocation technique can be used to measure the electrical conductivity of the ground by a non-contact means.

Radiolocation: Figure 3. Using a nulling technique to measure field angle—note the clinometer attached to the side of the receiver loop antenna. (Photo by Mike Bedford)

The fact that the electrical conductivity of the rock can affect what is generally assumed to be a purely magnetic measurement is an important observation, demonstrating that magnetic induction is not the only phenomenon at work. It is the predominant effect only when the separation of the transmitter and receiver is much less than a "skin depth"; this being a figure of merit used to describe the extent to which electromagnetic waves penetrate into a conductor. If this condition cannot be met, the "secondary field" caused by induced currents becomes significant and prevents accurate measurement of a. Additionally, neither the depth equation nor the inverse-cube law hold true in these conditions. A useful GZ measurement is still possible, but depth determination is prone to errors of around 20% at two skin depths. It is for this reason that the accuracy of deep radio-locations must be called into question.

Close to a transmitter, skin depth does not have the usual physical interpretation, but is nevertheless defined, formulaically, in the way familiar to geophysicists. In the presence of a water table or conducting overburden, skin depth can be very low. It may vary from under 10m (conductivity 0.01 Ω^{-1} m^{-1}, frequency 100 kHz) to over 500 m (0.001 Ω^{-1}

m^{-1}, 1 kHz). Techniques for correcting the errors due to deep radiolocation are being developed (Pease, 1997).

When radiolocation leads to new cave entrances being opened, this may not always be for the best. In Dale Barn Cave (East Kingsdale, Yorkshire), divers radiolocated an aven that was then excavated in an impressive engineering operation. This opening of the far reaches of a cave to non-divers—with the attendant question of cave conservation—is not unique. Several points in the far reaches of the Gaping Gill system (Yorkshire) are known to be very close to the surface but so far remain unexcavated. In Wales, radiolocation aided the opening of a "back door" entrance to Ogof Draenen and this led to fierce arguments about the need to balance the needs of cave explorers and rescuers with the need for cave conservation (Lovett, 1999). With a new understanding of how magnetic fields propagate in rock, it is likely that location systems will develop further, becoming more widespread and easier to use. Although a useful aid to surveying, the need for conservation must be borne in mind.

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Works Cited

Note: The *Cave Radio & Electronics Group* and the *Cave Surveying Group* are special-interest groups of the British Cave Research Association.

France, S. 2001. Cave surveying by radio-location–2. *Cave Radio and Electronics Group Journal,* 44:21–23

Gibson, D. 1998. Radiolocation errors arising from a tilted loop. *Compass Points (BCRA Cave Surveying Group Newsletter),* 21:18–20

Glover, R.R. 1973. Cave depth measurement by magnetic induction. *Lancaster University Speleological Society Journal,* 1(3):66–72

Glover, R.R. 1976. Cave surveying by electromagnetic induction. In *Surveying Caves,* edited by B.Ellis, Bridgwater: British Cave Research Association

Lovett, B. 1999. Making an entrance, stage left…*Descent,* 147:24

Pease, B. 1997. Determining depth by radiolocation: An extreme case. *Cave Radio and Electronics Group Journal,* 27:22–25

Further Reading

Gibson, D. 1996. How accurate is radio-location? *Cave and Karst Science,* 23(2):77–80

A discussion of some of the geophysical causes of errors in radiolocation.

Gibson, D. 2000. A channel sounder for sub-surface communications: Part 2–computer simulation of a small buried loop. *Cave Radio and Electronics Group Journal,* 41:29–32

Some theoretical background to recent work on radiolocation at extreme depth, using formulations given by Wait (1982).

Gibson, D. 2001. Cave radio notebook. 46: The role of skin depth in cave radio. *Cave Radio and Electronics Group Journal,* 45:28

A note explaining that for radiolocation, skin depth does not have the physical interpretation usually given.

Gibson, D. 2001. Cave surveying by radio-location–1. *Cave Radio and Electronics Group Journal,* 43:24–26

An introduction to a series on radiolocation that collects together existing knowledge and outlines new techniques. It includes references to practical articles on beacon construction.
Wait, J.R. 1982. *Geo-Electromagnetism,* New York: Academic Press
This is a highly mathematical book, but it describes in detail the behaviour of electromagnetic fields in a conducting medium and is the basis of current work in the field (e.g. see Gibson, 2000).

Historical Further Reading

Brooks, N, & Ellis, B. 1956. An independent check on the survey of Ogof Ffynnon Ddu. *South Wales Caving Club Newsletter,* 16:1–2
This is one of the earliest reports of cavers using radiolocation. No detail is given.
Mixon, W. 1966. Locating an underground transmitter by surface measurements. *National Speleological Society News,* 24(4):61, 74–75
This article covers the principles in a similar manner to Glover (1973, 1976).

Useful Websites

David Gibson's Cave Radio page at http://www.caves.org.uk/radio/ includes links to sites that discuss cave communications and radiolocation.
The British Cave Research Association's Cave Radio & Electronics Group maintains a website at http://www.bcra.org.uk/creg/
The US-based National Speleological Society has a section for cave electronics, with a website at http://www.caves.org/section/commelect/

RADON IN CAVES

Radon, the heaviest naturally occurring gaseous element, is inert, colourless, and odourless. Although it has 20 known radioactive isotopes, the most significant is Rn and the remainder of this article is concerned solely with this radioactive gas. ^{222}Rn is a decay product of ^{226}Ra (radium) which is itself part of the decay series of uranium (^{238}U), an element which is widely distributed in the Earth's crust, though generally in low concentrations. When radon in turn decays, it forms very small solid particles of other radioactive substances, the short-lived isotopes of lead (^{214}Pb), polonium (^{218}Po and ^{214}Po), and bismuth (^{214}Bi), which are collectively known as radon progeny or "daughters", before decaying into the stable element ^{206}Pb. The ratio of radon progeny to radon gas is called the equilibrium factor (F).

When first formed the radon progeny exist as free ions known as the unattached fraction. Some of the progeny attach themselves to ambient aerosols and are then called the attached fraction; others attach themselves to surfaces where decay takes place, a process known as plateout. As radon is a noble (inert) gas it is almost completely exhaled after inhalation with no effects on health. However, the radon progeny are very reactive, and if they are inhaled they are likely to be deposited in the lungs where the α-radiation from their decay can damage tissue. Longterm studies of uranium miners (e.g. Lubin *et al.*, 1994) have shown that exposure to high concentrations of radon progeny increases the risk of lung cancer and may also increase the risk of other cancers such as acute myeloid leukaemia. The majority of researchers are of the opinion that long-term exposure to lower concentrations of radon progeny in domestic housing also significantly increases the risk of lung cancer (Lubin & Boyce, 1997; Darby, 1998). However, there are still some workers who regard this link as unproven (e.g. Aley, 2000) and there is considerable debate over the risk to caver health from exposure to radon. This is considered later, after discussion on measurement methods and measured concentrations in caves.

The SI unit of radiation activity is the Becquerel (Bq) and the concentration of radon gas is expressed in Becquerels per cubic metre of air (Bq m^{-3}) although in North America the older unit of activity, the Curie, is still used and concentrations are often expressed in picoCuries (pCi, where 100 pCi $\simeq$3.7 Bq). The Potential Alpha Energy Concentration (PAEC), effectively the α-energy produced by radioactive decay of radon progeny, is usually measured in Working Levels (WL) and exposure levels are often expressed in working level hours (WLh, where 1 WLh is exposure to 1 WL for 1 hour) or Working Level Months (WLM, where 1 WLM=170 WLh). In most studies of radon in caves and mines the radiation dose accrued by an individual is calculated as a function of exposure time in a radiation environment (potential α-energy exposure) and is expressed in milliSieverts (mSv). There are many complexities in the conversion of measured radon gas concentrations into an estimate of radon progeny concentration and further problems in equating the amount of time exposed to progeny into an estimate of dose. However, the commonly used approximations are that 5 mSv $\simeq$68 WLh and that 3700 Bq m^{-3} of radon gas at equilibrium (F=1) is equivalent to 1 WL.

Track etch detectors are the most widely used method of measuring radon gas concentrations in cave air. These are passive devices containing an α-sensitive film in a sealed chamber that are left in a location for a period of time (7 days to 3 months depending on how high the concentrations are). They are then removed, etched, and the impacts counted. The activated carbon monitors that are commonly used in buildings have been less successful in caves due to absorption of water in the high humidity conditions usually present underground, and Friend (2000) has also reported problems with water ingress into some track etch detectors. Spot measurements of radon progeny may be made using the Kusnetz method whereby an air sample is drawn through a filter and the activity on the filter is counted. This is a simple and effective method routinely employed by the author in show caves in Britain and Ireland but it has the disadvantage that the activity must be counted between 40 and 90 minutes after sampling, precluding use at any distance from an entrance. There are also a variety of proprietary instruments for obtaining spot measurements of progeny but most are bulky and expensive, a notable exception being the Thompson & Nielson “Radon Sniffer” which has been used in caves by the author and others.

Concern over the risk to the health of cavers from exposure to radon first arose in the mid-1970s and since then there have been many thousand measurements in caves across the world, particularly those open to the public. Mean concentrations for caving regions range from 200 to over 3000 Bq m^{-3} but averages for an individual cave system may be more than ten times higher (Hyland & Gunn, 1994). The highest measured concentration in a natural limestone cave (as opposed to a mine) is thought to be the 155 000 Bq m^{-3} recorded by Gunn *et al.* (1991) at Giants Hole in Derbyshire, England. The concentration of radon at any point will be a complex function of emanation, exhalation, and the cave climate. Emanation is the net radon production rate in the rock walls of a cave, or in unconsolidated sediment within the cave, and ultimately depends on the concentration of uranium (which then decays to radium) in the material. Exhalation is the proportion of radon produced that is released into the atmosphere. As radon is an inert gas it is able to diffuse away from the place where it is produced and some atoms travel from within the rock/sediment grain to a pore and thence to a crack and the cave atmosphere. Exhalation is influenced by geological factors (Ball *et al.,* 1991) and by climate, especially barometric pressure. Radon is a soluble gas and hence may be added to, or less commonly removed from, the cave atmosphere by water. Once in the cave the radon gas concentration will be modified by natural ventilation (if any) and this will also influence the equilibrium factor and hence the concentration of radon progeny. The combination of all these factors means that radon/ radon progeny concentrations exhibit marked temporal variations (hourly, daily, and seasonally) and spatial variations (from region to region, from cave to cave within a region, and from site to site within a cave) which makes prediction very difficult. For example, a study in Britain during 1991–92 found that mean concentrations in the Peak District were almost eight times higher than some 90 km away in the Northern Pennines (Hyland & Gunn, 1994). Concentrations are generally lower in winter than in summer because there is a strong draught into most caves in winter whereas in summer the air tends to be more static or to draught out (see Climate of Caves).

Returning to the question of risk to cavers' health, it is important to distinguish between recreational users of caves and those who are employed to work underground as guides in show caves or adventure caves, as instructors at outdoor pursuits centres, or in some other capacity. In many countries legislation controls the amount of radiation that an employee may receive while at work. For example, in the United Kingdom the Ionising Radiations Regulations (1999) sets a maximum exposure of 15 mSv a^{-1} and states that anyone receiving more than 6 mSv a^{-1} must be designated as a "Classified Employee". Initial measurements showed that in some show caves the guides were receiving high radiation doses and it was necessary to install forced air ventilation systems to reduce the radon concentrations. This is very much a last resort when doses cannot be reduced by controlling exposure through changes to working patterns, as although the ventilation has proved to be very effective in reducing the radon concentrations it also changes the cave microclimate, possibly to the detriment of speleothems and cavernicoles. In Britain, and probably also in other countries, the radiation dose that individuals may accrue during recreational caving is not proscribed by law, although in Britain the National Caving Association (1996) has endorsed a recommendation from the National Radiological Protection Board (Kendall, 1995) that recreational cavers should not exceed an exposure of 10^6 Bq h m^{-3} (*c.* 3 mSv) in any one year. On the basis of a survey reported by Hyland & Gunn (1994), this represents just over 110 hours underground in the Peak District but almost 900 hours in the North Pennines, emphasizing the need for more data on the spatial and temporal variability in radon and radon progeny concentrations in individual caves.

While most recent publications have adopted the position that cavers should take precautions to reduce, or keep to a minimum, their radiation dose it should also be noted that several medical practitioners and experts in the field of radiation protection who are also active cavers are sceptical as to the risk that exposure to radon progeny poses to recreational cavers. These sceptics cite the facts that cavers are, in general, healthy individuals and that there are few, if any, known cases of cavers who were not also smokers dying of lung cancer. It has also been suggested that the cave environment may be particularly subject to plate out and to a low attached fraction of radon progeny although this has not been proven and some initial results suggest that the opposite may be the case. In the light of all the adverse publicity that has been given to radon, and particularly radon in caves, it may come as some surprise to learn that "Radon is used for therapeutic purposes in many medical facilities around the world. Bathing in radon water and *radon exposure in caves* [my italics] are the most widely employed forms of application" (Falkenbach *et al.*, 2002). This paper further states that there is a large body of evidence showing the beneficial long-term effects of radon therapy in rheumatic diseases and discusses "speleotherapeutic" radon exposure in Austria.

JOHN GUNN

Works Cited

Aley, T.J. 2000. Radon and radon daughters. Section 15.3 in *Standard Handbook of Environmental Science, Health and Technology,* edited by J.H.Lehr & J.K.Lehr, New York: McGraw-Hill

Ball, T.K., Cameron, D.G., Coleman, T.B. & Roberts, P.D. 1991. Behaviour of radon in the geological environment: A review. *Quarterly Journal of Engineering Geology,* 24:169–82

Darby, S. 1998. Risk of lung cancer associated with residential radon exposure in south-west England: A case-control study. *British Journal of Cancer,* 78:394–408

Falkenbach, A., Kleinschmidt, J., Soto, J. & Just, G. 2002. Radon progeny activity on skin and hair after speleotherapeutic radon exposure. *Journal of Environmental Radioactivity,* 62:217–23

Friend, C.R.L. 2000. Contribution of airflow to the control of seasonal variation in radon concentrations in Ogof Fynnon Ddu, Penwyllt, South Wales. *Cave and Karst Science,* 27:101–08

Gunn, J., Fletcher, S. & Prime, D. 1991. Research on radon in British limestone caves and mines, 1970–1990. *Cave Science,* 18:63–67

Hyland, R. & Gunn, J. 1994. International comparison of cave radon concentrations identifying the potential alpha radiation risks to British cave users. *Health Physics,* 67:176–79

Kendall, G.M. 1995. Limiting radon exposure in caves and abandoned mines. *Radiation Protection Bulletin,* 165:16–17

Lubin, J.H., Boice, J.D., Edling, C. *et al.* 1994. *Radon and Lung Cancer Risk: A Joint Analysis of 11 Underground Miners Studies,* Rockville, Maryland: Institutes of Health (National Institute for Health Publications 94/3644)

Lubin, J.H. & Boise, J.D. 1997. Lung cancer risk from residential radon: Meta analysis of eight epidemiological studies. *Journal of the National Cancer Institute,* 89:49–57

National Caving Association 1996. *Radon Underground* (report of the NCA Radon Working Group; summary available at http://web.ukonline.co.uk/nca/radonsum.htm)

Further Reading

Friend, C.R.L. 1996. Radon exposure during underground trips: A set of guidelines for cave and mine exploration in Britain. *Cave and Karst Science,* 23:49–56

International Commission on Radiological Protection (ICRP). 1993. *Protection Against Radon 222 at Home and at Work,* Oxford: Pergamon Press (Annals of the ICRP, 23(2); ICRP Publication 65)

RAMSAR SITES—WETLANDS OF INTERNATIONAL IMPORTANCE

The Convention on Wetlands is an intergovernmental treaty adopted in 1971 in the Iranian city of Ramsar, and hence is commonly known as the Ramsar Convention. It was the first global treaty on conservation and wise use (sustainable use) of wetlands as natural resources. "Wetlands of International Importance" (Ramsar Sites) are sites designated under the Ramsar Convention on Wetlands and represent those wetland areas within a country, or areas shared by two or more countries, that are important internationally, but also nationally and locally. The criteria for inclusion in the List fall into two types: sites containing representative, rare, or unique wetland types; and sites of international importance for conserving biological diversity. Ramsar Sites are designated "To develop and maintain an international network of wetlands which are important for the conservation of global biological diversity and for sustaining human life through the ecological and hydrological functions they perform." (Vision for the Ramsar list, from the 7th Meeting of the Conference of the Parties, May 1999.) Ramsar Sites cover a number of different habitat types based on the Ramsar Classification System which includes 42 categories grouped into marine and coastal wetlands, inland wetlands, and human-made wetlands. All three groups include "karst and other subterranean hydrological systems".

Although the importance of wetlands for their biodiversity values and for the well-being of their human communities has long been recognized, they are still among the most threatened ecosystems globally. Appropriate management of the whole catchment area (including both surface water and groundwater), and the wise use, that is sustainable use, of wetlands at national level and through international cooperation are essential for the conservation of dynamic and unstable wetland ecosystems. Technical and policy guidelines have been developed to assist countries in preparing their national wetland policies based on these principles.

Wetlands and karst systems have some key factors in common. They both depend on water and the hydrological system of the catchment area. The quality and quantity of water, in combination with other factors, are crucial for maintaining the form and structure of karst and also for maintaining the ecological character of wetlands. Both are extremely fragile systems: changes in one component can affect the ecosystem quality and considerably change its character. To conserve and maintain wetlands, including karst and other subterranean hydrological systems, requires good knowledge of their main characteristics and an understanding of the processes that form and sustain them.

In accordance with Article 2.2 of the Ramsar Convention, which deals with the Ramsar List, "wetlands should be selected for the List on account of their international significance in terms of biology, botany, zoology, limnology or hydrology". From this point of view, the principal wetland conservation values of karst and other subterranean hydrological systems are:

1. rarity of karst phenomena or functions;
2. inter-dependency and fragility of karst systems and their hydrological and hydrogeological characteristics;
3. rarity of these ecosystems and endemism of their species;
4. importance for conserving particular taxa of fauna and flora.

Additionally, the functions and values range from maintaining—on a sustainable basis—high-quality water for drinking and other human uses (water for grazing animals or agriculture, tourism, and recreation) to supporting life in cave systems.

The main goal of including subterranean wetlands in the Ramsar List is to assist in the conservation and wise use of subterranean wetland functions and values and in implementation of Ramsar principles and strategic guidelines. In general terms, many "living" karst areas are wetlands, both surface and subterranean. Both direct (e.g. visitors to caves, researchers) or indirect (e.g. pollution—particularly water pollution; dumping of solid waste or sewage; development of infrastructure; water abstraction, retention in reservoirs, and other uses) development pressures are increasing. Appropriate management, including conservation and sustainable use, is crucial to maintain the functions and values of the interacting karst surface and subterranean hydrological systems in the whole catchment area and to prevent or mitigate threats to karst wetlands. The Ramsar Convention can help first by fostering conservation and wise use of subterranean wetland systems in general, and second by ensuring that examples of the most characteristic karst wetlands are considered and added to the List of Wetlands of International Importance.

Karst Ramsar Sites

There are presently (August 2002) 133 Contracting Parties to the Convention, with 1180 wetland sites, covering 103.2 million ha, designated for inclusion in the Ramsar List of Wetlands of International Importance. Those karst and other subterranean hydrological systems (type Zk) included in the List are shown in the Table. Since the introduction of the subterranean wetland type (Zk) in 1996, 12 Ramsar Sites that include subterranean wetlands have been added to the List. Ten are in carbonate rocks, but for only six areas have karst subterranean hydrological systems been ranked remarkable or dominant. The three European sites (see Table) are also listed as World Heritage Sites. Škocjanske Jame (see separate entry) is an underground river cave system developed in the area of the "classical" karst area of Kras, Slovenia. The main hydrological characteristics are the

Ramsar Sites: Type Zk Sites (karst and other subterranean hydrological systems) included in the List of Wetlands of International Importance. The table shows all of the wetland types present in the site and the subdivision of type Zk, where Zk(a) designates marine and coastal karst wetland; Zk(b) inland karst wetland; and Zk(c) anthropogenic karst or other subterranean wetlands. All except Sites 2 and 3 are underlain by carbonate rocks; Sites 2 and 3 are "other subterranean hydrological systems". The list was correct in May 2002. Source: Ramsar Convention Bureau: Information Sheets on Ramsar Wetlands, provided by Dineke Beintema, Wetlands International, Wageningen, The Netherlands (http://www.wetlands.org/).

No.	Country	Sitename	Designated	Wetland Types	Type Zk
1	ALGERIA	La Vallée d'Iherir	02.02.2001	N,P,Ss,Y,**Zk**	Zk(b)
2	ALGERIA	Chott Ech Cherg, Sad'da	02.02.2001	Sp,Ss,Tp,Xf,Y,Zg,**Zk**	Zk(b)
3	ALGERIA	Oasis de Tamantit et Sid Ahmed Timmi	02.02.2001	R,Y,**Zk**	Zk(c)
4	CUBA	Ciénaga de Zapata	12.08,2001	A,B,C,D,E,F,G, L,M,N,O,P,Q,R, Sp,Ss,Tp,Ts,U,W ,Xf,Xp,Y,**Zk**	Zk(b)
5	HUNGARY	Baradla Cave System and Related Wetlands	14.08.2001	**Zk**	Zk(b)
6	GUATEMALA	Parque Nacional Laguna del Tigre	26.06.1990	M,N,O,P,R,Sp,Ss, Tp,Ts,Xf,Y,**Zk**	Zk(b)
7	MADAG ASCAR	Lac Tsiman ampetsotsa	25.09.1998	Q,**Zk**	Zk(b)
8	MEXICO	Dzilam (reserva estatal)	07.12.2000	A,H,J,**Zk**	Zk(b)
9	NICARAGUA	Cayos Miskitos y Franja Costera Immediata	08.11.2001	A,B,C,E,F,G,H,IJ, K,M,N,P,Tp, Ts,W,Xf,Zg,**Zk**	Zk(b)
10	PAPUA NEW GUINEA	Lake Kutubu	25.09.1998	M,N,O,Tp,Xf,**Zk**	Zk(b)
11	SLOVAK REPUBLIC	Domica	02.02.2001	**Zk,**Ts,	Zk(b)

12	SLOVENIA	Škocjanske jame	21.05.1999	**Zk**	Zk(b)

extremely high fluctuations of groundwater level, flowing river currents fed by rainwater, and pools of stagnant water. The underground river has a discharge ranging from 0.05 to >400 m^3s^{-1} and water levels in the cave have a 130 m range. The area contains typical karst phenomena and karst features developed at the contact between permeable and impermeable rocks and in the limestones. The cave system also provides a habitat for numerous endemic and endangered animal species. The Baradla-Domica Cave System (see entries on Aggtelek and Slovak Karst and on Aggtelek Caves, Archaeology), shared between Hungary and Slovakia, is the largest subterranean hydrological system of the karst plateau in the territory of the two countries. The site is characterized by a permanent subterranean river, ponds, many speleothems, and diverse representatives of subsurface fauna as well as rich archaeological remains. The Aggtelek and Slovak Karst provides a habitat for more than 500 species of troglobite, troglophile, and trogloxene animals including endemic species (such as *Niphargus aggtelekas*), as well as species first described from this region. The most important archaeological sites are the settlements of Bükk culture both inside and in front of the cave entrance, with charcoal drawings unique in Central Europe.

The Zk wetland type is still to be further elaborated and it is intended that more surface and subterranean karst wetlands will be included. Additions to the list in the 1990s include Lake Tsimanampetsotsa in Madagascar where caves and underground rivers adjoin the lake on its eastern side, and Lake Kutubu in Papua New Guinea which has major subterranean inflow and outflow. The remainder of this article briefly describes five areas that have the potential to be Zk sites.

The karst catchment area of the Ljubljanica River in Slovenia is a complex site that includes a series of intermittent lakes in karst poljes and caves with underground rivers and is a good example of the interaction and interdependency between surface and subterranean wetlands. In addition to the landforms (see Cerkniško Polje, Slovenia: History), there are more than 300 bird species known in the area and 11 fish species, some of which are uniquely adapted to the intermittent character of karst lakes. The area also has an extremely rich and endemic aquatic and terrestrial subterranean fauna (see Postojna-Planina Cave System, Slovenia: Biospeleology).

The Otway Basin of Southern Australia provides an excellent example of a subterranean wetland with two aquifers totally separated by an impermeable layer of clay sediments. Although the upper aquifer has become severely polluted as a result of human settlement, the lower continues to provide high-quality water for domestic and other purposes. In the southern part of the basin numerous cenotes penetrate the impermeable layer, but the separation of the aquifers is maintained by thermoclines. The most important biota consists of a diversity of freshwater stromatolites, the continuing survival of which is threatened by eutrophication.

One of the most famous and spectacular subterranean wetlands occurs at Waitomo in the North Island of New Zealand. The walls and roof of a large cave with a flowing river are covered with the larvae of a fly, commonly termed glow-worms because of the luminescence of their caudal segments. These live by using a drapery of sticky threads to catch small gnats or flies, which originate from the upstream waters exposed on the surface.

The small and very isolated mid-Atlantic island of Bermuda contains more than 150 known caves, many of which contain anchialine pools in their interior. The caves have been found to contain 75 stygobitic species (see Walsingham Caves, Bermuda: Biospeleology). Due to their limited distribution, the fragile nature of the anchialine cave habitat, and severe water pollution and/or development threats, 25 of these species are listed as critically endangered.

Caves and karst features are common in nearly all parts of Mexico's Yucatan Peninsula, where the world's largest known underwater caves carry water to the Caribbean Sea along the east coast (see Yucatan Phreas). The Yucatan State Secretary of Ecology has inventoried more than 3000 cenotes although less than 100 of these have been explored by divers or otherwise scientifically investigated. Biological investigations of these caves have revealed a rich stygobitic fauna that is primarily marine relict species. Deep-well injection of sewage near Merida in the interior of the Peninsula and at new resort developments along the Caribbean coast is adversely impacting water quality within the caves and groundwater.

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See also **Conservation: Protected Areas; World Heritage Sites**

References and Further Reading

Direction générale des forêts. 2001. *Atlas des zones humides algériennes d'importance internationale,* Alger: Direction générale des forêts, Ministère de L'agriculture.

Ramsar Convention Bureau. 1999. Resolution VII. 13: Guidelines for identifying and designating karst and other subterranean hydrological systems as Wetlands of International Importance, *People and Wetlands: The Vital Link,* San José, Costa Rica (Ramsar Convention on Wetlands, Conference Proceedings)

Ramsar Convention Bureau. 1996. Resolution VI.5: Inclusion of subterranean karst wetlands as a wetland type under the Ramsar Classification System, Brisbane, (Ramsar Convention on Wetlands, Conference Proceedings, vol. 4/12:16)

Ramsar Convention Bureau. 1998. Report of the Sub-regional Workshop (21–23 September 1998, Postojna, Slovenia)

Ramsar Convention Bureau. 2000. *Ramsar Handbooks for the Wise Use of Wetlands,* vols 1–9, Gland, Switzerland: Ramsar Convention Bureau

Ramsar Convention Bureau. 2000. *Strategic Framework and Guidelines for the Future Development of the List of Wetlands of International Importance,* vol. 7, Gland, Switzerland: Ramsar Convention Bureau (Ramsar Handbooks for the Wise Use of Wetlands, vol. 7)

UNESCO. 1994. *Ramsar Convention on Wetlands,* convention text, Certified copy, Paris, 13 July 1994

For detailed information on the Ramsar Convention see also http://ramsar.org/.

RECREATIONAL CAVING

The earliest cave exploration was curiosity-led, most visits being made for the advancement of science, particularly archaeology. Inevitably some of these scientists developed an interest in exploring caves for their own sake, and individuals emerged for whom the primary motivation was exploration. However, most of the early explorers also developed a strong interest in one or more areas of cave science (speleology), the classic example being Edouard Alfred Martel (1859–1938).

Cave exploration and documentation remained the realm of scientists and speleologists until the end of the 19th century. However, since the latter part of the 20th century there has been a steady increase in what is now called recreational caving. This form of caving activity is one of “going caving purely for the joy of caving” similar to the way that others enjoy walking or any other outdoor leisure pursuit. Thus, by the start of the 21st century, speleology, cave exploration, and recreational caving were all well established throughout the world with a huge range of clubs (see Exploration Societies) to cater for their different needs. The popularity of caves and caving is indicated by the large number of links to sites on the web. Advances in techniques for exploring caves have been such that clubs are less important than they once were as a source of communal equipment, but they remain important for training in the practical aspects of caving and in instilling a respect for the cave environment.

Recreational caving, as a separate activity from cave exploration, probably began with the development of outdoor pursuit groups such as the scouting (formed in 1908) and girl guide (formed in 1910) movements. These groups began a trend that saw visits to adventurous outdoor areas such as wild rivers, mountains, and caves as places to develop the “character” of individuals and groups. This form of activity was taken to new levels when companies were formed in the late 1980s to provide small through to large corporations with activities that developed “management” and “team-building” skills for staff members. Some of these activities were conducted in inappropriate caves resulting in detrimental impacts on the cave environment.

Another aspect of recreational caving occurs when individuals accidentally locate a cave entrance and with no prior experience or knowledge “visit the cave”. Generally these visitors are ill-informed about the cave environment and therefore put themselves as well as the cave at risk from their activities. Some may go on to join exploration societies and become experienced cavers, but regrettably others indulge in acts of cave vandalism.

By the 1980s a significant quantity of cave exploration had been conducted in areas that were easily accessible from major centres of population. This meant that continued exploration would require greater technical effort or travel to more remote areas. Such high levels of exploration did occur but there was also a significant growth in the number of cavers who enjoyed visiting known and fully explored caves for their beauty, serenity, or purely the thrill of the sporting experience. This also added to the high levels of recreational caving throughout the world. An inevitable consequence of the increased numbers of recreational cavers has been significant impacts on popular caves. The lack of new caves or extensions to older systems in these areas of high visitation has led to significant changes in caving habits, including the development of speed caving and “speleo olympics”. However, the majority of caver visits around the world are still for the pure joy of going caving and showing visitors or first-time cavers the fun, beauty, and tranquility of the cave environment. Unfortunately not everyone understands the fragility of the cave environment and terrible vandalism, both deliberate and accidental, has been inflicted on many caves. Examples of this vandalism can be seen on the Cave Vandalism website at http://wasg.iinet.net.au/vandals.html.

Concern over the impacts of recreational cavers on sites in Australia led to the development of a Minimal Impact Caving Code (MICC). Codes of Practice or Ethics had been developed previously but the recreational impacts of cavers was still known to be significant (Spate & Hamilton-Smith, 1991). After consulting with cavers from around the world (using the internet) during the early 1990s, the cavers drafting the Australian MICC drew on a wide range of knowledge and experience in formulating the code that was finally adopted by the Australian Speleological Federation in 1995.

Other countries have followed the Australian lead with MICCs being developed to suit the requirements of caves in the United States in 1995 and Great Britain in 1999. These techniques are designed to reduce caver impacts by encouraging cavers to think carefully about every caving trip. Impacts can be minimized by track marking delicate areas of cave where trail widening can have significant impacts, or marking a single path, where a number of passages lead to the same location, to reduce impacts on the other trails. The development of MICCs does not ensure that cavers abide by them or even put them into practice. The strong support of both cave managers and cavers is required if using minimal impact caving techniques is to reduce the everyday impact of cavers.

Karst management throughout the world has been forced to change as outdoor recreational organizations and companies placed demands for access to cave and karst resources upon them. Karst management plans have to balance the needs for access with the management desire to conserve karst resources.

The major challenges that modern recreational cavers face are the increasing restrictions being placed upon them by cave managers who are attempting to protect the cave resource they are managing. These include the requirements for recognized leader qualifications and for protection of landowners, fellow cavers, and committees from possible legal action by providing public liability insurance. Further restrictions are likely to be applied by lawmakers as they deal with health and safety concerns.

The most recent development in recreational caving is the construction of commercial artificial caves, similar to artificial climbing walls, where groups can enjoy the “fun” of underground activity without the impact on the “natural” environment. These artificial caves can combine several of the adventurous activities associated with caving, such as oozing through mud, squeezes, water, climbing, and descending pitches all into one “cave”. Although a “natural” cave may contain these features, they are likely to be more widely distributed. There has even been a genuine rescue from one such cave in Britain when a participant became trapped in a squeeze!

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Work Cited

Spate, A. & Hamilton-Smith, E. 1991. Cavers impacts—some theoretical and applied considerations. In *Proceedings of the 9th Biennial Conference of the Australasian Cave and*

Karst Management Association, edited by P.Bell, Margaret River, Western Australia: Australasian Cave and Karst Management Association

Useful Websites

Speleo Link http://hum.amu.edu.pl/~sgp/spec/links.html
Australian Speleological Federation Standards and Guidelines, http://www.caves.org.au/standards/set-standards.htm
US Minimum Impact Caving Code, http://www.caves.org/committee/conservation/www/b_caving/caving_rules.htm
National Caving Association of Great Britain Minimum Impact Caving Code, http://web.ukonline.co.uk/nca/canda/mimpcode.htm
TeamBuilding website example http://www.teambuildinginc.com/retreats_a_caving.htm
Outdoor Adventures-Caving http://www.mountainmayhem.com/caving.html

RELIGIOUS SITES

Mountains are visible and powerful elements in the landscape, and many have become important focal points for mythology (Bernbaum, 1997). In contrast, caves are hidden and hence perhaps unlikely candidates for veneration. Yet many sacred mountains contain caves that form part of their story, and caves share many of the attributes that have underpinned the attribution of sacredness to mountains, including their capacity to evoke a sense of mystery and the eternal. Hence, caves and other karst features have acquired profound spiritual significance in many parts of the world. Some karstic religious sites bear physical testimony to adoption by successive traditions, while some remain shared between faiths.

The religious significance of caves and karst varies across and within traditions. Christianity, professed by *c.* 33% of the world's population, is arguably the most anthropocentric religion the world has seen, and rejects animism and pantheism in favour of a monotheistic outlook. Nevertheless, numerous karst sites are considered holy by Christians, as at the Massabielle Grotto and spring at Lourdes, where the Catholic girl Bernadette is said to have witnessed apparitions of the Virgin Mary in 1858. Worship of a landform would represent unacceptable idolatry within the rapidly growing Islamic tradition (covering 22% of the world's population). However, caves are very significant within the traditions of Hinduism (*c.* 15%), Buddhism (*c.* 6%), traditional Chinese religions including Taoism and Confucianism (4%), primal and indigenous faiths (3%), and a wide variety of smaller traditions. Neither are caves necessarily irrelevant for some among the *c.* 14% of the world's population who profess no preference for any particular religion, not all of whom are atheists or agnostics.

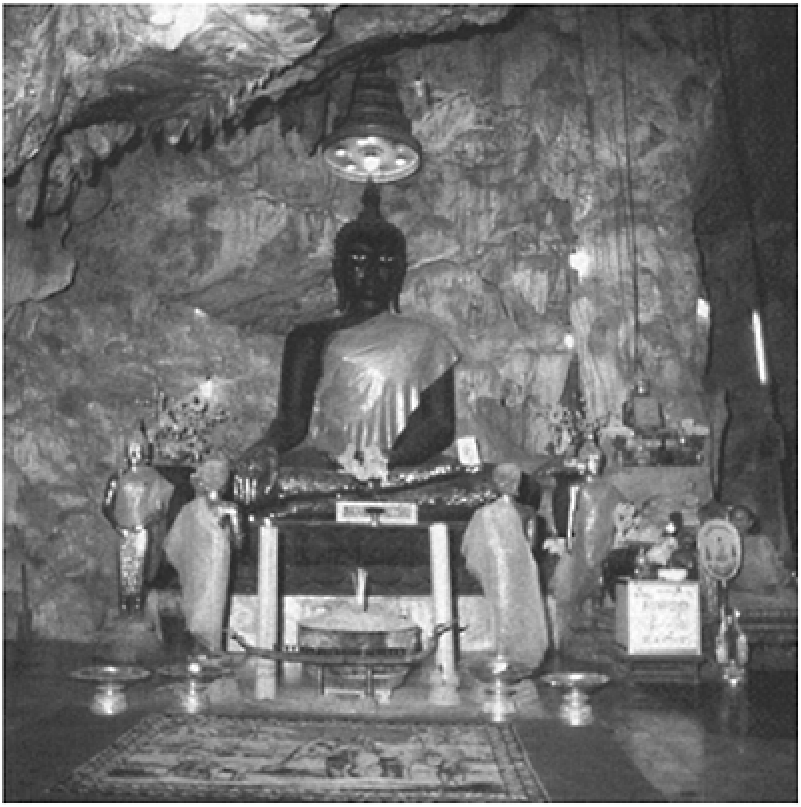
Various types of karst landforms are considered sacred. Limestone summits such as the world's highest peak, Chomolungma or Sagarmatha, Goddess Mother of the Earth (Everest), and karst towers elsewhere, are or have been important to a number of traditions, including local Buddhism and Chinese Taoism and Confucianism. Followers of animist traditions in southeast Asia still make offerings to the spirits at curiously shaped limestone outcrops. The identification of the nurturing Earth as female by many cultures is linked to a perception that caves are womblike, and the phallic connotations of speleothems have also been recognized (Dunkley, 1995). Some sacred caves are entirely artificial. The pyramids of Egypt have sometimes been interpreted as artificial sacred mountains inside which caves were deliberately constructed. Pilgrimage is an important part of the experience of some sites. Thus, visits to the Elephanta caves in India entail three journeys: across water, up a mountain, and into the cave, which serve to promote abandonment of the everyday world. Some karstic springs are also objects of veneration, and healing or divinatory properties may be attributed to their waters.

Sites Around the World

Flower pollen in a Neanderthal burial in Shanidar Cave, northern Iraq (see separate entry), suggests the use of caves to give expression to the spiritual 60 000 years ago. Although their meaning is unclear, ice-age paintings in caves such as Lascaux in France (see Vézère Caves, France: Archaeology) are among other early physical legacies that suggest caves were imbued with religious significance. The mixing of human blood with ochre used for artwork in Wargata Mina, Tasmania, emphasizes the probability of spiritual meaning.

Votive offerings have been found in a cave on Mt Ida in Crete, said to be the birthplace of Zeus, the father of the gods in Greek mythology. Among the many sacred caves of Crete are Eileithyia Cave, used for cult rituals from the Neolithic until the 5th century BC and sacred to Eileithyia, the goddess of childbirth; Kamares Cave, sacred since the Minoan period and possibly also dedicated to Eileithyia; and the cave of Agia Parajkevi Skotinou, a site of religious importance in antiquity and Christian times. Caves were also used for rites connected with the Phrygian mother goddess Cybele.

A cave at the World Heritage-listed Delphi site beneath sacred Mt Parnassus was sacred to Pan and the nymph Corycia. Remains of two fountains that date from the Archaic period and Roman era occur at the Castalian Spring, where niches cut in the rock face may have held offerings to the nymph Castalia. The female deity of the Earth was worshipped at Delphi during the Mycenaean period. In the early 3rd century BC the site became dominated by the Aetolians, and in 191 BC it was conquered by the Romans. It lost its religious significance with the spread of Christianity.



Religious Sites: A black statue of Buddha on a shrine in Sriwilai Cave, Tha Pra District, Thailand. (Photo by John Gunn)

In the Christian faith, the parish church of St Paul's in Rabat, Malta, includes a grotto where St Paul is said to have lived during a three-month stay on the island in 60 AD following a shipwreck. Due to its supposed miraculous properties, soft limestone from this cave continued to enjoy popularity as a cure for fevers long after cave carbonate ceased to be widely used medicinally in the mid-18th century (Shaw, 1992). A cave near Cavadova in the Cantabrian Mountains of Spain is said to have provided refuge for King Pelayo who led the Christians in a battle that saw the first victory of the Christians over the Moors, a victory of great symbolic significance in the Christian conquest of Spain. A chapel in the entrance to Cavadonga Cave dates from the 8th century. Probably the most celebrated of Christian sites today is at Lourdes, where three chapels have been built, with the main Basilica of St Pius X accommodating 30 000 worshippers. Christian ceremonies are still occasionally conducted within caves, some of which, such as Lucas Cave at Jenolan, Australia, have been formally consecrated as churches.

Hindu societies have established many shrines in caves. The Batu Caves in Malaysia (see photograph in Asia: Southeast entry) attract over 800 000 devotees during the festival of Thaipusam. The Ajanta and Ellora caves near Bombay are significant for three major Indian religions, and include both carved temples and wall paintings. Reliefs, sculptures, and a temple at Elephanta are dedicated to the Hindu god Lord Shiva and probably date back to the Silhara kings of the 9th–12th centuries AD.

The Hindu site of Amarnath Cave at 3888 m altitude in the Kashmir Himalayas attracts pilgrims who worship at an ice stalagmite. Some caves formed in ice are also of religious significance. Examples occur at *c.* 4200 m in the central Himalayas, where the Bhagirath River, which discharges from two meltwater outflow caves in the snout of the Gangotria Glacier, joins with the Alakanada River that discharges from a glacier in the next valley to form the sacred Ganges River.

At Kusma, west of Pokhara in Nepal, lies the famous Hindu shrine of Gupteswary Cave. Other shrines occur south of Pokhara in the Mahabharat Hills and at Halesi Cave, on the east bank of the Dudh Kosi-Sun Kosi confluence, which is used for a festival on the birthday of Ram. Other Nepalese Hindu shrines include Goraknath Cave in the Bagmati Valley and Shivaji Cave, Bhojpur. The karstic spring complex at Muktinath at *c.* 3800 m in the Annapurna Himal, close to the Tibetan border, is sacred to both Hindus and Buddhists. The sight of pilgrims gathering waters from the springs and fountains in the more developed Hindu sector recalls images of Christians collecting Holy Water from Lourdes. The darkness within a curtained, cave-like recess beneath the altar in a simple Buddhist gompa is lit by a natural fire burning gas that issues from rock crevices beside the emerging springwater.

In China the divine power or spirit of the Tao permeates all things and beings, animate and inanimate. Karst sites of religious significance are widespread. For example, in Guangxi Province, the walls of caves in the hill that contains the heavily visited Longuin tourist cave in the city of Guilin bear inscriptions that span 77 different dynasties, with 93 inscriptions from the Sung dynasty alone (see colour page 4). More than 200 statues, mostly 50–200 cm high, have been carved into the limestone outcrops of Western Hill in Guilin. They date from the spread of Buddhism into southern China during the Tang dynasty.

Kham altars and inscriptions from the 9th and 10th centuries occur in Phong Nha Cave, north—central Vietnam. Cave shrines are also found amid the Huong Tich Mountains. In the Marble Mountains near Danang, one karst tower is a pilgrimage site and Buddhist temples have been established in its caves, together with some Confucian shrines. Some of these caves were Hindu shrines during the reign of the Champa.

In Thailand, where *c.* 95% of the population profess Buddhism, at least 200 caves are currently used for worship, meditation, or retreat (see photograph). Some have been utilized for over 1000 years, and on the frontiers of settlement the religious use of new caves continues to be initiated (Munier, 1998; Dunkley, 1995). Statuary and other relics also occur in numerous caves in Burma (Myanmar), including Pindaya Cave, Shwe Ohm-min Cave, and Mimehtu Cave in southern Shan State, and the Bingyi Caves and Kogun Cave near Moulemein (Mawlamyine) (Dunkley *et al.,* 1989). In Japan, many legends are associated with lava tube caves on sacred Mt Fuji. Shotoku Taishi, a 6th-century prince, is said to have descended the crater into a vast cavern where he spoke to a fire-breathing dragon who transformed into the Buddha of All-Illuminating Wisdom, dwelling in the cave palace to save all sentient beings. In the 17th century the founder of the Fuji-ko sect is said to have taken up residence in one sacred cave where he stood immobile in a meditative bid to restore stability to a nation riven with unrest.

In Central America, caves and cenotes have played a major role in the religious traditions of Maya peoples for over 2000 years and were the location of elaborate rites (Bower, 1998). Classic Maya settlements constructed from AD 250–900 appear to have been placed strategically over caves that had great religious and political significance. There is evidence to suggest the alignment of major structures with cave passages underneath them, including a large cave under the El Duende Pyramid, Guatemala. Offerings and relics likely to have been used by shaman have been reported from at least three caves in southern Belize (see also America, Central: Archaeological Caves).

In Oceania, lava tube caves are significant for indigenous people in Hawaii who follow traditions associated with the fiery goddess of volcanoes, Pele. For Australian Aborigines, natural landmarks that form part of an extended kinship system are the centres for religion and ceremony. One gaping cave entrance at Uluru is considered to be the wailing mouth of a grief-stricken mother of the carpet-snake people, whose son was struck down by a venomous snake warrior, while another cave important to the hare wallaby men is still used for male initiation. Only in a few cases are deeper karst caves known to have been entered.

Management

Nothwithstanding the sacred status with which karstic and other cave sites have been imbued, many remain vulnerable to damage and land-use decisions. Some karstic religious sites have been deliberately targeted during political and military conflicts in order to demoralize or assert dominance over devotees, as in the defacing of statuary and inscriptions on karst hills in China during the ascendancy of Mao's Red Guard. During the undeclared war in Laos in 1969, an unmarked but probably American aircraft fired a single rocket into Tham Phiu, killing 400 villagers who had fled into the sanctuary of this religious site. In some cases the sense of security and protection felt at sacred sites may encourage defenders to base themselves in cave temples, which may place the site at risk. The entrance to Phong Nha Cave bears a legacy of heavy air raids during the American war against Vietnamese forces who stored munitions in the cave. Similarly, bullet-pocked masonry amid the cave shrines of the Marble Mountains attests to the heavy fighting that occurred there during the American war.

Extensive physical modification of the entrances to sacred caves is common, as at Ajanta. Cave walls may be modified through the execution of wall inscriptions and, in a few cases, stalagmites have been carved to enhance their similarity to religious icons. Some sites are closely safeguarded from harm and even the eyes of the uninitiated, but others attract a multitude of devotees, creating severe environmental pressures. The small grottoes that formed the initial focus of worship are sometimes overwhelmed by construction of major temple complexes, as at Koanoi, Thailand, and at Lourdes. Concerns about the degradation of the natural environment that might be felt by a karst geo-ecologist may hold little sway in decisions regarding a feature that for devotees may—in becoming sacred—have lost its original status as a landform and have been transformed into an inherently incorruptible embodiment of the Divine.

However, the solitude, tranquility, and peace that facilitated the initial attribution of sacredness may be lost entirely if crowding or physical transformation go too far, and many practical difficulties may also arise. The increasingly large numbers of pilgrims reaching Muktinath since access conditions eased in the late 1970s have resulted in severe deforestation to obtain fuel for heating and cooking, and the development of accommodation blocks has seriously detracted from its aesthetic qualities.

Some cave and karst shrines have been formally designated for natural or cultural heritage conservation, such as the World Heritage Ajanta Caves. But in other cases a major extractive industry can occur very close to a religious site, as at Batu Caves, where nearby limestone quarrying has been a significant management issue. In Hawaii, lava tube caves of cultural significance have been polluted by the dumping of refuse and the diversion of urban stormwaters. In 1988 the spring at Lourdes was found to have been contaminated by infiltration from a rubbish tip 7 km distant. Human-induced climate change also has management implications, most obviously for sacred caves in rapidly retreating glaciers such as those at the source of the Ganges.

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See also **Burials in Caves; Folklore and Mythology**

Works Cited

Bernbaum, E. 1997. *Sacred Mountains of the World,* Berkeley: University of California Press

Bower, B. 1998. Sacred secrets of the caves (Mayan archaeology). *Science News,* January 24, 1998

Dunkley, J.R. 1995. *The Caves of Thailand,* Sydney: Speleological Research Council

Dunkley, J.R., Sefton, M., Nichterlein, D. & Taylor, J. 1989. Karst and caves of Burma (Myanmar). *Cave Science,* 16(3):123–31

Munier, C. 1998. *Sacred Rocks and Buddhist Caves in Thailand,* Bangkok: White Lotus

Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney, Speleological Society

Further Reading

Fergusson, J. & Burgess, J. 1880. *Cave Temples of India,* London: Allen; reprinted New Delhi: South Asia Books, 1969

Flood, J. 1983. *Archaeology of the Dreamtime,* Sydney: Collins; revised edition, New Haven, Connecticut: Yale University Press

Hayden, D. 1987. Caves. In *Encyclopedia of Religion,* edited by M. Eliade, vol. 3, New York: Macmillan

Kiernan, K. 1995. Genesis 1:31 versus managing the devout: On the spiritual and religious use of karst. *Cave Management in Australasia,* 11:208–21

Scully, V. 1962. *The Earth, The Temple, and the Gods: Greek Sacred Architecture,* New Haven, Connecticut: Yale University Press

RESTORATION OF CAVES AND SPELEOTHEM REPAIR

Human visitation can have negative impacts on caves and their contents. Cave restoration efforts serve to remediate or repair damage caused by carelessness, inadvertent actions, or intentional vandalism. Project planning for cave restoration often begins with thorough inventory and documentation of the features within. Prior to restoration and repair, the cave fauna, flora, microbiota, habitat, clastic sediments, speleothems, hydrological and geological features, as well as archaeological and paleontological resources should be evaluated. The extent of damage, proposed restoration strategies, and potential future impacts should be recorded. Careful planning and implementation is required to minimize alteration of cave resources and the first objective of cave restoration should always be: *Do no harm*.

Cave restoration planning should center on one of three objectives. Decisions will focus on 1) restoration to a former natural condition; 2) restoration to a previous historic period; or 3) simple improvement of the aesthetic state without harming resources. In a show cave with decades of accumulated impact, partial restoration may be the best achievable option whereas restoration to a former natural condition is more likely to be successful in a wild cave that is not as ecologically disturbed. Doline and stream-sink cleanups are common in karst terrains where these features are often used as trash dumps. Removal of garbage and debris mitigates pollution and improves groundwater quality.

Caving groups volunteer thousands of hours annually to cave and karst restorations, donating time, labour, materials, and expertise for conservation efforts. On public and private lands in the United States and in many other countries, cavers provide significant volunteer value for cave and karst protection projects. When funding is available, cost-shares, partial reimbursements, cooperative agreements, and project contracts with caving groups provide support for ongoing restoration projects.

Cave Restoration Tasks

Cave restoration projects employ a variety of tasks, tools, and skills. For example, projects might include rubble and debris removal, mud removal, spray paint cleaning, lint picking, speleothem cleaning and repair, doline and stream-sink clean-out, or habitat restoration. Large projects removing rubble, artificial fill, and debris often require multiple project days scheduled over several years. Other projects require minimal time and human resources. For example, sponging away a single muddy footprint left on pristine flowstone can prevent permanent calcification of the imprint. Smaller, more delicate restoration projects on gypsum or cave pearls may require only a few hours of attention from one or two cavers (Figure 1).

Cavers should follow stringent minimum-impact guidelines when restoring recently discovered chambers. Pristine environments deserve careful restoration strategies and require changing to fresh, clean garments. Sensitive areas with suspected microbial significance might require more specialized clean-room techniques or sterile procedures if restoration tasks are necessary (Hildreth-Werker & Werker, 1999). In caves that have had high levels of visitation or historic commercial use, negative impacts are less likely to occur from restoration efforts. A good example is Moondyne, a severely damaged former show cave in Australia that had been closed since 1959. Labour-intensive restoration

Cave Restoration and Speleothem Repair: Figure 1. Clad in a tyvek suit, this caver uses clean room technique to restore cave pearls found in the Pearlsian Gulf of Lechuguilla Cave in New Mexico. (Photo by Val Hildreth-Werker) in the 1990s involved removal of all rubbish, pathways, and other infrastructure, and cleaning of the walls and speleothems. The cave was restored to a virtually pristine condition and now serves as a guided education site (Bell, 1993).

After evaluation and documentation of the site, restoration typically begins with collection of litter and removal of contemporary graffiti. Consultation with scientists as well as historical and cultural preservation experts is always appropriate before erasing graffiti and removing trash. The history of an area may be literally written on the cave walls and should be protected. Pictographs, petroglyphs, and historic signatures may be layered under contemporary graffiti. Also, historically important mud glyphs may be easily overlooked. Significant historical, prehistorical, geological, mineralogical, climatological, or biological resources may be present, but visible only to the trained eye. Removing contemporary trash and graffiti or emphasizing historic and scientific significance can result in increased visitor respect for cave resources (Goodbar, 2003).

Restoration projects can facilitate species recovery. Restoring entrance features, airflow, or hydrological conditions may support rehabilitation of species and habitats (Aley, 1989). Old trash and wood piles may be providing habitats for particular cave species and should be removed in stages to allow fauna to migrate to new areas and biofilms to recover. Some restoration involves carefully removing lint and dust (garment fibres, epidermal matter, hair, and small particles of debris) from along tour trails where it accumulates, discolouring formations and providing a habitat for opportunistic organisms (Jablonsky, Kraemer & Yett, 1995).

Groups of cavers working multi-day sessions are needed to restore speleothems covered with excavation sediments or to remove construction debris and artificially deposited clastic sediments added in show cave chambers to make flat floors. For example, in the late 1980s, tonnes of clay and rock were removed to restore natural floors at Wisconsin's Mystery Cave (Netherton, 1993). Sediment restoration also takes place at Caverns of Sonora in Texas where 50 or more cavers gather for annual bucket brigade projects. Teams remove tonnes of blast rock from trail construction, yet recognize and leave the natural breakdown in place (Veni, 1998).

Restoration leaders should evaluate the degree of previous impact in a cave passage and plan methods to avoid creating new damage. Trails through cave passages can be clearly marked to help confine visitor impact. Even in wild caves, travelling on durable surfaces and previously compacted routes will aid in preservation of sediments, small floor speleothems, and invertebrate populations. Unfortunately, if footprints are visible beyond the designated paths, others will tend to follow and trails will expand. If footprints remain outside of delineated trails, they can be erased to restore the natural appearance of clastic sediments. Gentle combing motions with lightweight nylon brushes will erase footprints and avoid stirring up dust (Hildreth-Werker & Werker, 1997). Deep footprints in rock flour or sand can be camouflaged with natural sediments taken from alongside the trail. Removing visible traces of human travel tends to mitigate future damage.

Tools for Cave Restoration

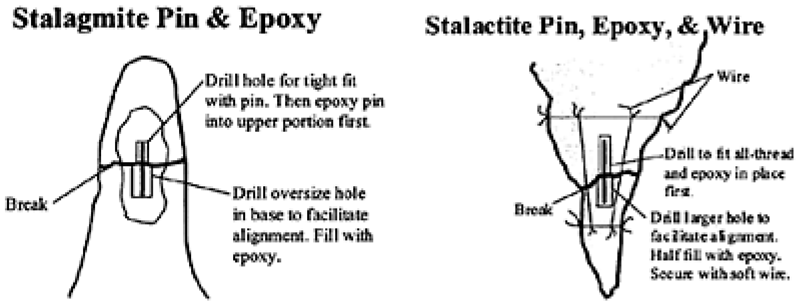
Appropriate tools for restoration are chosen according to the task. Some projects require toothbrushes or tweezers, while others require shovels or power drills. In show caves, industrial skills and equipment are required to accomplish infrastructure-related tasks such as removal or remediation of wiring, guardrails, walkways, or electrical transformers that may be contaminated with PCBs. It is wise to contact hazardous waste removal experts if toxic waste is encountered during cave or doline restoration. For the cleaning and repair of delicate speleothems, different types of tools and expertise are necessary. For restoration in wild caves, lightweight, compact tools are typically preferred. Scrub brushes with nylon bristles, soft absorbent sponges, vinyl gloves, flexible plastic scrapers, buckets, hand-held sprayers, water, and human perseverance are effective tools for cleaning speleothems and many cave surfaces. Catchments, towels, or sponge dams are placed downslope to capture restoration runoff, which is then removed from the cave and properly disposed.

Studies at the Jenolan Caves, Australia, first indicated that pressurized water is safe for cleaning durable speleothems (Bonwick, Ellis & Bonwick, 1986). However, more recent analysis with a scanning electron microscope found that the cave surfaces were suffering some damage (Spate & Moses, 1993). Current practice is to minimize washing, to use low-pressure water, and to sometimes use a wet-dry vacuum cleaner. Caution must be exercised to avoid harming fragile speleothems, splattering nearby cave features, or destroying cave life with streams of highpressure water. Water from within the cave, ideally percolation water, should be used for restoration because water from the surface may be chemically aggressive and lead to speleothem damage.

Opportunistic photosynthetic organisms often grow near electric lights in show caves (see Tourist Caves: Algae and Lampenflora). Sodium hypochlorite solutions and other chemical agents have been used to control lamp flora, but must be used only at a minimum concentration, applied only where required, and rinsed carefully to avoid indiscriminate killing of cave biota. Manufactured chemicals are not recommended for cave cleaning tasks since fumes, residues, and by-products can be harmful to biota and cave systems. Anthropogenic agents typically produce toxic by-products through out-gassing and degradation. Recommendations for improved control of undesirable algae and microflora include advanced lighting technologies and wavelengths selected to inhibit photosynthesis. Recent experience demonstrates that with properly designed, located, and controlled lighting, lamp flora can be eliminated.

Speleothem Repair Tools and Materials

Specialized products that are relatively safe for long-term applications in cave systems are used for repair tasks. Recommended products include archival epoxies and museum-grade cyanoacrylate adhesives. Degradation and out-gassing characteristics are reduced and longevity characteristics are strengthened in these products (Werker, 2003). High tensile strength cement products that contain minimal calcium hydroxide are recommended if cement is required for cave projects. High-austenitic stainless steels are resistant to corrosion and are more suitable to cave environments than many other construction materials. For stalagmite and stalactite repair, austenitic stainless round stock or threaded rod is installed as a supporting rod to pin the speleothem pieces back in place (Figure 2). Fracture sites and repair seams can be filled with a mixture of archival epoxy and rock dust (Veni, 1997). Draperies, soda straws, helictites, gypsum



Cave Restoration and Speleothem Repair: Figure 2. Repair of stalactites and stalagmites using pin and epoxy method. (Drawings by Jim C.Werker)

crust, flowstone, rimstone dams, and even large speleothems can be repaired (Werker, 2003). Poulter (1987) and others have utilized similar technology in Australia.

Research is needed to define the safest materials for use in subterranean systems. Cave biologists and chemists should confirm the safety of product characteristics before manufactured chemicals are placed in cave environments, whether for construction of infrastructure or for repair and restoration (Spate *et al.*, 1998). Cave conservation and management will benefit from materials data gained through laboratory analyses and field monitoring to document the degradation, out-gassing, and longevity characteristics of materials placed in cave systems.

As speleological research increases and as we understand more about the ecological processes of cave and karst systems, restoration and repair techniques will continue to evolve and become less intrusive. In the future, identification of cave-safe materials will help define improved practices for cleaning and speleothem repair. Cavers who perform restoration and repair are actively defining low-impact caving techniques. If visitor and caver ethics improve to avoid unnecessary impacts to cave passages, the need for restoration and repair may decline (see minimal impact codes in Recreational Caving entry).

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Works Cited

Aley, T. 1989. Restoration and maintenance of natural cave microclimates. *National Speleological Society News*, 47(2):39–40

Bell, P. 1993. Moondyne Cave: Development to guided adventure. *Cave Management in Australasia,* 10:9–11

Bonwick, J., Ellis, R. & Bonwick, M. 1986. Cleaning, restoration, and redevelopment of show caves in Australia. In *Proceedings of the Ninth International Congress of Speleology,* vol 2:221–23

Goodbar, J. 2003. Cave graffiti: The writing is on the wall. In *Cave Conservation and Restoration,* edited by V.Hildreth-Werker & J.C.Werker, Huntsville, Alabama: National Speleological Society
Hildreth-Werker, V. & Werker, J.C. 1997. Lechuguilla restoration: Techniques learned in the Southwest. *National Speleological Society News,* 55(4):107–13
Hildreth-Werker, V, & Werker, J.C. 1999. Restoration, trail designation, and microbial preservation in Lechuguilla Cave. In *Proceedings of the National Cave Management Symposium 1997,* edited by R.R.Stitt, Bellingham, Washington: National Cave Management Symposium Steering Committee
Jablonsky, P., Kraemer, S. & Yett, W. 1995. Lint in caves. In *Proceedings of the National Cave Management Symposium 1993,* edited by D.L.Pate, Carlsbad, New Mexico: National Cave Management Symposium Steering Committee
Netherton, W. 1993. Mystery Cave trails: Past, present and future. In *1989 National Cave Management Proceedings,* edited by J.R. Jorden & R.K.Obele, New Braunfels, Texas: Texas Parks and Wildlife Department
Poulter, N. 1987. The restoration of the Jewel Casket, Yallingup Cave, W.A. *Australian Caver,* 115:6–8
Spate, A. & Moses, C. 1993. Impacts of high pressure cleaning: A case study at Jenolan. *Cave Management in Australasia,* 10:45–48
Spate, A, Hamilton-Smith, E., Little, L. & Holland, E. 1998. Best practice and tourist cave engineering. *Cave Management in Australasia,* 12:97–109
Veni, G. 1997. Spelothems: Preservation, display, and restoration. In *Cave Minerals of the World,* 2nd edition, edited by C.A.Hill & P.Forti, Huntsville, Alabama: National Speleological Society
Veni, G. 1998. 1998 Sonora restoration project. *The Texas Caver,* 43(6):87–89. Reprinted in *SpeleoDigest,* 1999:301–02
Werker, J.C. 2003. Speleothem repair techniques. In *Cave Conservation and Restoration,* edited by V.Hildreth-Werker & J.C.Werker, Huntsville, Alabama: National Speleological Society

Further Reading

Hildreth-Werker, V. & Werker, J.C. (editors) 2003. *Cave Conservation and Restoration,* Huntsville, Alabama: National Speleological Society

RUSSIA AND UKRAINE

Russia and Ukraine have large areas of karst and the Western Ukraine contains one of the largest gypsum karst areas in the world. The karst may be considered in three areas.

European Sector

This covers the large Precambrian craton that occupies most of the Ukraine and the European part of Russia. It extends from the Arctic Ocean to the Black Sea. Karst is developed mainly in various intrastratal settings (deep-seated, subjacent, entrenched, and denuded) in carbonates (limestones, dolomites, and chalk) and evaporites (gypsum and salt) of different ages. In many regions, karst develops in intercalating sulfate-carbonate successions. Most of the significant caves in the region are in gypsum.

The Northern Russian province includes the Pinega (see Pinega Gypsum Caves) and North Dvina karsts in the Lower Permian sulfates, some of the largest integrated gypsum karst regions in Europe. The gypsum-anhydrite sequence, in places intercalated with dolomites and limestones, is commonly 40–60 m thick and lies at shallow depth. It supports a spectacular variety of karst landforms and hydrological features. More than 360 gypsum caves are now known in these regions, with a total length of over 100 km (Malkov & Gurkalo, 1999).

The Central Russian province occupies the centre of the Eastern European Plain, which corresponds to the southern part of the structural Moscow depression. Karst is developed in the Carboniferous and Upper Devonian limestones and dolomites. Drilling has proved that deep-seated karst in artesian conditions is present in many localities. Caves are rare (the longest being Poneretka Cave in the Valday Upland, with 1430 m of passage)

Russia and Ukraine: Generalized map of the major areas of karst in Russia, Ukraine, and the Asian and Baltic republics, including karst on both carbonate and evaporite rocks. The larger areas, in the grey tone, include complex smaller outcrops of non-karstic rocks.

but surface karst landforms, such as dolines and dry valleys, are common in the areas of subjacent and entrenched karst.

The Kama-Middle Volga province lies between the Volga River and the Ural Mountains, mainly within the Kama River catchment. Karst is developed in Permian sulfates, dolomites, and limestones and in Carboniferous and Devonian carbonate rocks. Collapse and subsidence dolines are common in many areas, originating from active karstification at various depths. The most intensely karstified areas are those within paleo-valleys and alluvial plains, where karst breakdowns may propagate through unconsolidated cover up to 100 m thick. Caves are abundant in the areas of entrenched karst, particularly in the gypsum karst areas in the easternmost, Kamsko-Ufimsky region. There are more that 200 known gypsum caves in the latter region, the largest being the 5700 m long Kungur Ice Cave.

The Fore-Caspian province lies in the southeastern part of the Eastern European Plain, north of the Caspian Sea. Over 1500 salt diapirs are known in the region, some close to the surface and some being denuded. They support open salt and gypsum karst, and gypsum caves are known in the caprocks (e.g. Baskunchakskaja, 1438 m long).

The Moldavian-Ukrainian province includes, within the borders of Ukraine, the Podol'sko-Bukovinsky region of gypsum karst, the Prichernomorsky region of limestone karst, the Krivorozhsky region of quartzite and carbonate karst, and the Donetzk region of gypsum and carbonate karst. The Podol'sko-Bukovinsky region in the Western Ukraine is internationally renowned for its giant maze caves in Neogene gypsum. It is a model example of artesian speleogenesis (Klimchouk, 2000), and contains the five longest gypsum caves in the world, accounting for well over half of the total known length of gypsum caves worldwide (see Ukraine Gypsum Caves and Karst). Few caves are known in the calcareous sandstones (Stradchanska, 360 m long and Studencheskaja, 242 m long). The Prichernomorsky lowland is located north of the Black Sea, with karst developed in the Neogene limestones. Isolated fissure-like caves of artesian origin are occasionally seen in old limestone mines around Odessa, the largest being the caves of Novorossijskaja (1404 m) and Natalina (1292 m). Caves up to 150 m long, partially submerged beneath the sea, are known in the coastal cliffs of the Tarkhankut peninsula, Crimea. In the Krivorozhsky region caves have been found in Precambrian dolomites and ferruginous quartzites.

The Carpathians extend as an arc from Slovakia through Ukraine to Romania, and the Ukrainian segment is composed mainly of flysch. Small caves are known in the exotic massifs of Upper Jurassic and Lower Cretaceous limestones (Druzhba, 256 m long), but interesting caves are also found in conglomerates (Krasny Kamen', 900 m long and 56 m deep) and in sandstones (Prokhodnoj Dvor, 520 m long, 40 m deep).

The Crimean Mountains lie in the south of the Crimean peninsula in Ukraine and structurally continue as the Caucasus Mountains along the southern border of Russia. Both mountain regions belong to the Alpine folded system. The Crimean karst is in a chain of low plateau-like massifs of Upper Jurassic limestones, with remarkable development of open karst, and almost 1100 caves are documented (see Crimea, Ukraine).

Urals Region

The Urals region includes the Hercynian folded system of the Ural Mountains and the foredeep that separates the Urals from the adjacent Eastern European craton. The mountains, which extend north to south for almost 2000 km, are eroded and rounded, and largely covered with forests. Gypsum karst with a variety of karstic landforms and some caves (Ishcheevskaja Cave, 1000 m long) occurs widely in the Fore-Ural. In the Ural fold mountains carbonate karst predominates, developed in Paleozoic limestones and dolomites. Because of stripe tectonics, contact karst is common. The largest vauclusian karst springs are located in the Western Urals (the Goluboje Ozero spring, dived to −56 m, and the Krasny Kljuch Spring, dived to −38 m). Caves are numerous, particularly in the southern part of the Western Ural province. The largest caves are the Sumgan-Koutuk Cave (9860 m long and 130 m deep), Kinderlinskaja (7900 m long, 185 m deep, with a 230 m long and 48 m deep siphon) and Kizelovskaja-Viasherskaja System (7600 m long, 43 m deep). Of special archaeological interest are the Kapova Cave (2640 m long, 103 m deep) with Paleolithic rock paintings, as well as the Ignatjevskaja and Staromuradymovskaja caves in the Central Urals.

Siberia and the Far East

In Siberia, a huge taiga-covered territory that lies east of the Ural Mountains, karst is not very common, but some important karst regions are studied in the mountains of southern Siberia, in the Sikhote-Alyn’ range of the Far East, and on the island of Sakhalin (see Siberia entry). The mountains of Altaj and Sajan of southern Siberia are both large ranges with flat tops and locally jagged ridges, rising above 2200 and sometimes above 3000 m, but they differ in their geological evolution and tectonics. The Altaj are Hercynian, the Sajan are Caledonian, and the Salair-Kuznetzk forms a transitional tectonic zone. In the Altaj more than 210 caves have been explored in the Rifean and Devonian limestones, including Altajskaja (4175 m long, 240 m deep), Tutkushskaja (1400 m long, 200 m deep), and Kektash (1780 m long, 340 m deep). In the Sajan, particularly in the Eastern Sajan range, caves are abundant and varied. Some large caves occur in the Cambrian limestones (e.g. Zhenevskaja, 6000 m long, 65 m deep, Kubinskaja, 3000 m long, 274 m deep and Torgashynskaja, 1560 m long, 75 m deep). In Lysanskaja Cave (2400 m long) eight siphons have been explored up to 95 m long and 20 m deep. The most remarkable speleological features of the region are caves in the Badzhejsky area, developed in Ordovician conglomerates. These include the Bol’shaja Oreshnaja Cave (47 000 m long, 155 m deep), the world’s largest conglomerate cave and the second longest cave in Russia, and some other significant caves (e.g. Badzhejskaja, 5900 m long, 240 m deep). In the Salajr-Kuznetzk province caves occur mainly in the Lower Cambrian limestones, where more than 120 caves are documented, including the Jaschik Pandorry Cave, a complex 3-D system, 10 000 m long and 180 m deep.

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See also **Asia, Central; Caucasus, Georgia; Crimea, Ukraine; Krubera Cave; Pinega Gypsum Caves, Siberia; Ukraine Gypsum Caves and Karst**

Works Cited

Klimchouk, A.B. 2000. Speleogenesis of great gypsum mazes in the Western Ukraine. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreyboldt, Huntsville, Alabama: National Speleological Society

Malkov, V.N. & Gurkalo, E.N. 1999. Speleological regionalization and distribution of caves in the Arkhangelsk region. *Peschery (Caves): Inter-university Scientific Transactions,* Perm: Perm University: 10–15 (in Russian)

Further Reading

Chikishev, A.G. 1979. *Problems of the Karst Studies of the Russian Plain,* Moscow: Moscow University (in Russian)

Dublyansky, V.N. & Dublyanskaya, G.N. 1992. *Mapping, Regionalization and Engineering-Geological Assessment of Karstified Terrains,* Novosibirsk (in Russian)

Gvozdetsky, N.A. 1962. Issues of the geographic regionalization of karst on the territory of the USSR. In *Obshchie voprosy karstovedenija,* Moscow: Academy of Science (in Russian)

Gvozdetsky, N.A. 1981. *Karst,* Moscow: Mysl. (in Russian)

Ivanov, B.N. 1972. Carbonate karst of the Ukraine and Moldavia. In *Karst in Carbonate Rocks,* Moscow: Moscow University (in Russian); Transactions of the Moscow Society of Naturalists, vol. 47 (in Russian)

Klimchouk, A.B. & Dublyansky, V.N. 1993. The state of the speleological investigations of the territory of the former USSR. *Svet (The Light),* 1–2 (7–8):24–27 (in Russian)

Maximovich, G.A. 1962a. Tectonic regularities of the karst distribution on the territory of the USSR. In *Obshchie voprosy karstovedenija,* Moscow: Academy of Science: 40–54 (in Russian)

Maximovich, G.A. 1962b. Distribution and regionalization of karst of the USSR. *Gidrogeologija and karstovedenije,* vol. 1, Perm: Perm University (in Russian)

Maximovich, G.A. & Kostarev, V.P. 1973. Karst regions of the Ural and Fore-Ural. In *Voprosy fisicheskoj geografii Urala,* Transactions of Perm University, vol. 308 (in Russian)

S

SALUKKAN KALLANG, INDONESIA: BIOSPELEOLOGY

The impressive cone karst of Maros lies in South Sulawesi (Indonesia) between 4°7′ S and 5°1′ S. It is a rugged limestone plateau of Eocene to middle Miocene age, with basaltic and dioritic intrusions of middle Miocene to late Pliocene age. These dykes and sills have strongly influenced the karstification; in particular they are at the origin of a network of narrow and deep corridors which constitute an unusual feature of the karst landscape in Maros (Brouquisse, 1986). Among the more than 150 caves known in this region (Bedos *et al.,* 1994), the caves of the system Gua Salukkan Kallang-Towakkalak (SKT) are outstanding for their beauty and their length. SKT contains more than 24 km of underground passages, including over 10 km of a large underground river, in five different caves: Gua Wattanang (440 m), Gua Tanette (9.7 km), Gua Batu Neraka (750 m), Lubang Kabut (1145 m), and Gua Salukkan Kallang (12.5 km) (Figure 1). Several other caves probably correspond with dismantled relict levels of the system, including the giant shafts of Lubang Tomanangna (−190 m) and Lubang Kapa Kapasa (−210 m). The resurgence is an undived sump at an altitude of 40 m, more than 10 km from the easternmost river sinks that are thought to feed it.

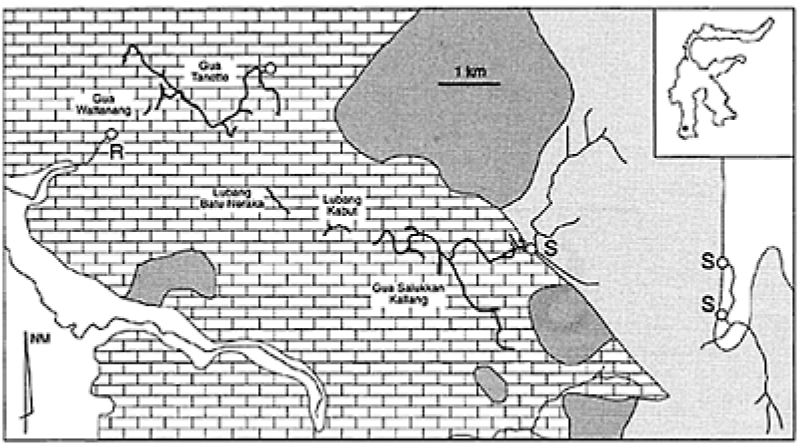
The fauna of the SKT system is patchily distributed. Stygobitic fauna is only found in small endogenous inlets, whereas the main river is populated by epigean species of fish and invertebrates. For most of their length, the SKT galleries appear at first sight to be totally devoid of terrestrial life. Terrestrial animals are concentrated around flood debris along the river banks, and on bat, swiftlet, and cricket droppings scattered in the system. Guano accumulations, typical of many caves in Southeast Asia, are rare and small in SKT. In spite of this severe shortage of favourable habitats, the SKT subterranean fauna is more diverse than that of any other Southeast Asian and even tropical cave system studied until now (Deharveng & Bedos, 2000) (see Asia, Southeast: Biospeleology).

Ninety-three species have been recorded in the SKT system, excluding bats and swiftlets which have never been studied in detail in the Maros karst. Non-troglobitic species are the most numerous. Most are trogloxene species, brought into the system by the annual floods of December to February, especially strong in Maros. This dominance of outside species is in line with observations elsewhere in the tropics. Guano communities are also diverse, with 19 recorded species. Some are guanophiles also found outside, but several are known only from caves, like the Cambalopsidae millipedes, which are among the most numerous arthropods in SKT. The cave-restricted component of the SKT fauna (guanobitic—troglobitic, troglobitic, and stygobitic species) represents 30% of the total richness.

The most conspicuous invertebrates of SKT are the giant arthropods, typical of Southeast Asian caves. They are associated with energy-rich habitats and are frequently seen on cave walls near guano piles or cave entrances. The giant arthropod community consists of a dense population of a large rhaphidophorid cricket, which is preyed upon by heteropodid spiders, amblypygids, and centipedes. Rhaphidophorid crickets may disperse their droppings far from their feeding place, providing food resources for troglobites in the energy-poor areas of the caves. Giant arthropods do not exhibit any morphological adaptation to cave life, although they are mainly or exclusively found in caves. They have fairly wide distributions, i.e. neither restricted to the SKT system nor to the Maros karst.

The terrestrial meso—and micro-arthropod groups present in virtually any cave of Southeast Asia also occur in SKT: schizomids, several families of small spiders (Ctenidae, Pholcidae, and Ochyroceratidae in SKT), cambalopsid millipedes, entomobryid Collembola, and nocticolid cockroaches; these troglobitic or guanobitic-troglobitic species are often modified in relation to subterranean life (eyes and pigment reduced or lost, elongated appendages).

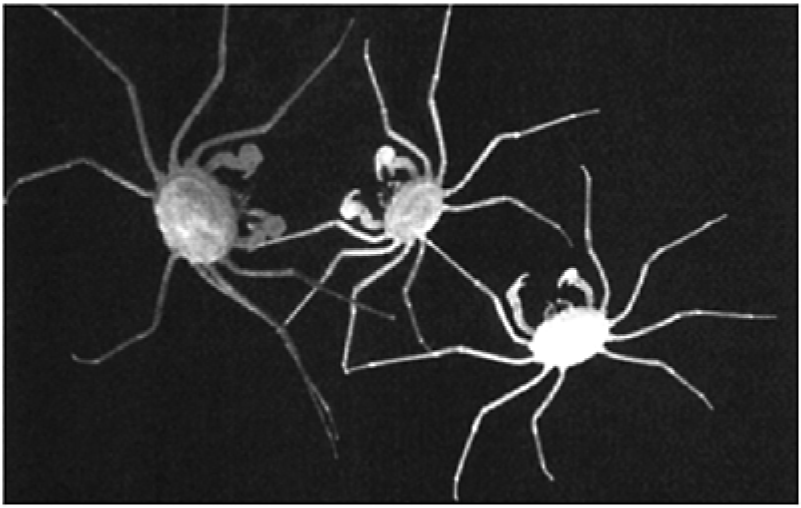
The stygobitic fauna, far less rich than the troglobitic fauna in SKT, includes representatives of two groups regularly found in Southeast Asian caves: *Dugesia leclerci*, a flatworm of a widespread tropical genus, and an undetermined Bogidiellidae—an



Salukkan Kallang, Indonesia: Biospeleology: Figure 1. Map of the Gua Salukkan Kallang-Towakkalak underground system in the Maros karst. White: alluvial deposits; bricks: limestone; pale grey: sedimentary and volcanic rocks of the Camba formation; dark grey: basalt and diorite; R: resurgence of Towakkalak; S: sink; thick lines: cave passages; thin lines: epigean

amphipod family frequent in many subterranean habitats worldwide. Like most troglobites, these stygobites are local endemics, with related species in other Southeast Asian caves.

The SKT system also hosts more unexpected animals. The pterostichid beetle, *Mateuellus troglobioticus,* is the only subterranean representative in the world of the tribe Abacetini. Several taxa exhibit a high level of troglomorphy. Among terrestrial animals, the palpigrad *Eukoenenia maros* is the second troglomorphic species of this genus for tropical Asia, whereas many cave species are known from Mediterranean regions. The campodeid *Lepidocampa hypogaea* is the second troglobitic species of the widespread and speciose tropical genus *Lepidocampa*. The aquatic fauna has comparatively more remarkable species. An undescribed microphthalmic fish of the genus *Bostrychus* occurs at very low density in the SKT system. At least two atyid shrimps are present in SKT: one is microphthalmic with a size similar to outside species of the family; the other is much larger and totally blind. But the most interesting species in SKT is a tiny aquatic crab: *Cancrocaeca xenomorpha* (Ng, 1991, Figure 2), which represents the first and the only known case of adaptation



Salukkan Kallang (Indonesia): Biospeleology: Figure 2. The troglomorphic crab *Cancrocaeca xenomorpha*.

to cave life for the primarily marine family Hymenosomatidae. It also shows the highest degree of eye regression in the world for a cave crab.

Biogeographically, SKT has a typical Southeast Asian cave fauna, enriched by elements of disputable origin (such as *Mateuellus troglobioticus*), possibly derived from local species. The hymenosomatid crab *Cancrocaeca xenomorpha* is the only indication of a possible relationship with the Australasian region, as several species of this family live in the fresh waters of Australia and Papua New Guinea (Ng, 1991). At a finer scale, biogeographical affinities remain obscure, given our very poor taxonomic knowledge of subterranean tropical fauna, and the absence of reference phylogenetic frameworks for any of the taxa concerned.

New hotspots of subterranean biodiversity will be discovered in the future, given the huge extension of undocumented karst areas in the tropics. But investigations in the last decade in tropical America and Southeast Asia have not modified the current figure: the SKT system remains the richest hotspot of tropical cave biodiversity (Deharveng & Bedos, 2000), followed by the Air Jernih cave system of Mulu (Malaysia: Sarawak), the species richness of which is described in detail by Chapman (1984). The conservation of the SKT biological richness is therefore a concern at a world level. The SKT system and its surface drainage area, partly included in the Nature Reserve of Karaenta, remain relatively undisturbed, but the growing human pressure on the surroundings is a real problem. The lowlands are heavily populated, and deforestation is progressing in the wildest parts of the karst. The opening of two new big limestone quarries recently brought unprecedented threats to the local subterranean ecosystems. The uniqueness of the Maros karst regarding landscape, geodiversity, and archaeology is, however, increasingly recognized and may help in the coming years in proposing relevant management measures to protect this exceptional biodiversity hot spot.

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See also **Asia, Southeast: Biospeleology**

Works Cited

Bedos, A., Brouquisse, F., Deharveng, L., Leclerc, P. & Rigal, D. 1994. Grandes cavités du karst de Maros [Big caves of the Maros karst]. In *Indonésie 92, rapport spéléologique,* Toulouse: Association Pyrenéenne de Spéléologie

Brouquisse, F. 1986. Cadre géologique [Geological context]. In *Expedition Thaï-Maros 85, rapport spéléologique et scientifique,* Toulouse: Association Pyrenéenne de Spéléologie

Chapman, P. 1984. 1. The invertebrate fauna of the caves of Gunung Mulu National Park. *The Sarawak Museum Journal,* 30(51):1–18

Deharveng, L. & Bedos, A. 2000. The cave fauna of Southeast Asia: Origin, evolution and ecology. In *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver and W.F.Humphreys, Amsterdam and New York: Elsevier

Ng, P.K. 1991. *Cancrocaeca xenomorpha,* new genus and species, a blind troglobitic freshwater hymenosomatid (Crustacea: Decapoda: Brachyura) from Sulawesi, Indonesia. *Raffles Bulletin of Zoology,* 39(1):59–73

SEDIMENTS: ALLOCHTHONOUS CLASTIC

A good deal of the material to be seen in any cave is derived from its catchment, transported into the cave by water, wind, mass movement, or even glacial processes. These sediments have an allochthonous origin, in comparison to the sediments formed within the cave, which have an autochthonous origin. This transport from surface to underground may be episodic, and material may have been temporarily stored in small terraces or floodplains prior to entering the cave. Thus the material may have already been altered by weathering or sorting since leaving its source area in a catchment.

Over human timescales earth surface processes tend to be quiescent, punctuated by a very few high-energy events due to floods, landslides, dust storms, or storm surges. Over the longer timescale of a cave's life, often measured in millions or tens of millions of years, such events are more commonplace. During these extreme geomorphic events a great deal of material can be brought into a cave, and often the accompanying flows of water will rework the existing sediments quite profoundly. A flood may bring in coarser sands and gravels that will be deposited as thick beds, often partly eroding then sealing in older deposits. If the cave floods, then slow settling from a deep pool will produce thick deposits of fine clays, often banded, and containing organic layers which indicate either discrete phases in flooding or the successive contributions of tributary valleys feeding the cave system. In a lake deposit we generally have a more complete record of all events in the catchment. In a cave these may have been partially or totally eroded, leaving a fragmented record that is very hard to interpret. Abrupt lateral facies change, unconformities, and stratigraphic reversals may all be present, and require detailed study of sedimentary architecture to unravel. Significant conceptual advances have been made in basin sedimentation models using three-dimensional analysis of sediment facies derived from vertical sections, drill holes, and remote sensing techniques. The application of these techniques to cave sediments is in its infancy, but offers very good prospects. The confined nature of most cave sediments, and the haphazard exposure of good sections, will necessitate the more intensive excavation of sections and the use of non-invasive techniques such as seismic reflection, resistivity, and ground-penetrating radar. There is also an ethical question regarding the information gain relative to the destruction of cave sediment stratification; this scarce resource can only be excavated once.

Caves can be seen as underground gorges and floodplains, in which sedimentation proceeds in modes similar to those of surface streams. This provides a conceptual scheme for sedimentation processes where water is the transporting agent. The major difference between the surface and underground streams is that in the latter, the water and sediment are confined within a conduit. This results in two main effects. First, dramatic fluctuations in water level due to either flood stage or to passage morphology result in steep gradients in energy along a cave passage. There is thus a greater range of sediment textures per unit length of channel than on the surface. This affects both estimation of past flow velocities from sediments, and also stratigraphic correlation. Second, subsequent flows of water down a particular cave passage may wholly or partially remove the sediment deposited by a prior event. The resistance of an individual parcel of sediment to this process of reworking will depend on its texture and on the passage geometry at the site.

The degree of this reworking will largely depend on the texture of the sediment. Thus, the large particles of boulder size, and the very fine cohesive clays will both be resistant to reworking once emplaced in a cave, In Westmoreland Cave (Mole Creek, Tasmania) dolerite boulders of Last Glacial age are wedged in the passages and appear little altered by weathering. In contrast, sand-sized sediments will be readily moved and reworked. This is due to the velocity of erosion being higher than the velocity of transport for very coarse and extremely fine particles. In Mammoth Cave (Kentucky) successive floods may move backflooding deposits of silt from the underground stream to higher elevations. After every flood, a thin layer of clay is deposited over all submerged passages. Some parcels of sediment may be shunted into side passages during very high floods and will remain there unaltered beyond the reach of successive flow events. Other parcels may be sealed in by rapid flowstone growth. Finally, sediments may persist in caves for a long time when they are resistant to water erosion. Murphy (1999) has described clays derived from relict glacial rock flour overlain by more modern goethite cemented cobbles in a flooded Yorkshire cave.

In many karst areas sediments enter the cave by the agency of wind or gravity fall, the rate being dependent on sediment supply and the trapping effects of surface vegetation as well. Where the entrance is a shaft or tube, such as at Naracoorte Caves in South Australia, then the sediments and animal bones will accumulate by gravity fall as a cone or pile at the base of the shaft (see photo). Some sediment will be transported further down the slope of the cone to form a colluvial fan. Both the cone and the fan will have rills or channels where water has eroded the accumulating sediments. Tabular layers of clean washed sand interspersed with red sand or clay layers provide further evidence of sorting during water flows. Small slumps or mass movements are likely to occur when high rates of sediment supply block the entrance shaft, allowing water to pond. The extent to which this slumping occurs depends on the nature of the sediment, its water content, and the hydraulic head of water above the deposit. This periodic slumping also causes some alignment of bones and spreads them over the cave floor. Cave sediments may thus be deposited by either gravity-fall or water transport processes. The distinction between these becomes blurred when we consider such processes as turbidity currents sliding down steep sediment banks into a cave pool, or the injection of fluidized mudflows into tropical cave passages by landslides (Gillieson, 1986).

Allochthonous Clastic Sediments: Huge sand cone in Sand Cave, Joanna (near Naracoorte Caves). (Photo by Steven Bourne)

Once emplaced into a cave, any sediment is existing under conditions of total darkness, near constant high humidity, and near constant temperature. This reduces the amount of chemical alteration that can occur. However, with time some migration of solutes into and out of the sediment will occur. This may be as the result of wetting and drying cycles due to floods. In this context the porosity and mean grain size of the sediments has a great influence on the degree of diagenesis. Spectacular blue and red banded clay sediments in Selminum Tem, New Guinea, owe their banding to alternate layers of very fine clay and slightly coarser silt (Gillieson, 1986). Reducing conditions are maintained in the fine clays, with a dominance of ferrous iron salts, while in the silts the increased porosity allows oxidation and a dominance of ferric iron. Sediment banks are commonly cemented by iron oxide bands or by calcite from drips. Truly ancient sediments have reaction rims, which may penetrate into the adjoining rock surfaces. At Bungonia and Jenolan Caves, New South Wales, secondary dolomite and pyrite are common constituents of the paleokarst facies. This can make their identification and analysis very difficult, but scientists are beginning to realize the great extent and value of ancient sediments as paleokarst indicators in caves (Osborne, 1995).

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See also **Paleoenvironments: Clastic Sediments**

Works Cited

Gillieson, D.S. 1986. Cave sedimentation in the New Guinea Highlands. *Earth Surface Processes and Landforms,* 11:533–43

Murphy, P.J. 1999. Sediment studies in Joint Hole, Chapel-le-dale, Yorskhire. *Cave and Karst Science,* 26(2):87–90

Osborne, R.A.L. 1995. Evidence for two phases of late Palaeozoic karstification, cave development and sediment filling in southeastern Australia. *Cave and Karst Science,* 22(1):39–44

Further Reading

Bull, P.A. 1982. Some fine-grained sedimentation phenomena in caves. *Earth Surface Processes and Landforms,* 6:11–22

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman, Chapter 8: Cave Interior Deposits, pp.316–30

Ford. T.D. 2001. *Sediments in Caves,* London British Cave Research Association (BCRA Studies 9)

Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwells

Moriarty, K.C., McCulloch, M.T., Wells, R.T. & McDowell, M.C. 2000. Mid-Pleistocene cave fills, megafaunal remains and climate change at Naracoorte, South Australia: Towards a predictive model using U/Th dating of speleothems. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 159:113–43

Osborne, R.A.L. 1984. Lateral facies change, unconformities and stratigraphic reversals: their significance for cave sediment stratigraphy. *Cave Science,* 11(3): 175–84

SEDIMENTS: AUTOCHTHONOUS CLASTIC

Caves become filled with a variety of materials both during development and after their formation. These include chemical deposits (speleothems such as stalactites and flowstone) and clastic sediments (broken rock material). The clastic sediments may be “allochthonous” (originating outside of the cave, for example from sinking streams bearing alluvium), or may be “autochthonous” (originating within the cave). The latter are perhaps the least studied of all cave deposits, but are a diverse group of materials that form by a variety of processes.

The most familiar of these materials is breakdown (from the process by the same name or as “incasion”) which forms by the collapse of the walls or ceiling of the cave. The breakdown is classified by size, ranging from blocks to chips. Blocks are composed of more than one original bed, and can be quite large; volumes of greater than 25 000 m^3 have been documented. Slabs are fragments of a single bed, generally a few cubic metres in volume. Chips are derived from the destruction of a bed, and have volumes in the cubic centimetre range.

Collapse occurs when the mechanical strength of the rock mass is exceeded. Breaks usually happen along existing zones of weakness; joints, bedding planes, or faults. Although the heterogeneous nature of natural rock masses makes prediction complicated, it is possible to model the process of breakdown using reasonable assumptions. The simplest case (White, 1988) is for a cave passage developed in flat-lying rocks. Under this instance, overlying beds of limestone may be considered as mechanical beams. The critical thickness of the beam (the thickness at which it will fail under its own weight) is given by:

$$t = \frac{\rho l^2}{2S}$$

For this case, in consistent units, t=thickness of beam, ρ=rock density, l=beam length (roof span), and S=flexural stress.

The process of natural breakdown is only rarely observed directly; usually only the result is seen. Davies (1951) suggested that most breakdown found in caves fell soon after the cave was initially drained of water (transition from phreatic to vadose conditions). The loss of buoyant support to the wall and roof promotes this collapse. Although it is found throughout many caves, breakdown is more likely to occur at spots where support of the ceiling is lessened. Passage intersections are one such point. Others are places where one passage overlies another. Sometimes the process of breakdown is the only mechanism to connect two passages. Some of the most voluminous cave chambers were formed (at least partially) by breakdown processes. Conversely, many formerly continuous passages are now blocked, at least in terms of human exploration, by massive breakdown piles (see photo). This autochthonous sediment may be removed from the cave by ongoing stream action, by both chemical and mechanical erosion.

The size of the breakdown is greatly affected by the characteristics of the existing rock, specifically the bedding thickness, joint spacing, and type of limestone. Thick bedding and wide joint spacing promote large block breakdown. The specific mechanical or chemical process that is operating may also affect the size.

Processes other than removal of underlying support can also act to promote breakdown of the cave walls. In those regions where winter temperatures reach freezing, water within the wall rock near the entrance of the cave may freeze. This generates a tremendous pressure that may shatter the rock in a process known as frost wedging (or gelifraction). A similar process is thought to occur via mineralogical processes. Secondary gypsum or halite grows in the bedding planes of some cave walls and the pressure of crystallization may then break the material apart (White & White, 1969; White & White, 2000: p.428). Halite may also crystallize in the pores of rock, resulting in the creation of detrital piles of sand-sized salt and bedrock particles.

Direct observation of collapse events that form breakdown is documented, but rare. Some have been massive, such as a 35 ton event in the Rotunda Room in Mammoth Cave, Kentucky (United States), in 1994 (USNPS, undated). No one was injured. The collapse was caused by frost wedging brought on by an unusual cold period. In June 1984 a massive collapse (*c.* 150 tonnes) occurred in Valhalla Pit, Alabama (United States), resulting in the death of two cavers (Knutson, Sims & Sims, 1985).

Autochthonous Clastic Sediments: Passage blocked by chip breakdown, Greenbrier River Cave, West Virginia (United States). (Photo by Ira Sasowsky).

No specific triggering event was identified. Earthquakes have been postulated as initiators of breakdown but Davies (1951) noted that the New Madrid earthquake (1811, Richter magnitude 8) did not cause any collapses at Mammoth Cave (Kentucky), even though it was just 250 km away.

Weathering earth (detritus) is the term assigned to the insoluble material that remains after dissolution of the limestone while the cave is being formed. It is usually fine-grained (clay to sand size), and difficult to distinguish from allochthonous sediments that have been washed in to the cave. Sometimes it clings to moist walls of the cave, forming a pattern known as mud vermiculations. Coarse material may also result from autogenic processes. If the host rock for the cave is rich in chert, insoluble nodules of this material may collect on the floor of the cave in substantial quantities.

In caves formed by ascending sulfur-rich waters, a peculiar type of clastic/chemical sediment may be found. Alunite is an aluminosulfate mineral that forms by reaction of existing detrital clays with acidic water. It has proved valuable as a dating tool in some areas (Polyak *et al.*, 1998). Also in these settings, reaction of limestone with sulfuric waters may create thick rinds of gypsum that fall to the floor of the cave after it has been drained.

Autochthonous clastic sediments have the potential to provide other sorts of useful information about the cave and its surrounding environment. As our understanding of these deposits and processes increases, they are certain to become a focus of additional scientific studies (see Paleoenvironments: Clastic Sediments). Biologically derived materials may also, arguably, be considered as autochthonous sediments but these are discussed in three separate entries on Sediments: Biogenic, Guano, and Organic Deposits in Caves.

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Works Cited

Davies, W.E. 1951. Mechanics of cave breakdown. *NSS Bulletin,* 13: 36–43

Knutson, S., Sims, M. & Sims, L. 1985. American caving accidents. *NSS News,* 43(11) pt. 2:355–67

Polyak, V.J., McIntosh, W.C., Güven, N. & Provencio, P. 1998. Age and origin of Carlsbad Cavern and related caves from 40Ar/ 39Ar of Alunite. *Science,* 279:1919–22

United States National Park Service, Undated. *Rockfall*. Electronic publication available at http://www.nps.gov/maca/rockfall.pdf

White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

White, E.L. & White, W.B. 1969. Processes of cavern breakdown. *NSS Bulletin,* 31(4):83–96

White, E.L. & White, W.B. 2000. Breakdown morphology. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Further Reading

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer

Davies, W.E. 1949. Features of cavern breakdown. *NSS Bulletin,* 11:34–35

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman. Section 7.12 discusses Breakdown in caves.

Ford, T.D. 2001. *Sediments in Caves,* London: British Cave Research Association (BCRA Cave Studies Series, 9)

A short introduction to cave sediments for the educated caver.

SEDIMENTS: BIOGENIC

Biogenic sediments in caves can be divided into three major types: detrital (external material directly transported from the surface), internal (excrement or guano produced by animals inside the cave), and secondary (material formed inside the cave).

Detrital sediments in caves are formed from biogenic material directly transported from the surface, including soil, dung, peat, woody matter, suspended organic material, animal bodies, and garbage flushed into the cave by rain water or air flow. Their composition does not differ significantly from that of the same material on the surface. Sometimes peat forms small stalactites (Hill & Forti, 1997). The rest of the material forms sediments on the floor of the caves.

The main internal sediment is excrement (guano; see separate entry), which sometimes forms huge deposits inside caves. It is very good manure, rich in nitrates and phosphates, and so is sometimes mined in caves. It is even the main part of the export of Guanaco Island (northern Peru). Guano frequently reacts with the bedrock or clays and forms many cave minerals, as described below.

Secondary biogenic sediments, sometimes referred as biogenic speleothems (Forti, 2001), are of much greater interest because they differ significantly from surface sediments. They are produced by biomineralization, which can be divided into three types: (i) induced minerals formed by biogenic mineralization, (ii) matrix minerals formed by transformation of organic bodies, and (iii) nucleation minerals formed by microorganisms as centres of nucleation.

Induced mineralization

Biogenic mineralization produces 88 biogenic cave minerals classified by origin to guanogenic, microbiogenic, osteogenic, and anthropogenic minerals, and also organic deposits (e.g. mumijo) which do not have a definite chemical composition. Seventythree guanogenic cave minerals are formed by the reaction of bat guano and animal excrement with cave bedrock and minerals. Phosphates, nitrates, chlorides, sulfates, and organics are derived from the guano or excrement to form cave minerals. Some of the guanogenic minerals are found only in caves. Some carbonate minerals also have a guanogenic origin. Two minerals are known to be formed only by combustion of cave guano (Martini, 1994).

Microbiogenic minerals can be formed directly by microorganisms by biomineralization through enzymes (Northup *et al.,* 1997), or by producing substances that lead to the precipitation of minerals (e.g. by changing the pH of their surroundings). Microbial processes in caves (see separate entry) often involve redox reactions produced by aerobic (chemolithotrophic) microorganisms, which obtain energy directly from the oxidation of inorganic compound or by anaerobic (heterotrophs) organisms which obtain energy from the oxidation of organic matter and reduce inorganic compounds. The “sulfur cycle” (see Microbial Processes in Caves) is such a process, whereby both sulfur-oxidizing and sulfate-reducing bacteria are involved. They produce a wide variety of cave minerals: most frequently native sulphur, gypsum, and iron oxides-hydroxides, but other less common forms such as celestite, fibroferrite, opal, endellite, pyrolusite, and marcasite have been reported in the literature (Hill & Forti, 1997). In total, 19 cave minerals are known to be formed by microorganisms.

Deposition of saltpetre (KNO_3) and all other cave nitrates is driven by nitrifying bacteria. Moreover, at least a part of the chemical reactions which lead to the mineralization of guano are surely controlled by microorganisms.

Fungi, algae, and bacteria have all been implicated in the precipitation of carbonate dripstones but it has not been proved if these microorganisms were actively involved in precipitation or whether they were just accidentally buried there. Algae can trigger the precipitation of calcium carbonate from solution, and may subsequently trap and bind the particles to carbonate speleothems. This may occur as the algae take up carbon dioxide during photosynthesis causing $CaCO_3$ to precipitate. Algae will only contribute to carbonate deposition at the entrance and twilight region of caves. Finally, bacteria that utilize carbon dioxide (such as *Thothrix* in the sulfur cycle) have been proved to cause accelerated carbonate speleothem growth (Forti, 2001).

Moonmilk is a precipitate that seems to be originated by microbiological reactions. In fact, two of the four possible mechanisms for the evolution of moonmilk (Hill & Forti, 1997) are biochemical corrosion of the bedrock by organic acid produced by microorganisms (*Arthrobacter*, Flavobacterium, and *Pseudomonas*), and active precipitation of moonmilk by bacteria *(Macromonas bipunctata)*.

Osteogenic cave minerals are formed by the reaction of bones with mineralizing solutions in caves and only two such minerals are formed in this way.

Two cave minerals are known to result from human activity. Vaterite forms on remains of carbide introduced by cavers (Hill & Forti, 1997) and one large calcite flowstone in Italy has been described as derived by the living activity of larvae of a troglobitic insect *(Tricoptera wormaldia)* (Poluzzi & Minguzzi, 1998). Its complex genesis has been referred to the large community of larvae living inside the cave on the surface of wide anthropogenic organic deposits. It is thought that the larval respiration caused the production of large amounts of carbon dioxide, which in turn reacted with water saturated by gypsum, thus causing the deposition of calcite just around the larvae.

Organic formations that do not have a fixed chemical composition include pigotite, amberat, mumijo, and asphalt. Pigotite is formed by leaching of granitic or quartzitic rocks in the presence of organic matter and an acidic environment. Amberat is composed of the dung and urine of cave rats. Mumijo is a black, very soluble substance formed from the excrement of small animals (rabbits or mice) in dry caves of Central Asia by organic reactions (with the help of chemolithotrophic bacteria), which allows slow migration of the soluble substances of the excrement to form mumijo. It has strong and spicy smell and is used in traditional medicine. Asphalt is derived from petroleum-bearing rocks (Sasowsky & Palmer, 1994). Sometimes the large amount of organic matter produced in the "sulfur cycle" allows the evolution of speleothems (pseudo-stalactites) consisting of a single organic mat (mucus), which are normally called "mucolites".

Matrix mineralization

Matrix biogenic mineralization produces minerals formed by transformation of organic bodies, most commonly represented by rootsicles. When roots enter cave voids their surface may become a preferential area for the flow of seeping water and for calcium carbonate deposition. Speleothems growing over roots are normally called "rootsicles" (Hill & Forti, 1997). In wet tropical environments, the root complexes of large trees may become the main driving factor for the evolution of those peculiar speleothems, called "showerhead".

In show caves, where light is artificially supplied, plants may halt calcium carbonate deposition or even cause the corrosion of speleothems, due to the acid secretion of their roots (see Tourist Caves: Algae and Lampenflora)

Nucleation biomineralization

Microorganisms also can be centres of nucleation. Fungal hyphae may act as nuclei for crystallization and as a site for attachment for crystals. Algae can trigger the precipitation of calcium carbonate, subsequently trapping and binding the particles to carbonate speleothems. Algae respire CO_2 consequently causing precipitation of $CaCO_3$.

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See also **Guano; Microbial Processes in Caves; Organic Resources in Caves**

Works Cited

Forti P. 2001. Biogenic speleothems: An overview. *Abstracts of the XVth International Symposium of Biospeleology,* 3–6

Hill, C.A. & Forti, P. 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society

Martini, J. 1994. Two new minerals originated from bat guano combustion in Arnheim cave, Namibia. *South African Speleological Association Bulletin,* 33:66–69

Northup, D.E., Reysenbach, A.L. & Pace, N.R. 1997. Microorganisms and speleothems in *Cave Minerals of the World,* 2nd edition, edited by C.A.Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Poluzzi, A. & Minguzzi, V. 1998. Un caso di biocostruzione in un ambiente di grotta. *Memorie dell Instituto Italiano di Speleologica,* 10:93–100

Sasowsky, I.D. & Palmer, M.V. (editors) 1994. *Breakthroughs in Karst Geomicrobiology and Redox Geochemistry,* Charlestown, West Virginia: Karst Waters Institute

Further Reading

Ehrlich, H.L. (editor) 1996. *Geomicrobiology,* 3rd edition, New York: Dekker

Frye, G. (editor) 1984. *Encyclopedia of Mineralogy,* Stroudsburg, Pennsylvania: Hutchinson Ross

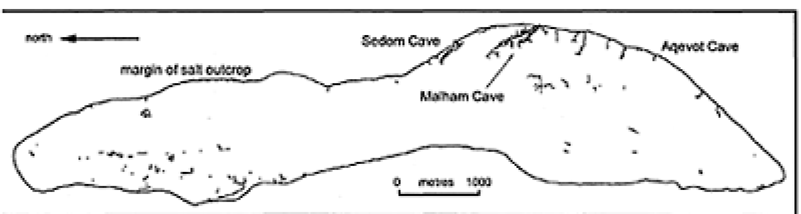
Shopov, Y.Y. 1989. Genetic classification of cave minerals. *Proceedings of the 10th International Congress of Speleology,* vol. 1, edited by A.Kosà, Budapest: Hungarian Speleological Society

SEDOM SALT KARST, ISRAEL

Mount Sedom is the world's best-studied salt karst region, containing the largest known salt cave. It is also the lowest and one of the most arid karst regions worldwide (annual precipitation *c*. 50 mm). The caves have been explored systematically since 1981.

The exposed head of a diapir, composed of Neogene salt beds, forms the elongated (11 by 1.5 km) ridge of Mount Sedom within the Dead Sea graben. The diapir ranges in height from 400 m below sea level to 160 m below sea level. The mean estimated diapir rising rate is about 6–7 mm per year (Frumkin, 1996) and it is still rising. Salt karst has developed in the upper part of the diapir, where salt beds are vertical or steeply inclined. They often yield under the shear stress induced by salt tectonics and develop minor faults. Horizontal fissures are rarely found in Mount Sedom. Before its subaerial extrusion, the top of the rising diapir suffered dissolution by groundwater. Residual, relatively insoluble anhydrite, shale, and dolomite accumulated above the salt, forming a cap-rock up to 50 m thick. The top of the cap-rock is a roughly tabular desert surface.

Some 107 caves have been explored in Mount Sedom with a total length of c.20 km (Figure 1). The caves formed during the Holocene and the oldest cave passage has been dated to c.8000 years BP (Frumkin *et al.*, 1991) by radiocarbon dating of wood twigs carried and deposited by cave streams. The lower levels of the caves still carry floodwater during infrequent rainfall events. The floodwater flows from surface runoff from many small (up to 0.7 km^2) ephemeral catchments, developed on the cap-rock. The flow is captured into fissures which enlarge to form shafts. Sodium chloride concentration in flood flow increases dramatically within the caves, from *c.* 10 g l^{-1} at stream sinks up to 200–350 g l^{-1} (Frumkin, 1994). Most floodwaters remain chemically aggressive while flowing rapidly within cave passages. Apart from dissolution, cave development is promoted by physical erosion attributed to fast-flowing water, cutting into the soft salt. After a short inception period, salt caves develop mainly by open-channel flow. The cave retains a downstream slope, supporting gravitational sediment-rich flow. The larger caves consist of a vertical shaft at the sink point or slightly downstream, and a salt passage draining the shaft. Shafts with a surface catchment area <200–300 m^2 usually do not have a draining passage; the small discharge infiltrates in the bottom of the shaft towards the water table. The typical passage in Mount Sedom caves is a vadose canyon, developed along a joint, bedding plane, or fault within the salt. Young passages are often steep, incised in bedrock, and follow the initial fissure closely. Older passages are often more sinuous, moderately inclined (a few %), and their floor is shielded by alluvium. Some wide passages with highly developed meander notches are indicative of flow without much recent downcutting; lateral migration of meanders sometimes causes destruction of earlier canyon walls. Downward development of passages is achieved either by incision of a passage floor or by a stream capture to a lower-level passage. The older caves in Mount Sedom have several tiered levels above the modern channel.



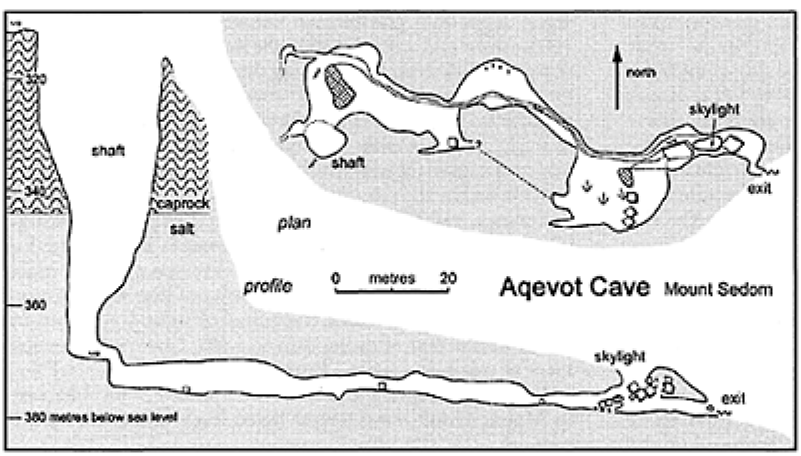
Sedom Salt Karst: Figure 1. Outline map of the known cave passages in the Mount Sedom salt dome, Israel.

Cave passages are either ingrowing vadose canyons or wide low passages with flat ceilings and corrosion bevels, developed by paragenetic dissolution (Frumkin, 1998). Some cross sections have been deformed by Holocene tectonics. The development of a cave profile and morphological features such as meanders and notches is sometimes constrained by less soluble layers (dolomite, shales, anhydrite) interbedded within the salt. Nickpoints in a passage profile are often associated with insoluble beds. Dolomite beds are the most prominent, as they are much more resistant to both dissolution and erosion, relative to the salt.

Many caves are integrated systems—they can be physically traversed along the full distance from sink to outlet (Figure 2). The largest caves, Malham Cave (the longest known salt cave; 5591 m long, 135 m deep) and Sedom Cave (1799 m long) drain to the south basin of the Dead Sea, the hydrologic base level of the region. They are branchwork caves, each with several stream passages joining underground. Residence time of floodwater in these caves is short, measured in minutes up to a few hours in a single flow event. Integrated cave systems are developed along the margins of the rising diapir, where conditions are favourable: hydraulic gradients are high, and fissures are long, open, and abundant because of lithostatic stress release.

Caves in the central portions of the mountain, terminating above the water table, appear to have no distinct outlet. These are referred to as “inlet” caves. The downstream parts of inlet caves often contain silt and clay banks with no continuation of explorable passages. Water ponded in the bottom of these caves has been found to become saturated with salt within a few hours. This evidence suggests that the limit of exploration is also a hydraulic limit between two sequential modes of water flow: rapid turbulent floods prevailing from the sink to the cave bottom, and diffuse infiltration below the bottom of the explorable passage, down to the output boundary of Mount Sedom. Three of the studied caves in northern Mount Sedom supported perennial brine ponds at least throughout the period 1984–95. The ponds are perched some tens of metres above the water table, and their levels seems to be controlled by fissure widths which decrease with depth. Water level in each lake also differs from the others by tens of metres. Both dissolution and precipitation features are observed on walls bordering ponds, as well as on cave walls where ponds have dried out. Horizontal notches indicate levels of aggressive water temporarily diluting the pond during floods. Large secondary halite crystals on some cave walls indicate supersaturation of the ponded water between successive floods. The ground plan of inlet caves range between three end members: elongated conduit, chamber, and maze, depending on fissuring properties of the rock and the hydraulic head applied by flash floods.

Most integrated cave systems originated in the past as inlet caves, created by a capture of subaerial channel into a cap-rock



Sedom Salt Karst: Figure 2. Plan and profile of Aqevot Cave.

fissure. Diversionary routes are common where earlier conduits are blocked by alluvium, until a connection is established with an output point and a stable condition is achieved in ground plan. If a connection to the output boundary is not established, the cave continues to evolve as an inlet cave.

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Works Cited

Frumkin, A. 1994. Hydrology and denudation rates of halite karst. *Journal of Hydrology,* 162:171–89

Frumkin, A. 1996. Uplift rate relative to base level of a salt diapir (Dead Sea, Israel), as indicated by cave levels. In *Salt Tectonics,* edited by G.I.Alsop, D.J.Blundell & I.Davison, London: Geological Society

Frumkin, A. 1998. Salt cave cross sections and their paleoenvironmental implications. *Geomorphology,* 23:183–91

Frumkin, A., Magaritz, M., Carmi, I. & Zak, I. 1991. The Holocene climatic record of the salt caves of Mount Sedom, Israel. *The Holocene,* 1(3):191–200

Further Reading

Frumkin, A. 1994. Morphology and development of salt caves. *Bulletin of the National Speleological Society,* 56:82–95

Frumkin, A. 1996. Determining the exposure age of a karst landscape. *Quaternary Research,* 46:99–106

Frumkin, A. 1996. Structure of northern Mount Sedom salt diapir (Israel) from cave evidence and surface morphology. *Israel Journal of Earth Sciences,* 45:73–80

Frumkin, A. 1997. Liquid Crystal Cave, Israel. In Cave Minerals of the World, edited by C.Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Frumkin, A. 2000. Speleogenesis in salt—the Mount Sedom area, Israel. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Frumkin, A. & Ford, D.C. 1995. Rapid entrenchment of stream profiles in the salt caves of Mount Sedom, Israel. *Earth Surface Processes and Landforms,* 20:139–52

Frumkin, A. & Raz, E. 2001. Collapse and subsidence associated with salt karstification along the Dead Sea. *Carbonates and Evaporites,* 16(2):117–30

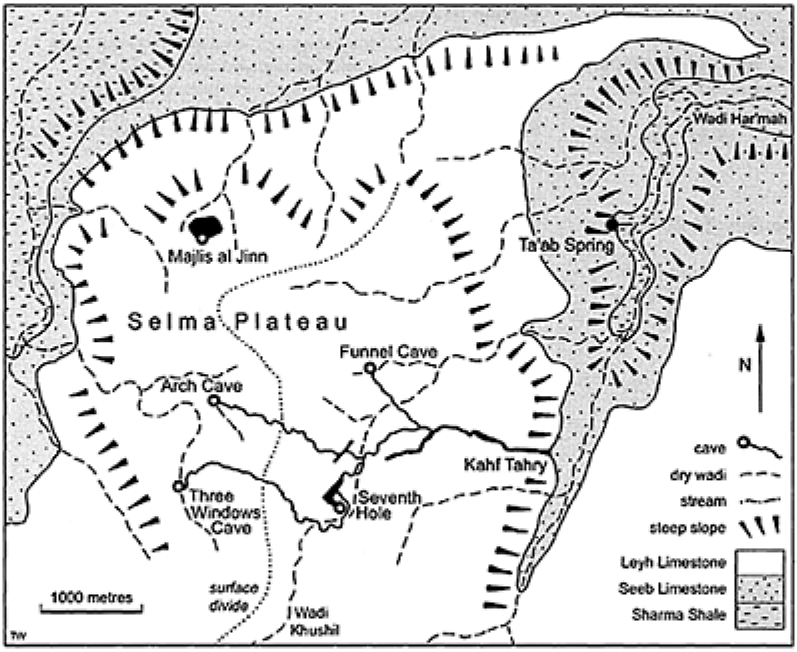
SELMA PLATEAU CAVES, OMAN

Huge cave passages lie hidden beneath the nearly barren, remote highlands of the Selma Plateau in northern Oman. Local legend states that God honoured a brave shepherd girl, Selma, by sending down seven stars that created the seven vertical shafts on the plateau today. Three of the shafts drop into one of the world's largest cave rooms, Majlis Al Jinn (Meeting Hall of the Spirits). The other four link into a cave system 11.5 km long and 385 m deep. The dimensions and vertical development of these caves seem remarkably incongruous with the current arid climate of the region.

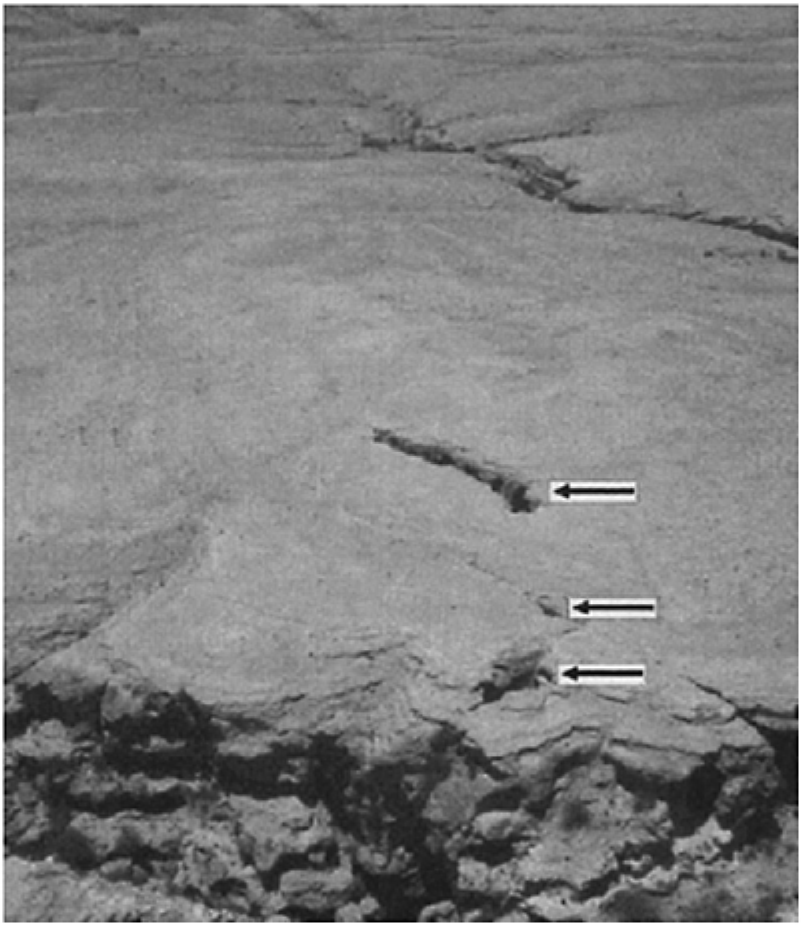
The three shafts that break through the roof of Majlis Al Jinn, provide access and sunlight into the Meeting Room of the Spirits. An X-shaped hole, Khonshilat beyn Al Hiyool, is the largest entrance and drops 136 m near the south side of the room below. The slightly smaller Khonshilat Maqandeli (the name local people also apply to the cave below) drops the shortest distance, 118m, from a nearly circular hole 20 m in diameter. The smallest entrance, Khoshilat Minqod, provides the most dramatic entrance with a 158 m descent into the centre of the massive chamber. The cave consists of a single chamber approximately 300 m×200 m×100 m (Davison, 1985); its measured volume is 3.9 million m^3. The chamber is evenly rounded in plan and has a gently domed roof. All three shafts are on joint intersections, which have almost no influence on the chamber slope. The ceiling is nearly devoid of speleothems, although some dripstone hangs from alcove walls. Sand, silt, and clay sediments mostly cover the floor. A cracked mudflat fills most of the northern quarter of the floor. Sparse breakdown lies on the floor, mostly on the eastern side of the room, but conspicuously less abundant than might be expected in a chamber of this size. Apparently relict flowstone, cave pearls, and large coral pipes cover parts of the west-central floor and provide some hints to an earlier, wetter time in the cave's history. Dripping water from the ceiling initially formed coral pipes as pillars of sediment under protective caps of more resistant material (in the same manner as "hoodoos" on the surface). The pillars and cap rocks became calcified and coated with splatter cave coral. Much of the sediment has been eroded from under the coral pipes in Majlis Al Jinn, commonly leaving behind mostly hollow coral pipe shells. No known passages extend from the chamber.

The other large shaft entrances of the Selma Plateau are Bayn Halayn (Arch Cave), Kahf Khasha (Funnel Cave), Kahf Aqabat Khushil (Seventh Hole), and Three Window Cave (Figure 1). All four shafts lie in the floors of wadis cut 5–20 m deep across the plateau surface. They carry floodwater in storm events. The four caves all descend joint-guided shafts for about 250 m, then drain down the dip of 5–10° and converge into a cave system before resurging (Thomas & Robinson, 1997; Ganter, 1998). Seventh Hole (Figure 2) has broken shafts dropping 250 m into the head of the Canyon Room, 200 m long and 80 m wide. Its outlet streamway descends to meet larger and older passages with eroded stalagmites and cemented fills. These continue to the now intermittent resurgence of Kahf Tahry, truncated in its canyon wall. Three Window Cave offers a superb through trip, 6 km long dropping 385 m with 39 pitches of 3–34 m, many over large gour barriers, sometimes into pools of crystal-clear water. Its long streamway enters the base of the Canyon Room below Seventh Hole. The other tributary passages are smaller, but Funnel Cave has a clean shaft of 170 m just inside its entrance.

The caves of the Selma Plateau developed in the Middle Eocene Seeb Formation, a massive, argillaceous, bioclastic, basinal limestone with subordinate clastic units. An upper, unnamed marly member probably forms the ceiling of Majlis Al Jinn. Most of that chamber and all of the other caves lie in the stratigraphically lower, cliff-forming Leyh Member of the Seeb Formation. The caves immediately drop through the typically resistant, bioclastic calcarenite of the upper and middle layers, forming low-gradient trunk passages in the lower parts of the formation, which are interbedded marl, clayey limestone, and



Selma Plateau Caves, Oman: Figure 1. Outline map of the Selma Plateau, with the Selma Cave System (with the four sink entrances and the Kahf Tahry outlet) and also the cave chamber of Majlis al Jinn.



Selma Plateau Caves, Oman: Figure 2. Arrows point to the entrances of Seventh Hole, as seen from the air southsoutheast of the cave. Note the lack of surface drainage entering these entrances, yet the largest chamber of the Selma cave system lies at the base of the entrance drops. (Photo by Louise Hose)

nodular bioclastic limestone. Kahf Tahry also formed in this lower unit, suggesting that a stratigraphic barrier may have perched cave development.

In the Miocene, the Seeb Formation experienced a northeast—southwest compression phase of Alpine deformation that uplifted the Oman Mountains. The Selma Plateau gently arched up without significant faulting. Uplift of a few tens of metres continued into the Quaternary.

While recognized as a spectacular karst region, the Selma Plateau has received very little speleological investigation beyond initial cave exploration. Far more mysteries remain than clear understanding of the regional speleogenic history. Majlis Al Jinn appears to be the product of hypogenic waters rising from depth, dissolving the huge chamber beneath a structurally strong dome ceiling, leaving only insoluble sediments behind. If so, the cave formed when the water table was much higher than it is today, probably millions of years ago. No attempt has yet been made to determine the age of the cave or the validity of the hypogenic origin hypothesis.

The large size of the rooms and passages in the main cave system demands some explanation. The Canyon Room and the four entrance shafts could represent former conduits of rising, hypogenic, acidic groundwater, within an environment comparable to that which formed Majlis Al Jinn. When erosion exposed these previously buried conduits, they were invaded by surface waters—the wadis beyond the sinks are much reduced in size. Alternatively, Seventh Hole and the Canyon Room may simply be a much older sink with an outlet to the large lower passages now obscured.

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Works Cited

Davison, W.D. Jr. 1985. Majlis Al Jinn Cave, Muscat: Sultanate of Oman, Public Authority for Resources (Report PAWR 85–20)

Thomas, V. & Robinson, L. 1997. Oman ’97. *Caves and Caving,* 76:25–28

Further Reading

Bechennec, F., Le Metour, J. & Roger, J. 1992. Geological map of Tiwi Sheet (scale 1:100 000) with explanatory notes. Muscat: Sultanate of Oman, Ministry of Petroleum and Minerals, Directorate General of Minerals

Burns, S.J., Fleitmann, D., Matter, A., Neff, U. & Mangini, A. 2001. Speleothem evidence from Oman for continental pluvial events during interglacial periods. *Geology,* 29:623–26

Burns, S.J., Matter, A., Frank, N. & Mangini, A. 1998. Speleothembased paleoclimate record from northern Oman. *Geology,* 26: 499–502

Ganter, J. 1998. Caving on the Selmeh Plateau, Sultanate of Oman. *NSS News,* April 1998:100–108

Hanna, S. & Belushi, M.A. 1996. *Introduction to the Caves of Oman,* Muscat: Sultan Qaboos University

SEWU CONE KARST, JAVA

Gunung Sewu means Thousand Hills, but there are probably ten times that number of small rounded limestone hills in an unbroken karst of over 1000 km^2. Lying along the south coast of Java, just southeast of the city of Yogyakarta, the Sewu karst is formed in a belt of Miocene reef limestones. These lie on the flank of the chain of active volcanoes that makes up the core of Java. The climate is equatorial, with little seasonal or diurnal temperature variation from a mean of 26°C, and an annual rainfall of 2000 mm, all of which occurs between November and April.

The major feature of Gunung Sewu is the surface topography. The limestone hills are remarkably uniform in size and shape, each being about 200 m in diameter and 50 m high. They were first described by Herbert Lehman as the type example of kegelkarst, or cone karst. However, the hills are actually hemispherical (Figure 1). They do not have the sharp summits of the truly conical hills now known in the fengcong cone karsts of South China. Gunung Sewu certainly constitutes a classic karst landscape, but is perhaps better regarded as the type area for hemispherical karst, which is matched elsewhere in the world, notably in Sulawesi's Bohol karst and in Jamaica's Cockpit Country.

The rounded profile of the hills is probably created by a greater degree of rock head (the rock surface beneath unconsolidated deposits) dissolution beneath thicker soils retained on the hilltops. The origin of this soil is therefore critical and diagnostic, and in Gunung Sewu it may owe its longevity at least in part to regular renewal by airfall ash from the nearby volcanoes. When soil is stripped from the hills by erosion, slope profiles adjust to the gradient and the karst matures into a landscape of conical hills, as in China.

The conical hills of Gunung Sewu have broadly concordant summit levels that rise to about 400 m above sea-level in the centre of the karst. Between them, depressions are floored by thick layers of smectite-rich soils, derived largely from volcanic ash. The overall pattern of these depressions reveals the dendritic systems of the valleys, but these are now broken into strings of dolines. It appears that valleys were superimposed on to the limestone on a surface close to the level of the summit trend, before being segmented by karstic capture. Combined with the small dimensions of the passages in most of the caves, this suggests that the karst landscape is fairly young, even though the hills show a uniformity indicative of maturity.

There are no long surface stream courses, as all drainage finds a sink within a very short distance. The few surface rivers that drain into the karst from inland catchments also sink into open caves. There is little recognizable structure within the limestones, and therefore little geological influence on the topography. Some areas of softer, more chalky limestones have slightly more gentle hill slopes, and the chalk of the Wonosari Plateau, north of Gunung Sewu, has a gently rolling topography. Its diffuse groundwater flow beneath a shallow water table feeds into the limestone karst at an interdigitated facies boundary, and rapidly descends to depth in the more permeable cavernous limestone.

Gunung Sewu has a high rural population, with many small villages of farmers, who tend every bit of soil on the doline floors and also struggle to terrace and farm some of the hill slopes. In the long dry season there is a serious shortage of water, and many farmers have to carry water from the few accessible cave sources, often involving time-consuming candle-lit underground scrambling. A series of deep boreholes in the karst proved to be almost dry, and yielded no usable water resources.

Consequently, two small teams of British cavers systematically explored the caves of central and western Gunung Sewu in 1982–83. Their purpose was to discover better supplies of underground water that could be reached by shallow wells or deeper (targeted) boreholes. They visited 257 sinks and mapped 216 caves, most of which were shafts; 28 reached more than

Sewu Cone Karst, Java: Figure 1. The landscape of seemingly endless conical hills that makes the Gunung Sewu karst. It is clear that most hills are actually hemispherical and not as uniformly conical as those in the Chinese Karst. (Photo by Tony Waltham)

Sewu Cone Karst, Java: Figure 2. The shaft of Gua Lebak Bareng, 140 m deep. (Photo by Andy Eavis)

100 m deep, and nine extended to more than a kilometre of passages (Willis *et al.*, 1984). Most caves drop steeply or vertically (Figure 2) to sump pools on the regional water table, which rises inland with a mean gradient of 1:150. A minority of longer caves have either youthful meandering canyons or sections of larger partially drained phreatic tunnels. There is no consistent pattern of sequentially developed old caves, and few dry high-level passages are known. Nearly all the caves in central Gunung Sewu drain to a single choked resurgence on the beach at Baron Bay. This lies in a recess between cones that are spectacularly undercut and truncated along the ocean coastline.

The largest underground flows are the two small rivers that are fed from the Wonosari Plateau. The Kali Suci drains through a series of short but large caves, before passing across the floor of the dramatic Grubug shaft, 65 m deep below its small daylight eyehole, and descending a flight of cascades to a sump. This marks the water table in a trough defined by its efficient conduit flow through to the Baron resurgence on a gradient of only 1:750. The Bribin Cave carries a small river through 3 km of lakes in a tunnel mostly 20 m high and wide.

The eastern end of the Gunung Sewu karst was explored by another team of cavers in 1984 (Stoddard, 1985). This area has fewer deep shafts and more long stream caves, including the splendid Luweng Jaran with 12 km of passage including a very long streamway and some beautifully decorated high-levels.

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See also **Cone Karst**

Works Cited

Stoddard, S. 1985. Anglo-Australian Speleological Expedition to Java, 1984. *Cave Science,* 12(2):49–60

Willis, R.G., Boothroyd, C. & Briggs, N. 1984. The caves of Gunung Sewu, Java. *Cave Science,* 11(3):119–53

Further Reading

Lehman, H. 1936. Morphologische Studien auf Java. *Geographische Abhandlungen,* Serie 3, 9:1–114

Waltham, A.C., Smart, P.L., Friederich, H., Eavis, A.J. & Atkinson, T.C. 1983. The caves of Gunung Sewu, Java. *Cave Science,* 10(2):55–96

SHANIDAR CAVE, IRAQ: ARCHAEOLOGY

Shanidar Cave overlooks a tributary of the Tigris River in northeastern Iraq. It is famous for its nine Middle Paleolithic burials known as the Shanidar Neanderthals (1–9), found by Ralph Solecki in excavations between 1953 and 1960. The diseased state of one of the skeletons and the “flower burial” of another of these Neanderthals has changed our view of Neanderthals from ape-like and brutal creatures to beings showing altruism and compassion.

The cave, eroded in the Middle Cretaceous limestone of the Zagros Mountains, has yielded the partial skeletal remains of two infants and seven adult Neanderthals from the Middle Paleolithic, 28 representatives of anatomically modern humans from the Holocene, and a wealth of floral, faunal, and cultural data. The Neanderthal sample is the largest from the Middle East, providing an almost continuous sequence of human evolution, from the appearance of Neanderthals through to the appearance of modern humans and the domestication of plants and animals. The Neanderthal sample is divided into two groups: the typical Neanderthals (Shanidar 1, 3, 5) ^{14}C-dated at more than 45 000 years BP and the Early Neanderthals (Shanidar 2, 4, 6, 7, 8, 9) tentatively dated between 65 000 and 100 000 years BP.

Solecki excavated only the central part of the cave down to bedrock, and found five major layers: A, B1, B2, C, and D. The sediments consist of a loamy soil and numerous rocks. The rocks came from the roof of the cave after at least five major rock falls. Some of the Neanderthal skeletons were found badly crushed under the debris. The most convincing evidence for a death caused by a rock fall comes from Shanidar 5. His pelvis was beneath a rock, his legs' anterior surfaces were facing down and his trunk was bent backwards so that the skull was at the other side of the rock next to the pelvis.

The skeletal remains from Shanidar Cave are described in a monograph by Eric Trinkhaus. Shanidar 1 sustained a massive blow to the right side that badly damaged his right arm, foot, and leg, and a crushing fracture to the left eye that would have rendered his left eye blind. These injuries, which had occurred long before his death, are merely evidence that he could not have been an effective hunter, not necessarily that he was treated with compassion. Shanidar 4 became famous as the "flower burial". It is the best example of an intentional burial from the Middle Paleolithic. Shanidar 4, 6, 8, and 9 were found superimposed on each other in a natural rocky crypt. Usually, crypts and pits are considered as evidence of intentional burial. The covering of the Shanidar 4 skeleton by rocks may have prevented carnivores from exhuming the body. Indeed, skeletal remains of carnivores have been found in the cave, such as wolf, jackal, fox, and brown bear. Therefore, the completeness of Shanidar 4 skeleton is attributable to its covering by rocks and not to the absence of carnivores from the site. Besides, no comparatively well-preserved animal skeletons have been found in the cave.

The Shanidar 4 skeleton was found in a "fetal position", i.e. with his legs flexed. This may imply either an intentional burial or simply a desire to accommodate the corpse in the small confines of the rocky crypt. Flexed skeletons are generally considered as evidence of intentional burial, even though one cannot distinguish a ritual or religious burial from that of a corpse disposal. The presence of exceptional "grave goods", such as flowers, is another line of evidence for an intentional ritual burial. Solecki had already collected some 50 soil samples from the occupational deposits. When he uncovered the remains of Shanidar 4, he collected some representative samples from the crypt area below Shanidar 4 for pollen analysis. He noticed that there were two distinct layers—one just above and one just below the skeleton of Shanidar 4. The soil of the upper layer was a loose light brown sandy loam, and it was apparently disturbed by rodents. The lower soil was a very tough dark-brown organic loam interlayered with flowstone sheets.

Palynological analysis of the upper soil by Leroi-Gourhan showed that it had only isolated pollen grains, as did the samples from the rest of the cave. In the lower soil, however, there were extraordinary amounts of herbaceous and arboreal plants. There were not just isolated pollen grains but compact masses of fossilized pollen, many in the form of anthers—145 of them. In addition, the lower soil contained a large amount of noncarbonized (unburned) wood (oak, pine, juniper, ash, and fir). In fact, there was a whole layer of organic material full of wood fragments and flower anthers that could have been used as a sort of bedding. This gives a special character to the whole cave and shows that Shanidar 4 is an intentional burial. This does not mean that the flowers had the same meaning for the dead Neanderthals as they have today for us. For instance, the flower anthers were found beneath the skeleton and one of the flowers is covered with lots of spikes.

A criticism of the hypothesis that Shanidar 4 had been buried intentionally with flowers was based on the following assertions, that:

1. There were no grave pits in the cave;
2. There was no good stratigraphic evidence;
3. The superimposition of the skeletons shows temporal separations, not contemporaneity;
4. The rocky crypt was a shelter;
5. Only one anther was found;
6. The wind and rodents may have carried the tree branches and the flowers into the burial;
7. There was no sampling for pollen analysis from the other areas of the cave;
8. The rock fall preserved the pollen, unlike the other areas of the cave where no large concentrations of pollen were found;
9. No stratum of pollen was identified;
10. The pollen was not fossil, but contamination at the time of excavation; and
11. The intact nature of the skeleton of Shanidar 4 was due to the lack of carnivores in the cave.

In view of the fact that the above arguments are unsound, it is concluded that Shanidar 4 was at least an intentional burial. A thick layer of blossomed herbaceous and arboreal plants had been placed beneath the body of Shanidar 4.

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Further Reading

Constable, G. 1980. *The Neanderthals,* New York: Time-Life Books

Dettwyler, K.A. 1991. Can paleopathology provide evidence for "compassion"? *American Journal of Physical Anthropology,* 84: 375–84

Gargett, R.H. 1989. Grave shortcomings. The evidence for Neanderthal burial. *Current Anthropology,* 30(2): 157–90

Leroi-Gourhan, A. 1975. The flowers found with Shanidar IV, a Neanderthal burial in Iraq. *Science,* 190:562–64

Perkins, D. 1964. Prehistoric fauna from Shanidar, Iraq. *Science,* 144:1565–66

Solecki, R.S. 1963. Prehistory in Shanidar Valley, Northern Iraq. *Science,* 139:179–93

Solecki, R.S. 1971. *Shanidar, The First Flower People,* New York: Knopf.

Solecki, R.S. 1975. Shanidar IV, a Neanderthal flower burial in Northern Iraq. *Sciencc,* 190:880–81

Solecki, R.S. 1977. The implications of the Shanidar cave Neanderthal flower burial. *Annals of the New York Academy of Sciences,* 293:114–24

Stringer, C. & Gamble, C. 1993. *In Search of the Neanderthals: Solving the Puzzle of Human Origins,* London and New York, Thames and Hudson

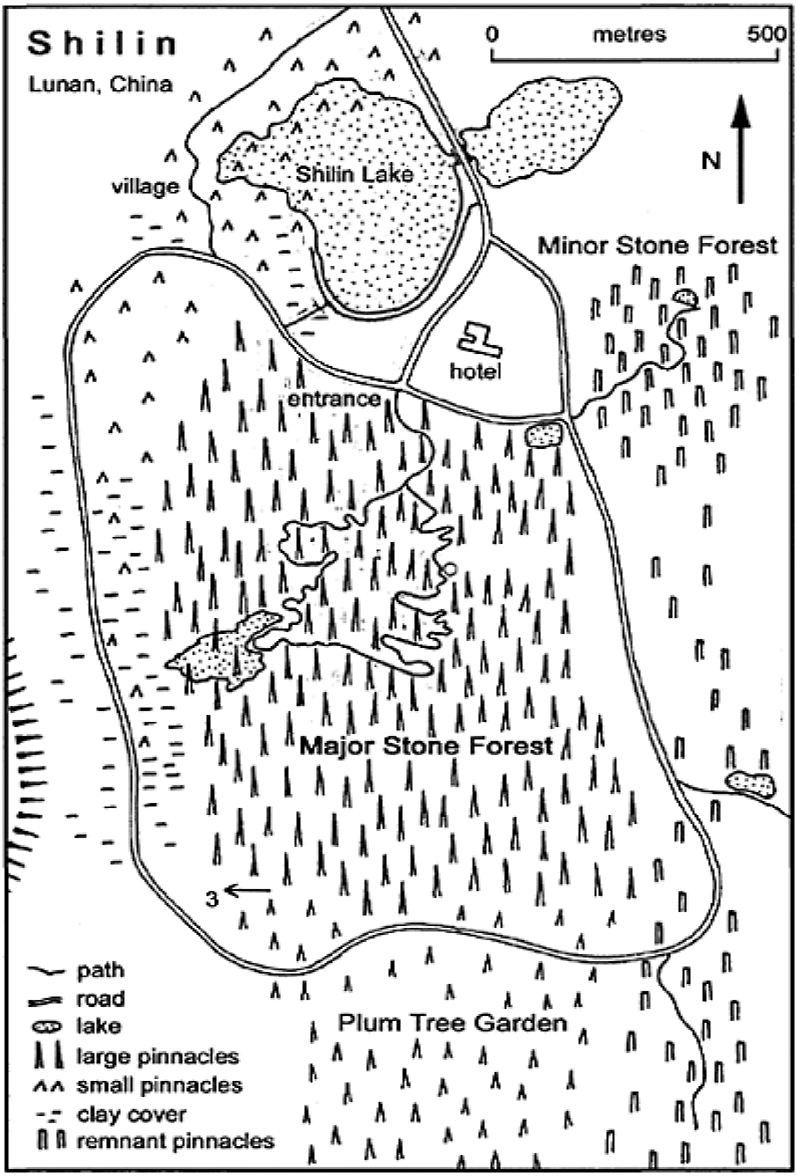
Trinkaus, E. 1983. *The Shanidar Neandertals,* New York: Academic Press

SHILIN STONE FOREST, CHINA

Areas of spectacular pinnacle karst in southern China have so many tall, closely-packed limestone pinnacles, that for 2300 years they have been known as shilin—which translates as stone forest. They differ from pinnacle karst elsewhere in their complex geological evolution. The largest and best known is the type example at Shilin, in Lunan County, Yunnan Province (Figure 1), but there are many more similar stone forests, both in Yunnan and elsewhere in China.

The stone forests occur in exposed beds of massive limestone, which dip at less than 10°. The finest occur in the Permian Maokou Limestone, but some are on other Permian and Carboniferous beds. The limestone is broken by sub-vertical joints, which have been eaten out by dissolution to form deep fissures, slots, and canyons between the tall and narrow blocks of limestone that remain. The limestone is fretted by rainwater into pinnacles and arêtes, which are scored by long deep rinnenkarren, with razor-sharp crests on all the ridges and summits (Figure 2). Pinnacles are mostly 10–30 m tall, but some reach 50 m; bedding planes in the limestone generally prevent the formation of any taller pinnacles. Collapses and toppling failures do occur, but most pinnacles are stable; the low bedding dip and nearly vertical jointing are critical factors in this respect. The pinnacles are bare rock and there is little or no vegetation in the intervening fissures. It is possible to walk around in much of the network of fissures and canyons between the pinnacles; the Shilin site at Lunan has had tourist trails through it since 1614, during the Ming dynasty.

As in all well-developed pinnacle karst, the modern morphology is largely the result of a long period of dissolutional erosion by plentiful rainwater, charged with carbon dioxide in a warm climate. The sharp crests and intervening rillenkarren are evidence of erosion by direct rainfall. Pinnacle walls that have evolved under vegetation are more fretted, with random channels etched into them. Nearly all rock surfaces are dark grey, due to a crust rich in blue-green algae. The lower parts of many pinnacles have smoother faces with rounded ribs, and it is clear that these surfaces have evolved under water or beneath saturated masses of organic soil. Horizontal swamp notches indicate the role of gently flowing water at the local base level, while other pinnacles can be seen still half buried in soil, where sub-soil rockhead dissolution has been significant.



Shilin Stone Forest, China: Figure 1. Outline distribution of the main types of pinnacle karst at Shilin, the type stone forest at Lunan, China.

Shilin Stone Forest, China: Figure 2. The central part of the stone forest at Shilin, with the pagoda-style temple perched on the pinnacles to provide a viewpoint for visitors who are otherwise trapped on footpaths between the pinnacle bases. (Photo by Tony Waltham)

A transect across the Lunan Shilin reveals the recent geomorphological evolution of the landforms. The Major Stone Forest occupies an area of about 100 ha; it slopes and dips gently to the west towards a clay-floored basin. Within this, proto-pinnacles that project from the clay as stone teeth a few metres high have well-rounded surfaces that have clearly not long been exposed to rainwater corrosion. On the eastern side of the main stone forest, the Minor Stone Forest and a field of isolated, shattered pinnacles, up to 20 m tall, together represent an old age, degraded version of the shilin landform. Further east, the entire limestone bed has been removed by subaerial erosion.

This evolutionary sequence accounts for the main landforms of Shilin, and can be repeated in many other pinnacle karsts. The special factor of the Chinese shilin is its much longer evolutionary history. The Maokou limestone was indurated and then uplifted soon after its deposition. Its surface was first exposed to karstic erosion in the late Permian. It was then covered by the basalts and tuffs of the Upper Permian Ermei Volcanics. Subsoil dissolution continued beneath the tuffs, creating a pinnacled rockhead. This was then partly exposed and further carved into a small-scale version of pinnacle karst, in a Mesozoic tropical environment. Regional subsidence caused a second burial of the limestone, as Eocene red clays accumulated in lakes that gradually extended across the karst. Only in the Quaternary did uplift initiate re-exposure of the limestone. The newly uncovered surfaces were already eroded into pinnacles, but these have been considerably deepened and sharpened by rainwater within the modern environment.

Within Lunan County, a number of separate smaller stone forests provide the evidence for this long evolution. Different sites have pinnacles half covered by basalt lavas, Permian tuffs and Eocene red clays; some also have pinnacles that are half submerged in modern lakes. In each case, the pinnacles can be seen at some stage of evolution towards their modern form. It is the inherited fossil karst features that distinguish the stone forests of shilin from the areas of pinnacle karst recorded elsewhere, notably at Mount Kaijende and Mulu (see separate entries).

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See also **Karren**

Further Reading

Ford, D.C., Salomon, J.-N. & Williams, P.W. 1996. "Les forêts de Pierre" de Lunan (Yunnan, Chine). *Karstologia,* 28(2): 25EJ 40

Song L. 1986. Origination of stone forests in China. *International Journal of Speleology,* 15:3–13

Song L., Waltham, T., Cao N. & Wang F. (editors) 1997. *Stone forest, a treasure of natural heritage,* Beijing: China Environmental Science Press

SIBERIA, RUSSIA

There are more than 1400 caves known in Siberia, being widely spread along the south of the area. Gorniy Altai, the East Sayan Upland, the southern part of Central Siberian Upland, the Primorsky Range and the Priolkhonskoye Plateau near Lake Baikal, Sikhote-Alin' in the Far East, and Sakhalin Island are the most investigated speleologically (see map in Russia entry). Karst caves are the most numerous, and although crevice caves are very widespread on the Siberian Platform, only a few have been explored. Caves formed by abrasion are very common on the coasts of the Pacific Ocean, Lake Baikal, and reservoirs. Weathering caves, grottos, and niches are rather numerous, but they attract speleological investigation relatively rarely, owing to their small sizes. More than 30 volcanic caves have been mapped on the Kamchatka Peninsula and Kuril Islands, and a glacier cave has been described in the Baikalskiy Range.

The karstic caves are found in rocks from a wide range of geological ages—Archean, Proterozoic, all divisions of the Paleozoic, Triassic, and Jurassic—and are usually developed in calcitic and dolomitic marbles, limestones, dolomites, and carbonate rocks of mixed composition. But caves in other karst rock types also occur, for example, caves in carbonatites, calcyphyres, skarns, gypsum, gypsum anhydritic rocks, carbonate conglomerates, dolomitized gravelites, and sandstones.

The Gorniy Altay Mountains contain more then 400 caves. The largest are the Altayskaya (4175 m long, 248 m deep), Këktash (2300 m long, 350 m deep), Tutkushskaya (1400 m long, 218m deep), and Soantekhnicheskaya (900 m long, 215m deep) caves.

More than 100 karst caves are known in Upper Proterozoic and Cambrian carbonate rocks in Kuznetskiy Alatau and Gornaya Shoriya. The largest are the Korolëva (5070 m long, 171 m deep), Fantaziya (6200 m long, 272 m deep), and Yashchik Pandory (10 100 m long, 182 m deep) caves. Yashchik Pandory is in massive Lower Cambrian limestone. The upper level is rich in ancient calcite speleothems. The lower level lies at the water table, where cave lakes occupy one-third of the passages in dry seasons.

174 karst caves have been explored in the East Sayan Upland. A few significant karst caves, Bol'shaya Oreshnaya (47 000 m long, 197 m deep), Badzheyskaya (6000 m long, 170 m deep), Tëmnaya (2500 m long, 55 m deep), Rucheynaya (1300 m long, 85 m deep), are developed in Ordovician carbonate conglomerates. Bol'shaya Oreshnaya is the longest conglomerate cave in the world. It is a deep and spacious ancient phreatic labyrinth, which consists of inclined and horizontal passages, with chambers, pits, crevices, cellular parts, lakes, streams, and a large flooded zone. Karbonatitovaya Cave is the only one in carbonatites known in the world.

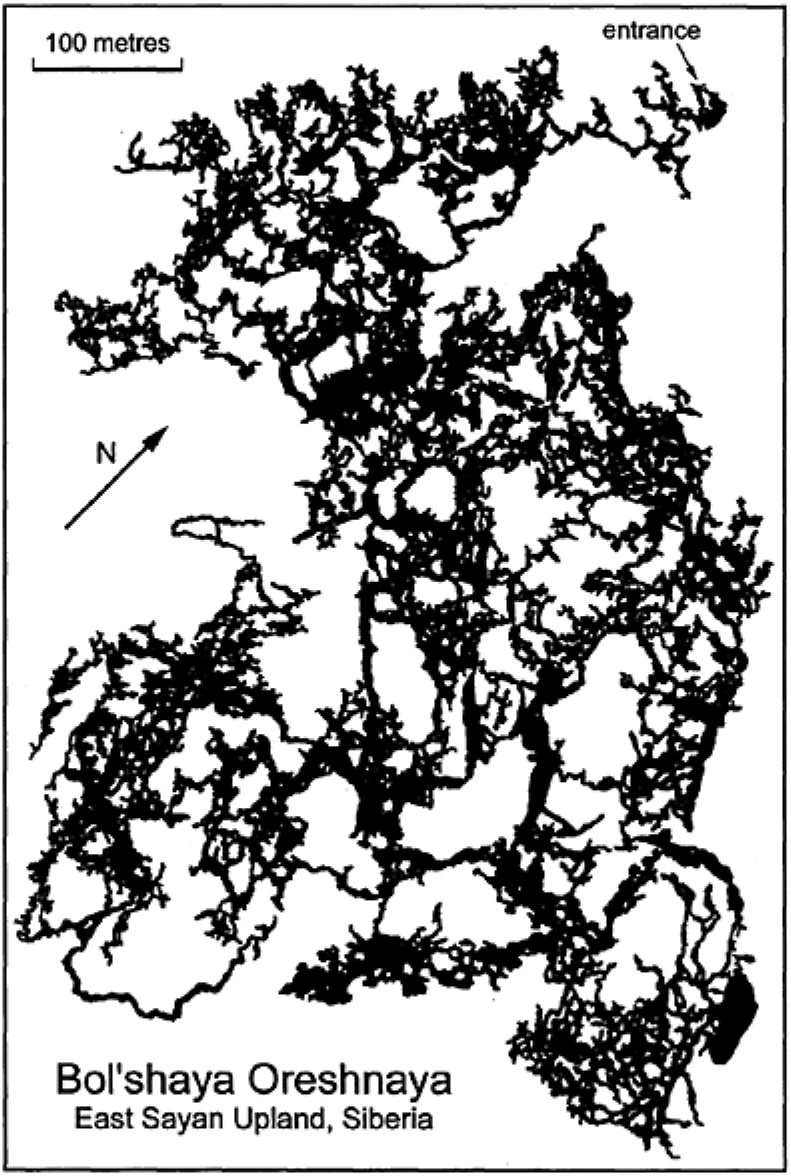
There are 26 karst caves on the south of the Central Siberian Upland. The largest are Botovskaya Cave (57 260 m long, 6 m deep), the longest maze in Siberia and Russia, developed in Lower Ordovician limestones and sandstones, and Argarakanskaya Cave (8300 m long, 56 m deep) in Lower Cambrian limestones.

In the middle part of the Central Siberian Upland, 14 small horizontal solution caves in Ordovician gypsum are known at the Vilyey River. The largest, Oyusutskaya-9 Cave, has a length of 95 m.

At the east of the Siberian Platform, 12 karst carbonate caves with a total length of 2245 m were found in the Yudoma-Mayskiy Foredeep. The largest, Abagy-Dzhie (1400 m long, 8 m deep), is a horizontal water table labyrinth in Riphean dolomitized limestones. Lakes cover 70% of the cave floor.

The Khamar-Daban Range has only seven caves developed in Lower Proterozoic marbles and limestones. The Primorsky Range and Priolkhonskoye Plateau are the most speleologically investigated among the mountains surrounding Lake Baikal. They contain 55 and 24 caves respectively. Ancient phreatic caves, developed in Upper Archean—Lower Proterozoic graphite marbles, scarns, and calcyphyres on the Priolkhonskoye Plateau, are the most interesting. Some of them were formed in pre-Middle Miocene time (Aya, Ryadovaya, Oktyabr'skaya), some in pre-Eocene time (Mechta, Bol'shaya Baydinskaya, Shamanskaya Caves).

The other ranges (Baikalskiy, Barguzinskiy, Ikatskiy, Morskoy), situated around Lake Baikal, contain single karst, weathering, glacier, and abrasion caves. Kal'tsitovaya Cave, developed in Upper Proterozoic limestone in the Morskoy Range, has a hydrothermal genesis. It has tube-shaped inclined passages, encrusted with hydrothermal calcite 20 cm thick.



Siberia, Russia: Bol’shaya Oreshnaya Cave, the longest conglomerate cave in the world (survey by the Divnogorsky SpeleoClub), showing 36 km of surveyed passages as of 1987 (presently the cave length is 47 km).

The Stanovoye Upland, which includes the Severo—Muyskiy, Delyun-Uranskiy, and Aglan-Yan Ranges, contains 35 caves in Cambrian limestones. Most caves are relict corrosional/erosion cavities. A few caves in Aglan-Yan Range are active, formed by recent water streams. The karst shaft Klyuch in Severo-Muyskiy Range is the deepest, at 57 m.

Six karst caves, connected with Upper Riphean—Lower Cambrian tremolite limestones, have been studied on the Vitim Upland. The largest, Dolganskaya Yama (5120 m long, 125 m deep), is a compound volume labyrinth of steeply inclined, vertical, and horizontal passages. Multiple branched systems of large organic tubes (spongework) are in the ceilings. Calcite flowstones and corallite cones are widespread. There are also two siphon lakes.

Among 30 caves known in Selenginskaya Dauriya, there are only two formed in limestones, the rest being weathering cavities. They were developed in various effusive, intrusive, and sedimentary rocks of the Lower Cambrian, Upper Paleozoic, Mesozoic, and Miocene ages. All of them are small.

The Mongolo-Okhotskiy folded belt has been explored very slightly. In the western part, in the Onon and Gazimur River basins, only small karst caves are described (Lurgikanskaya, Monasytuyskaya, Soktuyskaya, etc.) developed in the Riphean, Lower Cambrian, Silurian, and Devonian marbles and limestones. In the eastern part of the belt there are only four small karst caves. The Bureinskiy Median Mass includes 65 karst caves, with a total length of 2473 m, in Proterozoic carbonate rocks. Most of them are situated in the Lesser Kningan Range. The largest is Ledovaya Cave (385 m long, 64 m deep).

Cambrian, Carboniferous, Permian, and Triassic limestones are very widespread in Sikhote-Alin’. Two hundred karst and four volcanic caves, with a total length of 11 700 m have been investigated. The largest are the Proshchal’naya (3200 m long, 73 m deep), Spasskaya (2220 m long, 16m deep), and Solyanik (425 m long, 125 m deep) caves.

The karst caves of the Sakhalin Island are in Upper Jurassic reef limestones in the East Sakhalin Mountains. During the last 20 years, 56 karst caves with a total length of 1415 m have been discovered. The most significant are the Kaskadnaya (208 m long, 123 m deep) and Vaydinskaya (300 m long, 64 m deep) caves.

Paleolithic sites have been studied in Strashnaya, Bukhtarminskaya, Ust’-Kanskaya, and Denisova caves in Gorniy Altay, and in Dvuglazka and Grot Proskuryakova Caves in Kuznetskiy Alatau, Dyuktaiskaya Cave in Yakutia, and the Geographicheskogo Obshchestva in the Far East. Mesolithic sites and younger cultural horizons have been studied in Eleneva Cave near Krasnoyarsk city and in Bol’shaya Ludarskaya Cave near Lake Baikal. Neolithic sites were excavated in the Aydashinskaya Cave in Kuznetskiy Alatau, in the Boro-Khukhan, Shamanskaya, Uzurskaya, Skriper, Obukheikha, and Tonta caves near Lake Baikal, and in the Chërtovy Vorota, Letuchaya Mysh, and Vereshchagina caves in the Far East. Bronze Age sites have been explored in Vereshchagina, Denisova, and Aydashinskaya Caves. Iron Age, Middle Age, and Contemporary Ethnography sites have been discovered in the numerous caves in Gorniy Altay, in the Yenisey River Basin, near Lake Baikal, and in the Far East.

Paleontological investigation of Siberian caves has continued for over 150 years. Vertebrate fossils from more than 100 caves have been studied in different regions of southern Siberia and Sakhalin Island. The Upper Pleistocene and Holocene fauna remains are the most studied (Ovodov, 1980). Only a few caves contain more ancient bones. The most ancient fossils were found in Aya Cave near Lake Baikal. Numerous Middle Miocene remains of mammals (Lagomorphs of the Amphilaginae family, and rodents of the *Gobicricetodon* genus/Zapodidae family), a tortoise of the *Trionyx* genus, and an extinct snake-headed fish of the *Channa* genus were extracted (Filippov *et al.,* 2000). The bones of two extinct species of bears have been discovered in Siberian caves: the small cave bear, *Ursus (Spelaearctos) rossicus Borisjak,* from the Strashnaya Cave in Gorniy Altay, and *Ursus (Selenarctos) sp.*, close to the Himalayan species, from Botovskaya Cave (Ovodov & Filippov, 2000). Middle Pleistocene small mammal fauna have been described in the Stariy Zamok cave in Eastern Siberia. Nine species of bats are found in the caves of the Far East, six species in Transbaikalian and Sakhalin caves, and eight species in Pribaikalia and Krasnoyarsk territory. They belong to the genera *Myotis, Plecotus, Murina,* and *Ambliotus*.

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Works Cited

Filippov, A.G., Erbajeva, M.A. & Sychevskaya, E.K. 2000. Miotsenovye otlozheniya v peshchere Aya na Baikale [Miocene deposits in the Aya Cave near Baikal]. *Geologiya i geofizika* [Geology and Geophysics], 41(5):754–63

Ovodov, N.D. & Filippov, A.G. 2000. Vymershie medvedi Sibiri [Extinct bears of Siberia]. In *Paleogeografiya kamennogo veka. Korrelyatsiya prirodnykh sobytiy i arkheologicheskikh kul'tur paleolita Severnoy Azii i sopredel'nykh territoriy* [Paleogeography of the Stone Age. Correlation of Natural Events and Archaeological Paleolithic Cultures of Northern Asia and Surrounding Territories], Krasnoyarsk

Ovodov, N.D. 1980. Peshchernye mestonakhozhdeniya ostatkov mlekopitayushchikh Sibiri i Dal'nego Vostoka [Cave Sites of Fossil Mammals in Siberia and the Far East]. In *Karst Dal'nego Vostoka i Sibiri* [Karst of the Far East and Siberia], Vladivostok: Academy of Sciences of the USSR, Far East Scientific Center

Further Reading

Bersenev, Y.I. 1989. Karst Dal'nego Vostoka [Karst of the Far East], Moscow: Nauka

Filippov, A.G. 1993. Peshcheri Irkutskoi oblasti [Caves of the Irkutsk Region]. In *Peshchery. Itogi issledovaniy* [Caves. Results of Investigations], Perm: Perm University Publishing House

Filippov, A.G. 1993. Peshery Buryatii [Caves of Buryatia]. In *Peshchery. Itogi issledovaniy* [Caves. Results of Investigations], Perm: Perm University Publishing House

Filippov, A.G. 1997. Gravity caves of the Siberian Platform. In *Proceedings of the 12th Interational Congress of Speleology,* 1, Switzerland, La Chaux-de-Fonds

Filippov, A.G. 2000. Speleogenesis of the Botovskaya Cave, Eastern Siberia. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer and W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Molodin, V.I., Bobrov, V.V. & Ravnoushkin, V.N. 1980. *Aydashinskaya peshchera* [Aydashinskaya Cave], Novosibirsk: Nauka

Tsykin, R.A. 1990. *Karst Sibiri* [Karst of Siberia], Krasnoyarsk: Krasnoyarsk University Publishing House

http://www.cavingclub.fegi.ru/ has a list of the Far East and Sakhalin Island caves

SIEBENHENGSTE, SWITZERLAND

The cave region of Siebenhengste is one of the world's major speleological sites. It includes more than 280 km of passages over a vertical range of 1500 m. The multiphase cave system is one of the best examples of the relationship between surface morphology and cave genesis, and may help to elucidate the morphological evolution of the northern rim of the Alps from the Mio-Pliocene to the Pleistocene.

The Siebenhengste is situated in the northwestern part of the Alps, adjacent to the Molasse basin. From Lake Thun at 558 m altitude, the system extends up to the Schrattenfluh, a massif that lies beyond the deeply incised valley of the Emme. The entire chain forms a southeast-dipping slope, cut to the northwest by steep cliffs. The upper parts, between 1700 m and 2000 m altitude, are either largely denuded and composed of limestone pavement, or still covered with sandstone and grassy soil. At lower altitudes, sandstone is predominant, and firs grow on the swampy ground. The annual precipitation is between 1500 and 2000 mm.

The cave system known as Réseau Siebenhengste-Hohgant (149 km long and 1340 m deep) is composed of the labyrinth of Siebenhengste, the F1 at Hohgant, and the Faustloch (see Figure). Other well-known caves are St Beatus Cave (12 km long), a tourist cave, and the scientifically interesting Bärenschacht (60 km long), which represents the downstream part of the Siebenhengste (Funcken *et al.*, 2001). The other most important caves are A2 (14 km) and K2 (16 km). Since the cave genesis is multiphase, it is impossible to indicate a general cave morphology. The Siebenhengste and A2 labyrinth consists of phreatic looping galleries draining to the northeast, which are interlaced with younger shafts and meandering canyons crossing them and continuing towards the Zone profonde. There, the main phreatic tube coming from F1 continues to Faustloch and to the almost fully phreatic Bärenschacht. F1, K2, and St Beatus Cave show huge meanders in their upper parts.

On top of a siliceous Lower Cretaceous limestone the 40- to 50-m thick Drusberg marls normally form the impermeable base of the karstic system. Above this lies the 150–200-m thick Schrattenkalk, the main karstic aquifer, where most of the caves are found. The Kieselkalk to Schrattenkalk sequence is lower Cretaceous in age. The Upper Cretaceous, consisting of about 20 m of Gault sandstone and Seewen limestone, is only found in thin layers in the extreme southeast. The overlying Hohgant series of sandstones is of Eocene age, up to 200 m thick. Karstification may occur in its calcareous layers, creating several cave conduits superimposed on the Schrattenkalk system, but largely unconnected with it.

The general geological structure is a monoclinal slope, dipping to the southeast at about 15–30°, which is interrupted by a large normal fault, extending from Lake Thun up to the Schrattenfluh (Hohgant-Sundlauenen fault). The throw of the fault is around 150 m in the Hohgant region and increases to more than 1000 m in Sundlauenen, thus interrupting the continuous dip of the Cretaceous and Eocene sediments. Observations mainly in Bärenschacht indicate that the main fault was active during sediment deposition in the Lower Cretaceous and continued its activity into the Eocene. Related to this, a karst void was filled with Upper Cretaceous sandstone (Hauselmann *et al.*, 1999).

Another karstification took place during the Upper Cretaceous to the Eocene transgression, but only traces survive.

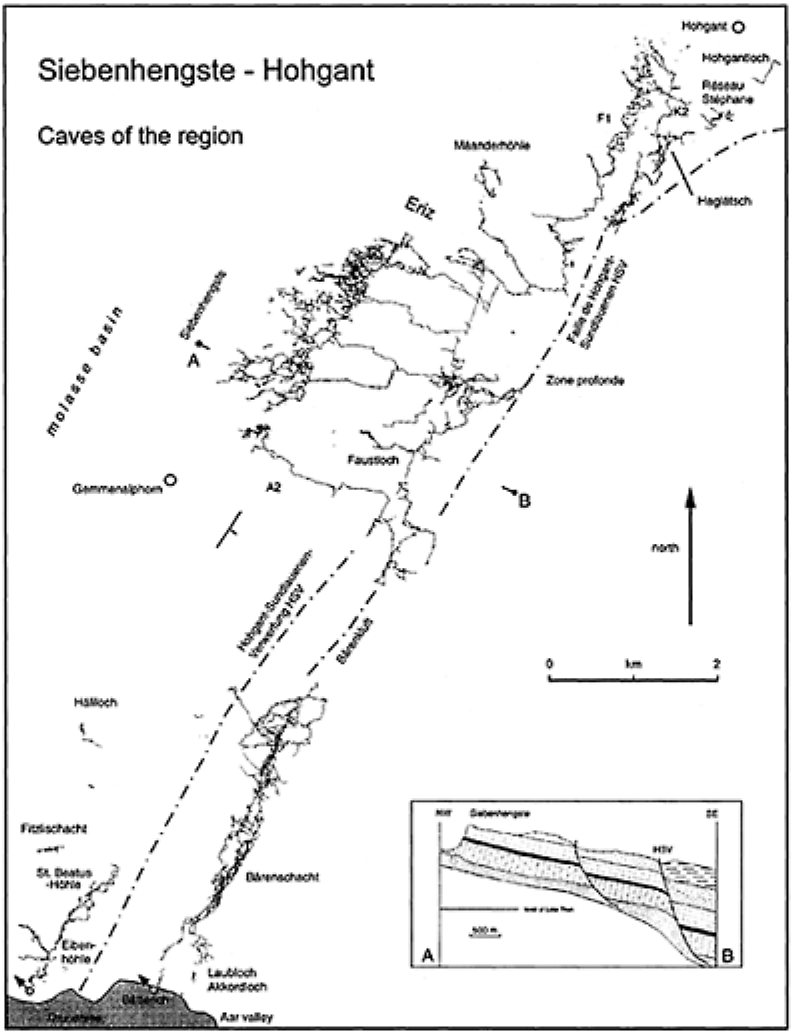
The cave region is divided into two catchment areas, the smaller one being the St Beatus cave system, west of the main fault (see map). The other one extends from the springs of Bätterich and Gelberbrunnen beside Lake Thun through Bärenschacht, Faustloch, Siebenhengste, and Hohgant, up to the Schrattenfluh, thereby draining three massifs.

Soon after cave exploration allowed the connection of several caves, the first observations suggested a genesis in distinct phases. Today, we can recognize 13 distinct phases (Jeannin *et al.,* 2000), the 13th one being connected with the present-day water table. The genesis of these phases may be linked to the height of the respective springs by following the phreatic tubes and observing vadose-phreatic transitions. Since there are no indications that the springs were dammed by surface processes, we can conclude that they were located on the valley floors. Therefore, the succession of the phases. indicates a series of valley deepenings.

The uppermost phases of cave genesis have been found mainly in Siebenhengste, and to a lesser extent also in the Hohgant area. The altitudes of the springs were 1900, 1800, 1720, 1585, and 1505 m successively. The overall morphology indicates that the springs were located in the Eriz Valley. We postulate that at this time the Aare Valley (Lake Thun) did not yet exist and that the Eriz may be the river-bed of the paleo-Aare. The next series of phases had their springs in the Aare Valley.

Therefore, an important geomorphic event has to be placed between the phases of the 1505 m and 1440 m springs, turning the flow direction 180° and drying up most of the Eriz springs.

The springs of the lower phases are located at 1440, 1145, 890, 805, 760, 700, 660, and 558 m. It appears that the phases reflect floodwater conditions, with inclinations of around 2°. Observations of gallery morphology indicate a time of long stability for each phase, followed by a rapid base-level lowering and readjustment of the flow-paths to the new conditions. The hydrological connection to the neighbouring Schrattenfluh Massif is thought to have occurred when the spring was at the 660 m level.



Siebenhengste, Switzerland: Outline map of the known cave passages in the region of Siebenhengste, Switzerland.

Since the Aar Valley was subject to Quaternary glaciations, the base-level lowering of the last eight phases is thought to been caused by the glaciers. A relative chronology of erosional and depositional events has been established, and some cave deposits have been dated, indicating both a base-level deepening by glaciers, as well as ages of more than 350 000 years ago for the phase with the 760-m spring. So we have to assume that the oldest galleries, in upper Siebenhengste, are at least early Pleistocene in age, but a

Pliocene or even Miocene genesis is also possible, since there is morphological and sedimentological evidence that the first galleries were formed before glaciation began.

Both the speleological exploration and the scientific investigation are still continuing, although technical difficulties in the shafts, the danger of floods, and narrow passages all hinder rapid progress.

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Works Cited

Funcken, L., Moens, M. & Gillet, R. 2001. Bärenschacht—l'interminable exploration. *Stalactite,* 52(1):9–22

Häuselmann, Ph., Jeannin, P.-Y. & Bitterli, T. 1999. Relations between karst and tectonics: the case-study of the cave system north of Lake Thun (Bern, Switzerland). *Geodinamica Acta,* 12: 377–88

Jeannin, P.-Y., Bitterli, T. & Häuselmann, Ph. 2000. Genesis of a large cave system: the case study of the North of Lake Thun system (Canton Bern, Switzerland). In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N. Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Further Reading

Bitterli, T. 1988. Das Karstsystem Sieben Hengste-Hohgant-Schrattenfluh, Versuch einer Synthese. *Stalactite,* 38(1–2):10–22

Bitterli, T. 1990. Das Réseau des Lausannois. *Höhlenforschung im Gebiet Sieben Hengste—Hohgant,* 2

Bitterli, T., Funcken, L. & Jeannin, P.-Y. 1991. Der Bärenschacht—der alte Traum von -950 m Tiefe. *Stalactite,* 41(2):71–92

Funcken, L. 1994. Bärenschacht—plus de 36 kilometres postsiphon. Une exploration hors du commun. *Stalactite,* 44(2):55–81

Funcken, L. 1997. Explorations récentes au Faustloch, réseau des Sieben Hengste, Suisse. *Proceedings of the 12th International Congress of Speleology,* vol. 4, La Chaux-de-Fonds: International Union of Speleology

Gerber, M., Bitterli, T., Jeannin, P.-Y. & Morel, Ch. 1994. A2 Loubenegg. *Höhlenforschung im Gebiet Sieben Hengste-Hohgant,* 3

Häuselmann, Ph. 1999. Le Bärenschacht (Berne, Suisse): Etude de l'aval du Réseau des Sieben Hengste. *Etudes de géographie physique, suppl*. XXVIII:113–16

Häuselmann, Ph., Schafheutle, M., Huber, L. & Brandt, C. 2000. Prospektion Laublochgegend-Waldegg. *Höhlenforschung im Gebiet Sieben Hengste—Hohgant,* 4

Hof, A. 1997. Labyrinthes et Sieben Hengste. *Proceedings of the 12th International Congress of Speleology,* vol. 1, La Chaux-de-Fonds: International Union of Speleology

Hof, A, Rovilles, Ph., & Jeannin, P.-Y. 1984. Le Réseau. Höhlenforschungim Gebiet Sieben Hengste-Hohgant, 0

Jeannin, P.-Y. 1991. Mise en evidence d'importantes glaciations anciennes par l'étude des remplissages karstiques du Réseau des Siebenhengste (chaîne bordière helvetique). *Eclogae Geologicae Helveticae,* 84(1):207–21

Back issues 2–4 of *Höhlenforschung im Gebiet Siebenhengste-Hohgant* are best obtained from SpeleoProjects (http://www.speleoprojects.com/): 0–1 are out of print.

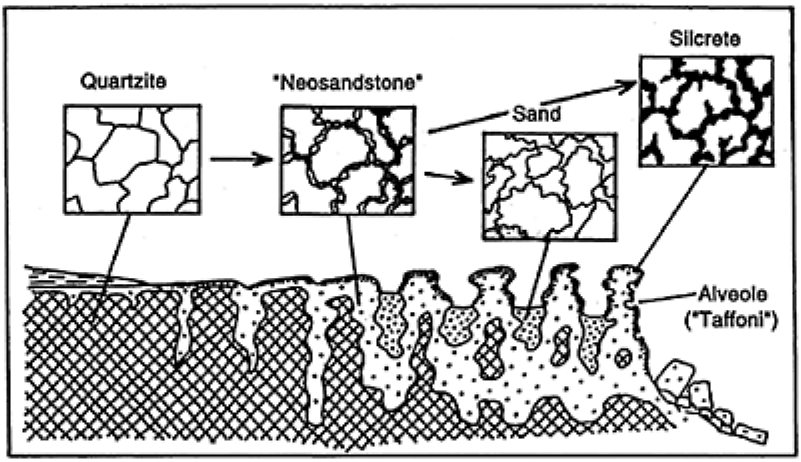
SILICATE KARST

This entry covers karst development in siliceous rocks, dominantly quartzites, but also lithologies such as granite and basic rocks. In the past, these rocks were regarded as unsuitable for karst development, although surface morphologies similar to those on carbonate rocks (e.g. karren, pavements of clints delineated by grikes and fields of pinnacles) were observed on quartzite, sandstone, and on nearly all other silica and silicate lithologies. In the 1970s, the exploration in Venezuela (especially the Roraima quartzite in southern Venezuela) of spectacular caves, potholes, swallow holes, resurgences, dolines, and poljes, showed scientists that important karstic features can develop in quartzite. The best silicate karst developments have been reported from Venezuela and Brazil (see Quartzite Karst of South America), and from South Africa and Australia. Sandstones with a carbonate matrix, which host important cave systems, are not treated here, since their formation is controlled by the same weathering process as carbonate rocks.

Exokarst

Weathering of exposed siliceous rocks commonly leads to the formation of a range of karren forms, particularly kamenitzas and rinnenkarren. Pavements showing grikes are less common, and these are usually less well developed than comparable features produced on carbonates. The most spectacular features are produced by weathering under soil cover—a process which is conducive to progressive formation of sand and clay in quartzite and felsic rocks along joints and bedding planes. By erosion of the soft, deeply altered material, unaltered or only moderately weathered rock is left standing as pinnacles and towers in the case of quartzite, and as tors, domes, and heaps of large rounded boulders in the case of granite. These features are ubiquitous worldwide.

In the figure, this process is illustrated for the case of quartzite, which is the most favourable lithology for siliceous karst development. In this case, the weathering involves the dissolution of quartz along crystal boundaries, a process leading to progressive weakening of the rock into a “neosandstone”, and eventually into loose sand (see Dissolution: Silicate Rocks). Very often this weathered quartzite has been misinterpreted as a sandstone by field geologists. The grains constituting the neosandstone are generally very jagged and interlocked, a texture inherited from the parent quartzite. In some cases, slabs of this weathered rock may display an odd flexibility, due to articulation of the grains, a quartzite variety that has been called “itacolumite”. Especially for climates comprising dry seasons, the pinnacles are often indurated at the surface by an opal matrix deposited by evaporation (see Figure).



Silicate Karst: Cartoon illustrating the weathering and development of pinnacle fields in quartzite, showing the progressive disintegration of the rock into sand, which is then removed by erosion, thus exhuming the pinnacles of moderately weathered or unweathered quartzite. In humid climates with dry seasons, during periodic evapotranspiration, amorphous hydrated silica (opal) precipitates and forms a hard surficial crust (silcrete) by cementing the interstices in the weathered quartzite. Alveoles (or tafoni) form by disintegration of the softer weathered quartzite underneath, in places where the silcrete did not develop well, which is mainly in the hollows. The term “neosandstone” is suggested as the moderately weathered quartzite has been misinterpreted as sandstone in many instances by field geologists.

The time necessary to produce quartzite pinnacle fields, including the endokarsts that may be associated with them, has been estimated from calculations in some instances where the parameters are known: volume of rock removed, surface drained, rainfall, recharge, and silica in groundwater. In the case of the Berlin system, developed in a relatively thin quartzite bed (see the section below on the silicate karst of southern Africa), it appears that it took no more than two million years to form, perhaps less. This order of magnitude also seems to be applicable to other systems in southern Africa, which show a shallow development. Longer periods were required to develop larger systems, comprising spectacular tall tower fields and massive caves, as for example in Venezuela and north Australia, where the weathering was much deeper. In these cases, the weathering period may have been over 10 million years. Such long periods of weathering can develop preferentially if the topography is smooth and more or less peneplaned, since in rugged terrains mechanical erosion can supersede the chemical process. Therefore it is likely that such tower fields are exhumed after periods of continental uplift and subsequent renewal of erosion.

Endokarst

Although the surface morphology outlined above is suggestive of karst scenery, the fluvial drainage remains surficial in most cases—large exokarst landforms (dolines and poljes) and features diagnostic of endokarst (potholes, swallow holes, caves, and resurgences) are rare. For instance, in South Africa the latter features are developed on less than 1% of the quartzite outcrops and are generally grouped in very localized systems. The cave networks are often located close to escarpments, particularly where the former open at the base of cliffs on the down-dip side of inclined plateaux. Usually these systems do not extend more than a few hundred metres from the resurgences, but exceptionally are more than one kilometre long. They do not develop into the central parts of large plateaux, in contrast with the classic carbonate karst where entire massifs are affected by endokarstic dissolution where the climate is sufficiently humid. Typically, the quartzite caves occur in mountains with high rainfall regimes.

The caves are often developed at the contact with impervious rocks such as shale, siltstone, and schist. The base level can also be controlled by the depth to which weathering can occur, as is the case where the quartzite formation is very thick. Typical keyhole passages and canyons have been observed, although they are not very common. The passages generally display square cross sections or show ceilings arched over a flat floor of impervious rock that forms the riverbed, sometimes making up the bulk of the cavity volume. The fissure-like passages that developed along vertical joints are often observed where the base level is not lithologically controlled. A characteristic feature of some caves is the extreme variation in the size of a single passage, which in a downstream direction can narrow from a 10 m diameter tunnel into a narrow tube impenetrable to a caver. This irregularity is controlled by variations in the degree of quartzite weathering. The majority of the quartzite caves are vadose and still active, although relict levels have been observed in some complex systems, generally only slightly above the active sections.

One unusual type of quartzite cave has developed along linear rifts recently formed by gravity tectonics. These caves run parallel to the edges of plateaux and include some of the deepest potholetype caves in quartzite. They have similarities to crevice caves (see separate entry) but are considered here because they capture small surface streams that contribute to speleogenesis. Such caves have been reported in Zimbabwe, South Africa, Brazil, and Venezuela.

In silicate rocks other than quartzite, the karst phenomena are less typical. Caves in granite are relatively frequent and have been reported, for example in Australia, California, Zimbabwe, and Swaziland. They often consist of shallow active caves developed along relatively important streams, disappearing into valley-floor accumulations of rounded granite boulders, up to several metres across. Generally, these boulders are nuclei of unweathered rock freed from their saprolitic matrix by surface erosion. The distance between the swallow hole and the resurgence may be over one kilometre in some cases, as in California and in Swaziland. Due to the chaotic nature of the boulder accumulation and the volume of the flow, in many cases the underground streams cannot be explored. Rare cases of short passages entirely developed in granite have been reported (see section below, Silicate karst of Australia).

A special mention must be made here of quartzite—dolerite caves, which are developed in the upper parts of deeply weathered dolerite sills intruded into quartzite. They are well developed in South Africa. The ceilings of the caves are flat and consist of hard quartzite, but the passages themselves are entirely developed in the red clay derived from the dolerite.

Subsequent to their formation, caves of volcanic origin sometimes capture surface streams, which contribute somewhat to their enlargement (e.g. Mouret, 1993). As the caves proper are not of karst origin, they are not considered here (see Volcanic Caves entry).

Silicate Karst of Southern Africa

Three main quartzite cave areas have been identified in this subcontinent and are described here as examples of silicate karst (see map in Africa, Subsaharan entry). The characteristics differ considerably from one place to another.

Cape Peninsula

This small district is situated immediately south of Cape Town, where about 100 caves are known in a fairly pure, tabular quartzite of Ordovician age, which is several hundred metres thick. They occur mainly in the rounded summit areas of mountains, but only extend to relatively shallow depths. Most of them are active, vadose, and controlled by a network of vertical joints, along which the quartzite had initially been weathered into a very friable material which disintegrates easily into white sand, as observed in the caves. Sometimes this joint network gives the cave systems a “pseudo-phreatic” pattern. The base levels seem to be controlled by harder, less-weathered quartzite at depth. The longest cave is Ronan’s Well (800 m long). In the same area a few caves are developed along linear rifts parallel to the edge of tabular plateaux. One of them, the Bat-Giant System, reaches a total length of 1650 m.

Mpumalanga Escarpment

In the northeast corner of South Africa, this escarpment marks the geographical transition from the High-Feld to the Low-Feld region and geologically coincides with the eastern termination of the Transvaal Basin, which is filled with Late Archean to Early Proterozoic sediments. About 60 caves have been reported in the fairly pure quartzite of the Wolkberg Group and of the Black Reef Formation (both uppermost Archean), and of the Pretoria Group (Lower Proterozoic). The strata are affected by static regional-contact metamorphism, but are undeformed and monoclinal, dipping westwards.

The Berlin karst systems, near Nelspruit, are the most spectacular both in their surface expression (pinnacles and dolines) and in their caves. They developed within an inclined plateau of Black Reef quartzite, 25 m thick, with a 30 cm thick layer of shale-like tuff interstratified close to its base. The caves are grouped into two systems totalling about 2.5 km of vadose passages. Surface water is collected by large dolines, and flows through the caves towards resurgences located down dip. The great majority of the passages are developed on the thin tuff layer, which everywhere constitutes the impervious base level. The cross sections are flat to equidimensional and show extreme variations in size along the same passage: large chambers, which formed in zones of deeply weathered, friable, quartzite can narrow down to impenetrable channels where the alteration of the rock has been relatively mild.

Another important system is developed in the Daspoort Formation of the Pretoria Group. About 50 small dolines, and swallow holes occur on a 25 m thick quartzite forming a plateau inclined to the north at 5 to 10°. A few of them give access to caves developed at shallow depths below the surface. The water captured by dolines flows through the caves and reappears at resurgences on the down-dip edge of the plateau. The most Important system is Magnet Cave, developed at depths of 5 m or less under the plateau, but in which 2.4 km of passages have been mapped. Access to the cave is through a large number of dolines generated by roof collapse. The shallow depth of the system is demarcated by a 10–40 cm thick shaly tuff forming an impervious barrier, which is visible on the floor of all the passages. Most of the passages are flat. In this cave, an unusual phenomenon is the frequent diffluences of active streams into side passages, some of which remain active even during periods of low flow. This is facilitated by the very flat shaly floor, which widely spreads the flow. The phenomenon produced a complex passage pattern reminiscent of a phreatic cave.

Quartzite—dolerite caves have been reported in the same area. They are developed in the Wolkberg Group, the Black Reef Formation, and the Pretoria Group, and are almost entirely vadose. The most important of them is Mogoto Cave (1.6 km), which is developed in a 3 m thick dolerite sill that intrudes the Black Reef quartzite, forming a plateau inclined at 25° to the west.

Chimanimani Mountains

This area is located on the border between Zimbabwe and Mozambique. The karst phenomena are restricted to a small (<1 km^2) plateau perched at an altitude of 2200 m, receiving a high rainfall and underlain by several hundred metres of quartzite belonging to the Umkondo Group (Early Proterozoic). The plateau is criss-crossed by a network of rift-type potholes collecting small surface streams, the deepest of them reaching 305 m below the surface. No horizontal collector passages were reached at the bottoms, but a resurgence was located at about 500 m below the plateau, giving access to a small cave, which is also rift related. In the caves the quartzite is variably friable, indicating weathering.

Silicate Karst of Australia

Remarkable exokarst scenery has been observed in Upper Proterozoic siliceous cemented sandstone forming tabular plateaux in Arnhem Land, Northern Territory (Jennings, 1983; Wray, 1997). The best portion is the Ruined City, characterized by a “two stories” morphology. The lower storey is developed in a massive sandstone dissected into large rectangular blocks by a network of narrow linear gorges, up to 30 m deep, controlled by a joint system. On the flat top of the blocks, the upper storey is developed in a thinly bedded sandstone. It forms a field of towers reminiscent of the limestone karst of southern China, but smaller in size, as the pinnacles reach only a maximum height of about 20 m. The sandstone has been surficially hardened by a cement, probably composed of opal and iron oxides, under which the rock is soft and friable.

Caves appear to be rare, consisting of arches and short tunnels with several entrances. As the area is part of an Aboriginal tribal land, speleological investigations have been limited. The climate is relatively dry, with seasonal rainfall. Caves have been reported several kilometres to the northwest, in the East Kimberley, and also in Proterozoic quartzite. The most important is Whalemouth Cave, close to Turkey Creek. It formed by the disappearance of a stream flowing in a shallow valley on a quartzite plateau. It consists of a 220 m long tunnel with a large diameter, up to 60 m high and 45 m wide at the exit in the cliff face bordering the plateau.

In the Girraween National Park, southeast Queensland, caves have been reported in Triassic granite (Finlayson, 1982). All are active, generated by the disappearance of streams. They dominantly consist of narrow gorges developed along vertical joints by stream erosion from the surface, and subsequently more or less covered by large granite boulders, which form the ceiling of the caves. Nevertheless, in three places the passages formed entirely in granite from initial horizontal joints, but over short distances, for instance 25 m in Goebel’s Cave. In River Cave—the 50 m long active passage developed by a surface stream entrenching itself obliquely along a joint inclined at 20°—the floor and the ceiling are therefore in solid granite, but the upper side-wall is a boulder choke. In all the caves the rock is unweathered, and any saprolite, if present, has been washed away by stream erosion.

Speleogenesis

Particularly in Venezuela and South Africa, cave formation was by piping through zones of deeply weathered quartzite initially transformed into very friable neosandstone, by the dissolution process outlined above (see also Dissolution: Silicate Rocks). This dual speleogenetic model: weathering first, followed by mechanical removal of sand, has been more or less accepted since the 1960s. The piping process starts from a spring, where the local water table intersects the surface when the quartzite has lost enough cohesion. The first channels formed in this way are small-diameter pipes branching upstream. Where this regressive process reaches the surface, it may trap storm water or capture a stream, which results in enhanced erosion and enlargement of the pipes into accessible passages. At a more advanced stage the caves are segmented into several tunnels and bridge, by ceiling collapse and complete removal of the deeply weathered quartzite, and eventually are entirely transformed into subaerial canyons.

There is no accurate estimate of the time necessary for a quartzite cave to develop, except that the process must be geologically very fast, as observations of the rapid formation of cavities by suffosion in more or less sandy material have shown. It may be that a large majority of the quartzite cave systems are not older than a few thousands or tens of thousands of years, which contrasts with the much longer time required to weather the rock. Therefore, it appears that quartzite caves must be geologically ephemeral, with possible exceptions such as the Cueva del Cerro Autana in Venezuela. The fact that the majority of the caves are still active supports the theory that the caves are ephemeral in contrast to carbonate rocks, which may host very ancient relict caves.

In the case of gravity-tectonic rifts at the edges of plateaux, the formation of cavities is due to a variable extent to a process not controlled by water. However, water may play a role in secondary enlargement. Moreover, at the inception stage, rifting may allow deep penetration of water thereby promoting the weathering of quartzite at depths greater than usual. Like the other quartzite caves, the accessible voids are relatively young.

An important condition for the formation of quartzite caves is a flow fast enough to transport sand grains. This means that high gradients are essential and explains their preferential location in rugged terrains, their very dominant vadose nature, and their restricted location, i.e. caves cannot form everywhere in quartzite. This is perhaps the most important difference to the carbonate karsts, where solute concentrations are usually inversely related to flow rate and caves can be formed by water moving very slowly.

The preferential location of quartzite caves in humid areas is due to greatly increased infiltration into the ground, and to a thicker vegetation cover which slows surficial erosion and protects the deeply weathered rock. The disappearance of the cave systems may be more rapidly completed after a climatic change from humid to arid or semi-arid, due to sparser vegetation. This might be the case for the karst areas of northern Australia, where the climate is drier than in the other type area treated above, and where caves seem to exist only as relicts.

Speleogenesis in other silicate rocks may follow a similar two-stage process to that in quartzites. However, caves are less well developed, probably due to the incongruent dissolution of most silicates, like feldspar, a process that leaves impervious clayey residues, which are less amenable to piping (see entry, Dissolution: Silicate Rocks). According to Finlayson (1982), the Australian granite caves were initiated by tensional opening of horizontal joints following pressure release when the rock was exhumed as a result of erosion. An opening 1 or 2 cm wide might be sufficent to allow a flow fast enough to move sediment capable of mechanically eroding a cave passage. However, this process is only possible over short distances due to loss of head. Alternatively, the joint may have been enlarged by an initial solution process but this hypothesis seems less likely as no significant pervasive weathering has been observed along the joints, and because the clay minerals have a clogging effect which impedes piping. Quartzite—dolerite caves are an exception, and in this case the quartzite is practically unweathered, but the dolerite is altered to red clay. Due to the irregular compaction of the weathered dolerite, thin planar voids developed between the sill and the quartzite and were subsequently considerably enlarged by surface water. The caves formed exclusively by erosion of the clay, whereas the quartzite acted only as a rigid roof protecting the passages from collapse.

There are exceptions to the two-phase speleogenetic model, as, in some rare cases, cavities are formed in quartzite directly by dissolution along joints, as in carbonates. They have been observed in mines, however, and formed under unusual conditions at several 100°C, in a hydrothermal environment. Under these conditions the solubility and the dissolution rate of quartz are both much higher, thus explaining the formation process.

Pseudokarst Versus Karst

In this review the term "karst" has been applied to silicate. However, there is some controversy about this appellation, as some scientists are of the opinion that karst morphology must essentially be due to dissolution. For them, the term "pseudokarst" should be used in the cases where the morphology resembles a karst, but the genesis is not to be accounted for by dissolution (see Pseudokarst entry). As some of these authors think that dissolution does not play a significant role in silicate rocks, they use the term "pseudokarst" instead of karst. Other authors support the use of the term "karst" for silicate rocks, arguing that solution plays an important role, especially in the case of quartzite, where dissolution of quartz is congruent. Some of the "karst" proponents add that the difference between matter removed as ions and molecules, or as larger particles, is minimal, and does not justify two appellations for a very similar process and for a comparable morphological result. It was pointed out that in the case of limestone caves, speleogenesis implies not only transport of solutes, but also of detritus in variable proportions. This indicates that mechanical erosion can play an important role in impure limestone, and suggests a continuum between carbonate and silicate karst (see "karstic and pseudokarstic processes in quartzite caves" in the Pseudokarst entry). It was proposed that the definition of karst should be revised into: "a morphology due to ground water circulation and characterized by the more or less complete disappearance of the surficial drainage systems" (Martini, 1987). It is mainly on this basis that the Slovenian karst has been selected as the type area: the diagnostic features would then be dolines, poljes, swallow holes, resurgences, and caves, provided that their origin is bound to water circulation. If this definition were to be adopted then the pavements and pinnacle fields would not be considered to be typically part of a karst morphology. The term "pseudokarst" would then apply to a morphology where underground cave drainage is missing, as for instance in the cases of volcanic cavities, deflation pans, dune morphology, etc., which are not generated by underground drainage.

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Works Cited

Finlayson, B. 1982. Granite caves in Girraween National Park, Southeast Queensland. *Helictite,* 20:53–59

Jennings, J.N. 1983. Sandstone pseudokarst or karst? In *Aspects of Australian Sandstone Landscapes,* edited by R.W.Young & G.C. Nanson, Wollongong, New South Wales: University of Wollongong

Martini, J. 1987. Les phénomèmes karstiques des quartzites d'Afrique du Sud. *Karstologia,* 9:45–52

Mouret, C. 1993. Formation of underground streams in volcanic rocks: Tahiti, French Polynesia, and Bali, Indonesia. *Proceedings of the 11th International Congress of Speleology,* Supplement, edited by Zhang Shouyue, Beijing: Secretariat, XI International Congress of Speleology

Further Reading

Chabert, C. & Courbon, P. (editors) 1997. *Atlas des Cavités non Calcaires du Monde,* Paris:Union Internationale de Spéléologie

Marker, M. & Swart, P. 1995. Pseudokarst in the Western Cape, South Africa. *Cave and Karst Science,* 22(1):31–38

Martini, J.E.J. 2000. Quartzite caves in Southern Africa. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Wray, R. 1997. Quartzite dissolution: karst or pseudokarst. *Cave and Karst Science,* 24(2):81–86

Includes references to most of the significant earlier papers on sandstone karst/pseudokarst in Australia

Younger, P.L. & Stunnell, J.M. 1995. Karst and pseudokarst: an artificial distinction. In *Geomorphology and Groundwater,* edited by A.G.Brown, Chichester and New York: Wiley

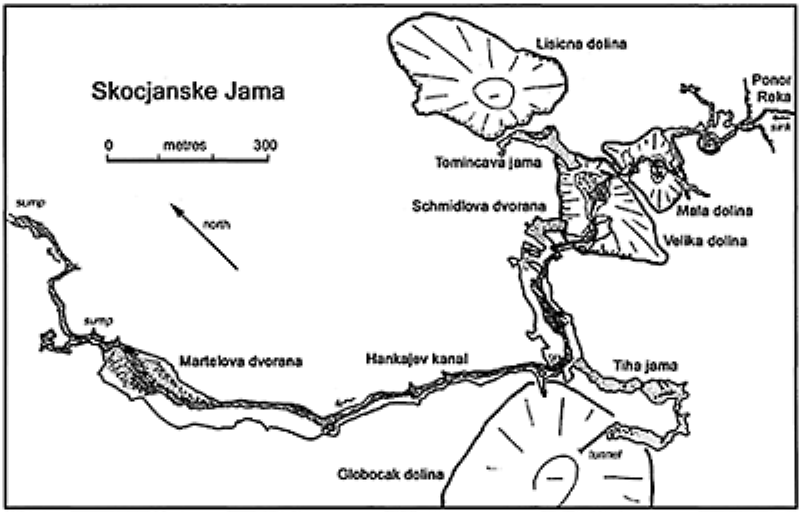
ŠKOCJANSKE JAMA, SLOVENIA

Škocjanske Jama is the second largest show cave in Slovenia, with 55 000 visitors in 2001. The influent cave is 5800 m long and 250 m deep, and is situated on the southeast side of the Kras plateau in western Slovenia (see entry, Kras, Slovenia). Because of its large chambers, the grand dimensions of the river gallery, the magnificent sink of the River Reka, the deep collapse dolines, and the heroic history of its exploration Škocjan is a World Heritage Site on the natural heritage list of UNESCO, while the caves and the karst above are protected as a regional park.

The Škocjanske caves are developed in thickly-bedded Cretaceous rudist limestone and thinly-bedded Paleocene dark limestone, dipping southwest (Habič *et al.,* 1993). In the Cretaceous limestone, where most of the cave is developed, 15–125 m thick beds of rock are characteristic between tectonized bedding planes, with most proto channels developed along these structures. Fractures and fracture zones (north-south and northwest-southeast) are the other significant morphological controls. The fracture zones can be up to a few dozen metres wide. Phreatic loops, large chambers, and some collapse dolines are developed along them.

The cave was formed by the sinking of the River Reka flowing from Eocene flysch rocks, which are mostly composed of sandstone. Large variations of the discharge (mean annual discharge is 8.18 $m^3 s^{-1}$, maximum discharge measured was 387 $m^3 s^{-1}$) cause floods within the cave. Heights of the usual annual floods are about 20 m, exceptional floods are about 100 m, and the highest recorded flood reached a height of 132 m in the cave.

The Reka River enters the cave 80 m below Škocjan village, at an altitude of 317 m (Figure 1). After 200 m of gallery, the river re-emerges and flows through two collapse dolines divided by a short gallery. The Velika doline is *c*. 160 m deep, with its floor at an altitude of 270 m (Figure 2). The Reka then flows into the main part of the cave. This is a massive canyon 20–30 m wide and about 30–110 m high, heading mainly northwest (Figure 3). This continues as Hanke's Passage, *c.* 1 km long, 10–15 m wide, and 95 m high. The underground river passage widens in places, forming large chambers. At 308 m long, 123 m wide, and 146 m high, Martel's Chamber, with a volume of 2 100 000 m^3, is the largest chamber in the cave, and in the Kras plateau. After Martel's Chamber, the dimensions of the gallery are smaller, and lead to a sump, 20 m deep and 60 m

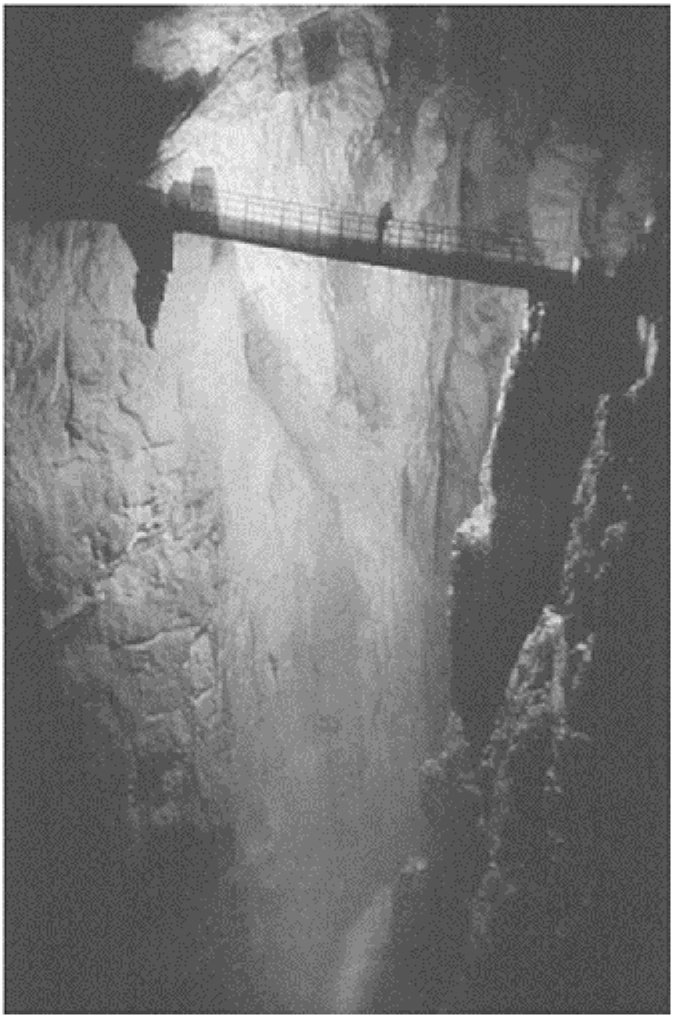


Škocjanske Jama: Figure 1. Plan survey of the Škocjanske Jama and its adjacent dolines, Slovenia.

long, that was dived in 1991. Beyond, there are some rapids with the terminal sump at an altitude of 190 m. Reka River then flows to Kačna Jama, about 900 m distant and 12 km long, after which its underground course splits into several separate flows that finally reappear at the coastal springs of the Timavo River, 40 km away.

High above the underground river there are some abandoned galleries. Most important is Tiha Jama (Silent Cave) discovered in 1904 and now connected by an artificial tunnel to the collapse doline of Globočak. The other gallery is Tominčeva Jama, with its entrance in the north wall of the Velika doline collapse; it is blocked by collapse material from one of the neighbouring dolines.

Škocjanske Jama: Figure 2. The entrance dolines of Škocjanske Jama, with the Reka River flowing through the deep shadows and into the main cave entrance almost directly beneath the camera. (Photo by Tony Waltham)



Škocjanske Jama: Figure 3. The massive vadose canyon of Hankajev kanal with the River Reka far below the bridge that carries the tourist trail out of the abandoned Tiha jama gallery on the left. (Photo by Tony Waltham)

There are several phases of evolution evident in the cave. Large galleries have paragenetic levelling of their roof at an altitude 320 m. A canyon, 90 m deep was later entrenched into them, after a regional decline of the water-table level in the plateau. However, the oldest part of the cave system can be seen on the surface as a section of a large unroofed cave, 1.8 km in length. Karst denudation exposed remains of the cave with fluvial sediments deposited in cave environment, flowstone, and stalagmites. These cave remains are probably of Pliocene age.

There are several collapse dolines near the cave. They are several hundred metres wide and up to 160 m deep. The largest is Sekelak, with a volume of 8.5 million m^3.

There are some archaeological remains in the entrance parts of the cave, the oldest dating to the Neolithic period. Above the entrance there was a Bronze Age settlement. The caves were mentioned in antiquity and the first attempt of water tracing was done by F.Imperato in 1599. The entrance part to the collapse dolines was explored when Egenhafner swam through in 1816. Exploration down the lakes and rapids of the Reka were performed by J.Svetina in 1839, and then by A.Schmidl in 1851, but his boats were destroyed by a high flood. In 1884, a caving branch of the alpinist club from Trieste, guided by A. Hanke, and later J.Marinitsch, continued with the exploration. In the first year they passed the sixth waterfall, the main obstacle to previous explorers, and reached the terminal sump in 1890. The high level part of the cave, Tiha Jama, was discovered in 1904, but only in 1991 was the terminal sump dived and 600 m of new passages explored.

Since 1823 the entrance parts of the caves have been used for tourism. Between 1884 and 1905 some bridges (Figure 3) and several kilometres of pathways were made, most of them cut by hand in vertical or overhanging walls high above the Reka. In 1933, the tunnel from the Globočak collapse doline was excavated into Tiha Jama, providing the loop for the tourist cave trail which ranks as one of the finest in the world. In 1959 the cave was electrified and in 1986 the elevator and tourist centre at the entrance to the cave was built.

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Works Cited

Habič, P. Knez, M., Kogovšek, J., Kranjc, A., Mihevc, A., Slabe, T., Šebela, S. & Zupan, N. 1989. Škocjanske Jame speleological revue, *International Journal of Speleoleology,* 18(1[-]2):1–42

Further Reading

Kranjc, M. 2001. Škocjanske jame, an addition to bibliography. *Acta Carsologica,* 30/1:213–28

Kranjc, M., Knez, M., Mihevc, A., Kogovšek, J., Slabe, T., Šebela, S. & Hajna, N.Z. 1998. Typical karst area: Škocjanske jame, Slovenia. In *Global Karst Correlation,* edited by Yuan Daoxian & Lui Zaihva, New York: Science Press

Mihevc, A. 2001. *Speleogeneza Divaškega krasa,* [Speleogenesis of the Divača karst] Ljubljana: Založba ZRC SAZU

http://www.wcmc.org.uk/protected_areas/data/wh/skocjan.html From the World Conservation Monitoring Centre, a useful compilation of geographic and conservation information

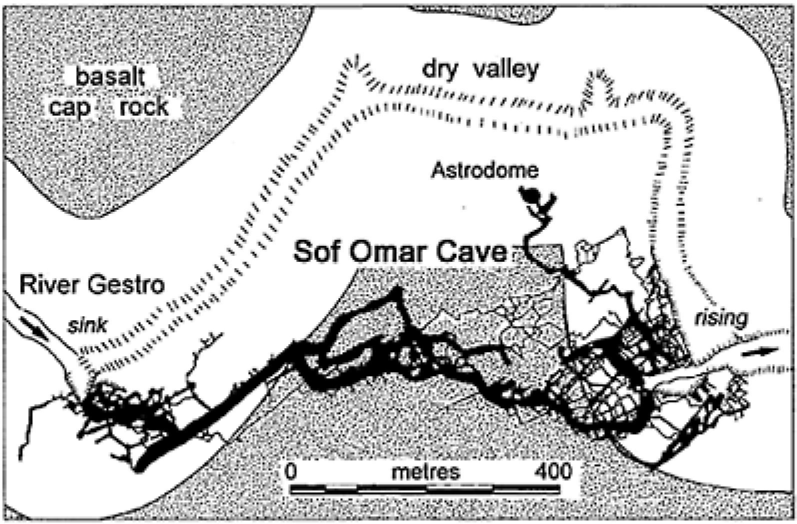
SOF OMAR CAVE, ETHIOPIA

Sof Omar Cave is one of the longest known caves in Africa (>15 km), and is an outstanding example of a cave formed by a large river, of a meander cutoff cave, and of a flood water maze cave. The cave is located at the village of Sof Omar in Bale Province, Ethiopia, some 300 km southeast of Addis Ababa, and is formed in the thick-bedded Jurassic Antalo Limestone. The limestone is overlain by Tertiary basalts which form a plateau in the area. The Webi Gestro river has incised a 150 m deep gorge in the plateau, cutting through the basalts to expose the underlying limestone. The source of the river is in the 4300 m high Bale Mountains 120 km upstream of the cave, and the catchment area for the river is 3800 km^2.

Sof Omar Cave has formed at a prominent meander in the river (Figure 1). The groundwater flow path across the neck of the meander offered a shorter flow path and a steeper hydraulic gradient than flow on the surface around the meander loop. The capture of surface water apparently occurred in two stages. In the first stage a cave passage was formed which bypassed the downstream 600 m of the dry valley. This now-dry passage has a substantial fill of sediments. In the cave it terminates upstream at a large circular breakdown chamber, the Astrodome. In the second stage the river was captured underground at its current sink point, which is 700 m further upstream from the original sink point. The current underground river passage is 2000 m long and averages 20 m in width and height (Figure 2). There are several sections of relict river passage of similar size, which were abandoned when the river migrated to its present course. One of these relict passages is blocked by limestone and basalt boulders where a roof collapse stopes up to the plateau above, where there is a large doline. The modern underground river passage is substantially larger than the relict route via the Astrodome, suggesting that the river has followed the modern route for a longer period than the Astrodome route.

In the dry season, between November and March, the river in the cave averages 1 m in depth and is confined to just one passage. However, in the wet season the river rises at least 7 m and floods several kilometres of smaller passages. Steep hydraulic gradients and chemically aggressive waters have combined to produce similar dissolution rates along many different pathways, resulting in a flood water maze. There are two major sets of joints in the cave, with strikes of 20° and 110°, and both sets have been used by flood waters to create a gridiron pattern of passages about 1 m in width. Passages have formed either along these joints or at the intersection between these joints and nearhorizontal bedding planes. At the downstream end of the cave there are two superimposed mazes, each having formed at the intersection of a prominent bedding plane with the major joints.

The cave is an Islamic Holy Place with a shrine in a dry passage close to the upstream entrance, and the areas close to the entrances have probably been visited for a considerable



Sof Omar, Ethiopia: Figure 1. Map of Sof Omar Cave. The unshaded areas along the valley are underlain by limestone.

Sof Omar, Ethiopia: Figure 2. The Great Dome and the end of Safari Straight, Sof Omar cave. (Photo by John Gunn) period. The main river passage and several side passages were mapped in 1966, and the cave was comprehensively explored and mapped in 1972, revealing a total length of 15 km of passage. The spectacular nature of a surface river going underground for a distance of 1 km and the easy nature of the cave have made it a tourist destination, though the cave is a long way from major population centres.

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Further Reading

Amatt, S.N., Catlin, D., Ramsden, P.R., Ramsden, R.W., Raynor, T. Renvoize, T. & Worthington, S.R.H. 1973. The caves of Ethiopia. *Transactions of the Cave Research Group of Great Britain,* 15:107–68

Brown, L., Gunn, J., Walker, C. & Williams, O. 1998. *Cave Ethiopia ’95 and ’96 Expedition Report*, Huddersfield: Limestone Research Group, University of Huddersfield

Palmer, A.N. 1975. The origin of maze caves. *NSS Bulletin,* 37:56–76

Robson, G.E. 1967. Caves of Sof Omar. *Geographical Journal,* 133: 344–48

SOILS ON CARBONATE KARST

Soils on carbonate karst may be autogenic (authigenic) or allogenic. Autogenic soils are formed in place from the insoluble impurities left over following dissolution and leaching of the bulk of the carbonate parent material. Allogenic soils are formed from superficial deposits transported and deposited over the carbonate rocks by gravity, water, glaciers, or wind.

Soils of allogenic origin are common on carbonate areas throughout the world. Materials derived from higher elevation, noncarbonate areas and deposited over lower elevation carbonate rocks may form colluvial or alluvial soils. Colluvial soils are frequent on the Central Appalachian carbonate region of the United States and one common example is the Clarksburg silt loam, a gray-brown podzolic soil of the order Alfisols (complete descriptions of the US soils mentioned in this report can be viewed at http://www.statlab.iastate.edu/soils/nssc/). This soil forms in colluvium accumulated by water action and soil creep. Alluvial soils form along stream terraces and stream channels incised into the carbonate bedrock. Alluvial soils also form in dolines where materials derived from carbonate bedrock are transported by water and deposited as alluvium in the doline bottom. The alluvium then weathers to form an alluvial soil like the Lindside silt loam (order Inceptisol) and the Huntington silt loam (order Mollisol), both common to the Central Appalachian carbonate region. Chavies fine sandy loam (order Alfisol) is an example of an alluvial soil along stream terraces and channels. It is formed in alluvium washed chiefly from upland areas under-lain by acid sandstone and shale. Other allogenic sources of soilforming materials are glacial till and morainic deposits, aeolian deposits (loess), and volcanic ash. These drift materials can result in thick soil covers over karst bedrock. Loess soil depths exceeding 10 m occur over carbonate bedrock in the Midwestern United States.

Soils formed in Quaternary loessic parent material over limestone are found in the Peak District (England) and glacial drift material deposited over carbonate bedrock is common in Britain and Ireland as well as in the United States. The Central Plain of Ireland is a large, low-lying region dominated by limestone rocks and covered in soils formed in glacial drift up to 60 m thick. Thick drift deposits obscure karst expressions in the underlying carbonate bedrock. Diffuse infiltration and greater water storativity is characteristic of soils formed on thick drift deposits thus limiting karst development in the bedrock. Soils developed in tephra (volcanic ash) deposited over limestone are common in Japan and in the King Country New Zealand (see New Zealand), where the Pleistocene tephra is up to 10m thick and forms a yellow-brown loam. Development of an ironpan in the B horizon concentrates subsurface drainage and encourages dissolution of the underlying limestone.

Soils of authigenic origin exhibit many common characteristics around the world, but differences do occur due to characteristics of the carbonate bedrock from which they are derived, climate, leaching, topography, and history of land use. The primary source of authigenic soil-forming materials over carbonate bedrock is the insoluble residual material resulting from weathering and dissolution of the carbonate bedrock. The world's most well-developed karst regions occur on nearly pure limestone with less than 10% insoluble material. In regions with a warm, moist, climate soil formation is rapid on most lithologies (e.g., less than 50 000 years to form one metre of soil), but in areas with carbonate bedrock the low volume of soil-forming insoluble residual material results in shallow soil depths. For example, Yuan *et al.* (1991) estimated that 250 000 to 850 000 years are required to form one metre of soil from limestone in the tropical Guangxi region of south China. The bedrock frequently crops out in karst landscapes, and soil depths can vary, in short distances, from zero to several metres where soil has accumulated in low points on the highly undulating bedrock surface.

The shallowness of most autogenic soils over carbonate bedrock, coupled with their well-drained and free drainage into the bedrock, make them highly susceptible to drought and this makes establishment and maintenance of continuous plant cover difficult, resulting in accelerating erosion and a lack of organic matter accumulation in the surface soil layer. Seasonally dry periods coupled with the droughty nature of karst soils in the Mediterranean region and in Australia severely dry plant canopies and fires are frequent. Fires leave the soil surface unprotected and severe erosion has led to complete denudation of the soil cover on some sloped areas in the Mediterranean region.

The chemical and physical characteristics of soil developed over carbonate rocks are primarily determined by amount of leaching and the local climate. White (1988: chapter 8) states that the primary modification of the insoluble soil-forming materials is the preferential leaching of silica. In the tropics, high leaching rates and warm temperatures cause the removal of virtually all of the silica leaving behind aluminium, which is immobile. High-aluminium tropical soils are known as bauxite and are mined for aluminium (see Bauxite Deposits in Karst). Cooler temperatures reduce the rate of removal of silica and clay and iron minerals hydrate. Where temperatures are warmer there is more leaching of silica and clays, which tend to accumulate in deeper soil layers, and dehydration of iron minerals. The clays in these soils are often red and are regionally referred to as "red clays" in the United States and "terra rossa" in Europe. Two US examples of these soils are the southern and central Appalachian Frederick and Frankstown silt loams (order Ultisol) and the Cumberland silt loam (order Alfisol) common to the Mammoth Cave, Kentucky area.

Thick karst soils such as those developed on allogenic drift materials deposited over limestone have an ability to store large volumes of water in contrast to the thin autogenic karst soils. Higher water storage capacity tends to even out flows and create a diffuse infiltration to the bedrock. Thin autogenic karst soils, in combination with high infiltration rates, create flashy flows and rapidly dry out between storms. The droughtiness associated with thin autogenic karst soils minimizes the opportunity to accumulate organic materials in the soil, which can substantially increase soil water-holding capacity and reduce soil erodability.

Soils are usually the first defence against movement of contaminants into groundwater. The ability of soils to act as buffers depends on their chemical nature, permeability, and thickness. Autogenic karst soils are generally thin and well drained, thus limiting their ability to physically filter and detain contaminants and pathogens long enough for natural purification and neutralization to take place. Droughty conditions found in thin, well-drained karst soils limit actual evapotranspiration, which can be an important mechanism for removal of some contaminants by vaporization. For further discussion of herbicide, pesticide, and fertilizer leaching through karst soils see Groundwater Pollution: Dispersed.

Soils are fundamental to successful agricultural pursuits. The thin and uneven nature of autogenic karst soils makes them difficult or impossible to till in many karst regions. Agricultural systems that do not depend on tillage for success are often the systems of choice on thin karst soils. Examples of those systems are forages in grazed pasture systems, viticulture, and trees as part of forestry or orchard operations. Grazed pasture systems on autogenic and allogenic karst soils are well known throughout the world with some of the most productive grassland systems in the world occurring in the United Kingdom and Europe, United States, New Zealand, and Australia. The Appalachian region of the United States has about 18% agricultural land (Boyer & Pasquarell, 1995), but more than one-third of the region's agricultural output occurs on karst land and is made up mostly of livestock systems on grazed grasslands and orchard production of apples, peaches, and nuts. Much of the rest of the region's karst land is forested and produces some of the world's finest quality hardwoods for furniture production. Successful viticulture depends on well-drained soils that experience a dry season toward the end of the growing season. Wines produced from grapes grown on karst soils of the Mediterranean region are famous and among the best quality wines worldwide. Other important regions for viticulture are New York State and southern Australia where limestone soils are common.

Soils over carbonate bedrock present technical and environmental challenges for construction projects. Thin soils, uneven bedrock surfaces, and removal of soil through subsurface drainage into the karst bedrock often cause failures in highways and building foundations (see Construction on Karst). Many of the clays found in karst subsoils are subject to extreme shrinking and swelling further complicating competent construction. Landfills and sewage lagoons depend on thick soil mantles in order to operate properly. The thin, well-drained soils common to karst land are not generally suitable for either construction. Even when synthetic liners are used the uneven nature of the carbonate bedrock and drainage from below can cause catastrophic failure. Thick soils over carbonate bedrock are also subject to failure because of the under-drained nature of karst. Several sewage lagoons holding domestic sewage and liquid swine manure have failed on the thick soils covering carbonate bedrock in southeastern Minnesota (United States). Although those structures were constructed with heavy synthetic liners, soil was removed from under the liners by subsurface drainage into the carbonate bedrock and catastrophic failures occurred introducing contaminants and pathogens into the local groundwater and springs.

Conservation and protection of fragile soil resources over karst carbonate bedrock is a daunting task, which is discussed in Soil Erosion and Sedimentation. Briefly, practices that encourage plant growth and discourage unnatural accumulation of running water are essential for the protection of karst soils.

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Works Cited

Boyer, D.G. & Pasquarell, G.C. 1995. Nitrate concentrations in karst springs in an extensively grazed area. *Water Resources Bulletin,* 31:729–36

White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

Yuan D. *et al.* 1991. *Karst of China*. Beijing: Geological Publishing House

Further Reading

Curtis, L.F., Courtney, F.M. & Trudgill, S.T. 1976. *Soils in the British Isles,* London and New York: Longman

Drew, D.P. 1983. Accelerated soil erosion in a karst area: The Burren, Western Ireland. *Journal of Hydrology,* 61:113–24

Trudgill, S.T. 1985. *Limestone Geomorphology,* London and New York: Longman (pp.66–70 and 116–22 discuss soil formation and erosion)

Useful Websites

UK Soil Survey and Land Research Centre, http://www.silsoe.cranfield.ac.uk/sslrc/

US National Soil Survey Center, http://www.stadab.iastate.edu/soils/nssc/

US Department of Agriculture, Natural Resources Conservation Service, http://www.nrcs.usda.gov/

SOIL EROSION AND SEDIMENTATION

Soil erosion is the detachment and transport of soil by water, wind, ice, or gravity. Soil erosion caused by natural and geological processes tends to be slow, but episodic, and in equilibrium with soil-forming processes. The influences of man's activities on soil erosion are evident all around us. Urbanization, agriculture, deforestation, construction, and recreation are among the most important activities of man that often accelerate rates of soil erosion.

In order for soil erosion to take place, soil particles must first be detached from the soil surface. The energy required to accomplish this is most commonly provided by raindrop splash or energy supplied by movement of accumulated water either as sheet flow across the soil surface or as concentrated flow in rills. Plant cover is the most effective natural means of controlling soil erosion. Plant canopies effectively reduce the kinetic energy of falling raindrops, thus reducing detachment of soil particles by raindrop splash. Plants also inhibit the accleration of flowing water and often improve the infiltration capacity of soil, effectively reducing the opportunity for surface water to accumulate in detention hollows. Plants also contribute the organic matter found in surface soil layers. Organic matter in surface soil is important from an erosion standpoint because it increases the water-holding capacity of the soil and improves infiltration capacity by maintaining soil aggregates. The shallow depth of many autogenic karst soils, coupled with their well-drained nature and free drainage into the bedrock, make these soils highly subject to drought. This in turn makes establishment and maintenance of continuous plant cover difficult resulting in accelerated erosion and a lack of organic matter accumulation in the surface soil layer. Seasonally dry periods coupled with the droughty nature of karst soils in the Mediterranean region (Gams *et al.*, 1993) and in Australia (Gillieson, 1993) severely impact plant canopies and fires are frequent. Fires leave the soil surface unprotected and severe erosion has led to complete denudation of the soil cover on some steep karst areas in the Mediterranean region (Gams *et al.*, 1993). Karst soils are further discussed in the entry Soils on Carbonate Karst.

There are many published examples of soil erosion occurring on karst lands as a result of deforestation and agricultural exploitation. Nearly every essay in the book entitled *Karst Terrains: Environmental Changes and Human Impact* (Williams, 1993) contains at least one example of severe soil erosion as a result of deforestation and agriculture. Highly variable soil depths and exposed bedrock make many karst soils difficult to cultivate so grazing of improved or natural pastures is often the landuse of choice. Poor management and overgrazing lead to reduced plant cover, exposed soil surfaces, and compacted soil—all factors that accelerate soil erosion.

Many studies have found that runoff increases following deforestation in proportion to the area of land cleared. Hence, soil erosion is the primary consequence of deforestation and is directly related to hillslope length and gradient and the amount of precipitation and runoff. Harding and Ford (1993) studied the effects of clearcutting on soil erosion and forest regeneration on limestone slopes in Vancouver Island, British Columbia. They found soil erosion was most severe on the slopes that were too steep to have developed a dense epikarst adequate for trapping eroding soil particles. Very little forest regeneration had taken place on bare limestone slopes with little trapped sediment. Indeed, on the best of sites, only 20% of the original volume of timber had grown 75 years after logging. The study led the authors to conclude that glaciated and karstified slopes in British Columbia are vulnerable to soil erosion and desertification that is permanent in terms of human history. Ford (1987) found that clearcutting on karstified limestone and dolomite plains in Ontario, Canada, also led to complete loss of soil and litter over broad areas. However, the epikarst was well developed, resulting in efficient trapping of eroding soil particles, nutrients, and water in the karren troughs and microcaves. Hence the forest was able to re-establish itself, but with a higher proportion of undesirable tree species growing to a much lower height than the original forest.

In the Burren plateau karst of Ireland (see separate entry) thin soils, large areas of bare rock, and sparse vegetation have been attributed to glacial erosion. However, accumulations of older brown-earth soils in grikes and layers of reddish-brown mineral soils under ancient walls (in contrast to modern walls resting directly on bare rock surfaces or thin layers of rendzina soil) led Drew (1983) to argue that the Burren was once covered by an extensive layer of soils formed in glacial drift. During the Bronze Age, deforestation resulted in soil erosion that removed most of the extensive mineral soil leaving the area bare and unproductive. Since the Bronze Age a sparse residual rendzina soil has been developing and exists in small patches of 1–5 cm thickness between vast areas of bare limestone pavement. Deforestation and early agriculture with resultant soil erosion have also been blamed for the bare appearance of karst in the Mediterranean, Yugoslavia, and the northern Pennines of England.

Stone forest aquifers in the south China karst belt (see Shilin Stone Forest) have suffered reduced recharge as a result of deforestation and soil erosion on upgradient karst slopes. The stone forest aquifer consists of a deep (up to 100 m), well-developed epikarst infilled with externally derived sediments, soils, karst breccias, and residual clays (Huntoon, 1992). Massive soil erosion from the low-lying karst plains left a virtual “forest” of rock spires and towers that at one time made up a highly developed epikarstic zone hidden by a continuous soil mantle. The remaining network of roofless dissolution-widened fissures, cavities, and tubes now create a shallow aquifer with low water storage capacity. A high degree of lateral permeability rapidly drains the epikarst aquifer. At one time the hills surrounding the karst plains were forested and supplied a steady recharge of water. Nearly complete deforestation since 1958 has created a loss of what the Chinese call their green reservoir and the amplitude of the flood/drought cycle has been intensified. Desertification has commenced on drier sites, and the hills are characterized by scanty vegetation, parched and highly eroded red soils, and bare limestone: the water-holding capacity of the limestone hills has been severely compromised. The lack of plentiful and good-quality water in the region has made this one of the poorest economic regions of China.

Many pollutants and human pathogens are known to attach themselves to sediments. Increases in sediment loads may lead to associated increases in contaminants. Phosphorus is one important example of a contaminant that binds tightly to soil particles. Increased soil erosion and rapid transport of sediment and phosphorus through karst systems can lead to eutrophication in downstream surface water bodies. Accelerated sediment loads also lead to higher costs of maintaining water treatment facilities and filling in of water-holding reservoirs. Increased sediment loads in karst systems may also lead to plugging of conduit systems thereby altering local hydrology, which then leads to urban flooding, surface collapses, and clogged water systems. Severe soil erosion from road-building sites in Papua New Guinea (James, 1993) covered karst surfaces creating an unstable surface. Infilling of caves with sediments caused subsurface drainage to become surface drainage with increased flooding and springs dried up. Effects of externally derived sediments on karst systems are discussed in the entry on Sediments: Allochthonous Clastic. Suitable soil conservation strategies need to be developed specifically for the special conditions that exist on karst.

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See also **Forests on Karst**

Works Cited

Drew, D.P. 1983. Accelerated soil erosion in a karst area: The Burren, Western Ireland. *Journal of Hydrology,* 61:113–24

Ford, D.C. 1987. Effects of glaciation and permafrost on the development of karst in Canada. *Earth Surface Processes and Landforms,* 12:507–21

Gams, I., Nicod, J., Sauro, M., Julian, E. & Anthony, U. 1993. Environmental change and human impact on the Mediterranean karsts of France, Italy and the Dinaric Region. In *Karst Terrains: Environmental Changes and Human Impact,* edited by P.W. Williams

Gillieson, D. 1993. Environmental change and human impact on karst in arid and semi-arid Australia. In *Karst Terrains: Environmental Changes and Human Impact,* edited by P.W. Williams

Harding, K.A. & Ford, D.C. 1993. Impacts of primary deforestation upon limestone slopes in Northern Vancouver Island, British Columbia. *Environmental Geology,* 21:137–43

Huntoon, P.W. 1992. Hydrogeologic characteristics and deforestation of the stone forest aquifers of south China. *Ground Water,* 30:167–76

James, J.M. 1993. Burial and infilling of a karst in Papua New Guinea by road erosion sediments. *Environmental Geology,* 21:144–51

Williams, P.W. (editor) 1993. *Karst Terrains: Environmental Changes and Human Impact,* Cremlingen-Destedt: Catena

Further Reading

Hardwick, P. & Gunn, J. 1990. Soil erosion in cavernous limestone catchments. In *Soil Erosion on Agricultural Land,* edited by J. Boardman, I.D.L.Foster & J.A.Dearing, New York: Wiley

Morgan, R.P.C. 1995. *Soil Erosion and Conservation,* 2nd edition, Harlow, Essex: Longman, and New York: Wiley

SOLUTION BRECCIAS

Solution breccias are common and widespread geographically and throughout the geological record. The brecciation may occur entirely within one soluble rock (usually limestone or dolostone) or where more soluble evaporite rocks are removed in mixed evaporite-carbonate or evaporite-clastic rock sequences. It may be extended upwards by mechanical failure (stoping) into overlying insoluble strata. For example, dissolution of *c.* 180 m of salt has propagated through 400 m of carbonates overlain by *c.* 650 m of clays, mudstones, and sandstones at a site in Saskatchewan, Canada.

Brecciation can occur during the earliest stages of diagenesis (eogenesis), when evaporites are dissolved in supratidal carbonate sequences, or where caves in case-hardened carbonate sand dunes collapse. It is common at interstratal sites during deep burial (mesogenesis), caused by the expulsion of trapped sea water and other basinal fluids or by invading hydrothermal waters, and it may extend to pressure solution (stylolite) depths of 4 km or more. It is also common in superficial karst terrains, where circulating meteoric waters are known to brecciate carbonate rocks at depths as great as 2 km.

Breccia fabrics and matrix

Stanton (1966) recognized three principal fabrics (Figure 1):

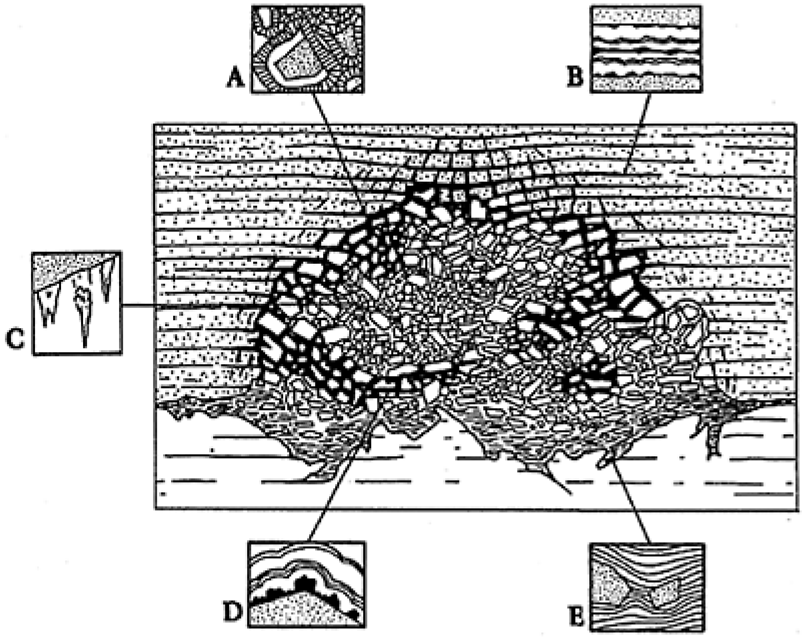
1. Crackle breccia, where beds sag apart and crack upon dissolutional removal of support, but there is little displacement;
2. Pack breccia, where large fragments (clasts) support each other in a pile. The clasts have usually dropped and vary from partly rotated to completely disorganized (chaotic brecciation) in orientation. Globally, sizes of such clasts in a pile range from small pebbles to “cyclopean breccias” of blocks of hundreds of cubic metres, but are normally more limited within any given breccia;
3. Float breccia, where the larger fragments are separated from each other and “float in” (are supported by) a matrix of fine material.

A genetic association of these fabrics is often found, consisting of crackle breccias at the top and around the perimeter of a body, pack breccia within it where beds are thicker, and float breccias at the base or where beds are thin. In some Mississippi Valley Type (MVT) lead-zinc deposits, these may be underlain by a basal “trash” zone of insoluble residua (see Figure 1; Sangster, 1988; Dźulyński & Sass-Gutkiewicz, 1989).

Clast-supported breccias may consist simply of clasts and voids, with little or no matrix or cement. This is most common in breccias in dolines and caves that are actively developing today. Matrix is usually present in eogenetic and mesogenetic breccias, consisting of carbonate fines and insoluble residua that have filtered down or (more rarely) washed-in sands and clays. Older breccias of all types will normally display partial or complete cementation. Calcite is the principal cement, but aragonite, dolomite, and gypsum are also common. In MVT the chief cements are dolomite, pyrite, galena, and sphalerite.

Form and location of the principal types of breccia bodies

Solution breccias are common on the surface and underground in modern karst terrains, chiefly where dolines, river cliffs, or shafts and chambers in caves have collapsed. Individual collapses may be millions of cubic metres in volume. Where surficial



Solution Breccias: Figure 1. Model for a breccia-hosted lead-zinc deposit in limestone or dolostone, illustrating "crackle brecciation" around the perimeter; "chaotic pack breccia" with void-filling cements (black) in the centre and "float breccia" in a matrix of "trash" (insoluble residua) at the base. Enlargements **A–D** show the typical microstratigraphy of calcite or dolomite cements at different places in the breccia; **E** details float stratigraphy in the trash. From Dźulyński & Sass-Gutkiewicz (1989).

Solution Breccias: Figure 2. A breccia pipe of solutionally undermined and collapsed limestone blocks with an open cavity at the top where void migration is still continuing: exposed in an island cliff in Ha Long Bay, Vietnam. (Photo by Tony Waltham)

collapses are preserved in buried paleokarsts, Choquette and James (1988) term them "mantle breccias".

Extensive brecciation is usually present where the proximal margins of buried salt bodies on the continents are subject to dissolution by groundwaters penetrating the cover rocks, creating a receding "salt slope" (Ford & Williams, 1989, p.460). In Manitoba and

Saskatchewan, the salt slope of a Devonian deposit is c.800 km in length and now at a mean depth of 200 m below the surface. It has receded (been "subroded") westwards for an average of 130 km since burial during the Devonian Period. Breccia pipes (Figure 2), also called "geological organs", "breakthroughs", or "prismatic bodies" by various authors, are the most widely reported breccia bodies, with thousands of examples being described in the world literature (Bosák *et al.,* 1989). Diameters range from <10 m to >10 km, with a majority being 20–250 m. Most are plumb-vertical, with reported heights ranging from 20 m to more than 1000 m. Higher examples have usually stoped upwards through one or more cover formations, which may include siliciclastics, coal measures, and extrusive volcanic rocks. The upward termination may be in undisturbed rock, in downfaulted but not brecciated strata, in a closed depression at the surface, or even upstanding as a firmly cemented and now-resistant "castille" above an erosional plain (as described by Hill, 1996, in New Mexico). Most breccia pipes originate in point dissolution of salt (occasionally of gypsum or anhydrite) above a fracture junction, anticlinal crest, or buried reef that channels groundwater. They may be targets for the later precipitation of economic ore, such as the well-known uranium pipes of the Grand Canyon, Arizona (Huntoon, 1996).

Other forms are described in most detail from MVT deposits (e.g. Sangster, 1988). Breccia domes typically 30–100 m in diameter are similar to breakdown rooms in modern caves or transitional to breccia pipes. Tabular or sinuous forms are wide but shallow breccias extending for 1 km or more, often along paleoreef margins. Straight linear features ("runs") and reticulate mazes include individual breccia-filled corridors up to 30 m high, 150 m or more wide, and one or more km in length. Most of these features occur at relatively shallow depths beneath longexposure paleokarst surfaces, and are believed to be genetically associated with them. Some are attributed to brecciation and subsequent sulfide ore (cement) deposition from invading hydrothermal solutions.

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See also **Bear Rock Karst; Sulfide Minerals in Karst**

Works Cited

Bosák, P., Ford, D.C., Glazek, J. & Horácek, I. (editors) 1989. *Paleokarst: A Systematic and Regional Review,* Amsterdam: Elsevier

Choquette, P.W. & James, N.P. 1988. Introduction. In *Paleokarst,* edited by N.P.James & P.W.Choquette, New York and London: Springer

Dźulyński, S. & Sass-Gutkiewicz, M. 1989. Pb-Zn ores. In *Paleokarst: A Systematic and Regional Review,* edited by P.Bosák, D.C.Ford, J.Glazek & J.Horaček, Amsterdam: Elsevier

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology*, London and Boston: Unwin Hyman

Hill, C.A. 1996. *Geology of the Delaware Basin, Guadalupe, Apache and Glass Mountains, New Mexico and Texas,* Midland, Texas: Society for Sedimentary Geology

Huntoon, P.W. 1996. Large-basin ground water circulation and paleo-reconstruction of circulation leading to uranium mineralization in Grand Canyon breccia pipes, Arizona. *The Mountain Geologist*, 33(3):71–84

Sangster, D.F. 1988. Breccia-hosted lead-zinc deposits in carbonate rocks. In *Paleokarst*, edited by N.P.James & P.W.Choquette, New York and London: Springer

Stanton, R.J. 1966. The solution brecciation process. *Geological Society of America, Bulletin,* 77:843–48

SOVIET UNION: SPELEOLOGICAL HISTORY

There are numerous early mentions, going back to the 4th century BC, of caves in the territories that later composed the Russian Empire and Soviet Union. However, it was during the 18th century that a scientific approach to the study of karst phenomena, and caves in particular, emerged in Russia. Five main periods can be broadly distinguished in the subsequent history of cave exploration and study (Gorbunova, 1988, 1990; Gorbunova & Dublyansky, 1999; Dublyansky, 1999). The distinction between the periods is based on changes in political and economical systems, predominant concepts about caves and their significance, motives for exploration, and ways in which cave exploration and study developed.

18th century

The conquest and development of huge territories of Ural and Siberia in the far north of the Russian empire was accompanied by a series of expeditions commissioned by the state to study and explore natural resources. Their reports contained many significant data about karst and caves. The first detailed field manual on the study of caves was compiled by Professor Johan Gmelin for the Kamchatka Expedition (also known as the Great North Expedition) of the St Peterbourg Academy of Science, carried out between 1733 and 1743. In the second half of the 18th century, the great Russian naturalist, Michail Lomonosov, expressed many important theories about the nature of karst phenomena and caves, cave formations, and microclimate. It is noteworthy that many of the earlier scholars realized that caves in both limestone and gypsum had similar features.

19th century to early 20th century

This period is noted for remarkable growth in data about the karst and caves of the Russian Empire. Such data were supplied by numerous regional geographical and geological expeditions and by missions that investigated the Empire's outlying districts, such as Crimea, Caucasus, Ural, Central Asia, Western and Eastern Siberia, and the Far East. At the beginning of the 19th century, V.Severgin published the first countrywide review of caves in the Russian state. In the second half of the century systematic efforts were made to study the natural resources of the state's huge territories, stimulated by the burst in the industrial development of the central and far east regions and by construction of railroads, and generating many cave descriptions and maps.

Specialized work in some caves included studies of cave paleontology (A.Ivanov), ice formations (E.Fedorov), microclimate (Ju.Listov), and archaeology (A.Kirkor and G.Ossovsky). In 1887 Listov published a detailed field manual of his cave studies, which covered aspects of geology, morphology, hydrogeology, formations and sediments, microclimate, speleogenesis, and local folklore. In the 1890s, the Crimean-Caucasian Mountaineering Club was established in Crimea and its members made many explorations and studies of caves. It was one of the first examples of the involvement in cave studies of enthusiastic amateurs organized in a public society, a phenomenon that emerged at the same time in Western Europe as a result of initiatives by E.A.Martel, and later developed into what is now termed speleology.

From the beginning of the 20th century, the number and significance of regional karst cave studies continued to grow exponentially in all the main regions of the Russian Empire, particularly in relation with systematic geological mapping. In 1900, a fundamental book *About Karst Phenomena in Russia* was published by Alexander Kruber. In this and later publications, Kruber not only gave a painstaking characterization of many karst regions and caves, but he also laid some important theoretical principles of karst and cave science. His role in karstology and speleology in Russia and Ukraine is somewhat comparable with that of E.A.Martel in Western Europe. The important distinction, however, is that Kruber did not found amateur speleological societies, as did Martel. Martel visited Russia in 1903, at the invitation of the Minister of Agriculture and Russian Domains (Cigna, 1977).

1917–1957

The revolutions of 1917 and the subsequent civil war and terror of Stalin's regime interrupted many common activities, including cave and karst studies. Scientific and applied geological research were resumed in many regions during the 1920s, with incidental caves studies. There were many karst research projects during the subsequent decades (with the natural exception of the World War II years) because the demands of industrial development in many karst terrains stimulated regional investigations as well as progress in the theory and methods of karst studies. The All-Union karstological conferences, held in 1933, 1947, and 1956, reviewed the advances and outlined the tasks for future researchers. The latter conference, held in Moscow, was attended by over 2000 participants representing 284 institutions.

By 1957, several karstological schools, led by eminent scientists (N.Gvozdetsky, B.Ivanov, G.Lykoshin, G.Maksimovich, I.Popov, D.Sokolov, N.Sokolov, A.Stupishin and others) had formed in various scientific institutions. However, exploration and study of caves had not advanced to the same extent during this period. Unlike many countries of Western Europe and North America, where the main progress in cave exploration during the 20th century was linked with amateur speleological activity organized in clubs and societies, no such speleological movement evolved in the Soviet Union during the first half of the century. This was due to continued economic hardships and the nature of the totalitarian regime. Instead, the state, concerned with military use of caves for missile sites and underground constructions, made efforts to organize the exploration and study of caves through governmental organizations. Such activities were shrouded in secrecy, especially between 1942 and 1956. Later, inventory and documentation of natural caves was included in the duties of the Ministry of Geology. However, the state-driven efforts were not too successful in terms of the number and size of caves explored. By the end of 1957, no more than 1000 caves, mainly easily accessible and small, were known in the entire Soviet Union. The longest cave remained Kungur Ice Cave in Ural (4.7 km), known since the 18th century, and the deepest cave was the Bottomless Pit in Crimea, where a depth of 100 m was reached in 1927. In view of the remarkable achievements made at that time in cave exploration in Western Europe and North America, it seemed that the Soviet Union was irreversibly behind. The weak state of speleological exploration and research was recognized by leading karst scientists, and was reflected in the resolution of the All-Union Karst Conference held in Moscow in 1956. This conference also pointed out the need for involving amateurs in cave exploration through the development of caving movements.

1958–1991

It is believed that modern speleology in the Soviet Union was born in 1958. There were several coinciding reasons that provided a boost to cave exploration and studies. In that year, the Interdepartmental Karst Commission was created under the Academy of Sciences to coordinate and advance karst and cave studies. The state undertook measures to promote and support outdoor sports, such as mountaineering, hiking, and wild rafting, directing them to exploration; caving found a natural place in such a system. The recognition by leading karst scientists of the significance of cave studies motivated them to encourage amateur exploration activity. Last but not least, publication in Russian of mass circulation books, by Norbert Casteret (in 1956 and 1959) and William Halliday (in 1962), had encouraged many young people to devote themselves to cave exploration.

In 1958 a scientific institution, called the Complex Karst Expedition, based in Crimea, was formed under the Ukrainian Academy of Sciences. In subsequent years, it established a sound practice of cooperation between scientists of various fields and sporting cavers, while carrying out the systematic study of caves in the Crimean Mountains and the rest of Ukraine. Encouraged by eminent karstologist Dr Boris Ivanov, Victor Dublyansky and Vladimir Iljukhin were instrumental in developing the organizational structure of the caving movement throughout the Soviet Union. In 1962 the first national field caving seminar was held in Crimea, where principles of exploration techniques and methods of cave study were laid down, as well as the structure of the training system. Amateur caving groups and clubs appeared in many regions and their enthusiastic exploration activity generated massive new data on caves. The pace of cave exploration in the USSR, since 1958, can be illustrated by the following facts:

1. The length of mapped passages in two caves, Ozerna and Optimistychna in Ukraine, passed 100 km in 1974 and 1975 respectively;
2. The threshold of 1000 m depth was reached in 1976 in Kievskaja (KILSI) cave in Tien Shan and by 1991 there were 5 caves over 1000 m deep in the country, the deepest being Pantjukhina Cave in the Caucasus (1508 m);
3. By 1991, the number of explored caves in the USSR exceeded 7500 (cf. less than 1000 explored caves in 1957)

In 1965, Soviet speleologists attended the International Union of Speleology (UIS) Congress for the first time and in 1977, the National Association of Soviet Speleologists (NASS) joined the UIS. The growth in cave exploration in almost every region of the country stimulated considerably the development of karst and cave science. Between 1958 and 1991, about 85 major scientific conferences and symposia were held, over 50 monographs or thematic collections of papers were published and several tens of PhD dissertations were defended on karst and caves. Soviet speleology became an important part of the international speleological scene.

1992 to the Present

After the breakup of the USSR at the end of 1991, the Ukrainian Speleological Association (established in 1992) and the Russian Speleological Union (established in 1996) maintained lively exploration activity in many regions of the former Soviet Union. Among the most remarkable achievements of the recent period are: (1) surveying of Optimistychna Cave in the Western Ukraine to 214 km; (2) exploration of Botovskaya Cave in Siberia for over 32 km; (3) exploration of the deepest cave in the North (Russian) Caucasus, Gorlo Barloga, to a depth of 870 m; (4) exploration in January 2000 of what was then the deepest cave in the world, Krubera in the Arabika Massif, Georgia; and (5) exploration of a 1530 m deep cave, Sarma, in Arabika.

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See also **Asia, Central; Caucasus, Georgia; Crimea, Ukraine; Krubera Cave, Georgia; Pinega Gypsum Caves, Russia; Russia and Ukraine; Siberia; Ukraine Gypsum Caves and Karst**

Works Cited

Cigna, A. 1977. Martel’s voyage to Russia in 1903. *International Journal of Speleology,* 26(3–4):79–87

Dublyansky, V.N. 1999. From the history of domestic speleology (XVIII century). *Peschery* [Caves], Perm: Perm University: 127–55 (in Russian)

Gorbunova, K.A. 1988. From the history of domestic speleology (the first half of the XX century). *Peschery* [Caves], Perm: Perm University: 96–104 (in Russian)

Gorbunova, K.A. 1990. From the history of domestic speleology (XIX century—the beginning of the XX century). *Peschery* [Caves], Perm: Perm University: 96–105 (in Russian)

Gorbunova, K.A. & Dublyansky, V.N. 1999. From the history of domestic speleology (the first half of the XX century). *Peschery* [Caves], Perm: Perm University: 116–26 (in Russian)

Further Reading

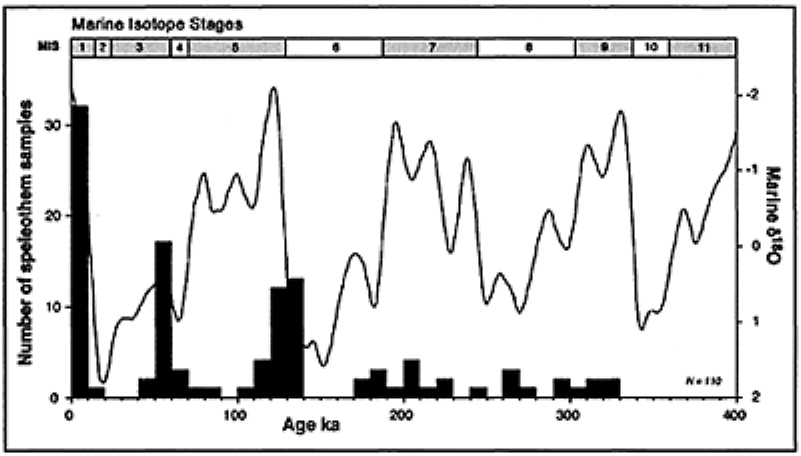
Gusev, A. (editor) 1997. *35 Years of the Speleology Club MGU (Moscow State University) 1961–1996,* Moscow: Speleology Club (in Russian)

Dublyansky, V.N. & Ilyukhin, V.V. 1987. Speleology in the USSR. *Studies in Speleology,* 7:5–15

SPANNAGEL CAVE, AUSTRIA

The Central Alps of Austria (see Europe, Alpine for location map) are occupied by crystalline rocks and karst features are restricted to the presence of carbonates (mainly marbles) and carbonate-bearing schists. Cave systems are typically located at altitudes in excess of 2000 m and are commonly spatially associated with glaciated areas. At the head of the Tux Valley in the western Zillertal Alps of Tyrol in western Austria, a number of high-altitude caves are present in the vicinity of the Spannagel Hut (2528 m). The largest of these caves is Spannagel Cave, the longest cave in the province of Tyrol, with a total surveyed length of 9 km. The cave developed in upper Jurassic calcite marbles of the Hochstegen Formation, which form a 20–30 m thick unit sandwiched between gneisses and dipping north—northwest. The structural setting in conjunction with the vicinity to the Hintertux Glacier are key factors controlling cave formation in this area. Marginal moraines of the glacial advance during the Little Ice Age show that even fairly recently some parts of the cave systems were in a subglacial position.

Initial conduits formed along the well-developed bedding planes and the prominent east-west and north-south-trending fractures (Jacoby & Krejci, 1992). The most common passage types are vadose canyons, typically no more than 1–2 m wide, which extend down to the base of the marble. Meandering streams are episodically active in these canyons and their peak discharges are only a few litres per second even during snow melt. The stream beds show pothole-like erosion features cut into the underlying gneiss and filled by sandy gravel. The modern streams are incapable of creating such features, thus



Spannagel Cave, Austria: Histogram of dated speleothems from Spannagel Cave correlated with late Pleistocene climatic variations.

indicating their ancient origin. Phreatic passages are preserved in the interior portions of both the western and the northern branch of the cave system. These passages show circular to oval cross sections and abundant large scallops on both walls, floors, and ceilings. Many were developed in the highest possible position within the marble, i.e. just beneath the overlying granitic gneiss. These phreatic tubes are commonly cut by vadose canyons giving rise to keyhole profiles. Many passages of Spannagel Cave show active destruction due to collapse, particular those located close to the surface. As a result, these passages develop elongate near-rectangular cross sections.

Spannagel Cave is currently unaffected by meltwaters from the nearby glaciers, but the cave most probably acted as a subglacial drainage system for meltwaters during the Pleistocene glaciations. Well-rounded allochthonous gneiss cobbles reaching a maximum diameter of 500 mm, derived from the nearby glaciated areas, are present even in the most distant parts of the cave system, attesting to their entrainment by high-energy streams.

The climate of Spannagel Cave is well known due to a number of continuous temperature records obtained by data loggers in various parts of the cave system. With the exception of the northernmost section close to the main entrance—which is operated as a show cave—the remaining cave system is characterized by an air temperature between +1.2 and +2.4°C. The higher temperature within this range is restricted to the westernmost branch of the cave, where overburden reaches 190 m. None of the interior sites show seasonal temperature variations. Air flow in Spannagel Cave is strongly controlled by the outside temperature (and pressure): during the cold season air ascends through the relatively warm cave and exits at the main entrance, i.e. at the highest position within the system. During the warm season, typically commencing in May, air flow reverses and warm air enters the exterior parts in the south. During October the difference between outside pressure and in-cave pressure diminishes, giving rise to stagnant conditions, which are slowly superseded by the establishment of a new upward-oriented winter flow regime, typically by early November. Relative humidity inside the cave is in excess of 96%, regardless of season. Likewise, the partial pressure of carbon dioxide in the cave air, which ranges from 280 to 325 ppmv, does not reveal a seasonal pattern.

A noteworthy feature of Spannagel cave system is the presence of calcite speleothems, some of which are active today, despite cave air temperatures only slightly above freezing. Speleothems include flowstones, stalagmites, stalactites, soda straws, spar, and helictites composed of low-Mg calcite, as well as gypsum encrustations of walls, ceilings, and calcite stalactites. Ancient speleothems, however, are more abundant than modern ones and commonly show evidence of subsequent erosion and/or dissolution. Due to the fact that seepage waters have to migrate through the overlying granitic gneiss, both dripwaters and speleothems are exceptionally rich in U (up to 218 ppm). Mass spectrometric U-Th disequilibrium dating on a large number of samples from this cave reveals a wide range of ages, from more than 400 000 years to essentially modern (Spötl *et al.*, 2003), thus demonstrating (a) the high age of this cave system, and (b) that the environmental conditions at this high-alpine site repeatedly permitted speleothem growth during the Quaternary period. The distribution of U-Th ages mimics the well-known glacial-interglacial climate pattern in that the majority of the dates fall within interglacials (marine isotope stages 1, 5e, 7, and 9), but there is also evidence that stalagmites and flowstones formed during pronounced warm intervals within glacials, e.g. during isotope stage 3 (see Figure; Spötl & Mangini, 2002).

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See also **Calcareous Alps, Austria**

Works Cited

Jacoby, E. Krejci, G. 1992. Die Höhle beim Spannagelhaus [The Cave near Spannagelhaus, Tyrol, Austria]. *Wissenschaftliche Beihefte zur Zeitschrift "Die Höhle"*, 26:1–148

Spötl, C., Burns, S.J., Frank, N., Mangini, A. & Pavuza, R. 2003. Speleothems from the high-alpine Spannagel Cave, Zillertal Alps (Austria). In *Studies of Cave Sediments,* edited by I.D. Sasowsky & J.Mylroie, Dortrecht: Kluwer, in press

Spötl, C. & Mangini, A. 2002. Stalagmite from the Austrian Alps reveals Dansgaard-Oeschger events during isotope stage 3: Implications for the absolute chronology of Greenland ice cores. *Earth Planetary Science Letters,* 203:507–18

SPECIATION

Speciation, the process by which one species evolves into a different species or splits over time into two or more new descendant species, has been effectively reviewed in cave animals by Barr & Holsinger (1985), Sbordoni *et al.* (2000), and in aquatic cavernicoles by Coineau & Boutin (1992) and Holsinger (2000). Readers are referred to these works for extensive analysis of the general models and data used by researchers in the field.

A difficulty with all discussions of speciation is that there is usually an underlying assumption that the species being discussed conform to the biological species model. This model assumes that genetic isolation is the key factor associated with the origin of new species and that gene exchange is the cement that holds a species together. In some cases, where a given bisexual species is generally confined to a region where underground movement between different cave habitats occurs regularly, it is possible this model may apply. This appears to be true for cave beetles in many cases. Often the model is either questionable or clearly inapplicable. First, gene flow is not essential to maintaining species identity—as is shown by the existence of species in asexual organisms, which are quite comparable to those seen in sexual species. A second problem lies in the assumption that spatially separated cave systems which harbour the same species of cave organisms but have physical barriers to underground gene flow, are maintained as one species by occasional interchange via surface populations. There is very strong evidence that even when large surface populations of the same species exist there is rarely significant gene interchange between the surface and hypogean populations (Kane & Culver, 1992; Wilkens, 1988). Furthermore, since the biological species concept depends on gene flow and cave species, with very few exceptions, are determined on phenotype, using the biological species concept requires similarity or pattern between the phenotypic and biological species. The evidence so far available rarely supports this similarity of pattern (Kane & Culver, 1992; Sbordoni *et al.,* 1987; 2000).

Which model or models to use is thus an area fraught with controversy. Kevin de Queiroz (1998) proposes that the conflict among concepts of the species stems largely from a confusion between species concepts and species criteria. He says that most of this argument concerns the criteria by which species are determined, originated, or maintained and that there is a general agreement concerning species concepts "…that species are segments of population-level evolutionary lineages" (de Queiroz, 1998, p.63).

If we accept this concept of species then speciation becomes the process of developing such segments and the problem becomes one of defining the "segments". A good argument can be made for defining the segment phenotypically since phenotypic "segments" are those subject to selection, and selective forces have no way of determining genotype directly. Furthermore, there is some evidence that while the forces of selection have much to do with morphological or phenotypic speciation, they have little to do with genetic speciation (Sbordoni *et al.,* 2000, p.469). Genetic speciation studies almost never involve genes associated with morphological features of adaptive importance and thus cannot be subject to selection, which is the final determinant of lineages.

Since the Barr & Holsinger review (1985), some workers have emphasized the suitability of the Wrightian adaptive shift model for cave speciation, where adaptation is an active adaptive shift to novel habitats rather than a negative reaction of an ancestral population to unfavourable surface conditions (see Howarth, 1987; Culver, 1987), but most earlier works and many recent works support a primarily or even a strictly allopatric model for cave animal speciation, where species formation arises from common ancestors separated by geographical boundaries. Some investigators have offered evidence supporting parapatric (involving contiguous populations) (Howarth, 1987; Peck, 1990) or peripatric (Sbordoni *et al.,* 1985) speciation. Holsinger (2000) makes an important and clear distinction between two types of speciation in cave organisms. The first type (phase 1) involves the evolutionary changes a species makes when it first successfully invades caves. The second (phase 2) involves changes made in established cave lineages. These two evolutionary processes are very different, both in mechanism and products. The first produces often unclear changes in physiology, little or no troglomorphy, and has a heavy association with preadaptations. Thus, in any group of organisms, many genera or families never make the transition from phase 1 to phase 2 while many others do. The second phase usually involves clear morphological, physiological, and behavioural changes and often results in increased troglomorphy. Phase 1 speciation has been the subject of most speciation controversy and for terrestrial faunas, this has largely focused on the question of what environmental conditions are responsible for, or at least associated with, the initial cave invasions and cave adaptation. The first and most widely applied theory was the Pleistocene climatic shift or climatic relict model. This model views the development of cave faunas as a result of invasion of caves and subsequent isolation in these by external climatic changes eradicating the ancestral surface populations. This extinction of surface faunas could be a result of rising or lowering of temperatures so that there are warm and cold relict species or lineages. There appears to be substantial evidence for both types of relicts in temperate karst regions in Europe and North America, which were the first to be well studied. As a result of increased knowledge of tropical cave faunas the adaptive shift theory or local habitat shift model was developed (Howarth, 1973; 1987). This theory was elaborated upon and extended by other workers and proposes that troglobites evolve from preadapted forms which actively invade caves to exploit new niches and are evolved from native fauna (Holsinger, 2000). Their evolution is regarded as a continuing process and not an episodic one as in the relict theory. In addition, by implication the speciation is parapatric rather than allopatric.

Sbordoni *et al.* (2000) point out that many tropical environments went through major environmental shifts during the Pleistocene. In addition they point out that the degree of troglomorphy in cave faunas is high where the surface conditions make movement between caves improbable and troglomorphy is low or absent where such movement should be easy. They say "…it is hard to deny the prevalent relictual character of both terrestrial and aquatic cave communities…".

Whether or not aquatic cave communities are predominantly relictual, they pose some problems not seen in terrestrial organisms. The first of these is the problem of how they got into the caves. There are two excellent reviews by Holsinger (2000) and Coineau & Boutin (1992) detailing the processes. In summary they involve invasion into caves via interstitial and crevicular habitats from marine habitats, evolution from organisms stranded by regression of marine habitats, and evolution from freshwater ancestors largely via stream capture, spring failure, or lowered water tables. The invasion of caves by marine animals involves a double adaptation since the species have to develop freshwater tolerance and either preadapted or adaptive for subterranean environments.

Whether terrestrial or aquatic, the species which become successful cave lineages in the deeper reaches of caves are a small percentage of those which have the opportunity of doing so. The most fundamental unanswered question remains: what physiological and behavioural characteristics allow certain groups to readily make this transition and not others? Many forms become successful troglophiles, often dominant where there is little or no competition from highly adapted or troglomorphic species, but fail to produce any derivative highly adapted species. While there appear to be obvious (usually unsubstantiated) reasons for this in some cases, usually the reasons are not apparent.

Speciation within troglobitic lineages is almost certainly primarily due to allopatric speciation (Sbordoni *et al.,* 2000) although the fact that frequent cases of species pairs exist, frequently involving species with different levels of troglomorphy, may offer some suggestion that other speciation modes may sometimes play a role. The spatially limited distribution of troglobite species, the degree of subdivision of populations, and isolation of these from each other all lend themselves well to the process of allopatric speciation. Furthermore the distribution pattern of troglobitic and primarily cavernicole troglophiles further supports the idea that allopatric speciation is dominant (Christiansen & Culver, 1987).

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See also **Adaptation; Colonization; Evolution of Hypogean Fauna**

Works Cited

Barr, T.C., Jr. & Holsinger, J.R. 1985. Speciation in cave faunas. *Annual Review of Ecology and Systematics,* 16:313–37

Christiansen, K. & Culver, D. 1987. Biogeography and distribution of cave Collembola. *Journal of Biogeography*, 14:459–77

Coineau, N. & Boutin, C. 1992. Biological processes in space and time colonization, evolution, and speciation in interstitial stygiobionts. In *The Natural History of Biospeleology,* edited by A. Camacho, Madrid: Museo Nacional de Ciencias Naturales

Culver, D.C. 1987. The role of gradualism and punctuation in cave adaptation. *International Journal of Speleolology*, 16:17–31

De Queiroz, K. 1998. The general concept of species, species criteria and the process of speciation. In *Endless Forms, Species and Speciatiori,* edited by D.J.Howard & S.H.Berlocher, Oxford and New York: Oxford University Press

Holsinger, J. 2000. Ecological derivation, colonization, and speciation. Population genetic structure, speciation and evolutionary rates in cave-dwelling organisms. In *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F. Humphreys, Amsterdam and New York: Elsevier

Howarth, F.G. 1973. The cavernicolous fauna of Hawaiian lava tubes. I Introduction. *Pacific Insects,* 15:139–51

Howarth, F.G. 1987. The evolution of non-relictual tropical troglobites. *International Journal of Speleology,* 16:1–16

Kane, T. & Culver, D. 1992. Biological processes in space and time, analysis of adaptation. In *The Natural History of Biospeleology,* edited by A.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Peck, S.B. 1990. Eyeless arthropods of the Galapagos Islands, Ecuador: Composition and origin of the cryptozoic fauna of a young, Tropical Oceanic Archipelago. *Biotropica,* 22(4):366–81

Sbordoni, V., Allegrucci, G. Cesaroni, D., Sbordoni, M. & de Matthaeis, E. 1985. Genetic structure of populations and species of Dolichopod cave crickets: Evidence of peripatric divergence. *Bolletim di Zoologia,* 52:139–56

Sbordoni, V., Allegrucci, G., Caccone, A., Carchini, G. & Cesaroni, D. 1987. Microevolutionary studies in Dolichopodinae cave crickets. In *Evolutionary Biology of Orthopteroid Insects,* edited by B.M.Baccetti, Chichester: Horwood and New York: Halstead Press

Sbordoni, V., Allegrucci, G. & Cesaroni, D. 2000. Population genetic structure, speciation and evolutionary rates in cave-dwelling organisms. In *Subterranean Ecosystems,* edited by H. Wilkens, D.C.Culver & W.F.Humphreys, Amsterdam and New York: Elsevier

Wilkens, H. 1988. Evolution and genetics of epigean and cave *Astynax fasciatus* (Characidae, Pisces): Support for the neutral mutation theory. *Evolutionary Biology,* 23:271–367

Further Reading

Claridge, M.F., Dawal, H.A. & Wilson M.R. (editors) 1997. *Species: The Units of Biodiversity,* London and New York: Chapman Hall

Harrison, R. 1998. Linking evolutionary pattern and process. In *Endless Forms, Species and Speciation,* edited by D.J.Howard & S.H.Berlocher, Oxford and New York: Oxford University Press

Smith, A.B. 1994. *Systematics and the Fossil Record: Documenting Evolutionary Patterns,* Oxford and Cambridge, Massachusetts: Blackwell Science

Sbordoni, V. 1982. Advances in speciation of cave animals. In *Mechanisms of Speciation,* edited by C.Barrigozzi, New York: Liss

Slobodchikoff, C.N. (editor) 1976. *Concepts of Species,* Stroudsburg, Pennsylvania: Dowden, Hutchinson and Ross

Wiley, E.O. 1978. The evolutionary species concept reconsidered. *Systematic Zoology,* 27:17–26

Wilson, R.A. (editor) 1999. *Species: New Interdisciplinary Essays,* Cambridge Massachusetts: MIT Press

SPELEOGENESIS

Etymologically, speleogenesis is the origin of caves. In a wider sense the term means not only the actual origin but also the entire life history of caves from gestation to obliteration (complete infilling or decay). Ideally speleogenetic study should explain comprehensively why and how caves originate and develop, and which factors guide these processes. Clearly an object must be defined before its genesis can be studied, but the notion of cave genesis makes little sense when applied strictly to the set of objects that conform to the common anthropocentric definition of caves (see Caves entry). Much of the data important for speleogenetic analysis derives from direct observations in explorable caves. However, restrictions imposed by the human entry requirement make the limits bounds of the objects under study (and hence their structure and shapes) accidental, artificial, and discontinuous. Thus they differ greatly from those of the natural systems that originated to perform a specific hydrogeological function, and from which caves developed. Moreover, the formative processes begin to operate and the forms themselves begin to be created with cavity sizes much smaller than those that may be entered by humans. The problem of speleogenesis in its broadest sense is further complicated methodologically because speleogenetic processes are so diverse in nature that no attempt to contrive an integral theoretical approach to the problem seems feasible. The solution lies in viewing each apparent genetic class of cave separately, and setting up criteria to define them based on the essential characteristics and functions of caves as natural systems. This approach is realized most comprehensively with regard to solution (karst) caves. These caves have been created principally by dissolution of bedrock by water circulating through pre-existing networks of openings such as fissures and pores. These caves are most abundant and important scientifically and practically, and they are the principal concern of karstology and geospeleology. Speleogenesis in the narrow sense followed here concerns the origin of solution caves and knowledge of related issues. A general overview of cave origin by other processes is provided in the entry on Caves. For greater detail see also Crevice Caves, Glacial Caves, Littoral Caves, Piping Caves, Volcanic Caves, and Pseudokarst.

Solution caves form where subsurface water flow is strong enough to remove dissolved bedrock and to keep undersaturated water in contact with the rock. As mobile groundwater is the principal agent of speleogenesis, speleogenetic study is closely linked to hydrogeology. Dissolutional enlargement of earlier porosity gives rise to a conduit structure organized to facilitate fluid circulation in a downgradient direction. Therefore, from the hydrogeological perspective speleogenesis is the creation and evolution of organized conduit permeability in soluble rocks, the principal concern of karst hydrogeology. An understanding of the principles of speleogenesis and its most important controls is indispensable to the proper comprehension of the evolution and behaviour of karst systems in general and of karst aquifers in particular.

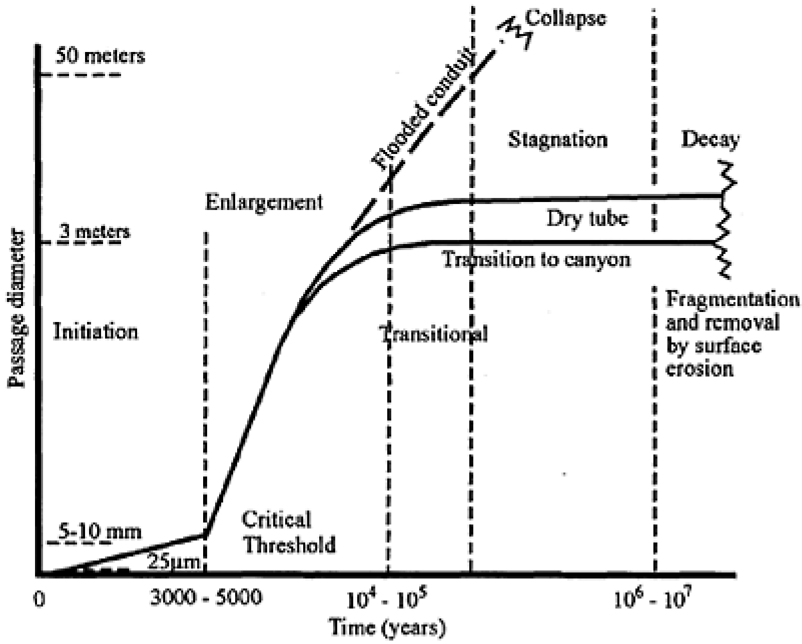
No single speleogenetic model can be applied to a wide variety of geological and hydrological settings (see Speleogenesis Theories: Post-1890). Different dissolutional mechanisms operate on different lithologies and in different settings to produce caves. Evaporite rocks such as gypsum and common salt dissolve by simple two-phase dissociation, and dissolution rates are controlled solely by diffusion. Significant dissolution of carbonate rocks relies on more complex mechanisms involving additional sources of acidity such as carbonic acid produced by carbon dioxide, hydrosulfuric acid produced by hydrogen sulfide, and sulfuric acid produced by the oxidation of H_2S or of metallic sulfides. Some processes may enhance or rejuvenate dissolutional aggressiveness, e.g. the mixing of waters of disparate chemistry, cooling of water, sulfate reduction, and de-dolomitization. Carbonate dissolution by carbonic acid groundwater dominates overwhelmingly in near-surface environments, but other mechanisms are more important in deep-seated settings.

Modern speleogenetic views appreciate the crucial importance of the preparatory (inception), initiation (gestation), and early development (rapid growth) stages in building up the pattern of conduits that evolve into explorable cave systems. An understanding of the initiation mechanisms comes from modelling based on the combined consideration of equilibrium chemistry, dissolution kinetics, and flow dynamics (see Speleogenesis: Computer Models). Such studies have revealed the basic functional relationships between conduit growth and other variables. The stage of initiation of the original flow path, during which it conducts nearly saturated water, is slow, covering geologically lengthy timespans. A positive feedback loop operates between discharge and the growth rate, making the mechanism self-accelerating. Widening of an initial opening causes increased flow through it. Thus, dissolution rates increase along the entire flow path, and so on. The rapid enlargement stage begins when water can pass through the entire conduit while preserving considerable undersaturation. This represents the breakthrough event, resulting in a boost of the growth rate up to a certain limit (about 0.01–0.1 cm a^{-1} in limestones), if hydrogeological settings permit increasing discharge. After breakthrough, conduit enlargement is almost independent of discharge. At typical hydraulic gradients the switch to rapid dissolution kinetics coincides approximately with the laminar flow-turbulent flow transition, and with the onset of sediment transport. This combined threshold, the most significant in speleogenesis, occurs within the growing conduit's aperture range from about 5–15 mm, and indicates the birth of a proper solution cave.

Understanding of cave pattern formation requires that the mechanisms of initiation and early development be viewed in a broad geological and hydrogeological context. The evolutionary typology of karst considers the entire life cycle of a soluble formation, from deposition (syngenetic karst) through deep burial and re-emergence (the group of intrastratal karst types: deep-seated, subjacent, entrenched, and denuded) to complete exposure. The "pure line" of exposed development is represented by the open karst type, which is karst evolved solely when soluble rock has been exposed at the surface, or developed in formations that have not experienced burial at all. Different types of karst, which concurrently represent the stages of karst development, are marked by characteristic associations of the structural prerequisites for groundwater flow and speleogenesis, flow regime, recharge mode and recharge/discharge configurations, groundwater chemistry, and degree of inheritance from earlier conditions. To generalize further consideration and help to emphasize the primary importance of the principal hydrogeological conditions, three major speleogenetic settings are distinguished: (1) coastal and oceanic; (2) deep-seated and confined; and (3) unconfined (see entries on each of these for more details)

Although coastal and oceanic settings are commonly characterized by unconfined circulation, they are treated separately because of the specific conditions for speleogenesis determined by the dissolution of porous, poorly indurated carbonates by mixing of waters of contrasting chemistry at the halocline. Spongework cave patterns are most common in these settings.

The distinctions between confined and unconfined settings influence speleogenesis in many ways. Most aggressive recharge to unconfined karst aquifers comes from the surface, whereas speleogenesis in confined settings relies on aggressiveness supplied to soluble rocks by recharge from adjacent, commonly underlying, formations. Carbonic acid dissolution predominates



Speleogenesis: The evolutionary history of a single conduit (from White, 1988).

overwhelmingly in unconfined carbonate aquifers, whereas under confined settings speleogenesis occurs through a great variety of dissolutional mechanisms. In terms of the conduit initiation and early development model, differences in the hydraulic controls of growing conduits are of primary importance. Under unconfined phreatic conditions the resistance of conduits themselves, particularly of their narrowest parts, governs discharge through them. Discharge increases with the growth of the conduit at the expense of piracy from less favourable routes. Simultaneously the positive feedback loop between discharge and enlargement rate gives rise to strong competition and selective speleogenetic development. The result is that sparse branchwork cave patterns form most commonly in unconfined settings. By contrast, in confined aquifer systems several factors act to suppress the selective, competitive development of conduits at the early stage, but to favour formation of pervasive maze cave patterns where structural prerequisites are appropriate. Discharge through conduits in confined aquifer systems is constrained at certain levels by the hydraulic properties of adjacent feeding beds (inflow control) or confining beds (outflow control). Recharge that enters soluble rock from adjacent permeable but insoluble rock is commonly dispersed and available equally to many original openings. Last but not least, transverse circulation through a soluble unit sandwiched between other permeable rocks, a common relationship in sedimentary basins, imposes rather short flow distances that favour the growth of many openings at compatible rates.

Somewhat specialized speleogenetic conditions occur where hypogene fluids, commonly enriched in H2S, flow upwards at sedimentary basin margins, to enter adjacent carbonate massifs and mix with oxygenated meteoric waters. The resultant sulfuric acid causes a burst of aggressiveness that generates complex 3D ramiform or network patterns. Details of cave morphologies depend on the structure of the host limestones, the extent (depth) of the mixing zone, the presence of the confining cover beds, and on whether hypogene water inflow is localized or dispersed. Replacement of calcite with gypsum and subsequent dissolution of the latter may also play a part. Somewhat similar patterns form where hypogene fluids, either juvenile or connate, are heated and enriched with CO_2. Aggressiveness is generated by the cooling of water rising from depth. Such mechanisms are commonly distinguished, respectively, as sulfuric acid speleogenesis and hydrothermal speleogenesis, or collectively as hypogenic speleogenesis.

Confined aquifers contain water at pressures greater than atmospheric, and the head lies above the base of the confining beds. In contrast, unconfined settings offer a variety of hydrodynamic zones (saturated zone below the water table, unsaturated zone above it, and the zone of intermittent saturation near the water table). Each zone displays distinct groundwater chemistry and flow regimes. Up to the 1960s there was much debate on whether caves form preferentially in the phreatic or vadose zones, or near the water table (see: Speleogenesis Theories: Post-1890). Modern approaches integrate a drainage basin wide analysis of geomorphic history and an analysis of optimum hydraulic path development in varying structural conditions. Much speleogenesis commences in the phreatic zone, although with lowering of the water table it continues in all zones, each of which leaves characteristic imprints on cave morphology. Varying recharge conditions, local structural peculiarities, and, especially, multi-phase geomorphic development may give rise to complex cave systems where branchwork patterns superimpose and interconnect, or combine with clusters of maze patterns.

Thus far only the initiation and enlargement of solution caves has been considered. When caves are decoupled from their formational settings, they become largely or entirely fossilized (see Paleokarst). This is a stage of stagnation, dominated by breakdown fragmentation and infilling by chemical and clastic sediments. The complete life history of a cave (see Figure) includes the decay or obliteration stage. This may be related to various geomorphic processes, such as erosional incision, lateral undercutting, and unroofing by overall denudational lowering of the land surface. The life of caves commonly spans a few million years, but may be much shorter (in intensively glaciated areas, in shallow settings, or in evaporite rocks) or far longer. In extreme cases caves have survived since Paleozoic or even late Proterozoic times.

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See also **Inception of Caves**

Further Reading

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)
Gabrovšek, F. 2000. *The Evolution of Early Karst Aquifers: From Simple Principles to Complex Models,* Ljubljana: Zalozba, ZRC
Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwells
Klimchouk, A.B., Ford, D.C., Palmer, A.N. & Dreybrodt, W. (editors) 2000. *Speleogenesis: Evolution of Karst Aquifers,* Huntsville, Alabama: National Speleological Society. Particularly the following papers:
Dublyansky, Y. Hydrothermal speleogenesis: Its settings and peculiar features.
Hill, C. Sulfuric acid hypogene karst in the Guadalupe Mountains.
Klimchouk, A.B. Speleogenesis under deep-seated and confined settings.
Klimchouk, A.B. & Ford, D.C. Types of karst and evolution of hydrogeological settings.
White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

SPELEOGENESIS THEORIES: EARLY

When the book of Genesis was regarded as a geological textbook, the context in which people thought about speleogenesis was very different to the accumulated knowledge that forms its background now. The age of the Earth was believed to be very young, therefore fast processes of cave formation had to be sought. Thus, it is not surprising that some of the earlier hypotheses took advantage of tectonics (to leave natural cavities), rocks that were still soft and so could be eroded rapidly, and the vast erosive power of the waters of the biblical Flood draining down to the Abyss beneath. Alternatives and variants of these included the suggestion that soluble rock salt had once occupied the places that became caves, and a logical argument that the bodies of animals drowned in the Flood and buried in the deposited mud must have decomposed, with the resulting gases forming cavities before the mud hardened.

Although these ideas were not then as foolish as they now appear, none of them was even at the start of the trail that has led to the still-developing knowledge of today. They form the protohistory of the subject. But there were elements of some of these rapid processes that play an important part in modern theories. The power of water in the Deluge drains was recognized, and the faults resulting from tectonic movements do provide planes of weakness in which caves can begin to develop.

Early modern ideas about speleogenesis developed in several stages. First came the recognition that the Earth was not so new after all, and so time was available for caves to be formed by the slow removal of solid material. At first, no distinction was made between erosion and solution, and erosion, being easier to understand, was introduced several centuries earlier. Then the process of solution became recognized as a separate agency, with its action eventually being attributed to an acid from the air that was later identified as carbon dioxide. For a long time all this activity was assumed to take place when it could be seen, in streams that were the underground equivalent of surface streams. These successive stages did not occur neatly as a steady progress from the simple to the advanced. They overlapped: some writers were unaware of others' work, and some continued to hold on to the more primitive ideas because they did not sufficiently examine the evidence or because they were under the influence of religious conviction.

The process of erosion was of course no different from the erosion involved in some of the Flood hypotheses; it was the recognition that it could be carried out by normal streams that constituted the advance. The realization that hard rock could be eroded in this way, at a rate sufficient to account for existing caves, did not occur until the 18th century. However, a long time before that there were intermediate ideas such as removal of soft inclusions in the rock by erosion and the action of water as a modifying agent after a tectonic origin. John Hutton, in 1780, suggested another such intermediate idea, that streams of present-day size had formed cave passages by eroding the rock while it was still new and hence relatively soft.

The idea of limestone being gradually dissolved away by solution rather than erosion in water was mainly a 19th-century concept arising from the more detailed and more precise examination of caves at that time. In a few cases the water was supposed to be hot or fiercely acidic; in others, before the presence of carbon dioxide in rain-water was realized, it was thought to be ordinary pure water.

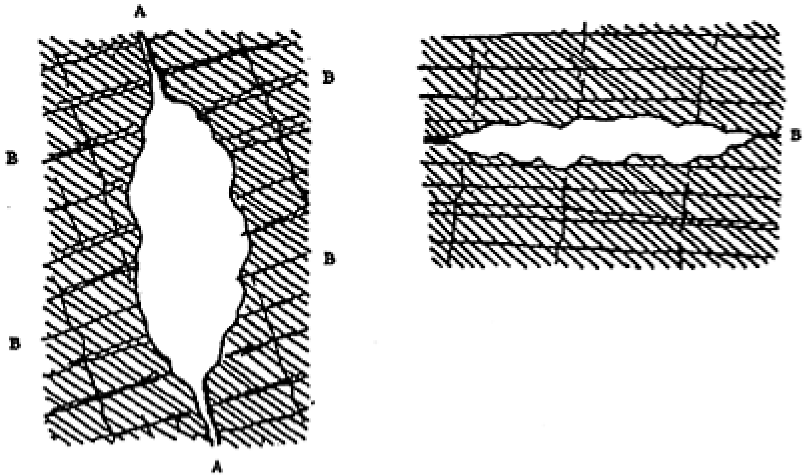
The concept of solution in especially aggressive water persisted in various forms throughout the 19th century, but it had no direct effect on the subsequent understanding of normal speleogenesis. What it did do was to emphasize to later workers the fact that solution in an acid was often the best or the only way of explaining certain characteristics of caves.

A real understanding of this was not possible until the existence of phlogiston was disproved and oxygen identified in the 1780s as an essential element in combustion, by which carbon dioxide was formed. Observation might, and did, suggest solution before that time, and indeed the earlier concepts of unspecified aerial acid did allow some approach towards understanding the chemistry involved.

At first there were some who accepted the fact that limestone was dissolved in carbonic acid to the extent necessary to account for stalactites, but could not bring themselves to believe that this effect could wholly explain the formation of large cavities and caves.

In 1830 the importance of dissolved carbon dioxide in rendering the cave water acidic was properly appreciated by Charles Lyell and by [C.]E.Thirria and soon afterwards the function of joints as the initiators of the solution process was recognized. At first solution was thought of as occurring in the vadose zone, i.e. where trickling and flowing water could be actually seen; it was not until 1870 that phreatic solution was suggested and only in the 1890s and afterwards was it advocated as a major factor in speleogenesis. The 1870 recognition that much cave

Speleogenesis Theories, Early: Figure 1. Dr Franklen Evans, who in 1870 was the first to state that some caves are formed in the phreatic zone.



Speleogenesis Theories, Early: Figure 2. Diagrams by Dupont in 1894 showing typical cross sections of joint- and bedding-determined cave passages formed by solution when completely full of water. AA is a joint; BB are bedding planes.

formation occurred below the water table was made in a littleknown paper by Franklen Evans, a medical doctor in Wales (Figure 1).

By the turn of the 20th century therefore, three main theories of speleogenesis existed, each of them correct in certain circumstances. Armand Flamache maintained that erosion alone was sufficient to form caves; E.A.Martel and others believed that a combination of both vadose solution and erosion provided the complete explanation; while Edouard Dupont (Figure 2) and Alfred Grund considered that phreatic solution was the principal factor. Each of these schools maintained its own point of view as if it were applicable in all cases and hence two major arguments arose, one between the advocates of erosion and solution and the other between the vadose and the phreatic solutionists. Gradually, very gradually in some cases, both disagreements were resolved by the realization that the three processes were all valid and that they operated in combination, either together or successively, in varying proportions according the local circumstances.

The disparity of viewpoints had been due largely to the varied experience of their exponents and the different regions with which they were familiar.

TREVOR SHAW

Further Reading

Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society
This gives much more information, with references to the original sources.
Shaw, T.R., 2000 Views on cave formation before 1900. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society
A fuller treatment than in this entry, with references.

SPELEOGENESIS THEORIES: POST-1890

Recognition of noteworthy speleogenesis (cave development) theories is inevitably time-related and subjective. Seemingly insignificant factors may become crucial as keys to broader theories, and ideas that appeared misguided against the groundswell of contemporary science may later gain credibility. Among a plethora of ideas, some ludicrous or bizarre, many strands of later speleogenetic thinking existed before 1900. Major theories that matured in the early 20th century grew from the more reasonable of the earlier ideas.

Towards the end of the 19th century geomorphological investigation of surface karst led to increased speculation about subsurface karst and underground water. Cvijić (1893) discussed surface development in the Dinaric karst and later (1918) linked karst landforms to sub-surface hydrology. He also described dry, transitional and saturated hydrographic zones (now better known as vadose, shallow phreatic, and deep phreatic zones), fuelling much subsequent controversy. Cvijić considered the transitional zone to be the major speleogenetic focus, with groundwater movement concentrated at the water table.

Early in the 20th century two pre-eminent geomorphologists, A.Penck and W.M.Davis, studied the Classical and Dinaric karsts. Prejudiced by their near-patriarchal assertions, two conflicting models began to evolve, typified in the work of Grund (1903) and Katzer (1909). Grund believed that karst aquifers divide into two broad zones, a lower zone saturated by stagnant water, and a higher zone where water circulates in open caves above a regional water table. In contrast, Katzer denied the existence of a saturated zone and a water table, but assumed all karst water follows open cavities from surface sinks to topographically lower springs. He considered caves to be mutually independent, because the intervening rock is virtually impermeable. From these early ideas, three outwardly conflicting general theories eventually emerged, identifying the speleogenetic focus as the deep phreatic zone, the shallow phreatic zone, or the vadose zone.

Davis himself was the main advocate of deep phreatic development, publishing “The origin of limestone caverns” in 1930, when he was 80 years old. Following Grund’s basic theme, he considered that speleogenesis begins when freshwater replaces primitive brines trapped during sedimentation and retained during limestone diagenesis. He visualized slow dissolutional initiation of groundwater routes, possibly at great depth, and distinguished between this and subsequent void enlargement. Emphasizing the potentially vast timescales of cavern formation, he predicted deepseated processes lasting tens or hundreds of millions of years, with shallower but still sub-water-table growth progressing more quickly. Flooded passages originating at depth are eventually drained following relative uplift. This two-cycle model explains caves that must have originated below a water table but which clearly occupy levels well above contemporary water tables.

By implication, ideas in Lehmann's (1932) publication "Die Hydrographie des Karstes" may also relate to deep phreatic speleogenesis. This was the only European contribution to the contemporary debate to gain serious recognition, but was overlooked or ignored by most North American and British researchers. Basing his reasoning on the then current understanding of fluid mechanics, Lehmann believed speleogenesis would not commence unless "initial cavities" *(Urhohlräume)* at least 2 mm wide existed within the rock. A minimal primary permeability *(hydrographische Wegsamkeit)* was also necessary, as water ingress and egress to and from the rock are required to initiate flow. Both aspects now appear to relate most closely to the phreatic, particularly deep phreatic, processes predicted by Grund and Davis. However, Lehmann's view that karst cavities are mutually independent and unrelated, has more in common with the views of Katzer.

Extensive field observations allowed Bretz (1942) to classify cave features as diagnostic of passage growth either in the phreatic or vadose zones. He supported and enhanced the broad Davisian model, postulating a third phase between Davis's phreatic and vadose cycles. He believed that, during this intermediate phase, flooded voids below the water table are progressively filled by red clay.

Early shallow phreatic theories were typified by Swinnerton's (1932) ideas, which re-emphasized Cvijić's threefold hydrographic zone division. Swinnerton acknowledged limited deep dissolution, but believed that most dissolutional growth takes place within a fluctuating shallow phreatic or water-table zone. Subsequently, following uplift and drainage of formerly flooded passages, cave modification and growth continue in the vadose zone.

Ideas presented by Gardner (1935) are commonly quoted as exemplifying vadose speleogenesis theories, but actually include aspects relating to early sub-water-table development. Gardner described dominantly down-dip passage formation commencing in relatively thin "carrier beds" or "aquifers", which somehow favour cave development. He suggested that, although static groundwater exists at depth, surface valley incision (Figure 1) is required to initiate gravitational down-dip flow and concomitant dissolution along intersected carrier beds. Continued downcutting eventually intersects lower carrier beds, leaving upper levels abandoned as caves forming along lower beds capture their drainage. Whereas Gardner's theory undeniably described vadose modification within stratigraphically determined zones, pre-drainage dissolution along the carrier beds must, by definition, have been a phreatic process.

Another aspect of vadose cave development was introduced by Malott (1937), within an abstract describing his "invasion theory of cavern development". He suggested that after uplift and water-table lowering, percolating meteoric water gathers in pre-existing primitive voids within the rock and channels downwards towards the water table, selectively enlarging preferred routes. As with Gardner's ideas, Malott's abstract related mainly to vadose modification, and the origin of the primitive phreatic cavities that guided the process was barely discussed.

From these brief descriptions it is clear that overlap existed between theories that seemed to champion either deep phreatic, shallow phreatic, or vadose-dominated speleogenesis. Considering the heat supposedly generated by this controversy, it is interesting to revisit a statement made by Martel in 1896, long predating the theories:

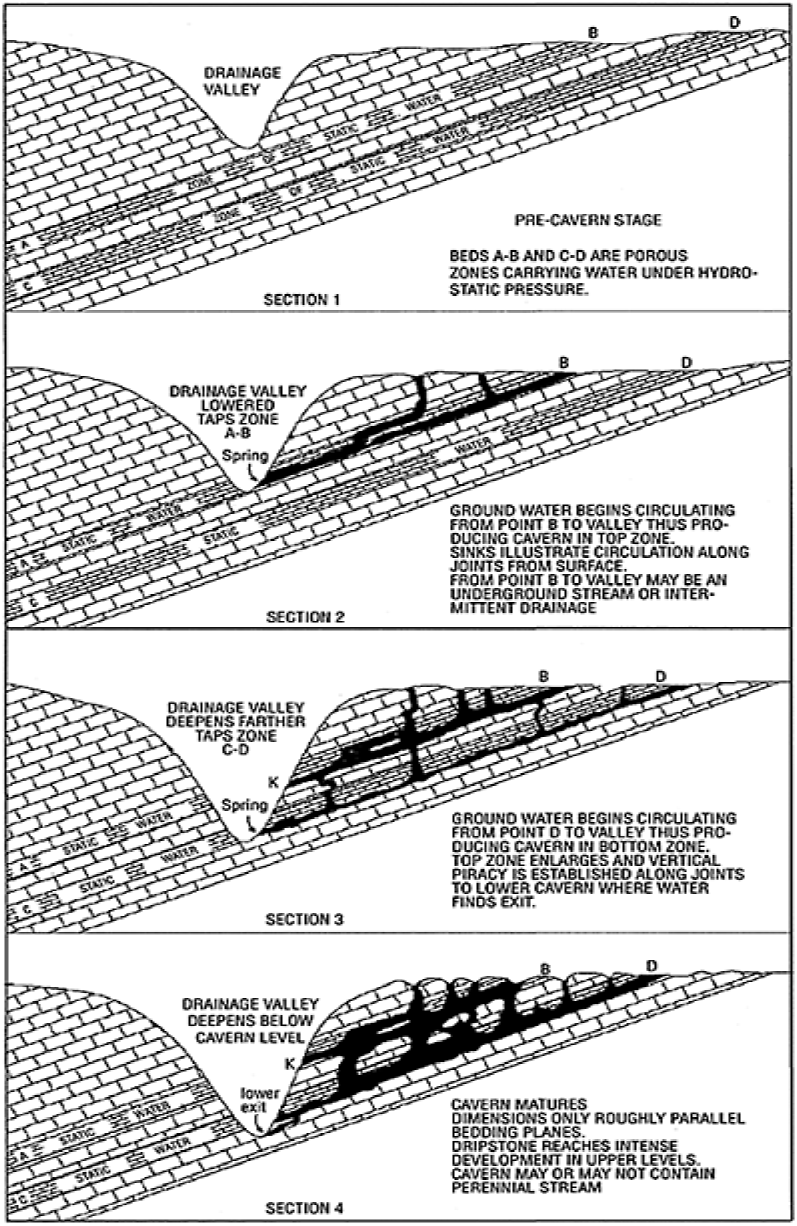
> No theory about the origin of caves is universal: those that have been put forward have generally claimed to be too inclusive; almost all of them are partially correct; the whole truth lies sometimes in their combination, sometimes in the application of a particular one in a particular case. (Martel, 1896, pp.53–54).

With hindsight, each major school of thought accommodated aspects of cave origin or modification in all three hydrographic situations. Rather than the viability of each aspect being in dispute, it was simply a question of which was dominant. As pointed out by Martel, this would actually vary temporally and locally.

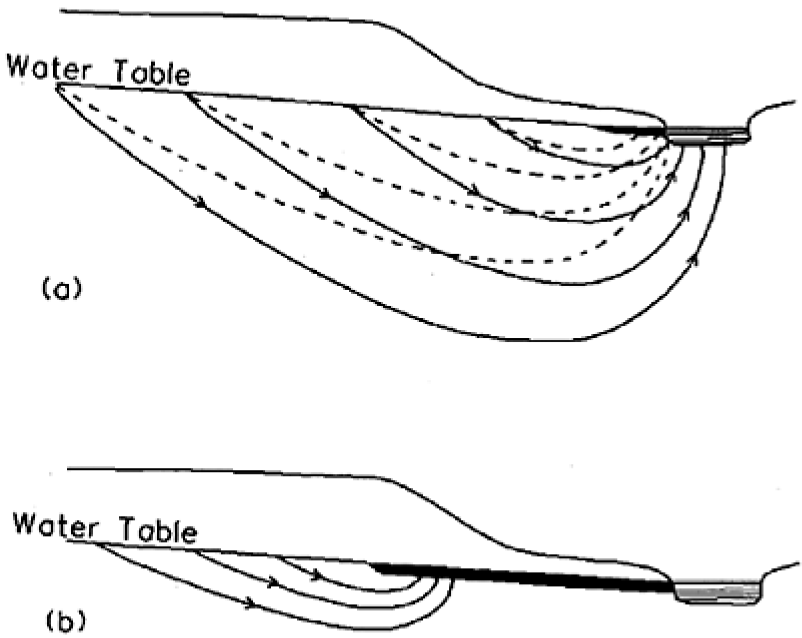
Partial corroboration of Martel's vision was provided by Rhoades and Sinacori (1941), who published a mainly mathematical consideration of underground flow. By assuming that water behaviour in limestone terrains fits idealized flow patterns deduced for isotropic aquifers, they demonstrated that both deep phreatic and shallow phreatic processes do operate, and can coexist at the same locality. Significant deep dissolution occurs during the early drainage of an uplifted rock mass towards a specific discharge point. Over time voids near the discharge point enlarge preferentially and a master conduit cuts back headwards, following the local water table. Eventually, shallow processes dominate over deep-seated alternatives (Figure 2).

During the next 20 years or so interest turned away from hydrographic zones, towards more detailed considerations of underlying processes and mechanisms. No further generic works of major stature appeared, yet many specific contributions were published, mostly reflecting an overall improved knowledge of actual caves, or of chemical and hydrological factors involved in their development. Without doubt, as in the past, valuable ideas were published and overlooked in languages unfamiliar to the leading scientists, whatever their nationality, and effort was duplicated in different countries. This is nowhere better exemplified than by Laptev's (1939) Russian publication on mixing water dissolution, which was overlooked in the West and later revisited independently by Bögli.

Some other significant contributions pre-dating the next major advance must at least be mentioned. Howard (1964) questioned how meteoric water could remain aggressive and capable of dissolution when, theoretically, it should be neutralized within 10 mm of entering the rock. His conclusion that acid must be created within the rock if early voids are to form has only relatively recently found wider favour. Also in 1964, Bögli



Speleogenesis Theories: Post-1890: Figure 1. Sketch sections illustrating the origin and development of a large limestone cavern (redrawn after Gardner, 1935, from Lowe, 2000).



Speleogenesis Theories: Post-1890: Figure 2. Groundwater flow development stages in limestone according to Rhoades and Sinacori. Broken lines in (a) indicate the changes produced by backward growth of a water table cave from the discharge point. Diagram (b) shows the theoretical effect after significant conduit growth (redrawn after Rhoades & Sinacori, 1941, from Lowe, 2000).

described the possibility of "mixture corrosion", whereby two saturated waters can combine and become capable of additional dissolution. This has considerable impact upon cave modification in a variety of contexts. Ford (1965) introduced a new cave development model, which eventually evolved into the Ford-Ewers model, discussed below. In 1966 S.N.Davis questioned how and why water could move along rock joints that are barely more permeable than the surrounding rock. Concluding that mechanisms other than gravity must be involved, he suggested that "groundwater pumping" related dominantly to earth tides was implicated. In 1975 Palmer published "The origin of maze caves", a seminal work that received and has retained widespread acceptance. All of these and other, arguably equally pivotal, ideas from authors including S.A.Durov, C.A.Kaye, P.K.Weyl, J.V. Thrailkill, O.Langmuir, J.N.Jennings, and A.C.Waltham, all contributing to knowledge of aspects of cave development, are traceable via the sources of further reading listed below.

In the context of the earlier controversy, White and Longyear (1962) suggested that "The multitudinous theories…are neither correct nor incorrect in the general case, they are irrelevant…". This was quoted by Ford (1965) when presenting his new cave origin model, based largely upon study in the Mendip Hills. Ford's ideas, with a strengthened geological component, grew into the more widely applicable Ford-Ewers model (1978), which negated earlier controversy. The possibilities and explanations presented within the model were accepted widely, and White (1988) asked "…'Do caves form above, at or below the water table?' To all of these possibilities, the Ford-Ewers model answers, 'yes!'."

The Ford-Ewers model, sometimes referred to as the fissure frequency hypothesis or the four-state model, forms the common ground of most current international speleogenetic thinking. Its applicability is described in various modern texts (see Further Reading) and details need not be examined here. Broadly, how ever, explanations for cave frameworks, including deep phreatic loops, sub-horizontal vadose streamways alternating with waterfilled tubes, and deep shaft systems, are related to the availability of fissures (including bedding plane discontinuities) within the rock mass.

Since the appearance of the Ford-Ewers model, views of some aspects of cave development have changed, and advances have been made in various branches of speleogenetic study. Some of these are discussed further in the entries on Inception of Caves; Speleogenesis; Speleogenesis: Coastal and Oceanic Settings; Speleogenesis: Computer Models; Speleogenesis: Deep-seated and Confined Settings; and Speleogenesis: Unconfined Settings.

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See also **Karst Hydrology: History**

Works Cited

Bögli, A. 1964. Mischungskorrosion—ein Beiträg zur Verkarstungsproblem [Mixture corrosion—a contribution to the karst problem]. *Erdkunde,* 18:83–92

Bretz, J.H. 1942. Vadose and phreatic features of limestone caves. *Journal of Geology,* 50:675–811

Cvijić, J. 1893. Das Karstphänomen [The karst phenomenon]. *Geographische Abhandlung,* 5(3):218–329

Cvijić, J. 1918. Hydrographie souterraine et evolution morphologique du Karst [Underground hydrology and morphological evolution of karst]. *Recueil des Travaux de l'Institute de Géographie Alpine,* 4(4):375–426

Davis, S.N. 1966. Initiation of ground-water flow in jointed limestone. *National Speleological Society Bulletin,* 28:111–18

Davis, W.M. 1930. Origin of limestone caverns. *Geological Society of America Bulletin,* 41:475–628

Ford, D.C. 1965. The origin of limestone caverns: A model from the central Mendip Hills, England. *Bulletin of the National Speleological Society of America,* 27:109–32

Ford, D.C. & Ewers, R.O. 1978. The development of limestone cave systems in the dimensions of length and depth. *Canadian Journal of Earth Sciences,* 15:1783–98

Gardner, J.H. 1935. Origin and development of limestone caverns. *Bulletin of the Geological Society of America,* 46:1255–74

Grund, A. 1903. Die Karsthydrographie: Studien aus Westbosnien [Karst hydrology: Studies from West Bosnia]. *Geographische Abhandlungen,* 7:103–200
Howard, A.D. 1964. Processes of limestone cave development. *International Journal of Speleology,* 1:47–60
Katzer, F. 1909. *Karst und Karsthydrographie. Zur Kunde der Balkanhalbinsel [Karst and Karst Hydrology. For Understanding the Balkan Peninsula],* Sarajevo: Kajon
Laptev, F.F. 1939. Aggressive action of water on carbonate rocks, gypsum and concrete. *Trudy Spetgeo,* vol. 1, Moscow and Leningrad: GONTI
Lehmann, O. 1932. Die Hydrographie des Karstes [Karst Hydrology]. In *Enzyklopädie der Erdkunde* [Encyclopedia of Geography], edited by O.Kende, Leipzig and Vienna: Franz Deuticke
Malott, C.A. 1937. Invasion theory of cavern development [abstract]. *Proceedings of the Geological Society of America* for 1937, p.323
Martel, E.A. 1896. Applications géologiques de la spéléologie. *Annales des Mines,* Paris, sér- 9, 10:53–54
Palmer, A.N. 1975. The origin of maze caves. *National Speleological Society Bulletin,* 37:57–76
Rhoades, R. & Sinacori, N.M. 1941. Patterns of groundwater flow and solution. *Journal of Geology,* 49:785–94
Swinnerton, A.C. 1932. Origin of limestone caverns. *Geological Society of America Bulletin,* 43:662–93
White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press
White, W.B. & Longyear, J. 1962. Some limitations on speleogenetic speculation imposed by the hydraulics of water flow in limestone. *National Speleological Society, Nittany Grotto Newsletter,* 10:155–67

Further Reading

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)
Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman
Lowe, D.J. 1992. A historical review of concepts of speleogenesis. *Cave Science,* 19(3):63–90
Lowe, D.J. 2000. Development of speleogenetic ideas in the 20th century: The early modern approach. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.
Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society
Palmer, A.N. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin,* 103:1–21
Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society
Shaw, T.R. 2000. Views on cave formation before 1900. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society
Watson, R.A. & White, W.B. 1985. The history of American theories of cave origin. In *Geologists and Ideas: A History of North American Geology,* edited by E.T.Drake & W.M.Jordan, Boulder, Colorado: Geological Society of America (Geological Society of America, Centennial Special vol. 1)

White, W.B. 2000. Development of speleogenetic ideas in the 20th century: The modern period, 1957 to the present. In *Speleogenesis: Evolution of Karst Aquifers*, edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

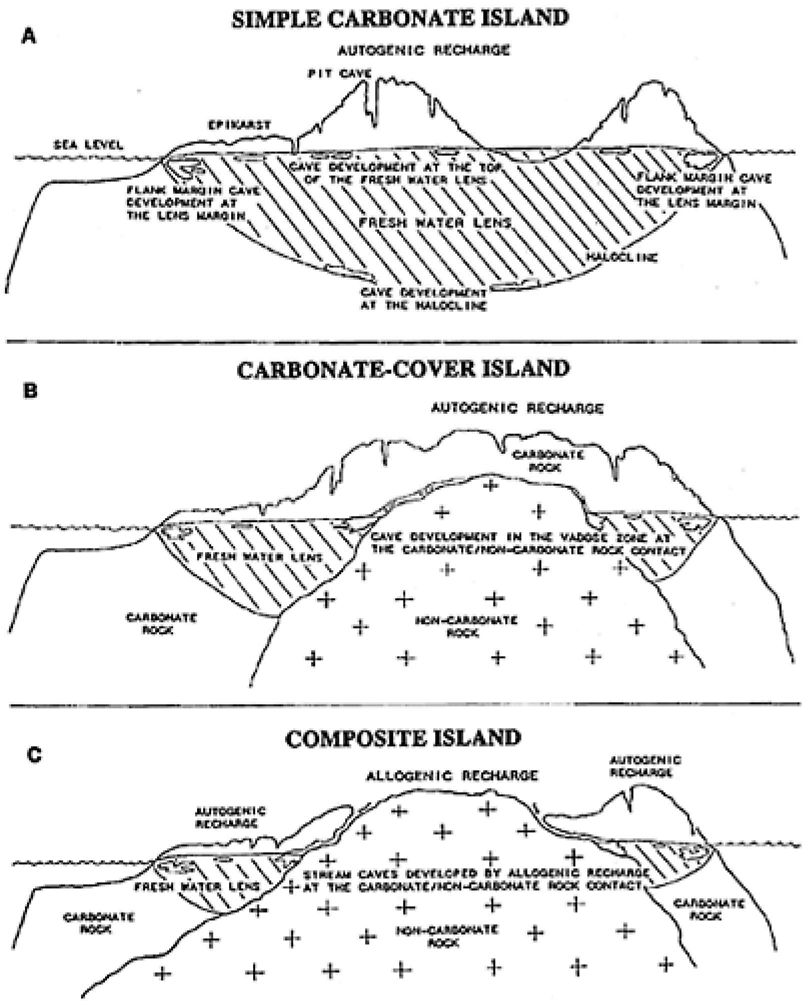
SPELEOGENESIS: COASTAL AND OCEANIC SETTINGS

Cave development, or speleogenesis, in coastal or oceanic settings is very different from that found in the interior of continents. These differences depend on three main factors that are a direct result of the proximity to the coast: the soluble rocks are young; sea-water and freshwater mixing occurs; and sea-level change has occurred. First, in most parts of the world, the coastal limestones and dolomites (hereafter collectively called “carbonates”) are geologically young, commonly less than 25 million years old. They have not been transported far from their place of origin, and have not undergone the alteration or diagenesis caused by deep burial over long periods of time. As a result, they are not as crystallized and dense as the ancient carbonates found in continental interiors. This type of youthful, porous carbonate is called “eogenetic”. Second, these young carbonates contain a freshwater lens, the result of denser sea water intruding from the coast beneath the less-dense fresh water (Figure 1A). The term “lens” refers to the shape of this freshwater body, which is thin at the coastline but thickens inland. Within the island, where the freshwater body continues to the coast on the far side, it thins again, such that, when seen in cross section, the water body takes the shape of a lens (Vacher, 1988). Where sea water and fresh water come into contact within the carbonate rock, their chemistry becomes mixed and they are able to dissolve the rock, even though each water body separately might have been fully saturated with carbonate (Back *et al.*, 1986). Third, the coastal location means that the freshwater lens will migrate if sea level changes, as the lens is floating on the sea water. If sea level changes, and the freshwater lens changes position as a result, then the site of carbonate dissolution and speleogenesis also changes. All carbonate islands and coastlines around the world have experienced sea-level change during the Pleistocene, caused by changing ice volumes on the continents, called “glacioeustatic” sea-level changes. Some islands, such as Guam (Mylroie *et al.*, 2001) or Isla de Mona (Frank *et al.*, 1998), have also experienced tectonic movement, which causes “local” sea-level change, in that it does not affect coasts elsewhere. Such local changes overprint the record of glacio-eustatic sea-level change for these islands. The synthesis of the characteristic features of island karst into a coherent conceptual framework has been called the Carbonate Island Karst Model (Mylroie *et al.*, 2001).

Karst development can also be influenced by the nature of the carbonate rocks. There are many depositional environments for carbonates, some of which can be spatially very close together, such as reef, lagoon, beach, and dune settings. Because the rock is young (or eogenetic) and has not been recrystallized and altered, the initial differences in the type of carbonate deposited are much more obvious than in older rocks. These differences can influence water flow and therefore dissolution rates and pathways.

Carbonate islands create a speleogenetic environment which differs from that which occurs along the carbonate coastline of a continent. For example, small carbonate islands like Bermuda are very different from large coastlines such as the Yucatan of Mexico. On an island, all the water present must be derived from meteoric precipitation falling on the carbonate rocks of the island; this recharge is called autogenic water. There is no water inflow from adjacent areas, as can occur where the continental interior collects water and discharges it through carbonate rocks along the coast (known as allogenic recharge). For small islands especially, the amount of water available can be very limited.

The simplest way to show the unique cave development found in carbonate islands and coasts is to look at a small island made entirely of carbonate rocks. Carbonate rock dissolves in the lens, preferentially in two locations. Water from rainfall enters the ground from and moves downward through the vadose zone to the top of the freshwater lens at the water table. At that point, the vadose water mixes with the phreatic water at the top of the lens. Even though both waters might be saturated with respect to carbonate, when they mix an undersaturated solution may result, and the water becomes capable of dissolving more rock (Bögli, 1980). In small islands, single-or multiple-chamber caves may develop at the top of the lens (Figure 1). These caves tend to be low and wide, and of an oval to suboval plan. In islands with low relief, such as the Bahamas, these voids will have thin roofs and will be prone to collapse. Such collapse voids are called “banana holes”, and can occur in densities of up to 3000 km^{-2} (Mylroie, Carew & Vacher, 1995). At the base of the lens, fresh water is in contact with sea water, and as noted earlier, when these waters mix, the resulting combination is capable of dissolving more rock. Small caves may develop here as well. But in both cases, at the top and bottom of the lens, the caves formed are not true conduits, but only mixing chambers. They contain no flow markings indicating turbulent flow or other features found in stream caves. In addition, both the top of the lens and the base of the lens constitute a density interface. Organic material may collect at such interfaces. When the organic material decomposes and oxidizes, it creates extra carbon dioxide to help drive more dissolution of the rock. If the organic material is abundant, then the system may use up all the oxygen to become anoxic. Under such conditions, materials like hydrogen sulfide and other acids may form, greatly increasing the dissolution of the rock (Bottrell *et al.*, 1991).



Speleogenesis: Coastal and Oceanic Settings: Figure 1. Sea-level and basement relationships for carbonate islands (with some vertical exaggeration). (A) The simple carbonate island, with no noncarbonate rock within the region of the freshwater lens. (B) The carbonate-cover island, where noncarbonate rock at depth can deflect vadose flow and distort the freshwater lens. (C) The composite island, where noncarbonate rock influences both surface and subsurface flow.

At the margin or edge of the lens, where it is close to its discharge point to the sea, the two favourable mixing zones for rock dissolution are superimposed on each other (Figure 1). The lens is also decreasing in cross-sectional area at this point, so the water discharge is faster as it is forced through a smaller area. Reactants come together quickly, and the products are removed quickly. All these factors are cumulative, and lead to the production of a special type of cave called a flank-margin cave (Mylroie, Carew & Vacher, 1995). The term "margin" refers to the position of the cave at the margin of the lens, and the term "flank" refers to the cave's position under the flank of the high ground that forms the island. These caves are the largest of those found on small carbonate islands. They are also not true conduits, but rather are mixing chambers sitting in the diffuse flow path at the edge of the freshwater lens. Flank-margin caves can be very large: some with over 1 km of surveyed passages are known from the Bahamas, and on Isla de Mona over 19 km of passages have been mapped for a single cave. These numbers are a little misleading, in that all these caves tend to be a collection of oval and suboval chambers and short, straight passage segments, in a very maze-like pattern (Figure 2; see also survey in Mona entry).

In addition, carbonate islands can be subdivided into three categories (Figure 1) based on the relationship between the sea level and any carbonate/noncarbonate contact. Many carbonate islands are built on volcanic pedestals, over which the carbonate rock has been deposited in layers of variable thickness. Simple carbonate islands (Figure 1A) have no noncarbonate rocks exposed at the surface or inside the island within the range of glacio-eustatic sea-level change. Islands with a carbonate cover (Figure 1B) have noncarbonate rocks beneath a carbonate veneer, and the contact between them is within the position of the freshwater lens for all or part of a glacio-eustatic cycle. Composite islands (Figure 1C) contain carbonate and noncarbonate rocks exposed on the surface.

On islands with a carbonate cover, water descending through the vadose zone is shunted along the carbonate/noncarbonate contact, producing stream caves carrying water to the freshwater lens. In composite islands, this process is augmented by the development of sinks and insurgences at the surface expression of the carbonate/noncarbonate contact. The noncarbonate outcrop acts as a large catchment funnelling dissolutionally aggressive allogenic water on to the adjacent carbonate rocks. In the phreatic zone of carbonate cover and composite islands, the lens can be subdivided into the "basal zone", where the base of the fresh water forms the transition zone to the underlying sea water, and the "parabasal zone", where the base of the fresh water rests on noncarbonate rock (Mink & Vacher, 1997).

The surface of carbonate islands contain a characteristic epikarst, with unusual morphology as a result of the youthful age of the carbonates and the pervasive presence of salt spray. In the absence of allogenic catchments on adjacent noncarbonate terrain, sinking streams, blind valleys, and springs are rarely found. Closed depressions are common, but many represent tectonic features, or constructional features produced by deposition, such as fossil lagoons or swales between dune deposits. These depressions, while internally drained by dissolution pathways, were not created by dissolutional excavation. Vadose flow along the contact between the carbonates and noncarbonates, however, can undercut the overlying carbonates, producing large collapse voids that may prograde to the surface, as observed on Bermuda (Mylroie, Carew & Vacher, 1995) and Guam (Mylroie *et al.,* 2001).

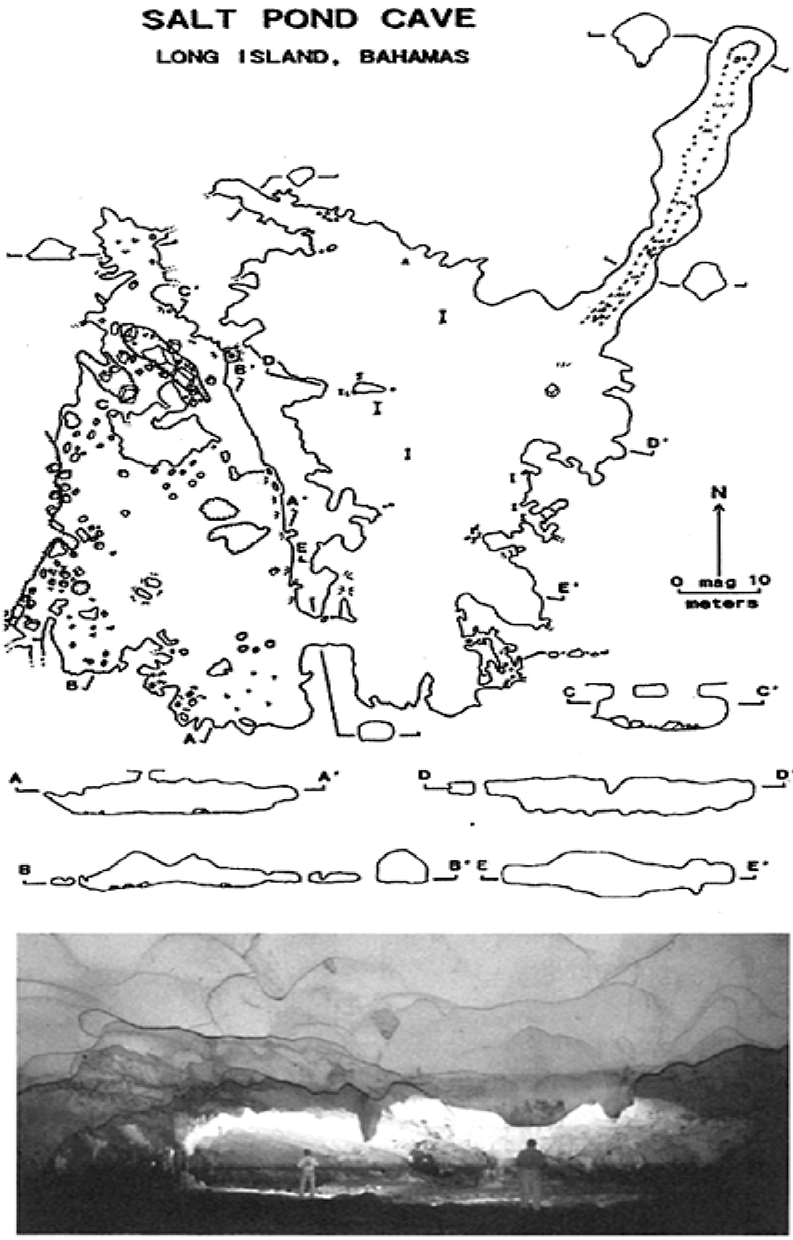
In many islands, caves have developed during the Pleistocene in Pleistocene-aged carbonate rocks. In some cases, it appears that the cave development occurred almost simultaneously with the deposition of the rocks; these caves are called “syngenetic caves” (Jennings, 1968; see also Syngenetic Karst). As an example, in the Bahamas, carbonates are deposited when glaciers melt and sea level rises on to the flat island platforms. Carbonate sediment production begins, and the sediments are washed up into beaches and then blown up into dunes and form rocks

called “eolian calcarenites” or “eolianites”. Sea level commonly continues to rise in this situation, a freshwater lens is created within the eolianites, and flank-margin cave development begins. If sea level falls, then the caves are drained. Throughout the Bahamas, there are numerous flank-margin caves that formed during the last interglacial 131 000 to 119 000 years ago, when the glaciers melted back a little more than in the present interglacial and sea level was 6 m higher. Some of these caves are formed in rocks that were deposited earlier in the Pleistocene (Mylroie, Carew & Vacher, 1995), and some are in rocks deposited early in the same sea-level event that then later continued to rise and produce the caves.

These caves can have chambers that are 14 000 m^3 in volume, and 1 km of passages. They all formed in a small time window of 10 000 to 12 000 years, when sea-level was higher than at present, during the last interglacial (131 000 to 119 000 years ago). The extremely large caves on Isla de Mona are as much as 2 million years old (Panuska *et al.,* 1998). Their large size is a result of their development prior to the glaciations of the Pleistocene, such that sea level stayed constant for a long time and mixing dissolution was able to excavate very large caves. Exploration by submarines in the Bahamas has shown that flankmargin caves also developed when sea level was lower during glaciations (Mylroie, Carew & Vacher, 1995).

When islands become large, or when there are extensive limestone coastlines, then the freshwater lens will change from diffuse flow to conduit flow. As an island becomes larger (as when sea level falls during glaciation) an ever-increasing amount of water must go through a proportionally smaller perimeter, and under these conditions, conduit flow begins. The lens is distorted by conduit flow, as it can now discharge laterally to conduits. Flankmargin cave development is inhibited as a result. In the Bahamas, large conduit systems are found at depths that equate to a sea level that would expose the shallow banks, dramatically increasing the size of the island. At today’s sea levels, the islands are much smaller and only flank-margin caves are forming.

JOHN MYLROIE



Speleogenesis: Coastal and Oceanic Settings: Figure 2. Salt Pond Cave, Long Island, Bahamas. (A) Map. (B) Photograph of the main chamber, looking north. Note the wide, low aspect of the chamber, and the dissolution surfaces on the floor and ceiling. The cave was mined for guano in the 1800s and the dark stain line represents the original guano level. (Photo by John Mylroie)

See also **Blue Holes of Bahamas; Caribbean Islands; Littoral Caves; Mona, Puerto Rico**

Works Cited

Back, W., Hanshaw, B.B., Herman, J.S. & Van Driel, J.N. 1986. Differential dissolution of a Pleistocene reef in the ground-water mixing zone of coastal Yucatan, Mexico. *Geology,* 14:137–40

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)

Bottrell, S.H., Smart, P.L., Whitaker, F. & Raiswell, R. 1991. Geochemistry and isotope systematics of sulphur in the mixing zone of Bahamian blue holes. *Applied Geochemistry,* 6:97–103

Frank, E.F., Mylroie, J., Troester, J., Alexander, E.C. & Carew, J.L. 1998. Karst development and speleologenesis, Isla de Mona, Puerto Rico. *Journal of Cave and Karst Studies,* 60(2): 73–83

Jennings, J.N. 1968. Syngenetic karst in Australia. In *Contributions to the Study of Karst,* edited by P.W.Williams & J.N.Jennings, Canberra, Australia, Australian National University Research School of Pacific Studies

Mink, J.F. & Vacher, H.L. 1997. Hydrogeology of northern Guam. In *Geology and Hydrogeology of Carbonate Islands,* edited by H.L. Vacher & T.M.Quinn, Amsterdam and New York: Elsevier

Mylroie, J.E., Carew, J.L. & Vacher, H.L. 1995. Karst development in the Bahamas and Bermuda. In *Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda,* edited by H.A.Curran & B.White, Boulder, Colorado: Geological Society of America

Mylroie, J.E., Jenson, J.W., Taborosi, D., Jocson, J.M.U., Vann, D.T. & Wexel, C. 2001. Karst features of Guam in terms of a general model of carbonate island karst. *Journal of Cave and Karst Studies,* 63(1):9–22

Panuska, B.C., Mylroie, J.M., Armentrout, D. & McFarlane, D. 1998. Magnetostratigraphy of Cueva del Aleman, Isla de Mona, Puerto Rico and the species duration of Audobon's Shearwater. *Journal of Cave and Karst Studies,* 60(2):96–100

Vacher, H.L. 1988. Dupuit-Ghyben-Herzberg analysis of stripisland lenses. *Geological Society of America Bulletin,* 100:580–91

Further Reading

Carbonates and Evaporites 10(2), 1995 is a special issue devoted to the 1995 Paleokarst Field Conference held on San Salvador Island, Bahamas in February 1995. It contains a number of papers dealing with island and coastal karst

James, N.P. & Choquette, P.W. (editors) 1988. *Paleokarst*, New York: Springer
Journal of Cave and Karst Studies 60(2), 1998 is a special issue devoted to caves on Isla de Mona, Puerto Rico
Palmer, R.J. 1989. *Deep Into Blue Holes: The Story of the Andros Project,* London: Unwin Hyman
Purdy, E.G. & Bertram, G.T. 1993. *Carbonate Concepts from the Maldives, Indian Ocean,* Tulsa, Oklahoma: American Association of Petroleum Geologists
Vacher, H.L. & Quinn, T.M. (editors) 1997. *Geology and Hydrogeology of Carbonate Islands,* Amsterdam and New York: Elsevier

SPELEOGENESIS: COMPUTER MODELS

Many models of speleogenesis have been proposed on the basis of observations in caves. However, since the early 1980s efforts have been made to understand speleogenesis beginning from basic principles of fluid flow in fractures and conduits and the physical chemistry of limestone or gypsum dissolution (see Dissolution: Carbonate Rocks, and Dissolution: Evaporite Rocks). In the first models, simple scenarios of the evolution of a single karst conduit were investigated by digital computation. These provided basic elements for further research and are therefore discussed here in some detail.

We consider a one-dimensional fracture with aperture width *a* and length L. Water aggressive to limestone is driven through it by a hydraulic head *h*. As water flows from the entrance down the hydraulic gradient it dissolves the rock and the fracture widens. Widening is fastest at the entrance but slows down when the solution approaches equilibrium further downstream. To calculate the amount of widening by dissolution one needs information on bedrock retreat as a function of the chemical composition of the solution. Early knowledge of calcite dissolution suggested a linear rate law where the rate R_1 is given by

$$R_1 = \mathrm{k}_1 \,(1 - c/c_{eq}) \tag{1a}$$

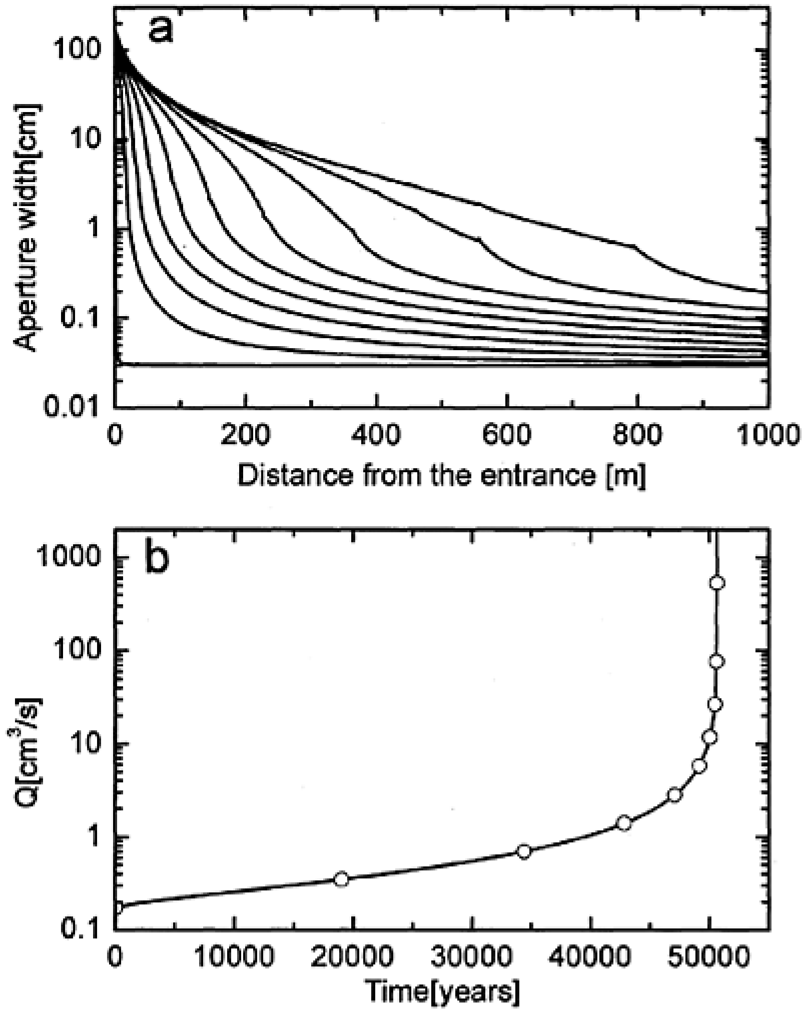
and k_1 is a constant in mmol $cm^{-2}s^{-1}$, c is the calcium concentration and c_{eq} is the equilibrium concentration with respect to calcite or gypsum, respectively. However, this rate law predicts that conduit water would become saturated close to the entrance and therefore caves could not originate at all. The apparent contradiction was resolved by Palmer (1984) who suggested that close to equilibrium dissolution must be inhibited to such an extent that the water can penetrate deeply into the rock without becoming saturated. It was found later by experiment that above about 90% of the equilibrium concentration c_{eq} a nonlinear rate law is valid both for limestone and gypsum:

$$R_n = \mathrm{k}_n \,(1 - c/c_{eq})^n \tag{1b}$$

where k_n is the higher order rate constant, and n is between 3 and 6 depending on lithology. With such a rate law applied digital modelling proved successful and results were obtained which could explain early conduit evolution in scales of both length and time. For example, take a fracture 1 m wide and 1000 m long, with an initial aperture width of *a*=0.03 cm. The hydraulic head at its entrance is 10 m and zero at its exit. Figure 1a illustrates the profiles sculptured by dissolution for various times. At the onset of karstification a funnel-like shape is created at the fracture entrance while further along widening is even but very slow. The small increase of aperture width at the exit triggers a positive feedback loop. The flow through the fracture increases with the third power of the exit aperture width. Increase of flow rates enhances dissolutional widening and vice versa. This can be seen from Figure 1b which depicts the flow through the fracture. The open circles denote the times of the profiles shown in Figure 1a. Flow and correspondingly widening at the exit are initially slow but accelerate until within a very short time span a dramatic increase in flow and in fracture width is observed. After the breakthrough flow becomes turbulent. The conduit widens rapidly and evenly until the hydraulic head can no longer be supported. Flow and further evolution of the cave will therefore be controlled by recharge and the conduit will then widen evenly, and eventually become vadose. It is interesting to note that even though this evolution model of a single conduit seems complex an analytical estimation for the breakthrough time *T* can be given (Dreybrodt, 1996; Dreybrodt & Gabrovšek, 2000; Gabrovšek, 2000) by the relation

$$T = \tau \cdot \left(\frac{L^2}{h}\right)^{\frac{n}{n-1}} \cdot a^{-\frac{2^{n-1}}{n-1}} \cdot (k_n)^{\frac{1}{n-1}} \cdot (c_{eq})^{-\frac{n-1}{n-1}} \qquad (2)$$

where *T* is in years, a is the initial aperture width, units are in cm, mol cm^{-3}, mol cm^{-2} s^{-1} respectively, and $\tau=10^{-13}$ This equation is a consequence of the positive feedback loop by which breakthrough occurs when the exit width has been opened to about three times its initial value (cf. Figure 1a). Equation 2 reveals how the parameters determining cave evolution relate to *T* in a simple way.

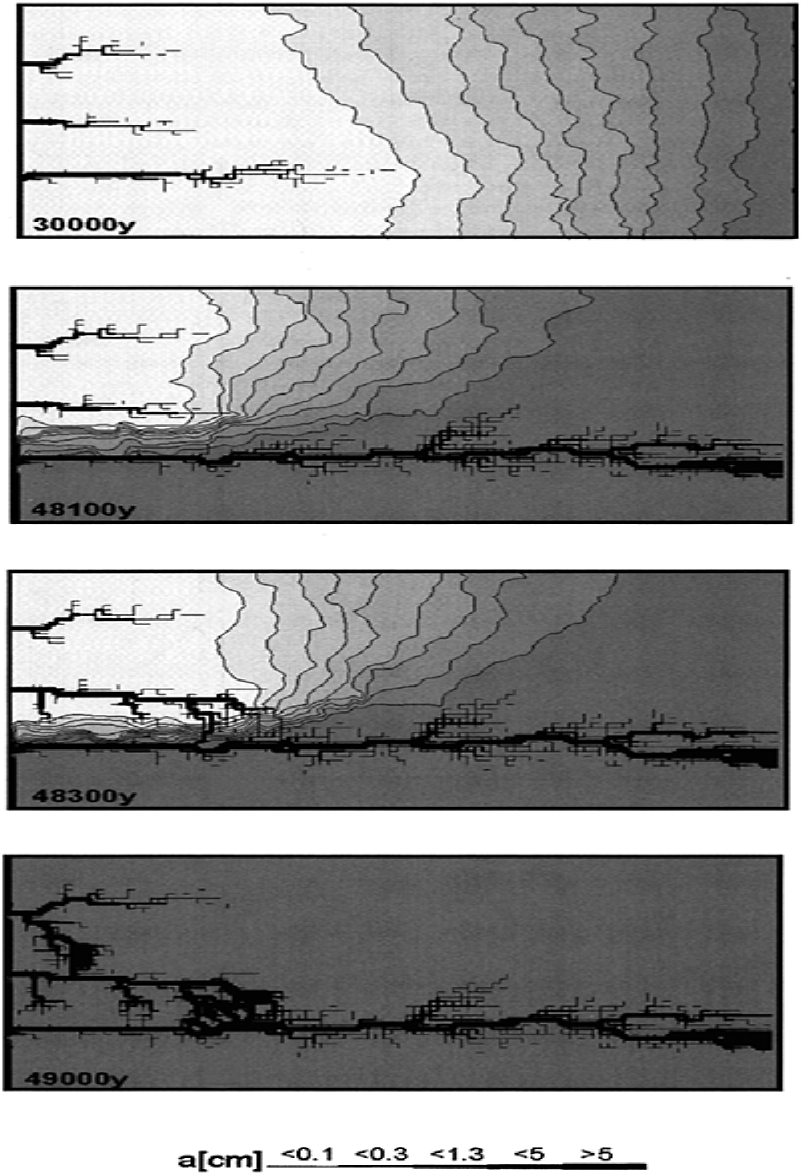


Speleogenesis: Computer Models: Figure 1. Evolution of a single conduit. a) Profiles of aperture widths. b) Flow through conduit in dependence on time. The open circles mark the times for which the profiles in a) are shown.

Modelling of cave evolution has been extended to two-dimensional nets of fractures with similar boundary conditions: inputs of constant heads at the upper boundary and output points at zero head at base level (Dreybrodt & Siemers, 2000). Figure 2 represents an example. The aquifer consists of a limestone bed 1 m thick, 1 km long, and 500 m wide. It is dissected into two orthogonal sets of fractures spaced at 10 m apart. The fracture aperture widths are statistically distributed (lognormal) with average of 0.02 cm, and 20% of fractures have been omitted. The hydraulic head acting at the input points at the left side is 10 m and zero at the base level to the right. The upper and lower margins are impermeable. Figure 2 illustrates the evolution of conduits and the head distribution in the aquifer. A competition of several conduits is observed until one breaks through. After breakthrough the hydraulic head acting on that channel breaks down and flow is restricted to constant recharge of 1000 $cm^3 s^{-1}$. Consequently the hydraulic head drops and flow of the nearest competing channel is directed towards the leading conduit such that a cave system becomes integrated. This simulation confirms the Ewers speleogenetic high-dip-model (see Ford & Williams, 1989). It is important to note that breakthrough times for two-dimensional nets with boundary conditions of constant head show an analogous dependence on the parameters as in equation 2, provided L is taken as the length of the aquifer (Siemers & Dreybrodt, 1998). Many different scenarios for cave evolution have been simulated for constant head conditions, such as Ewers' low-dip-model, where several rows of input points with different distances are subjected to equal heads. Those inputs closest to the output first experience breakthrough. Thereafter conduits start to grow from the more distant inputs and connect to inputs from which channels have already succeeded in breaking through. By this way a cave system integrates headwards. Differing lithologies of bedrock in aquifers can also be simulated. They can cause isolated cave systems without entrances and exits or caves with entrances but no exits (Dreybrodt & Siemers, 2000). Two-dimensional modelling enables one also to investigate the role of mixing corrosion as a cave-forming mechanism. Although in combination with linear dissolution mixing corrosion is insignificant as a cave-forming process, in combination with nonlinear kinetics (see equation 1b) it can play an important role in the evolution of cave systems under constant head conditions (Gabrovšek & Dreybrodt, 2000). Subterranean sources of CO_2, either from volcanic sources or the production of CO_2 by microbial action can also enhance karstification (Gabrovšek, Menne & Dreybrodt, 2000).

Where dam sites are constructed in limestone or gypsum terrains unnaturally steep hydraulic gradients arise. The question of whether karstification under such conditions can be intensified to such an extent that the structure might be endangered during its lifetime has been investigated by modelling (Dreybrodt, Romanov & Gabrovšek, 2002). Although such models must be treated with care it cannot be excluded that karstification below dam sites can lead to serious problems.

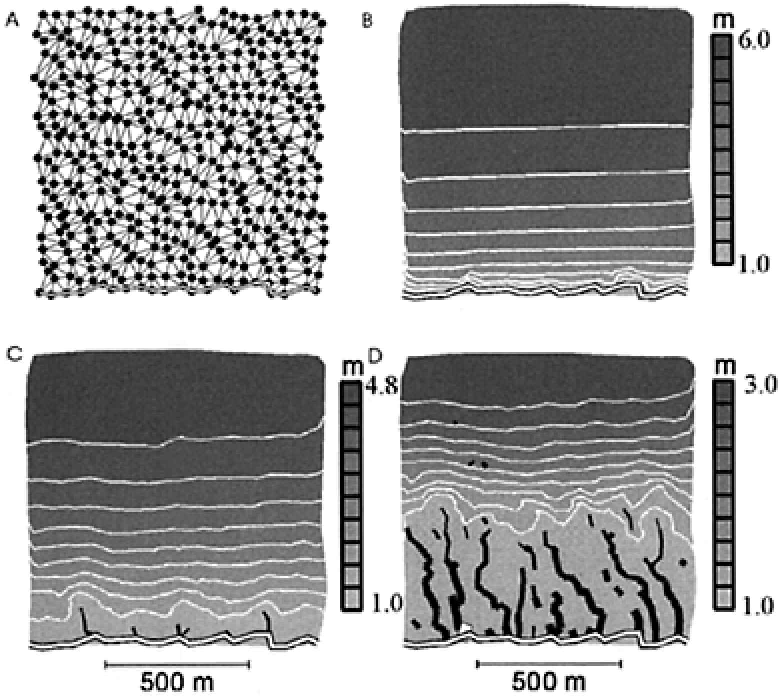
So far all models presented have boundary conditions of constant head in common. Those are most likely to be valid in the early evolution of conduits. The later state of natural karstification after breakthrough is governed by recharge from the catchment area and by turbulent flow in the major conduits. In this case one has to model constant recharge at the input points.



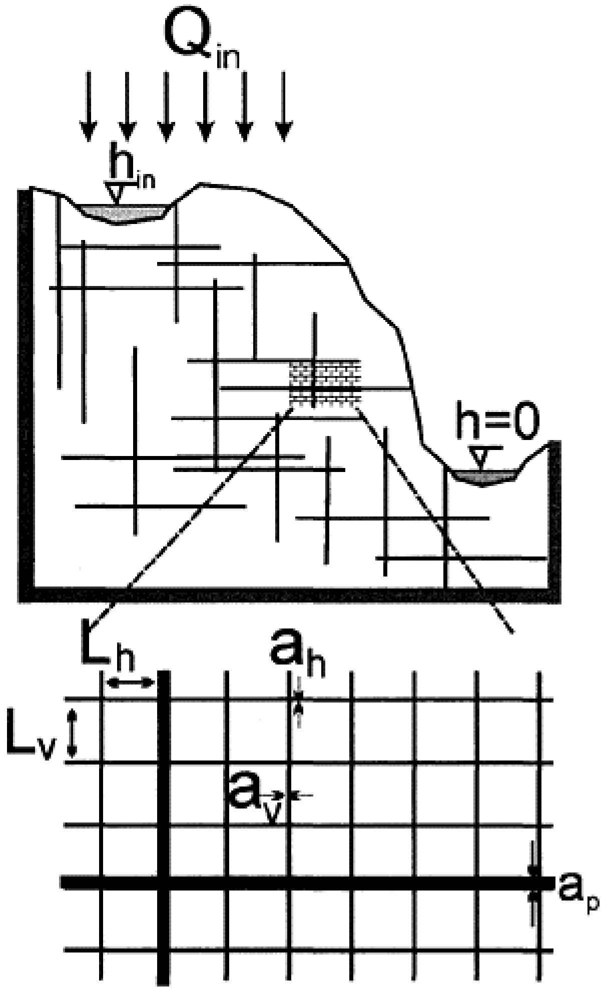
Speleogenesis: Computer Models: Figure 2. Evolution of conduits and distribution of heads for a two-dimensional aquifer under constant head conditions. The isolines of the head are given in steps of 1 m.

The further evolution of karst aquifers after breakthrough has been modelled by employing a combined continuum and discrete pipe network concept. This approach is based upon hydraulic coupling of a pipe network of larger prominent conduits (e.g. those after breakthrough) to a continuum with given hydraulic conductivity. This continuum represents the system of unwidened narrow fissures constituting most of the aquifer's storage. A constant recharge is supplied to the continuum, and also directly into the pipes. Exchange of water between the pipe system and the continuum is proportional to the head difference between the pipe-flow system and the continuum at the particular nodes, where they intersect. A further assumption is that the solution entering from the continuum into the pipe system is close to equilibrium with respect to calcite (e.g. 90% of c_{eq}). Models restricting dissolutional widening to the pipe systems only have been presented (Clemens *et al.* 1997; Sauter & Liedl, 2000). This modelling approach has been extended by Kaufmann and Braun (2000) to karst aquifer evolution in fractured, porous rocks by finite element techniques, with much higher spatial resolution. This approach, although basically similar to that of Clemens *et al.* (1997) avoids some parameters which are difficult to specify. Figure 3 illustrates an example of their results. Figure 3a shows the modelling domain, where the thin lines denote fractures and the dots are input points. The fractures are embedded into a porous matrix with conductivity of 10^{-5} m s^{-1}. A river at the bottom fixes the head at 1 m. All other boundaries are impermeable. Initial width of all fractures is 0.2 mm. Recharge of 400 mm a^{-1} is evenly distributed. Figure 3b shows the head distribution at time zero. After 2800 years some fractures have enlarged and grown headwards (Figure 3c). The distribution of hydraulic heads has changed. After 8000 years a net of conduits has developed headwards.

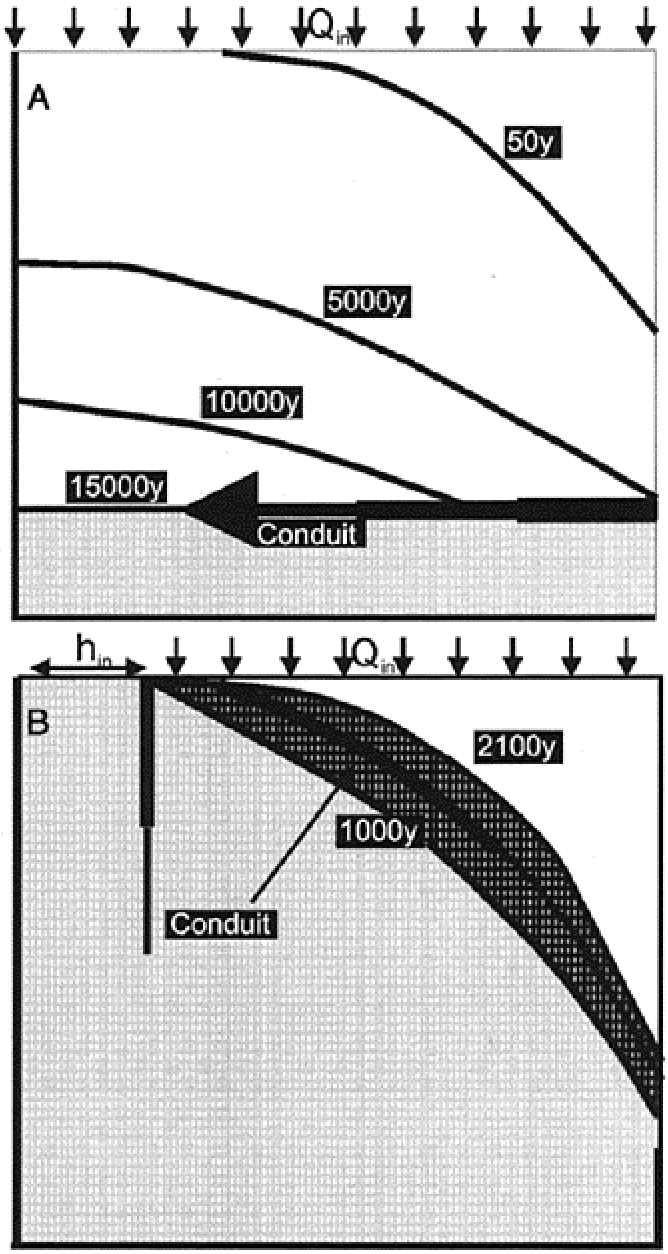
Models presented so far deal with the evolution of karst aquifers in the dimensions of length and breadth. Recent modelling of the evolution in the dimensions of length and depth has been reported by Gabrovšek and Dreybrodt (2001). The modelling domain consists of the vertical cross section of a small karstic plateau, 200 m long and 30 m high as illustrated by Figure 4. Recharge Q is evenly distributed across the surface and seeps through the fractures of the aquifer down to base level, represented by a river, or emerges from the seepage face of the cliff on the right hand side. All other boundaries are impermeable. The rock is fissured by some wide prominent fractures with aperture widths a_p=0.02 cm. These are embedded into a net of narrow fractures with aperture widths a_v or a_h of 0.005 cm, and a vertical spacing L_v=0.5 m. Horizontal spacing L_h is 2 m. First model scenarios omitted all prominent fractures to obtain a homogeneous aquifer, where water enters at the plateau and seeps downwards to the water table. Due to dissolution of the rock in the vadose zone its calcium concentration at the water table is about 90% of equilibrium concentration. Dissolution in the phreatic zone is primarily restricted to a narrow fringe at the water table, where permeability increases such that water flow is directed along the water table. The water table drops continuously until it reaches the river. Flow is concentrated towards the spring and a conduit grows headwards along the water table declining to become horizontal at base level. The final result is a water table cave as suggested by Swinnerton (1932). Figure 5a illustrates this evolution of the water table. If in addition to recharge an input region of constant head h_{in} is added, the water table is kept stable, because increasing permeability



Speleogenesis: Computer Models: Figure 3. Evolution of an aquifer in fractured porous rocks with a constant recharge of 400 mm a^{-1}. The white lines show the head distribution. The aquifer drains into the river. (From Kaufmann & Braun, 2000)



Speleogenesis: Computer Models: Figure 4. Modelling domain for evolution of an aquifer in dimension of length and depth. (From Gabrovšek & Dreybrodt, 2001)



Speleogenesis: Computer Models: Figure 5. A) Evolution of the water table for an aquifer under conditions of constant recharge. B) A region of constant head h_{in} is added. First the water table is low (1000 years) and determined by recharge. As a conduit grows from the region of constant head h_i it rises. The dark shaded area is the region where dissolution is most active.

of the rock is compensated by increasing flow from the input. Conduits grow along the water table towards base level until breakthrough occurs. This is illustrated by Figure 5b. Vadose flow in the cave will determine its further evolution. Such a behaviour was predicted by Rhoades and Sinacori (1941) from field observations. If one incorporates a net of prominent fractures with significantly larger aperture widths, deep phreatic loops grow below the water table as predicted in Ford's four-state-model (see Ford & Williams, 1989).

In summary, modelling has been successful in explaining empirical theories of cave genesis. In the future it will be of utmost importance to a deeper understanding of the way by which physical and chemical processes govern karst and its evolution.

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See also **Groundwater in Karst: Mathematical Models; Speleogenesis; Speleogenesis: Deep-Seated and Confined Settings; Speleogenesis: Unconfined Settings**

Works Cited

Clemens, T., Hückinghaus, D., Sauter, M., Liedl, R. & Teutsch, G. 1997. Modelling the genesis of karst aquifer systems using a coupled reactive network model. In *Hard Rock Hydrosystems,* edited by T.Pointet, Wallingford, Oxfordshire: IAHS

Dreybrodt, W. 1996. Principles of early development of karst conduits under natural and man-made conditions revealed by mathematical analysis of numerical models. *Water Resources Research,* 32:2923–35

Dreybrodt W. & Gabrovšek, F. 2000. Dynamics of the evolution of a single karst conduit. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Dreybrodt, W. & Siemers, J. 2000. Cave evolution on two-dimensional networks of primary fractures in limestone. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Dreybrodt, W., Romanov, D. & Gabrovšek, F. 2002. Karstification below dam sites: A model of increasing leakage in reservoirs. *Environmental Geology,* 42:518–24.

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Gabrovšek, F. 2000. *Evolution of Early Karst Aquifers: From Simple Principles to Complex Models,* Ljubljana, Slovenia: Zalozba ZRC

Gabrovšek, F., Menne, B. & Dreybrodt, W. 2000. A model of early evolution of karst conduits affected by subterranean CO_2 sources. *Environmental Geology,* 39:531–43

Gabrovšek, F. & Dreybrodt, W. 2000. Role of mixing corrosion in calcite-aggressive H2O−CO2−CaCO3 solutions in the early evolution of karst aquifers in limestone. *Water Resources Research,* 36:1179–88

Gabrovšek, F. & Dreybrodt, W. 2001. A model of the early evolution of karst aquifers in limestone in the dimensions of length and depth. *Journal of Hydrology,* 240:27–34

Kaufmann, G. & Braun, J. 2000. Karst aquifer evolution in fractured, porous rocks. *Water Resources Research,* 36:1381–92

Palmer, A.N. 1984. Recent trends in karst geomorphology. *Journal of Geological Education,* 32:247–53

Rhoades, R. & Sinacori, M.N. 1941. The pattern of ground-water flow and solution. *Journal of Geology,* 49:785–94

Sauter, M. & Liedl, R. 2000. Modelling karst aquifer genesis using a coupled continuum-pipe flow model. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N. Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Siemers, J. & Dreybrodt, W. 1998. Early development of karst aquifers on percolation networks of fractures in limestone. *Water Resources Research,* 34:409–19

Swinnerton, A.C. 1932. Origin of limestone caverns. *Geological Society of America Bulletin,* 34:662–93

Further Reading

Dreybrodt, W. 1990. The role of dissolution kinetics in the development of karstification in limestone: A model simulation of karst evolution. *Journal of Geology,* 98:639–55

Palmer, A.N. 1991. The origin and morphology of limestone caves. *Geological Society of America Bulletin,* 103:1–21

SPELEOGENESIS: DEEP-SEATED AND CONFINED SETTINGS

For a long time, traditional theories on the origin of caves and karst were largely concerned with shallow and unconfined settings, ultimately implying a close hydrological and morphogenetic relationship between the surface and subsurface. The common view was that karst processes and speleogenesis commence only when soluble rocks are exposed, whether immediately after deposition or after prolonged burial, and receive recharge from the overlying surface. Features at considerable depth were commonly treated as paleokarst. However, exposure of a soluble formation at the surface represents only a minor, although important, part of its karstification history that may commence during the deep-seated intrastratal stage that precedes exposure. The last decades of the 20th century witnessed a rapid increase in the recognition of speleogenesis with no apparent relation to the surface.

When related to speleogenesis, the term "deep-seated" does not carry a genetic meaning, but implies considerable spatial remoteness and separation from the surface. The term "hypogenic speleogenesis" is more genetically specific, indicating that cave-forming mechanisms rely on aggressiveness that has been produced at depth beneath the surface. "Confined" and "artesian" refer to hydrodynamics, and imply that groundwater is under pressure in a bed or stratum confined by less-permeable rocks or sediment above it. The hydraulic heads in this type of aquifer lie above the base of the confining beds. As far as groundwater dynamics is concerned, the vast majority of deepseated and hypogenic speleogenesis occurs in confined settings, or in settings that are unconfined but paragenetic or subsequent to confinement. Hence, the terms deep-seated, hypogenic, and artesian speleogenesis refer to closely related and overlapping, although not entirely equivalent, concepts.

The "classic" concept of artesian flow assumes that recharge of confined aquifers occurs only in limited areas, where they crop out at the surface (usually at basin margins) and that groundwaters move laterally through separate aquifers within the area of confinement. These simplistic assumptions have created a major problem in interpreting artesian speleogenesis. After moving for a considerable distance, and for a long time, through a soluble rock unit, water should be incapable of significant dissolution in the confined flow area. However, modern hydrogeologists are well aware that there are virtually no impervious rocks or sediments, just large contrasts in permeabilities. Hydraulic continuity in basins, and close cross-formational communication between aquifers, are common characteristics of artesian settings (Shestopalov, 1981; Töth, 1995). Artesian aquifers commonly receive significant proportions of their recharge from vertically adjacent formations, not only from exposed marginal recharge areas. Adoption of these views into karstology has allowed the reconciliation of many controversial points of view regarding the interpretation of speleogenesis in confined settings (Klimchouk, 2000).

Artesian basins containing carbonate and sulfate formations are widespread throughout cratonic and foreland regions. Within confined areas, cross-formational flow is predominantly ascending, being more intense in areas underlying prominent topographic lows, such as large river valleys. Most of the aggressive recharge to soluble units in confined settings comes from the underlying aquifer formations. Recharge can be dispersed across wide areas, which favours the formation of maze patterns, or can be focused locally, along high-permeability pathways such as fault zones. Cross communication between formations of different lithology and zones with contrasting geochemical environments or different physical conditions supports the operation of a wide variety of dissolutional mechanisms which, under deepseated and confined settings, may lead to the formation of caves.

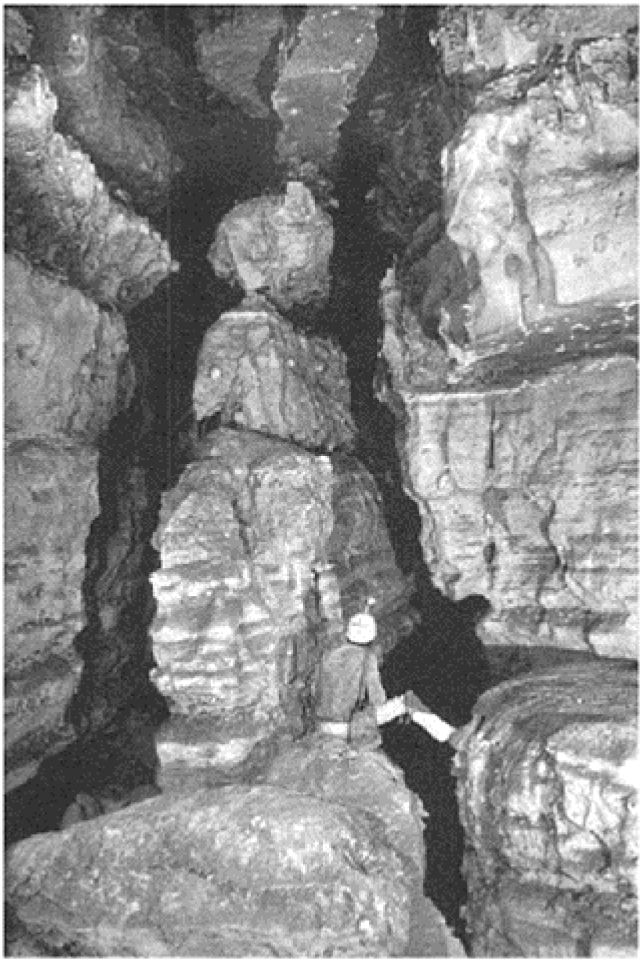
Aggressiveness in some cases represents an original undersaturation of groundwater with respect to the solid phase that is being entered, such as in the case of low-sulfate waters from underlying carbonates or sandstones entering a gypsum bed. It can also reflect the acquisition of new sources of acid (e.g. by oxidation of hydrogen sulfide), or be due to a number of mechanisms that rejuvenate the dissolutional capacity of fluids, such as the mixing of groundwaters of contrasting chemistry, the cooling of water, sulfate reduction and dedolomitization.

Carbonic acid dissolution, which dominates overwhelmingly in unconfined carbonate aquifers, also operates as a hypogenic agent, although the origin of the acidity is different. It can be related to CO_2 generated from igneous processes, to thermometamorphism of carbonates, or to thermal degradation and oxidation of deep-seated organic compounds by mineral oxidants. Creation of significant caves by hypogenic carbonic acid depends mainly upon the rejuvenation of aggressiveness by mixing, or by a drop in temperature. The latter mechanism is distinguished as hydrothermal speleogenesis, occurring in high-gradient zones where ascending flow is localized along faults.

The dissolution of carbonates by hydrosulfuric acid is another important speleogenetic process in deep-seated anoxic environments where there are sufficient sulfate sources for reduction, and where the H_2S generated can escape from the reducing zones—settings typical of the margins of sedimentary basins containing evaporate formations. In shallower conditions, where H_2S-bearing waters rise to interact with oxygenated meteoric groundwaters, sulfuric acid dissolution can be a very strong speleogenetic agent. Substantial sulfuric acid dissolution can also be caused by oxidation of metallic sulfides such as pyrite, where it is localized in ore bodies or along certain horizons or bedding planes.

Dissolution in deep-seated and confined settings is commonly slow, due to the prevailing sluggish circulation and, hence, to mass-balance restrictions. However, being operative over prolonged periods of geological time, it is generally important for cave inception, that is the opening up of pathways for further, more effective, circulation (Lowe & Gunn, 1997). Creation of significant caves occurs when continuing uplift brings stratified artesian aquifers closer to the eroding surface, or where local, highly effective flow-paths discharge deep-seated fluids into shallower aquifers. Both situations serve to activate groundwater circulation. Cave patterns depend mainly upon structural conditions, mode of recharge, and degree of confinement, rather than upon particular dissolution mechanisms.

In cases of transverse circulation across a uniformly fissured soluble bed enclosed within a stratified artesian system, dispersed aggressive recharge and short flow distances favour the formation of maze patterns. Discharges through fissures, and hence the rates of fissure enlargement, are kept uniform by restrictions imposed by the hydraulic properties of the feeder bed or the confining bed. Examples include some of the longest caves in both limestones (Wind and Jewel caves, see separate entry and Figure 1, in the Lower Carboniferous Madison Limestone of South Dakota, United States, and Botovskaja Cave in the Lower Ordovician limestones of Siberia) and gypsum (Optimistychna, Ozerna, and other giant mazes in the Miocene gypsum of the western Ukraine; see Ukraine Gypsum Caves). Smaller but no less significant caves are Fuchslabyrinth and Moestrof caves in the Muschelkalk limestones of Germany and Luxemburg, Knock



Speleogenesis: Deep-Seated and Confined Settings: Figure 1. Wind Cave, South Dakota, is a network maze consisting mainly of irregular fissure-like passages. The cave was formed along zones of paleokarst and former sulfate zones by mixing of at least two groundwater sources, probably including deep-seated waters. (Photo by Art Palmer)

Speleogenesis: Deep-Seated and Confined Settings: Figure 2. Geophyzicheskaya Cave, one of the large hypogene caves in the Karljuksky region, Kugitang Range. (Photo by Alexander Klimchouk)

Fell Caverns in the Carboniferous limestones of the United Kingdom, Estremera Cave in the Neogene gypsum of Spain, and Denis Parisis cave in the Paleogene gypsum of France. High passage density, strong fissure guidance and the presence of numerous feeder channels at the bottom, and outlet features at the top, of the layered passage systems are characteristic of such caves.

A specific mechanism of cave development driven by natural convection in confined settings is exemplified by the vast rooms intercepted by many mines in the Harz region of Germany. Aggressive water from the underlying aquifer attacks the bottom of the massive Zechstein (Upper Permian) gypsum bed. Once saturated, the water becomes denser and returns into the aquifer, being replaced by the less-dense aggressive water (Kempe, 1996).

Focused rising of deep-seated fluids into massive carbonate rocks commonly creates irregular large rooms or more complex ramifying patterns of merged rooms and smaller maze-like or separately rising passages diverging from them. Cave development occurs due to different mechanisms where aggressive fluids enter carbonates or where aggressiveness peaks (e.g. in the high thermal gradient zone in cases of hydrothermal speleogenesis, or in the zone of mixing of H_2S-bearing waters with the oxygenated meteoric waters in cases of sulfuric acid speleogenesis). Such caves are most likely to occur in carbonate build-ups at the margins of sedimentary basins (e.g. Carlsbad Caverns and Lechuguilla Cave, see separate entry, other caves in the Guadalupe Mountains, New Mexico, United States, the Cupp-Coutunn system, see separate entry, and other caves in the Karljuksky region of Turkmenistan, Figure 2) or in deep fault zones in tectonically active regions (e.g. Vento Cave, Frasassi [see Frasassi entry] and caves in the Buda Hills in Budapest, Hungary). An outstanding example of a giant cave created by, and still filled with, thermal water under high pressure is the cavern intercepted by deep drilling in Archaean marbles in the Rhodope mountains of Bulgaria (Dublyansky, 2000). This cavern, with an estimated volume of 237.6 million m^3 and a maximum intersected vertical dimension of 1341 m, is by far the largest known (although not directly explored) cave, by volume, in the world.

ALEXANDER KLIMCHOUK

See also **Inception of Caves; Patterns of Caves; Speleogenesis (various entries)**

Works Cited

Dublyansky, V.N. 2000. A giant hydrothermal cavity in the Rhodope Mountains. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Kempe, S. 1996. Gypsum karst of Germany. In *Gypsum Karst of the World,* edited by A.B.Klimchouk, D.Lowe, A.Cooper and U. Sauro, *International Journal of Speleology,* Theme issue 25(3–4)

Klimchouk, A.B. 2000. Speleogenesis under deep-seated and confined settings. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Lowe, D.J. & Gunn, J. 1997. Carbonate speleogenesis: An inception horizon hypothesis. *Acta Carsologica,* 26(2):457–88

Shestopalov, V.M. 1981. *Natural Resources of Underground Water of Platform Artesian Basins of the Ukraine,* Kiev: Naukova Dumka (in Russian)

Töth, J. 1995. Hydraulic continuity in large sedimentary basins. *Hydrogeology Journal,* 3(4):4–15

Further Reading

Dublyansky, Y. 2000. Hydrothermal speleogenesis: Its settings and peculiar features. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London: Unwin Hyman

Ford, T.D. 1995. Some thoughts on hydrothermal caves. *Cave and Karst Science,* 22 (3):107–18

Hill, C. 2000. Sulfuric acid hypogene karst in the Guadalupe Mountains. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Klimchouk, A.B., Ford, D.C., Palmer, A.N. & Dreybrodt, W. (editors) 2000. *Speleogenesis: Evolution of Karst Aquifers,* Huntsville, Alabama: National Speleological Society

Lowe, D.J. & Gunn, J. 1995. The role of strong acid in speleoinception and subsequent cavern development. In *Environmental Effects on Karst Terrains,* edited by I.Barany-Kevei special issue of *Acta Geographica,* 34:33–60
Palmer, A.N. 1991. Origin and morphology of limestone caves. *Geological Society of America Bulletin,* 103:1–21
Palmer, A.N. 1995. Geochemical models for the origin of macroscopic solution porosity in carbonate rocks. In *Unconformities and Porosity in Carbonate Strata,* edited by A.D. Budd, A.H.Saller & P.M.Harris, Tulsa, Oklahoma: American Association of Petroleum Geologists

SPELEOGENESIS: UNCONFINED SETTINGS

Dissolution caves in unconfined settings are created by meteoric water circulating at relatively shallow depths. The flow between sinkpoints and springs is contained within the soluble strata. It does not rise into them from below and does not tend to pass so deep beneath insoluble and impermeable confining strata that it is geothermally heated to a significant degree. The great majority of explored caves longer than 100 m or so belong to this class. Transitions to the types developed in young coastal rocks or in deep-seated and confined settings do occur.

In most cases the passages (conduits) of unconfined caves have developed along fissures such as bedding planes, joints, and faults, rather than through interlinked pores in the matrix of the rock. Fissure control of cave patterns is overwhelmingly predominant in the carbonate and sulfate rocks. Due to its greater solubility, salt can display important matrix (intergranular) permeability and caves developed in it may have patterns similar to those of coastal caves in young, porous limestones.

The great, fissure-guided cave systems of the world are three-dimensional complexes, usually with multiple "levels" created to drain to springs at successively lower elevations. For genetic analysis, plan patterns are considered first, then development in depth, considering, to begin with, only initial caves (the earliest level).

Development of the Plan Patterns of Caves

The simplest situation is that of a single conduit formed by one sinking stream—the case shown in Figure 1a. There are innumerable examples in nature, such as underground captures across the necks of entrenched river meanders. The controls which determine whether speleogenesis can occur, and the rate of development where it can, are the aperture of the fissure or linked sequence of fissures to be penetrated, their length, the hydraulic head, and the solvent capacity of the water. The kinetics of the carbonate and sulfate minerals in normal waters are non-linear—groundwater rapidly dissolves up to about 90% of its solvent capacity and thereafter approaches thermodynamic equilibrium (chemical saturation) asymptotically. Physical simulations and computer models show that there is initial competition between dissolutional microconduits, each slowly extending its 90% saturation position towards the output boundary, which will be a spring line or a pre-existing passage (Dreybrodt, 2000). One, or a few get ahead, gaining a hydraulic head ("equipotential") advantage (Figure 1a, frames 2 and 3). "Breakthrough" occurs when the rapid (~90%) front reaches the output. The winning conduit will be only ~1 cm in diameter initially, but will enlarge rapidly and capture most of the flow from its competitors, greatly reducing their rates of extension.

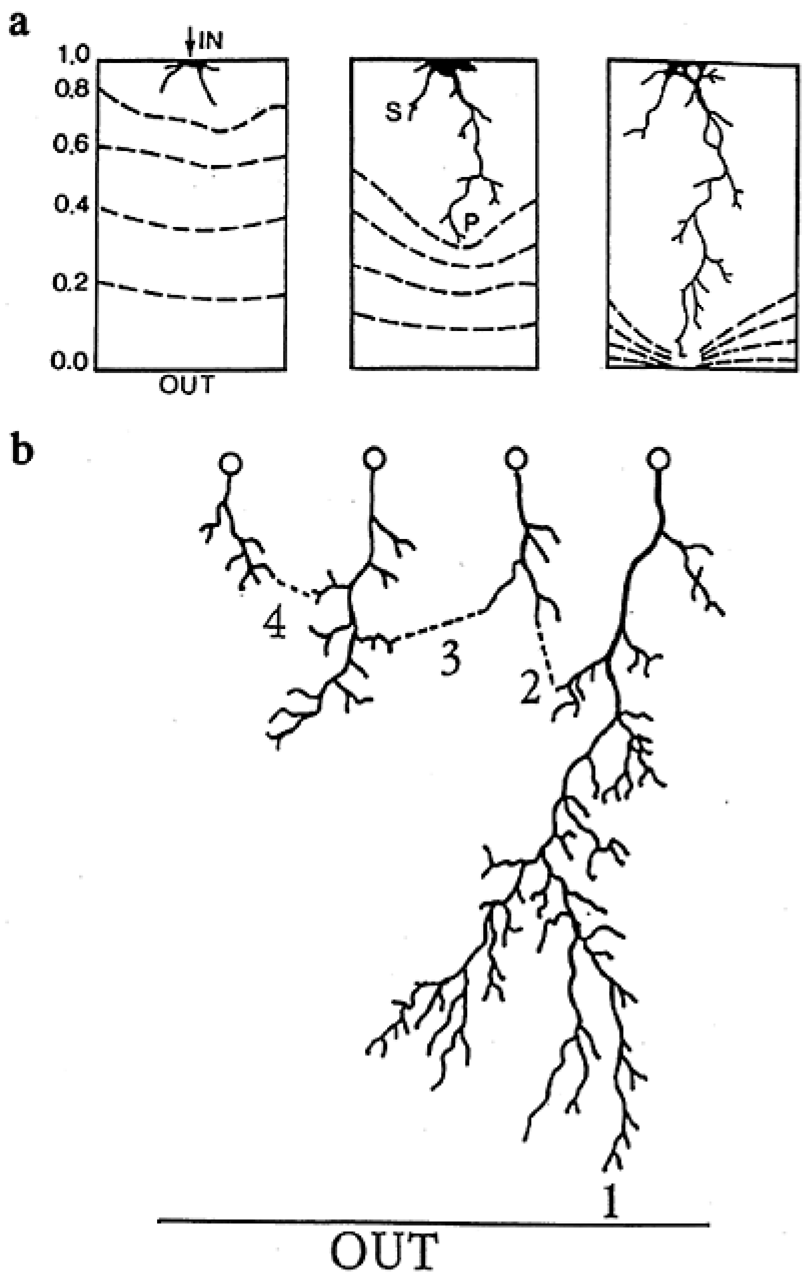
Sinuous, branching patterns, as shown, are most common in bedding planes. The form tends to be more direct in joints and faults. Minimum continuous apertures for effective penetration to occur are believed to be between 10 and 100 microns.

More often, a cave will have multiple inputs. Figure 1b shows the inputs in one rank, such as occurs where allogenic streams sink along a contact with limestone. In this particular model, the distance to the output boundary is the same for all inputs, as are the hydraulic head, amount of water available, and its solvent capacity. Nevertheless, because initial apertures chance to be slightly more advantageous there, the right-hand micro-conduit gets ahead, distorting the equipotential pressure field in its favour and eventually breaking through first (1). The others then break through to it in the sequence 2–3–4, linking up between the nearest branches. This creates a dendritic (tree-like) network of channels, feeding one trunk conduit to one spring. The sinuosity in the figure is characteristic of genesis in bedding planes or low-angle thrust faults. Where joint control is dominant, linking patterns are more angular.

Where initial fissure apertures are similar at all inputs also, equidimensional mazes of conduits may develop, with rectilinear patterns in joints and anastomoses in bedding planes. They can aggregate many kilometres when mapped but rarely have long overall flowpaths (more than 1 km or so). Many are floodwater mazes (Palmer, 2000) formed in the entrance zones of longer caves, because allogenic floods impact strongly there and surface erosion has unloaded the jointing, permitting it to gape; the mazes discharge into dendritic collectors downstream.

In nature, aperture, distance, hydraulic head, amount, and solvent capacity of water all tend to differ between inputs, however. Many caves are destined to have more distorted patterns than that of Figure 1b from the onset. In particular, in dipping strata, potential spring lines are often along the geological strike (i.e. on the left or right side of the figure), giving flowpath length advantages to one or a few inputs, as at Hölloch and Siebenhengstehöhle in Switzerland (see separate entries).

Broad areal karsts, such as limestone pavements, doline fields, or cockpit country, drain into many ranks of inputs, often with highly irregular patterns. Nevertheless, the principles of conduit initiation, competition and link-up remain the same as above. Broadly dendritic patterns of dissolution passages are created, beginning with the inputs closest to potential springpoints or otherwise most effectively connected to them. The surface forms themselves (dolines, cockpits, etc.) cannot develop to significant size until their conduit drains have broken through to join the cave.



Speleogenesis: Unconfined Settings: Figure 1. (a) The competitive extension of dissolutional microconduits across a fissure with anisotropic porosity. "P"=principal or victor conduit; "S"= secondary conduits. Dashed lines are hydraulic equipotentials. (b) Competitive extension where there are multiple inputs in one rank. Numbers and dashed lines indicate the predicted sequence of breakthrough connections that will occur. Both figures are drawings of actual dissolution experiments with plaster models—see Ford and Williams (1989), pp.249–261, for details.

Development in Length and Depth

The patterns that unconfined cave systems should display, when viewed in long section between the sinkpoints and springs, have been the subject of much debate, with different speleologists advocating development chiefly above the water table, below it, or along it (see Speleogenesis Theories: Post 1890; Ford, 1998). A resolution proposed by the author is presented here.

There can be three groundwater zones in unconfined karst settings:

1. an uppermost zone that is wholly vadose; i.e. water flows by gravity alone, through fissures in aerated rock. When it is very wet, the fissures may fill briefly but this does not affect cave development significantly;
2. a zone which is waterfilled initially but drains progressively as its local microconduits break through to springs or preexisting caves and become enlarged, drawing the water table down;
3. a phreatic zone of water-filled fissures beneath a water table (piezometric surface). It may include an epiphreatic (seasonally or episodically flooded) zone of lateral transmission.

Caves in Zone 1 tend to be sequences of shafts down the steepest fractures, linked together by short, often sinuous, stream canyons. Gravitational control of flow is predominant. These caves are best developed in young mountain terrains where rapid uplift and stressing opens vertical fractures wide and to substantial depths. The majority of the world's caves that are deeper than 1 km or so, gain most or all of their depth in this zone. Krubera (Voronja) Cave in Georgia (see separate entry), until 2003 the depth record holder, is a fine example. Where the karst rock formations are relatively thin and/or were little stressed during uplift, however, Zone 1 conditions may never have existed.

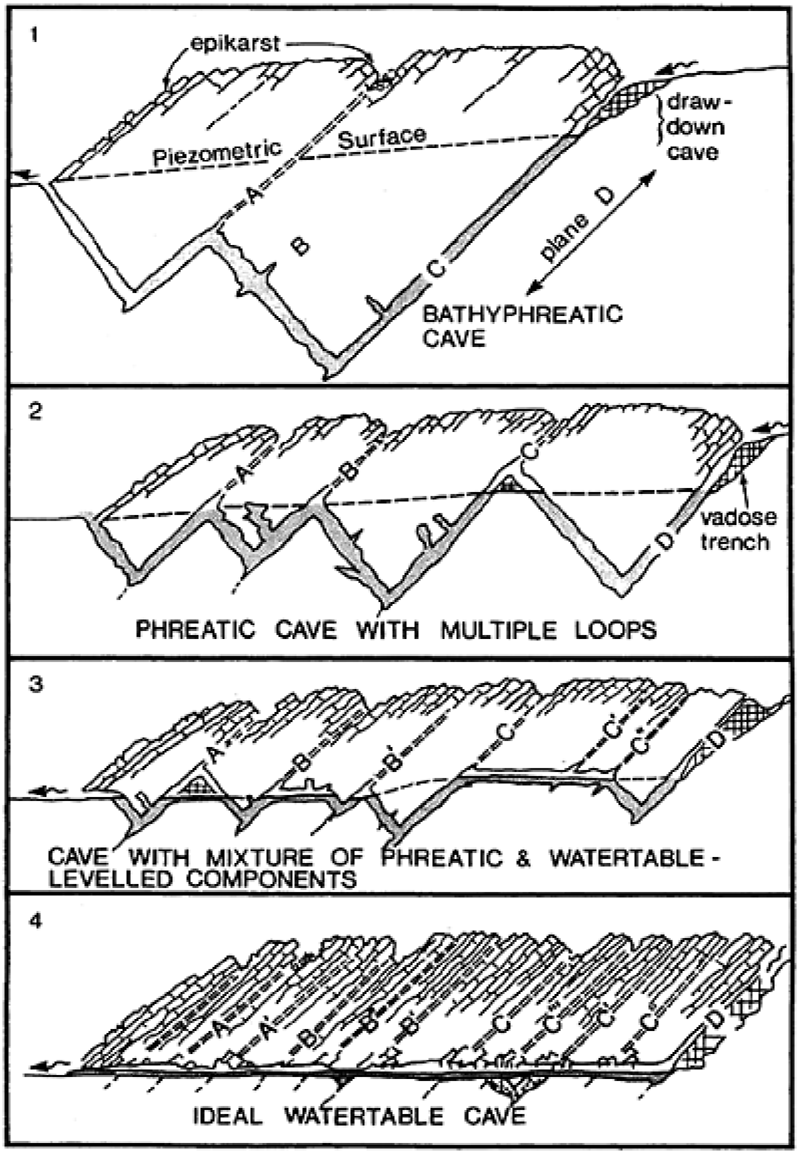
Cave passages in Zone 2 (the "drawdown vadose zone"—Ford, 2000) display initial phreatic forms such as elliptical cross sections in bedding planes, but with subsequent gravitational entrenchments beneath them. This combination can be found locally in Zone 1 also, where linking passages are perched on shale bands or other obstructions. The proportion of phreatic to vadose form may increase with depth. In vertical shafts, early phreatic features tend to be destroyed by the splashing water. Once drained, Zone 2 may be invaded by new streams if surface input points happen to be relocated, e.g. by glacial action; this introduces younger, wholly vadose forms—"invasion vadose" morphology.

Entire cave systems, from sinkpoints to springs, can develop wholly within Zone 1 and/or Zone 2 settings, especially where karst strata are perched on insoluble rocks above regional base levels. There can be deep gravitational entrenchment into the insolubles; e.g. some "contact caves" in Greenbrier County, West Virginia, have 90%+ of their volume in erodible shales beneath the limestones that hosted the initial passages. However, most extensive cave systems have substantial Zone 3 (phreatic or water-table) sections. Their length is usually greater than that of the vadose parts.

System geometry becomes more complex and varied in Zone 3. The four basic possibilities are best understood where strata dip steeply, as shown schematically in Figure 2–the "four state model". If the density of penetrable and interconnected fissures is very low, geologic structure may force the microconduits to follow courses below the elevation of the spring ("phreatic loops"). A State 1 system passes from Zone 2 to the spring via one sub-water-table loop. In State 2 there is a sequence of loops whose crests fix the local elevations of the water table. Where frequency and interconnection of penetrable fissures is greater, the cave may display a mixture of loops and gently graded passages at the water table (State 3). Very high frequency permits continuous, gently graded, development along the water table (State 4), similar to caves in young, porous limestones. There is probably phreatic looping to depths of 1000 m or more in some State 1 caves. Individual loops greater than 250 m deep are common in State 2.

States may vary in different sectors of extensive caves, reflecting changes in geologic conditions. In some multilevel caves there is more State 3 or 4 morphology in the lower, younger levels, as a consequence of dissolution progressing widely in the aquifer. In addition to frequency, fissure orientation can also be important; e.g. in Figure 2, one exceptionally open vertical fracture along the plane of the page between sink and spring could yield a State 4 cave instead of the deep State 1 loop. These variables underline the fact that phreatic cave patterns can rarely be predicted in detail.

By definition, a cave is a void large enough for human entry. Many unconfined systems will include considerable lengths of passages that are too small for humans but, nevertheless, originate and function in the same manner as the enterable systems. At the other end of the scale are active river passages (vadose, water-table, and phreatic) that are tens of metres in diameter; White (1988, p.287) discusses evolutionary histories for such large conduits.



Speleogenesis: Unconfined Settings: Figure 2. The Four State Model that differentiates the system geometry of unconfined phreatic and water-table caves. See Ford and Williams, 1989, pp.261–271, for details.

Multi-level (Multi-phase) Caves

As noted, most extensive cave systems have two or more “levels” that developed to drain to successively lower springs—“level” denoting the historical succession but not implying that the galleries must be near-horizontal; often, there is a sequence of State 2 or 3 geometries. In vadose caves, the lower levels may be simple entrenchments beneath the older passages. Where there is water table or phreatic development, the new springs are usually offset laterally tens to hundreds of metres or more. Distributary patterns are sometimes seen. The new springs steepen the hydraulic gradient in the downstream section of the old cave, which then adjusts to its new “level” in a sequence of breakthrough undercaptures (*French*—“soutirages”) that move the hydraulic steepening progressively upstream along the trunk and tributaries. Portions of individual capture links are incorporated into the final dendritic pattern of the new level but others are left redundant, becoming drained relicts or silted backwaters; see Ford and & Williams 1989, p.275, for an example.

Superimposition of successive levels, redundant links, and intruding invasion vadose caves from new sinkpoints, make maps of great systems such as Mammoth Cave, Kentucky (see separate entry), more complicated in appearance than almost any other geomorphic or hydrogeologic phenomena. Explorers can never be sure what will be seen around the next corner or up the next climb.

DEREK FORD

See also **Groundwater in Karst: Conceptual Models; Inception of Caves; Morphology of Caves; Morphometry of Caves; Patterns of Caves; Speleogenesis: Deep-Seated and Confined Settings**

Works Cited

Dreybrodt, W. (editor) 2000. Part 4: Theoretical Fundamentals of Speleogenetic processes. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Ford, D.C. 1998. Perspectives in karst hydrogeology and cavern genesis. *Bulletin d’Hydrogéologie,* 16:9–29

Ford, D.C. (editor) 2000. Part 5.3 Speleogenesis Under Unconfined Settings. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Palmer, A.N. 2000. Hydrogeologic control of cave patterns. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

White, W.B. 1988. *Geomorphology and Hydrology of Karst Terrains,* Oxford and New York: Oxford University Press

Further Reading

Bögli, A. 1980. *Karst Hydrology and Physical Speleology,* Berlin and New York: Springer (original German edition, 1978)
Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwells

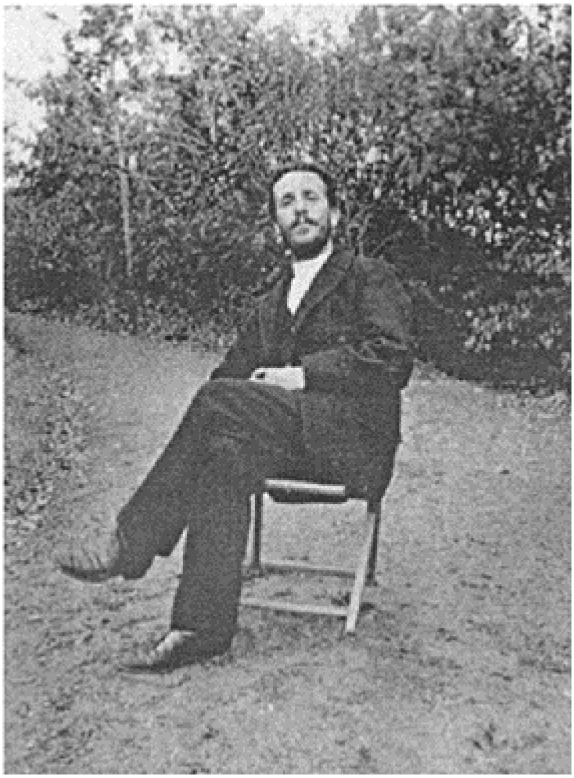
SPELEOLOGISTS

It has been exceedingly difficult to select people to be included in this biographical entry as the most significant speleologists of all time. The ones selected are people who have had the greatest influence on the subject overall, whether by making extensive regional studies of the karst at an early period, thus setting a standard of professionalism (for example, Xu Xiake, see Asia, Northeast: History entry, or Valvasor and Nagel); by extending the range of cave studies into a multidisciplinary subject, including fauna, flora, environment, and high-quality mapping (for example, Schmidl); by establishing international collaboration and specialist publication on caves, for example, Martel; or by extensive popular writing about their own and other explorations, thus making the subject known all over the world and inspiring many to take up caving for sport or for science (for example, Casteret). In every case these people have done much more than what is mentioned above, most notably vast amounts of original exploration. It has been necessary to leave out many others who have also made notable explorations or otherwise extended the knowledge of karst. However, some of them are mentioned in the regional history entries.

Speleologists: Figure 1. J.W.Valvasor aged about 48, in 1689.

Johann Weichard Valvasor (1641–93)
Baron Valvasor (Figure 1) was born in Ljubljana, Slovenia, and actively explored caves in that region from 1678 to 1689. He published descriptions of 13 of them, many for the first time, and his plan of Podpeška jama is only the second known printed map of a natural cave. His observations on the associated underground rivers are also of importance. The complex behaviour of the Cerknica intermittent karst lake caused him to attempt to explain it by a system of underground lakes and reservoirs (see entry or Cerknica Polje). This was published first as a paper in the *Philosophical Transactions* (of the Royal Society of Lon

Speleologists: Figure 2. Adolf Schmidl.



Speleologists: Figure 3. Martel in 1895.

don) in 1687, and as a result he was elected a member of that Society, among the most eminent men in Europe. Valvasor's wider reputation rests on his monumental topographical book on Slovenia, *Die Ehre des Herzogthums Crain…* (1689), which comprised 2872 large pages in four volumes. Many chapters in this are concerned with karst, and all his own cave explorations are contained in it. The cost of publication exhausted his considerable fortune and he had to sell his castle and his library. He died soon afterwards—a martyr to his enthusiasm and dedication.

The significance of his work on karst and caves lay very largely in the fact that he described his own original observations. The span of years over which he studied the karst and the detail of his descriptions all contributed to his importance, but most significant was his realization, for the first time, that caves and subterranean streams were an integral part of the whole system of karst hydrology. He was thus the first true speleologist.

Speleologists: Figure 4. Casteret aged 52, photographed at Montréjeau in 1949 by Winifred Hooper and reproduced by permission.

Joseph Anton Nagel (1717–1800)
Nagel was born at Rittberg in Westphalia (Germany), but spent most of his life in Austria, where he was attached to the Emperor's court as a mathematician. After this he held posts in the University of Vienna and was keeper of the royal scientific collections (the basis of the present natural history museum). It was by command of the Emperor Franz I that Nagel undertook his travels in the cave areas of the old Austro-Hungarian Empire, and his lengthy manuscript reports, illustrated by a series of drawings, were lodged in the Royal Library in Vienna. His Austrian visit took place in 1747 and in the following year he made two extensive journeys of several weeks each in Slovenia, followed by a tour of some of the karst regions of Moravia (now in the Czech Republic). His cave visits in Austria were of relatively minor importance, but in Moravia he penetrated 416 m into Sloup Cave (measuring the distance remarkably accurately as 406 m) and explored part of Cisařská jeskyně. In Slovenia he produced the first plans of Postojnska jama, Vilenica, and Socerbska jama; ventured 660 m into Planinska jama; and

descended Črna jama to the underground Pivka. His many other visits there include what seems to be the first one to Zeljnske jame near Kočevje, of which he also made a plan.

Nagel is significant for his determined examination of caves in several totally different areas. He was the first to do this, thereby anticipating the better known 19th-century figures such as Schmidl, Kraus, and Martel. He did not, however, discuss the regional characteristics of each set of caves.

Adolf Schmidl (1802–63)

Schmidl (Figure 2) was described by Martel as "the real originator of speleology or the scientific study of caves". He was born on 18 May 1802 at Königswart (now Kynžvart) in the Czech Republic, and came to Vienna in his youth, where he studied philosophy and law from 1819 to 1825. His cave explorations (between 1850 and 1856) were made when he was working in Vienna. From 1857 until his death on 20 November 1863 he was professor of geography at the Polytechnic at Budapest.

Nearly all Schmidl's cave exploration took place in Slovenia, Austria, and Hungary. He set out with the avowed intention of "establishing the exact topography of the caves" of Slovenia, exploring and recording meticulously and having accurate surveys made by his companion Ivan Rudolf. His accounts of the several caves of the Postojna system, and at Predjama, Škocjanska jama, Križna jama, and other caves provided the first exact descriptions of them. In Postojnska jama itself, his major achievement was the discovery of nearly half a kilometre more of the underground river Pivka. The most important of his findings were published in his book *Die Grotten und Höhlen von Adelsberg, Lueg, Planina und Laas* (1854), together with a discussion on cave fauna, cave meteorology, and other scientific aspects of cave research. In the opinion of Martel, this book was "the real starting point of speleology". In 1855 Schmidl turned his attention to Austria. In particular he explored the Geldloch and published a plan. His account is very detailed and pays particular attention to temperatures and to barometric pressures as a means of determining altitudes. It was in the same paper that he drew attention to Strein's 16th-century exploration of the cave, and printed Strein's manuscript in its entirety. In August of the following year he made a thorough investigation of the Aggtelek cave in Hungary, which, with its length of 8667 m, remained the longest cave in Europe until 1893. Once again he included tables of temperatures and also a note on cave fauna.

Schmidl made a conscious effort to bring the various branches of cave study together, both in research and in publication, and it is significant that the earliest word for this purpose in any language, Höhlenkunde, meaning cave study, was introduced by Schmidl in 1850. It is this breadth of his interests in cave studies, coupled with the extent of his discoveries and the technical difficulties that he surmounted, that justify Schmidl's reputation.

Édouard Alfred Martel (1859–1938)

Martel (Figure 3) was born at Pontoise in northern France and practised law in Paris from 1887 until 1899, after which he devoted himself entirely to caves and to writing. Martel's explorations were the basis of all his cave work. Without them he would have had nothing with which to influence people, and he would not have had the data to support his ideas on underground water flow and other scientific matters. Indeed, his main objectives were to explore, survey, record, and publish, which he did to an impressive extent over many years. The exact number of explorations during his entire career has never been worked out, but has been estimated to be about 1500. Even by the end of 1893 (after only six years of exploration) he had visited 230 caves. Of the 110 vertical caves included in this number, 90 were previously undescended; of 120 mainly horizontal caves, 30 were previously unentered, and 45 had not been explored fully. Also by this time, he had surveyed 28 km of cave passages himself, while his collaborators had surveyed another 22 km.

Most of his discoveries were made in the course of 26 annual "campaigns", from 1888 to 1913, although he continued his cave studies and writing after World War I and up to his death in 1938. The campaigns took place in seventeen countries: France, Belgium, Germany, Ireland, England, Norway, Switzerland, the Czech Republic, Slovakia, Hungary, Slovenia, Greece, Italy, Spain, Turkey, Russia, and the United States. All the discoveries were fully published at the time. Experienced as he was in exploring many different kinds of ever more difficult caves, it is only to be expected that Martel developed some of the basic techniques involved. In 1889 he and Gaupillat were the first to use telephones in caves, where they found them useful on deep shafts, especially any that were more than 100 m deep. Their apparatus was fairly light for the time, being about 8 cm in diameter and weighing 480 g, and they used it successfully with as much as 400 m of wire. Martel's other claim for originality in equipment was in the cave use of the folding canvas canoe. The volume and quality of his publications are as impressive as his explorations. He produced some 20 books and 780 papers, many of them in scientific journals of the highest quality. Many of his writings were also translated and published abroad.

Martel was more than just a cave explorer, cave researcher, and writer. He also consciously caused the study of caves to spread into countries outside the European core where it was already flourishing. He was a leader who inspired and encouraged people to investigate the caves and karst problems of their own lands. The Société de Spéléologie, founded by Martel in Paris in 1895, enjoyed high scientific standing from the outset, and it was one means by which he contrived the extension of cave study into an international subject. Foreign membership of the Société was remarkably high. Some 21% of the founder members lived outside France, indicating the close links already existing before 1895. Between 1895 and 1904 the proportion rose to 29%; in addition three foreign cave societies were members. Many papers by foreign contributors, most of them members, were published in the Société's journal, *Spelunca*, comprising between 14% and 50% of the papers printed in individual years.

There can be no doubt about the extent of Martel's personal links with speleology in other countries. Of his 26 annual campaigns of exploration, 19 went outside France in what are now 20 nations and, in addition, he made lecture tours and other visits abroad. At least 61 of his own publications on caves appeared elsewhere in his lifetime. Many of these were papers presented to learned societies, and there were also popular articles and the texts of public lectures; other were simply translations or reprints of work already published in France, showing the interest with which this was regarded abroad.

Norbert Casteret (1897–1987)

Born at Saint-Martory in Haute-Garonne (France), a soldier in World War I, and an enthusiastic skier and swimmer, Casteret (Figure 4) approached cave exploration more as a dedicated sportsman than a scientist. His achievement of over 2000 caves explored, including many very major ones, was done mostly from 1922 till when he was over 60, but his 35 m rope climb in and out of the Gouffre de Planque was made at the age of 15. Six of his new discoveries, including Montespan, contained prehistoric art. Other specially notable explorations were in the Grotte de la Cigalère, the Gouffre Martel (then the deepest in France), and the Henne-Morte. Although the discoveries that he made during his long period of active exploration were extensive and important, speleology was already an established subject in his lifetime, and similar explorations of equal difficulty were being made elsewhere.

What sets Casteret apart is his writing, conveying his enthusiasm as well as his results to the general public and hence inspiring many young people to take up cave exploration. His 47 books have been translated into 16 languages and some have been published in Braille. The diversity of Casteret's achievements is reflected in the medals that he received, which include the Croix de Guerre, 4 gold medals from geographical and sporting organizations, and 3 life-saving medals (one of them earned when he was 78).

TREVOR SHAW

See also **Archaeologists; Biospeleologists; Geoscientists**

Further Reading

André, D. (editor) 1999. *L'homme qui voyageait pour les gouffres. Actes du colloque tenu a Mende les 17 et 18 octobre 1997* [The man who travelled for caves], Mende: Archives départementales de la Lozère Proceedings of a symposium in honour of Martel

Casteret, N. 1943. *E.A. Martel, explorateur du monde souterrain* [E.A. Martel, Explorer of the Underground World], Paris: Gallimard

Chabert, J. 1986. *Norbert Casteret: bibliographie,* Paris: Gandini and Spelunca Librairie (with supplement, *Complements et rectificatifs*, by M.Casteret and J.Chabert, 1997)

Chabert, C. & de Courval, M. 1971. *E.A.Martel 1859–1938 bibliographie,* Paris: Spéléo-Club de Paris

Jolfre, J. 1992. *Norbert Casteret explorateur d'abîmes* [Norbert Casteret Cave Explorer], Toulouse: Milan

Reisp, B. 1983. *Kranjski polihistor Janez Vajkard Valvasor* [Carniolan polymath J.W.Valvasor], Ljubljana: Mladinska Knjiga

Salzer, H., 1931. *Die Höhlen- und Karstforschungen des Hofmathematikers Joseph Anton Nagel* [The Cave and Karst Researches of the Court Mathematician J.A.Nagel], *Speläologisches Jahrbuch,* 10–12:111–21 & Taf. VII–XI

Shaw, T.R. 1978. Adolf Schmidl (1802–1863) the father of modern speleology? *International Journal of Speleology,* 10:253–67

Shaw, T.R. 1992. *History of Cave Science, the Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society

Gives extra information on all except Casteret

SPELEOTHEM STUDIES: HISTORY

As in the case of speleogenesis history, explanations of how speleothems formed were influenced by the wider beliefs of the time. As late as the 18th century it was commonly thought that rocks, especially crystals and mineral ores, grew: that they possessed a form of life lower than that of plants but rather similar. So it is no surprise to find that this idea was once applied to stalactite growths. Explanations of speleothem growth can be divided into three classes: those in which the material grows as a living substance; those in which it is deposited in some way from underground vapours; and those in which dripping water is either congealed into stone or deposits stony material that it has carried with it.

The belief that rocks and minerals grow like plants was applied to speleothems in the 17th and early 18th centuries. It was subsequently developed and persisted even into the 19th century. It was first advocated by John Beaumont, who studied caves in the Mendip Hills of England and presented his conclusions to the Royal Society in 1676. Like most of his contemporaries, Beaumont believed that fossil shells had grown in the rock where they were found, so the application of the idea to stalagmites was a logical extension of that belief. Better known is J.P. Tournefort's visit to the cave in the Greek island of Antiparos in August 1700 (see Figure in Caves in History: The Eastern Mediterranean). The exploration was moderately difficult for the time, involving rope descents and the use of a rigid ladder brought in for the purpose, but Tournefort's main interest was in the origin of speleothems. He noted what looked like the growth rings of trees, and stated that "These stems of marble must certainly vegetate".

The vapours occurring in caves, either from normal underground humidity or derived from deep in the earth, were held by some to condense or deposit to form stalactites or else to cause the ordinary percolating water to solidify. In one theory, vapours were believed to provide the nourishment that enabled vegetative growth to proceed.

Dripping water was most commonly regarded as the source of speleothem material. In some cases it was believed to congeal of itself from a variety of causes; in others it was supposed to consist of or contain a "lapidifying juice", whose special nature enabled it to turn into stone. A natural development of this idea considered that the petrifying material was a stony substance already present in the water, and gradually the distinction was made between material in suspension and in solution. Slowly, from the beginning of the 18th century, it came to be realized that the presence of this material was made possible by the water containing an acid of some sort, which enabled it to dissolve part of the surrounding rock. The recognition of the atmospheric origin of this acid, and finally, in 1812, of the chemical reactions involved, brings us to the present day.

Typical of early statements at the start of the pathway to modern thought is this one of 1655 by the Danish professor, Olaus Worm. He wrote that speleothems are:

> Formed by deposition from water which has rock-forming properties because it carries within itself finely divided mineral matter…. Dripping down from a high crack, it adheres where it can in the shape of a cone…(quoted in Shaw, 1992)

Although he and several others spoke of the water depositing its particles or salts, they did not say what they thought caused the deposition. The first person explicitly to attribute the deposition of stalactitic matter to the effect of evaporation of water was Karl Nicolaus Lang, in 1708. But as yet there was no suspicion that it was an acid that caused the solution of these "salts" and that it was evaporation of this acid that caused the deposition.

The explanations incorporating such an acid can be divided into three groups. First come those (1700 to 1742) in which the solution of rocky material is aided by some unspecified acid in the atmosphere, which may be what is now recognized as carbon dioxide. Then comes another group (1782 to 1794) in which the atmospheric acid seems to be equivalent in every way to carbon dioxide, although recognition of its chemical composition was still delayed by the waning concept of phlogiston. And finally, from 1812 onwards, the role of carbon dioxide was fully appreciated. The unspecified acid was described as the "acid spirit of the atmosphere" or, more often, simply as "the aerial acid". J.G Lesser in 1735 suggested that rock material was dissolved by the acid, but that this material was deposited in caves by the evaporation of water. A few years later, however, in 1742, Louis Bourget associated the deposition with the release of an "air" from the water.

In 1812 the distinguished French naturalist, Georges Cuvier, suggested that deposition occurred as the acid gas escaped from the water, and he was the first person positively to identify this gas as carbonic acid:

> Certain waters, after dissolving calcareous substances by means of the superabundant carbonic acid with which they are impregnated, allow these substances to crystallize after the acid has evaporated; and, in this manner, form stalactites, and other concretions. (Quoted in Shaw, 1992)

This acid solution theory became generally, although not universally, accepted in the first half of the 19th century, in contrast to its sporadic and partial appearance before 1812. Two factors probably brought this about. The clear and authoritative statements in English by the very influential scientists Cuvier and Benjamin Silliman made it available in at least two languages, and the demise of the phlogiston theory enabled the chemical action of carbon dioxide in the solution of limestone to be more clearly understood. The carbon dioxide involved in the processes of solution and deposition was at first either implied to come from atmospheric air, or else its origin was ignored altogether. It was left to Justus von Liebig in about 1840 to associate the production of the gas by rotting vegetation with its concentration in the soil and the rock beneath. Liebig also appreciated for the first time that it was only the excess of carbon dioxide over and above the equilibrium quantity that was released in the cave.

Since 1900 there has been a large growth in interest in mineralogy and types of speleothems (see entries on Speleothems).

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Further Reading

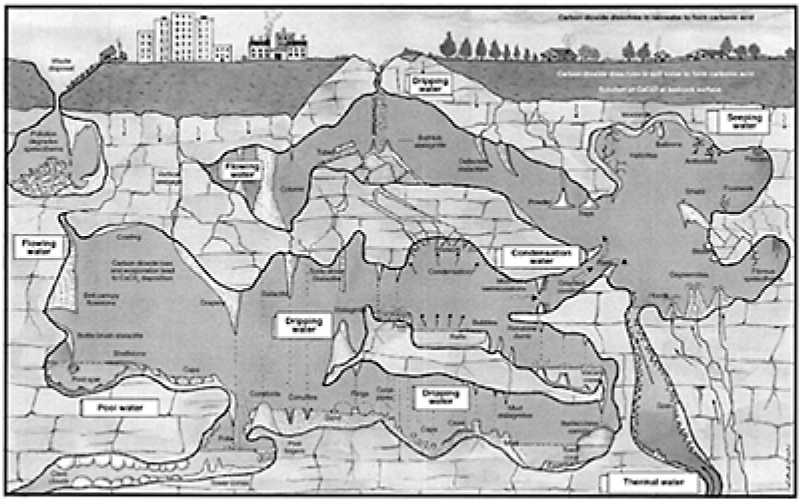
Shaw, T.R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society
This gives much more information, with references to the original sources.
Shaw, T.R. 1997. Historical introduction. In *Cave Minerals of the World,* by C.Hill & P.Forti, 2nd edition, Huntsville, Alabama: National Speleological Society
A much fuller treatment than in this entry, with references and including also non-calcite speleothems.

SPELEOTHEMS: CARBONATE

A speleothem is a secondary mineral deposit formed in caves (Moore, 1952). The term refers to the mode of occurrence of a cave mineral; i.e. its morphology, or how it looks, not to its composition. This section covers carbonate speleothems. For a discussion of the various other mineral classes that form speleothems in caves, refer to the entry on Minerals in Caves.

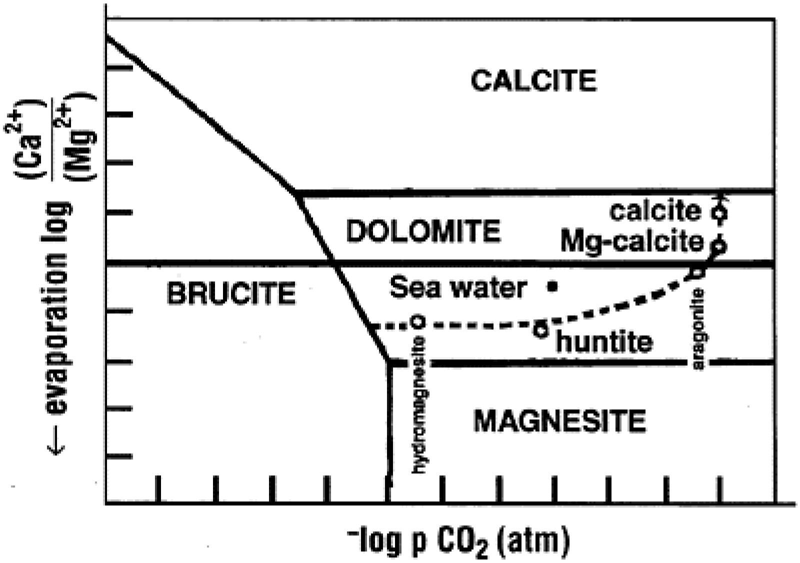
The carbonates, a group that has the $(CO_3)^{2-}$ anion as its essential component, are the most important class of cave minerals. The two most common cave minerals, calcite ($CaCO_3$) and aragonite ($CaCO_3$), belong to this class and together probably comprise >95% of all mineral deposits in caves. Hydromagnesite $[Mg_5(CO_3)_4(OH)_2 \cdot 4H_2O]$ is the third most common carbonate cave mineral, and is probably the most common constituent of moonmilk in dolostone caves. Carbonate speleothems have been used by humans for medicinal and other purposes for over 2000 years.

Practically all of the various forms that speleothems display in caves are represented by the carbonate minerals, with the exception of fibrous speleothems, which is the main form taken by the sulfate minerals (see Speleothems: Evaporite). Hill & Forti (1997) classified speleothems into 38 “official” types, based primarily on morphology and secondarily on origin and crystallography. These various types form from flowing water, dripping water, pool water, seeping water, condensation water, and thermal water (or a combination of two or more of these processes) (see Figure 1 and photos in colour plate section). Carbonate speleothem types (and subtypes) formed primarily from dripping water are stalactites, stalagmites, columns, coralloids, conulites, coral pipes, showerheads, cave rings, and cave caps. Those formed from flowing water are flowstone, draperies, and canopies. Types and subtypes formed from pool water (at or near the surface of the pool) are cave rafts, shelfstone, rimstone dams, cave pearls, folia, pool fingers, cave bubbles, cave cups, “bottle-brush” stalactites, tower coral, cave cones, and pool spar; those formed in deep pools or in the “phreatic zone” (zone of saturation) are cave clouds and cave mammillaries. Seeping water can create a variety of speleothems: helictites, moonmilk, boxwork, frostwork, anthodites, shields, coatings, crusts, cave blisters, cave balloons, cave tubes, and powder. Condensation water forms rims, cave trays, and oriented coralloids, and thermal water forms large spar crystals and geysermites. Variation of colour and luminescence in these speleothem types is due to impurities in solution (see Speleothems: Luminescence).

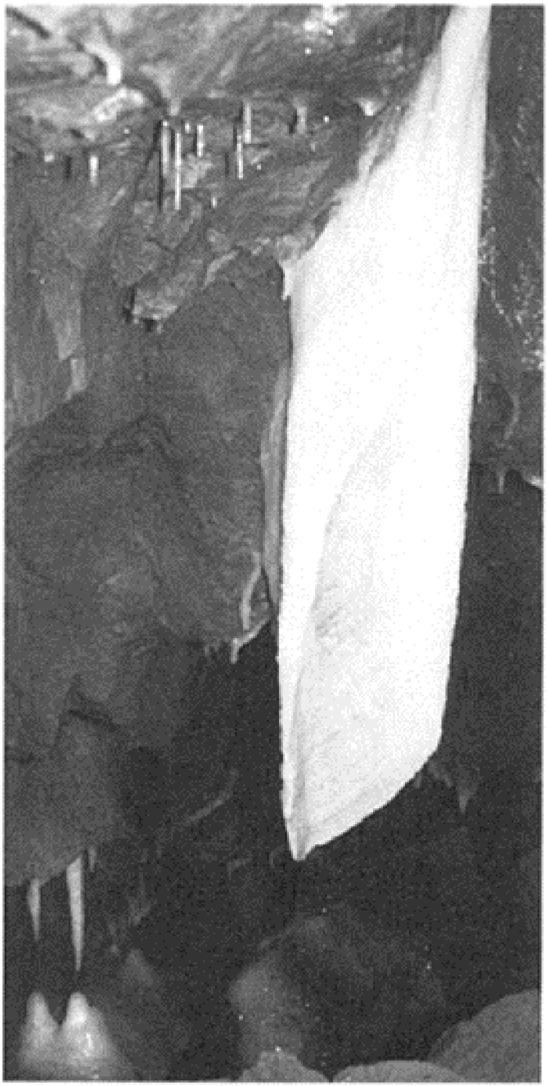


Speleothems: Carbonate: Figure 1. Diagram of various carbonate speleothem types and subtypes formed by flowing water, dripping water, pool water, seeping water, condensation water, and thermal water. From *Cave Minerals of the World,* Hill & Forti, 2nd edition. Drawing by Luciano Casoni.

The chemical evolution of cave waters with regard to the precipitation of carbonate speleothems can be divided into three stages (Holland *et al.,* 1964): (1) carbonation in the soil zone, where rainwater picks up carbon dioxide to form a weak carbonic acid (Figure 1); (2) dissolution of carbonate bedrock, where the carbonic acid dissolves limestone (and dolostone) bedrock; and (3) carbonate precipitation, where carbon dioxide exchange with the cave air, and to a lesser degree evaporation, causes carbonate speleothems to precipitate.



Speleothems: Carbonate: Figure 2. A graph showing the evolution of cave water with respect to increasing evaporation and carbon dioxide loss. After Lippman (1973). From *Cave Minerals of the World*, Hill & Forti, 2nd edition.



Speleothems: Carbonate: Figure 3. The Angel’s Wing, a pure white calcite curtain in Shatter Cave, Mendip Hills, England. (Photo by John Gunn)

The relative amount of carbon dioxide loss, evaporation, and the amount of magnesium in solution determines the carbonate mineral species that will precipitate (Figure 2, follow dashed line and arrow). As groundwater entering a cave degasses carbon dioxide, calcite is precipitated so that the magnesium ion increases relative to the calcium ion (i.e.

the Mg/Ca ratio increases). After calcite, magnesium-enriched calcite (Mg-calcite) precipitates, then aragonite (Mg/Ca ratio>2.9), then huntite, then hydromagnesite (Mg/Ca>16). Aragonite, the polymorph of calcite (both have the same chemical composition but different crystal structures), can usually (but not always) be distinguished from calcite because it displays a needle-like habit.

In the last few decades, carbonate speleothems (in particular stalagmites and flowstone) have proved important to many fields of research such as absolute dating (Ford, 1997), paleoclimatology and paleoenvironmental reconstruction (see Paleoenvironments: Speleothems); and paleoseismology (see Paleotectonics from Speleothems). Hill & Forti (1997) list hundreds of published papers dealing with these categories.

Because carbonate (and other) speleothems are often rare or fragile, every effort should be made to preserve them within the cave environment. Conservation efforts in both wild and show caves have included: (1) limiting access to mineralogically sensitive caves by gating or other techniques (Veni, 1997); (2) monitoring the cave environment with respect to temperature, humidity, carbon dioxide, and lighting levels (Cabrol, 1997; Veni, 1997); (3) effecting repair of broken speleothems (Veni, 1997); and (4) restricting collection of speleothems and cave minerals, even for scientific sampling. Cave minerals and speleothems belong in, and should stay in, caves!

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See also **Minerals in Caves; Speleothems: Evaporite; Speleothems: Luminescence; Speleothem Studies: History**

Works Cited

Cabrol, P. 1997. Protection of speleothems. In *Cave Minerals of the World,* 2nd edition, edited by C.A.Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Ford, D.C. 1997. Dating and paleo-environmental studies of speleothems. In *Cave Minerals of the World,* 2nd edition, edited by C.A.Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Hill, C.A. & Forti, P. (editors) 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society

Holland, H.D., Kirsipu, T.W., Huebner, J.S. & Oxburgh, U.M. 1964. On some aspects of the chemical evolution of cave waters. *Journal of Geology,* 72:36–67

Lippman, F. 1973. *Sedimentary Carbonate Minerals,* Berlin and New York: Springer

Moore, G.W. 1952. Speleothem—a new cave term. *National Speleological Society News,* 10(6):2

Veni, G. 1997. Speleothems: preservation, display, and restoration. In *Cave Minerals of the World,* 2nd edition, edited by C.A. Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Further Reading

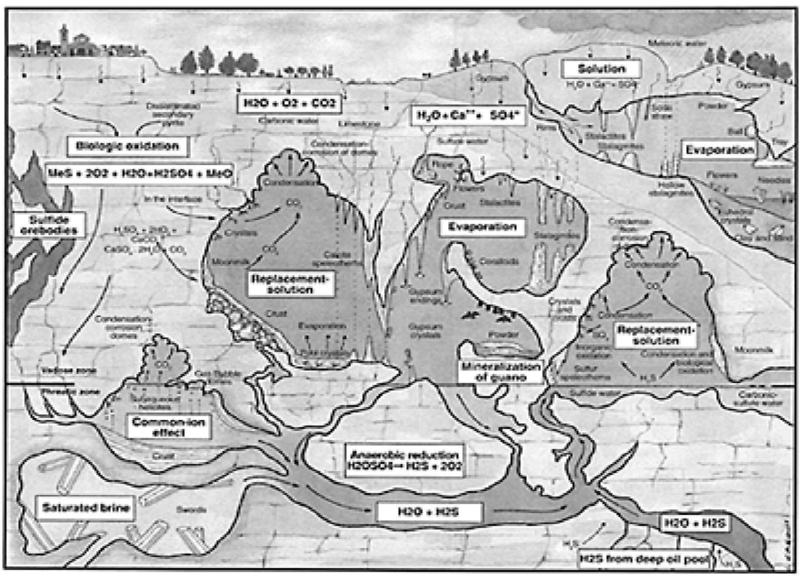
Hill, C.A. & Forti, P. (editors) 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society

SPELEOTHEMS: EVAPORITE

A speleothem is a secondary mineral deposit formed in caves (Moore, 1952). The term refers to the mode of occurrence of a cave mineral, i.e. its morphology, or how it looks, not to its composition (Hill & Forti, 1997). Evaporite speleothems are those where deposition is controlled primarily by evaporation, even though a number of different mechanisms may be involved in the evaporative process (see Figure 1).

The two main classes of evaporite minerals in caves are the sulfates and halides (for other cave mineral classes, see Minerals in Caves). Sulfates represent the largest class, with gypsum ($CaSO_4 \cdot 2H_2O$) being by far the most common cave sulfate and the third most common cave mineral after calcite and aragonite (it is estimated that gypsum represents *c.* 2–3% of all cave deposits). Halide speleothems are much less abundant than sulfates, usually forming where halite (NaCl) bedrock exists in the overburden, but also, rarely, forming from bat guano. The best and widest display of halide speleothems has been described from the Mount Sedom caves of Israel (Frumkin & Forti, 1997).

The depositional environments under which evaporite speleothems form are varied: (1) a limestone, gypsum, or halite rock



Speleothems, Evaporite: Figure 1. All mechanisms causing sulfate deposition in caves. From *Cave Minerals of the World,* Hill & Forti, Second Edition. Drawing by Luciano Casoni.

setting; (2) lava tubes; (3) bat guano; (4) associated with ore bodies; and (5) associated with fumarole activity. Evaporite speleothems can assume almost all the same forms as carbonate speleothems (see Speleothems: Carbonate), but they usually display a fibrous or filamentary habit. Fibrous speleothems can be divided into four subtypes, depending on the length of the crystal fibres and the way in which the fibres intertwine with each other: (1) single crystals (hair); (2) bunches of single crystals (cotton) (Figure 2); (3) fibres matted together (rope) (Figure 3); and (4) fibres that split (flowers). Often one or more of these subtypes will occur together; e.g. all four types coexist in Valea Rea Cave, Romania (Onac *et al.*, 1995).

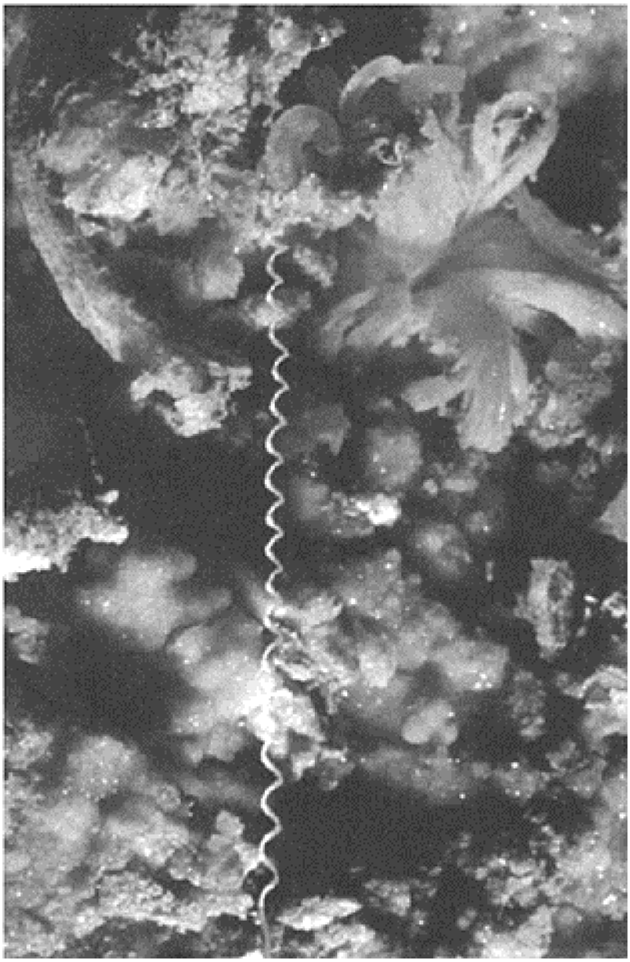
Even where evaporite speleothems do form as dripstone (Figure 4), the distinct genetic mechanism under which these form (i.e. supersaturation due to evaporation) causes them to differ in morphology from carbonate speleothems. For example, sulfate stalactites are typically more contorted or multibranched than carbonate stalactites, and their growth depends, almost exclusively, upon surficial percolation water rather than upon water that feeds through a central tube. This commonly results in the central tube being absent, or partially (if not completely) obstructed. Furthermore, the effect of permanent air currents with respect to carbonate and evaporite stalactites is exactly the opposite. In the carbonate case, growth is controlled by CO_2 diffusion, and because such diffusion is not influenced by air currents, the stalactite is deflected in the direction of air movement (i.e. in the same direction that the water droplets are deviated before they fall). However, in evaporite speleothems, the inverse effect dominates, and so stalactites deviate towards the source of the air current where maximum evaporation is occurring.

Compared with the carbonates, evaporite minerals form helictites only rarely and with extreme difficulty. This is because the process of evaporation leads to a greater obstruction of the helictite’s feeding capillary. Also, it is much easier for wind-related speleothems, such as rims and trays, to develop in an evaporative environment. Euhedral crystal occurrences are also more common: gypsum crystals may range from a few microns (gypsum powder) up to several metres (gypsum swords) in length.

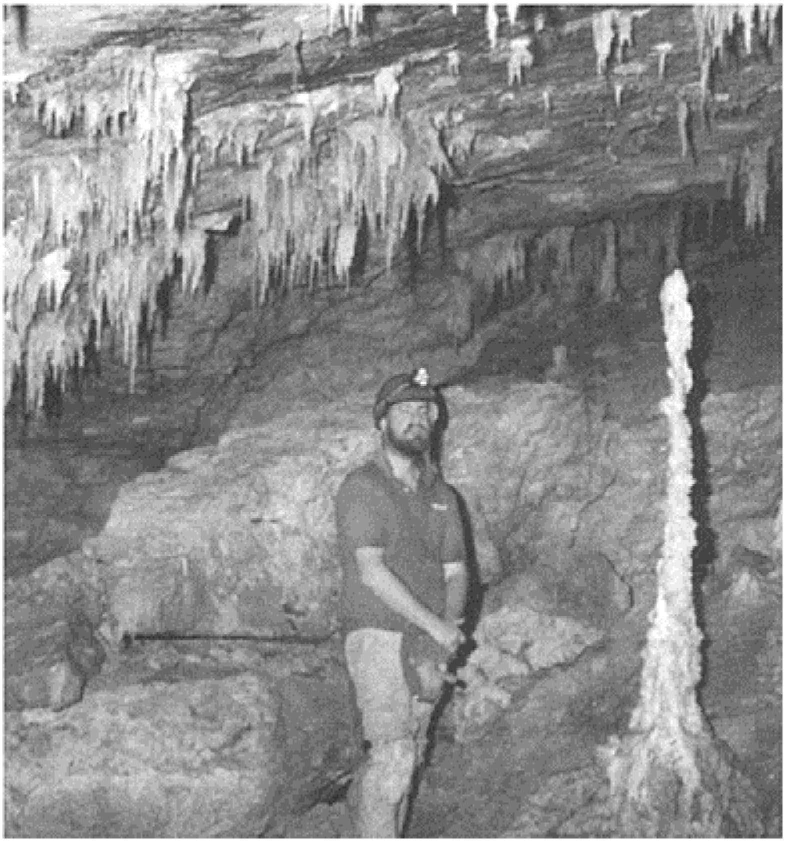
Since the minerals making up evaporite speleothems are often highly soluble, these speleothems can therefore have shorter “life-spans” in caves than carbonate speleothems. For example, thenardite (Na_2SO_4) speleothems are only deposited in the volcanic caves of Mount Etna, Italy during the initial hot and dry time

of lava tube formation. This thenardite rapidly transforms into mirabilite as water seeps into the cave and the temperature falls; then it completely dissolves when the cave reaches equilibrium conditions and the seeping water stops evaporating. Often evaporite speleothems are seasonally ephemeral, like the mirabilite and epsomite flowers present in the gypsum caves of Bologna in Italy and the gypsum powders found in the Pinega (Russia) and New Mexico (United States) gypsum caves (Forti, 1996).

Speleothems, Evaporite: Figure 2. A pile of selenite crystals in the Zhucaojing cave, in the Xingwen karst of China, where pyrite beds overlying the limestone provide a ready source of sulfur and sulfate. (Photo by Andy Eavis)



Speleothems, Evaporite: Figure 3. "The Spring", a gypsum rope in Puketiti Flower Cave, New Zealand. (Photo by John Gunn)



Speleothems, Evaporite: Figure 4. Salt stalagmite, Thamapana Cave, Nullarbor Plain, Australia. (Photo by John Gunn)

Evaporite speleothems—in particular gypsum—have proved to be useful tools for paleoclimatic studies. The abundance of calcite and gypsum speleothems in caves formed in gypsum rock depends strictly on the climate of the area in which the cave is located (Calaforra & Forti, 1999). Therefore, where there is a sudden change in the depositional record (from dominant calcite to dominant gypsum, or vice versa, or even to no deposition), it is reasonable to suppose that the climate of the area had changed during this time.

Extra effort is required to preserve evaporite speleothems, due to their fragile crystal form (e.g. hair, cotton, flowers) and to their unstable nature outside the cave environment (i.e. many evaporite minerals disintegrate into powder when removed from a cave). Like carbonate speleothems and all cave minerals, these belong in, and should stay in, caves!

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See also **Minerals in Caves**

Works Cited

Calaforra, J.M. & Forti, P. 1999. May the speleothems developing in gypsum karst be considered paleoclimatic indicators? *Abstracts, International Union for Quaternary Research, 15th International Congress, August, 1999, Durban, South Africa,* Durban: International Union for Quaternary Research

Forti, P. 1996. Speleothems and cave minerals in gypsum caves. *International Journal of Speleology,* 25(3–4):91–104

Frumkin, A. & Forti, P. 1997. Liquid Crystal Cave. In *Cave Minerals of the World,* 2nd edition, C.A.Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Hill, C.A. & Forti, P. 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society

Moore, G.W. 1952. Speleothem—a new cave term. *National Speleological Society News,* 10(6):2

Onac, B.P., Bengeanu, M., Botez, M. & Zeh, J. 1995. Preliminary report on the mineralogy of Valea Rea Cave (Bihor Mountains, Romania). *Theoretical and Applied Karstology,* 8:75–9

Further Reading

Hill, C.A. & Forti, P. 1997. *Cave Minerals of the World,* 2nd edition, Huntsville, Alabama: National Speleological Society

SPELEOTHEMS: LUMINESCENCE

Many speleothems exhibit luminescence when exposed to ultra-violet (UV) light sources or other high-energy beams. Nearly 50 minerals known in caves have the capacity to exhibit luminescence, but so far, only 17 are actually observed to be luminescent in speleothems. For detailed explanation of luminescence types and properties of minerals, refer to Shopov (1997). Most known luminescent centres in calcite are inorganic ions of Mn, Tb, Er, Dy, U, Eu, Sm, and Ce. Claims that Sr causes luminescence in carbonates and Cu in calcite and aragonite are in error, as are suggestions that visible luminescence in calcite may be Pb-activated, because Pb emits only ultraviolet light. Minerals contain many admixtures. Usually several centres activate luminescence of the sample and the measured spectrum is the sum of the spectra of two or more of them. Conventional luminescent research methods have a number of disadvantages when applied to speleothems, so several special methods have been developed (see Table).

Luminescence of minerals formed at normal cave temperatures is due mainly to molecular ions and sorbed organic molecules. Luminescence of uranyl ions (Figure 1) is also very common in such speleothems. Before using a speleothem for any paleoenvironmental work, it is necessary to determine that all of its luminescence is due to organics.

Calcite speleothems frequently display luminescence, which is produced by calcium salts of fulvic and humic acids (Shopov, Dermendjiev & Buyukliev, 1989) derived from soils above the cave (White & Brennan, 1989; van Beynan *et al.*, 2001). These acids are released by the roots of living plants, and by the decomposition of dead vegetative matter. Root release is modulated by visible solar radiation via photosynthesis, while rates of decomposition depend exponentially upon soil temperature. Soil temperatures are controlled chiefly by solar infrared and visible radiation (Shopov *et al.*, 1994) where soils are bare or grass-covered, and by air temperatures where soils are covered by forest or bush. In the first case, microzonality of luminescence of speleothems can be used as an indirect Solar Activity (SA) index, and in the second case, as a paleotemperature proxy.

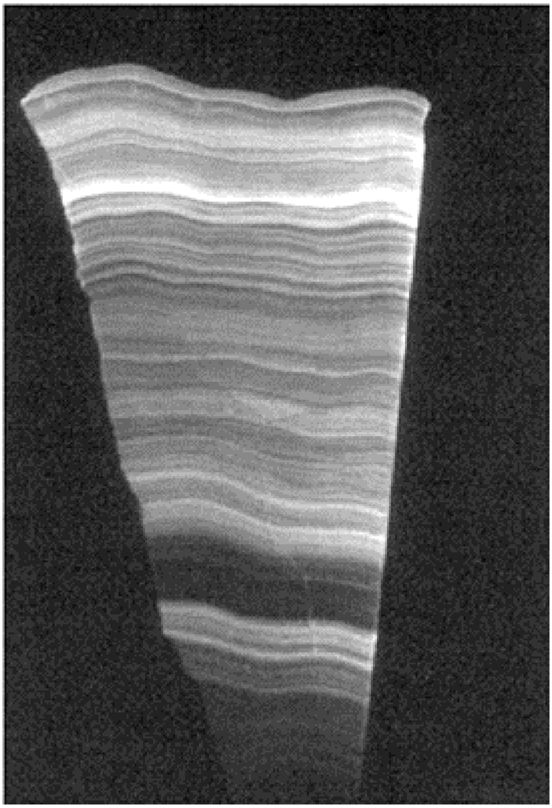
A time series of a Solar Activity (SA) index "Microzonality of Luminescence of Speleothems" can be obtained by Laser Luminescence Microzonal Analysis (LLMZA) of cave flowstones (see Table).

The luminescing organics in speleothems can be divided into four types: (1) calcium salts of fulvic acids; (2) calcium salts of humic acids; (3) calcium salts of huminomelanic acids; and (4) organic esters. All these four types are usually present in a single speleothem, as hundreds of different compounds with similar

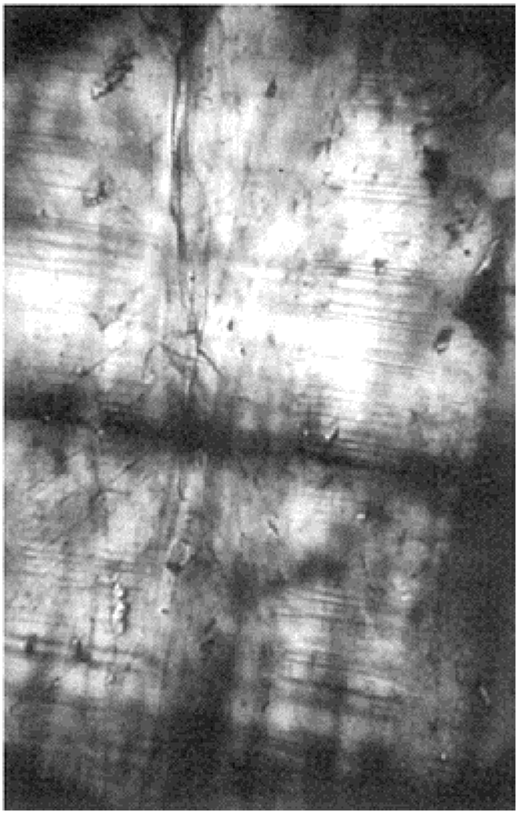
Speleothems: Luminescence: Special speleothem luminescence research methods.

Method	Authors	Obtainable information
I. Impulse Photography of Luminescence (IPL): 1. Photography of phosphorescence (IPP) 2. Photography of fluorescence & phosphorescence (IPFP).	Shopov & Tsankov (1985) Shopov & Grynberg (1985)	Diagnostics of minerals; registration of colour and zonality of fluorescence, phosphorescence and its spectra; UV photography; extraction of single mineral samples; chemical changes of the mineral-forming solution; climate and solar activity variations during the Quaternary.
II. Laser Luminescent—MicroZonal Analysis (LLMZA)	Shopov(1987)	Microzonality of luminescence; changes of the mineral-forming conditions. High resolution records of climate and solar activity variations. Reconstruction of annual rainfall and annual temperature in the past. Estimation of past cosmic rays and galactic cosmic rays. Speleothem growth hiatuses.
III. Colour Slide Spectrophotometry (CSS)	Shopov & Georgiev (1989)	Wide-band spectra of phosphorescence, fluorescence, and diffuse reflectance of minerals; spectra of quick processes.
IV. Autocalibration Dating (ACD)	*Shopov et al.* (1991)	High precision speleothem dating of speleothems of any age, climatic and solar activity cycles, variations of the speleothem growth rate.
V. Time Resolved Photography of Phosphorescence (TRPP)	*Shopov et al.* (1996)	Determination of the lifetime of the luminescent centre. Uplift of the region. Past mixing of surface and epithermal or hydrothermal waters during mineral growth. Estimation of the temperature of deposition, plus all information obtainable by IPP.

Speleothems: Luminescence: Figure 1. Annual banding of luminescence of uranyl ions in a calcite flowstone, due to variations in pH of the water (also in colour plate section).



Speleothems: Luminescence: Figure 2. Luminescence of calcite growing over glacial and interglacial periods with variations of the luminescence colour due to changes in vegetation growing over the cave.



Speleothems: Luminescence: Figure 3. Annual banding of luminescence of organics in a flowstone cross section. Microscopic magnification×50. Dark parts are clay inclusions. Fluid inclusions are visible as bubbles and some crystal surfaces are also visible.

chemical behaviour but different molecular weights. The concentration distribution of these compounds (and their luminescence spectra) depends on the type of soils and plants over the cave, so study of the spectra can yield information about paleosoils and past vegetation. Colour changes in the visible portion of the luminescence spectrum imply major changes in plant ecology and thus organic matter decomposition, but are rarely observed (Figure 2).

Speleothem growth rate may vary significantly within a single speleothem (Shopov *et al.*, 1994). Where there are no growth interruptions (hiatuses), such variations represent rainfall variation. Luminescence techniques can visualize annual microbanding on a scale of 20–60 μm that is not visible in normal light (Figure 3). If this banding is visible in normal light, or the luminescence curves have sharp profiles or jumps (e.g. as in Baker *et al.*, 1993), it suggests that speleothem growth ceased for a certain period during the year and that such time series are not useful for deriving rainfall proxy records for paleoclimate studies.

Luminescence in high-temperature hydrothermal minerals is mainly due to cations, because any molecular ions and molecules are destroyed. It signifies the hydrothermal conditions under which the minerals form. Minerals deposited from low-temperature hydrothermal solutions display short-lived fluorescence, due to the cations, and longer duration phosphorescence due to molecular ions. Where calcite has only orange-red, short-lived phosphorescence, it is an indicator of very high-temperature hydrothermal solutions (>300°C). But if it has also long-time phosphorescence, then it is a lower-temperature deposit. The minimum temperature for the appearance of orange-red luminescence is estimated to be between 46°C and 60°C. Luminescence of hydrothermal calcite formed at lower temperatures than these is similar to the standard meteoric speleothem luminescence shown in Figure 1.

The tectonic uplift history of an area can be deduced from luminescence in combination with absolute dating (Shopov *et al.*, 1996), where the luminescence is due to epithermal mineralizing solutions in the older parts of a speleothem deposit, but the mixing of these waters with meteoric waters containing organics appears in the younger parts.

Finally, luminescence may be used to estimate the absolute age of the speleothem itself by the autocalibration dating method (Shopov *et al.*, 1991), which has been shown to be the most precise method for samples younger than 2000 years (Shopov *et al.*, 1994).

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See also **Paleoenvironments: Speleothems**

Works Cited

Baker, A., Smart, P.L., Edwards, R.L. & Richards, D.A. 1993. Annual growth banding in a cave stalagmite. *Nature,* 304:518–20

Shopov, Y.Y. & Grynberg, M.A. 1985. A new method for direct photography of luminescence. *Exped. Ann. Sofia Univ.* 1:139–45

Shopov, Y.Y. & Tsankov, L.T. 1985. A photographic apparatus for luminescent analysis (B. Patent 40439 from 30 Aug. 1985). *Bulletin of Institute for Inventions and Rationalizations,* 12:1–7

Shopov, Y.Y. 1987. Laser luminescent microzonal analysis: A new method for investigation of the alterations of climate and solar activity during the Quaternary. In *Problems of Karst Study of Mountainous Countries,* edited by T.Kiknadze, Tbilisi, Georgia: Meisniereba

Shopov, Y.Y. & Georgiev, L.N. 1989. CS-Spectrophotometry: A new method for direct registration of spectra of variable processes. *Abstracts of XXVI Colloquium Spectroscopicum Internationale,* vol. 3, edited by D.L.Tsalev, Sofia, Bulgaria

Shopov, Y.Y., Dermendjiev, V. & Buyukliev, G. 1989. Investigation on the variations of climate and solar activity by a new method—LLMZA of cave flowstore from Bulgaria. *Proceedings of the 10th International Congress of Speleology,* vol.1, edited by A. Kosà, Budapest: Hungarian Speleological Society

Shopov, Y.Y. Dermendjiev, V. & Buyukliev, G. 1991. A new method for dating of natural materials with periodical macrostructure by autocalibration and its application for study of the solar activity in the past. In *Proceedings of the International Conference on Environmental*

Changes in Karst Areas, edited by U. Sauro, A.Bondesan & M.Meneghel, Padova: Dipartimento di Geografia, Universita di Padova
Shopov, Y.Y., Ford, D.C. & Schwarcz, H.P. 1994. Luminescent micro-banding in speleothems: High-resolution chronology and paleoclimate. *Geology,* 22:407–10
Shopov, Y.Y., Tsankov, L., Buck M. & Ford, D.C. 1996. Time resolved photography of phosphorescence: A new technique for study of thermal history and uplift of thermal caves. In *Climate Change: The Karst Record,* edited by S.-E.Lauritzen, Charlestown, West Virginia: Karst Waters Institute
Shopov, Y.Y. 1997. Luminescence of cave minerals. In *Cave Minerals of the World,* 2nd edition, edited by C.A.Hill & P. Forti, Huntsville, Alabama: National Speleological Society
van Beynan, P.E., Bourbonniere, R., Ford, D.C. & Schwarcz, H.P. 2001 Causes of colour and fluorescence in speleothems. *Chemical Geology,* 175(3–4):319–41
White, W.B. & Brennan, E.S. 1989. Luminescence of speleothems due to fulvic acid and other activators. *Proceedings of the 10th International Congress of Speleology,* vol. 1, edited by T. Hazslinszky & K.Bolner-Takacs, Budapest: Hungarian Speleological Society

SPELEOTHERAPY

Speleotherapy is a special type of medical treatment, involving subterranean environments and their specific microclimate. It is a therapeutic method, which is used for rehabilitation in curing respiratory diseases, asthma, and allergies (Horvath, 1989). It has been documented from prehistoric times, when humans were using caves for both shelter and ritual. The modern application of speleotherapy began in the 1950s, when speleotherapeutic centres were established in some Eastern and Central European countries, bringing together experts in speleology, medicine, especially pulmology, and natural sciences. In the United States and United Kingdom, speleotherapy is not known to be practised.

During World War II, the inhabitants of Ennepetal, Germany, used to take shelter in Kluterthöhle. Dr Karl Hermann Spannagel (1909–86) was surprised by the improvement in the health of asthma sufferers while they visited the cave. Soon after the end of the war, he began to study the therapeutic effects of caves in treating bronchial asthma, chronic bronchitis, and pertussis (whopping cough) (Schmidt, 1989). He described the properties of the environment of Kluterthöhle that gave rise to the therapeutic effects, and in 1949 published medical reports, praising the therapeutic effects of the cave climate on certain illness of the respiratory tract.

Following his pioneering work, modern speleotherapy was initiated in the karst caves of Hungary and Slovakia. In order to find out the beneficial factors of the cave environment, intensive research was carried out by national medical institutions to evaluate the pulmonary parameters of their patients. The remarkable findings resulted in the creation of an international society, which was established to provide international links, therapeutic protocols, and a scientific approach in treating an increasing number of adults and children suffering from asthma and other allergic diseases. The Speleotherapy Commission of the International Speleological Union (UIS) was set up in 1969 by representatives from Austria, Czechoslovakia, France, Germany, Hungary, and Italy.

The effects of speleotherapy are clearly shown in improved pulmonary function, reduction of non-specific bronchial hyper-activity, and the improvement of the humoral and the cellular response of the immune system. After the cure is completed, the aggravation of disease is rare and drug consumption is reduced. Furthermore, this leads to a reduction in the cost of treatment in hospital or at home, and also to a reduction in absences from school or work. The quality of life of these patients is highly improved.

Patients stay in the cave for four hours a day or more, depending on the microclimatic conditions and the medical facilities available. The patients perform physical activities, and take part in sports and breathing exercises. Educational programmes are normally organized By medical staff, giving information about lung diseases, self-help, and relaxation. Medical surveys are regularly undertaken throughout the whole course of therapy. In most speleocentres the therapy consists of three treatments which last for three weeks and are repeated every six or eight months. Speleotherapy as an additional method of healing enhances the rehabilitation of patients. The effects of gymnastics, breath rehabilitation, training, and musical therapy are intensified in the cave (Horvath, 1989).

The agreeable environment of caves chosen for speleotherapy is felt as one enters the underground space, due to so-called passive or indirect healing effects. In these caves the air temperature is fairly constant, and natural ventilation provides an optimal exchange of the air in the cave. The cave provides a comfortable stress-free climate, which has a strong relaxation effect (Horvath, 1989). The absence of inorganic, organic, and biological pollutants favours the treatment of allergies. Due to the absence of pathogenic micro-organisms, the atmosphere is sterile. The absence of air pollution is one of the most important passive curative factors of the cave microclimate. In spite of the fact that some small amounts of external pollutants can enter the cave on patients' clothes, the microclimate will purify the air of the cave, ensuring its biological and mechanical cleanliness. This extraordinary characteristic is attributed to high relative humidity (>90%), aerosols, radioactivity, and ionization.

Aerosol particles in the cave atmosphere contain dissolved substances, including very high concentrations of calcium and magnesium together with sodium, potassium, iodine, fluorine, and trace elements. Inhaled into the respiratory tract, these ions can exert a local anti-inflammatory, mucolytic effect and can stimulate removal of mucus from the lungs. Aerosols, together with the radioactivity and ionization, create a very complex system, which is perhaps the most important factor from the point of view of the biological activity of the cave climate.

The CO_2 level can be many times higher in the caves than in the outdoor air (see Carbon Dioxide-Enriched Cave Air). This stimulates deeper breathing and has a direct anti-spasmodic effect. The CO_2 also increases the ionization of calcium. The O_2 concentration is slightly lower than on the surface, but this difference has no biological significance. Pollutant gas components (SO_2, NO_2, NH_3, etc.) and O_3 are absent from the air of caves chosen for speleotherapy.

The radioactive gas radon is present in all caves (see Radon in Caves), but concentrations are usually low in sites used for speleotherapy, and the radiation dose never exceeds the levels permitted by national regulations and laws. Radon is thought to result in ionization, a bio-positive effect called hormesis, and the stimulation of the immune system. The bio-positive effect can be observed in the induction of DNA repair enzymes, the effect of detoxification, and the induction of regulative polypeptide synthesis. A combination of all these speleoclimatic parameters is thought to be responsible for the healing effect.

Karst caves, artificial caves, or operating and closed mines are only suitable for speleotherapy if they fulfil specific physical, chemical, and biological criteria. There are three categories of speleotherapy sites: cold caves, rock salt and potash mines, and natural and artificial thermal caves. In cold caves the average temperature ranges from 6°C to 10°C, and the relative humidity from 80 to 100%. These caves are used particularly for the treatment of respiratory diseases. In Central European countries, as well as in the Caucasus, speleotherapy centres have been established predominantly in cold caves.

In Germany there are over 12 speleotherapy centres, including the Kluterthöhle (Ennepetal), which was one of the first caves to be listed by the German Balneologic society (for the medicinal use of water baths). In Austria, speleotherapy centres have been established in four natural karst caves. In Sežana, Slovenia, there is a speleotherapy centre located in an artificial cave used as a shelter during World War II. In this locality only adult patients are treated. In Slovakia, speleotherapy for children has a long tradition and extraordinary results in Bystra cave. In the Czech republic there are centres in four caves and in Zlaté Hory, an old gold mine. Hungary has a 40-year tradition of speleotherapy, with centres in Tapolca, Miskole, Budapest and in the Baradla—Domica cave system.

Rock salt and potash mines have a distinctive microclimate with temperatures of 13–20°C and a relative humidity of 45–70%. This speleoclimate is characterized by its strong aerosol effect. Apart from respiratory diseases, it is also used for the treatment of cardiovascular diseases, bacterial and atypical dermatitis, neurodermitis, psoriasis and burns. In Eastern European countries, there are extensive rock salt and potash deposits and some large speleotherapy centres have been set up 100–400 m underground. The favourable temperature permits long-term visits either during the day or through the night. Different treatment methods are applied for different illnesses. This type of speleotherapeutic treatment has been practised for more than 30 years in the Ukraine (Starobin salt mines), the Minsk region (Belarus), the Perm region of the Western Urals (Russia), in Wieliczka (Poland), and in Romania. Special environments have been created in artificial chambers, which provide nearly the same conditions as in the cave, with an emphasis on aerosol concentration. These are now widely used in Uzghorod and Kiev, Ukraine and Perm, Russia.

The third category of speleotherapy sites includes natural and artificial thermal caves with warm or hot air temperatures, with or without elevated radioactivity. Rheumatic and other illnesses can be treated by speleotherapy in these caves. In Central Europe the Gastein Heillstollen is one of the leading centres in this field, and has been operating since 1952. The cave's climate is characterized by a radon concentration (^{222}Rn) of 4.5 nanocuries per litre of air, with temperatures of 38–4l.5°C and relative humidities of 70–95%.

Taking care of patients undergoing speleological treatment in caves also involves a concern for the cave microclimate, speleothems, and the entire underground ecosystem. Only intact, well-preserved, and protected caves can offer the beneficial effects needed for speleotherapy, which is why this activity is closely connected with geological and speleological research.

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Works Cited

Horvath, T. 1989. Possibilities of speleotherapy in the treatment of children's asthma. In *Allergie and Immunologie, Interasma '89. Proceedings of Symposium on Speleotherapy,* edited by J.Přbyl & D.Řičny, Brno: Institute of Geography of CSAS 126:7–11

Schmidt, H. 1989. Speleotherapy in the Klutert Cave. In *Allergie and Immunologie, Interasma '89. Proceedings of Symposium on Speleotherapy,* edited by J.Přbyl & D.Řičny, Brno: Institute of Geography of CSAS 126:13–14

Further Reading

Beamon, S. 1998. Taking the healing airs. *Descent,* 144. 22–23

Ŕíčný, D., Sandri, B. & Trimmel, H. 1994. Beiträge zu Speläotherapie und Höhlenklima *Proceedings of the 10th International Symposium of Speleotherapy, Bad Bleiberg, 1992,* Vienna: Speleotherapy Commission of the International Union of Speleology: vol. 2:306

International Symposium of Speleotherapy Solotvino, Abstracts. Ukraine, 1998 Speleotherapy Commission of the International Union of Speleology.

Proceedings of the 11th International Symposium of Speleotherapy, Zlaté Hory: EDEL, 1999

Slovak Environmental Agency (editors) 1997. *Conference on Protection and Medical Utilisation of Karst Environment,* Banská Bystrica, Slovakia: DALI

SPRINGS

Karst springs are those places where karst groundwater emerges at the surface. Karst spring discharge ranges over seven orders of magnitude, from seeps of a few millilitres per second to large springs with average flows exceeding 20 $m^3 s^{-1}$ (Table 1). Flow may be steady, seasonal, periodic, or intermittent, and may even reverse. Karst springs are predominantly found at low topographic positions, such as valley floors, although they may be concealed beneath alluvium, rivers, lakes, or the sea (vrulja). Some karst springs emerge at more elevated positions, usually as a result of geological or geomorphological controls on their position.

Springs in non-karst rocks may result from the convergence of flow in a topographic depression or from the concentration of flow along open fractures such as faults, joints, or bedding planes. Flow in porous media is limited by hydraulic conductivity, so that associated springs almost always have very small flow, often discharging over an extensive "seepage face." Larger springs are possible in fractured rocks such as basalt, where flow may be concentrated along open or weathered fractures. What distinguishes karst springs is that they are the output points from a dendritic network of conduits, and therefore tend to be both larger and more variable in discharge and quality than springs arising from coarse granular or fractured media.

Springs: Table 1. Large springs of the world (after Ford & Williams, 1989 and Milanović, 2000, modified).

Spring	Flow (m^3s^{-1})	Basin (km^2)
Tobio, Papua New Guinea	>100	–
Matali, Papua New Guinea	90	350
Trebišnjica, Herzegovina	80	1140
Bussento, Italy	>76	–
Dumanli, Turkey	50	2800
Galowe, Papua New Guinea	40	–
Ras el ain, Syria	39	–
Tisu, China	38	1000
Ljubljanica, Slovenia	39	1100
Stella, Italy	34	–
Ombla, Croatia	34	600
Chingshui, China	33	1000
Spring Creek, Florida	33	>1500
Oluk Köprü, Turkey	>30	>1000
Timavo, Italy	30	>1000
Frio, Mexico	28	>1000
Yedi Miyarlar, Turkey	>25	>1000
Mchishta, Georgia	25	–
Buna, Herzegovina	24	110
Coy, Mexico	24	>1000
Liu longdong, China	24	–
Kirkgozler, Turkey	24	–
Silver, Florida	23	1900
Rainbow, Florida	22	>1500
Vaucluse, France	21	1100
Sinjac (Piva), Yugoslavia	21	500
Bunica, Herzegovina	20	510

Grab-Ruda, Croatia	20	390
Trollosen, Spitzbergen	20	–

In general, karst springs can be considered in terms of their hydrological function, their geological position, and their karstic drainage or "plumbing". These controls exert an influence on spring hydrology and hydrochemistry, allowing a diagnosis of aquifer form and function from measurements of spring water. This is particularly important in evaluation of spring water as a resource and in assessment of the overall condition of the aquifer. Karst springs have been classified in many different ways, and Table 2 shows eight different attributes. In theory, these attributes could be combined to describe a spring. For instance the spring at Sof Omar Cave, Ethiopia could be described as a "perennial, full-flow, gravity resurgence". In practice, most karst springs are described in terms of their most important attribute, depending upon the interest of the observer and the context of the application.

General Hydrology

Springs represent the outlet of water recharged at higher elevations, and stored and routed (conveyed) through the karst aquifer. In general, the larger the body of stored water relative to aquifer flow, the greater is the residence time of the water, and the more steady (consistent) will be spring flow. It is convenient to consider the energy of water at any point in an aquifer in terms of "hydraulic head": the elevation to which water would rise up a standpipe opening at that point. Groundwater always flows from high to low head, at a rate driven by the rate of fall in head, and governed by the resistance of the flow route. Thus a steady perennial spring will exhibit consistent distribution of head in the aquifer whereas seasonal and intermittent springs will show marked variation in the hydraulic head in the aquifer. Reversing springs, or "estavelles", occur where head in the aquifer is sometimes lower than head in a connecting water body such as a river or lake, forcing surface water into the aquifer.

Hydraulic head is the sum of local elevation and water pressure. Springs in which water is derived from open passages with free surface streams are driven by elevation head and termed gravity springs. In contrast, springs where water rises from depth are pressure springs. The most profound pressure springs are termed "Vauclusian" springs after the Fontaine de Vaucluse, France, which has been dived to a depth of 315 m. In some cases, the internal hydraulic head in an aquifer greatly exceeds that required to drive the flow of water. Springs with excess hydraulic head exhibit a marked upwelling or jet, and are sometimes termed "artesian" springs.

Geological Controls on Karst Springs

The location and form of karst springs is determined primarily by the distribution of karst rocks, and the pattern of potential flow paths (fractures) in the rock. Where karst rocks are intermixed with impermeable rocks, the latter act as barriers to groundwater flow, and karst springs tend to develop as "contact springs" where the boundary between the karst and impermeable rock is exposed at the surface. Where the impermeable unit underlies the karst, it enhances the elevation of the karst water, and the spring (and aquifer) is considered "perched", as it lies above the topographically optimum discharge point.

Where the impermeable unit overlies the karst aquifer, it enhances the pressure of karst water, and springs are then described as "confined"

Springs: Table 2. Classification of karst springs according to different attributes.

Parameter	Type		Name for spring
Flow duration	continuous	steady	perennial: base flow
		variable	perennial
		periodic	ebbing and flowing, rhythmic or episodic
	discontinuous		intermittent
	non-existent		paleo- or abandoned spring
Reversing flow	reversing		estavelle
	non-reversing		(no specific term)
Conduit type at spring	open conduit (with airspace)		gravity spring
	water-filled conduit		pressure, artesian or Vauclusian spring
Geology	aquiclude underlies spring		contact spring
	aquiclude overlies spring		confined or artesian spring
	spring rises through alluvium		alluviated spring
	fault		fault-controlled spring
	joint		joint-controlled spring
	bedding plane		bedding plane-controlled spring
Topographic position	at valley floor		local base level or graded spring
	above valley floor		hanging (rejuvenated) spring
	below valley floor		buried spring
Relationship to bodies of surface water	at sea or lake level		base level spring
	below sea level		submarine spring (vrulja)
	below lake level		sublacustrine spring
	between high tide and low tide		intertidal spring

	above bodies of surface water	hanging (rejuvenated) spring
Distributaries	distributary with most variable or intermittent discharge (usually the highest one)	overflow spring
	distributary with steadiest discharge (usually the lowest one)	underflow spring
	intermediate distributary	underflow-overflow spring
	no distributaries	full-flow spring
Recharge	autogenic recharge	exsurgence
	allogenic recharge	resurgence
Chemistry	dilute water	fresh water spring
	enriched water	mineralized spring
	saline water	saline/brackish spring
	saturated with carbonates (tufa)	petrifying, tufaceous spring
	saturated with hydrogen sulfide	sulfur spring
	saturated with iron hydroxide	chalybeate (ochre) spring
	hot water	thermal spring
Culture/exploitation	religious	shrine
	fish culture	hatchery spring
	livestock and irrigation	watering spring
	bottled water	bottling spring
	brewing, distilling	brewery, distilling spring

and are often artesian. Confined springs tend to benefit from greater water storage than perched springs, and so exhibit more sustained flow. In many cases, karst springs may be concealed beneath permeable but insoluble materials such as river alluvium or talus. The term "quicksand" describes sandy material that is continually boiling in an alluviated spring orifice.

The primary flow routes in most karst aquifers are determined by the presence of discontinuities such as joints, bedding planes, and faults. In many cases, fractures direct karst conduits away from the lowest elevations favoured by consideration of hydraulic gradients, resulting in vertical and horizontal displacement of the spring from the expected topographic outlet point. Such springs are described as being "controlled" by the respective geological feature.

Geomorphological Controls on Karst Springs

Water tends to follow the steepest hydraulic gradient to a discharge point, so that springs tend to occur in valleys, and on the outside of river meander bends. Changes in landscape influence springs through erosional deepening and depositional infilling of valleys. If an underground karst stream is exposed by erosion, then a new spring may develop at the breach and the original downstream passage will be abandoned. The effect of valley deepening may be to leave an existing spring above the valley floor, and to permit a lower outlet to develop. The original spring tends to be progressively abandoned as lower outlets develop, often resulting in a suite of immature underflow springs and intermittent overflows. Valley infill may block former springs, rejuvenating former high level outlets and creating alluvial springs in the valley floor. Changes in sea level have a similar redirectional effect. Many submarine karst springs (vrulja) that presumably developed during Pleistocene low sea levels still function following postglacial rises in sea level.

Karst Controls on Springs

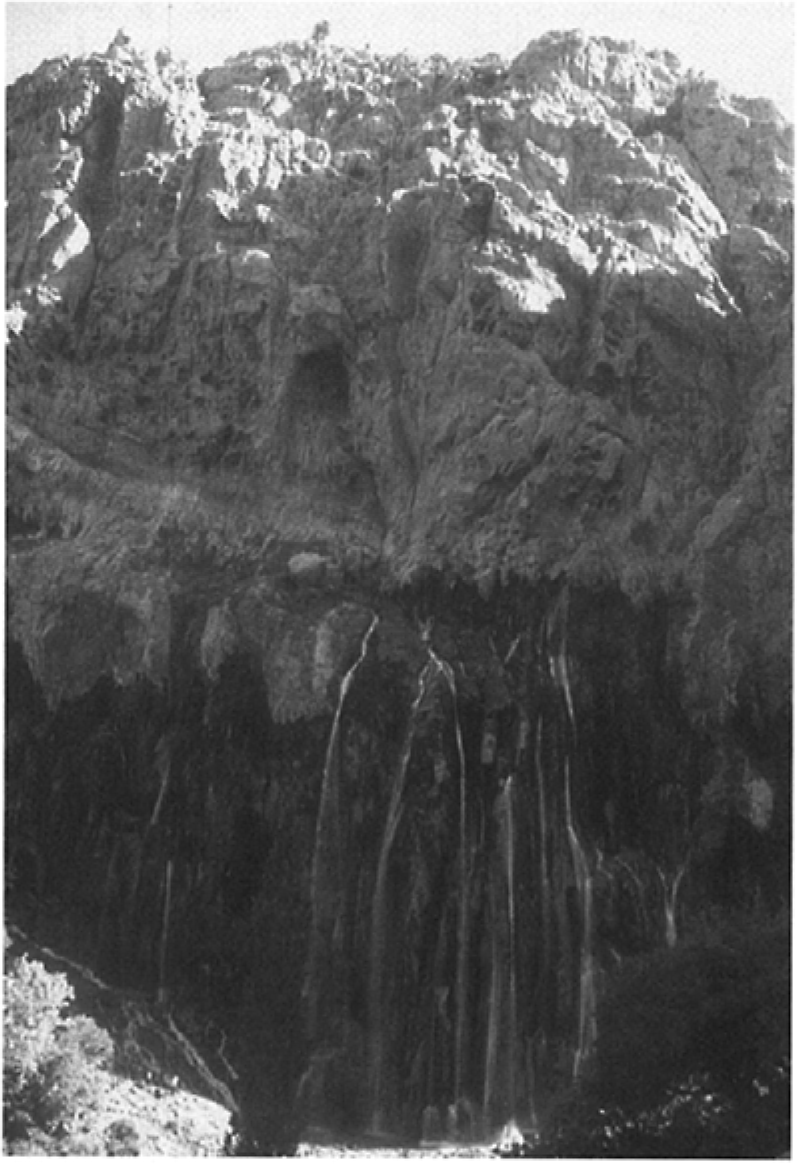
The quality and magnitude of flow from a karst spring reflects the form and function of the karst aquifer, and in particular the recharge processes and the conduit network. Springs deriving much of their water from allogenic surface catchments are known as resurgences. They exhibit properties closely related to those of the surface catchment: typically variable flow and unreliable water quality. Springs in autogenic aquifers, which receive the bulk of their recharge from a karst surface, are known as exsurgences, and exhibit less variability in discharge and composition. Where recharge to the limestone aquifer is moderated by thick unconsolidated deposits exsurgences are even less variable. For example, in Florida the overburden provides significant storage and buffers the underlying aquifer from fluctuations in recharge and water quality. Variable springs are most highly developed where the karst aquifer has massive, bare limestone exposed at the surface, limited storage, and small extent. Karst springs draining aquifers with substantial storage, or relatively isolated from surface recharge by overlying strata, will tend to exhibit more steady behaviour. In the past, such flow behaviour has been attributed to distinctive “diffuse” and “conduit” Karst aquifers, but it is now recognized that recharge or underflow-overflow effects are responsible, and that a diffuse karst aquifer is an oxymoron.

Most karst drainage systems are dendritic in form like surface drainage channels; thus smaller tributaries come together to generate a progressively larger stream, emerging at a single, integrative spring. However, geomorphic history and geology endow many karst aquifers with multiple levels of conduits, often punctuated by vertical shafts, so that karst flow systems may exhibit three-dimensional features uncommon or impossible in surface drainage systems. Often a single conduit discharges through a number of distributary springs. Both valley deepening and infilling can result in distributaries. Aquifers experiencing variations in hydraulic head (i.e. internal water level) as flow varies may show flow-dependent distributaries. Where distributary springs occur across a range of elevations, they fall into a vertical hierarchy. The lowermost members are “underflows” and tend to exhibit steady flow. In contrast, the overflow springs are intermittent, or show much greater variability in flow. Such effects may not necessarily be associated with multiple springs; in some cases internal overflows develop, for example in a high-level bypass to an obstruction in a streamway. However, the karst spring may exhibit sudden changes in composition and flow as such internal overflows are activated.

A few karst springs show remarkable periodicity in their flow, with a typical period of minutes to hours. In general, this is attributed to the existence of an internal siphon which progressively fills and drains. However, periodicity may be restricted to specific flow conditions, or the form of the pulse may not match the hydraulics of a simple siphon, and more complex "plumbing" has to be invoked. Periodicity in hydrothermal springs is seen in geysers. The key feature of geysers is the warming of a pressurized body of water to boiling point and the explosive spontaneous boiling occurring as pressure is released.

Many karst springs occur adjacent to or beneath the surface of rivers, lakes, or the sea; the majority are likely unacknowledged. The interaction between the aquifer and the external water body rests on the hydraulic head distribution and the pattern of connections (springs, sinks, and estavelles) that exists. The relationship is most complex where the timing of peak flow (and head) differs between the aquifer and water body. Often the aquifer response lags that of the surface water body. The result is a phase of inflow to the aquifer, followed by an expulsion of the recently influent water, followed by the original aquifer water, chased by actual storm water. A reach of river channel

Springs: Figure 1. Giant Springs lie on the banks of the Missouri River at Great Falls. Montana, United States. They produce a steady flow of 3–6 $m^3 s^{-1}$ from a deep aquifer karst with an extensive catchment to the south. (Photo by Tony Waltham)



Springs: Figure 2. Margoon Waterfall Spring in the Zagros Mountain Range, Fars Province, Iran. This perennial spring has an average discharge of 800 $l\ s^{-1}$ and emerges 58 m above the base of the cliff. Water emerges at 2200 m above sea level from Asmari Formation limestone (Oligo-Miocene) on a nearly vertical normal fault. (Photo by John Gunn)

encountering multiple karst conduits may show delightfully complex patterns of sinking, transmission, and rising in successive pools.

Hydraulic head is primarily dependent on elevation and pressure, but density of water may have an influence too. The greater density of seawater means that it has slightly greater hydraulic head than an equivalent fresh water body. This is most conspicuous in the visible discharge mound of many submarine springs (vrulja) as the fresh water rises to the surface. However, it may be more significant in driving subtle groundwater circulation in marine settings. Deeper openings in a submarine distributary may act as inflow points for saline water. Within the aquifer, the seawater rises, mixes with freshwater and emerges as brackish springs, often slightly above sea level. Similar density effects may develop in hydrothermal waters, but have not been extensively investigated.

Where karst spring water is supersaturated, calcareous tufa deposits develop at the orifice and downstream. Such petrifying springs mantle all objects in calcite, and often build up distinctive mounds and barrages in areas of peak precipitation (see Travertine). A peculiar property of such springs is “self-damming”, arising from enhanced precipitation in the thinner, more turbulent free surface flows over the lip and outer surface of the barrier. Spectacular rimstone dams may occasionally reach many metres in height, but are prone to leakage and sudden abandonment fuelled by the enhancement of hydraulic head that they engender.

Hydraulic Influences on Karst Spring Discharge

The relationship between karst spring behaviour and the hydraulics of the aquifer permits analysis and simulation to aid research and management. Attempts to derive the internal plumbing of the aquifer are often ambiguous and constrained by the necessity of substituting a limited number of simplified equivalent components for the likely complexity of the system. Hydraulic modelling indicates that open channels accommodate changes in flow with limited change in water level, compared to closed (water-filled) conduits. In other words once a cave streamway fills at a point, relatively large head (water level) changes will occur. A second important feature is that during floods, restrictions result in disproportionate rises in head. Large heads (i.e. high water levels) and rapid changes in head are common during floods. The former may induce flow-dependent routing of water to distributary springs. Spring discharge is often moderated by the water stored and released by large head changes. Both phenomena have startled and trapped cave explorers.

Hydraulic head in a conduit changes with the balance between inflow and outflow, with the resulting volume causing more or less head change depending on the form of the conduit. In complex karst aquifers, all of the various inlets, stores, overflows, and outlets develop their own local head, depending on their form and flow conditions. This can result in significant internal rerouting of water under variable flow conditions. Moreover, the rerouting effects may not appear to be reproducible under superficially similar conditions. Development of simple spring-rainfall-response models has been an objective of karst hydrogeologists for many years. Such idiosyncratic nonlinearity as arises from rerouting effects has been a major cause of frustration for such modelling attempts.

As the aquifer drains, and spring flow declines, water is withdrawn from aquifer storage. The resulting flow recession may be modelled by a simple exponential dependence of flow on time. The inverse of the exponential parameter has units of time, and can be taken as an indicator of the residence time of water in the aquifer. Integration of the exponential model provides estimates of aquifer volume.

Quality of Karst Spring Waters

The water emerging from a karst spring consists of a mixture of water from various recharge routes and storage zones. As the environment and duration of recharge, and storage vary, so too will the resulting composition of the water. For example, allogenic recharge water will tend to be more turbid and chemically dilute than autogenic recharge. Long-term storage may result in depletion of the dissolved oxygen in the water, and deep flow may lead to warming or mineralization. In principle, these natural tracers should allow the source and routing of karst spring water to be derived. However, many of these characteristics (e.g. temperature, turbidity, dissolved oxygen, hardness) do not have fixed values associated with particular environments, they are not conserved in transit, and mixing with other waters may induce chemical reactions. Nevertheless, it is often possible to develop empirical characterization for particular karst aquifers to allow discrimination of the proportion of basic water sources contributing to spring flow. The chemical composition of spring waters often results in distinctive deposits, biota, and exploitation, allowing a chemical classification.

Karst Springs as a Water Resource

The sustained, accessible supply of good quality water at karst springs has made them an important traditional water resource, especially in those regions where surface water is scarce. However, many karst springs have proven unreliable in both quality and quantity of supply, and have been superseded by wells and pumps. Karst springs are now regarded as valuable integrators of the aquifer, and, compared to observation wells, provide comprehensive monitoring sites for assessment of contamination and supply. The hydraulic and chemical principles described above, coupled with groundwater tracing allow catchment area, origin, storage, and routing to be determined. However, such interpretation requires considerable simplification, and seldom acknowledges the nonlinear and apparently idiosyncratic behaviour that is often revealed by sustained, comprehensive monitoring of springs. Nevertheless, the water quality of springs has a profound influence on their use, both as water sources and cultural resources.

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Further Reading

Bonacci, O. 1987. *Karst Hydrology, with Special Reference to the Dinaric Karst,* Berlin and New York: Springer

Bonacci, O. 2001. Analysis of the maximum discharge of Karst springs. *Hydrogeology Journal,* 9:328–38.

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Mangin, A. 1969. Etude hydraulique du mécanisme d'intermittence de Fontestorbes (Ariège). *Annales de Spéléologie,* 24(2):255–98

Milanović, P.T. 2000. *Geological Engineering in Karst,* Belgrade: Zebra

Newson, M.D. 1971. A model of subterranean limestone erosion in the British Isles based on hydrology. *Transactions of the Institute of British Geographers,* 54:55–70

Ray, J.A. 1997. Overflow conduit systems in Kentucky: A consequence of limited underflow capacity. In *The Engineering Geology and Hydrogeology of Karst Terranes: Proceedings of the Sixth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst,* edited by B.F.Beck & J.B. Stephenson, Rotterdam: Balkema: 69–76

Smart, C.C. 1988. Artificial tracer techniques for the determination of the structure of conduit aquifers. *Groundwater,* 26:445–53

Smart, C.C. & Ford, D.C. 1986. Structure and function of a conduit aquifer. *Canadian Journal of Earth Sciences,* 23:919–29

Worthington, S.R.H., Davies, G.J. & Quinlan, J.F. 1992. Geochemistry of springs in temperate carbonate aquifers: Recharge type explains most of the variation. *Proceedings of the Fifth Conference on the Hydrology of Limestone and Fractured Aquifers,* edited by P.Chauve & F.Zwahlen, Besançon: University of Besançon, vol. 2:341–48

STAMPS AND POSTCARDS

Philately is one of the most popular hobbies in the world. Postage stamps and cancellations (marks that void a stamp through the use of a bar, wavy line, picture, or special wording) are unique, and at times valuable records of history, geography, politics, art, and numerous other aspects of human civilization. From the earliest years of the hobby, most philatelists have preferred to collect by country. However, since the mid-1950s, many philatelists have become increasingly interested in topical stamp collecting, on a wide variety of specific themes or subjects, for example caves and bats. A third and recent subcategory of stamp collecting is deltiology—the study and collecting of postcards.

The First Stamps and Postcards

In 1837, English schoolmaster and civil servant Rowland Hill proposed the idea of the adhesive postage stamp as one of many postal reforms in Britain. Through Hill's efforts, on 1 May 1840, Britain issued the world's first official adhesive postage stamp, a one-penny denomination universally referred to as the Penny Black. By 1860 most nations had adopted postage stamps. Designs at first imitated those of Britain, with portraits usually depicting heads of state and symbols, or artistic designs, generally being national in character. Pictorial designs were increasingly used toward the end of the 19th century, including those of caves; cave fauna such as bats, salamanders, and blind fish; cave scientists and speleologists; rock and cave art; and minerals.

The first stamp with an illustrated bat was designed in 1894 by the China Custom Post to commemorate the birthday of the Empress Dowager. The 1–candareen (Chinese monetary value) and the 9-candareen stamps both have five stylized bats (called “wu fu”) in a ring surrounding the tree of life. These symbolize the five great happinesses—health, wealth, long life, good luck, and tranquility (Figure 1). The first true picture of a bat appeared on three different denominations of a 1948 Chile stamp. It depicted the Yellowed-shouldered Bat, *Sturnia lilium,* and was printed in three colours (Figure 2).

Stamps depicting caves first appeared in 1925, when Lebanon issued a postage-due stamp depicting Pigeon Grotto, and next in 1930, when they issued a second Pigeon Grotto stamp used for regular mail. From then on, nations around the world issued stamps referencing caves, including depictions of entrances; rooms with many formations; stalagmites and stalactites; cave streams; and tourists (Figure 3). Minerals, rock art, and natural bridges are other areas that can be collected on stamps, of which the 1899 natural bridge stamp issued by Tasmania depicting Tasman’s Arch is an example (Figure 4).

The earliest known illustrations of caves on postcards are Kuhstall in Saxony (used in 1887), Einhornhöhle in the Harz mountains (1890), and the Blue Grotto in Capri (1893). Established “show” caves throughout the world began publishing large numbers of cards and, by 1910, millions were sold at cave souvenir shops, “promoting” the cave by mailing to friends and relatives, or collected as personal remembrances (Figure 5).

Postcards and Stamps: Figure 1. China (Scott No. 16) Five bats surrounding the Tree of Life

Figure 2. Chile (Scott No. 255m)
Yellow-shouldered Bat

Figure 3. Austria (Scott No. 1496)
Entrance to Peggau Cave, Styria

4

Figure 4. Tasmania (Scott No. 89) Tasman's Arch

5

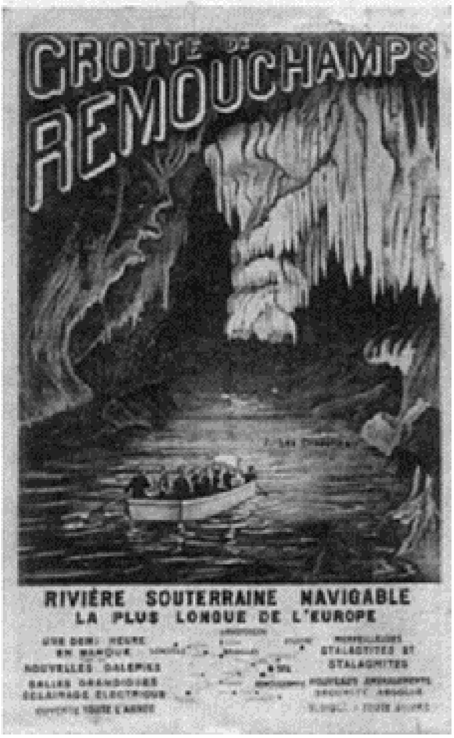


Figure 5. Grotte de Remouchamps 1925 postcard

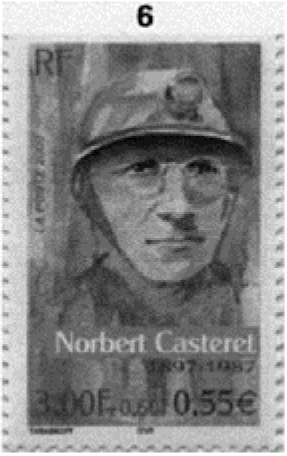


Figure 6. France (Scott No. B703) Norbert Casteret

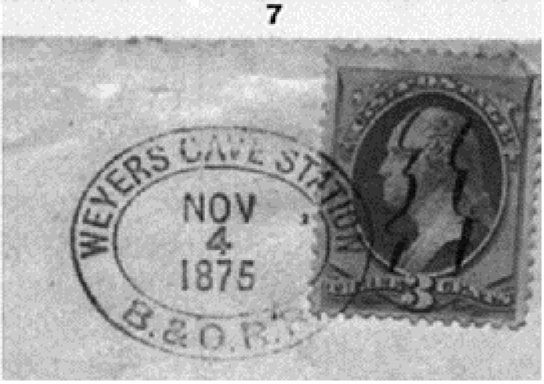


Figure 7. A 1875 cancellation from Weyers Cave Station on the Baltimore and Ohio Railroad, United States.

Cave scientists and speleologists have also been pictured on stamps. In 2000, France honoured three speleologists: Norbert Casteret (Figure 6), Haroun Tazieff, and Jacques-Yves Cousteau, for their exploration of caves around the world, and for furthering knowledge in the cave sciences both underground and underwater. Emil Racoviță (the father of biospeleology), Lazarro Spallanzani (who discovered echo-location in bats), and Dr Joseph Pawan (a Trinidad bacteriologist who identified the rabies virus in the vampire bat) are just a few of the cave scientists depicted on stamps.

The final collector's frontier is speleological cancellations. The cancellation can be from a city or town that has the word "cave, grotto, cavern" in its postmark (Figure 7), or a postmark with speleological reference, such as a bat or a caver' s helmet and lamp. Cancellations can also commemorate a significant event like a Regional Speleological Meeting, the Annual NSS Convention in the United States, or an Annual Music Festival like the Concert Simponic held in Peştera Româneşti-Timis in Romania. Cancellations and postmarks date back to the early 1800s. This area of collecting is the most difficult as there are usually no checklists and the postmarks are not catalogued. Often philatelists who collect in certain areas of interest write the handbook and checklist so that collectors with similar interests can have a starting point. The American Philatelic Research Library in Pennsylvania is one of the best in the world for this type of research.

Organizations and Publications

The American Topical Association (ATA), in Arlington, Texas, is one of the specialized organizations of stamp collectors in the United States. It publishes a bi-monthly magazine, *Topical Times*, as well as special handbooks. The ATA has checklists for many cave and cave-related topics, one of which is *Handbook 128*, entitled *Bats in Philately: A Comprehensive Illustrative Study and List of Bats on Stamps*. The largest general organization for stamp collectors in the Western Hemisphere is the American Philatelic Society (APS), in State College, Pennsylvania, which publishes a monthly journal, *The American Philatelist*. Since 1863, the Scott Publishing Company has produced the Scott Standard Postage Stamp Catalogue, which is the most widely used by North American collectors. It is published annually in a six-volume set, which lists every adhesive postage stamp ever issued and their current value. In Europe similar references for stamps are the *Stanley Gibbons Catalogues*, *Yvert et Tellier's Catalogues*, and *Michel's Catalogue*. An affiliate of the National Speleological Society is the Speleophilatelic Section, which publishes a quarterly journal: *The Underground Post*. Its European counterpart, published at least three times a year, is *Speleophilately International*.

Collecting Procedures

One of the attractions of stamp and postcard collecting is the ease of getting started. With access to enough incoming mail, especially from abroad, a person can build a collection at little or no expense. Tens of thousands of items, including many older issues, can be bought for pennies. However, the harder to find and rare items can cost upwards of tens of thousands of dollars. Little special equipment is required. A collector needs only an album to house the collection, hinges, or other types of mounts to attach the stamps to the pages, and a pair of stamp tongs with which to handle them. Stamps and accessories can be readily purchased from a professional stamp dealer in nearly every city, or from those who operate exclusively by mail. A search of the Internet for websites that specialize in stamps, postcards, and cancellations will surprise you. One only needs to join a stamp club and enjoy caving from the top of the kitchen table.

THOMAS LERA

See also **Art Showing Caves**

Internet References

For the American Philatelic Society: http://www.stamps.org/
For the American Topical Association: http://home.prcn.org/~pauld/ata/index.html
For over 4200 Philatelic Resources on the Internet, including references for all catalogues: http://www.myexecpc.com/~joeluft/resource.html

Further Reading

Irwin, D.J. 1986. Picture postcards of caves and caving. *American Spelean History Association Journal*, 20(1):1–29
Lera, T.M. 1995. *Bats in Philately,* Albuquerque, New Mexico: American Topical Association
Lera, T.M. 2000. Archaeology and cave art. *NSS News,* 58(11): 314–15 and 326
Lera, T.M. 200 1a. A journey into Earth. *Scott Stamp Monthly,* 19(1):70–72
Lera, T.M. 2001b. Cave exploring. *Topical Times,* January/ February: 22–24
Stepanek, V.J. & Friedrich, W.-P. (editors) 1998. Special issue. *Nyctalus (N.F.)* 6:3–108

STRIPE KARST

Stripe karst forms along narrow outcrops of steeply dipping karstic rock beds. This is an extreme case of contact karst, where the allogenic contact perimeter is very large relative to the area of the karst outcrop. Stripe karst is the dominant karst found in metamorphic marble outcrops of the Scandinavian Caledonides, and is named the "Norwegian karst type", as it was first described there (Horn, 1937). Analysis of the geometric properties of a stripe suggests that stripe karst can be defined as a narrow karst outcrop with length to width ratio greater than 3, and is fully developed when the ratio reaches 30. The absolute width is equal to or less than twice the penetration length of allogenic contact karstification. In most cases this width limit is some hundred metres. Impermeable and insoluble rocks, forming aquicludes, surround and isolate individual karst stripes (Lauritzen, 2001). Two or more stripe outcrops may exist side by side as independent aquifers with no hydrological communication except for surface runoff.

Stripe Karst: Figure 1. Marble stripe karst outcrop at Svartisen, north Norway. The steeply dipping stripe is only 20–30 m thick, but extends laterally for almost 10 km. This outcrop hosts the Pikhåg Caves. (Photo by Stein-Erik Lauritzen)

Stripe karst develops characteristically in metamorphic carbonates where multiple folding results in very complicated outcrop patterns. Subsequent erosion exposes these beds at various angles of dip and intersection with the land surface.

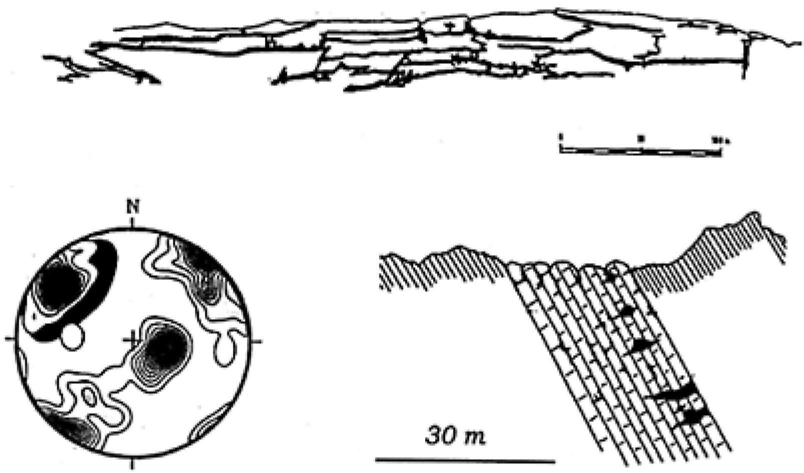
Karstification is intensive at lithological contacts between marble and mica schists, but also at those between different marble types. Mica schist contacts often contain iron oxides and sulfides, giving rise to sulfuric acid speleogenesis; many caves were initiated along such contacts.

Stripe karst contacts are classified into three main types. At gentle dips, karstification can take place at the confined upper contact, at the perched lower contact, or at both. Even in very steeply dipping beds caves tend to concentrate along one of the contacts, most frequently at the hanging wall contact. In many cases, speleogenesis starts under phreatic conditions at the upper, confining contacts (which may also carry sulfide mineralization), but caves may cut down towards the lower contact under vadose conditions and become perched.

Due to metamorphic recrystallization, primary voids are absent, and speleogenesis is entirely dependent on fractures formed subsequently in regimes of brittle deformation. Commonly, two orthogonal sets of fracture occur, which together with the allogenic contact plane form a “box” unit. This may display various attitudes depending on stratal dip and fracture orientation, which fall into six cases when high and low stratal dips are included.

Stripe karst cave systems form four main morphotypes: subvertical, tiered phreatic networks or mazes; low dip phreatic networks or mazes; looping systems with vadose trenches; and linear drainage systems. The various morphotypes do show systematic dependence on stratal dip of the allogenic stripe contacts, of the type of contacts, and to a lesser extent, the fracture patterns (Lauritzen, 2001).

Karstification depth in stripes can penetrate beyond 100 m below the land surface. Some areas display a high density of grikes at the surface, which may be taken as a kind of epikarst. Due to the high erosion rates prevailing during the Quaternary,



Stripe Karst: Figure 2. The Pikhåg Caves, Svartisen. Top: vertical section of the tiered network, forming 2000+m of phreatic tubes. Lower left: Stereonet pole-plot of guiding fractures (contours) and marble/mica schist interface (black). Lower right: cross section through the stripe, showing cave concentration at and near the overhanging wall contact. From Lauritzen (2001).

stripe karsts in Scandinavia are relatively young: although many caves are several glacial cycles old, no unequivocal evidence of pre-glacial, or Tertiary caves has yet been recognized. A typical example of stripe karst is the Pikhågan outcrop and caves in Norway (Figures 1 and 2).

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Works Cited

Horn, G. 1937. Über einige Karsthöhlen in Norwegen. *Mitteilungen für Höhlen und Karstforschung,* 1993.

Lauritzen, S.E. 2001. Marble stripe karst of the Scandinavian Caledonides: An end-member in the contact karst spectrum. *Acta Carsologica,* 30:47–79

SUBTERRANEAN ECOLOGY

Subterranean ecology is concerned with the study of the interactions that determine the distribution, abundance, and characteristics of the biological communities within habitats beneath the land surface. There are a wide range of subterranean habitats covering most latitudes and encompassing terrestrial and aquatic environments (freshwater, brackish, and marine) including caves, interstitial groundwater habitats, and the open voids connected by cracks and fissures within karstic environments (the Mesovoid Shallow Substratum or MSS; Juberthie, 2000). Many factors influence the communities within individual subterranean habitats including resource availability (particularly food), interactions between organisms of the same or different species (intraspecific and interspecific competition), the degree of isolation from the surface (epigean) and other subterranean (hypogean) habitats, and the impact of human activity. Significant advances regarding our understanding of the evolution and natural selection of organisms within subterranean environments have been made, although much has still to be learnt.

Abiotic Environment

The physical and chemical characteristics of individual subterranean ecosystems may be highly variable and locally significant. Two factors are of primary importance in determining the structure and functioning of subterranean biotic communities: the absence of light, and thermal regime. Permanent darkness is the single factor that separates all subterranean habitats from epigean systems. However, it is important to recognize that significant interactions occur between surface and subterranean ecosystems in threshold zones (ecotones) where light and the influence of epigean primary productivity may be attenuated due to the presence of plant roots or the transport of dissolved and particulate allochthonous organic material short distances underground.

The thermal characteristics of an environment are a primary determinant of the rates of chemical and biological processes. Temperature within subterranean ecosystems is strongly influenced by both latitude and altitude and is usually close to the mean annual surface air temperature in the epigean environment (see Climate of Caves). Subterranean air temperature is usually relatively constant throughout the year, although cave morphology may exert a strong influence, causing a cold trap in some caves, while in others with large bat populations temperature may be elevated to between 30–45°C. In most caves humidity is usually high (relative humidity>95%) and the distinction between aquatic and terrestrial realms is not always clear. Water temperature typically displays a low amplitude variation but may experience relatively slow to medium-term changes depending on the volume of water and speed of transfer from epigean environments. In salinity-stratified anchialine caves, there is a steep thermal gradient associated with depth. This may reflect both evaporation of water at the surface and geothermal warming from below.

Trophic Characteristics

Hypogean ecosystems are food limited when compared to photosynthetic epigean systems and as a result most subterranean food-chains and webs are relatively simple with few trophic links (see Food Resources). In the absence of direct sunlight energy, subterranean food webs are almost exclusively heterotrophic and largely dependent upon the transport of allochthonous primary productivity from surface habitats. However, compared to epigean food webs energy transfer is highly efficient between each trophic level and there may be considerable variability in both the volume and quality of the organic material input into individual systems.

Energy limitation is a primary determinant of community abundance in most subterranean ecosystems. The primary consumers of dissolved and particulate organic material (DOM and POM) are bacteria, protozoa, and fungi. Micro- and macroinvertebrate taxa and higher organisms (e.g., amphibians and fish) consume these organisms if present. However, most taxa do not usually have specialized diets and will utilize a wide range of food resources. In many terrestrial subterranean systems the distribution of organic material is patchy and its input episodic. As a result the distribution, abundance, and diversity of terrestrial taxa may strongly reflect the predictability of the input of coarse and fine particulate organic matter (CPOM and FPOM), including faecal material (guano) from birds, bats, or large arthropods, or animal carcasses (Poulson & Lavoie, 2000).

Hypogean systems in direct contact with sinking surface streams have been studied in greater detail than most other subterranean ecosystems. Typically these systems have a greater input of CPOM, such as leaf litter and woody debris, than systems fed by autogenic percolation water. The pulsed nature of the input and the highly variable quality of the material strongly influences both the structure and composition of the aquatic community. In systems with sinking streams a large potential energy input may occur.

Research on the trophic basis of subterranean ecosystems has indicated a wide variety of energy resources utilized by organisms at a range of spatial and temporal scales, including communities supported by guano transported into caves by birds and bats in tropical caves and near-surface cave systems dependent on plant and tree roots (Wilkens, Humphreys & Culver, 2000). The discovery of a chemoautotrophically driven cave system, independent from sunlight energy was arguably one of the most important ecological discoveries since the identification of faunal communities associated with deep-sea thermal vents (see Movile Cave). The use of stable isotope tracing has begun to clearly identify the feeding linkages and hierarchy of subterranean food webs in a number of locations, although many feeding relationships are still poorly understood (Pohlman, Cifuentes & Iliffe, 2000).

Biological and Ecological Characteristics

Given the comparative scarcity of resources in subterranean habitats it is not surprising that the faunal communities are typified by lower diversities of taxa and abundances of individuals than epigean habitats. In addition, due to the non-uniform distribution of resources the spatial distribution of organisms is patchy. The threshold/transition zone between the epigean and hypogean environment is usually the most biologically diverse and supports greater abundances of organisms than deeper subterranean habitats. The degree to which individual organisms are adapted to hypogean environments is variable. Historically all cave organisms were given the prefix "troglo- " but the term stygofauna is now widely used for all subterranean aquatic fauna, whether or not they are found in caves *sensu stricto*. There is no equivalent common term referring to the whole terrestrial subterranean fauna. However, since the introduction of the prefix stygo- for aquatic organisms, the prefix troglo- is increasingly being used specifically to describe terrestrial cave organisms (see Organisms: Classification). Most contemporary authors distinguish between three groups of organisms in both aquatic and terrestrial subterranean habitats. Trogloxenes (terrestrial) and stygoxenes (aquatic) are organisms that do not normally occur in subterranean enviornments but may accidentally, or in some instances actively, enter hypogean habitats in search of food. They are unable to complete their life cycle underground but may play an important role in the functioning of subterranean ecosystems, contributing significant inputs of organic material in the form of faeces and carcasses, and taking the roles of predators and / or prey of subterranean organisms. Troglophiles and stygophiles encompass taxa that are able to live, exploit resources, and successfully reproduce and maintain populations within the subterranean environment, but are not exclusively confined to them. Stygophilic organisms have been subdivided into three groups: (1) permanent hyporheic taxa that may be present in the subterranean environment during any stage of their life history; (2) amphibitic taxa whose life cycles require the use of both surface and groundwater environments; and (3) occasional hyporheic taxa that actively utilize the resources in the subterranean environment and may seek refuge there during unfavourable conditions (e.g. floods or droughts) (Gibert *et al.,* 1994). Troglobites and stygobites are obligate occupants of subterranean habitats that do not normally occur in epigean environments, although they may be recorded in shallow hypogean environments.

Many troglobitic and stygobitic organisms, and some troglophilic and stygophilic populations, may be geographically restricted to a limited number of sites or even endemic to individual cave systems. Many of the organisms display morphological, physiological, and/or behavioural characteristics related to the physical limitations of the subterranean environment. The evolution and natural selection of subterranean organisms has stimulated considerable interest since the work of Charles Darwin (see Evolution of Hypogean Fauna). However, the mechanism(s) and time required for the development of adaptive (e.g., enhanced development of sensory organs) and regressive (e.g, reduction or absence of eyes) troglomorphic characteristics has stimulated much debate (Culver, Kane & Fong, 1995) (see the six Adaptation entries).

The morphological characteristics of subterranean fauna (troglomorphism, see Adaption: Morphological entries) include the widely reported absence of pigmentation and regression or complete absence of eyes (e.g., the European cave salamander *Proteus anguinus* and many troglophllic Crustacea). Some stygophilic and troglophilic arthropods have longer appendages (e.g., antennae and legs) compared to other epigean organisms with close affinities (e.g., cave crickets from the family Rhaphidophoridae). Many hypogean terrestrial arthropods have thin and less waxy cuticles to facilitate the removal of water through the integument due to the high relative humidity within many subterranean habitats (Juberthie, 2000). Some groundwater organisms are typically longer and thinner (vermiform) than their surface water counterparts, probably to facilitate movement between interstitial spaces. Other morphological characters indicative of subterranean organisms include the reduction or absence of scales in fish (e.g. *Sinocyclocheilus hyalinus:* Cyprinidae), the modification of feet and claws (e.g. subterranean planthoppers), and the development of highly sensitive chemical and mechanical receptors to provide subterranean organisms with detailed information about their surrounding environment.

A range of troglomorphic physiological and behavioural characteristics have been recorded in subterranean organisms. In response to the comparatively stable environment and absence of light many taxa do not respond, or have reduced responses, to daily cycles (circadian rhythms). Many taxa have slow metabolic processes and a greater resistance to starvation in response to the scarce energy resources (spatially and temporally) (Hervant, Mathieu & Barre, 1999). Growth and reproductive rates (including number of eggs and offspring per brood) of stygobitic and troglobitic taxa are usually lower than epigean taxa, and both development time to maturity and longevity are usually greater. However, in some instances when environmental conditions fluctuate, some populations, particularly troglophilic and stygophilic organisms, may take on the characteristics of epigean populations. A range of behavioural adaptations have been recorded in subterranean environments including a decrease in the aggregation of some terrestrial taxa (e.g., Collembola); a reduced response to natural alarm substances in cave fish (e.g., *Astyanax fasciatus* (Characidae) and *Caecobarbus geertsii* (Cyprinidae)) and an increased sensitivity to vibration and reduced aggression between individuals of the same species (intraspecific competition) (Parzefall, 1992). The role and development of these behavioural characteristics is providing a greater understanding of the evolution of hypogean organisms and the compensatory benefits that they give the organism within subterranean environments.

Disturbance and Conservation

Within ecology, disturbance is acknowledged as a primary force of structural change. It is widely assumed that subterranean ecosystems, and the communities that occupy them, are relatively stable when compared to epigean systems. Anthropogenic activities and pollution constitute the most serious threat of disturbance to the natural functioning of both aquatic and terrestrial subterranean ecosystems (see also Conservation: Cave Biota). However, since the impacts of human activities on subterranean ecosystems are largely unseen they have historically been poorly documented. In addition, the diffuse nature of many pollution sources has meant that it has not always been possible to quantify the impacts on subterranean communities. Agricultural activities in epigean catchments may lead to a significant increase in the volume of nutrients entering hypogean environments and as a result change the structure of the subterranean food web. In extreme instances microbial communities may proliferate and the indigenous subterranean community may be displaced by epigean taxa (Notenboom, Plénet & Turquin, 1994). Management activities, such as the closure of cave entrances, have led to the reduction and even extinction of some bat populations. In open cave systems, the number of human visitors, particularly to show caves, may lead to significant changes to the micro-climate and the cave atmospheric chemistry. Visitors and recreational cavers may inadvertently carry and deposit organic matter within caves and potentially introduce epigean taxa. In addition, algae and higher plants may be able to colonize show caves where artificial illumination occurs (see Tourist Caves: Algae and Lampenflora). This primary productivity potentially changes the trophic basis of the cave and may be utilized by hypogean taxa, but may also allow the colonization and the development of populations of epigean taxa.

The organisms within subterranean environments may provide valuable information regarding the evolution and functioning of natural ecosystems. However, our greatest challenges may involve the protection of hypogean habitats and organisms from the deleterious impacts associated with anthropogenic activity so that future generations can obtain a greater understanding of ecosystem processes and subterranean ecology.

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See also **Biology of Caves; Food Resources**

Works Cited

Culver, D.C., Kane, T.C. & Fong, D.W. 1995. *Adaptation and Natural Selection in Caves: The Evolution* of Gammarus minus, Cambridge, Massachusetts: Harvard University Press

Gibert, J., Stanford, J.A., Dole-Oliver, M.-J. & Ward, J.V. 1994. Basic attributes of groundwater ecosystems and prospects for research. In *Groundwater Ecology,* edited by J.Gibert, D.L.Danielopol & J.A.Stanford, San Diego and London: Academic Press

Hervant, F., Mathieu, J. & Barre, H. 1999. Comparative study on the metabolic responses of subterranean and surface-dwelling amphipods to long-term starvation and subsequent refeeding. *Journal of Experimental Biology,* 202:3587–95

Juberthie, C. 2000. The diversity of the karstic and pseudokarstic habitats in the world. In *Subterranean Ecosystems,* edited by H.Wilkens, W.F.Humphreys & D.C.Culver, Amsterdam and New York: Elsevier

Notenboom, J., Plénet, S. & Turquin, M.-J. 1994. Groundwater contamination and its impact on groundwater animals and ecosystems. In *Groundwater Ecology,* edited by J.Gibert, D.L. Danielopol & J.A.Stanford, San Diego and London: Academic Press

Parzefall, J. 1992. Behavioural aspects in animals living in caves. In *The Natural History of Biospeleology,* edited by A.I.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Pohlman, J.W, Cifuentes, L.A. & Iliffe, T.M. 2000. Food web dynamics and biochemistry of anchialine caves: A stable isotope approach. In *Subterranean Ecosystems,* edited by H.Wilkens, W.F. Humphreys & D.C.Culver, Amsterdam and New York: Elsevier

Poulson, T.L. & Lavoie, K.H. 2000. The trophic basis of subsurface ecosystems. In *Subterranean Ecosystems,* edited by H.Wilkens, W.F.Humphreys & D.C.Culver, Amsterdam and New York: Elsevier

Wilkens, H., Humpreys, W.F. & Culver, D.C. (editors) 2000. *Subterranean Ecosystems,* Amsterdam and New York: Elsevier

Further Reading

Camacho, A.I. 1992. *The Natural History of Biospeleology,* Madrid: Museo Nacional de Ciencias Naturales

Chapman, P. 1993. *Caves and Cave Life*, London: HarperCollins

Gibert, J., Danielopol, D.L. & Stanford, J.A. (editors) 1994. *Groundwater Ecology*. London and San Diego: Academic Press

Gibert, J., Mathieu, J. & Fournier, F. 1997. *Groundwater/Surface Water Ecotones: Biological and Hydrological Interactions and Management Options,* Cambridge and New York: Cambridge University Press

Wilkens, H., Humpreys, W.F. & Culver, D.C. (editors) 2000. *Subterranean Ecosystems,* Amsterdam and New York: Elsevier

SUBTERRANEAN HABITATS

Hypogean or subterranean habitats can be defined as habitable places within the hypogean realm, this being a comparatively closed space below the soil or below the barren rock surface (see Figure). Hypogean habitats are dark, their environmental parameters are comparatively stable, food input is limited, and so is the potential for colonization. Apart from darkness and environmental stability, lack of food—caused by the absence of photo-autotrophs and barriers to external inputs—is one of the most influential ecological factors. The endogean (edaphic) environment (i.e. the soil zone immediately below the surface), although dark, is not classified as a hypogean habitat because it contains rich and varied food resources, in contrast with the deeper zones. There are also some habitats related to the edaphic ones, known collectively as the aquatic Mesovoid Shallow Substratum (MSS), including the hyporheic habitat with *Niphargus* spp., and water-saturated soils in Brazilian llanos (grassy soils), which contain a rich copepod fauna. These habitats can be considered as ecotones (transition or threshold habitats) to various epigean habitats, rather than as hypogean habitats. This same approach has been used to identify other ecotones such as anchialine pools. However, since these habitats have traditionally been studied by biospeleologists, they have been included in this review.

Several attempts have been made to classify hypogean habitats, biotopes, or communities, for example the comparatively loose classifications of Vandel (1965) or Camacho (1992); a classification limited to the aquatic environment by Vandel (1968) and Husmann (1970); and a very detailed classification by Juberthie (1983). The classification presented here is based on large-scale habitat differences; the trophic base and smallscale habitat differences, which together (in aphotic habitats) are the equivalent of the composition of the plant community in epigean habitats; and biogeographical factors (with the proviso that the presence of other species also defines each species' environment) or ecological factors underpinning the composition of the animal community. The classification follows the Council of Europe directives (Devilliers & Devilliers-Terschuren, 1996) and takes into account the main ideas of the previous authors. For the sake of clarity it is presented hierarchically. The Encyclopedia has separate entries on Anchialine, Entrance, Interstitial, Marine, and Thermal Water Habitats.

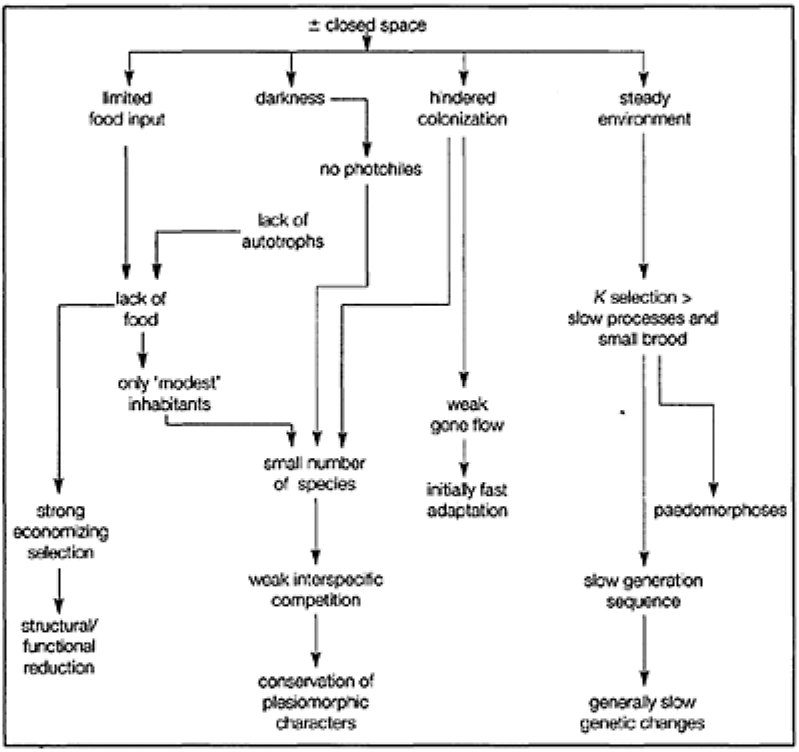
Like any epigean patch of land, a cave may include a number of habitats. The following classification could assist in deciding whether to protect formally (legally) a cave system based on the diversity of the habitats it contains. It can also give an explanation of the high (or low) biotic diversity in a system, along with the ecological basis for its conservation.

Terrestrial Hypogean Habitats

The Terrestrial Interstitial Environment (Terrestrial MSS) is a systems of interconnected channels in deposits of scree (or dry gravel) not infilled by soil. Such deposits are usually covered by layers of more or less compact soil. This habitat is present worldwide in rocky areas. The terrestrial interstitial habitat may be considered as an ecotone between the soil (edaphic) and the crevicular or cave environment. Climatic conditions resemble those in caves, while the food input may be comparatively high. Terrestrial interstitial habitats may be subdivided into:

1. Terrestrial interstitial habitats in carbonate (karst) territories (equivalent to “terrestrial epikarst”) which are sometimes inhabited by highly troglomorphic troglobites (particularly beetles) and by edaphic animals. They probably form an important route for migration of future troglobites into caves.
2. Terrestrial interstitial habitats in nonkarst lithologies, primarily utilized by edaphic animal species.

Cave Entrance and Crevicular Habitats are parts of caves or crevices where daylight penetrates. The depth of light penetration depends on the position, general direction, and shape of the void, and of the width of its opening to the exterior. The light gradually diminishes in its intensity and loses its spectral constituents with distance from the opening; other climatic factors gradually attain their hypogean values. A selection of phototrophs are present, disappearing gradually in this order: flowering plants, ferns, mosses, green algae, and finally cyanobacteria. These habitats are present worldwide and may be considered as ecotones between the surface and dark cave habitats. The subordinate categories below (shallow and wider voids) may be divided further by a combination of the following characteristics:



Hypogean Habitats: Interrelations between some characteristics of typical hypogean habitats. (Reproduced from: *Sket, B. 1996*)

regions poor in troglobites vs. regions rich in troglobites; biogeographical/faunistic regions;

wooded areas, vs. open humid areas, vs. arid areas;

the presence of trogloxene/troglophile invertebrate assemblages (Rhaphidophoridae, Opiliones, Gastropoda, etc.);

habitats of trogloxene vertebrates;

containing hibernating and/or estivating (i.e. resting during hot periods) animal colonies.

1. Shallow crevices are narrow spaces in the fractured rock which may be connected with deeper (dark) crevicular or cave systems. They may be inhabited by selected epigean sighted species, particularly spiders and pseudoscorpions.
2. Habitats in the entrance parts of caves (or artificial cavities) are wider voids in the rock, which may continue into dark cave habitats. They mainly contain trogloxene or accidental animal species, sometimes constituting characteristic parietal faunas of resting (hibernating or estivating) species (particularly some Lepidoptera, Trichoptera,

and Diptera), of photophobic migrants feeding outside daily (particularly Rhaphidophoridae crickets); various accidentals and troglobites are also regularly present. These habitats have developed worldwide in karst and volcanic regions.

Dark Cave and Crevicular Habitats are dark voids in the rock, which can be inhabited by small animals. They are potentially present worldwide in karst and volcanic regions, but in general are inhabited only in temperate to tropical areas. The subordinate types below may be further subdivided on the basis of rock type (karst vs. lava), climate (tropical vs. warm temperate vs. cold temperate regions), and biogeographical region.

Dark cave terrestrial habitats with a high input of allochthonous organic matter can be considered as ecotones with surface terrestrial habitats, particularly with endogean ones. If present, organically enriched deposits may be inhabited by a random assemblage of non-troglomorphic surface (mainly soil) animals. The wider surroundings of these deposits are often comparatively densely populated by troglobites, if they exist in the region. This habitat may be further subdivided according to the origin and composition of food deposits:

1. Input of food (wood, foliage with soil) by abiotic means (streams, wind, or falling into the habitat). Soil-like deposits may be inhabited by a selection of accidental migrants from the soil;
2. Input of food (guano, bird droppings) by animal vectors of particular groups or species (e.g. bat colonies, the oil-bird *Steatornis*, swiftlets *(Aerodramus)*, and cave crickets). In temperate regions the deposits may be similarly inhabited as above, while in tropical caves they may be particularly rich in Microlepidoptera larvae and in cockroaches (Blattaria). In the case of the latter, predators (like Amblypygi) may be very abundant around them;
3. Input of food by plant growth (e.g. penetrating tree rootlets) is particularly common in lava caves because they usually have a relatively thin rock cover. Species feeding on roots are mainly weevils (Coleoptera: Curculionidae) or homopterans (Homoptera: Cixiidae);
4. Input of food from autochthonous (chemoautotrophic) production in the cave water may be limited to deep parts of the cave. The taxonomic composition of the animal community on such food deposits (which mainly comprise bacterial and fungal mats) may depend strongly on the randomness of the local immigration.

Energetically poor, dark cave habitats are inhabited by scarce trogloxene through to troglobitic faunas. Since all cave organisms are bound to the substratum, rather than the void itself, moderately wide crevices are essentially the same habitat as wider cave corridors. They may be classified further by a combination of biogeographical position and any set of climatic and substratum characteristics, as described below:

1. In cold areas they are inhabited by a small population of trogloxenes, and only exceptionally by troglobites (e.g. the beetle *Glacicavicola*);
2. In warm temperate areas they may be inhabited by locally rich troglobitic faunas; around perennial ice deposits in caves in temperate areas, with temperatures close to 0°C and a wet substratum, there are often diverse and dense beetle faunas, with some species (e.g. *Astagobius* spp.) being specialists of this environment;

3. In the tropics they may be inhabited by a few troglobites, as well as scarce edaphic and other lucifugous (light-avoiding) forest animals;
4. On rocky walls, which are usually covered by a thin layer of clay that is regularly wetted, dark cave habitats may be inhabited or visited by snails (*Zospeum* spp.), pseudoscorpions, and beetles (however, their complete habitat often includes clay deposits for breeding);
5. Clay and silt deposits are often inhabited by millipedes and some beetles;
6. The cave hygropetric habitat, which is a rocky wall covered by a thin film of trickling water, is inhabited by some amphibious, originally terrestrial or originally aquatic animals. Some highly troglomorphic leptodirine beetles (e.g. *Hadesia vasiceki*) are specialized for this habitat, while other animals (e.g. the amphipod *Typhlogammarus mrazeki*) are facultative. This habitat is known only from some caves in the Dinaric karst and the Southern Calcareous Alps.

Aquatic Hypogean Habitats

Aquatic Habitats in Unconsolidated Sediments (Interstitial Waters) are water-filled systems of interconnected voids between grains of unconsolidated sediments—mainly gravel and sand. The interstitial space within one sediment deposit is normally contiguous: the length of the channels is immense, while their width depends on the size of the smallest sediment particles. The habitat in any region may be continuous over long geological periods, although it may (together with streams) gradually change its position and its character. If the substrate cover above the interstitial water body is thin, the temperature may vary daily in the upper layers, and variations may be extreme if the substrate is dark in colour. These habitats are generally inhabited by a selection of benthic animals and by a rich array of particularly small and slender specialized troglomorphic animals. Interstitial habitats have developed worldwide, in non-karstic and karstic regions, and even within caves. The subordinate types below may be further classified in combination with sediment grain size (stygopsammal in sand, stygopsephal in gravel); average temperature; high-order biogeographical position; and type of pollution.

Marine and coastal interstitial habitats include the marine mesopsammal zone, which is developed worldwide in sandy parts of the shallow sea bottom. It is an ecotone with different types of the marine benthic habitats. The characteristic inhabitants include Nematoda, Turbellaria, Copepoda: Harpacticoida and Ostracoda; in coarser sediments, some larger crustaceans: Amphipoda and Isopoda. The habitat may be further subdivided according to detritus content and depth. Secondly, coastal or mixohaline interstitial waters are present worldwide along sandy or gravelly sea coasts where an influx of fresh water from the continental side occurs (similar habitats have developed in dry landlocked areas; they are often regarded as marine relicts, but may in fact be secondarily saline). The remarkable spatial and temporal variability of most climatic parameters (temperature, salinity, and oxygen) is particularly characteristic of this type of habitat. The fauna consists largely of non-troglomorphic and troglomorphic Nerillidae (Annelida) and crustaceans (Copepoda, Isopoda, and Amphipoda). It may be further subdivided by salinity level and salinity fluctuation.

Freshwater phreatic interstitial habitats are potentially present worldwide on land along stream channels, and in sediment-filled depressions. They are often excellent sources of potable water. Benthic animals may be scarce in these habitats and they may be inhabited by a rich assemblage of small troglomorphic and/or stygobitic Oligochaeta, Copepoda, Amphipoda, and Isopoda. In cold climates, the interstitial fauna may be limited to nonstygobites in the hyporheal. The hyporheal and phreatic subordinate classes below may be further subdivided by average temperature, and location (non-karst, karst surface, or within a cave). These to a large extent define the characteristics of the fauna.

The hyporheal zone is by its position and ecological parameters an ecotone below the stream benthic zone. Climatic parameters are variable and the food input is high; the oxygen concentration may gradually diminish towards the phreatic zone. It is inhabited by small benthic animals and some interstitial stygobites; Hydracarina and Oligochaeta from both categories may be particularly numerous. This layer may be important as a refugium of the benthal fauna during dry periods.

The phreatic zone comprises layers of interstitial water below the hyporheic ecotone or away from the stream bed. Here, the ecological and faunistic influences from the epigean environment diminish. The fluctuations in ecological parameters are extremely low, particularly daily; the parameters may also be spatially homogeneous. The surface layers are comparatively well supplied with organic matter, and therefore have rich bacterial floras and locally rich stygobite faunas. Deeper layers are almost devoid of food, which has been exhausted in the surface layers. The deep phreatic zone is thus inhabited only by rare and particularly specialized stygobites. Both layer types may be further subdivided by the combination of depth and character of the cover above the water body (which also influences the food input); water-body exchange time; current speed; and degree of oxygenation.

Aquatic Habitats in Porous Rocks are waters in rock crevices, karst conduits (whether the voids are accessible to humans or not), or in volcanic caves. Each of the subcategories below may be further subdivided according to climatic zone, biogeographical position, and geological character.

Hypogean beds of perennial sinking streams (a perennial sinking river is a stream on the surface with an established flora/vegetation and fauna, which sinks underground) are ecotones with the epigean river habitats. Epigean plants and animals may in part drift underground to form a potential food source, while some animals may penetrate underground as competitors to the obligate hypogean biota. In the hypogean parts of these streams, the communities are composed of stygoxene, stygophile, and stygobite organisms, the latter gradually prevailing with the distance from the ponor (swallow hole). In a population of a stygophile species, troglomorphism may increase clinally (gradually) in the same direction. Climatic parameters may to some degree (depending on the distance from the sink, water mass, and the current) vary daily and yearly. As a result, food input may also vary, depending on the season and the intensity of the precipitation. Such habitats have developed worldwide in karst regions. The environment may be further subdivided, according to the distance from the sink, which defines the volume and quality of food; the composition of local surface fauna and local cave fauna; and whether it is absolutely dark, or illuminated from the sink or from the resurgence.

Hypogean beds of intermittent sinking streams only superficially resemble the habitat of perennial sinking streams; the intermittent rivers lack an established vegetation and fauna; however, terrestrial organisms (alive or dead) which drift, will enrich the food supply underground. Therefore, the hypogean parts of the stream may be inhabited by dense populations of local stygobitic species. The variability of climatic parameters and food input are as for perennial sinking streams. These habitats have developed worldwide in karst regions.

Cave waters with autochthonous energy resources are mineral waters with nutrients (such as sulfur and hydrocarbons) on which chemoautotrophic bacteria may flourish, building the nourishing substratum for heterotrophic bacteria and fungi on which higher animals may feed. Very few caves containing this type of habitat have been reported, but Movile Cave in Romania (see separate entry) is a notable example. Cave waters with autochthonous energy resources, which are also open to the surface, are regularly invaded by epigean animal species, while stygobites are scarce or absent. Cave waters with autochthonous energy resources that are not open to the surface may be inhabited by very diverse, sometimes rich, stygobitic faunas. Owing to isolation these fauna may be of a very different taxonomic composition compared with other local hypogean faunas. This type of habitat is particularly rare (or little known) and could be further subdivided by the type of energy source.

Percolation waters are bodies of water originating from the more or less diffuse trickling of water through mostly narrow crevices in the rock. The lack of a food supply is particularly characteristic—it is limited mainly to particles brought from the surface or imported secondarily (underground) from other habitats. In general, climatic parameters are particularly stable in these habitats. They are inhabited by highly specialized troglomorphic species, and Crustacea predominate. They have developed worldwide in karst, but are less common in volcanic rocks. Where wider crevices are present, the percolation water may be ecologically identical with the intermittent sinking streams.

Waters in fissure systems in the rock (mainly in the aeration zone) have primarily been studied in the ceiling layers above caves in epikarst, although they can develop away from any cave. The narrow space is characteristic—in some the water may be held by capillary pressure. Their fauna primarily consists of Copepoda (particularly Harpacticoida) and smaller Amphipoda; facultatively amphibious terrestrials (e.g. Collembola) may also be present.

Cave waters mainly originating from percolation may be classified further according to habitat configuration: trickles, streamlets, puddles, rimstone pools, pools, lakelets; by the position within the cave system: at the water table or in the aeration cave layer ("zone"); and by connections to, and food input from, other habitats. These habitats may be inhabited by a rich assortment of stygobitic animals, particularly crustaceans, and sometimes fish and amphibians; some extraordinary taxa (e.g. Polychaeta, Porifera) may also be present.

Anchialine (anchihaline) habitats are waters in voids near the coast, where sea water is responsible for their mixohalinity (differnt mixtures of fresh and marine waters) and/or the presence of marine-derived animal species. Hydrographical connections to the sea—as well as to the continent—are hypogean, while the contact of the water body with the open air is restricted to at least some degree. Habitats can potentially develop along all the sea coasts, but anchialine fauna have been found only in tropical to warm temperate regions. The subordinate categories can further be divided according to a combination of characters: lava vs. karst; average temperatures; and biogeographical regions.

Euhaline (marine) anchialine cave habitats are very deep seacaves or the euhaline parts of mixohaline anchialine caves. This constitutes an ecotone between hypogean habitats and sea caves. Salinity, temperature, and the low food input may be very stable, and the habitat is sheltered from elevated summer temperatures (particularly if the channel is directed downwards). They are inhabited by some slow-moving, or sessile, marine stygophiles, including some deep-sea animals (e.g. sponges: Pharetronida and Hexactinellida; fish: Ophidiidae) as well as some stygobites (e.g. Crustacea: Remipedia, some Isopoda).

Open anchialine pools are coastal pools connected to the sea by cave corridors. The water body is stratified according to salinity. There is a general similarity to shallow-marine habitats, particularly in the presence of phototrophic algae and fluctuation of climatic parameters. The cave-like character of these habitats is exhibited by their limited accessibility to invading biota, as well as by the presence of some stygobites. Apart from a number of marine biota, some stygophiles and stygobites inhabit anchialine pools; most characteristic are taxonomically diverse red shrimps, amphipods: Hadziidae, some copepods, and ophidiid fishes. They may be further classified by distance from and degree of connection to the sea, the salinity regime, and the distance from the equator.

Mixohaline and freshwater anchialine caves are real caves with an anchialine regime, but which are not able to be invaded by epigean marine biota. They may also be dark corridors connected to anchialine pools. A salinity stratification prevents mixing of water layers, and more or less strongly de-oxygenated layers are characteristic. The caves are primarily inhabited by euryhaline stygobites of marine origin (e.g. a number of amphipods: Hadziidae, shrimps: *Typhlatya*, and fish: Ophidiidae), some of limnic origin (e.g. some amphipods: *Niphargus* and some copepods); a few euryhaline marine species may also be present. Habitats may further be classified by the salinity regime.

Thermal hypogean waters are hypogean waters with a temperature higher than the average yearly temperature of the area. The actual habitat comprises the ecotonal area close to the spring where allochthonous food is available. It may be inhabited by a very scarce fauna of relict stygobites, particularly the crustacean family Stenasellidae. Some are eurythermic and others are polystenothermic. The habitat is potentially present everywhere, but the stygobites that live there are known only from tropical to temperate regions. To become thermal, the hypogean waters have usually descended to a great depth in the Earth’s crust and are devoid of organic matter (food); however, they may be inhabited by chemoautotrophic bacteria. Thermal habitats may be divided further according to temperature; the absence or presence of chemoautotrophic bacteria; the presence of higher mineral concentrations; and their biogeographical position.

BORIS SKET

See also **Anchialine Habitats; Entrance Habitats; Interstitial Habitats (Aquatic); Interstitial Habitats (Terrestrial); Marine Cave Habitats; Thermal Water Habitats**

Works Cited

Camacho, A.I. 1992. A classification of the aquatic and terrestrial subterranean environment and their associated fauna. In *The Natural History of Biospeleology,* edited by A.I.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Devilliers, P. & Devilliers-Terschuren, J. 1996. *A Classification of Palearctic Habitats,* Strasburg: Council of Europe (Nature and Environment, 78)

Husmann, S. 1970. Weitere Vorschläge für eine Klassifizierung subterraner Biotope und Biocoenosen des Süsswasserfauna. *Internationale Revue der Gesammten Hydrobiologie,* 55(1):115–29

Juberthie, C. 1983. Le milieu souterrain: étendue et composition. *Mémoires de Biospéologie,* 10:17–65

Sket, B. 1996. The ecology of the anchihaline caves. *Trends in Ecology and Evolution,* 11(5):221–25.

Vandel, A. 1965. *Biospeleology: The Biology of' Cavernicolous Animals,* Oxford and New York: Pergamon Press (originally published in French, 1964)

Vandel, A. 1968. Le milieu aquatique souterrain. *Bulletin de la Société Zoologique de France,* 93(2):209–25

Further Reading

Bou, C. 1974. Les méthodes de récolte dans les eaux souterraines interstitielles. *Annales de Spéléologie,* 29(4):611–19

Chappuis, P.A. 1950. La récolte de la faune souterraine. *Notes Biospéologiques,* 5:1–29

Delamare-Deboutteville, C. 1960. *Biologie des eaux souterraines littorales et continentales* [Biology of littoral and continental hypogean waters]. Paris: Hermann

Ginet, R. & Decou, V. 1977. *Initiation a la biologie et a l'écologie souterraines* [Introduction to the biology and ecology of underground]. Paris: Delarge

Howarth, F.G. 1981. Lava tube ecosystem as a study site. In *Island Ecosystems: Biological Organization in Selected Hawaiian Communities,* edited by D.Mueller-Dombois, K.W.Bridges & H.L.Carson, Stroudsburg, Pennsylvania: Hutchinson

Juberthie, C. & Delay, B. 1981. Ecological and biological implications of the existence of a superficial underground compartment. *Proceedings of the 8th International Congress of Speleology,* Bowling Green, Kentucky: 203–06

Orghidan, T. 1959. Ein Lebensraum des unterirdischen Wassers: der hyporheische Biotop. *Archiv für Hydrobiologie,* 55:392–414

Sarbu, S. & Popa, R. 1992. A unique chemoautotrophically based cave ecosystem. In *The Natural History of Biospeleology,* edited by A.I.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Sket, B. 1977. Gegenseitige Beeinflussung der Wasserpollution und des Hoehlenmilieus. *Proceedings of the 6th International Congress of Speleology 1973,* vol. 5, Olomouc: International Union of Speleology

Sket, B. 1986. Ecology of the mixohaline hypogean fauna along the Yugoslav coast. *Stygologia,* 2(4):317–38

SULFIDE MINERALS IN KARST

Limestone is the host rock for two of the most important classes of economic sulfide mineralization, and thus karst terrains host many of the world's economic sulfide ore deposits. Many karst areas have long mining histories, extending back in Europe to at least Roman times and, in some cases, the Bronze Age. Exploitation of sulfide mineral resources has had a profound effect on the cultural and economic development of many karst regions, but mining and associated mineral processing has also caused environmental degradation in some areas. One notable impact has been drainage of the host limestone to exploit the sulfide minerals. For example, over a large part of the English Peak District (see separate entry) the karst hydrogeology has been profoundly influenced by the driving of lead mine drainage levels (soughs).

From a genetic perspective, sulfide deposits in limestone fall into two broad categories: "syngenetic" deposits, which formed at the same time as the limestones themselves were deposited or lithified; and "epigenetic" or "hydrothermal" deposits, which formed within the limestone after lithification. In the latter group, pre-existing karstic porosity and permeability may play an important role in determining or influencing the location and style of mineralization. Much more rarely, "secondary" sulfide minerals form within the cave environment, either as a result of hydrothermal processes or via microbiological processes in cave sediments.

The best known of the syngenetic limestone-hosted sulfide deposits are the "Irish-type" lead-zinc ores. In the Irish localities, after which the group is named, these formed at the same time as, or soon after, deposition of the host Lower Carboniferous limestone sequence. Lead isotopic and other studies show that lead (and, by analogy, other metals) was derived from the underlying lower Paleozoic basement by brines driven by hydrothermal convection (e.g. Mills *et al.,* 1987). Fault-hosted mineralization of the appropriate style, age, and lead isotopic composition has indeed been found in the Paleozoic basement rocks (Haggerty *et al.,* 1996). Sulfide was derived predominantly from bacterial reduction of seawater sulfate within the host limestone. Where the ascending metal-rich brines met the sulfide-rich limestone sediment pore waters a perfect environment for sulfide ore deposition was created, resulting in some of the world's major lead-zinc ore deposits.

The classic limestone-hosted epigenetic sulfide deposits are the Mississippi Valley-type lead-zinc deposits of North America. However, these are one example of a wide range of types of limestone-hosted lead-zinc deposits that are common worldwide. Other well-known and broadly similar deposits occur in the Carboniferous limestone of the Derbyshire Peak District, Yorkshire Dales, North Wales, and Mendip areas of Britain. Other classic localities worldwide are found in Silesia, the Eastern Alps, Anatolia, Russia, and Canada. In these deposits the lithified limestone provides a host for sulfide deposits formed in faults and other fractures as replacement deposits—where limestone has been dissolved by the ore-forming fluid and the porosity refilled—and as deposits in pre-existing karstic porosity.

The role of the limestone host rock in the formation of these deposits has long been debated and may be complex. Limestones are often massive and relatively brittle rocks and may thus have extensive fracture networks, which promote deep groundwater flow and assist the emplacement of mineralizing fluids. Preexisting karstic porosity in buried limestones will clearly enhance this effect. Limestones may also play a chemical role in the localization of mineralization in these deposits. It has been suggested that limestone can neutralize brines carrying H_2S and dissolved metals, resulting in sulfide mineral deposition. Clearly, in replacement-type deposits, there has been corrosion of limestone associated with ore emplacement, but in many other deposits these relationships do not exist.

The role of pre-existing karstic porosity in the formation of these deposits has often been significant or even crucial. Sass-Gustkiewicz (1983) showed that the style of mineralization in Silesian deposits was controlled by its relationship to pre-existing karstic porosity. At two major deposits in Canada (Pine Point and Nanisivik), mineralization is focused into zones of pre-existing karstic porosity. In the classic Derbyshire (England) localities, deep groundwater flow along fault systems allowed dissolutional development of passages that were later infilled with calcite, along with galena and sphalerite. However, even where ores are deposited in solution cavities away from the main faults, good evidence of replacement textures is rare and often equivocal (e.g. Ford & King, 1965). Solution cavity generation may be significantly separated in time from the later emplacement of ore minerals, even in apparently “replacive” deposits.

Perhaps the best-described example of “secondary” hydrothermal sulfide minerals in caves, are sulfide mineral inclusions in sparry calcite in the Cupp-Coutunn Cave system, Turkmenistan (see separate entry). These minerals formed when pre-existing cave passages were invaded by hot basinal brines; the same brines formed epigenetic fault-hosted galena mineralization in limestone at greater depths. Cinnabar and metacinnabar (sulfides of mercury) are known from the Gaudakskoy caves of the former USSR, where again they originate from thermal waters (Lazarev & Philenko, 1976).

Secondary cave sulfide minerals can also form at low temperatures, as a result of reactions of hydrogen sulfide produced by sulfate-reducing bacteria (see Microbial Processes in Caves). Bacterial sulfate reduction is ubiquitous in anoxic environments in marine systems, where sulfate is abundant, but is generally less significant in terrestrial aquatic environments, where sulfate concentrations are usually much lower. Iron sulfide mineral coatings formed in this way on cave walls, have been reported from the freshwater-marine mixing zones of the Bahamas (Bottrell *et al.*, 1991). Here, hydrogen sulfide is produced in a biologically active zone, localized within the density gradient of the mixing zone. Most of the sulfide is reoxidized in shallower groundwater, but some reacts with detrital iron oxides to form solid iron sulfide. Similarly, pyrite has been reported in sediments from phreatic caves in Florida (Martin & Harris, 1993). Such processes are likely to be less significant in caves with fresh waters. Seeman (1970) reported pyrite and marcasite (both forms of FeS2) in cave sediments, the sulfur source being sulfate evaporites, and Bottrell *et al.*, (1999) reported sulfide mineralization of wood fragments in freshwater sediments in the Speedwell Mine/Cave system of Derbyshire, England. Lauritzen & Bottrell (1994) describe iron sulfide spherules from thermoglacial karst springs in southern Svalbard, though these most likely originate from the deeper, thermal part of the cave system, where waters have higher salinity and have undergone bacterial sulfate reduction.

SIMON BOTTRELL

See also **Mineral Deposits in Karst**

Works Cited

Bottrell, S.H., Smart, P.L., Whitaker, F. & Raiswell, R. 1991. Geochemistry and isotope systematics of sulphur in the mixing zone of Bahamian blue holes. *Applied Geochemistry,* 6:97–103

Bottrell, S.H., Hardwick, P. & Gunn, J. 1999. Sediment dynamics in the Castleton karst, Derbyshire, UK. *Earth Surface Processes and Landforms,* 24:745–59

Ford, T.D. & King, R.J. 1965. Layered epigenetic galena-barite deposits in the Golconda Mine, Brassington, Derbyshire, England. *Economic Geology,* 60:1686–1701

Haggerty, R., Cliff, R.A. & Bottrell, S.H. 1996. Pb-isotope evidence for the timing of episodic mineralization on the Llanrwst and Llanfair-Talhaiarn orefields, north Wales. *Mineralium Deposita*, 31:93–97

Lauritzen, S.-E. & Bottrell, S.H. 1994. Microbiological activity in thermoglacial karst springs, south Spitzbergen. *Geomicrobiology Journal,* 12:161–73

Lazarev, J.S. & Philenko, G.D. 1976. Geologo-mineralogiceskie osobenosti Guardakskoy karstovoy peschery. *Peschery,* 16:45–63

Martin, H.W. & Harris, W.G. 1993. Mineralogy of clay sediments from three phreatic caves of the Suwanee River Basin. *NSS Bulletin,* 54:69–76

Mills, H., Halliday, A.N., Ashton, J.R., Anderson, I.K. & Russell, M.J. 1987. Origin of a giant orebody at Navan, Ireland. *Nature,* 327:233–35

Sass Gustkiewicz, M. 1983. Zinc-lead ore structures from the Upper Silesian region in the light of solution transfer. In *International Conference on Mississippi Valley Type Lead-Zinc Deposits,* edited by G.Kisvarsanyi, S.K.Grant, W.P.Pratt & J.W.Koenig, Rolla: University of Missouri

Seeman, R. 1970. Pyritfunde in der Dachstein-Mammuthohle (Oberosterreich). *Die Hohle,* 21:83–89

SURVEYING CAVES

Cave surveying is an attempt to accurately record the form of a cavity and, like much else in speleology, can involve a great deal of dedication and discomfort if it is to be done well. Cave surveys (or cave maps in US terminology) serve a range of purposes, from the most basic of describing the shape of the cave, through detailed mapping to enable further exploration or scientific work, to full 3D visualization techniques for the placing of archaeological remains.

History

The first known cave plan was published in *De ortu et causis subterraneorum* (Georg Agricola, 1546, p.146) and is of the Stufe di Nerone (Nero's Oven), Pozzuoli, near Naples (Italy). However this is a man-made cavern in tufa deposited from ancient hot springs. The first drawing of a natural cave was a very approximate sketch of the Baumannshöhle, made by Von Alvensleben in 1656, but it was never published and now resides in the archives of Magdeburg (Germany). Next was a rather more realistic sketch of Long Hole, Cheddar (United Kingdom) made before 1680 by John Aubrey, however this was not published until 1992 (Boycott, 1992).

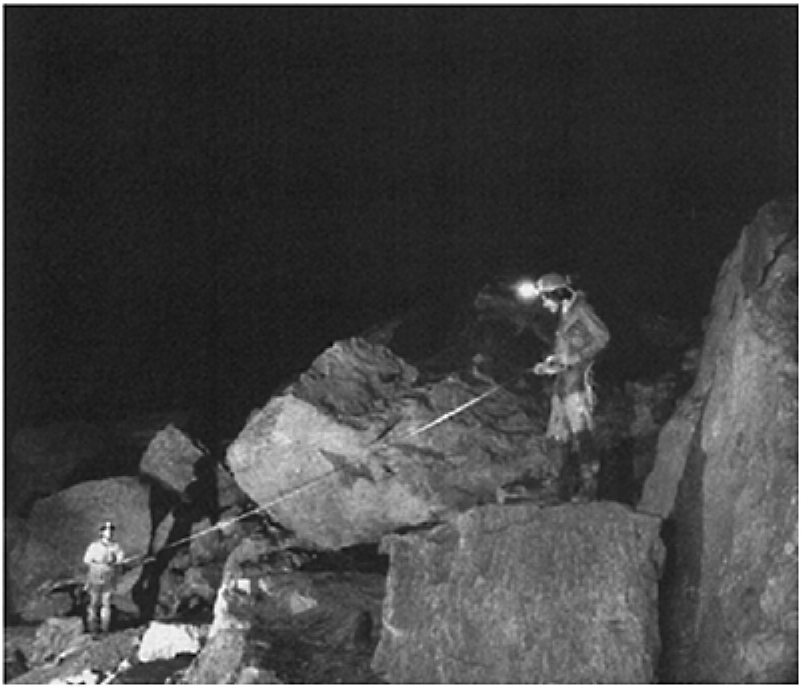
The first published cave survey was of Pen Park Hole, Bristol (United Kingdom) in 1683 (Mullan, 1993 and see figure in Britain and Ireland: History). The survey (plan and elevation) was made during the second descent of the cave in 1682 by Captain Greenville Collins (Southwell, 1683). This survey, whilst not accurate, gives a reasonable idea of the form of the cave, and as the captain was from a survey ship this was probably the first survey to use any instruments (for depth measurement at least).

There were several more surveys in the 18th century, of somewhat variable accuracy; an elevation of Demänova cave in Czechoslovakia (1719, by Juraj Buchholtz), better surveys of both Pen Park Hole (1775, by William White) and Baumannshöhle (1702, by Hardt), Postojna Cave, Slovenia (J.A.Nagel, 1748), Aggtelek, Hungary (1794, by József Sartory), a 1781 sketch of Madison's Cave by Thomas Jefferson (Jefferson, 1782, pp.34–36) (the first American cave map), and the caves of Sloup, Czechoslovakia (Süsz, 1800). Whilst some of these are quite good representations of the cave, the first genuinely accurate survey is a plan of the Grotte de Miremont, Rouffignac (France) in 1765, by Nicolas Thomas Bremontier, a civil engineer and inspector-general of highways. This plan and 27 cross sections must have been made with compass and tape or chain, and compares very well with the survey made by E.A.Martel 128 years later.

From 1800 on, surveying became intimately associated with cave exploration. Activity in the two fields expanded together—you can't tell what you've found unless you survey it, and the survey is often the key to further discoveries. Thus explorers started to make good quality surveys as they discovered new parts of a cave system. Perhaps the best example is the work to piece together the parts of the Postojna system in Slovenia between 1748 and 1852 (Shaw, 1992).

Surveying continued to develop in the 19th century, notably in Belgium, Slovenia, Australia, and the United States. In the United States, the main drive for surveying was as an aid to the exploitation of saltpeter deposits. The first measured survey there was an 1805 compass and chain map of Great Saltpeter by John James DuFour. This was followed by numerous surveys of Mammoth Cave, Kentucky, by far the most accurate of which was the one in 1834–35 by Edmund F. Lee, a professional surveyor, which took several months. Later surveyors were restricted by the showcave management, who obtained an injunction against publication of one survey as it would show that the cave extended beyond their land, potentially allowing another entrance to be opened and reduce their takings. Such surveys would also have spoiled the extravagant claims the management made for the length of the system (between 40 and 50 km by 1952, but claims for a length of 600 miles were made!).

The first underground theodolite (or transit) surveys were made by mine surveyors as the theodolite had become standard for mine surveys by 1832. The first definite theodolite cave survey was by a Mr Hodgeson in Ingleborough Cave, Yorkshire (United Kingdom) in 1838, under the direction of the landowner James W.Farrer. It seems possible that Edmund Lee's Mammoth Cave survey of 1835 was also done using such instruments, which would make it the first.



Surveying Caves: The original compass-and-tape survey of Sarawak Chamber in the Mulu karst; only when the survey was drawn up in the cave was it realized that the seemingly endless survey over the breakdown pile had made a loop through the world's largest underground chamber. (Photo by Andy Eavis)

Techniques

Details of the techniques used in early surveys are not often given so it is difficult to be specific about exact techniques. However a lot can be inferred by comparing with modern surveys and reading contemporary reports. The overall impression is that the techniques used have changed remarkably little since the end of the 18th century. A notebook with compass or transit/theodolite and tape or chain have been the tools of the trade up till the present day. Accuracy has improved with better equipment and technique as surveyors progressed from pacing through to marked ropes, tapes, chains, and towards the end of the 19th century the measurement of slope as well as direction. Over this time the size and weight of the instruments has improved significantly from heavy miner's dials in big wooden boxes to modern aluminium-bodied compasses and clinometers, introduced in the late 1960s. The earliest compass used a succession of concentric wax rings on which the needle directions were inscribed. This allowed the survey to be re-created on the surface. This was certainly used for mine surveying and was probably used in natural caves too. There have been very few instruments designed specifically for caving so available items have been pressed into service—such as mining instruments (compass, transit), theodolite, the Abney level, and the forester's clinometer.

The first detailed description of cave surveying techniques is by E.A.Martel (Martel, 1894, pp.24–28). He describes the construction of a canvas-covered notebook 12×17 cm composed of alternate pages of 1 mm/1 cm grid and blank, and with a notch cut out in the top right hand corner for a small compass to be attached. He worked with one assistant who carried a light and moved ahead until he was about to become obscured. Martel aligned the notebook using the compass, recorded the reading and then drew the corresponding line on the page, drawing the cave around this line, carefully keeping the notebook properly aligned with the compass. This is similar to the modern plane table technique. Distances were measured by pacing except where the terrain was too difficult, when a marked rope was used. Martel generally didn't record slight slopes, but noted that boulder slopes always rest at between 33 and 36 degrees.

Since the early days, cave surveying has consisted of marking points in the cave called stations, and measuring legs (US: shots) between them, although advanced electronic instruments may finally change this fundamental method in the 21st century. A leg is defined by the length, angle, and inclination between two stations. The development of cave surveying has really just been advances in the instruments used to make these measurements.

Arthur Butcher's seminal book, including CRG (Cave Research Group of Great Britain) grades based on instruments used, defined modern technique (Butcher, 1950). This prompted a great deal of surveying in the United Kingdom in the 1950s. William E.Davies and Lang Brod covered similar ground in the United States in the 1950s and 1960s (Brod, 1962). Bryan Ellis later modified the CRG grades to produce the BCRA (British Cave Research Association) grades defined in terms of accuracy, which have become widely used throughout the world (Ellis, 1976).

The standard method since the 1950s has been to use compass, clinometer, and tape although many less accurate surveys, especially in largely horizontal caves, miss out the inclination reading and some still use pacing or a chain for length. For higher accuracy a theodolite or transit is used: a transit is just a very precise compass, but a theodolite measures relative angles from a baseline at the entrance of the cave, so errors will accumulate as the survey length increases. Such high-accuracy surveys are rarely justified—usually only on main passages of important caves or if starting an expensive project such as blasting a new entrance or connection.

The aluminium-bodied Suunto compass and clinometer became popular in the 1960s, and although some American surveyors still persist with the classic Brunton pocket Transit compasses (invented c.1898), the Suunto and Sisteco/Silva equivalents have become standard the world over. Fibreglass tapes are preferred to metal tapes as they are much easier to handle underground.

In the 1970s and 1980s (in France and Switzerland particularly) the topofil became quite popular—this is a device that reels out thread to measure the distance, and incorporates the inclinometer and compass. It was quick, if slightly less accurate than conventional compass and tape, but its popularity has declined in recent years. Some groups of Russian and Ukranian surveyors use a water level to measure height difference, rather than angle. This has the advantage that it can be used round corners between any two stations the pipe will reach, and the height measurements can be done on a separate trip from the compass and tape survey. Other popular instruments used up until the 1970s include the Abney level to measure inclination up to about 60 degrees.

Drawing was done by simply transferring the direction and length measures to the page at a suitable scale (and allowing for slope), until around the 1960s when using calculators or computers to do the simple trigonometry became feasible. The resulting coordinates are plotted on graph paper. Recent advances in software and technology have enormously speeded up this drawing process so that the surveyor merely enters the data and immediately gets a finished plot of the legs, stations, and even passage size.

The advent of computers also made it possible to deal with survey errors systematically. Loops in caves are common and there will always be a discrepancy in the position of a point measured by two different routes. Mathematical techniques, originally developed by land surveyors and commonly referred to as “least squares loop closure”, find the best fit positions, assuming there are no gross errors (“blunders”). Techniques to identify blunders (which can be remarkably common in survey data, see Fish, 1999) are also now found in cave survey software. These can only be applied to blunders within loops.

The first cave survey software was written on university mainframes and the first survey to be produced with the aid of such software was of the Fergus River Cave, Ireland, in 1964 (Hanna, 1964). Since then innumerable programs have been written. In 1980 David McKenzie had a program called ellipse that would not only process the centreline but also plot the walls, and adjust them to fit as loop closures moved the centreline. This was not repeated on personal computers until Toporobot gained this functionality in about 1995. Toporobot, started in 1972 by Martin Heller, is one of the most long-lived programs, and is still popular and being developed today. It is unusual in that it defined and requires a particular surveying methodology to get the best out of it. Most other software instead reflects existing techniques and does its best to cater for them. SMAPS by Doug Dotson was very popular for many years in the 1980s, but ceased to be maintained in 1995 and has been superseded. Compass by Larry Fish is probably currently the most popular cave survey software in the world, having had long and consistent development with good documentation since the mid 1980s. The multiplatform, multilingual Survex by Olly Betts has also become popular since its creation in 1990. Many other programs are used, often being popular in a particular area. Modern software can generate impressive 3D models with rendered walls, overlay elevation details and maps, and do flythroughs as well as importing data from a number of sources.

Representing a 3D void, often of very complex shape, in 2D on paper has always been problematic and many techniques have arisen over the years to try to represent the cave as well as possible. Plans may be coloured to show multiple levels, elevations may be drawn as “extended elevations” where the passages are “unfolded” into one plane to better describe the slopes and feel of the cave at the expense of the representation of above/below relationships. Cross-sections and isometric views show the passage shape. Numerous symbols are used to indicate floor sediment type, speleothems, drops, climbs, slopes etc. Numerous standard symbol sets have been defined over the years, the latest being by the International Union of Speleology in 1999 (UIS, 1999).

Cave surveyors have always made use of new technology as soon as it becomes sufficiently robust, and at the turn of the 21st century electronic devices are becoming available which will probably mean significant changes to the cave surveying method over the next couple of decades. Martin Sluka of the Czech Republic made what is probably the first practical electronic cave surveying device in 1996–a laser distance-measuring device attached to a laser point, and electronic inclinometer with a conventional compass (Sluka, 1999). This took conventional readings but without the user having to move to the end point of the leg. Other researchers are working on completely electronic devices that are simply pointed at the next station and the readings internally recorded for later downloading (Auriga project, Martin Melzer http://home.nikocity-de/andymon/hfg/avriga4-htm). Inertial based devices that are simply carried through the cave recording a track are also possible; these produce data fundamentally different from the station+legs concept. Indeed, the Wakulla II project (in Florida) produced a device that worked in this way in 1998. It had a rotating scanning sonar head which traversed the (underwater) cave on a dive-scooter, automatically generating a helical 3–D scan of points describing the wall position, but it did weigh nearly 200 kg out of the water.

Underwater surveying is a particularly difficult task due to the poor visibility and lack of time. A depth gauge is used instead of measuring inclination and a dive line pre-marked with tags is used for distances. The compass is a wrist-compass, typically marked in 5 degree graduations. If the survey is done carefully (preferably in both directions along the line to make a loop) then quite good accuracies of 5% are obtainable. This has been standard technique since the 1950s (Lloyd, 1970). During the 1990s more accurate techniques have been developed by John Cordingley, made practical by better diving equipment allowing longer, warmer dives. A compass is screwed to an A4 slate and a fibreglass tape fitted with clothes pegs is used for distance. A dive computer is used for depth. All these improve accuracy so that 1% errors on 1 km loops are achievable (Cordingley, 1997). Cyrille Brandt has developed equally accurate techniques by two-man teams in European sumps.

Radiolocation is a technique to fix an underground point to the corresponding point on the surface, usually to find out where the extremities of a cave lie and reduce cumulative errors in the survey (see Radiolocation). Induction radio is used with a carefully levelled transmitter underground. A surface receiver can be used to find the point directly above the transmitter by searching for "nulls"—the plane in which a vertically held receiver loop receives no signal from the underground loop. Lines along nulls will intersect over the transmitter. The depth of the transmitter can be determined either using signal strength measurements, or by finding the point at which a null occurs when the receiver is held at 45 degrees to the perpendicular. It is also possible (but more difficult) to use the technique between two caves to help determine relative position.

WOOKEY

See also **Radiolocation**

Works Cited

Boycott, T. 1992. Cave references in John Aubrey's *Monumenta Britannica. University of Bristol Spelaeological Society Newsletter,* 8(3):5–9

Brod, L. 1962. Cave mapping: A systematic approach. *Missouri Speleology,* 4(1–2)

Butcher, A.L. 1950. *Cave Survey,* Warwickshire: Cave Research Group of Great Britain

Cordingley, J. 1997. Surveying underwater caves. *Compass Points,* 16:9–12

Ellis, B. (editor) 1976. *Surveying Caves,* Bridgwater British Cave Research Association

Fish, L. 1999. How common are blunders in cave survey data? *Compass Points,* 25

Glover, R.R. 1976. Cave surveying by electromagnetic induction. In *Surveying Caves,* edited by B.Ellis, Bridgwater: British Cave Research Association

Hanna, K. 1964. Survey. In D.J.Patmore & F.H.Nicholson, The Fergus River Cave, County Clare, Ireland. *Proceedings of the University of Bristol Spelaeological Society,* 10:285

Jefferson, T. 1782. *Notes on the State of Virginia,* Paris, privately printed (many later editions)

Lloyd, O.C. 1970. An underwater cave survey. *Transactions of the Cave Research Group,* 12(3):197–99

Martel, E.A. 1894. *Les abîmes* [The Depths], Paris: Delagrave

Mullan, G.J. 1993. Pen Park Hole, Bristol: A reassessment. *Proceedings of the University of Bristol Spelaeological Society,* 19(3): 291–311

Shaw, T. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society

Sluka, M. 1999. Surveying with digital instruments. *Compass Points,* 23

Southwell, R. 1683. A description of Pen Park Hole in Glocestershire. *Philosophical Transactions of the Royal Society,* 13: 2–6

UIS 1999. Cave symbols: The official UIS list. http://www.karto.ethz.ch/neumann-cgi/cave-symbol.pl

Further Reading

Day, A.J. 2002. *Cave Surveying,* British Cave Research Association

Dasher, G.R. 1994. *On Station,* Huntsville, Alabama: National Speleological Society

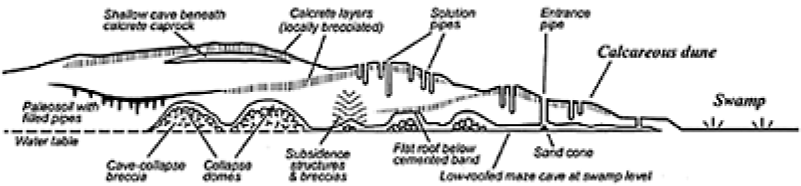
Grossenbacher, Y. 1991. *Topoghraphie Souterrain,* Editions du Fond, Société Suisse de Spéléologie

SYNGENETIC KARST

Syngenetic karst is a term coined by Jennings (1968) for karst features, including caves, that form within a soft, porous, soluble sediment at the same time as it is being cemented into a rock. Thus, speleogenesis and lithogenesis are concurrent.

Jennings was describing the active karst geomorphology of the Quaternary dune calcarenites of Australia. Concurrent studies by sedimentologists of paleokarst horizons at unconformities in the stratigraphic record used the related concept of eogenetic diagenesis: processes that affect a newly formed carbonate or evaporite sediment when it is exposed to subaerial weathering and meteoric waters (Choquette & Pray, 1970). The resulting eogenetic karst (or “soft-rock karst”) is distinguished from telogenetic (“hard-rock”) karst, that has developed on hard indurated limestones that have been re-exposed after a deep burial stage.

The terms syngenetic and eogenetic overlap but involve different viewpoints. The former is best used for geomorphological studies of modern soft-rock karsts; whereas the latter is best retained for diagenetic studies of paleokarst porosities, where the sequence of dissolution and cementation events is much more complex. Some, but not all, paleokarst is eogenetic: the separation of eogenetic, mesogenetic (burial), and telogenetic features



Syngenetic Karst: Figure 1. Features of syngenetic karst developed on a calcareous dunefield.

requires a detailed study of cement morphology, mineralogy, chemistry, and related dissolutional and brecciation features, at both the microscopic and macroscopic scale.

Some workers have applied the term “syngenetic cave” to lava tubes. Although that is an etymologically valid use of “syngenetic”, it is unrelated to the present topic.

Syngenetic karst has several distinctive features, as well as many that are shared with classical (telogenetic) karst. In the following discussion, dune calcarenites in a Mediterranean climate are used as an initial example (Figure 1). In calcareous dunes, percolating rainwater gradually converts the unconsolidated sand to limestone by dissolution and redeposition of calcium carbonate. This initially produces a cemented and locally brecciated calcrete layer near the surface (Figure 4). Terra rossa soils may also develop. Below this, the downward percolating water dissolves characteristic vertical solution pipes (Figure 2), and simultaneously cements the surrounding sand. Early cementation tends to be localized around roots, to form distinctive rhizomorphs or rhizocretions. Cementation can occlude the primary inter-granular porosity, but dissolution can generate localized secondary porosity of a mouldic, vuggy, or cavernous character.

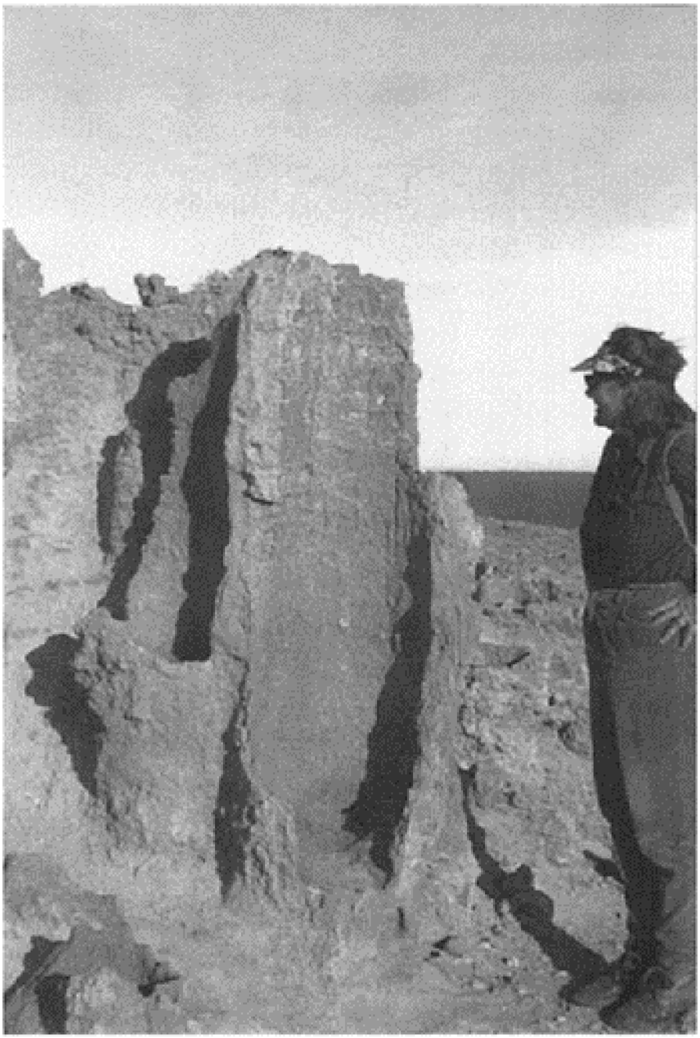
Mixing corrosion occurs where percolation water meets the water table, which is typically controlled by the level of a nearby swampy plain, which also provides acidic water. Near the coast, water levels fluctuate with changing sea levels, and further complexity results from a thin freshwater lens floating above sea water, which results in two mixing zones, above and below the lens (see Speleogenesis: Coastal and Oceanic Settings).

In the early stages of solution, the loose sand subsides at once into any incipient cavities, possibly forming soft-sediment deformation structures. Once the rock is sufficiently hardened to support a roof, caves can develop. Horizontal cave systems of low, wide, irregular, interconnected chambers and passages (see Salt Pond Cave figure in Speleogenesis: Coastal and Oceanic Settings) form, either in the zone of maximum solution at the water table, or by subsidence of loose material from beneath stable calcrete layers. Flat cave roofs are common; either marking the limit of solution at the top of the water table, or where collapse has reached the base of an indurated (cap rock) zone. Where a shallow impermeable basement occurs, its topography may concentrate water flow along buried valleys to form linear caves.

Sizable caves can form in less than 100 000 years. Surface dissolutional sculpturing is rare, as there is little solid rock for it to act upon. However, some sculpturing can occur on exposed calcrete layers.

The subsidence of partly-consolidated material can form a variety of breccias and sag structures; these can be further cemented as diagenesis continues (Figure 3). Mantling breccias can occur as part of the surface soil (Figure 4). Within the caves, breakdown of the soft rock is extensive. In many cases, rubble-filled collapse domes largely supplant the original dissolutional cave system at the water table. Subsidence may reach to the surface to form dolines. In paleokarst exposures, these collapse areas would appear as both discordant and concordant (intrastratal) breccias. In extreme cases, mass subsidence of broad areas can generate a chaotic surface of tumbled blocks and fissures.

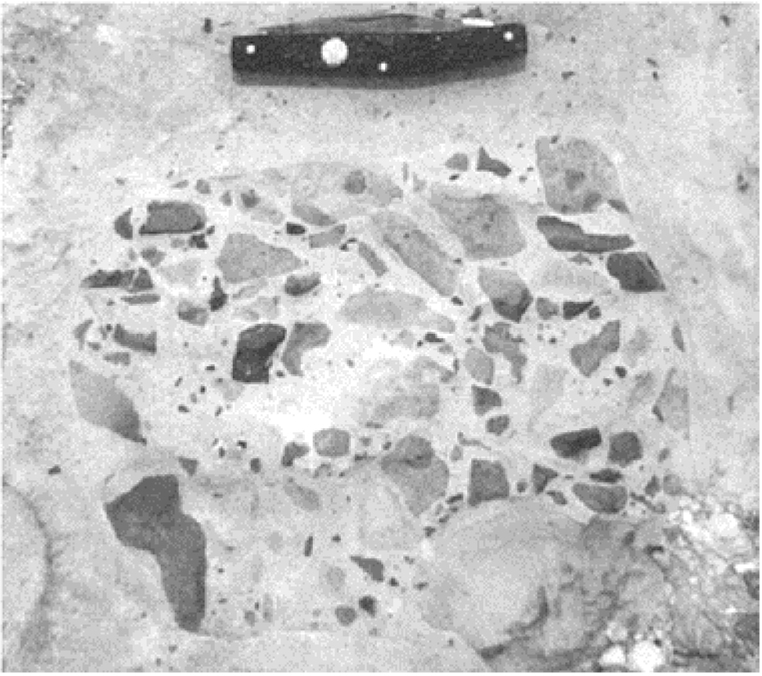
Variations can occur in different climates or sediments. For example, calcrete is supposedly best developed in semi-arid climates, whereas dissolution and brecciation are more abundant in wet climates. Sequences of marine sediments undergoing cyclic emergence can develop syngenetic breccia layers and karst surfaces at the top of each cycle. In coarse-grained sediments, preferential dissolution of aragonite fossils (e.g. coral) can form a coarse mouldic porosity. Where soluble evaporites are interbedded with carbonates, they may be removed completely to undermine the overlying carbonate beds and form extensive intrastratal brecciated layers (see separate entry, Evaporite Karst). However, such breccias can also form in later mesogenetic and telogenetic settings, so are not necessarily eogenetic.



Syngenetic Karst: Figure 2. Solution pipes (or, more strictly, dissolution pipes) are distinctive features of syngenetic karst (Lyndberg & Taggart, 1995). They are vertical cylindrical tubes with cemented walls, typically 0.3 to 1 m in diameter, which can penetrate down from the surface as far as 20 m into the soft limestone. The pipes may contain soil and calcified roots (and root growth may have occurred hand-in-hand with dissolution of the pipe). They occur as isolated features, or in clusters with spacings as close as less than a metre. (Photo by Ken Grimes)

Syngenetic Karst: Figure 3. Subsidence structure in syngenetic karst. Thin horizontal beds of a beach calcarenite were partly cemented into individual plates that then subsided as dissolution undermined them. Continuing cementation stabilized the tilted beds before the present cave formed. (Photo by Ken Grimes)

Dissolutional porosity generated during the eogenetic stage of paleokarsts can direct water flow and further dissolution during the later mesogenetic and telogenetic stages (see Inception



Syngenetic Karst: Figure 4.
Calcreted, multi-generation, mantling breccia in dune calcarenite. The large, 20 cm clast contains at least two earlier generations of smaller clasts. Note the blackened pebbles: some authors have suggested that these may indicate carbon derived from fires. (Shinn & Lidz, pp.117–31 *in* James & Choquette, 1987)

in Caves), and also host ore minerals or hydrocarbons. (See Sulfide Minerals in Karst; Hydrocarbons in Karst.)

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See also **Evaporite Karst; Paleokarst; Speleogenesis: Coastal and Oceanic Settings**

Works Cited

Choquette, P.W. & Pray, L.C. 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. *American Association of Petroleum Geologists Bulletin,* 54:207–50

James, N.P. & Choquette, P.W. (editors) 1987. *Paleokarst,* New York: Springer

The introduction has useful summaries of meteoric diagenesis and breccias. Many of the paleokarsts described in this book are at least partly eogenetic in origin.

Jennings, J.N. 1968. Syngenetic karst in Australia. In *Contributions to the Study of Karst,* edited by P.W.Williams & J.N.Jennings, Canberra: Research School of Pacific Studies, Australian National University

Lyndberg, J. & Taggart, B.E. 1995. Dissolution pipes in northern Puerto Rico: An exhumed paleokarst. *Carbonates and Evaporites,* 10(2):171–83

A review and case study of "solution pipes"—a distinctive feature of syngenetic karst.

Further Reading

Esteban, M. & Klappa, C.F. 1983. Subaerial exposure environment. In *Carbonate Depositional Environments,* edited by P.A.Scholle, D.G.Bebout & C.H.Moore, Tulsa, Oklahoma: American Association of Petroleum Geologists

A well-illustrated review of karst and related meteoric diagenetic features. Many, but not all, of the examples are of syngenetic karsts.

Klimchouk, A.B. & Ford, D.C. 2000. Lithological and structural controls of dissolutional cave development. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C. Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

Page 56 describes breccias in interbedded sulphates & carbonates, but not all these are syngenetic. Page 60 discusses diagenetic stages, including the eogenetic stage.

Moore, C.H. 1989. *Carbonate Diagenesis and Porosity,* Amsterdam and New York: Elsevier A detailed review of carbonate and evaporate sediments and the evolution of their secondary porosity. Chapter 3 describes the tools used to determine the nature and timing of solutional and cementation events. Chapter 5 discusses evaporites. Chapter 7 discusses meteoric diagenesis (both eogenetic and telogenetic).

Mylroie, J.E., Jenson, J.W., Taborosi, D., Jocson, J.M.U., Vann, D.T., & Wexel, C. 2001. Karst features of Guam in terms of a general model of carbonate island karst. *Journal of Cave and Karst Studies,* 63(1):9–22

Their model involves eogenesis (i.e. syngenesis) in young, porous limestones exposed by uplift or sea-level change.

White, S. 2000. Syngenetic karst in coastal dune limestone: A review. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B. Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt, Huntsville, Alabama: National Speleological Society

A recent case study from Australia.

T

TALUS CAVES

Talus caves are interconnected spaces between rocks, large enough for humans to enter and investigate, and which extend beyond daylight; or, a single such space beneath one or more boulders. They are produced by a variety of processes and commonly interface with crevice caves, and through erosion, with multiprocess caves. Alternative names in the literature include avalanche caves, block-field caves, boulder caves, purgatory caves, rockpile caves, rockslide caves, scree caves, and slope failure caves.

Significance

Many speleologists consider talus caves to be inconsequential, but Sweden's Bodagrottorna has more than 2800 m of passages. These are the commonest type of cave in Sweden, and a growing literature in several languages is centred around proceedings volumes of international symposia on pseudokarst convened in Europe. Sjöberg (1989a) found that about 15% of Swedish examples have high scientific and/or recreational values. Some in temperate climates are natural deep-freezes, containing unseasonal snow and forming ice *in situ* through mechanisms which may be of special importance on Mars (see Extraterrestrial Caves). Many others provide microclimates favourable to specialized flora and fauna, including relict populations. Others, in arid regions, protect running or ponded water from evaporation. Some talus caves in California (United States) provide delightful recreational caving, and others have been developed successfully as show caves (e.g. the widely advertized Lost River Caves and Polar Caves, New Hampshire, United States). In Pinnacles National Monument (California), Bear Gulch Cave is an especially popular tourist attraction and an important bat roost. In south-eastern California and elsewhere, talus caves served as human habitations as late as the 20th century. In Europe, others are sites of cultural and archaeological significance. In Sweden, some talus caves are considered to be important indicators of recent tectonic activity, while others in present and past littoral zones are indicators of abrasive capacity of small seas like the Baltic. Because cavers commonly underestimate them, however, some talus caves are especially dangerous to recreational cavers. One of Colorado's Lost Creek caves has claimed the life of an experienced, well-equipped caver, and another nearly died in a similar cave in California's Thunder Canyon.

Distribution of Talus Caves

Talus caves are found worldwide; almost everywhere that competent rocks in steep terrains fracture into large angular blocks or undergo spheroidal weathering. In the United States they are found from Maine and South Carolina to California and Washington state. In the northeastern part of the United States they occur especially in anorthosite, but others are found in granite, gneiss, schist, marble, and other metamorphic rocks. They also occur in some volcanic and sedimentary rocks including limestone, where a few small examples are near-end features of the karst cycle.

Types and Classifications

In Europe, talus caves have been studied intensively, and have been classified by process, by lithology, and by a combination of these. Many writers have mentioned frost wedging and erosion in their formation. Most classifications have been applied to relatively small regions. In Sweden, Sjöberg (1989b) found four types of talus ("boulder") caves: glacial boulder caves; abrasive boulder caves; one boulder cave formed by frost wedging; and neotectonic boulder caves. Sjöberg's glacial boulder caves include caves in coarse moraines and caves in erratics. The latter include both boulder piles and caves in single split blocks. His abrasive boulder caves are littoral features (see Littoral Caves). The single frost-wedged cave was formed during a sudden 19th-century event when a large rock slab separated and slid down a cliff (similar caves are present in canyons and along cliffs in other parts of the world, including Hawaii).

Unfortunately, Sjöberg gave no information on the size of these caves. Clearly the largest and most important type are in the group he termed "neotectonic boulder caves". These are in Archean rocks largely located in the Swedish section of the Fennoscandinavian uplift. Sjöberg subdivided these as talus caves in split roches moutonnées, and talus caves in collapsed mountain slopes. Sjöberg and others found that roches moutonnées containing talus caves were "perfectly formed" or "perfectly rounded". They were striated by glacial flow prior to tectonic activity which formed the caves during late deglaciation. These chaotic boulder piles include Bodagrottorna, the largest nonkarstic cave in Sweden, with more than 2800 m of passages formed *in situ*. Most of the Swedish caves "in collapsed mountain slopes" are within a belt of high neotectonic activity. These are within voluminous talus accumulations and consist of "more or less vertical caves with bigger grottoes connected by narrow passages". In Sweden, length of passages in this type of cave reaches several hundred metres. Sjöberg also found one unusual cave in a displaced mountain top. It is a maze cave beneath a summit block, 110 by 50 by 10 m, which slid two or three metres along a slope of 15 to 20 degrees. Rounded forms in part of the cave indicated that a smaller, weathered cave existed before sliding occurred.

Striebel (1999) identified other types of talus caves and specific processes which formed them. Among them are caves formed by several types of erosion, frost splitting, and rock movement. Specific types included: (1) "woolsack" and "mattress" caves in tors and other features resulting from spheroidal weathering of granite (the names derive from the general shape of the boulders forming the caves); (2) "gorge bottom caves" (called "purgatory caves" in some parts of the United States); and (3) "erosion boulder caves" or "boulder fragment caves" (gorge bottom caves in which a labyrinthine conduit has been eroded between boulders).

In the United States, the commonest types of talus caves are rockslide/rockpile caves and purgatory caves ("gorge bottom caves").

Rockslide/Rockpile Caves

Rockslide or rockpile caves are slope failure features found at the base of cliffs and on slopes where they form boulder fields. A variety of mechanisms is involved: block glide, grusification, and others. On steep slopes, some represent a stage of disintegration of crevice caves during mass movement. Caves formed partially as crevices and partly in talus are common in rock masses undergoing different rates of downslope movement. Many maps of what initially are believed to be talus caves reveal patterns of gravity-sliding crevice caves. Others develop more dramatically. Especially well known are the Polar Caves (New Hampshire, United States) where chemical weathering of feldspars and mica along semi-vertical joints has loosened large blocks on a receding cliff 70 m high. Together with frost action, instability of the oversteepened cliff has dislodged blocks up to 12 m in diameter, forming jumbled talus caves at its base.

Other well-known US rockslide/rockfall caves include Yosemite Falls Indian Cave, California; Chuckanut Mountain Caves, Washington state; TSOD Cave, New York state; MDBATHS Cave, New Hampshire; and Rockhouse Cave, South Carolina. Entirely within an area 90 by 250 m and with a relief of 50 m, TSOD Cave is listed as 4 km long. Few parts of it are more than 6 m from one of 355 entrances (Narducci, 1991). However, figures cited for some multi-kilometre rockpile caves in the northeastern United States have been challenged. This is because some measurements attributed to a single cave may have been made in several adjoining caves together with uncovered spaces between them.

Purgatory Caves

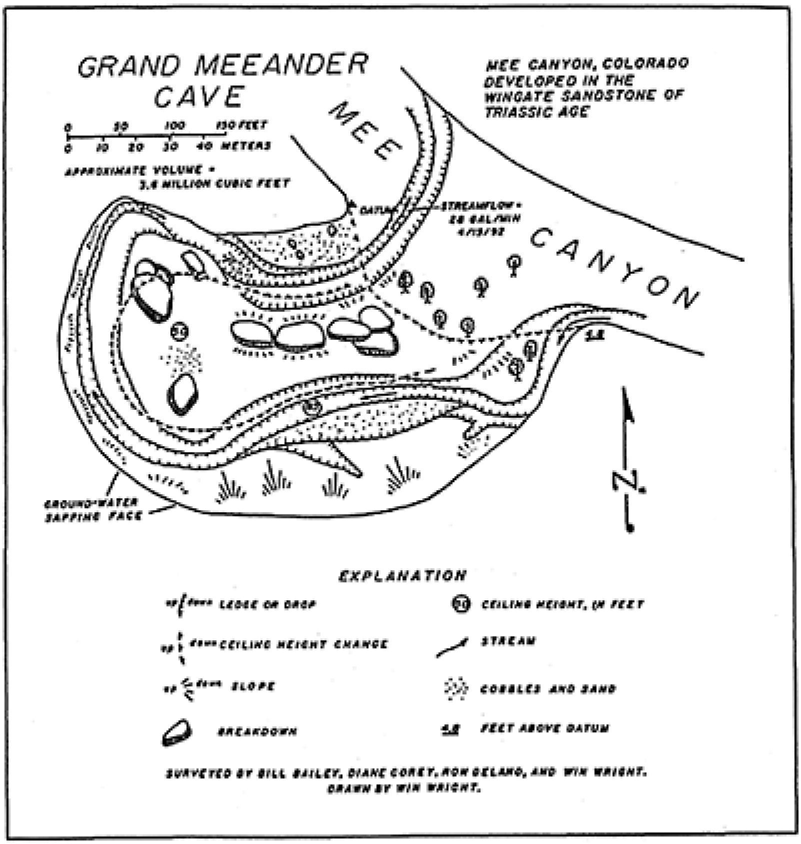
The term "purgatory cave" is in common use only in California and parts of the northeastern United States but conforms to usage in the American Geological Institute's *Glossary of Geology*. No other term for these caves is in common use in English-language speleology. In part, this reflects the distribution of these gorge bottom caves that are formed by talus partially filling narrow, steep-walled gorges and a few narrow grabens. Even in comparatively arid regions, large examples commonly contain streams and small ponds (Figure 1). Characteristically their features change almost from metre to metre, with large and small rooms, abrupt overhanging drops, and tight squeezes. Many contain evidence of extensive mechanical abrasion; the Greenhorn Cave System is a notable California example, 1.8 km long, 152 m deep and segmented at only two locations. Its abrasion-smoothed walls are scenic delights and provide wonderful recreational caving. Others in California contain sheets of travertine and other speleothems.

Interfaces and Multiprocess Caves

Well-known examples of caves intermediate between talus and crevice caves include North Carolina's 1.6 km Bat Cave (United States) and Hungary's 370 m Csorgo-Lyuk, the longest nonkarstic cave in that country. Combined purgatory-rockpile caves are not uncommon in the northeastern United States, and Thunder Canyon Cave is a purgatory cave formed along a series of crevices in California. In Llano County, Texas (United

States), 350 m Enchanted Rock Cave was roofed by granite talus after fracturing, weathering, grusification, and "mechanical suffosion" (Elliott & Veni, 1994). Colorado's Grand Meeander Cave (United States) is an extraordinary example of multiprocess speleogenesis. It became a cave when an accumulation of fallen rock blocked much of the overhang of a huge sandstone alcove formed by groundwater sapping (Wright, 1994), with particulate transport by piping and stream erosion (Figure 2). Washington state's Boulder (Boulder Creek) Cave (United States) is a smaller example in volcanic rock. The impressive Lost Creek

Talus Caves: Figure 1. This granite talus cave ("purgatory cave") in the southern California desert has a small perennial stream. (Photo by William R.Halliday)



Talus Caves: Figure 2. Grand Meeander Cave, Colorado (United States), a multiprocess alcove which rockfall converted into a cave. It is one of the very few meander niches which extends beyond daylight. Courtesy Richard Rhinehart.

Pseudokarst (Colorado, United States) is an erosional feature so unusual that it is not universally accepted as a talus pseudokarst. It apparently is the result of multiprocess speleogenesis largely *in situ*. Located at an altitude of 2700 m in the Rocky Mountains, it combines alpine talus accumulation and piping and erosion by a mountain torrent and its tributaries. Enormous quantities of granitic sand and debris have been cleared from caves and giant sinkholes in this system, which is located within a narrow 5 km dendritic complex of large pseudokarstic windows, flat-stacked boulders, and sizeable ridges of partially grusified granite. Lost Creek disappears into swallet caves many times, reappearing from resurgence caves to flow across flat-bottomed dolines. It passes through ridges up to 600 m wide and 60 m high (Hose, 1996). The relative amounts of overroofing by tumbling and sliding of boulders, by slumping into the pseudokarstic conduits, and of speleogenesis *in situ* is not clear. About a century ago, engineers built a dam in this pseudokarst without realizing that the planned reservoir would immediately empty through the talus. Striebel (1999) and Sjöberg (1989a; 1989b) have documented smaller talus pseudokarsts formed by in-situ fragmentation and erosion.

Talus Caves as Glacières

Some talus and crevice caves in temperate zones are efficient natural deep-freezes containing unseasonal snow and ice. Ice usually is found in one of two locations: where cold air settles to an impenetrable layer, with residual show and ice at and near the bottom, or where settling occurs along an inclined layer or back and forth through rocks, with ice near an egress at the bottom.

Mechanisms that have been proposed as explanations for this disproportionate trapping of snow and cold air are adiabatic cooling, evaporation from a very large surface area, and multiple small obstacles serving as baffles. In the United States, recorded examples are especially common in the northeastern states and in West Virginia.

Martian Analogues of Terrestrial Talus Caves

Malin and Edgett (2000) have reported several Martian features which may be analogous to terrestrial pseudokarsts (see also Extraterrestrial Caves). One consists of talus accumulations where cliff alcoves are littered with boulders “several metres to several decimetres in diameter”. These are immediately downslope from locations of presumed recent outbursts of water which presumably flowed into or through the boulder piles. On Earth, talus accumulations with these parameters commonly contain talus caves. On Mars, they may protect residual ice from ablation.

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Works Cited

Elliott, W. & Veni, G. (editors) 1994. Enchanted Rock Cave. In *The Caves and Karst of Texas: NSS Convention Guidebook*, Huntsville, Alabama: National Speleological Society

Hose, L. 1996. The Lost Park Reservoir Project, Park County, Colorado. In *The Caves and Karst of Colorado: 1996 NSS Convention Guidebook,* edited by R.Kolstad, Huntsville, Alabama: National Speleological Society

Malin, M. & Edgett, K. 2000. Evidence for recent groundwater seepage and surface runoff on Mars. *Science,* 288:2330–35

Narducci, M. (editor) 1991. *Guide to the Caves of the Northeast: NSS Convention Guidebook,* Huntsville, Alabama: National Speleological Society

Sjöberg, R. 1989a. Caves as indicators of neotectonics in Sweden. In *2nd Symposium on Pseudokarst: Proceedings of the Symposium in Janocicky near Broumov 1985,* Prague: Czech Speleological Society

Sjöberg, R. 1989b. An inventory of caves in the county of Vasternorrland, north Sweden. In *2nd Symposium on Pseudokarst: Proceedings of the Symposium in Janocicky near Broumov 1985,* Prague: Czech Speleological Society

Striebel, T. 1999. Working meeting “Caves in Sandstone and in Granite”. *Mittteilungsheft der Höhlenforschungsgruppe Blaustein* (Germany), 15:45–53

Wright, W. 1994. The hydrogeology of Grand Meeander Cave. *Rocky Mountain Caving,* 11:18–19

Further Reading

Proceedings volumes of the international symposia on pseudokarst, most recent volume being *Proceedings of the 6th International Symposium on Pseudokarst, Galyatető, Hungary, 1996,* edited by I. Eszterhás & S.Sárkozi

Newsletter of the Commission for Pseudokarst of the International Union of Speleology, edited by Istvan Eszterhás (www.clubs.privateweb.at/speleoaustria/pseudokarst.htm)

Balch, E.S. 1900. *Glacières, or Freezing Caverns,* Philadelphia: Allen, Lane and Scott; reprinted 1970 with a new introduction by W.R.Halliday, New York: Johnson Reprint Company

Bunnell, D. & Richards, B. 1986. Granite corrasional caves in California. In *Proceedings of the 9th International Congress of Speleology,* vol. 2, Barcelona: IBYNSA: 11

Engel, T. 1993. *Caves of the Eastern Adirondacks,* 2nd edition, privately published

Evans, J. *et al.* (editors) 1979. *An Introduction to the Caves of the Northeast: Guidebook for the 1979 NSS Convention,* Huntsville, Alabama: National Speleological Society

Perry, C. 1946. *New England's Buried Treasure,* New York: Stephen Daye Press

THERMAL WATER HABITATS

Those thermal waters categorized as hypogean habitats comprise all hypogean waters with temperatures higher than the annual average for the locality in which they occur (thermal springs, designated as *Umraumfremde Quellen* by Vouk, 1953, also constitute part of this habitat). According to Schwabe, thermal waters are among the oldest freshwater habitats on Earth, and, as they have shown great stability over geological time, they may harbour relict faunas. Since these waters have mostly been warmed in the deeper layers of the Earth's crust, they are largely devoid of organic material (except where chemo-autotrophic bacteria proliferate). Higher temperatures lower the solubility of gases and therefore the dissolved oxygen content; higher temperatures also enhance the metabolism of poikilothermal (or cold-blooded) animals. Therefore, thermal waters are generally harsher environments than non-thermal hypogean ones. Faunal populations in the hypogean areas of thermal waters may be extremely sparse. However, in the threshold habitats of springs, which may be enriched with food from the surface, these waters may be inhabited by rich populations of stygobitic animals (Sket & Velkovrh, 1981). Stygobites, with their typically very low metabolism, are generally well adapted for life in these habitats. Taxonomically, the inhabitants of thermal waters may be simply populations of eurythermal (tolerant of a wide range of temperatures) species, or stenothermal (specialized for a defined temperature range) subspecies or species.

By far the most common inhabitants of thermal hypogean waters are crustaceans, and the only ubiquitous inhabitants are species of the Family Stenasellidae. Near the formerly ice-covered areas of southern Europe, thermal springs (15–28°C) are almost the only known localities supporting stenasellids, such as *Balkanostenasellus skopljensis* in Slovenia and *Protelsonia hungarica* in Croatia. These populations are probably relicts of thermophilic animals from the pre-Pleistocene period. But even in the subtropics and tropics, some stenasellids occur in thermal springs: i.e. *Stenasellus pardii* and *S. costai* in Somalia at 29–31°C, *Johanella purpurea* in Algeria at 29°C, and *Mexistenasellus coahuila* in Mexico at 24–34°C. Their ecology indicates that the group originated in warmer geological periods. *M. coahuila* and *S. costai* both inhabit high-temperature waters, even those with less than 2 mg l^{-1} oxygen and in the presence of hydrogen sulfide. In an exceptional case, the adaptation of stenasellids may be in the opposite direction, for example, some populations of *Stenasellus virei hussoni* live at very low temperatures (less than 6°C) in the Pyrenees.

The most widely known extreme thermostygobite (specialized for warm hypogean waters) is the thermosbaenacean *Thermosbaena mirabilis* (described by Monod, 1924). Its dense population inhabits cyanobacterial mats in the baths of El Hamma, Gabes, Tunisia, at 45°C. Since it also occurs in dark hypogean thermal waters, displays troglomorphism, and is a member of an exclusively stygobitic group, this is almost certainly a stygobitic species, which also flourishes in illuminated areas that contain more food but are without direct competitors. The most extreme thermostygobite appears to be the bathynellacean *Thermobathynella adami,* which has been recorded from a spring in Zaire with a temperature of 55°C.

Only in Slovenia has the regional fauna of thermal hypogean waters been investigated systematically. This fauna consists of 16 stygobitic species (up to five in one locality) of which only two appear to be polystenothermal (specialized to higher temperatures): the sphaeromatid isopod *Monolistra (Microlistra) calopyge* and the gastropod *Hadziella* sp., while the others (e.g. some *Niphargus* spp., the interstitial *Parabathynella stygia*) also occur in cold hypogean waters. Animals were found at temperatures of 15–28°C (normal temperatures in the continental parts of Slovenia are around 10°C) and they were usually found in waters with low oxygen concentrations of 5.5–7.5 mg 1^{-1}. The faunistically richest thermal system known is at the springs at Cuatro Cienagas in Coahuila, Mexico; the water temperature is 29.5–34°C, and the oxygen concentration is 1.7–4.1 mg l^{-1} (often below 50% saturation). Their stygobitic fauna consists of at least five species of gastropods (*Paludiscala caramba*, *Coahuilix hubbsi*, and others), two amphipods (*Mexiweckelia* spp.), three cirolanid isopods (*Speocirolana thermydronis, Sphaerolana* spp.), and the stenasellid *Mexistenasellus coahuila*.

Only a few preliminary studies regarding the biology of stygobites from thermal waters have been undertaken. *Balkanostenasellus skopljensis thermalis,* which occurs in a Bosnian spring at 24°C has been kept successfully for longer periods at 16°C. *Protelsonia hungarica thermalis* can be found in springs and interstitial water in western Croatia at 18.2–24.4°C, while it can survive a temperature range of 13–28°C and shows an optimum at 20°C in the laboratory. It definitely could not survive at the normal local temperature of approximately 10°C.

BORIS SKET

Works Cited

Monod, T. 1924. Sur un type nouveau de Malacostrace: *Thermosbaena mirabilis* nov. gen. nov. sp. [About a new type of Malacostraca: *Thermosbaena mirabilis* nov. gen. nov. sp.]. *Bulletin de la Société Zoologique de France,* 49:58–68

Sket, B. & Velkovrh, F. 1981. Podzemeljske živali v termalnih vodah [Subterranean animals in thermal waters]. *Biološki vestnik,* 29(2):91–120
Vouk, V. 1953. Umraumfremde Quellen [Surrounding alien springs]. *Archiv für Hydrobiologie,* 48(1):129–33

Further Reading

Barker, D. 1959. The distribution and systematic position of the Thermosbaenacea. *Hydrobiologia,* 13(3):209–35
Lattinger-Penko, R. 1970. Verification expérimentale de l'interdependance de la distribution de *Stenasellus hungaricus thermalis* (Crustace, Isopode) et les conditions de temperature du biotope) [Experimental verification of the interdependence between the distribution of *Stenasellus hungaricus thermalis* (Crustacea, Isopoda) and the temperature conditions of the biotope]. *Annales de Spéléologie,* 25(2):319–34
Magniez, G. 1974. Données faunistiques et écologiques sur les Stenasellidae (Crustacea, Isopoda, Asellota) des eaux souterraines [Ecological and faunistic data on the Stenasellidae (Crustacea, Isopoda, Asellota) of subterranean waters]. *International Journal of Speleology,* 6(1):1–80
Taylor, D.W. 1966. A remarkable snail fauna from Coahuila, Mexico. *Veliger,* 9(2):152–228
Zilch, R. 1972. Beitrag zur Verbreitung und Entwicklungsbiologie der Thermosbaenacea [Contribution to the distribution and the developmental biology of Thermosbaenacea]. *Internationale Revue der Gesammten Hydrobiologie,* 57(1):75–107

TOURISM AND CAVES: HISTORY

The overall human relationship to caves probably comprises three major phases. The first is marked by extensive use of caves for shelter, habitation, and ritual purposes. Caves were not feared or avoided, but often appear to have provided desirable residential locations. The transition to the next phase seems to mark a significant step in cultural evolution. Although some cave sites continued to be utilized in various ways, many were abandoned, and there seems to have been a flowering of legends which portrayed caves as places to be feared, often because they were reputed to be the abode of various imagined monsters or evil spirits. Although climatic change and other physical explanations have often been evoked, it could be argued that this transition marks the beginning of curiosity, and the asking of questions about the natural world. Caves, being difficult to explain within the framework of everyday experience, became explicable only in terms of such myths.

Progressively, at different times in different cultures, this curiosity was translated into the final phase of travel and investigation, and the beginnings of the natural sciences. Shaw (1992: pp.7–8) commences his seminal history with the travels of Assyrian kings some 3000 years ago—and there were doubtless earlier travellers who failed to leave any record for us. The great rise in investigatory and other more-or-less individualized travel came with the 15th and 16th centuries, particularly in Europe. Many travellers have since visited and described caves (see, for example, Shaw, 2000). Perhaps one of the more remarkable of these early travellers was Xu Xiake (1586–1641) of China, who is said to be the only Chinese to have travelled throughout his own country for his own satisfaction rather than for official or military purposes, and who spent 34 years doing so (see Asia, Northeast: History).

Tourism is perhaps defined as the progressive democratization and commercialization of travel and could be considered to have arisen out of the early years of the industrial revolution. The distinction between travellers and tourism is a fuzzy one, of course. Herodotus refers to paying guides in some sites of particular interest *c*. 450–400 BC, and certainly travellers to Vilenica Cave in Slovenia were being charged a fee for access at least by the early part of the 17th century. For this reason, Vilenica is now generally recognized as one of the first “Show Caves”.

The event which best marks the beginning of modern tourism took place on 5th July 1841, when Thomas Cook’s first excursion left Leicester for an outing to Loughborough. By this time, some of the great tourist caves of the world were open to the public. Postojnska (Postojna, Adelsberg) Cave had been gradually commercialized from the beginning of the 19th century; Wookey Hole in Britain, known for some 2000 years, similarly underwent progressive commercialization at about the same time; and commercial tours commenced at Mammoth Cave (United States) in 1816.

The greatest development of cave tourism occurred in the second half of the 19th century. New caves were continually being discovered, and many of these were selected for commercial development. An especially interesting development occurred in Australia, where both the Naracoorte and Jenolan Caves attracted a rapidly growing number of visitors from the 1860s onwards. By the 1880s, Jenolan was undeniably the best-known and one of the most popular tourist destinations of the country. Its success was such that following the economic depression of the 1890s, state governments commenced to employ surveyors or prospectors to search for other caves that might also provide a similar economic resource for the tourism industry. Many of the other show caves of the nation were discovered and developed during this period. Jenolan was also of considerable interest in that it was the site of pioneering development of technology in cave tourism, with extensive use of clockwork-driven magnesium ribbon lamps for visitor display, the first experimental electric lighting in caves (1880), and the first use of hydroelectric generation in Australia. Electric lighting proved to be a dominant technology in cave tourism, with early permanent installations at Kraushohle (1883), Postojnska (1884), and Jenolan (1887).

One interesting aspect of these early caves was the extent to which travellers and discoverers, together with early managers or guides, became famous personalities. Examples include Stephen Bishop at Mammoth Cave, William Gough at Cheddar (Somerset, Great Britain), and Jeremiah Wilson at Jenolan. It would be easy to name many others. Many appear to have been extroverts who cultivated this reputation as a means of making their site more attractive to visitors. Even to this day, they remain as heroes of exploration, fabled raconteurs or comics, and guides of exaggerated wisdom. Some, who were initially men of little education, took up an interest in reading and literature in order to be able to converse in more positive ways with tourists, who were often people of relatively higher status and greater learning.

Eventually, the cave tourism experience became remarkably stereotyped, with visitors being grouped into parties, each led through brightly lit caves along fixed pathways by a talking guide. As a result, the immense enthusiasm for caves which characterized the 19th century industry gradually faded. Early attempts to recover the quality of cave tourism and to more effectively compete with the growing range of alternative tourist sites tended to concentrate on the improvement of infrastructural arrangements such as pathways and lighting. Certainly as technology has improved, this has led to an improvement in presentation and display. However, uniformity of the cave tourism experience and boredom are not changed by the caves being more brightly lit. More adequate attempts to diversify and enhance the quality of the personal experience itself, by changing the very character of the tour have generally only developed since 1990. Some exciting innovations are also to be found in countries entering into mass tourism for the first time and offering experiences growing out of their own cultural patterns rather than merely copying previous eurocentric models.

The other important development, particularly since the 1980s, has been the increasing role of both research and monitoring in the management of cave tourism—both the quality of the visitor experience and the impact of tourism on the cave and surrounding environment. Monitoring of environmental factors such as air quality and air-borne debris are covered in separate entries, as is research on the growth of algae and lampenflora, induced by the artificial lighting. The entry on Tourist Caves describes contemporary environmental and visitor monitoring and assessment.

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Works Cited

Shaw, Trevor R. 1992. *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900,* 2nd edition, Broadway, New South Wales: Sydney Speleological Society

Shaw, Trevor R. 2000. *Foreign Travellers in the Slovene Karst 1537–1900,* Ljubljana: ZRC Publishing and Karst Research Institute at ZRC SAZU

TOURIST CAVES

Tourist caves can be simply defined as those displayed to the general public in return for a fee or other financial consideration. The history of this tradition dates back to at least the early 17th century (see Tourism and Caves: History). Tourist caves may be managed by governmental agencies, non-governmental organizations (e.g., speleological clubs, religious communities), and individuals or corporations operating as a commercial business. People have always been fascinated by caves for a wide variety of reasons, such as mystery and curiosity, fantasy, and appreciation of beauty, so it is not at all surprising that visiting caves became commercialized. In the words of a 15th-century commentator on village markets, “No sooner does one man find a way of enjoying himself, than another finds a way to make a penny from it.” Owners and managers have a wide range of objectives. Some doubtless have a purely financial motivation. Others wish to share their enthusiasm for the beauty and wonder of caves with other people; to use caves as a wonderful opportunity for environmental appreciation or education, or as a site for spiritual experience, prayer, or meditation. This article will deal in turn with the following aspects of tourist caves:

1. Visitor experiences.
2. Approaches adopted by management to shape these experiences to meet their own assumptions, values, or objectives.
3. The physical infrastructure used to facilitate access to the caves, including possible guidelines for its development.
4. Real and potential impacts of tourism in karst areas.
5. Assessment and monitoring of both environmental change and visitor experience in order to guide corrective action in conservation or tour management.

Visitor experiences are largely shaped by management practices and the kinds of opportunities made available to the public. Because most visitors have little understanding of possible alternatives in tour management, the result is a closed and self-reinforcing circle, where visitor expectations reflect what is already offered, rather than seeking new and different kinds of experience. All too often, the experience is a stereotyped one, where visitors are allocated to groups and led through a brightly lit cave along a (usually) concrete pathway by a guide who talks at the group, giving his or her version of what they are seeing. The visitor experience thus ranges from boredom to a general level of satisfaction in which the key dimension is often the personality and approach of the guide rather than any quality of the cave itself. Guides may recognize this and give considerable attention to customer relations, or alternatively, offer a dramatic or comic performance to their visitors. However, a gradually widening diversity of opportunities is offered today in the attempt to enhance visitor experience and retain market share in an increasingly competitive tourism marketplace.

It is perhaps useful at this point to consider the experiences which are least often provided. Being alone in the cave is only very rarely provided, and then usually unintentionally. Yet those who have been alone in a cave often speak of this as a very special and highly valued experience. One young woman who was able to walk alone into a cave and then turned her light off to sit in the dark said afterwards, “I could hear the Earth thinking!” Even if not alone, there is rarely a genuine opportunity for peaceful meditation, although some may find this during an unguided tour. Personal inquiry and investigation is all too rare, although some guides with a sense of creativity are able to turn even a group tour into a personalized quest and experience of inquiry. Even some so-called “adventure” tours are simply another version of the stereotyped tour, distinguished only by the absence of constructed paths and fixed lighting.

An increasing problem for guiding practice is the multilingualism of visitors. Some countries give attention to linguistic skills in selection of guides and may provide printed materials in a wide range of languages. Alternatively, they may seek the support of international tourism agencies in provision of interpretation. Others rely entirely upon self-guided tours, sometimes with signs highlighting special features, audio commentary, or other displays. Still others simply leave all communication to the unfortunate guides, who may simply shout louder in the hope that somehow, this may enhance understanding.

Talking to visitors is usually termed interpretation, though this extremely simplistic view of interpretation is based on the straightforward communication of the guide's cognitive perspective on the cave. The emotive and affective experience of the cave is either ignored or forgotten. A more radical view of the problem that is gaining increasing support is that the interpretation, even if well done, endeavours to compensate for poor presentation of the cave experience. From this perspective, the whole manner of presentation must be reviewed to make the cave experience much more self-evident to the visitor.

Contemporary approaches to the enhancement or improvement of visitor experience include:

1. Training of those guides who provide the traditional guided tour to offer a more interesting presentation and to increase the actual involvement of visitors in shaping the cave experience.
2. Asking guides to accompany rather than lead the party, joining in conversation with visitors rather than delivering a formal presentation.
3. Altering the lighting arrangements within the cave to provide an ambience of drama or mystery, or highlighting special features while leaving other parts of the cave in virtual darkness.
4. Offering unguided (often called self-guided or self-timing) tours where visitors move through the cave at their own pace. Effective tours of this kind normally still provide a staff presence within the cave for both safety and visitor comfort reasons and as an information source in responding to visitor questions. Particularly in Asia, many sacred sites and temple caves offer what amounts to an unguided tour in which visitors move through at their own pace. Some of these may provide the opportunity for prayer or meditation. Many have elaborate shrines or other constructed development to enhance the religious experience (see Religious Sites).
5. Offering unguided tours of caves with pathways and possibly some other infrastructure but without fixed lighting. Each visitor is provided with a hand-held light to carry out their own search for interesting features.
6. Offering what are commonly termed adventure tours. Visitors are provided with helmets, overalls, and appropriate footwear (if necessary) and are conducted through either totally undeveloped caves or caves where there has been only minimal development to improve safety.
7. Providing walking routes through surface karst features. These are increasingly popular, but rarely is the opportunity taken to genuinely demonstrate the relationship between surface and subterranean features.
8. Providing the opportunity for guides to work as field assistants in research programs at the cave or park for which they have responsibility so that they are better able to communicate the nature of scientific research to visitors.
9. Providing for current researchers or other cave scientists to undertake leadership of tours as guest guides on special occasions.
10. Undertaking restoration work. Restoration of caves is becoming increasingly important, and a restored cave may even become a special feature in itself (e.g., Bell 1994; see also Restoration and Speleothem Repair). Further, restoration often provides an opportunity to involve members of the general public in work teams, and hence to immensely deepen their appreciation of the cave environment.

11. Providing various forms of artificial entertainment such as the screening of video tapes, holographic presentations, use of sound and light or dramatised presentations (see Music in Caves), staged performances, and even the use of robots. Unless these are of outstanding merit, they probably do more to detract from the natural values of the cave than to accentuate them.
12. Assisting movement through the cave with some form of vehicular transport. The most long-standing and well-known example is probably the miniature train at Postojnska in Slovenia. Other examples include boats, buses with a transparent top, or other motorized vehicles. If these are done tastefully and appropriately they may even enhance the experience rather than simply be a practical convenience. Certainly the spectacular boat journey in the lower levels of Jeita Cave (Lebanon) or the voyage through Ghar Alisadr (Iran) are regarded as two of the highlights of contemporary cave tourism experience.

The in-cave experience may be supported with various presentations on the surface. Sometimes these are totally irrelevant to the cave, but they often include visitor centres with a diversity of interpretive information or other scientific displays. A few of these are now providing clear information on conservation and tour management to enhance visitor understanding of the opportunities and constraints in cave tourism. The more elaborate may include museum-level presentation (e.g. Waitomo Museum of Caves, New Zealand). At the Naracoorte World Heritage Area (Australia), visitors to the Wonambi Fossil Centre see computerized robots of extinct species within a reproduction of a Pleistocene forest and swamp. Alternatively, they may visit the Bat Interpretation Centre where they view real-time video imagery of the immense population of bats in one of the caves.

For many years, guide books of varying quality were made available to visitors. Currently, they are more likely to find only a choice of brightly coloured postcards, folders or brochures, or photographic books. However, there are still outstanding examples where visitors are able to obtain quality guides and environmental books that relate either to the cave or to the region as a whole. A small number of sites also offer videotapes or CD presentations. A diversity of souvenirs and gifts may also be available but rarely contribute to the understanding or appreciation of the cave itself. Regrettably, in some countries speleothems taken from the caves are themselves sold as souvenirs, thus giving respectability to continuing vandalism.

A major opportunity for improved practice is provided by the various regular or occasional conferences of cave and karst managers. Regional conferences have been held regularly in Australasia (since 1972) and the United States (since 1975), while international conferences are now convened (since 1990) by the International Show Caves Association (ISCA). Australia and New Zealand also have a continuing professional association: the Australasian Cave and Karst Management Association (ACKMA). The published proceedings of these conferences provide a growing body of significant literature on cave management.

The physical infrastructure in caves may have been in place since the 19th century and thus acquired an historical value. Many of the more recent installations have repeated the old pattern of extensive modification to the natural structure of the cave, neglect—and often destruction—of the floor with its extensive deposits and other evidence of regional geoclimatic history, and the use of insensitive and / or excessive lighting intensity. There are very few explicitly published guidelines to preferable infrastructure designs. Various engineering or accessibility standards may set structural and dimensional requirements, for example for stairs or pathways, but these are generally based upon building codes and not sensitive to natural environment or conditions. The outstanding examples of environment-sensitive codes come from Australia, where the *Burra Charter* (ICOMOS, 1999) provides guidelines for conservation management of cultural sites and the *Australian Natural Heritage Charter* (IUCN, 1996) provides similar guidelines for natural sites. Where a present installation has attained historic significance, any redevelopment should consider the principles provided in the *Burra Charter* while any cave development of infrastructure should recognize the Natural Heritage Charter. A number of guidelines are provided and some of those which have particular relevance to cave presentation and conservation management worldwide include:

1. In so far as possible, conservation management should only exercise minor interference or modification to the natural environment and only in so far as this is necessary to ensure conservation. Additions should only occur if they do not alter the natural characteristics of the site.
2. These additions must be clearly identified in one way or another, so that no confusion will arise between natural and introduced matter.
3. Any additions to the site, for instance pathways for access purposes, should be designed and constructed in such a way that they can be readily removed, allowing for complete reinstatement of natural conditions. (Obviously this precludes the traditional poured concrete pathways of many tourist caves.)
4. Comprehensive and detailed records should be kept of any modifications so that if necessary those modifications can be reversed.

Charters such as the Australian Natural Heritage Charter are also accompanied by publications such as the *Natural Heritage Places Handbook* (IUCN, 1998) as a more detailed practical guide to action. Cave managers in Australia have also done considerable work towards the development of practical guidelines (e.g., Spate *et al.*, 1998; Hamilton-Smith *et al.*, 1998). An international guidelines document designed to further improve practice in conservation management of tourist caves and other sites on karst lands is in preparation.

Tourism generates a wide range of impacts on karst sites, and particularly upon tourist caves themselves. On the surface, the most obvious impacts relate to the changes in vegetation and increase in soil erosion that result solely from visitors walking about the environment. Other issues include the increased demand on water reserves, problems of both solid and liquid waste disposal, increased vandalism, and ecological changes due to the disappearance of some species and the entry of invasive species. Every effort should be made to minimize these impacts but usually it will not be possible to eliminate them. The most damaging impacts within caves are currently a result of management actions in the development of inappropriate infrastructure and other destructive actions. These may well be reduced significantly at the planning, design, and construction stages but otherwise may demand very significant redevelopment if they are to be dealt with properly.

One of the implementation issues in conservation management is the common practice of many work crews leaving behind minor debris resulting from their work. Metal fragments from fabrication of guardrails, or cuttings of electric wiring, often introduce materials toxic to cave fauna. Small clippings of copper will generate compounds toxic to invertebrates, while the cadmium impurities in galvanizing are toxic to microbiota and so will inevitably damage the integrity of cave soils. Probably the most intractable of impacts, resulting directly from the presence of visitors is the accumulation of lint, consisting of fibres from clothing, dust carried in by visitors and flakes of human skin (see Tourist Caves: Airborne Debris). Visitors may also leave behind less visible evidence of their presence in the cave, including invasive species, some of which may be microbiota. Other impacts such as changes in temperature, relative humidity, and the level of carbon dioxide in the cave (see, Tourist Caves: Air Quality) may have a significant impact in low-energy caves. In conjunction with artificial lighting, they may have the further and more drastic effects of encouraging the phenomenon of lampenflora (algal and other plant growth; see Tourist Caves: Algae and Lampenflora). Again, lampenflora is best prevented at the design, planning, and construction stage. Its occurrence is simply evidence of poorly designed, excessive and/or wrongly located lighting. When it has occurred it should be removed as its continuing presence actually damages the rock substrate, and this can be most easily accomplished by using a very dilute sodium hypochlorite solution.

A vital part of good conservation management in any tourist area is the assessment and monitoring of change (see Monitoring). It is useful to emphasize the distinction that assessment is the process of making judgements about the significance and necessary action to deal with changes; monitoring is simply the act of consistent measurement of those changes in order to provide a database for assessment. A number of basic parameters should be subject to continuous monitoring simply to provide comprehensive knowledge of the environment including both seasonal changes and any extraordinary changes. The parameters which might be included in both surface and underground monitoring include temperature, relative humidity, carbon dioxide levels, the levels of radon and radon daughters, water quality and flow levels, and wind and other air movement patterns. Careful consideration must be given to measurement sites and such questions as the extent to which specific microclimates might demand attention. Further monitoring may be necessary to deal with identified problems or potential problems. This may well be on a continuous basis but where peak events (e.g. flooding) are of significance then special measurement and monitoring may need to be undertaken during these events. Monitoring also needs to relate to, and often be supported by, genuine research. Common assumptions about the nature and cause of problems may well be incorrect and if these problems are to be dealt with, it will be necessary to carry out research in order to delineate the causative processes.

While there is a genuine awareness of the need for environmental monitoring and it is commonly carried out in many karst areas, the quality of the visitor experience has not been subject to the same level of research and enquiry. Given the dependence of many tourist caves upon a continuing flow of visitors, it is vital that the assessment of visitor experience be systematically carried out. Perception and assessment of environmental quality by visitors is as important as that by managers. Visitors are often sensitive to issues which managers take for granted, while at thesame time, managers may well be sensitive to issues of which visitors are totally unaware. Thus, the program of assessment and monitoring needs to integrate both environmental and experiential monitoring (Hamilton-Smith, 2002). Systematic participant observation properly coupled with informal interviewing is a very powerful tool in monitoring of experience. In one simple example, observation showed that acts of vandalism that are of concern to managers are generally carried out by visitors at the rear end of tour groups, possibly because they cannot hear the guide and have become bored. Another successful example specifically examined motor coach tours to a major Australian cave destination. The researcher rode with bus tours to the destination, shared with passengers over lunch, joined with their cave tour, and then rode the bus back to the starting point. This study not only identified a number of organizational problems that were detracting from the experience, but also identified a major but previously unrecognized problem in the telling of inappropriate (often anti-environmental) jokes and anecdotes by tour drivers. However, observation alone is not enough and there should also be regular surveys of visitor values, attitudes, and experience, perhaps accompanied by occasional special studies that focus in more depth on revealed problems.

An interesting example of a survey study was carried out at Waitomo, New Zealand by Doorne (1998) in an examination of perceived crowding. Actual crowding was self-evident, and was the most common source of complaints from visitors. Doorne found that visitors of European origin defined crowding as being tightly forced into a small space with many other people as happened during most cave tours. Asian visitors, by contrast, defined crowding as having to join a queue in order to purchase tickets, and then again to actually join a tour. This greater understanding enabled the managers to develop more effective strategies to deal with the problem than was previously the case.

The most potent approach to minimizing undesirable impacts is undoubtedly ensuring the best attainable practice in planning, designing, and developing tourist caves and related tourism opportunities. Many problems are predictable and can be greatly reduced by effective planning in advance, and by not repeating the mistakes of the past.

This article can only be a brief review of issues and contemporary trends in tourist cave management. There are, in addition to the specific references provided below, an immense number of sources of information available. At the descriptive level, many countries publish directories of tourist caves, or even major guidebooks covering all caves in the country. These now seem to be less published and utilised than in the past, probably because the Internet provides a cheaper and more flexible access to the same information (http://www.showcaves.com/ provides an international listing of tourist caves).

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Works Cited

Australia ICOMOS. 1999. *The Burra Charter,* Melbourne: Australia ICOMOS (also available at http://www.icomos.org/burra_charter.html)

Australia IUCN. 1996. *Australian Natural Heritage Charter,* Canberra: Australian Heritage Commission and Australian Committee for IUCN (also available at http://www.ahc.gov.au/infores/publications/anhc/)

Australia IUCN. 1998. *Natural Heritage Places Handbook,* Sydney: Australian Committee for IUCN (also available at http://www.ahc.gov.au/infores/publications/nhnames/)

Bell, P. 1994. Moondyne Cave: Development to guided adventure. *Cave Management in Australasia,* 10:9–11

Doorne, S. 1999. *Visitor Experience at the Waitomo Glowworm Cave,* Wellington: Department of Conservation

Hamilton-Smith, E. 2002. Management assessment in karst areas. In Proceedings of the meeting on monitoring of karst areas, edited by A.Kranjc, *Acta Carsologia,* 31(1):13–20

Hamilton-Smith, E., McBeath, R. & Vavryn, D. 1998. Best practice in visitor management. *Cave and Karst Management in Australasia,* 12:85–96

Spate, A., Hamilton-Smith, E., Little, L. & Holland, E. 1998. Best practice and tourist cave engineering. *Cave and Karst Management in Australasia,* 12:97–109

Further Reading

Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwell

Watson, J., Hamilton-Smith, E., Gillieson, D. & Kiernan, K. (editors) 1997. *Guidelines for Cave and Karst Protection,* Cambridge: International Union for Conservation of Nature and Natural Resources

For further information on tourist cave conservation and visitor management, see the various series of conference proceedings, such as *Proceedings of the National Cave Management Symposium* (NSS), *Proceedings of the Australasian Cave and Karst Management Association* (ACKMA), and *Proceedings of the International Show Caves Association* (ISCA).

TOURIST CAVES: AIR QUALITY

The air quality in tourist caves has to be maintained, to safeguard the resource against corrosive gases, and to protect the health and comfort of tourists and staff. Tourists can create great changes in the cave microclimate and the composition of its atmosphere. Cigna (1993) regarded the three major impacts as being increases in carbon dioxide (CO_2) and temperature and changes in humidity. To these is added a reduction in oxygen (O_2) and increases in anthropogenic pollutant gases. Studies have had diverse aims, such as the protection of speleothems (Baker & Genty, 1998), the preservation of prehistoric paintings (Cabrol, 1997), and the health of sensitive cave fauna.

Recommended techniques for the analysis of cave air are nondispersive infrared spectroscopy (NDIR) and gas chromatography, both of which allow *in situ* continuous monitoring. NDIR instruments are recommended for analysis of CO_2. Gas chromatography instruments allow the concentration of other gases such as nitrogen, O_2, carbon monoxide, and methane to be obtained simultaneously with CO_2, but are expensive and require helium as the carrier gas. Grab samples taken in Tedlar bags can be measured in the laboratory, where trace gases can be identified and quantified by gas chromatography mass spectroscopy. The latter technique has been used to identify 71 trace gases present in the atmosphere of Jenolan Caves, Australia.

Carbon dioxide is a critical component in the solution and precipitation of calcium carbonate (calcite or limestone); these processes are illustrated in the following equation:

$$\text{Solution} \Rightarrow$$
$$CaCO_3(s) + CO_2(g) + H_2O(1) \leftrightharpoons Ca^{2+}(aq) + 2HCO_3^-(aq)$$
$$\Leftarrow \text{Precipitation}$$

CO_2 added to the system causes calcite solution, and its removal causes calcite precipitation. Thus, to corrode active calcite speleothems, the concentration of CO_2 must be higher in the cave atmosphere than in calcite-depositing waters. Increases of CO_2 in the cave air will initially reduce the rate at which active speleothems form and finally will cause their solution. The equation above supports a conclusion by Baker and Genty (1998), that speleothems depositing from solutions with high calcium concentrations can support greater increases in CO_2. These processes are temperature dependent and increases in temperature will alter the degree of CO_2 damage and rate at which it takes place.

Experimental data shows that there are no simple rules governing the behaviour of tourist-generated CO_2 within a cave or between caves. CO_2 accumulation from tourist respiration will depend on size and frequency of the cave tours, the energy the tourists expend in traversing the cave and the proportions of the caverns visited. The rate at which CO_2 levels return to background after tours finish, the relaxation time, depends on what mechanisms are available to remove CO_2 (see Carbon Dioxide-Enriched Cave Air).

Tourist-exhaled CO_2 is superimposed on a background of CO_2 from other sources. The background level of CO_2 is hard to establish and the assumption that it is the same as a nearby undeveloped cave is not valid. Background levels can be obtained experimentally during visitor-free periods. They are not constant and can vary by orders of magnitude. Despite difficulties in establishing reliable figures, over five years, a steady increase in background CO_2 has been observed at Jenolan Caves, Australia. O_2 to CO_2 ratios and $^{13}\delta C$ measurements show the increase is accompanied by an increase in the proportion of background CO_2 attributable to the respiration of micro-organisms. This is not surprising, as tourists add micro-organisms, and food for them, to the cave environment.

Fast relaxation times to background levels are desirable because the slow transfer of carbon dioxide from air to water is a necessary step in the solution of calcite. At most sites, ventilation controls relaxation times. Studies at Jenolan Caves, in the same cave system for the same time period, show that well-ventilated sites reach background in hours, whereas sites with poor ventilation take days.

If action is to be taken to reduce the.levels of CO_2 in a cave, thresholds should be established above which management action is necessary. In caves with active speleothems, two thresholds can be calculated by using aqueous geochemical models, a conservative corrosion threshold and a higher dissolution threshold, which takes into account the kinetics of calcite solution. Comprehensive air and water experimental data are required for threshold calculations. An unpublished study at Waitomo Caves, New Zealand, established a corrosion threshold of 2500 ppm CO_2. This figure has been used to manage tourist CO_2 in the Glow-Worm Cave. In the Jenolan Caves investigations, corrosion thresholds were found to range from 2700–28 000 ppm CO_2. In all cases, corrosion thresholds were not exceeded by the maximum CO_2 measured. In caves with inactive speleothems, there are no calcite saturated solutions to buffer increases in CO_2.

Thus corrosive condensates (see Condensation Corrosion), produced by tourists, are particularly harmful.

Automobile gases may be drawn into caves, if approach roads and car parks for tourist caves are poorly located (James *et al.*, 1998). Up to 200 litres of CO_2 are produced for every litre of gasoline. Automobile CO_2 can be identified from O_2 to CO_2 ratios and $^{13}\delta C$ studies. Automobiles also produce SO_x (sulfur oxides), NO_x (nitrogen oxides), VOCs (volatile organic compounds), and particulates. Speleothems have no protection against SO_x and NO_x gases that produce strong acids. VOCs are not likely to cause damage, although Young (1996) suggests that hydrocarbons may provide a food source for micro-organisms. At Jenolan Caves, the main access road passes through a cave and thousands of tourist vehicles use it each year. An investigation of air quality in the associated cave system found that gases attributable to automobile emissions had penetrated over a kilometre into the cave passages. Fortunately, even close to the road, SO_x, NO_x and VOCs concentrations were exceptionally low.

Health aspects of cave air quality are also important. The occupational health and safety limits for CO_2, O_2, and radon (see, Radon in Caves) in the work place are often controlled by legislation. Many of the gases in automobile emissions also have recommended levels, for example, that for benzene is 1 ppm over 8 hours. Osborne (1981) believes that a limit of 1000 ppm of CO_2 is necessary to avoid symptoms of hypercarnapia in tourists with poor health undergoing exercise. Despite this, he recommends a threshold limit of 0.5 v/v% CO_2 well below 1.25 v/v% CO_2 (Australian mine standard). Methods most frequently used to control air quality in tourist caves are reductions in visitor numbers and artificial ventilation. However, James (1994) has argued that control by forced ventilation could actually damage a cave. Thus, when developing caves for tourism, plans for maintaining air quality, without resorting to artificial ventilation, are a priority.

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Works Cited

Baker, A. & Genty, D. 1998. Environmental pressures on conserving cave speleothems: Effects of changing surface land use and increased cave tourism. *Journal of Environmental Management,* 53:165–75

Cabrol, P. 1997. Protection of speleothems. In *Cave Minerals of the World,* 2nd edition, edited by C.A.Hill & P.Forti, Huntsville, Alabama: National Speleological Society

Cigna, A.A. 1993. Environmental management of tourist caves. *Environmental Geology,* 21:173–80

James, J.M. 1994. Carbon dioxide in tourist cave air. *Comptes Rendus du Colloque International de Karstologie a Luxembourg,* 27: 187–95

James, J.M., Antill, S.J., Cooper, A. & Stone, D.J.M. 1998. Effect of automobile emissions on the Jenolan Caves. *Acta Carsologica,* 27(1):119–32

Osborne, R.A.L. 1981. Towards an air quality standard for tourist caves: Studies of carbon dioxide-enriched atmospheres in Gaden-Coral Cave, Wellington Caves, NSW. *Helictite,* 19:48–56

Young, P. 1996. Mouldering monuments. *New Scientist,* 2054:36–38

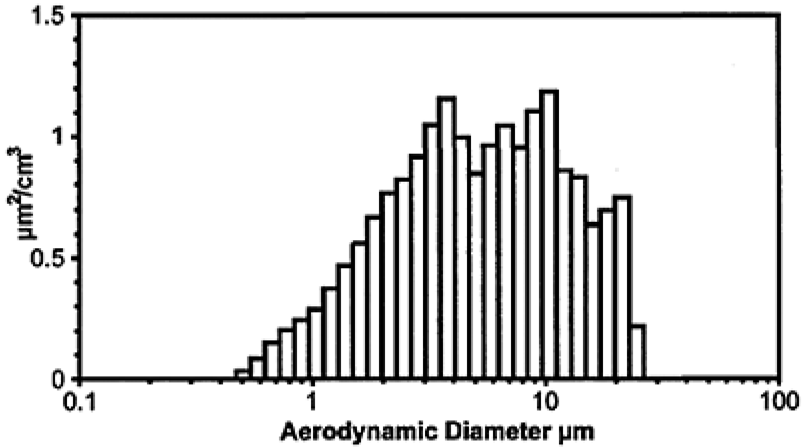
TOURIST CAVES: AIRBORNE DEBRIS

Caves that are used for tourist activities show obvious ill effects from the deposition of airborne particles. However, all caves that are entered by humans suffer from particle contamination, and caves also have particles transported from the surface by natural processes. Airborne particles in cave atmospheres, and deposits that result from them, have been studied with varied perspectives. Went (1970) investigated condensation nuclei (0.03µm diameter); these are generated mainly by combustion processes and persist for several days. The effects of cave tourism have been investigated by Jablonsky, Kraemer & Yett (1993) and there have been extensive studies of dust deposition in temple caves in China (Christoforou, Salmon & Cass, 1996).

The material deposited in caves generally consists of mineral particles, mainly clay minerals, as well as organic material; textile fibres, human dander (skin flakes) and hair, industrial dust and soot, and natural organic material; spores, pollen, plant dust, and insect bodies. The nature of the deposits in any cave depends on the sources of the dust and the processes that generate it within, or transport it into, the cave. Dust particles are often measured by their aerodynamic properties; here the aerodynamic diameter is used to describe particles. A particle of aerodynamic diameter 1 µm settles under the influence of gravity at the same rate as a spherical particle of 1 µm diameter and a density of 1 g cm^{-3}. The Table shows the settling rates of particles. Settling is the main process for deposition of larger particles. Particles less than 1 µm also are significantly moved by Brownian motion and will even attach to the underside of horizontal surfaces.

Measurements of airborne dust in caves, on the surface in a country area and in a city, show similar diameter distributions. The Figure is a measurement of air-borne dust in Jenolan Caves (New South Wales, Australia), during a cave tour. By plotting particle surface area against diameter, a distribution results that is more normally distributed than plotting particle numbers or particle mass against diameter, which produce skewed distributions.

Natural dust sources are aided by wind, which is the major agent for generating airborne dust from soil particles, pollen, spores, plant and insect material, as well as smoke and ash from wildfires and volcanoes. Natural dust is transported into caves by airflow from the surface, and caves with “chimney” circulations can transport air laden with dust to great depths, a possible cause of the mobile dust described by Holsinger (1962), in Boundless Cave, Virginia. Barometric “breathing” has deposited a massive sand dune in Mullamullang Cave, Nullarbor Plains, Australia. Slow, bi-directional air flow near the entrances of “static” caves will transport airborne dust significant distances from the entrance before the time needed for the dust to settle elapses. Aeolian deposits are to be expected in many caves in all climates, but are rarely reported.



Tourist Caves: Airborne Debris: Diameter distribution and concentration of dust particles in the air, as a cave tour passed a point in Jenolan Caves, New South Wales, Australia. Before the tour group arrived the concentration was very low.

Anthropogenic dust sources are mainly mining, agriculture, and transport, and in third-world countries, cooking fires are significant. Humans themselves are a source of hair and dander, while the clothes that they wear shed textile fibre fragments. Anthropogenic dust is transported into caves by the same processes as natural dust, but in addition, a major mechanism for transport of dust involves the textiles used for clothing. The total surface area of typical textile clothing is in the order of 150 m^2 kg^{-1}. This area is quite efficient at capturing airborne particles outside a cave. The flexible nature of textiles and the movement of the wearer then enable the particles to be dislodged from the clothing and re-entrained into the air inside the cave. A typical tourist in a show cave releases 1 μg s^{-1}.

Methods of measurement are many, but commonly dust can be captured by drawing air through a filter, it can be measured in a stream of air by optical means, or it can be collected on sample plates as it deposits. The data in the Figure were acquired by a TSI Aerodynamic Particle Sizer, which draws an air sample through two laser light beams, while the air stream is decelerating. The transit time determines the aerodynamic diameter of each particle. A simple method in caves is to use glass Petri dishes placed on horizontal surfaces, to sample the dustfall for a period of weeks (Michie, 1997). The dust film can then be examined microscopically, the light transmission of the dish can be measured, or the material can be removed for chemical or physical analysis.

Management of dust in tour caves is by design and control of the infrastructure (Michie, 1999). In a well-managed tour cave, the dust deposited by each visitor may be tens of thousands of times less than that deposited by "wild" cavers with dirty clothes. Re-entrainment of particles, which have fallen on walking surfaces, will occur if floors are not kept quite clean. Ideal paths are elevated above the cave floor, have solid side barriers up to knee height, are frequently cleaned of deposited material and are made of materials that will not fragment. The environment outside a tour cave should be kept dust free so that material will not be trapped in visitors' clothing and carried into the

Particle Diameter µm.	Brownian motion displacement in 10sec. (mm. RMS)	Settling Velocity m s^{-1}	Time to settle one metre
0.01	1.0	6.95×10^{-8}	166 days
0.1	0.12	8.65×10^{-7}	13.4 days
1	2.3×10^{-2}	3.48×10^{-5}	7.98 hours
10	7.0×10^{-3}	3.06×10^{-3}	327 sec.
100	2.2×10^{-3}	0.261	3.86 sec.

Tourist Caves: Airborne Debris: The Brownian motion displacement and settling rates of particles of different aerodynamic diameter (see Baron & Willeke 1993).

cave, or be carried into the cave by air exchange. Any form of combustion in a cave releases very fine particles (mainly carbon) which have a disproportionately large surface area and are extremely efficient at penetrating deep into caves and discolouring all surfaces.

The effects of anthropogenic dust on caves may be subtle, but threaten many cave values. In all show caves, the colour of decorations is degraded as they become covered with dust. In many caves this effect has not been noticed but there is awareness of the accumulation of textile fibres (only a minor component of dust) which are picked out by hand. At Jenolan Caves, one hundred years as a show cave resulted in severely degraded decorations that were only restored by steam cleaning or, as is now preferred, water spray cleaning (Bonwick & Ellis, 1985). This treatment is not without residual damage (Spate & Moses, 1993) and is impossible for many types of speleothem, so degradation may be irreversible.

Dust has a profound effect on the life forms in caves. The minerals and organic material may overwhelm the original food chain, and new opportunistic species may invade the cave, although natural dust may be an essential part of the food chain. Organic material is decomposed by fungi and bacteria, whereas natural textile fibres (cotton, wool, etc.) decompose to add to the food chain, but synthetic fibres endure to be cemented into surfaces. Fibre dyestuffs, which may be 10% of the mass of a textile, often contain heavy metals or undesirable chemicals that could cause damage to cave fauna or flora when the fibre degrades. The organic decomposition causes corrosion of mineral surfaces.

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Works Cited

Baron, P.A. & Willeke, K. 1993. Gas and particle motion. In *Aerosol Measurement: Principles, Techniques, and Applications,* edited by K.Willeke & P.A.Baron, New York: Van Nostrand Reinhold

Bonwick, J. & Ellis, R. 1985. New caves for old: Cleaning, restoration and redevelopment of show caves. In *Proceedings of the 6th Australasian Conference on Cave and Karst Management, Waitomo Caves, New Zealand,* edited by D.R.Williams & K.A. Wilde, Carlton South, Victoria: Australasian Cave and Karst Management Association

Christoforou, C.S., Salmon, L.G. & Cass, G.R. 1996. Fate of atmospheric particles within Buddhist cave temples at Yungang, China. *Environmental Science and Technology,* 30(12):3425–34

Holsinger, J.R. 1962. Shifting sands noted in Boundless Cave, Virginia. *NSS News,* 20(5):57–58

Jablonsky, P., Kraemer, S. & Yett, W. 1993. Lint in caves. In *Proceedings of the 9th National Cave Management Symposium, Carlsbad, New Mexico,* edited by D.L.Pate, Carlsbad, New Mexico: National Cave Management Symposium Steering Committee

Michie, N.A. 1997. The threat to caves of the human dust source. In *Proceedings of the 12th International Congress of Speleology,* vol. 5, La Chaux-de-Fonds, Switzerland: International Union of Speleology/Swiss Speleological Society

Michie, N.A. 1999. Management of dust in show caves. In *Cave Management in Australasia XII: Proceedings of the 13th Australasian Conference on Cave and Karst Management, Mount Gambier, South Australia,* edited by K.Henderson, Carlton South, Victoria: Australasian Cave and Karst Management Association

Spate, A. & Moses, C. 1993. Impacts of high pressure cleaning, a case study at Jenolan. In *Proceedings of the 10th Australasian Conference on Cave and Karst Management, Auckland, New Zealand,* Carlton South, Victoria: Australasian Cave and Karst Management Association

Went, F.W. 1970. Measuring cave air movements with condensation nuclei. *NSS Bulletin,* 35(1):1–9

Further Reading

Willeke, K. & Baron, P.A. (editors) 1993. *Aerosol Measurement: Principles, Techniques, and Applications,* New York: Van Nostrand Reinhold

A comprehensive textbook for modern aerosol science, measurement, and problems.

TOURIST CAVES: ALGAE AND LAMPENFLORA

Visible growths of algae, cyanobacteria (formerly known as bluegreen algae), mosses, and moss protonema (green filamentous structures arising from an asexual spore of moss) are common within electrically lit caves. In some caves lichens and ferns are also locally encountered. All such growths are termed lampenflora because of their association with electric lights.

Lampenflora change the natural appearance of cave features and, if not promptly treated, damage speleothem surfaces due to the production of organic acids which corrode the surface. In caves with prehistoric art (such as Lascaux) lampenflora are extremely destructive (Ruspoli, 1986). Management programmes to minimize and control lampenflora typically involve two strategies (Aley, Aley & Rhodes, 1984). First, light intensity/light duration thresholds are identified below which little or no visible plant growth will develop; light intensities on sensitive cave surfaces are then mostly kept below these thresholds. Second, lampenflora growth which does occur is treated with 5.25% sodium hypochlorite solution (bleach). However, the use of bleach solutions for control of lampenflora in caves with prehistoric art is likely to damage features of significance and is thus not likely to be a viable management strategy for such caves.

Lampenflora management strategies should not be predicated on an assumption that algae did not exist in the cave prior to the introduction of electric lighting for visitors. Studies by Claus (1962; 1964), Hajdu (1966), Kol (1967), and others demonstrate that many genera and species of algae and cyanobacteria grow in the perpetually dark portions of many caves. Such growth is generally not very obvious, is typically black in colour, and is limited to frequently or perennially wet cave surfaces. Some of the algal and cyanobacteria species found growing in the perpetually dark portions of caves become components of the lampenflora if the cave is electrically lit; many of these species are distributed widely around the world.

The composition of lampenflora varies substantially among caves in the United States which the author has studied. In 1984 in Carlsbad Caverns, New Mexico, lampenflora growths consisted of about 70% cyanobacteria, 20% green algae, and 10% moss protonema. In addition, there were diatoms present in about 25% of all of the clusters of lampenflora. Yellow-green algae were also present, but they were found in very few locations. Lampenflora were associated with 43% of the lights inspected in the Caverns, and the total number of lampenflora species present in the cave was estimated at 200. Carlsbad Caverns is in a semi-arid region and moisture availability is limiting even where lampenflora exist. In 1985 lampenflora growths in Oregon Caves, Oregon, consisted of about 15% mature moss, 10% moss protonema, 40% cyanobacteria, and 35% green algae. Diatoms were present in about half of the clusters of lampenflora, and the total number of lampenflora species present was estimated at 100. Oregon Caves has a Mediterranean climate with a dry summer. Most cave surfaces are routinely wet, and lampenflora were associated with every fixed light in the cave.

Visible lampenflora are usually limited to moist or wet surfaces. Soft surfaces (such as cave sediments and moonmilk) provide more moisture storage than hard surfaces (such as found on actively depositing speleothems). As a result, soft surfaces are more prone to the development of lampenflora and especially to the existence of luxuriant growths. However, hard surfaces often have adequate moisture to support lampenflora, especially in humid regions.

The total light energy received, a function of the intensity of the light and the duration of the lighting, is a critical factor for the establishment and growth of lampenflora. Theoretically, a period of continuous lighting for a given number of hours per day should yield more lampenflora growth than short periods of lighting which total the same number of hours per day. This is because plants make a number of chemical and physiological changes between light phase and dark phase conditions, and these changes require some time and plant energy. The management significance of this is that switching lights on and off multiple times during the course of a day in addition to reducing the total lighting period helps prevent or reduce lampenflora.

In general, the light necessary to produce lampenflora consisting of algae and cyanobacteria is less than the amount required for the establishment and growth of moss protonema. The establishment and growth of moss protonema requires less light than does the growth of mature moss, and ferns and lichens require still more light. In Carlsbad Caverns, 85% of the lampenflora received incident light intensities of 3.6 footcandles (39 lux) or more; a similar estimate for Oregon Caves was 4.2 footcandles (45 lux). Both of these caves were usually illuminated for most or all of the time that the cave was open for tours.

Light intensity, rather than the type or colour of the light, is the important factor. A notable exception is green light, since the photosynthetic pigment found in lampenflora primarily absorbs red and blue light and reflects green light, thus reducing photosynthetic efficiency. However, for aesthetic reasons, green cave lighting is an impractical strategy. Yellow lighting is a possible alternative, since algae do not strongly absorb yellow light. Due to filters that absorb parts of the white light spectrum, coloured lights produce lower incident light intensities on cave surfaces than do uncoloured lights of the same type and wattage; this accounts for the common observation that there is less lampenflora growth around lights using coloured filters than around white lights. For the same incident light intensities on moist cave surfaces, there is no detectable difference in lampenflora growths between fluorescent and incandescent lights.

Growth plots testing the extent of lampenflora growth on various cave substrates were established in both Carlsbad Caverns and Oregon Caves. Lint and other detritus from visitors and their clothing produced the most extensive and rapid lampenflora growths. Laundry products contain phosphates and residual phosphates are present in lint. Phosphates enhance algal growth in aquatic systems.

Many chemical agents have been tested for their ability to kill lampenflora. For most situations, 5.25% sodium hypochlorite solution applied as a light mist proves the most effective control while concurrently minimizing adverse impacts on cave features. More dilute solutions can be used, but they typically require the use of much more solution. The solution oxidizes the plant material and ruptures plant cells. One to two weeks after treatment fungal growth on the dead plant material will usually make it possible to wash the dead material from speleothems without scrubbing. Calcium hypochlorite solutions should not be used since they leave a calcium residue which is difficult to remove. Hydrogen peroxide is ineffective in controlling lampenflora.

Sodium hypochlorite should be carefully applied as a light mist on surfaces with lampenflora; multiple treatments should be used in areas with dense growth. Adverse impacts are minimized by treating areas as soon as the lampenflora is visible. Drippage or runoff of the treating solution should be captured; burlap or other fabric which will be oxidized by the treating solution can be placed adjacent to the target areas. While cave fauna could be killed if they come in direct contact with the sodium hypochlorite solution, the oxidizing ability of the solution (and thus its toxicity) diminishes rapidly in the presence of materials (such as lampenflora, cave lint, and burlap) which are subject to oxidation. Careful application and control of the sodium hypochlorite is the key to protecting cave fauna while conducting lampenflora control work (see Restoration of Caves and Speleothem Repair).

Recent advances in lighting, such as the use of fibre optics and low energy lamps, can permit more precise use of light in caves. If appropriately used, this enhanced control has the potential to permit cave lighting with reduced lampenflora growth.

TOM ALEY

See also **Biofilms**

Works Cited

Aley, T., Aley, C. & Rhodes, R. 1984. Control of exotic plant growth in Carlsbad Caverns, New Mexico. Proceedings of the 1984 National Cave Management Symposium. *Missouri Speleology,* 25(1–4):159–71

Claus, G. 1962. Data on the ecology of the algae of Peace Cave in Hungary. *Nova Hedwigia,* 4(1):55–79

Claus, G. 1964. Algae and their mode of life in the Baradla Cave at Aggtelek II. *International Journal of Speleology,* 1:13–20

Hajdu, L. 1966. Algological studies in the cave at Maytas Mount, Budapest, Hungary. *International Journal of Speleology,* 2:137–49

Kol, E. 1967. Algal growth experiments in the Baradla Cave at Aggtelek. *International Journal of Speleology,* 2:457–74

Ruspoli, M. 1986. *The Cave of Lascaux: The Final Photographs,* New York: Abrams and London: Thames and Hudson

Further Reading

Aley, T.J. 1996. Caves in crisis. *1997 Yearbook of Science and the Future,* edited by D.Calhoun, Chicago: Encyclopaedia Britannica

Gillieson, D. 1996. *Caves: Processes, Development and Management,* Oxford and Cambridge, Massachusetts: Blackwells

Giordano, M., Mobili, F., Pezzoni, V, Hein, M.K. & Davis, J.S. 2000. Photosynthesis in the caves of Frasassi (Italy). *Phycologia,* 39(5):384–89

Hazslinszky, T. (editor) 1985. *International Colloquium on Lamp Flora,* Budapest: Hungarian Speleological Society

Olson, R. 2003. Control of lamp flora in developed caves. In *Restoration and Conservation of Caves,* edited by V.Hildreth-Werker and J.Werker, Huntsville, Alabama: National Speleological Society

TOWER KARST

Tower karst landscapes represent perhaps the most spectacular terrain developed on carbonate rocks. Broadly, they consist of relatively isolated, often steep-sided, residual carbonate hills (towers) protruding from a near-planar surrounding corrosion surface, which is often alluviated and traversed by allogenic rivers that flow from outside the karst area. Some of the best-known tower karst landscapes are in southern China, particularly around Guilin in Guangxi (see Figure) and in Guizhou. Other notable examples occur throughout Southeast Asia, particularly in Malaysia, Thailand, Indonesia, and Vietnam; in Central America; and in the Caribbean Greater Antilles.

The towers, which dominate the landscape, are steep-sided to hemispherical residual hills, some over 200 m tall and 500 m in diameter. Various names have been ascribed to the towers and the overall landscape: in Chinese, tower karst is known as fenglin (peak forest) where towers are isolated, and fengcong (peak cluster) where groups of residual hills share a common exposed bedrock base; in Spanish the towers are termed mogotes; in French they are tourelles or pitons; in German Turmkarst; elsewhere they are known as “haystacks” and pepinos.

The towers are of variable morphology. Balazs (1973) suggested that four classes could be recognized on the basis of their height/width ratio: the Yangshuo, Organos, Sewu, and Tual types, named after their “type examples” in China, Cuba, Java, and Kai-Ketjil Island (Indonesia) respectively. Individual towers usually rise from a continuous carbonate surface, although this is often obscured by alluvium, and in some cases individuals are visibly connected to one or more of their neighbours with which they share a common basal “footprint”. In the vicinity of Alligator Pond, in southern Jamaica, towers rise from a continuous unmantled carbonate rock base. Other towers rise from a surface incorporating non-carbonate rocks, such as in the Sierra de los Organos, Cuba and in Chillagoe, Queensland, Australia. In Malaysia and in the Rio Frio area of the Cayo District, Belize, limestone hills are founded on granite, which forms the floor of the Rio Frio Cave. In Puerto Rico, the mogotes protrude through a cover of “blanket sands”; in Ha Long Bay, Vietnam, and elsewhere, drowned marine towers rise from the sea. Ford and Williams (1989) suggest that there are four major genetic types of tower karst: (1) residual hills protruding from a planed carbonate surface veneered by alluvium; (2) residual hills emerging from carbonate inliers in a planed surface cut mainly across non-carbonate rock; (3) carbonate hills protruding through an aggraded surface of clastic sediments that buries the underlying karst topography; and (4) isolated carbonate towers rising from steeply sloping pedestal bases of various lithologies.

Although some towers approach conical symmetry, most are actually asymmetrical, reflecting structural or other influences. Asymmetry of the mogotes of northern Puerto Rico was considered to be the result of directional preference in surface induration or case-hardening, but was shown by Day (1978) to be directionally inconsistent and related rather to structural control and basal undercutting. As the towers themselves are erosional remnants, it is the surrounding lowlands that are the focus of current karstic and fluvial geomorphic activity, and there exists a landscape duality in which the carbonate tower environment and the surrounding alluvial environment are quite distinct.

Tower slopes and hilltops are highly irregular, often with only a minimal soil cover. Slopes consist of combinations of vertical cliffs, inclined bedrock surfaces, “staircases”, or talus accumulations. Occasional rockfall episodes constitute a hazard in populated areas. By contrast, the intervening lowlands often have deep sediment covers produced by alluviation. Regional drainage is largely allogenic, although there may be significant autogenic inputs via springs at tower bases. Most tower karst is developed in mechanically competent carbonates that are able to support steep slopes (Day, 1982). Elsewhere, more friable carbonates have a surface induration, often referred to as case-hardening and in some cases exceeding a metre in thickness. Bedding, jointing, faulting, and lithological variation also influence tower morphology (Panos & Stelcl, 1968).

Cave systems associated with tower karst include active river caves dissecting the towers at the level of the surrounding low-lands, undercut marginal meander or foot caves or “swamp notches” (Jennings, 1976; McDonald, 1979), and largely abandoned formerly phreatic systems riddling the towers at higher elevations. Paleomagnetic studies of sediments from these caves have proven extremely valuable in deciphering the chronology of tower karst landscape evolution (Williams, 1987), indicating that they are time-transgressive landforms, with their summits being considerably older than their bases.

Spectacular tower karst landscapes attracted the attention of early Chinese travellers such as Xu Xiake, and Grund (1914) described the landscape as the “senile” stage in his karst evolutionary cycle. It was not until the mid-20th century, however, that the first widely available and systematic geomorphological studies of tower karst were undertaken in Asia and the Caribbean by Herbert Lehmann (1954) and others. Some of the most detailed observations of towers were made in the 1970s by McDonald (1976a,b; 1979), who drew particular attention to their perimeters and to the role of basal slope development, including undercutting by rivers.

Several models of tower karst formation and evolution have been proposed. Of particular concern is whether isolated karst towers (fenglin) represent a sequential evolution from previously linked fengcong hills, or whether the two develop independently under differing geological and environmental conditions. While both are possible, most evidence supports the latter hypothesis. Although tower karst is most often associated with humid tropical climates, relict examples occur in locations where equivalent climatic conditions formerly prevailed. Such relict tower karst has been recognized in central Europe (Bosák *et al.*, 1989). Analogous carbonate karst landscapes have also been identified in the Kimberley ranges of Western Australia and in the labyrinth karst of the Northwest Territory of Canada (Brook & Ford, 1978). A sandstone analog exists in Arnhem Land in the Northern Territory of Australia (see Silicate Karst).

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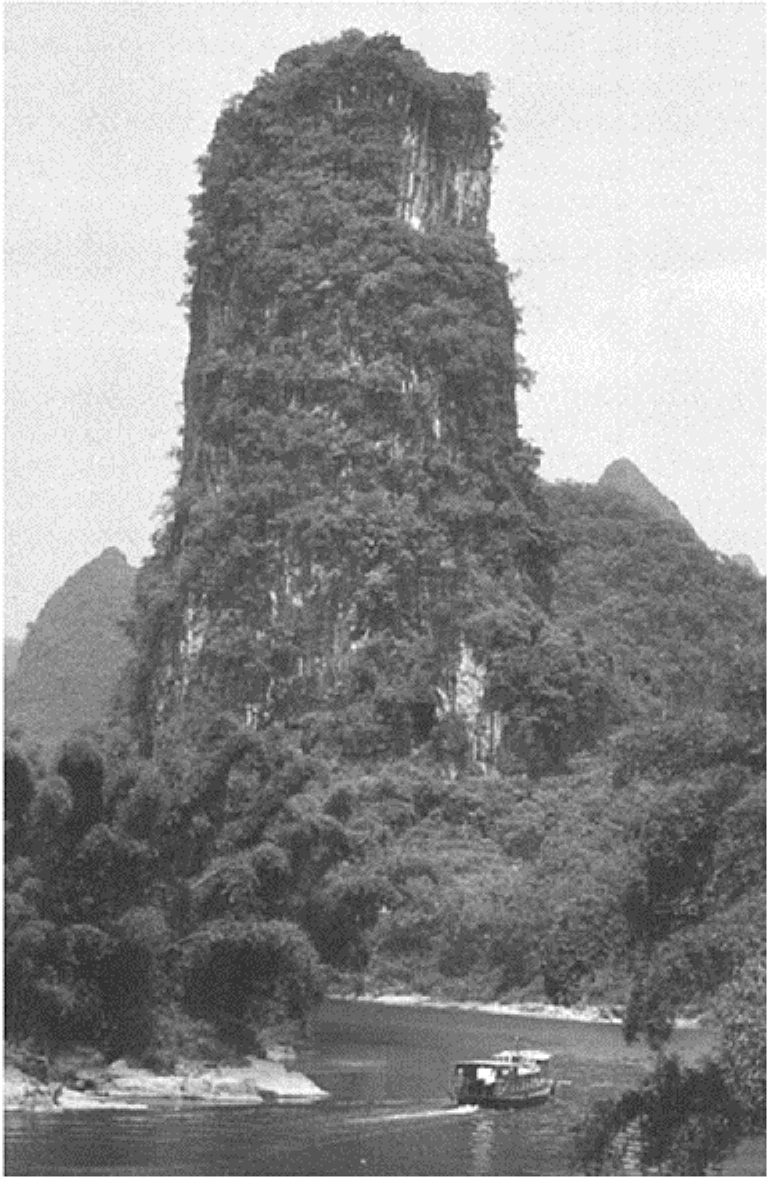


Tower Karst: A perfect example of a limestone tower beside the Jingbao River in the fenglin karst of Guangxi. (Photo by Tony Waltham)

See also **Cone Karst; Yangshuo Karst**

Works Cited

Balazs, D. 1973. Relief types of tropical karst areas. In *IGU Symposium on Karst Morphogenesis,* edited by L.Jakucs, Szeged: Attila Jozsef University: 16–32

Bosák, P., Ford, D.C., Glazek, J. & Horácek, I. 1989. *Paleokarst: A Systematic and Regional Review,* Amsterdam and New York: Elsevier

Brook, G.A. & Ford, D.C. 1978. The origin of labyrinth and tower karst and the climatic conditions necessary for their development. *Nature,* 275:493–96

Day, M.J. 1978. Morphology and distribution of residual limestone hills (mogotes) in the karst of northern Puerto Rico. *Bulletin of the Geological Society of America,* 89:426–32

Day, M.J. 1982. The influence of some material properties on the development of tropical karst terrain. *Transactions of the British Cave Research Association,* 9(1):27–37

Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman

Grund, A. 1914. Der geographische Zyklus im Karst. *Ges. Erdkunde,* 52:621–40 [The geographical cycle in the karst]. Translated and reprinted in *Karst Geomorphology,* edited by M.M.Sweeting, Stroudsburg, Pennsylvania: Hutchinson Ross, 1981

Jennings, J.N. 1976. A test of the importance of cliff-foot caves in tower karst development. *Zeitschrift für Geomorphologie Supplementbande,* 26:92–97

Lehmann, H. 1954. Der tropische Kegelkarst auf den grossen Antillen. *Erdkunde,* 8:130–39

McDonald, R.C. 1976a. Limestone morphology in south Sulawesi, Indonesia. *Zeitschrift für Geomorpholgie Supplementbande,* 26:71–91

McDonald, R.C. 1976b. Hillslope base depressions in tower karst topography of Belize. *Zeitschrift für Geomorpholgie Supplementbande,* 26:98–103

McDonald, R.C. 1979. Tower karst geomorphology in Belize. *Zeitschrift für Geomorphologie Supplementbande,* 32:35–45

Panos, V. & Stelcl, O. 1968. Physiographic and geologic control in development of Cuban mogotes. *Zeitschrift für Geomorphologie,* 12(2):117–73

Williams, P.W. 1987. Geomorphic inheritance and the development of tower karst. *Earth Surface Processes and Landforms,* 12(5):453–65

Further Reading

Monroe, W.H. 1968. The karst features of northern Puerto Rico. *Bulletin of the National Speleological Society,* 30:75–86

Sweeting, M.M. 1995. *Karst in China: Its Geomorphology and Environment,* Berlin and New York: Springer

Yuan D. 1991 (editor). *Karst of China,* Beijing: Geological Publishing House

TRAVERTINE

This term is applied to spring-deposited calcium carbonate, derived from the *Lapis tiburtinus* (rock of the Tiber), where it was quarried extensively as a building stone in Roman times. Travertine at the type locality, Bagni di Tivoli, is deposited by thermal springs permeating marine limestones, but travertines are deposited from a wide range of springs containing abundant Ca, and usually, abundant carbon dioxide. A related term is *calcareous tufa,* often used to describe the softer varieties of travertine, which were too weak for construction purposes. This term is still used widely, especially in Europe, though apt to be confused with the Italian *tufo,* a term (now largely defunct) for rocks of volcanic origin. Travertine has a broad definition encompassing calcareous tufa and cave calcite (speleothem), whose mechanism of formation is similar.

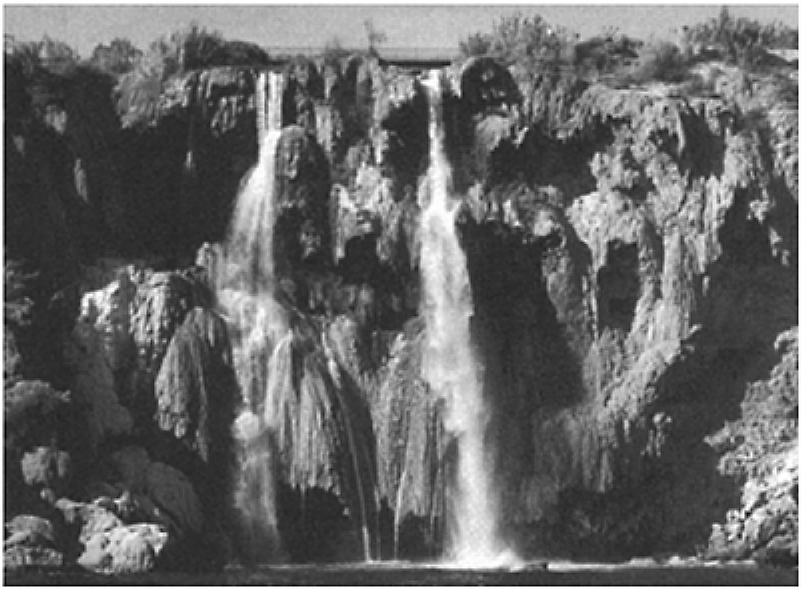
Most travertines are formed from waters containing calcium and bicarbonate ions through the following reaction:

$$Ca^{2+} + 2(HCO_3)^{2-} \leftrightharpoons CaCO_3 + CO_2 + H_2O$$

The reaction proceeds to the right when carbon dioxide is removed from the water by evasion to the atmosphere or by photosynthesis. Atmospheric evasion only occurs if the partial pressure of CO_2 in the water exceeds that of the atmosphere. This occurs in most springwaters, because CO_2 is added to water from a soil atmosphere rich in CO_2. However, travertine will only be precipitated if the Ca concentration is high enough to exceed the solubility product of the minerals calcite or aragonite. Typically, this requires water derived from a catchment containing limestone or gypsum, where the dissolved Ca exceeds about 1 mM l^{-1} (40 ppm). The removal of excess CO_2 is enhanced by water turbulence and warming. Sunny cascades are efficient at CO_2 removal and many of the best-known travertines are found on these. Bright sunshine also increases photosynthesis by aquatic plants, removing CO_2 below the atmospheric equilibrium level. The relative importance of the two processes, evasion and photosynthesis, depends upon springwater discharge, area of stream bed, stream morphometry, and climate. In general, travertines are deposited in the upper reaches of streams, and where discharge is high most CO_2 loss is by evasion. In small seeps in regions of low rainfall and high illumination, photosynthesis is probably more important. A small group of travertines, described as invasive meteogenes, result from the direct reaction of atmospheric CO_2 with a highly alkaline groundwater. They are formed on a small scale around lime-burning sites and in regions containing the rare mineral portlandite, both of which produce localized groundwaters containing calcium hydroxide.

Travertines show a wide range of morphologies due to development on different terrains. Most common are cascades and barrages. Cascades often become coated in travertine in karst regions and reach impressive dimensions. Well-known examples are the falls of Urach, Germany; Huangguoshu, China; Turner's Falls, Oklahoma; and the Reotier travertine cascade in the French Alps (Figure 1). At these sites, the rate of travertine erosion keeps pace with deposition, so the travertines form an inverted parabola shaped by the falling curtain of water. Where deposition exceeds erosion, large prograding aprons occur, such as those at Pamukkale, Turkey (see separate entry) and Mammoth Hot Springs, Wyoming. Occasionally, spectacular tall narrow channels are produced, e.g. the Gutersteiner Falls, Germany and the famous Pamukkale "self-built channels". Related to cascades are travertine dams. These differ only in impounding water behind them to form ponds or lakes and thus grow above the water line. Erosion exceeds deposition, and often a large series of apparently self-perpetuating dams are built across a river, leading to spectacular lake and waterfall scenery. The best known is Plitvice, Croatia (see Plitvice Lakes entry) but there are equally impressive sites in Afghanistan at Band e Amir (see photo in Indian Subcontinent entry), and in China (see separate entry, Huanglong and Jiuzhaigou). Dams may form in series, because the intervening lakes alter water chemistry by increasing residence time and photosynthesis, extending the precipitation process. The examples above originate from springs feeding rapidly descending watercourses, but where the terrain is flat, or deposition rapid, precipitation is localized around the spring orifice, forming a travertine mound. Mounds can reach impressive dimensions, such as Solomon's Prison in Iran (69 m) and the mound springs of the Lake Eyre Basin of Australia, but most are smaller, ranging from 5 m to less than half a metre in height. Many are fed by artesian springs. In Britain, the spring mounds of Great Close Mire in Yorkshire are noted for their rich flora. Other morphologies include fissure ridges, which are linear mounds forming along fault-springs, stream crusts, and cemented gravels. Stream crusts consist of travertine linings to the stream bed, which are of variable thickness (0.5–100 cm or more), often laminated and merging with cascades on steeper sections. In low to moderate flow rates (*c.* 20–100 cm s^{-1}) travertine often develops around mobile fragments of gravel to form

Travertine: Figure 1. The Reotier travertine cascade in the French alps showing rapid prograding carbonate deposition over a bluegreen algal/diatom biofilm. (Photo by Allan Pentecost)



Travertine. Figure 2. Water cascading into the Mediterranean Sea from the Antalya travertine terraces, which are among the largest freshwater carbonate deposits in the world. The cliffs are about 30 m high. (Photo by John Gunn)

rounded, laminated pebbles, termed oncoids or pisoids. Regular movement by the current permits all-round growth and eventual accumulation of oncoids into shoals or bars along some stream sections. Similar pebbles sometimes occur in the littoral zone of karstic lakes. Cemented gravels, similar to calcrete, are common where calcareous waters penetrate coarse alluvium. This can occur over broad floodplains and the resulting deposit, as hard as concrete, may weather out as travertine terraces. Such terraces are common around the Mediterranean Sea, for example at Antalya, Turkey (Figure 2). Other travertines erode soon after their formation, and can be redeposited as valley-fills or behind travertine-dammed lakes. These clastic travertines are usually soft, containing travertine "sand", oncoids, and fragments of "phytoherm" (incrustations on plants such as algae, bryophytes, and flowering plant stems). They are sometimes quarried for marl. Apart from their economic value, the deposits have been used widely in paleoecological and paleoenvironmental studies. Fossils of invertebrates, particularly Mollusca, Ostracoda, Vertebrata, and the impressions and pollen of plants, are often well preserved and have been used to reconstruct Quaternary environments.

Actively forming travertines are often rich in flora and fauna. The latter often harbours specialists, such as *Pericoma* larvae producing setae upon which the travertine is deposited, making travertines important for conservation. Dating of travertine using ^{14}C is often problematic due to the "hard water effect" but successful results have been achieved using Uranium series. Useful environmental data have also been obtained from their stable isotope geochemistry.

ALLAN PENTECOST

Further Reading

Bouyx, E. & Pias, J. 1971. Signification geologique des travertins d'Awpar (Afghanistan). *Compte Rendu Hebdomadaire des Seances et Mémoires de l'Académie des Sciences, Paris,* 273:2468–71

Chafetz, H.S. & Folk, R.L. 1984. Travertines: depositional morphology and the bacterially constructed constituents. *Journal of Sedimentary Petrology,* 54:289–316

Goudie, A.S., Viles, H.A. & Pentecost, A. 1993. The late-Holocene tufa decline in Europe. *The Holocene,* 3:181–6

Pedley, M. 1993. Sedimentology of the late Quaternary barrage tufas in the Wye and Lathkill valleys, north Derbyshire. *Proceedings of the Yorkshire Geological Society,* 49:197–206

Pentecost, A. 1995. The Quaternary travertine deposits of Europe and Asia Minor. *Quaternary Science Reviews,* 14:1005–28

TUNNELLING AND UNDERGROUND DAMS IN KARST

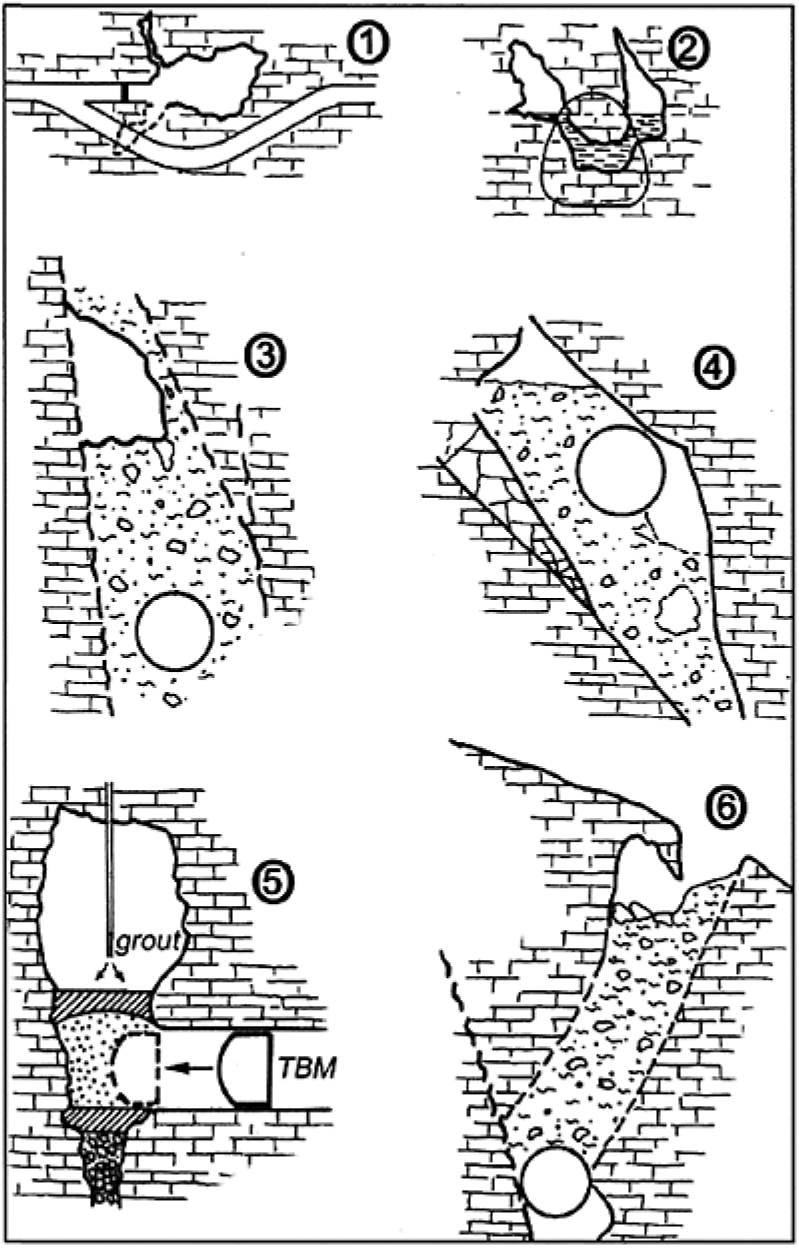
Man-made underground structures in karst include tunnels, large chambers, dams, and reservoirs. Excavation of tunnels, in the form of qanats, in arid regions such as Persia, Iraq, Egypt, and Libya is more than 3000 years old. In Iran, some were excavated in karstified limestone. Tunnels or galleries as a method of exploiting groundwater were well known for centuries throughout the Mediterranean and Middle East. A 1600 m long water transmission tunnel in limestone on the island of Samos (Greece) was excavated using hammer and chisel about 530 BC. Another purpose for ancient tunnel excavation in karst regions was drainage of temporarily flooded karst poljes (see Karst Hydrology: History).

Successful tunnel excavation requires reliable identification and mapping of cavernous zones in order to adjust the tunnel route to the actual geological conditions. The common investigation methods are detailed geological mapping at the surface, drilling, water level monitoring, geophysical surveys (from the surface and from within the tunnel), and speleological exploration. During excavation of tunnels and large chambers in karst, the major problems arise from the presence of faults and large caverns, and from groundwater intrusion. Of these, only caverns may be of such dimensions to represent a problem for which there may be no technical solution other than relocation. Tunnels appear to be the structures most vulnerable to damage or failure in karst, and this is especially true of high-pressure tunnels for hydroelectric power plants. If a karst conduit is encountered on the tunnel route, excavation progress can be slowed because of many different difficulties. These include excessive free space (which must be filled, bridged, or by-passed), caves which are filled and masked by sediments of unknown dimensions, geotechnical features that may require a change of excavation method to avoid complicated repair work, groundwater discharges into the tunnel, and undiscovered caverns close to the tunnel which can cause collapse during excavation or subsequent operation.

If, during excavation, a cavern is discovered on the tunnel route, its extreme dimensions may be a serious barrier to further progress. In certain cases, the only good solution is to construct a bypass or to relocate the tunnel route. Examples are the headrace tunnel at Capljina (Herzegovina), the traffic tunnel through the Velebit Mountain (Croatia), a tunnel on the Rome—Naples (Italy) railway line, and over 20 railway tunnels in China. Along the route of the Ucka road tunnel in Croatia, more than 1300 m of karst channels were investigated, including a cavern 175 m long and 70 m wide (Hudec, Bozicević & Bleiweiss 1980).

Especially unfavourable conditions occur when the groundwater level is (permanently or temporarily) above the tunnel axis, since excessive water inflow through karst conduits can provoke sudden tunnel flooding. Human lives and tunnelling equipment can be seriously endangered, particularly if there is no drainage by gravity. After six years of operation of the 6170 m long Sozina railway tunnel (Yugoslavia), it was flooded by an abrupt groundwater intrusion through karst channels, at a rate of 6.5 $m^3 s^{-1}$. A 1750 m long drainage tunnel, 2 m lower, and 15m from the main tunnel was excavated to resolve the problem. Without drainage by gravity, any groundwater intrusion of more than 1001 s^{-1} is an extremely serious problem. In those cases horizontal pilot boreholes and consolidation grouting ahead are employed prior to driving the tunnel. Floods in the tailrace tunnel of the Capljina reversible power plant (Herzegovina) and in the Kouhrang transmission tunnel (Iran) necessitated complex remedial works as there was no scope for gravity drainage.

Undiscovered or unsatisfactorily treated caverns around the tunnel lining can cause cracking of the lining and collapse during the tunnel operation. This problem is especially common in tunnels under pressure for hydroelectric power. The opposite problem may occur in water-tapping galleries which aim to intersect joints, joint systems, and zones containing active karst conduits. Gallery-tapping structures are successfully used for water supply in different parts of the Mediterranean region, including the Dinaric karst. For example, a 300 m long gallery collects the water supply of the town of Trogir, Croatia (Mijatović, 1984). At many sites the gallery is a water-collecting channel itself, but the water inflow is increased by drainage holes or wells driven from the gallery, as at the Lez Spring (France) and the Zvir Spring (Croatia).



Tunnelling in Karst: Examples of caverns found on a tunnel route. 1. Deviation of tunnel to bypass large empty cavern. 2. Cavern at water table level. 3 & 4. Caves filled with sediment. 5. Empty cavern ahead of TBM, requiring prior grouting. 6. Collapse at surface caused by tunnel tube excavated through cave fill.

Special care is needed when using a tunnel-boring machine (TBM) in karstified rock as TBM technology is not as flexible as conventional tunnelling. Major groundwater intrusions, large caverns, and caverns filled with clay can be complex technical problems for TBMs. Because of the vulnerability of TBM technology, very detailed geological, hydrogeological, geotechnical, and geophysical investigations are needed ahead of excavation so that any karstified zones (with possible large caverns) may be avoided by changing the tunnel alignment. If a TBM penetrates a clay-filled cavern, the usual consequence is sinking of the TBM head and in the worst case the TBM head can be completely lost. Because of this, all clay has to be removed and the cavern filled with concrete up to the level of the tunnel, or bridging technology has to be applied. Good examples of problems with TBM usage in a highly karstified zone are the Zakucac II headrace tunnel (Croatia), and the Fatnica-Bileca transmission tunnel (Herzegovina)

The problems of excavating large chambers in karstified rock are mostly related to groundwater intrusion and rock mass stability. Experience has shown that the treatment of large natural caves is easier than treatment of similar problems in tunnels, because of the larger working space. If a chamber is endangered by underground water the voids and cavities can be permanently stabilized by cleaning, filling by concrete, and grouting. In the case of flowing water or water under pressure, special treatment techniques have to be used. The ultimate condition for successful treatment is to stop the groundwater flow by prior grouting. In the vadose zone, treatment of empty caves is not necessary and only faults and large joints have to be protected by rock bolts and grouting. Large chambers in karst are mostly excavated for military purposes (shelters for submarines, ships, and planes) and for hydroelectric plants. One of the largest is the chamber for the Capljina power plant which is 98 m long, 29 m wide, and 77m high and is excavated in highly karstified rock 45 m below the groundwater level. The basic problems during excavation were the intersection of active karst channels resulting in intrusion of groundwater under pressure.

An artificial underground reservoir is a portion of an aquifer that has been improved to control the discharge regime of artificially stored water. Extensive cave systems and large natural chambers can provide significant storage. More than 20 underground reservoirs, with a storage capacity of between 1×10^5 and 1×10^7 m^3, have been created in the karst regions of China (Lu, 1986). A large underground reservoir was formed in Linlang Cave in Qiubei, Yunnan, in 1955–60. The annual average discharge of the karst conduit is 23.8 m^3 s^{-1}, and the maximum discharge exceeds 100 m^3 s^{-1}. Artificial storage in the karst channel system was achieved by constructing a 15 m high underground dam. A headrace tunnel provides 109 m of head for a power station with an installed capacity of 25 MW. In Guizhou, 16 underground dams have been constructed for irrigation. Five underground reservoirs have been designed on Miyako Island (Japan). The first one, Minafuku Dam (grout curtain 500 m long and 16.5 m high with a storage capacity of 720 000 m^3), was completed in 1979 (Yoshikawa & Shokohifard, 1993). An underground reservoir was constructed in the spring zone of Nevesinjsko polje (Herzegovina) by plugging a conduit in karstified Eocene conglomerate. However, because of inadequate manipulation and an abrupt increase of water pressure in the cave system the overburden above the underground reservoir collapsed.

A massive concrete plug, 10 m high and on average 3.5 m wide, was constructed to plug the channel outlet of the Obod estavelle at Fatnicko polje (Herzegovina). The peak discharge of the Obod is 60 $m^3 s^{-1}$ and the water pressure in the underground karst channel system increased rapidly to 1000 kN m^{-2}. Several tens of new springs appeared on the hill slopes 80–100 m above the plug level, and because of strong seismic shocks a road on the hillside started sliding and many houses at a distance of 250 to 300 m above the estavelle were damaged. To alleviate the pressure, blasting was used to create a 1.53×1.40 m opening in the concrete plug and within 6 hours all the artificially stored water was discharged.

The Ombla power plant (Croatia) has one of the largest underground damming and storage projects. The recorded discharge of the Ombla Spring is 2.3–112.5 $m^3 s^{-1}$ and the deepest cave conduit is about 150 m below sea level, and about 200 m behind the main spring outlet which is at sea level. The position of the flysch and the elevation of overflow springs limit the underground dam at about 100 m above sea level. Due to this height and the required overburden of the alignment, the arch-like underground dam will need to be located at least 200 m behind the spring outlet and it will be necessary to construct grout curtains and to plug karst channels.

Artificial underground reservoirs may be classified into three basic groups: storage within one karst channel; storage in all types of porosity and the aeration zone, including inactive channels; and underground storage which is physically coupled to surface reservoirs. Depending on geomorphological, hydrogeological, and geotechnical features, five general concepts can be identified for underground reservoir construction: (1) surface dam in front of the main discharge zone; (2) diaphragm wall connected to impervious or basement rocks; (3) plugging of individual caves to enable water storage in the system of karst conduits; (4) grout curtain favourable for construction of a wide watertight screen connected to impervious rocks; and (5) combination of these underground geotechnical structures.

In comparison with surface storage, underground water storage has many advantages: it does not flood fertile land; the problem of relocating infrastructure, residential facilities, and historical monuments does not exist; negative effects of evaporation, thermal stratification, and hydrodynamic, biological, and ecological effects are eliminated; sedimentation is negligible; failures of underground dams cannot be catastrophic; and destruction of landscape is minimal. However, the plugging of karst channels can cause floods in upstream depressions, the development of collapse and subsidence dolines at the surface, and induced local seismicity.

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See also **Dams and Reservoirs on Karst**

Works Cited

Hudec, M., Bozicević, S. & Bleiweiss, R. 1980. Support of cavern roof near Tunnel Ucka. *Proceedings of the 5th Yugoslav Symposium for Rock Mechanic and Underground Works, Split, Yugoslavia,* Yugoslav Society for Rock Mechanics

Lu Y. 1986. *Some Problems of Subsurface Reservoirs Constructed in Karst Regions of China,* Beijing: Institute of Hydrogeology and Engineering Geology, Chinese Academy of Geological Sciences

Mijatović, B. 1984. *Hydrogeology of the Dinaric Karst,* Hannover: Heise

Yoshikawa, M. & Shokohifard, G. 1993. *Underground Dams: A New Technology for Groundwater Resources Development*, Proceedings of the International Karst Symposium, Shiraz, Iran, edited by A. Afrasiabian, Iran: Ministry of Energy

Further Reading

Guoliang, C. 1994. Prediction of covered karst halls. *Proceedings of the 7th International IAEG Congress,* edited by R.Oliveira, L.F. Rodrigues, A.G.Coelho & A.P.Cunha, Rotterdam: Balkema

Milanović, P. 1997. Tunneling in karst: Common engineeringgeology problems. In *Proceedings of the International Symposium on Engineering Geology and the Environment,* edited by P.G. Marinos, G.C.Koukis, G.C.Tsiambaos & G.C.Stournaras, Rotterdam: Balkema

Milanović, P. 2000. *Geological Engineering in Karst,* Belgrade: Zebra

Milanović, P. 2000. Engineering problems in karst. In *Present State and Future Trends of Karst Studies: Proceedings of the 6th International Symposium and Field Seminar,* Paris: UNESCO

Yuan D. 1990. *The Construction of Underground Dams on Subterranean Streams in South China Karst,* Guilin: Institute of Karst Geology (also available at http://www.karst.edu.cn/igcp/igcp299/1991/part3–4.htm#341)

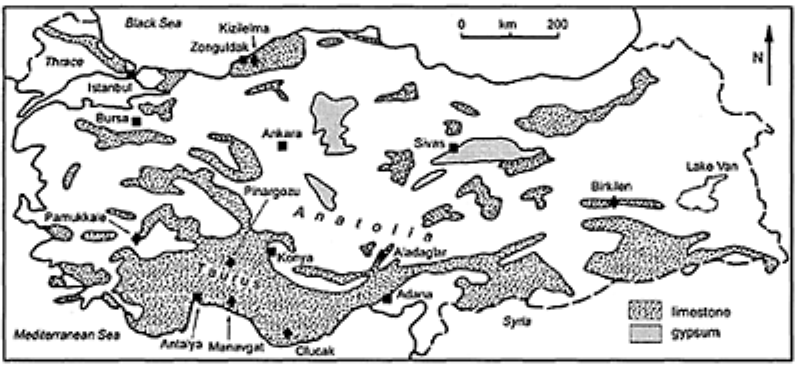
TURKEY

Limestone, dolomite, and other carbonate rocks cover about one third of Turkey's 250 000 km^2, and most are strongly karstified. The largest and most important limestone karst forms most of the Taurus Mountains, and there are also significant karst terrains in Southeast Anatolia (along the Syrian border), Central Anatolia (south and west of Ankara), and along the Anatolian Black Sea coast around Zonguldak and in Thrace, west of Istanbul (Figure 1). There are important regions of gypsum karst in eastern Anatolia around Sivas.

Temucin Aygen founded Turkish speleology when he invited foreign cavers to explore the caves of Anatolia in the mid-1960s and established the Turkish Speleological Society in 1964. Most early explorations were by foreign expeditions, but the country now has several active caving groups and a Karst Water Resources Centre (UKAM) at Hacettepe University in Ankara.

The Taurus Mountains, which formed by lateral and vertical tectonic movements upon rock units of various ages from Cambrian to Recent, form a continuous karst belt 200 km wide and 2000 km long across southern Turkey. They rise from near sea level to elevations of 2500–3750 m with high mountains, sharp peaks, deep valleys, narrow gorges, and rugged plateaus. The Taurus Mountain range is an eastern extension of the Alpine orogenic belt, and many karst features follow structural lineaments. The famous travertine terraces of Pamukkale (see separate entry) are of hydrothermal origin whereas travertines of freshwater karstic origin around Antalya are amongst the largest travertine deposits in the world (see photograph in Travertine entry). The Antalya terraces lack the beautiful pools of Pamukkale but end in a series of cliffs 30 m high with waterfalls dropping straight into the Mediterranean. Very fine caves and karst landforms are spread across almost the entire range, and include the following sites of particular note.

Manavgat Gorge, east of Antalya, is about 1000 m deep and at its foot is perhaps the most beautiful cave system in Turkey,



Turkey: Figure 1. The main outcrops of limestones (including dolomites) and gypsum in Turkey. Many of the soluble rocks are interbedded with shales, and some of these outcrops have minimal karst development.

Altinbesik Cave with 4500 m of passages. During winter and spring water level in the cave rises by more than 80m, completely flooding most of the known system, and all exploration has been during summer when the outflow ceases. The source of this, and several other springs in the gorge, is thought to include water that sinks on the southern shores of Lake Beysehir some 50 km to the north. The cave has been explored via a series of climbs, lakes, and through one sump of 120 m to a final sump, as yet undived. The nearby Martal Cave, which was discovered during a drought in 1998, contains over 1500 m of very large passage, including a cavern over 100 m in diameter. Further down the gorge, the Dumanli spring, now submerged by 120 m of water following construction of the Oymapinar Dam, had an estimated mean discharge of 50 $m^3 s^{-1}$ making it possibly the largest karst spring in the world issuing from a single opening (Karanjac & Günay, 1980). Some 30 km to the northwest, the Oluk Köprü Springs have a minimum discharge of 30 $m^3 s^{-1}$ most of which discharges from the Köprüçay Conglomerate in a narrow canyon a kilometre long.

Tilkiler Düdeni is the second longest cave in Turkey (6650 m), and was found during gallery excavations for the Oymapinar Dam on the Manavgat River. It is the largest of several caves formed in a Miocene conglomerate made up of limestone clasts in a carbonate matrix (Figure 2; see also Değirmenci *et al.*, 1994).

Kocain Cave, some 20 km from Antalya, is notable for its large entrance (35×70 m), a large chamber (600 m long, 50–60 m high), and for archaeological remains from Roman times.

Pinargözü Cave is 11 km west of Yenisarbademli in Isparta Province. It is the longest cave in Turkey with 15 km of passages which have been explored upwards from the resurgence via active streamways and cascades. The cave rises 720 m above the resurgence, and its water temperature is only 4–5°C.

Olucak is a plateau of 400 km^2 in Içel Province, the nearest town being Anamur. Miocene limestones, rising to 1800–2000 m above sea level, contain the two deepest caves in Turkey, Çukurpınar Cave (−1192 m, 3500 m long) and the 1377 m deep Peynirlikönü Cave (also known as Evren Gunay Cave). The entrances to these two caves are only 500 m apart but they trend in different directions. Both are typical Taurus streamsink caves with series of narrow, wet shafts.

Kirkgözler Springs. This group of closely spaced small magnitude springs 30 km north of Antalya formed along a fault that juxtaposes Taurus Mountain with impermeable Cretaceous ophiolites that underly the Antalya travertine plateau. They have a combined mean discharge of 24 $m^3 s^{-1}$ and are an important

Turkey: Figure 2. Rift passage in Kurukopru Cave, one of the longest caves in the Köprüçay Conglomerate. (Photo by John Gunn) water resource. Cave divers have explored two large water-filled conduits beyond the springs, Kirkgöz-Suluin which contains a water-filled chamber, the “Stadium”, that is about 100 m wide, 150 m long, and 35 m deep, and Kirkgöz–1. Underwater speleothems were discovered in Kirkgöz-Suluin indicating that the

Turkey: The deepest and longest caves in Turkey.

Cave	Location	Depth (m)	Length (m)
Peynirlikönü Dudeni	Anamur	1377	
ÇukurpInar Dudeni	Anamur	1192	3500
Kuyukule	Dedegöl	832	
Pinargözü	YeniIerbademli	720	15000
Südük Dudeni	Pozanti	640	
Subatagi Düdeni	Camlica	670	
Tilkiler Düdeni	Manavgat	159	6650
KIzIlelma Mağarasi	Zonguldak	145	6630

Turkey: Figure 3. Kizoren Obruk, one of many large collapse dolines in the Konya basin, part of the Central Anatolian karst. It has been important as a water resource for centuries, as shown by the old caravanseri on the far side of the obruk; water is still pumped for irrigation and potable supply (left of picture). (Photo by John Gunn) cave was not always flooded. Deep flooded conduits have also been explored at Dudenbasi (−60 m) and at Finike-Suluin (−120 m) which also has underwater speleothems.

Aladaglar is an extensive limestone massif north of Adana, with glaciokarstic surfaces and cave entrances at altitudes from 1200 m to over 3300 m. Karst springs with individual mean discharges of 1–8 $m^3 s^{-1}$ and a total discharge of about 32 $m^3 s^{-1}$ are grouped in four sites on the eastern flank of the massif, at elevations of 450–1100 m. There are also some large springs on the western flank and the high degree of flow concentration suggests that well-developed conduit systems are present. Structural and hydrogeochemical considerations indicate that most of the groundwater is recharged from the high-altitude karst surfaces and drained to the eastern flank springs (Bayari & Gurer, 1993). The depth potential for the underground drainage is thus well over 2000 m, and perhaps up to 2500–2900 m, so Aladaglar may contain the deepest karst hydrological system in the world, though water tracing is still in progress to prove this. Sütlük Düdeni (−640 m) and Subatagi (−670 m) are the deepest caves yet explored in the high karst.

Southeast Anatolia has clayey limestones around Gaziantep and Urfa that show poor karstification, but karstic features are widespread in Cretaceous and older limestones that crop out along the marginal fold belt. A karst ridge to the north contains the Birkilen Caves, including the splendid river passage carrying a major headwater of the River Tigris for 860 m from sink to resurgence and often therefore known as the Tigris Tunnel (see Karst Hydrology: History for an account of early exploration).

Central Anatolia is a closed basin bounded by high mountains. The average elevation is around 1200 m and the lowest point is Tuz Gölü (Salt Lake). There are karst zones in the Mesozoic recrystallized limestones of the Taurus belt along the southern margin of the basin, and also in Neogene lacustrine limestone (Obruk Limestone) in the centre of the basin. The limestone is named for the many large, steep-sided dolines (obruks, with maximum depth of 145 m) some of which are permanently flooded and provide an important water resource in an otherwise semi-arid region (Figure 3). The floor of the Konya basin consists of older karstified rocks and most drainage is underground, with the regional hydraulic gradient in the Neo-gene limestone towards Tuz Gölü.

The Black Sea coast of northwest Anatolia and Thrace has karst in lenticular limestone blocks that extend over limited areas. The Thrace karst has formed in Eocene limestone 100–150 m thick that extends as a thin belt nearly parallel to the Istranca massif. The reef limestones are indurated, hard, porous, thick bedded or massive, with many solution cavities. The rolling upland karst inland from Zonguldak is distinguished by a series of long cave systems with large flood-prone streamways and some very fine calcite decorations.

Gypsum karst extends over about 9000 km^2 in the Upper Kizilirmak basin of central and eastern Anatolia. Miocene gypsum, which contains rock salt (halite) interlayers, is the most extensive unit, underlying about half the basin. Karst features include dolines, ponors, poljes, and some small caves, but the most spectacular feature is the extensive polygonal karst east of Sivas. This has hundreds of adjacent rounded solution dolines and also a scatter of very large collapse features (Waltham, 2002). Recession coefficients and consistency of the spring discharges indicate that the gypsum aquifer has a large storage capacity and that groundwater flow occurs slowly, primarily through enlarged joints and fractures.

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Works Cited

Bayari, C.S. & Gürer, I. 1993. Use of hydrologic, hydrochemical and isotopic data in identification of groundwater flow patterns in Lower Zamanti Basin (Eastern Taurids-Turkey). DOGA: *Turkish Journal of Earth Science,* 2:49–59

Değirmenci, M., Bayari, C.S., Denizman, C. & Kurttas, T. 1994. Caves in conglomerates, Köprüçay basin: western Taurides-Turkey. *NSS Bulletin,* 56:14–22

Karanjac, J. & Günay, G. 1980. Dumanli spring, Turkey: The largest karstic spring in the world? *Journal of Hydrology,* 45:219–31

Waltham, T. 2002. Gypsum karst near Sivas, Turkey. *Cave and Karst Science,* 29(1):39–44

Further Reading

Bayari, C.S. & Ozbek, O. 1995. An inventory of karstic caves in the Taurus Mountain Range (Southern Turkey): Preliminary evaluation of geographic and hydrologic features. *Cave and Karst Science,* 21:81–92

Eroskay, S.O. & Günay, G. 1980. Tectogenetic classification and hydrogeological properties of the karst regions of Turkey. *Proceedings of 1st International Symposium on Karst Hydrogeology, 9–19 October 1979, Oymapinar,* Antalya, Turkey: DSIR Publication

Kaçaroğlu, F., Degirmenci, M. & Cerit, O. 2001. Water quality problems of a gypsiferous watershed: Upper Kızılırmak Basin, Sivas, Turkey. *Water, Air and Soil Pollution,* 128:161–80

Kincaid, T.R., 2000. Storage-Dominated vs Flow-Dominated Caves: A Hydraulic Model for Cave Development. Proceedings: Underwater Science and Technology Meeting—SBT2000, December 2–3, 2000. Middle East Technical University, Ankara, Turkey.

Kincaid, T.R., 2000. Mapping and Modeling the Morphology of Underwater Caves in the Taurus Mountains and Antalya Travertine Plateau, Southern Turkey. Proceedings: Underwater Science and Technology Meeting—SBT2000, December 2–3, 2000. Middle East Technical University, Ankara, Turkey.

Kincaid, T.R., 2000. Speleogenesis in the Kirkgozler Region of the Taurus Mountains, Southern Turkey. Proceedings: Underwater Science and Technology Meeting—SBT2000, December 2–3, 2000. Middle East Technical University, Ankara, Turkey.

The International Research and Application Center for Karst Water Resources (UKAM), Hacettepe University, Ankara, have published four field guides that contain a great deal of useful information, including road logs.

UKAM, 1985. Guide Book for Field Trip to Central Anatolian and Taurus Karst Regions, 13–19 July, 1985, International Symposium on Karst Water Resources, Ankara-Antalya, Turkey

UKAM, 1990. Guidebook for International Symposium and Field Seminar on Hydrogeologic Processes in Karst Terranes, 7–17 October 1990, Kemer-Antalya- Ankara.

UKAM, 1995. Guidebook for International Symposium and Field Seminar on Karst Waters & Environmental Impacts, 10–20 September 1995, Beldibi-Antalya, Turkey

UKAM, 2000. Guidebook for International Symposium and Field Seminar on Present State and Future Trends of Karst Studies, September 2000, Marmaris, Turkey.

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UKRAINE GYPSUM CAVES AND KARST

The extensive gypsum karst in the western Ukraine is renowned for its giant maze caves. It is internationally important as a model example of artesian speleogenesis (Klimchouk, 2000b). The region contains the five longest gypsum caves in the world. The host gypsum bed, ranging from a few metres to more than 40 m in thickness, is the main component of the Miocene evaporite formation that girdles the Carpathians to the northeast. The gypsum occurs on the southwestern edge of the Eastern European platform, where it extends along the Carpathian Foredeep for over 300 km in a belt ranging from several kilometres to 40–80 km wide (Figure 1). It occupies over 20 000 km^2, together with some separated areas that occur to the northeast of the unbroken belt.

Most Miocene rocks along the platform margin rest on the eroded terrigenous and carbonate Cretaceous sediments. The Miocene gypsum bed is variable in structure and texture. Most commonly it grades from microcrystalline massive gypsum in the lower part through to variably grained bedded gypsum in the middle, to megacrystalline rock in the upper horizon. A layer of evaporitic and epigenetic limestone, locally called "Ratynsky", commonly overlies the gypsum. This layer ranges from half a metre to more than 25 m in thickness. The gypsum and the Ratynsky limestone comprise the Tyrassky Formation, which is overlain by the Upper Badenian unit, represented either by argillaceous and marly limestones and sandstone or, adjacent to the foredeep, by marls and clays of the Kosovsky Formation. The total thickness of the capping marls and clays ranges from 40–60 m in the platform interior to 80–100 m or more in the areas adjacent to the regional faults that separate the platform edge from the foredeep.

Ukraine Gypsum Caves and Karst: Figure 1. Location of the gypsum karst of the Western Ukraine.

The present distribution of Miocene formations and the levels of their denudation exposure vary in a regular manner from the platform interior towards the foredeep. The Tyrassky Formation dips 1–3° towards the foredeep and is disrupted by block faults in the transition zone. To the south and southwest of the major Dniester Valley, large tectonic blocks drop down as a series of steps, the thickness of the clay overburden increases, and the depth of erosional entrenchment decreases. Along the tectonic boundary with the foredeep the Tyrassky Formation drops to a depth of 1000 m or more. This variation—he result of differential neotectonic movement—played an important role in the hydrogeological evolution of the Miocene aquifer system, and resulted in the differentiation of the platform edge into four zones. The gypsum was entirely removed by denudation within the first zone, but the other three zones represent distinct types of karst: entrenched, subjacent, and deep seated (Klimchouk, 2000b). The gypsum bed is largely drained in the entrenched karst zone, is partly inundated in the subjacent karst zone, and remains under artesian confinement in the deep-seated karst zone.

In hydrogeological terms the region represents the southwestern portion of the Volyno-Podolsky artesian basin (Shestopalov, 1989). The Sarmatian and Kosovsky clays and marls serve as an upper confining sequence. The lower part of the Kosovsky Formation and the limestone bed of the Tyrassky Formation form the original upper aquifer (above the gypsum), and the Lower Badenian sandy carbonate beds, in places together with Cretaceous sediments, form the lower aquifer (below the gypsum), the latter being the major regional one. The hydrogeologic role of the gypsum unit has changed with time, from initially being an aquiclude, intervening between two aquifers, to a karstified aquifer with well-developed conduit permeability (Klimchouk, 1997a, 2000a, b). The regional flow is from the platform interior, where confining clays and the gypsum are largely denuded, toward the large and deep Dniester Valley and the Carpathian foredeep. In the northwest section of the gypsum belt the confined conditions prevail across its entire width. In its wide southeast section the deeply incised valleys of Dniester and its left-hand tributaries divide the Miocene sequence into a number of isolated, deeply drained interfluves capped with the clays (Podol'sky area). This is the entrenched karst zone where most of the explored, presently relict, maze caves are located. To the south-southeast of the Dniester (Bukovinsky area) the gypsum remains largely intact and is partly inundated (the subjacent karst zone). Further in this direction, as the depth of the gypsum below the clays increases and entrenchment decreases, the Miocene aquifer system becomes confined (the deep-seated karst zone). In this zone the groundwater flow pattern includes a lateral component in the lower aquifer (and in the upper aquifer, but to a lesser extent) and an upward component through the gypsum in areas of potentiometric lows, where extensive cave systems develop, as evidenced by numerous data from exploratory drilling.

Eleven large caves over 2 km in length are known in the region (see Table). Most of these caves are located north of the Dniester River. Two other large caves, Zoloushka and Bukovinka, occur in the Bukovinsky region, near the Prut River and the border with Moldova and Romania, generally in the area of artesian flow within the Miocene aquifer system but within local, particularly uplifted blocks, where entrenchment into the upper part of the gypsum caused unconfined (water-table) conditions to be established in the Holocene. Most of the caves have only one entrance, either through swallow holes at the interfluves or from gypsum outcrops in the slopes of the major valleys. Some caves and their entrance series were known to local people from time immemorial (e.g. Ozernaya, Kristal'naya, Mlynki, Verteba), but others were discovered by cavers via digs (e.g. Optimistychna, Slavka, Atlantida). Two caves (Zoloushka and Bukovinka) became accessible when opened by gypsum quarries. Systematic cave exploration and mapping in the region began in the 1960s.

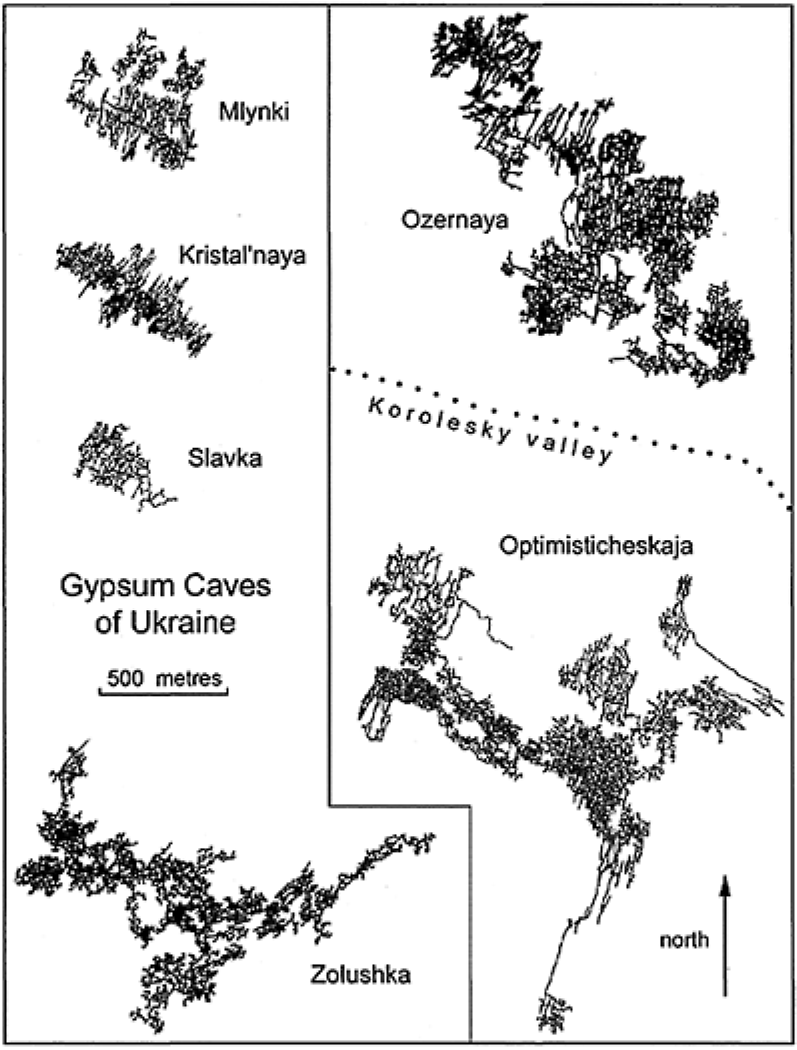
All the large gypsum caves in the region are mazes developed along vertical and steeply inclined fissures arranged into multistorey laterally extensive networks. Aggregating passages form lateral two- to four-storey systems that extend over areas of up to 1.5 km^2 (Figure 2). A notable feature of the mazes is the exceptionally high passage network density, which is characterized conveniently by using the ratio of a cave length to an area occupied by a cave system. This parameter varies from 118 (Verteba Cave) to 270 (Gostry Eovdy Cave) km km^{-2}, with the average value for the region being 164 km km^{-2}. Values of areal coverage and cave porosity (fractions of the total area and volume of the rock within a cave field, occupied by passages) vary for individual caves from 17.5 to 48.4% (average 29.5%) and from 2 to 12% (average 4.5%) respectively, being roughly an order of magnitude greater than these characteristics for typical unconfined caves. Optimistychna Cave (Optimisticheskaya in Russian spelling) is the longest gypsum cave, and the second-longest cave of any type known in the world, with more than 214 km of passages surveyed. By area and volume the largest caves are Ozernaya (330000 m^2 and 665000 m^3) and Zoloushka (305000 m^2 and 712000 m^3), followed by Optimistychna Cave (260000 m^2 and 520000 m^3).

Maze caves in the region were developed under confined conditions, due to upward transverse groundwater circulation between aquifers below and above the gypsum (Klimchouk, 1992, 2000b) (see Speleogenesis: Deep Seated and Confined Settings). According to the morphology, arrangement and hydrologic function of the cave mesoforms during the main (artesian) speleogenetic stage, three major components can be distinguished in the cave systems (Figure 3):

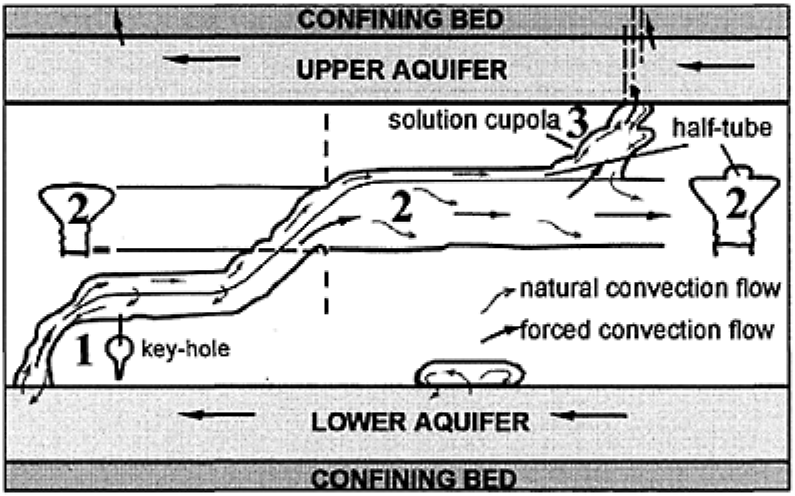
1. **Feeding channels,** the lowermost components in a system: vertical or subvertical conduits through which water rose from the sub-gypsum aquifer to the master passage networks. Such conduits are commonly separate but sometimes they form small networks at the lowermost part of the gypsum. The feeding channels join

Ukraine Gypsum Caves and Karst: Table. Morphometric parameters of large gypsum caves in the Western Ukraine.

No.	Cave	Length (km)	Average cross-sectional area (m^2)	Density of passages (km km^{-2})	Areal coverage (%)	Cave porosity (%)
1	Optimistychna	214.0	2.8	147	17.6	2.0
2	Ozernaya	117.0	6.0	150	44.6	5.0
3	Zoloushka	92.0	8.0	142	48.4	3.8
4	Mlynki	27.0	3.3	141	37.6	3.4
5	Kristal’naya	22.0	5.0	169	29.2	6.0
6	Slavka	9.1	3.7	139	27.6	3.4
7	Verteba	7.8	6.0	118	34.7	12.0
8	Atlantida	2.52	4.5	168	30.0	4.0
9	Bukovinka	2.4	2.5	120	21.5	4.4
10	Ugryn	2.12	3.8	177	33.3	5.7
11	Gostry Govdy	2.0	1.7	270	17.5	4.0



Ukraine Gypsum Caves and Karst: Figure 2. The very long gypsum caves of Ukraine drawn to the same scale. Ozernaya and Optimisticheskaja (Optimistychna) are shown in relation to each other, but the others are each at separate sites (after surveys by the cave clubs of L'vov, Ternopol, Chernivtsky, Kiev, and others).



Ukraine Gypsum Caves and Karst: Figure 3. Main morphogenetic features of maze cave systems in the western Ukraine shown according to their hydrologic functionality. 1=feeding channels, 2=master passages, 3=outlet features.

master passages located at the next upper level and scatter uniformly through their networks

2. **Master passages:** horizontal passages that form laterally extensive networks within certain horizons in the middle part of the gypsum bed (Figure 4). They received dispersed recharge from numerous feeding channels and conducted flow laterally to the nearest outlet feature
3. **Outlet features:** domes, cupolas, and vertical channels (dome pits) that rise from the ceiling of the master passages to the bottom of the overlying bed. They discharged water from cave systems to the overlying aquifer.

The predominant sediments in the maze caves of the region are successions of fine clays, with minor beds of silty clays. These fill passages to a variable extent and can reach 5–7 m in thickness. Breakdown deposits are also common. They include chip, slab, and block breakdown material from the gypsum, as well as more massive breakdown from the overlying formations. Calcite speleothems (stalactites, stalagmites, flowstones, and helictites)

Ukraine Gypsum Caves and Karst: Figure 4. “Master passage” in Ozernaya Cave. (Photo by John Gunn)

occur locally in zones of vertical water percolation from overlying formations. Gypsum crystals of different habits and sizes are the most common cave decorations. They are of largely subaerial origin. Hydroxides of Fe and Mn occur as powdery layers within the clay fill of many caves, indicating repeated transitional cycles from a reducing to an oxidizing geochemical environment. Massive deposition of Fe/Mn compounds in the form of powdery masses, coatings, stalactites, and stalagmites has occurred in Zoloushka Cave, where a rapid dewatering caused by groundwater abstraction during the last 50 years gave rise to a number of transitional geochemical processes, some of which appear to show considerable microbial involvement (Andrejchuk & Klimchouk, 2001).

The Western Ukrainian maze caves provide the most outstanding and unambiguous evidence for the transverse artesian speleogenetic model. The artesian speleogenesis in the Podol’sky region took place mainly during the late Pliocene through to the middle Pleistocene. It was induced by incision of the Dniester valley and its left-hand tributaries into the confining clays, and respective activation of the upward transverse groundwater flow within the underlying artesian system. Breaching of artesian confinement and further incision of the valleys during the middle Pleistocene caused substantial acceleration of groundwater circulation within the Miocene artesian system. The majority of passage growth probably occurred during this transitional period. Where the water table was established in the gypsum for a prolonged time, further widening of passages occurred due to horizontal notching at the water table. Eventually, with the water table dropping below the lower gypsum contact, cave systems in the entrenched karst zone became largely relict. Cave development under confined or semiconfined conditions continues today within the zones of deepseated and subjacent karst.

There are large bioepigenetic deposits of native sulfur in the pre-Carpathian region, within the deep-seated karst zone, associated with the Miocene gypsum bed. Sulfur is embedded in epigenetic calcite that partially (at the top) or wholly replaces the gypsum. The artesian "ascending" speleogenesis in the gypsum layer played a fundamental role in the origin of the sulfur deposits (Klimchouk, 1997b). This is not only because it provided the large amounts of dissolved sulfates needed to fuel the largescale sulfate reduction, but also because speleogenesis opened pathways for the flow of groundwater between the lower and upper aquifers through maze cave systems in the gypsum. Such a flow pattern and speleogenetic evolution within the gypsum provided the spatial and temporal framework within which the sulfur cycle processes took place, as well as controlling the geochemical environments, and the migration of reactants and reaction products between them.

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See also **Evaporite Karst; Speleogenesis: Deep Seated and Confined Settings**

Works Cited

Andrejchuk, V.N. & Klimchouk, A.B. 2001. Geomicrobiology and redox geochemistry of the karstified Miocene gypsum aquifer, Western Ukraine: a study from Zoloushka Cave. *Geomicrobiology,* 18(3):27–95

Klimchouk, A.B. 1992. Large gypsum caves in the Western Ukraine and their genesis. *Cave Science,* 19(1):3–11

Klimchouk, A.B. 1997a. The role of speleogenesis in the Miocene gypsum in the Western Ukraine in groundwater circulation in the multi-storey artesian system. In *Karst Waters and Environmental Impacts: Proceedings of the 5th International Symposium and Field Seminar on Karst Waters and Environmental Impacts, Antalya, Turkey, 10–20 September 1995,* edited by G. Günay & A.Johnson, Rotterdam: Balkema

Klimchouk, A.B. 1997b. The role of karst in the genesis of sulfur deposits, Pre-Carpathian region, Ukraine. *Environmental Geology,* 31:1–20

Klimchouk, A.B. 2000a. Speleogenesis under deep-seated and confined settings. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Klimchouk, A.B. 2000b. Speleogenesis of great gypsum mazes in the Western Ukraine. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Shestopalov, V.M. (editor) 1989. *Water Exchange in Hydrogeological Structures of the Ukraine: Water Exchange Under Natural Conditions,* Kiev: Naukova dumka (in Russian)

Further Reading

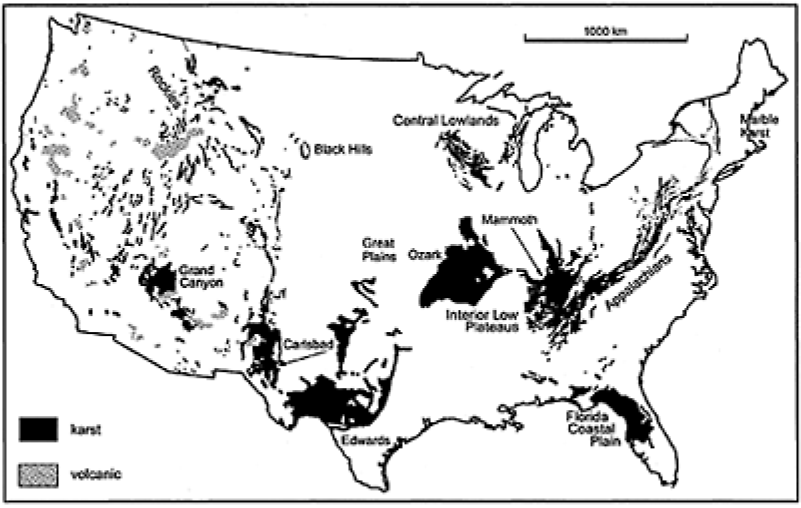
Klimchouk, A., Lowe, D., Cooper, A. & Sauro, U. (editors) 1996. *Gypsum Karst of the World,* International Journal of Speleology, Theme issue 25(3–4)

UNITED STATES OF AMERICA

The United States contains a wide variety of soluble rocks and karst types (Figure 1). It contains five of the world's seven longest caves (see Table), but because the thickest soluble rocks in the country are located in low-relief regions, its solution caves have limited depth. However, some of its volcanic caves on Hawaii have the greatest vertical extent of any in the world. (US sites described in more detail elsewhere in this volume are also shown in Figure 1.)

The most extensive karst regions of the United States are located in the Interior Low Plateaus (Figure 1) of the east-central states (Kentucky, Tennessee, Missouri, and neighbouring states). Carbonates of mainly Cambrian-Ordovician, Silurian-Devonian, and Mississippian (lower Carboniferous) age are exposed in broad plains and plateaux dissected by river valleys to depths rarely exceeding 200 m (Figure 2). Although continuous sections of soluble rocks are only 100–200 m thick, their low average dip of less than half a degree causes them to be exposed over large areas. Where carbonates are exposed, the karst consists of doline plains bordered by ponors that receive allogenic water from less soluble rocks. Farther downdip, the karst consists of dissected carbonate uplands capped by resistant clastic rocks. Caves are predominantly branchworks on several levels tied closely to the history of river entrenchment. The most notable, Mammoth Cave (Kentucky), is the longest cave in the world, with 557 km of mapped passages (see Mammoth Cave entry). Farther west in this region, in the Ozark Plateaux of Missouri and Arkansas, chert is so abundant in some of the carbonate rocks that residual chert fragments have accumulated to depths as much as 40 m, subduing much of the karst relief. Nevertheless, caves and large karst springs are abundant. Missouri alone contains more than 5400 documented caves and is second only to Tennessee (with more than 6300 caves) as the most cave-rich state.

The carbonate strata thicken eastward in the Appalachian Mountains (Figure 1; see Appalachian Mountains entry; Kastning & Kastning, 1991). The western half of the region is a broad plateau in which extensive karst occurs in bands in erosional escarpments and along entrenched valleys that have breached the overlying Pennsylvanian (late Carboniferous) caprock. The region contains many caves that typically consist of multilevel stream passages fed by vertical shafts up to 180 m deep (Figure 3). Farther east the Appalachians are strongly folded and faulted, producing long, linear karst belts in valleys and along ridge flanks. Most caves in these rocks are long strike-oriented stream passages. The deepest cave in the eastern part of the continent is the Omega Cave System, Virginia, with a vertical range of 384 m. Complex network mazes form where water enters through a thin permeable sandstone cap. Along the eastern border of this region is a broad valley floored by highly deformed Cambrian-Ordovician carbonates up to 4 km thick in nearly continuous sequences. Subsurface drainage is prevalent, but karst topography is subdued by the low relief. Accessible



United States of America: Figure 1. The main karst regions of the "lower 48" states of the United States. Not shown are Alaska (with its island karst areas) and the Hawaiian Islands (which are entirely volcanic).

United States of America: Longest caves in the United States.

Cave	State	Surveyed length (km)	Surveyed depth (m)
1. Mammoth Cave System	Kentucky	557	116
2. Jewel Cave	South Dakota	206	193
3. Lechuguilla Cave	New Mexico	180	478
4. Wind Cave	South Dakota	173	202
5. Fisher Ridge Cave System	Kentucky	169	109
6. Friars Hole Cave System	West Virginia	73	188
7. Kazumura Cave (Lava tube)	Hawaii	66	1101
8. Organ Cave System	West Virginia	64	148
9. Blue Spring Cave	Tennessee	53	71
10. Martin Ridge Cave System	Kentucky	52	96

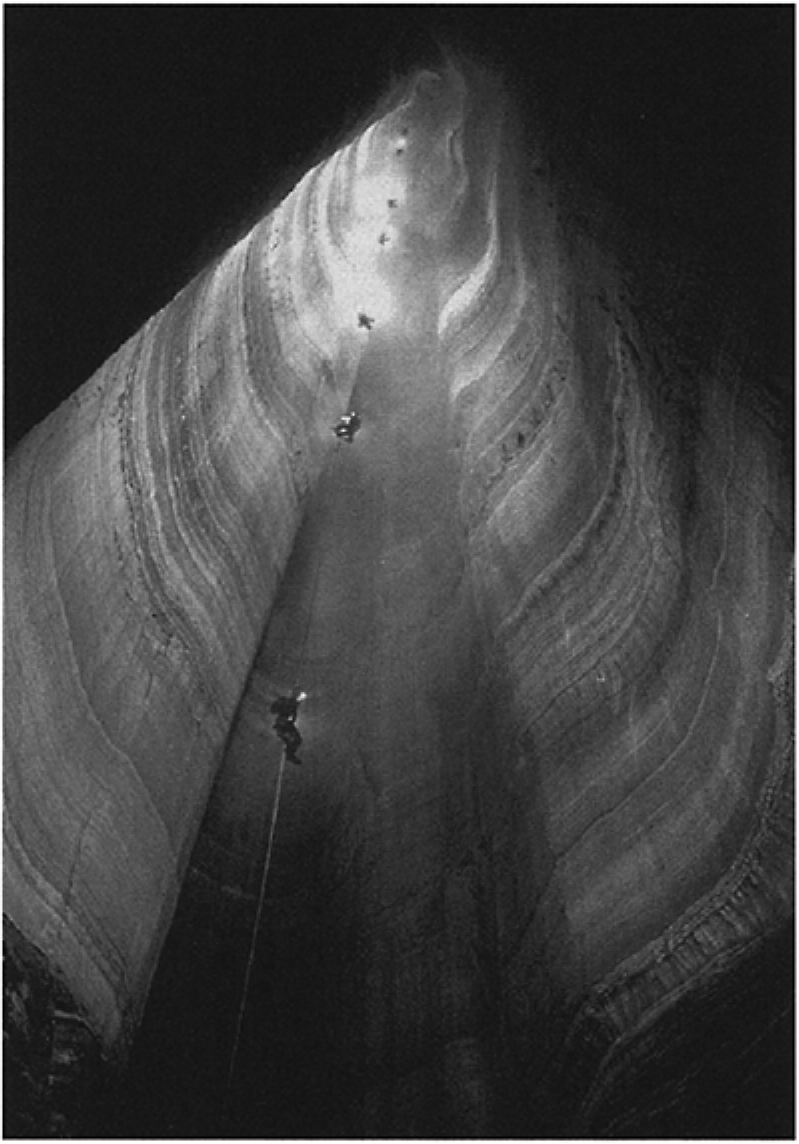
caves are restricted mainly to residual hills. Luray Caverns is the best-known example. Some caves in the folded Appalachians have little relationship to the surrounding topography or drainage patterns, which, together with maze-like patterns and mineralization by metallic ores, suggests a now-inactive hypogenic origin.

Along the eastern margin of the Appalachian Mountains, especially in the northeastern states, the strata have been highly metamorphosed, and karst and small caves are located in isolated patches of Precambrian and Paleozoic marble. The foothills of the Adirondack Mountains, New York, contain some of the world's oldest marbles, more than 1.2 billion years old. Its caves are apparently all of Pleistocene age, but there are scattered remnants of Precambrian paleokarst filled with basal Cambrian sandstone.

Lapping onto the eroded eastern and southern edges of the Appalachians in the southeastern United States are undeformed Tertiary strata of the Coastal Plain (Figure 1). These include porous carbonate rocks that form broad lowlands extending throughout much of Florida and parts of adjacent states. These strata are among the world's most productive aquifers. Solution and collapse dolines are common and are the cause of considerable property damage. Caves are abundant, mostly water-filled,

United States of America: Figure 2. Low-relief karst plains studded with dolines typify much of the Interior Low Plateaux. The Mitchell Plain of Indiana is shown here, with an outlier of sandstone-capped limestone in the background. (Photo by Art Palmer)

and still actively enlarging. A great quantity of water flows through the caves to springs along major rivers or the seacoast. Much of the flow to conduits is contributed by diffuse seepage through the permeable surrounding rock. Some relict caves are complex labyrinths, but most are rambling tubular passages with



United States of America: Figure 3. Caves in the Appalachian Mountains are strongly guided by folds and faults. Vertical shafts up to 180m deep are common in the southern Appalachians. This fault-controlled shaft in Ellison's Cave, Georgia, is the deepest known in the region (view looking upward). (Photo by Art Palmer)

crudely dendritic patterns. In general the water chemistry resembles that of most other temperate-climate karst areas, although dissolution is locally enhanced by seawater mixing along the coast and by oxidation of rising hydrogen sulfide. Late Pleistocene sea-level rise has flooded many caves and dolines, although in this low-relief region most cave development was already below the water table. Exploration of water-filled caves by divers indicates that the potential for discovery has barely been touched. The Leon Sinks Cave System in northwestern Florida is the longest known underwater cave in the United States, with a surveyed length of 30.5 km.

The broad glaciated Central Lowlands of the north-central United States (Figure 1) contain scattered karst areas on early Paleozoic carbonates where glacial sediment is thin or absent. Coldwater Cave in Iowa and Mystery Cave in Minnesota are the largest caves in the region, each more than 20 km long. Some are conduit systems, like those of the extensive karst plateaux to the south, but others, such as Mystery Cave, are angular fissure networks enlarged by water from river meander cutoffs. Many small fissure caves appear to be hypogenic, as they contain deposits of sulfide and other ore minerals. Deep-seated dissolution of evaporites has produced collapse breccias in some areas. Analysis of speleothems and sediments in caves of this region, as well as in those of the northeastern states, has helped to decipher local aspects of Pleistocene continental glaciation.

The Great Plains of the west-central United States are almost devoid of soluble rocks at the surface, except at the southern end, where nearly horizontal Cretaceous limestone and Permian gypsum are exposed, and in small uplifted fault blocks of Ordovician limestone. In the limestones, surface karst is subdued by the dry climate, although there are many high-discharge springs and large, well-decorated caves. Highly permeable Cretaceous carbonates are exposed along the Balcones Fault zone of central Texas and provide most of the region's water supply (see Edwards Aquifer; Edwards Aquifer: Biospeleology). Broad karst plateaux extend northwestward from the fault zone and include many notable caves. Honey Creek Cave, the longest in Texas (31 km), consists mainly of active stream passages requiring lengthy swims. The delicate helictite displays in the Caverns of Sonora are considered some of the world's most attractive. Bracken, Frio, and Ney Caves contain the nation's largest bat colonies. Bracken Cave alone has a population of 20–40 million Mexican free-tail bats. Some of the country's most productive petroleum reservoirs are located in Permian and Ordovician carbonates of west Texas, where much of the porosity is provided by deeply buried paleokarst, collapse of former cave systems, and deepseated dissolution.

Farther west and north, the Permian gypsum extends across large parts of Texas, New Mexico, Oklahoma, and Kansas (Johnson, 1996). The country's largest cave in gypsum is Jester Cave in Oklahoma, which is more than 10 km long. Much groundwater recharge to the gypsum takes place through ephemeral sinking streams, but most caves can be followed only a short distance before they become impenetrably small. Apparently these inputs feed large systems of diffuse flow that emerge at regional springs.

The Black Hills of South Dakota and Wyoming consist of an elongate dome that rises from the Great Plains as an easterly outlier of the Rocky Mountains (Figure 1). Limestone and scattered gypsum crop out in the foothills that ring the central core of igneous and metamorphic rocks. Surface karst is limited to a few dolines and sinking streams, but the region includes some of the world's largest, oldest, and most complex caves (see Wind and Jewel Caves).

The southwestern United States consists of arid faultbounded plateaux and mountains, many of them containing Paleozoic limestones and dolomites. Surface karst is virtually absent in this dry region, but many caves have formed by deepseated processes, including H_2S oxidation. Caves of this origin are especially abundant in the Permian reef complex of the Guadalupe Mountains, New Mexico (see Carlsbad Cavern and Lechuguilla Cave) and in Mississippian limestone exposed in the Grand Canyon and its tributaries (see Grand Canyon entry). The Guadalupes include some of the world's most exotic caves. Lechuguilla Cave, more than 170 km long, is widely considered the world's most beautiful cave, owing to its profuse and unusual mineral deposits.

Western mountain ranges contain hundreds of small exposures of Paleozoic limestone and dolomite. At high altitudes they have been exposed to alpine glaciation, which has destroyed some karst features, but in some areas karst and cave development has been enhanced where glacial features such as moraines and cirques concentrate groundwater recharge into the carbonate rocks. Many caves and sinking streams are located high above nearby valley bottoms, but their host rocks are rarely more than a few hundred metres thick. Therefore, deep caves are rare except where they follow tilted strata for long distances. Karst is common along the sedimentary flanks of most of the Rocky Mountain ranges. Columbine Crawl (473 m deep) and Great Expectations ("Great X") Cave (429 m deep) in Wyoming each once held the US depth record. Some caves in the Rockies show evidence for hypogenic origin, and certain maze caves were probably formed by mixing of deep and shallow water (e.g. Cave of the Winds in Colorado). The Sierra Nevada contains notable marble karst, and Lilburn Cave and Bigfoot Cave in California are two of the largest marble caves in the world. The rainy islands along the coast of southeastern Alaska have extensive karst. El Capitan Pit in Prince of Wales Island, Alaska, is the deepest known solution shaft in the United States, at 182 m.

United States of America: Figure 4. Exhumed mid-Carboniferous paleokarst is pervasive throughout much of the western United States. This example shows formerly sediment-filled caves intersected by the Bighorn River in Wyoming. (Photo by Art Palmer)

Paleokarst is abundant in the United States, and among several significant horizons are two that extend throughout much of the country (Palmer & Palmer, 1989). The lower horizon is developed in early Ordovician limestones and is best exposed in the southeastern United States, although it extends (mainly in the subsurface) across nearly the entire country. It includes a great deal of carbonate breccia and is host for economic-grade sulfide minerals, especially in Tennessee and Missouri, and petroleum in parts of the southwest. The upper paleokarst is developed on Mississippian (early Carboniferous) strata and is part of the widespread unconformity that forms the basis for dividing the Carboniferous of North America into two periods. This paleokarst is well exposed throughout the Rocky Mountain region and extends mainly in the subsurface as far as the east-central states (Figure 4). This is the paleokarst so prominent in the Black Hills.

Volcanic pseudokarst extends over broad areas of the western states, particularly Idaho, California, Oregon, Washington, and New Mexico (Halliday, 1960), but by far the most important volcanic region is the "big island" of Hawaii, the largest and southernmost in the Hawaiian island chain. Currently active volcanism supplies large flows that develop extensive caves, including the deepest and longest known lava caves in the world (see Hawaii Lava Tube Caves). Some Hawaiian lava flows have potential for caves exceeding 2000 m in vertical extent.

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Works Cited

Halliday, W.R. 1960. Pseudokarst in the United States. *National Speleological Society Bulletin,* 22(2):109–13

Johnson, K.S. 1996. Gypsum karst in the United States. In *Gypsum Karst of the World,* edited by A.Klimchouk, D.Lowe, A. Cooper & U.Sauro, *International Journal of Speleology,* 25(3–4)

Kastning, E.H. & Kastning, K.M. (editors) 1991. *Appalachian Karst: Proceedings of Appalachian Karst Symposium (Radford, Va.),* Huntsville, Alabama: National Speleological Society

Palmer, M.V. & Palmer, A.N. 1989. Paleokarst of the USA. In *Paleokarst: A Systematic and Regional Review,* edited by P.Bosák, D.Ford, J.Glazek & I.Horácek, Amsterdam: Elsevier

Further Reading

Halliday, W.R. 1976. *Depths of the Earth: Caves and Cavers of the United States,* New York: Harper & Row

Veni, G. & DuChene, H. (editors) 2001. *Living with Karst: A Fragile Foundation,* Alexandria, Virginia: American Geological Institute

V

VALLEYS IN KARST

The term “karst valley” was introduced by Cvijić (1893) who provided a fourfold classification into pocket, blind, semi-blind, and dry valleys. Blind and dry valleys were subdivided into primary valleys, formed by allogenic rivers flowing from impermeable rock, and secondary valleys, formed in the bed of a normal karst river. Roglic (1964) argued that the term “karst valley” should be discontinued because strictly valleys are the result of water flowing overly the surface and are formed by fluvial, as opposed to karstic processes. Sweeting (1972, p.103) suggested that many would find this an overly pedantic view but that karst valleys should be recognized as “the most important of the landforms occurring in the karst which are not produced by true karst processes”. Her fourfold classification into through (allogenic), blind and half-blind, pocket, and dry valleys is followed in this review. Valleys are a feature of most karst regions, the exceptions ‘being areas of polygonal karst where the whole surface is pitted by dolines, although even here there may be vestiges of former valley networks. However, there are also some karst regions where the surface is dissected by a dense network of valley systems forming a fluviokarst (see separate entry).

Through valleys are formed by rivers that have their origins on non-karst lithologies and which maintain perennial flow through the karst to the output boundary. The valley is incised by both dissolution and mechanical erosion. Most through valleys are steep-sided, and gorges are more common in karstic rocks than in other lithologies, partly because most carbonate rocks are mechanically strong and partly because of a general absence of surface runoffand consequent reduction in mass wasting. Antecedent gorges form where uplift occurs at a rate less than the river’s capacity to incise. There are four main reasons for the development of through valleys. First, karstification may not yet be sufficiently advanced; that is, the input from outside the karst exceeds the present capacity of the limestones to absorb it. In this case the river will usually be influent, with discharge decreasing both downstream and progressively over time. Second, the allogenic river may transport and deposit sufficient clastic material onto the karst to render the river bed virtually impermeable. In the third situation, the riverbed is rendered impermeable by permafrost but downcutting continues during summer melt periods. A fourth situation is where the hydraulic gradient is low and the river is at the local base level for drainage. In this case the river will usually be effluent, with discharge increasing downstream due to inputs from springs and direct recharge through the bed. The rivers Dove and Wye in

Derbyshire, England, and the Green River in Kentucky, United States, are good examples of the fourth sub-type.

Some influent rivers lose water to the karst gradually over a long reach; the upper Danube in Germany and the Takaka in New Zealand are good examples. However, it is much more common for flow to be lost at a point, or series of points. The processes of dissolution and transport of clastic sediment underground result in a gradual lowering of the bed at these sink points, and downstream of them the river has less erosive power. Hence, over time an upward step develops at the sink point. Underground, the capacity of the conduits increases as they are enlarged by erosion and ultimately the lowest sink may be able to accommodate the entire base flow. This is the first stage in the formation of a blind valley, but as the sink is overtopped at discharges greater than base flow it is commonly called a half-blind or semi-blind valley. The conduit system may later enlarge sufficiently for the sink to take even the highest of flood flows forming a true blind valley (Figure 1). During the intervening time the valley below the sink may become progressively vegetated and increasingly difficult to recognize as ever having carried a river. If the sink-point migrates upstream then the height of the closure at the end of the blind valley may be just a few metres, however, if a large river continues to sink at the same point for many years, and the hydraulic gradient is high, the closure may grow to several hundred metres.

Pocket valleys (or steepheads) are the reverse of blind valleys, since they occur in association with large springs close to the margins of karst areas. Most of them are short and may form

Valleys in Karst: Figure 1. Blind valley where Fell Beck sinks into

Gaping Gill on the slopes of Ingleborough, Yorkshire, England. (Photo by John Gunn)

by headward recession, as water from the spring undermines the rock above it, or by cavern collapse. Evidence for cavern collapse may be provided by a natural bridge, as at Marble Arch in County Fermanagh, Northern Ireland.

Dry valleys, lacking stream channels in their floor, are found on many lithologies but usually only close to the headwaters. An exception is where a dry valley forms as a consequence of river capture, a process that can occur on all lithologies. Long, well-developed dry valleys, are found in many karst areas, particularly where there are, or were, allogenic inputs, and are commonly similar in form to through valleys (Figure 2). Three major groups of hypotheses have been suggested for their formation: (1) differing climates in the past, with either greater rainfall or permafrost; (2) superimposition from non-karst strata followed by karstification of drainage; and (3) a fall in the level of the water table due to uplift of the land mass, incision of major valleys, or scarp recession. To these should be added the progressive desiccation of a through valley as the sink-point migrates

Valleys in Karst: Figure 2. Dry valley, Lathkill Dale in the Peak District fluviokarst, England. (Photo by John Gunn)

upstream. Over time the floor of a dry valley may become dissected by dolines and the original fluvial form may be lost completely, as has happened in the Waitomo area of New Zealand. Alternatively, a substantial increase in surface discharge, following climate change or blockage of underground conduits by sediment deposition, may result in previously relict dry valleys becoming re-activated.

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Works Cited

Cvijić, J. 1893. Das Karstphänomen. *Geographische Abhandlungen Wien,* 5(3):218–329

Roglic, J. 1964. "Karst valleys" in the Dinaric karst. *Erdkunde,* 18: 113–16

Sweeting, M.M. 1972. *Karst landforms,* London: Macmillan and New York: Columbia University Press, 1973 (Chapter 6 on Karst Valleys provides many examples)

Further Reading

Smith, D.I. 1975. The problems of limestone dry valleysimplications of recent work in limestone hydrology. In *Processes in Physical and Human Geography,* edited by R.Peel, M. Chisholm & P.Haggett, London: Heinemann: 130–47

Warwick, G.T. 1964. Dry valleys in the southern Pennines, England. *Erdkunde,* 18:116–23

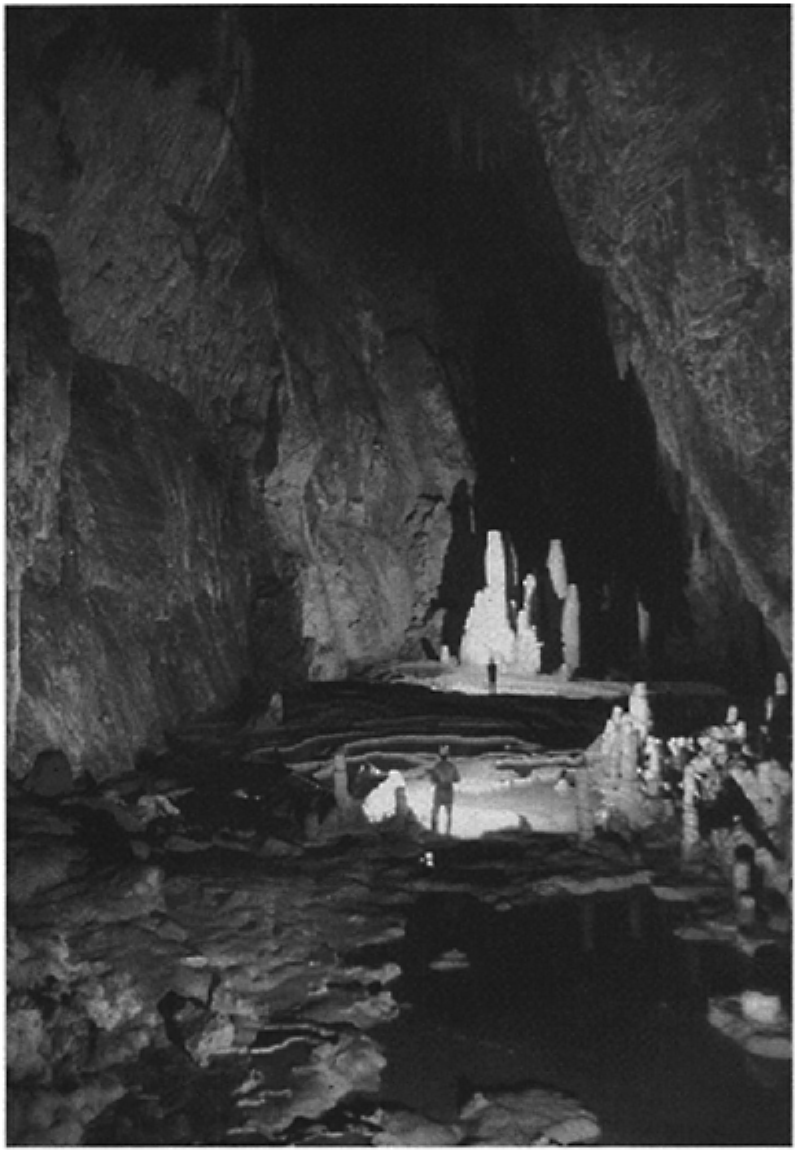
VERCORS, FRANCE

The Vercors extends over 1350 km^2 and is the largest alpine karst area in the Northern French Prealps (for location, see map in Europe, Alpine entry). The mean altitude is 1200 m and the highest peak is Grand Veymont (2341 m). The Vercors is bounded by high scarps and cut by deep gorges: Bourne crossvalley, Cholet reculée, Écouges canyon, and Combe Laval (Figure 1). The fold structures create stratigraphic ridges and valleys. Meadows and villages occur on the synclines in the Alpine molasse, whereas the anticlines of Urgonian limestone have produced a landscape of forest-covered hills. Altitudes rise eastward towards the High Plateau (1000–1600 m), reaching 1800–2000 m on the eastern scarps, with slopes carved into bare clints. This wilderness is protected in the largest French conservation area (17 000 ha). The folds follow a north-south trend, with a transverse saddle occupied by the Bourne gorge, toward which most of the underground drainage converges. Arbois is the third largest French spring, with a mean discharge of 8 m^3 s^{-1}, and drains a 230-km^2 catchment. During exceptional floods, several overflows act with the siphon d'Arbois, the Bournillon resurgence (80 m^3 s^{-1} and the Luire cave (60 m^3 s^{-1}), giving a total discharge of about 190 m^3 s^{-1}! The Grotte de la Luire, located 20 km from the springs, flows from the entrance following a 450 m deep backflooding—the highest recorded in the world.

Vercors contains a large number of major cave systems, including the Gouffre Berger, the first cave in the world to be explored to a depth of −1000 m (Figure 2). Geological structures determine the underground drainage pattern, which may follow the troughs of perched synclines (Clot d'Aspres systems), anticline limbs (the Berger cave), edges of dammed synclines (Trou qui Souffle, Luire), or recumbent fold saddles (Tonnerre). Shafts and canyons take most cave systems directly down through the 300–400 m thickness of cavernous Urgonian limestones, sometimes as a single shaft, such as Pot 2 (302 m deep). Water then concentrates along the underlying Hauterivian marls, where it is entrenched in huge galleries (such as in the Gournier, Figure 3, and the Berger). Perched karst branchworks (including the Grotte Brudour) are drained by springs located at the marl contact, at the head of reculées (such as the Cholet). Dammed karst systems form complex three-dimensional mazes by backflooding, with level storeys left by progressive base-level lowering (Trou qui Souffle, Luire). Vercors is the best-known karst in the Alps, due as much to the number of deep caves as to the many publications discussing their genesis (Audra, 1994, 1995a, 2001). Eocene Pyrenean movements created the folded structures, with which some paleokarst features are associated, including huge pockets filled with weathered soils.

Miocene sea level was located near the present-day 1000–1200 m altitude. The relief was moderate, and often corresponded with the axes of the anticlines. Some tunnel caves linked the synclinal poljes. These caves are now completely disconnected, truncated, or even unroofed by erosion (Grotte de Pré-Létang). The oldest ones predate the orogeny (>12 Ma) and were formed according to the Miocene sea base level; others were formed in Upper Miocene as the area was uplifted (Antre

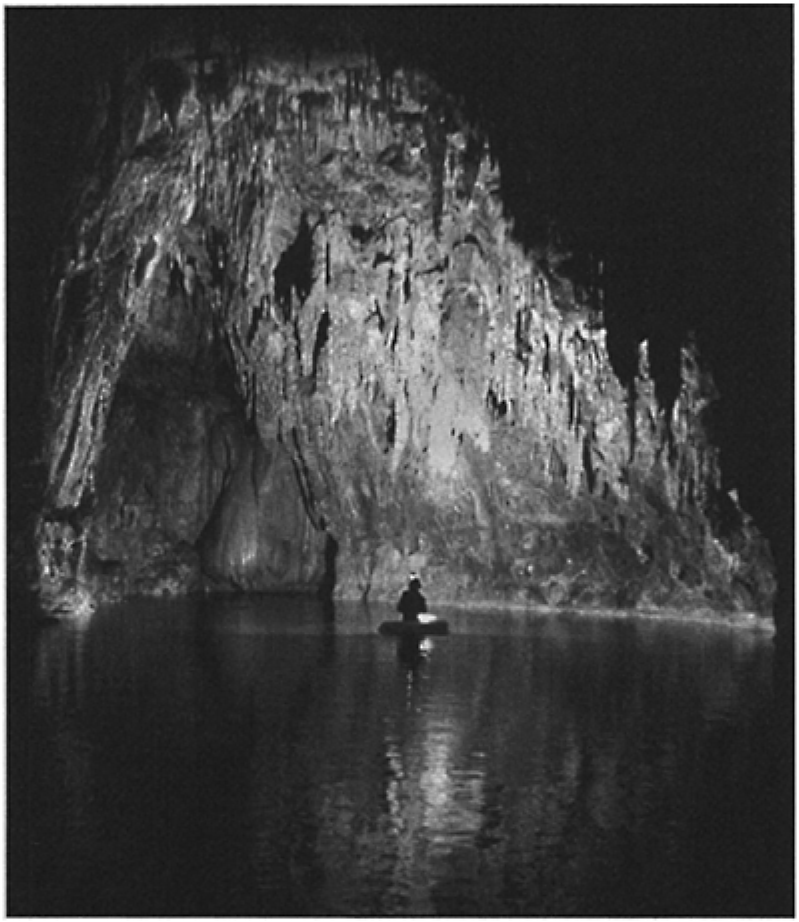
Vercors, France: Figure 1. A road winds along the massive cliff of Urgonian Limestone that forms the rim of the Combe Laval. (Photo by Tony Waltham)



Vercors, France: Figure 2. The Hall of the Thirteen in the main passage of the Gouffre Berger, here clearly aligned on massive inclined fractures as it follows roughly down the dip. (Photo by Tony Waltham) de Vénus, Coufin upper level). The Messinian fall in the base level (110 m below the present sea level in the Rhône valley) occurred during the main Rhodanian uplift (*c.* 5–6 million years ago). It caused valley entrenchment and the subsequent development of vertical cave systems that adapted to the new geological structure. The Zanclean transgression caused a prolonged sea-level highstand (lasting 1.5 million years). It ended the general deepening of both karst and valleys, and probably flooded the Messinian vadose systems that now appear as vauclusian springs (Taï, Diable). During this long period of stability, the largest and highest levels of major cave systems—located 200 m above the present base level—could have developed (Gournier, Bournillon, upper levels of Trou qui Souffle, Luire, Vallier); they were mostly related to synclinal poljes.

In these old cave systems, sediments are composed of residual quartz, heavy minerals, and clays (particularly kaolinite). They derive from the weathering of Upper Cretaceous sandstones and molasse in warm and humid conditions, producing an unconsolidated soil cover during the Tertiary (Audra, 1995b). This material was later removed and trapped in the karst. These sediments always constitute the oldest beds in the large alpine cave systems. They are covered by massive speleothems, frequently corroded by later inflows.

The Pliocene transgression created a morphogenetic break. However, the subsequent uplift finally stopped this morphogenic quiet period. Moreover, after the late Pliocene (*c.* 2.3 million years ago), a climatic cooling during the Pleistocene dominated the morphogenetic processes. During each glaciation, a morphogenic hiatus occurred. Consequently, the base level was lowered step by step, and poljes opened towards the Bourne Valley. However, karst evolution also depended on the position of the massif with respect to glaciers and base level. In western Vercors, where springs were located downstream from the glacier front, successive underground levels developed (Gournier, Coufin, Trou qui Souffle, Luire). In contrast, the evolution of areas located close to the large glaciers has nearly ended, leaving only some local entrenchment or invasion shafts in the vadose zone. Gouffre Vallier contains sediments linked to the first Plio-Quaternary glaciations (Audra & Rochette, 1993).



Vercors, France: Figure 3. The lake in the entrance chamber of the Grotte de Gournier. (Photo by Tony Waltham)

Two types of sediments correspond with Quaternary environments: gelifracts are characteristic of periglacial environments. They form talus fans at the bottom of shafts and outwash deposits in galleries (Delannoy, 1998). Glaciokarstic varves are silty, laminated sediments composed largely of calcite flakes. This material results mainly from glacial abrasion on rocky surfaces, and from mechanical erosion by torrential flow in the vadose zone. During the summer melt, suddenly large amounts of water were supplied to the karst system and could not be discharged when the outlets were blocked by moraines or glaciers (Maire, 1990). Flooding then occurred, sometimes over depths of several hundreds of metres. The important suspended load of glacial flour settled out in the calm, quiet lacustrine environment, thereby plugging the karstic voids. Water flow ceased in winter, and the systems drained slowly until the next seasonal cycle that produced a new lamina of sediment.

Up to now, theories of karst evolution have strongly favoured glacial processes. However, field evidence shows that glacial processes play a very limited role in the evolution of alpine caves, mostly causing plugging in epiphreatic conditions (Bini *et al.*, 1998). Nevertheless, on the surface, glacial tongues have carved out the surface landscape, producing typical glaciokarstic forms.

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Works Cited

Audra, Ph. 1994. *Karsts alpins. Genèse de grands réseaux souterrains. Exemples: le Tennengebirge (Autriche), l'Ile de Crémieu, la Chartreuse et le Vercors (France), Thesis,* Paris: Fédération française de spéléologie and Bordeaux: Association française de karstologie (Karstologia Mémoires, 5)

Audra, Ph. 1995a. Looking at alpine karst speleogenesis, with examples in France (Vercors, Chartreuse, Ile de Crémieu) and in Austria (Tennengebirge). *Cave and Karst Science,* 3:75–80

Audra, Ph. 1995b. Signification des remplissages des karsts de montagne. *Karstologia,* 25(2):13–20

Audra, Ph. 2001. French Alps karsts: study methods and recent advances. In *Cave Genesis in the Alpine Belt,* edited by Ph. Hauselmann & M.Monbaron, Freiburg: Institut de Géographie Université de Fribourg (UKPIK Rapports de recherches, vol. 10)

Audra, Ph. & Rochette, P. 1993. Premières traces de glaciations du Pléistocène inférieur dans le massif des Alpes. Datation par paléomagnétisme de remplissages a la grotte Vallier (Vercors, Isère, France). *Compte-rendu a l'Académie des Sciences,* 2(11): 1403–09

Bini, A., Tognini, P. & Zuccoli, L. 1998. Rapport entre karst et glaciers durant les glaciations dans les vallées préalpines du Sud des Alpes. *Karstologia,* 32:7–26

Debelmas, J. 1983. *Alpes du Dauphiné,* Paris: Masson

Delannoy, J.-J. 1998. Apport de l'endokarst dans la reconstitution morphogénique d'un karst. Exemple de l'antre de Vénus (Vercors, France). *Karstologia,* 31:27–41

Maire, R. 1990. La haute montagne calcaire. Thesis, *Karstologia Mémoires,* 3

Further Reading

Audra, Ph., Delannoy, J.-J. & Hobléa, F. 1993. Signification paléogéographique des réseaux perchés des Préalpes françaises du nord: exemples en Chartreuse et Vercors. *Études de géographie physique,* 22:3–17

Delannoy, J.-J. 1991. Vercors, histoire du relief. Carte géomorphologique commentée. Lans-en-Vercors: Parc Naturel Regional du Vercors

Delannoy, J.-J. 2000. Les paysages karstiques du Vercors. *Spéléo,* 21: 26–30

VÉZÈRE ARCHAEOLOGICAL CAVES, FRANCE

The Vézère river in the Périgord (Dordogne), southwest France, flows through limestone country which is riddled with caves and rock shelters, hundreds of which were occupied intensively during the last Ice Age by Neanderthals and modern humans, and about 25 of which were decorated. The Vézère caves became a World Heritage Site in 1979.

Scientific investigation of the Vézère sites began in the 1860s, when numerous shelters were excavated, and evidence was found for Ice Age occupation, the existence of Ice Age portable art, and the co-existence of people with extinct animals such as mammoths. For example, in 1864 an engraving of a mammoth on a piece of mammoth ivory was unearthed by Edouard Lartet in the rock shelter of La Madeleine. Some of the shelters in the valley became world-famous: La Madeleine gave its name to the Magdalenian period, the final cultural phase of the French Ice Age; Le Moustier gave its name to the Mousterian, the period of the Neanderthals; while the shelter of Cro-Magnon, below which some Ice Age burials were discovered in 1868, gave its name to anatomically modern humans.

Of the decorated caves, by far the most famous is that of Lascaux, which was discovered by four boys in 1940, and which contains the most spectacular collection of Ice Age wall art yet found (see colour plate section). It is best known for its 600 magnificent paintings of aurochs (wild cattle), horses, deer, and signs, but it also contains almost 1500 engravings dominated by horses. The decoration is highly complex, with numerous superimpositions, and clearly comprises a number of different episodes. The best-known feature is the Hall of the Bulls, containing several great aurochs figures, some of them 5 m in length, the biggest figures known in Ice Age art; the hall also contains an enigmatic figure, baptised the unicorn. One remarkable painted figure at the end of the Axial Gallery, dubbed the falling horse, is painted around a rock in such a way that the artist could never see the whole figure at once, yet when the figure is flattened out with photographs it proves to be in perfect proportion.

A shaft features a painted scene of what seems to be a bird-headed man with a wounded bison and a rhinoceros, which has often been interpreted in shamanistic terms, though with little justification. The narrow Cabinet of the Felines forms the farthest extremity of the cave, and is filled with engravings, including a remarkable horse seen from the front, as well as the eponymous felines. It was in a shaft in this narrow corridor that a piece of Ice Age twisted rope was found.

Stone tools for engraving were found in the cave's engraved zones. Many lamps were also recovered (one of them a particularly well-carved specimen in red sandstone), as well as 158 fragments of pigment, and colour-grinding equipment, including crude mortars and pestles, stained with pigment, and naturally hollowed stones still containing small amounts of powdered pigment. There are scratches and traces of use-wear on many of the mineral lumps. It was found that there were sources of ochre (red) and of manganese dioxide (black) within 500 m and 5 km of the cave respectively. The shades vary considerably—the colour of ochre is modifed by heat, and Ice Age people clearly knew this. At Lascaux they also mixed different powdered minerals and were apparently experimenting with different combinations and heating procedures.

Scaffolding was clearly used in some galleries to reach the upper walls and ceiling—one gallery preserves the actual sockets for beams that must have supported such a scaffold. Much of the cave floor was lost when the site was adapted for tourism in the 1940s, but the site was probably never a habitation, being visited briefly for artistic activity or ritual. Charcoal fragments from the cave floor have provided radiocarbon dates around 15 000 BC and in the 7th millennium BC. The cave was closed to tourists in 1963 owing to pollution—a “green sickness” consisting of a proliferation of algae, and a “white sickness” of crystal growth; it was possible to reverse the effects of the green sickness and arrest the development of the white; but to ensure the survival of the cave’s art, it has been necessary to restrict the number of visitors drastically. As compensation, a facsimile, Lascaux II, is now open nearby.

Among the other caves, three played an important role in the discovery and acceptance of the whole phenomenon of Ice Age cave art. It was at La Mouthe, in 1895, that the owner decided to remove some fill and exposed an unknown gallery. Engravings and paintings were discovered on its walls, and since there were Ice Age deposits in the blocking fill, it was clear that the images must also be from that period. In 1899 an Ice Age lamp was unearthed in the cave, carved in red sandstone and with an ibex engraved on it. This was the first evidence of a lighting system for cave art.

In 1901, engravings were found in the caves of Les Combarelles, near Les Eyzies; the principal cave, a long narrow corridor, contains hundreds of images of horses, bison, deer, mammoths, and humanoids, as well as rarer species such as bear, rhino, and big cat. They are attributed to the mid-Magdalenian period, *c.* 14 000 BC. A few days later, the rich art was found by local schoolteacher Denis Peyrony in the nearby cave of Font de Gaume—this cave contains 230 figures, including no less than 82 bison among which are many polychrome specimens. There are also famous images of horse, deer (including a rare scene, a male reindeer licking the forehead of a female reindeer), mammoths, and rhino, all attributable to the mid-Magdalenian period.

The sheer density and richness of Ice Age occupation in the Vézère valley led to Les Eyzies being dubbed the “Capital of Prehistory”. Analysis of faunal material from many sites has indicated that in many phases this region was primarily occupied during the winter months.

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Further Reading

1984. *L’Art des cavernes: Atlas des grottes ornées paléolithiques françaises* [Cave art: Atlas of the French palaeolithic decorated caves], Paris: Ministère de la Culture

Bahn, P.G. 1994. Lascaux: Composition or accumulation? *Zephyrus,* 47:3–13

Bahn, P.G. & Vertut, J. 1997. *Journey Through the Ice Age,* London: Weidenfeld and Nicolson and Berkeley: University of California Press

Barrière, C. 1997. L’art pariétal des grottes des Combarelles, *Paléo,* hors série (May)

Capitan, L., Breuil, H. & Peyrony, D. 1910. *La caverne de Font-de-Gaume aux Eyzies (Dordogne),* Monaco: A.Chêne

Capitan, L., Breuil, H. & Peyrony, D. 1924. *Les Combarelles aux Eyzies (Dordogne),* Paris: Masson
Laming-Emperaire, A. 1959. *Lascaux: Paintings and Engravings,* Harmondsworth, Middlesex and Baltimore, Maryland: Penguin
Leroi-Gourhan, A. & Allain, J. (editors) 1979. *Lascaux Inconnu,* Paris: Centre National de la Recherche Scientifique
Ruspoli, M. 1987. *The Cave of Lascaux: The Final Photographic Record,* London: Thames and Hudson and New York: Abrams

VILLA LUZ, CUEVA DE, MEXICO

An extraordinary cave with a remarkable ecosystem lies nestled in the coastal foothills of southern Mexico. Cueva de Villa Luz is about 3 km south of the village of Tapijulapa in the Municipio de Tacotalpa, Tabasco, Mexico, and local guides to the cave are readily available in the town's central plaza. The indigenous people have recognized Cueva de Villa Luz (also known as Cueva de las Sardinas) as unique since before historical memory. They noted a startling abundance of small, cave-adapted fish unaffected by surface droughts. When food became scarce, the cave continued to provide fish. The Zoque respected the sacredness of the cave and only harvested fish once or twice a year after solemn prayers and offerings to their gods. Today, *La Pesca de la Sardina* is re-enacted every Palm Sunday weekend and the fish continue to thrive in a robust ecosystem, unparalleled by any other cave in the world.

Nearly every remarkable feature in Villa Luz results from the dozens of hypogenic (deep) water inlets within the cave. These small, subterranean springs bring warm (28°C) solutions from hypogenic sources into the 2 km long air-filled cave. Abundant hydrogen sulfide and carbon dioxide gases are released immediately into the cave atmosphere. Episodic, intense gas releases cause extraordinary changes in local atmospheric compositions. Within only minutes, the hydrogen sulfide level can dramatically increase or the oxygen level rapidly decline to lethal amounts (Hose *et al.,* 2000). Some passages consistently contain dangerously high concentrations of carbon dioxide. The gases mix with water vapour in the cave air and moisture on the walls, forming sulfuric and carbonic acids. Some visitors have received chemical burns from drips or prolonged contact with the walls. The scientists studying this cave have developed unique techniques and equipment for ensuring their safety, including wearing acid gas masks, continuous portable electronic gas monitors, goggles to protect their eyes from dripping acid, and miniature scuba tanks for safe evacuation. While these conditions lead to a hazardous environment for speleologists, they also provide the necessities for other life beyond the reaches of light.

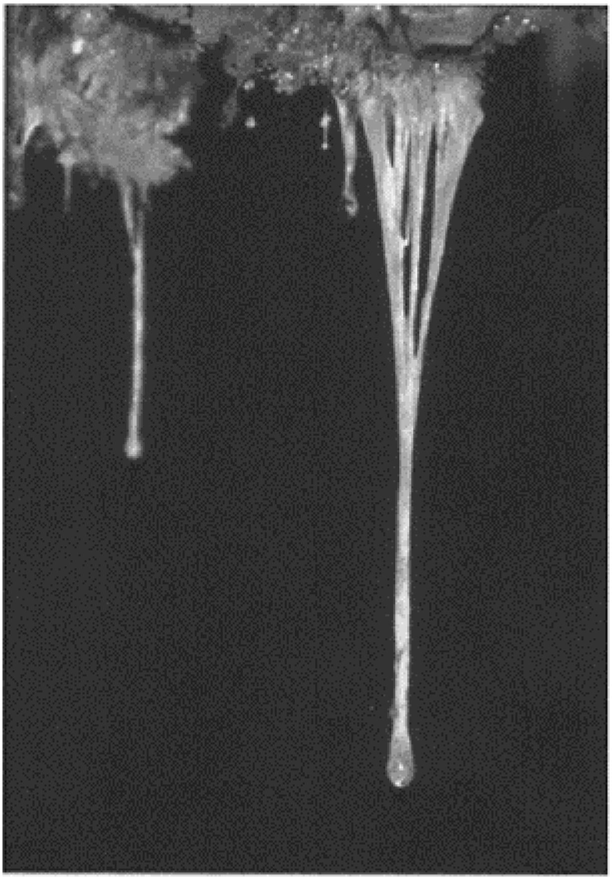
Ubiquitous microbes in the cave called chemoautotrophic bacteria are capable of using the energy of chemical reactions; they facilitate the oxidation of the hydrogen sulfide and use the resultant heat energy in the same manner as plants use light energy for photosynthesis. Although several reactions may take place, a typical one is the simple oxidation of hydrogen sulfide to produce sulfuric acid. This reaction releases 798 kJ mole^{-1} of energy, which the bacteria use with the readily available carbon dioxide and water to manufacture cells. Sulfur-oxidizing bacteria, abundant in the water and on the walls and ceiling of the cave, are the producers in the Villa Luz ecosystem.

The most notable bacteria are ephemeral, rubbery, white deposits that resemble stalactites, have the texture of mucous, and drip sulfuric acid. These “snottites” (see Figure) comprise colonies of diverse microbes and their drips have pH of 0–3 (Hose & Pisarowicz, 1999). They grow quickly, up to a centimetre in length a day, and cluster in areas of the cave with the highest atmospheric hydrogen sulfide concentrations. Researchers have identified *Thiobacillus* (a sulfur-oxidizing bacteria) as the genus of the dominant clones (Hose *et al.*, 2000).

Mites, worms, and other small organisms live within the snot-tites. Small, flying insects (most common is *Tendipes fulvipilus*), whose larvae graze on the bacteria, are so abundant in some areas that they fill the passages in buzzing clouds. Large populations of spiders, representing several species, capture the midges in their webs for their food. Many other insects inhabit the cave. At least three species of cave-adapted fish fill the top few centimetres of the streams. *Poecilia mexicana*, a mollie, is the dominant species. Most of the mollies lack any pigmentation. They are pink due to abnormally high levels of haemoglobin and mostly feed on bacteria along with lesser amounts of insects (Langecker *et al.*, 1996). A yet unidentified *Hemipterin* (bug) preys on the fish. At least four species of bats, including one vampire, also inhabit the cave. The varied and abundant organisms of the cave form a complex, but so far little investigated, ecosystem.

Cueva de Villa Luz has formed in a Cretaceous limestone sequence along the strike of the northwest limb of an anticline. The floor of the cave seems to represent the local water table level. It appears to be a very young cave with extraordinarily fast cave-forming processes at work. Highly aggressive sulfuric acid along with the milder carbonic acid are rapidly destroying the limestone bedrock and enlarging the cave.

Calcite exposed to sulfuric acid undergoes a replacement reaction that results in gypsum and carbonic acid. Since the air in Villa Luz is permeated with sulfuric acid, gypsum coats nearly all of the walls and ceiling in a variety of forms, including delicate selenite crystals and microcrystalline masses that resemble toothpaste. Gypsum does not react with the atmospheric sulfuric acid but does create a buffer between the vulnerable limestone bedrock and the acidic atmosphere. The gypsum coatings typically harbour sulfuric acid and record pH values of 1–3. Many microbes live within the nearly ubiquitous gypsum paste, probably facilitating the production of the sulfuric acid.



Cueva de Villa Luz, Mexico:
Snottites in Snot Heaven. Sulfuric acid drops at their tips have pHs of 0–3. (Photograph by Louise Hose)

The gypsum frequently drops from the ceiling and overhanging walls into the streams, which rapidly dissolve the highly soluble gypsum and remove it from the cave. Limestone exposed after the gypsum peels off the wall is again exposed to the sulfuric acid vapours, converts to gypsum, and the cycle continues as cave passages enlarge (Palmer & Palmer, 1998).

Sulfur folia and other elemental sulfur coatings drape walls near some of the most sulfur-rich springs. Deposits of sulfur folia have not been reported from any other cave in the world. The folia cover selenite (gypsum) crystals and appear to represent sub-aqueous deposits of sulfur now lining walls well above a flowing stream. Their origin is not clearly understood.

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See also **Microbial Processes in Caves**

Works Cited

Hose, L.D. *et al.* 2000. Effects of geomicrobiological processes in a hydrogen sulfide-rich, karst environment. *Chemical Geology: Special Geomicrobiology Issue,* 169:399–b423
Hose, L.D. & Pisarowicz, J.A. 1999. Cueva de Villa Luz, Tabasco, Mexico: Reconnaissance study of an active sulfur spring cave. *Journal of Cave and Karst Studies,* 61(1):13–21
Langecker, T.G., Wilkens, H. & Parzefall, J. 1996. Studies on the trophic structure of an energy-rich Mexican cave (Cueva de las Sardinas) containing sulphurous water. *Mémoires de Biospéléologie,* 23:121–25
Palmer, A.N. & Palmer, M.V. 1998. Geochemistry of Cueva de Villa Luz: An active H_2S cave [abstract]. *Journal of Cave and Karst Studies,* 60(3):88

Further Reading

Hose, L.D. 2001. Cave of the snottites. In *Caves: Exploring Hidden Realms,* M.R.Taylor, Washington, DC: National Geographic
Hose, L.D. 2001. La Pesca de la Sardina. *Association of Mexican Cave Studies Activities Newsletter,* 24:50
Hose, L.D. 1999. Cave of the sulfur eaters. *Natural History Magazine,* (April 1999):54–61
Pisarowicz, J.A. 2001. The acid test: Cueva de Villa Luz. *Association of Mexican Cave Studies Activities Newsletter,* 24:48–54

VJETRENICA, BOSNIA-HERZEGOVINA: BIOSPELEOLOGY

Vjetrenica is a cave with approximately 8 km of active and relict passages. It opens some metres above Popovo polje, near Zavala in southeast Herzegovina (Bosnia-Herzegovina), and drains into the polje without swallowing its waters. It is located some distance from any major sources of industrial or urban pollution. In the summertime, a strong wind up to 3 m s^{-1} blows continually from the entrance, giving the cave its name (*vjetar*=wind). However, the wind ceases after any significant rain, when a lake approximately 1 km inside the cave rises and closes a siphonlike structure. The direction of the wind during the winter is not known with certainty. If conditions are windless this does not alter the other meteorological parameters (temperature and humidity) in the main cave passage, at least not for a few days.

In summer, the temperature in the main passage is between 11 and 11.5°C, and the relative humidity is close to 100% right up to the entrance when the wind is blowing out of the cave. The summer temperature of all streams is slightly above 11°C. Climatic conditions in Vjetrenica appear to be fairly but not entirely constant, since the temperatures of the bottom sediment and of the lakes in the main passage have been measured down to 10.2°C. However, there are no measurements available for the winter months.

The lower parts of Vjetrenica are hydrologically active, and the upper parts have a modest network of small streams and well-aerated pools. The calcium content in all waters is between 43 and 50 mg l^{-1}, with sodium between 1.7 and 2.3 mg l^{-1}, while the potassium content is highly variable. Even in the remotest parts of Vjetrenica, dead plant material may be found, particularly in the streams. This material is most probably brought in by very high-energy streams of percolating water, falling from numerous cracks in the ceiling, after rain. The substrate of one small stream in the deep interior appears to be somewhat polluted with organic material. Trogloxene invertebrates are comparatively scarce even close to the entrance, and they cannot contribute significantly to the food resources of the cave. No bats have been observed in Vjetrenica.

Vjetrenica has attracted the interest of biologists for some time. It was highly praised by the Czech, Karel Absolon, and was later visited by the first expedition of the revived Slovenian caving club in 1932. It was frequently visited by foreigners (e.g. Remy, 1940), and after World War II there were numerous expeditions by biospeleologists from Ljubljana.

Vjetrenica is one of the most faunistically rich caves in the world (Culver & Sket, 2000), due to its biogeographical position in the Dinaric karst, its size, and its ecological heterogeneity. Vjetrenica is inhabited by more than 30 troglobites and 40 stygobites. There are only a few troglophiles or trogloxenes, and there are virtually no unspecialized aquatic inhabitants.

The threshold zone of the main passage and its side branches contain some entrance fauna characteristic of the region. The parietal fauna (on the cave walls) consists of resting moths *Triphosa sabaudiata* and large numbers (up to 10 specimens per square metre) of the dipteran *Limonia nubeculosa*. Cave crickets *Troglophilus* spp. and *Dolichopoda araneiformis* and the large odoriferous centipede *Apfelbeckia* sp. are scarce. *Trogulus torosus*, a large-bodied harvestman species and a regional endemic, is rare. Young crickets and centipedes can be found up to 400 m from the entrance.

The most common troglobite of the main corridor and remote parts is the large and highly troglomorphic beetle *Antroherpon apfelbecki;* some other beetles (*Speonesiotes* spp., *Neo-trechus* spp., *Aphaenopsis* spp.) are less common to extremely rare. The glomeridellid centipede *Typhloglomeris caeca* is limited to larger clay deposits. Single specimens of the harvestman *Travunia vjetrenicae* (Laniatores: Travuniidae) can be found in the active corridor known as the Absolonoy canal.

Particularly interesting is the hygropetric-like habitat (a thin film of water flowing down the rock) on walls with extensive flowstone, inhabited by the specialized leptodirine beetle *Hadesia vasiceki* and also by the large amphipod *Typhlogammarus mrazeki*.

The animal communities in the cave waters are very diverse. In the past, shallow pools in the main corridor contained abundant populations of shrimps (*Troglocaris* spp.) and amphipods *Hadzia fragilis*. However, it appears that this fauna was destroyed indirectly by activities related to tourism.

In the lakes of Donja Vjetrenica (Lower Vjetrenica), the large, spiny, and extremely troglomorphic amphipod *Niphargus balcanicus* is particularly characteristic, and this is also the only known locality for the mysid *Troglomysis vjetrenicensis*. The rapidly flowing small stream in the Absolonoy canal is particularly rich, with—among others—the predatory amphipod *Typhlogammarus,* rich colonies of tiny gastropods *Iglica absoloni,* and occasionally *Proteus anguinus*. The Veliko jezero (Great Lake) is particularly characterized by the specialized digger amphipod *Niphargus trullipes* and the less specialized but similarly large N. *vjetrenicensis*. Shrimps are also common. It should be mentioned that as many as three, and maybe even four, species of Atyidae shrimps are present in Vjetrenica *(Spelaeocaris pretneri, Troglocaris* cf. *anophthalmus, T. hercegovinensis,* and an undescribed *Troglocaris* sp.).

Tiny hydrobioid gastropods, *Lanzaia vjetrenicae,* and the serpulid worm, *Marifugia cavatica,* are characteristic of small streams in remote parts of Vjetrenica.

Biogeographical Relationships of the Fauna

A number of genera and species have a holo-Dinaric distribution: *Proteus, Marifugia,* the terrestrial gastropod *Zospeum amoenum,* the cockle *Congeria kusceri,* two species of *Troglocaris* shrimps, and others. *Titanethes hercegowinensis, Monolistra hercegoviniensis,* the shrimp *Spelaeocaris,* the leech *Dina absoloni,* and all of the beetle genera, have southeast mero-Dinaric distribution.

A number of *Niphargus* species, some isopods, the beetle *Hadesia,* and the centipede *Typhloglomeris* are narrow endemics even within the southeast Dinarides. For the time being, some species may be regarded as endemics of the Vjetrenica Cave. Two species are particularly enigmatic; the amphipod *Hadzia* and the mysid *Troglomysis* are indisputably species of coastal marine origin, but are incorporated here into a freshwater fauna not related to any recent or ancient seas.

Need to Protect the Faunas

Although far from obvious centres of pollution, the rich fauna of Vjetrenica is not immune from harm. Used batteries and similar waste left behind by tourists who have visited the cave in the past few years have already caused some damage. The use of any chemicals in the limited farming above the cave could cause more general problems, with the most potentially harmful being caused by the use of insecticides. The soil is very thin on the surface, and streams of percolating water are active in the cave just a few hours after rainfall. It is reasonable to assume that a large portion of the chemicals applied to the land could be washed into the caves via this route.

BORIS SKET

See also **Dinaric Karst: Biospeleology**

Works Cited

Culver, D.C. & Sket, B. 2000. Hotspots of subterranean biodiversity in caves and wells. *Journal of Cave and Karst Studies,* 62(1):11–17

Remy, P. 1940. Sur le mode de vie des *Hadesia* dans la grotte Vjetrenica. *Revue Française d'Entomologie,* 7:1–8

Further Reading

Sket, B. 2001. The hygropetric habitat in caves and its inhabitants. *Abstracts of the XVth International Symposium of Biospeleology,* Société Internationale de Biospéologie

VOLCANIC CAVES

The significance of volcanic caves is dependent on their size, type, contents, and location. Shield volcanoes generally owe their existence to the tendency of flowing lava to form tubes, in which it is insulated against convective and radiative heat loss. These tubes may conduct molten lava for tens of kilometres with a temperature loss of only 0.5 to 1.0°C km^{-1}. If drained, the largest of these tubes may persist as lava tube caves. An understanding of their origin, development, and features is important for comprehension of many volcanic locales. In addition, some lava tube caves are hydrologically important.

Hawaii's Kazumura Cave (US) is the longest on record (65.6 km). It is 32 km from end to end and has a vertical extent of 1100 m. Its floor plan is basically sinuous, with local braiding on one or more levels. It is notable for plunge pools up to about 20 m wide (Figure 1), more than 60 entrances and is never more than about 20 m below ground. Other types of volcanic caves contain cave art, habitations, and other cultural features, or are notable sites for recreation. Some are successful show caves and important nature reserves.

Volcanic caves (often called lava caves) also include hollow hornitos, hollow tumuli, lava rise and flow lobe caves, many moulds of trees, and eruptive fissures that intergrade into lava tube caves. Open vertical volcanic conduits are also included. Not included, however, are littoral and other crevice caves in volcanic rock (e.g. Fingal's Cave, Scotland), nor are piping caves in pyroclastics (see entries on Crevice Caves, Littoral Caves, and Piping Caves).

Lava Tube Caves and Lava Tubes

In the geological literature, the term "lava tube" has numerous contradictory meanings. For clarity it should be restricted to roofed conduits of flowing lava, either active, drained, or plugged. Such conduits are from a few centimetres to tens of metres in diameter, and from perhaps 0.1 m to many kilometres in length. Most lava tubes are too small or too full of lava to be considered caves. Advancing flow lobes, rifts carrying unconfined flow of lava, and lava trenches are not lava tubes. Shelly pahoehoe tubes are a special thin-skinned subtype found near rapidly degassing vents. Rarely, basalt dykes drain in the form of lava tubes (e.g. Cueva de la Fajanita, La Palma, Canary Islands).

Volcanic Caves: Figure 1. Eureka Falls in the upper part of Kazumura Cave, Hawaii, with the rims of a drained lava plunge pool at its foot. (Photo by Kevin Allred)

Origins and Development of Lava Tube Caves

Late in the 20th century, it became apparent that most lava tube caves form by two basic processes: crusting over of surface rivers of lava, and/or drainage of still-molten lava from beneath solidified crusts. Features of large lava tube caves (e.g. Kazumura Cave, Hawaii) show that they characteristically formed and developed within lava flow fields, as a result of a complex sequence of events.

In vent regions, currents of preferential flow develop within crusted flows. In gullied terrain (e.g. Ape Cave, Washington State), preferential flow follows the course of pre-existing gullies. In more uniform terrain (especially on less than 4 degrees of slope), sinuous currents develop in the flow field where lava can advance with minimal energy loss. Lava temperature and plasticity are initially uniformly high. With cooling of the flow field, these currents become increasingly demarcated from the surrounding lava, and become walled-off tubes. Where lava forms pools, braiding and distributary tubes form. Small surface tubes develop independently, or at points where lava escapes to the surface. Meltdown of lava between subparallel tubes may form large tube segments. If the supply of lava increases while the crust is still plastic, the original tube may become distended in one of several patterns discussed below. Drainage by thermal erosion and other mechanisms, such as backcutting at lavafalls, produces “master tubes”. Downcutting produces passages with volumes greater than that of the lava supply, creating free-surface lava rivers. It also deprives some braids of their lava supply and may drain them. This partial drainage also removes buoyant support and initiates breakdown. Except at low gradients, much of this material is carried down-tube. Blockages can cause breakouts, feeding surface flows containing additional small tubes (see below), much as in the inception phase.

On comparatively steep slopes (2–4 degrees), thermal erosion by comparatively shallow lava rivers commonly produces canyon passages with cutbanks and slipoff slopes. Some of these lava rivers eventually flow metres below their original bed, and create cavities much larger than their maximum flow. Where ceiling collapse introduces cold air, crusting of the surface of the lava river forms secondary ceilings. Below one degree of slope, tubes tend to be comparatively low and wide, with most or all of the tube filled with flowing lava rather than a free-surface river.

On gentle slopes, the molten interiors of advancing flow fronts are restrained by resistance of rapidly cooling peripheral lava. Similar to the situation at the vent, lava currents develop at points of low resistance. Repeated small breakouts occur and flow fronts advance by breakout and expansion of comparatively small flow lobes with thin "skins". Commonly these small lobes pile up rapidly in isolated segments of the flow front, then occur in another area, and then another. Under these conditions, the interior of each small lobe may remain hot for many days, and their "skins" characteristically break down, forming homogeneous flow fronts. Sometimes, however, breakouts from a single cooling lobe, or a complex of several partially homogenized lobes, may cause drainage beneath a stable crust, forming a flow lobe cave. Characteristically, these are elongate spaces 10–20 m wide and 1 −2m high, occurring singly, in sequences, or as three-dimensional clumps (nests). The longest recorded to date (Christmas Cave, Hawaii) has 632 m of passage and chambers on two levels.

Drainage, after pressurized injection of lava beneath a slightly plastic crust (subcrustal injection), may produce somewhat similar caves at the flow front and elsewhere in the flow field. These include two forms of hollow tumuli (domes or ridges projecting above the general surface of the flow), lava rise caves, and caves composed of a mixture of these forms. Sinuous hollow tumuli may be a few hundred metres long, with a chamber as much as 15m wide. Cavernous lava rises are of two types. One is a low, rounded dome with a second or collapsed centre tens of metres in diameter, with cave remnants in much or all of its perimeter ridge; some also have short patent drainage and or feeder tubes in addition. A few open into other drained features nearby. The other type of lava rise cave consists of somewhat tubular spaces following the course of long, narrow lava rises with a flat top. Characteristically, these caves are originally wide and low, but become narrowed by the irregular sagging of their plastic roof. Locally this may produce multiple parallel passages 1–2 m high, or only boundary ridge passages may remain. Some of these caves are hundreds of metres long and have features consistent with minor conduit flow. These may be regarded as primitive lava tube caves.

Volcanologists studying rivers of flowing lava have observed speleogenesis by crusting of their molten surfaces and by wedging of floating plates of lava. At least one cave on a steep slope on Mauna Loa volcano is roofed by wedged lava plates, but roof patterns of most recorded lava tube caves are not consistent with this type of speleogenesis. Further study is needed.

Lava Tube Caves in Higher Viscosity Lavas

Lava tube and related caves form primarily in low-viscosity pahoehoe basalt (and possibly carbonatite). Some also have been reported in higher-viscosity lavas, including clinkery basalt (aa lava), and a few in andesite (e.g. Nishiyuura Ana, Japan) and rhyolite. Most of Italy's Mt Etna is covered by aa lava, and many of its numerous lava tube caves are beneath or within aa lava. Although these have been extensively studied, details of the origin and development of lava tube caves in high viscosity lavas are not well understood.

Lava Tube Caves as Groundwater Conduits

Some lava tube caves can function as perennial, seasonal, or floodwater conduits for groundwater, with consequent public health implications. They function as leaky pipes, and underlying volcanic ash or dense unfractured basalt layers may contribute to such transport. Except at water tables, very large reservoir spaces with large adsorptive surfaces commonly underlie lava tubes elsewhere, and may minimize public health problems.

Underwater Lava Tube Caves

Extensive submarine lava flows have been deposited through submarine lava tubes. In addition, subaerial lava tube caves can be submerged by rising sea level. The best-known penetrable example is probably Tunel de la Atlantida (the submarine portion of the Cueva de Los Verdes System, Lanzarote, Canary Islands).

Ages of Lava Tube Caves

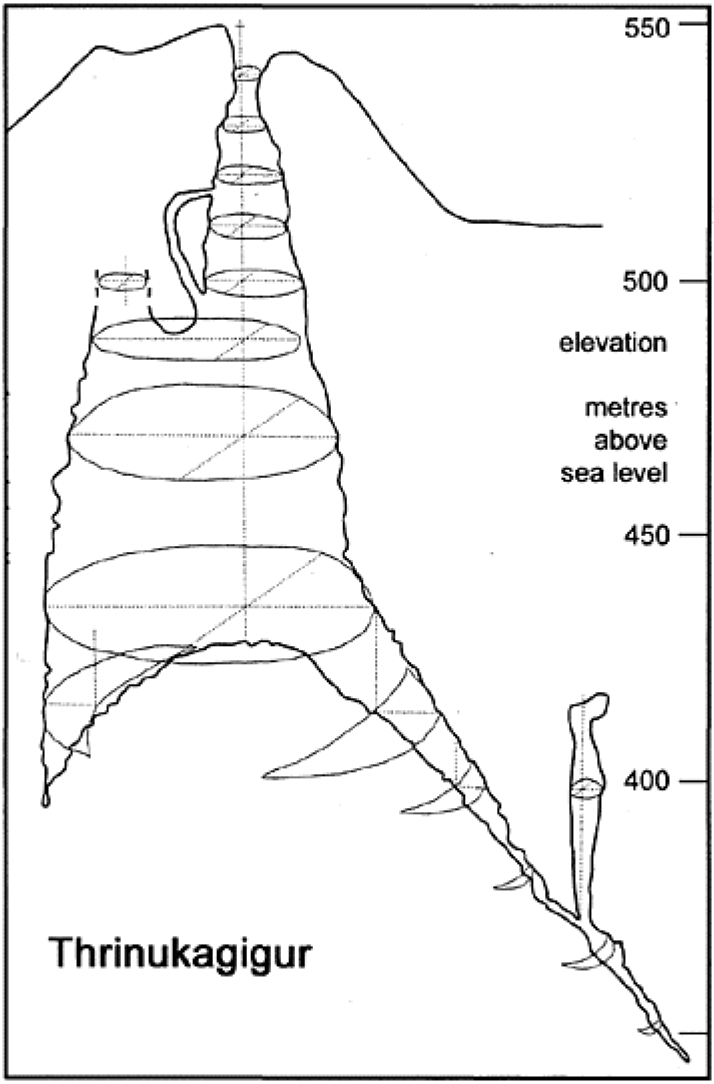
Most lava tube caves are much younger than their calcareous analogs, but a few have ages measured in millions of years. One near the bottom of a gorge on the island of Maui (Hawaii) is in a flow mapped as Tertiary, and another in mid-Pacific is considered to be 8 million years old. In central Europe, short fragments of lava tube caves in Paleogene volcanics still have lava stalactites *in situ*.

Open Vertical Volcanic Conduits and Related Features

Open vertical volcanic conduits occur in several forms (Skinner, 1993). Especially important are bottle-shaped pits and "inverted goblet" pits. At 204 m, Iceland's Thrinukagigur is the deepest subaerial example (Figure 2). Hawaii's Na One crater contains a similar pit which begins on a ledge near the bottom of the crater; the combined depth is 268 m. Divers have reached a depth of 123 m in the inner conduit of the underwater portion of Hawaii's Kauhako Crater; the bottom was not visible at that depth. In Japan, deep, extensive crevice caves in thick scoria have accreted linings. On Mt Etna, several eruptive fissures with accreted linings are roofed and continue downslope as ordinary lava tube caves.

Lava Mould Caves (Tree Mould Caves)

Occasionally, logjams entrapped in flowing lava have formed complexes of tree moulds, with some individual trees more than 2 m in diameter and 20 m long. An especially complex area is in Japan's Yoshida-tanai area. A comparatively small group exists in the Mt St Helen's National Volcanic Monument (US). Here a few upright tree moulds have charred wood in their stumps, suitable for ^{14}C dating. More rarely, petrified wood is present in older caves of this type. Similar moulds of animals are known.



Volcanic Caves: Figure 2. Vertical section of Thrinukagigur, Iceland, the world's deepest open volcanic conduit (survey by Arni Stefansson).

A cave consisting of a mould of a Tertiary rhinoceros can be entered near Blue Lake in Washington state (United States). Moulds of elephants are present on the flank of Nyiragongo volcano in central Africa. Interiors of a few buildings, overrun by high-viscosity lava on Mt Etna, have been found preserved in much the same way.

Specific Features of Volcanic Caves

In addition to nonspecific features, such as breakdown, inwash, and tectonic crevices, four principal types of features exist in volcanic caves: speleothems, speleogens, petromorphs, and rheogenic features. Larson (1993) has brought considerable order into their terminology, condensing more than 1000 published English-language names into 174 terms, most of which are now widely used. Of these, approximately 20 describe common features.

The range of minerals deposited in volcanic caves is considerably greater than in karstic caves (see separate entry, Cave Minerals). Small calcite stalactites are not uncommon in lava tube caves, and large calcite speleothems develop where limestone or calcareous sand dunes overlie or are adjacent to well-watered lava tube caves. Elsewhere, silica dripstone and flowstone speleothems are more common. In a few locations, they form large stalactitic masses. Gypsum and other sulfate speleothems are also very common. They may appear while lava tubes and crevices are still very hot and their composition evolves with cooling and changes in humidity. Tiny siliceous microgours are seen on some vertical walls.

The original definition of the term “speleothem” did not consider the possibility of lava dripstone. In practice, the term commonly has been extended to include speleothem-like forms composed of lava. Stalactitic types are especially notable for variety of form and content. Some of the most attractive consist of a shiny form of pitchstone. In contrast, some of dacite are broad, thin, granular, and dull black.

With a maximum length of 2–3 m, tubular lava stalactites are the commonest form in Hawaii, Iceland and some other areas, and the most studied. Their basic form and size is similar to “soda straw” calcite stalactites. They are extruded by differential “filter-pressed” segregation of crystals within cooling lava (Allred & Allred, 1998). Larger tubular stalactites with a patent canal are much less common. While still plastic, some lava tubular stalactites are deflected by wind currents. Others (“vermiforms”) twist for other reasons, and some have helictitic or coralloidal extensions. Still others flatten into “pipestem stalactites”. Tapered and “shark’s tooth” lava stalactites are also common. Tapered lava stalactites form from slumping of glaze, or as a result of simple dripping or streaming of lava. “Dip-layered” stalactites have multiple concentric layers caused by rise and fall of molten lava flowing beneath them, and are much less common. Where new lava pours into overhanging entrances of older caves, stalactitic columns may exceed 5 m in width and height and 1 m in thickness. Some have an attractive feathery surface.

Except at the base of lavafalls or other overhangs, where they may have the form of tall, symmetrical towers, lava stalagmites are characteristically tall thin accumulations of lava droplets a few centimetres to 2 m high (Figure 3). They tend to occur in rows, beneath drip lines. The size and shape of individual droplets vary from small globules to elongated teardrops more than 1 cm long, but tend to be consistent at each location. Where dripping lava is especially fluid, “worm nests” form instead of stalagmites. Rarely the droplets are poorly cohesive and form piles of partially agglutinated nodules instead of stalagmites. Lava spindles (stretched lava projections) up to about 2 cm develop

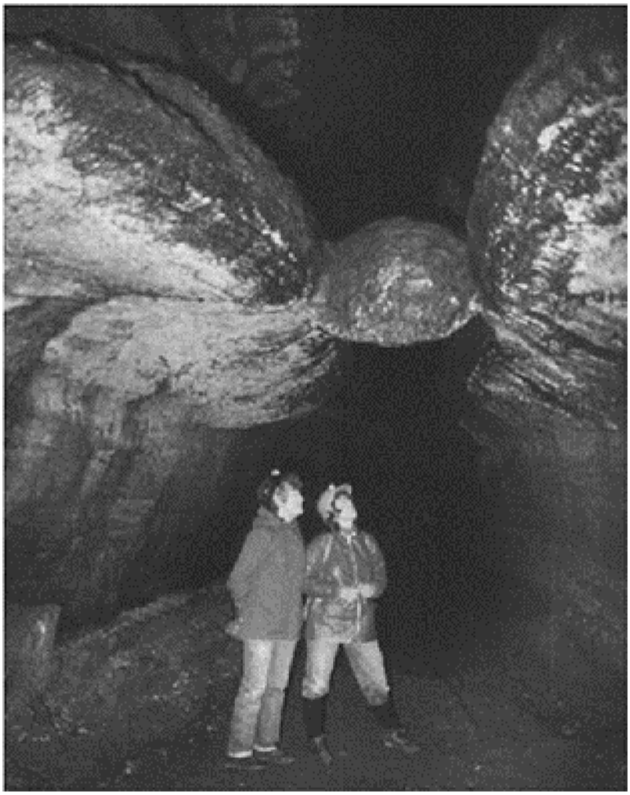
Volcanic Caves: Figure 3. An unusually fine group of stalagmites of solidified dripped lava glass in Apua Cave on Hawaii. (Photo by Tony Waltham)

where viscous lava surfaces pull apart. In areas of especially turbulent air currents (e.g. Kenya's Mt Suswa caves), thin lava strands have formed complexes resembling matted yarn. Complexes of spatter are common on walls, ceilings, and floors.

Many speleogens of lava tube caves resemble those of karstic caves. Solutional speleogens may occur in caves in lavas with unusually high sulfate and carbonate content (Larson, 1993). Others are the result of thermal erosion or plastic deformation. Probably the most impressive are plunge pools. These are as much as 20 m wide and several metres deep. Characteristically, large examples have collapsed crusts where underlying lava has drained. Usually they are found at the head of large chambers with vertical headwalls and tapered down-slope extensions. Lava karren, stalactitic pendants, cutbanks, and slipoff slopes are evidence of thermal erosion. Grooves and scratches cut by solid fragments in moving lava are common.

Rheogenic Features

Many types of rheogenic features result from lava flow in lava tube caves. Photographs in Larson's (1993) glossary depict these and other significant features. Primary ceilings commonly contain important clues to speleogenesis. These include wedged plates of lava that originally floated downstream on a lava river (Figure 4), and longitudinal seams where levees arched completely across such a river. Ceiling channels and longitudinal grooves and ridges caused by movement of lava against the ceiling are much more common. Cupolas are the result of upward pressure while lava still was plastic. Some extend upward to the underside of a hornito or short overflow level. Accreted linings are from 0.1 to over 20 cm in thickness, occurring singly or in multiples, which represent pulses of lava. Some uniformly coat the entire diameter of the passage. Others are thick at floor level (where they may merge with the floor) and taper upward, or curl outward into the passage, forming scrolls several centimetres in diameter. In a few caves which originally were wide at floor level and narrow near their ceiling, a succession of thick accreted



Volcanic Caves: Figure 4. A ball of congealed lava caught between levee

ledges in Ape Cave, United States.
(Photo by John Gunn)

linings has completely filled the upper part of the tube with what are seen as vertical lamina. Small fingers of accreted linings are often squeezed into cavities of extratubal material. Flow lines are markers of flowing lava at grade whereas strand lines are horizontal and are remnants of lava pools. Diagonal "drag lines" were cut and/or deposited while the level of a lava river was falling or rising.

Perhaps the simplest rheogenic features are patterns or textures along the centre or the entire width of the passage floor, with or without a longitudinal bulge. Of special beauty is a feathery dendritic pattern termed arborescent lava. "Tubes-in-tube" form where the lower part of a shallow intratubal flow has drained without its chilled upper surface sagging or collapsing. Where segmental collapse interrupts tubes-in-tube, residual bridges occur. Where tubes-in-tube are especially large, their ceilings may be confused with secondary ceilings. Where most of a tube-in-tube is lacking, levees and gutters may be prominent. Ledges and benches may result from incomplete development of large tubes-in-tube or secondary ceilings, from localized downcutting, or from simple accretion at the edges of a stable stream of flowing lava. Aprons are present where lava congealed while flowing downward into an underlying cavity. During turbulent flow, spatter, splashing, wind currents, and thermal erosion may combine to create fimbriated globular complexes on floors and on the edges of ledges, levees, and other overhangs.

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See also **Hawaii Lava Tube Caves**

Works Cited

Allred, K. & Allred, C. 1998. Tubular lava stalactites and other related segregations. *Journal of Cave and Karst Studies,* 60(2): 131–40

Grimes, K.G. 1995. Lava caves and channels of Mount Eccles, Victoria. *Vulcon Proceedings 1995,* Melbourne: Victoria Speleological Association

Halliday, W.R. 1998. Sheet flow caves of Kilauea Caldera, Hawaii County, Hawaii. *International Journal of Speleology,* 24B(1/4): 108

Larson, C. 1993. An illustrated glossary of lava tube features. *Western Speleological Survey Bulletin,* 87

Skinner, C. 1993. Open vertical volcanic conduits: a preliminary investigation of an unusual volcanic cave form with examples from Newberry Volcano and the central High Cascades of Oregon. In *Proceedings of the 3rd International Symposium of Vulcanospeleology 1982,* edited by W.Halliday, Seattle, Washington: International Speleological Foundation

Further Reading

Barone, N., Mirabella, O. & Licitra, G. (editors) 1987. *Atti, IV Symposium Internazionale di Vulcanospeleologia, Catania (Italy),* Catania: Centro Speleologico Etneo

Forti, P. (editor) 1998. Vulcanospeleology: Proceedings of 8th International Symposium on Vulcanospeleology, Nairobi, Kenya, *International Journal of Speleology,* 27B(1/4): 1–163

Halliday, W.R. (editor) 1976. *Proceedings of the (First) International Symposium on Vulcanospeleology and its Extraterrestrial Applications, White Salmon, Washington (US),* Seattle: Western Speleological Survey
Halliday, W.R. (editor) 1993. *Proceedings of the Third International Symposium on Vulcanospelelogy, Bend, Oregon (US),* Seattle: International Speleological Foundation
Journal of Geophysical Research, 103(B-11), 1998: special section on Long Lava Flows
Oromi Masoliver, P. (editor) 1996. *Proceedings, 7th International Symposium on Vulcanospeleology, Santa Cruz de La Palma, Canary Islands,* Sant Ciment de Llobregat (Barcelona): Forimpres, S.A.
Rea, G.T. (editor) 1992. *Proceedings, 6th International Symposium on Vulcanospeleology, Hilo, Hawaii (US),* Huntsville, Alabama: National Speleological Society
Walker, G.P.L. 1991. Structure, and origin by inflation under surface crusts, of tumuli, “lava rises”, “lava rise pits”, and “lavainflation clefts” in Hawaii. *Bulletin of Volcanology,* 53:546–58

VULCANOSPELEOLOGY: HISTORY

Vulcanospeleology is the study of caves in volcanic rocks—primarily lava tube caves and open vertical volcanic conduits. By some criteria, it is the fastest growing subdivision of speleology (see Volcanic Caves).

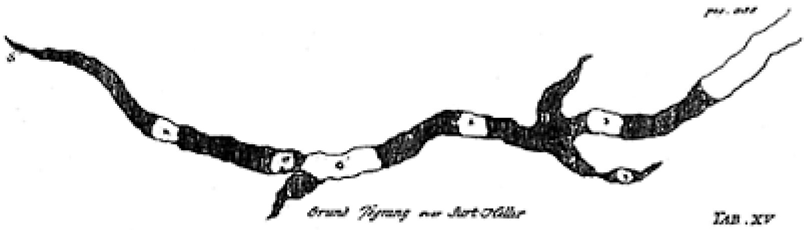
The history of human exploration of volcanic caves probably began on the lower slopes of Italy’s Mount Etna and Japan’s Mount Fuji. Natural human curiosity has drawn numerous visitors to these spectacular volcanoes from nearby centres of population and culture, throughout recorded time. A long continuum of written observations exists at Mount Etna. In the 1st century BC, Latin poet Titus Lucretius Carus wrote fancifully about “siliceous caves full of air and wind” on its slopes. In 1591 and 1698, some of its caves were mentioned in influential books by Fileoteo and Kircher. At Mount Fuji, a specific investigation of a lava tube cave was documented in 1203 and another in 1678. No true continuum developed here, however, and Japanese vulcanospeleologists had to begin anew after World War II.

In general, the volcanic caves of oceanic islands were the next to be investigated. Vikings and other early European voyagers encountered Iceland, and then other volcanic cave areas in the Atlantic Ocean. The world-famous Surtshellir (“Cave of the demon Surt”) is mentioned in Icelandic sagas from about 1000 years ago. By 1757 it was the site of the first published map of any lava tube cave (Figure 1). In 1991 a historic first successful descent of the world’s deepest known open vertical volcanic vent—Thrinukagigur, 204 m deep—was accomplished by Arni Stefansson.

In the Canary Islands, major explorations of Cueva del Viento and Cueva de San Marcos were documented in 1774 and 1776. Cueva de Los Verdes became a centre of local culture, and in 1857, Georg Hartung described it in considerable detail. Unfortunately, one picturesque illustration (Figure 2) misled science about the basic nature of lava tube caves for more than a century. The illustrator incorrectly depicted its overall form as that of a long, straight railroad tunnel. This misconception persists today.

Here and elsewhere, explorations and investigations eventually became more systematic and scientific. In 1965, Joaquin Montoriol-Pous began a notable wave of

Spanish-language vulcanospeleology. From the Canary Islands, this wave reached Iceland, the Galapagos Islands, and Rwanda. Included was the

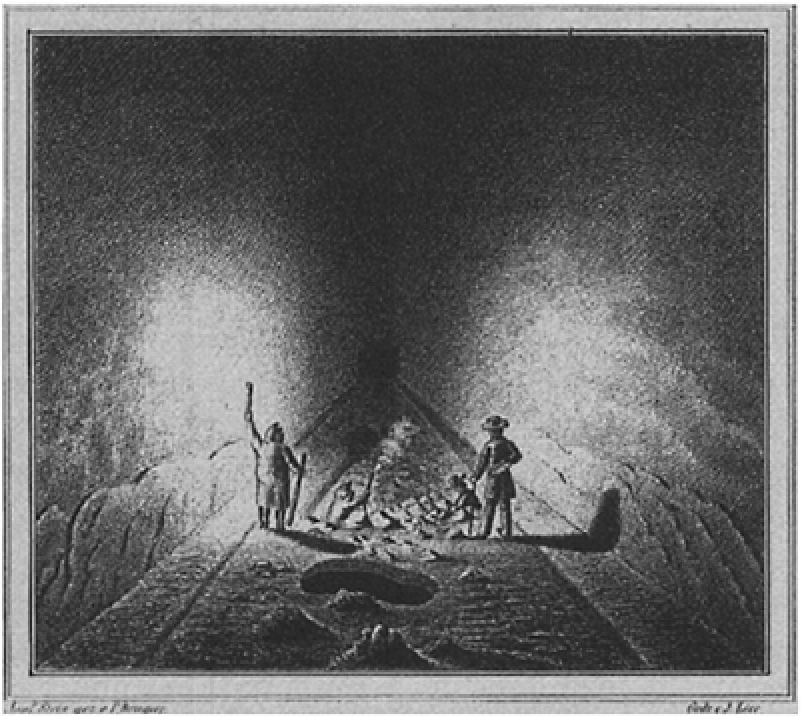


Vulcanospeleology, History: Figure 1. The first map of a lava tube cave. Plan of Iceland's Surtshellir system, published in 1757. Courtesy Jan Paul van der Pas.

prolonged exploration and documentation of Cueva del Viento, now recognized as the world's second-longest lava tube cave. Because of language barriers, however, this Spanish wave of vulcanospeleology was essentially isolated from rapid developments in vulcanospeleology elsewhere.

Shortly after the 15th-century settlement of the Azores, caves were discovered in many areas, including what became downtown Ponta Delgada and pasture land just outside Angra do Heroismo. Notable 19th-century accounts appeared in 1821 and 1873. In the last decades of the 20th century, Os Montanheiros led in systematic mapping and other documentation of caves throughout the archipelago.

In the Indian Ocean, English and French military expeditions and settlement resulted in considerable 18th- and 19th-century



Vulcanospeleology, History: Figure 2. 1857 artist's perception of Cueva de Los Verdes (Lanzarote Island, Spain). This engraving in a Swiss scientific periodical was the first widely disseminated illustration of a lava tube cave. Unfortunately it long misled the scholarly community into believing that such caves were little more than railroad tunnels. William R.Halliday Collection.

documentation of lava tube caves on the islands of Mauritius and Reunion. Theories about their origin were first published in 1804. From these pioneer works, a continuum of data entered the 20th-century French mainstream of speleology but not that of the English language. In the 1930s and 1940s, similar caves were reported on Grand Comoro Island and in northern Madagascar, but, in the chaos of decolonization, follow-up foundered until recent studies by Greg Middleton, there and in Mauritius.

In the Pacific Ocean, Montoriol-Pous and other Spanish vulcanospeleologists followed Charles Darwin to lava tube caves in the Galapagos Islands after a very long gap in observations. Perhaps surprisingly, repeated reports of lava tube caves on the isolated Easter Island began almost a century earlier. These were followed up by Thor Heyerdahl's archaeological investigations in the 1950s.

Hawaii, however, was the principal focus of world interest in the mid-Pacific during the 18th and 19th centuries. This strongly influenced the development of its vulcanospeleology. Certain Hawaiian lava tube caves had long been an integral part of native Hawaiian life. "Pre-contact" Hawaiian knowledge of these is better recorded in published recollections of newly Christianized 19th-century Hawaiians than in traditional chants. Around 1820, one of the first missionary houses in Hawaii was built at the entrance of Laniakea Cave, one of Hawaii's most celebrated lava caves. This and several other caves were described in some detail in 1823. Several broadly educated Christian missionaries soon observed lava tube caves in all stages of development. Some of them published accounts of what they saw, and began to record the processes observed in their formation. In 1849 James Dana was the first of many pioneer geologists to build on their work.

In 1912 Thomas Jaggar came to Hawaii and founded the Hawaiian Volcano Observatory on the rim of Kilauea Caldera. Jaggar knew several pioneer academic American speleologists, and his writings are full of references to caves. With publisher Lorrin Thurston and other Hawaiians he began the first real wave of Hawaiian speleology. In mid-century, Kenneth Emory's archaeological discoveries in Hawaiian caves expanded it significantly. In 1991, his pupil and successor Yosihiko Sinoto linked it to modern vulcanospeleology. The latter began in 1955, however, with an article reprinted three years later in the *Bulletin of the National Speleological Society*. Planetary geologists, and British, German, French, Japanese, and American speleologists, began increasingly intensive studies of Hawaiian caves. Following similar biological discoveries in Japan, in Hawaii important biospeleological discoveries began in the 1970s (see Hawaiian Islands: Biospeleology). Ultimately the Hawaii Chapter of the National Speleological Society and the Hawaii Speleological Survey emerged in leadership roles. Kevin and Carlene Allred directed the mapping of the 65.5 km Kazumura Cave, the world's longest lava-tube cave.

Continental lava tube caves generally have been the last to be explored and/or studied. Even fragmented tubular caves in Oligocene lava in southern Bulgaria have been recognized as lava tube caves only recently. In Africa, apparently only the tuff caves of Mount Elgon were known to 19th-century Europeans, and the history of vulcanospeleology in Africa largely is that of the Cave Exploration Group of East Africa in the latter half of the 20th century. Among projects led by Jim Simons, systematic exploration and mapping of Leviathan Cave in Kenya yielded a length of 10.5 km.

A somewhat similar pattern of discovery and exploration occurred in Australia. Some lava tube caves in the state of Victoria were known to Europeans by the mid-1880s, with some important reports as early as 1866. In eastern Australia, however, most volcanic caves were remote, and their exploration and study tends to be entirely 20th century.

Until late in the 19th century, the lava tube caves of the western United States were also remote and little known. After the American Civil War (1861–65), reports began to accumulate. Within a few years of the 1941 founding of the National Speleological Society (NSS), Erwin Bischoff brought some of them into the speleological mainstream. Vulcanospeleology then began to flower in the United States in the 1960s and 1970s, largely contemporaneously with its flowering in other parts of the world and initially independent of it. Publication of *Caves of California* and *Caves of Washington* (Halliday, 1962, 1963) systematized information on several especially important areas and introduced a body of terminology still in wide use. The Cascade and Oregon Chapters of the NSS became leaders in the systematic exploration and mapping of caves at Mount St Helens and elsewhere in the Pacific Northwest. The caves near Mount St Helens, and others near Bend, Oregon, soon were "discovered" by Ronald Greeley and other planetary geologists who applied their findings to extraterrestrial phenomena. Staff geologists of the US Geological Survey began to contribute influential papers. With NASA funding, Ronald Greeley created a world database on lava tube caves and their formation, located at Arizona State University.

In 1972 the NSS convened the first international symposium on lava tube caves, near Mount St Helens. Subsequently, others have been held in Italy (three in Catania), Japan, Kenya, the Canary islands, and two more in the United States (Bend, Oregon and Hilo, Hawaii). In 1993 the International Union of Speleology created a Commission on Volcanic Caves which facilitates communications between leaders of the field and organization of the international symposia.

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See also **Hawaii Lava Tube Caves; Volcanic Caves**

Works Cited

Halliday, W. 1962. *Caves of California,* Seattle: Western Speleological Survey

Halliday, W. 1963. *Caves of Washington,* Washington: Washington State Department of Conservation (Washington Division of Mines and Geology Information Circular No. 40)

Further Reading

The published *Proceedings of the International Symposia on Vulcanospeleology* contain much historical information. To date, *Proceedings* volumes have been published for the First, Third, Fourth, Sixth, Seventh, and Eighth symposia.

Banti, M. (editor) 1993. *Proceedings of the International Symposium on the Proto-history of Speleology,* Citta di Castello (Italy): Nuova Prhomos

Borges, P.A.V. & Silva, A. (editors) 1994. *Actas do III Congreso Nacional de Espeleologia et do I Encontro Internacional de Vulcanoespeleologia das Ilhas Atlanticas, 30 September-4 October 1992,* Acores, Portugal: Angra do Heroismo

Hernandez Pacheco, J.J., Izquierdo Zamora, L., Martin Esqivel, J.L., Medina Hernandez, A.L. & Oromi Masoliver, P. 1995. *La Cueva del Viento,* Tenerife: Consejería de Política Territorial del Gobierno de Canarias

Montoriol-Pous, J. & Montserrat, A. 1984. Vulcanoespeleologia Espanola: 1910–1977. *Sota Terra,* 5:2–14

The *Journal of Spelean History*, published by the American Spelean History Association (now the history section of the National Speleological Society, Huntsville, Alabama) also contains many articles on the history of volcanic caves.

W

WALSINGHAM CAVES, BERMUDA: BIOSPELEOLOGY

Bermuda and its extensive anchialine (coastal marine) caves are of exceptional biological and biogeographical significance due to their isolated mid-ocean location, unique geological history, and remarkably rich and diverse stygobitic fauna (Sket & Iliffe, 1980; Iliffe, Hart & Manning, 1983; Iliffe, 1994). Indeed, Bermuda's caves qualify as a biodiversity hot-spot of global importance. At least 78 endemic, cave-dwelling species, mostly crustaceans, have been identified from Bermuda caves, including two new orders, one new family, and 15 new genera. In order of abundance, Bermuda's anchialine fauna includes: 19 species of ostracods, 18 species of copepods, eight species of amphipods, six species of shrimp, four species of isopods, and four species of mites. Many of these species are found only in a single cave or cave system. Due to their limited distribution, the fragile nature of the marine cave habitat, and severe water pollution and/or development threats, 25 of these species have been listed as critically endangered (Baillie & Groombridge, 1996).

Bermuda is a volcanic seamount that formed in the Mid-Atlantic about 50–60 million years ago. Plate tectonics and seafloor spreading have maintained Bermuda's location relative to North America (about 1000 km off the Carolinas), while increasing its distance from Europe and Africa as the Atlantic Ocean enlarged. Thus, Bermuda has never been part of, or closer to, a continental landmass.

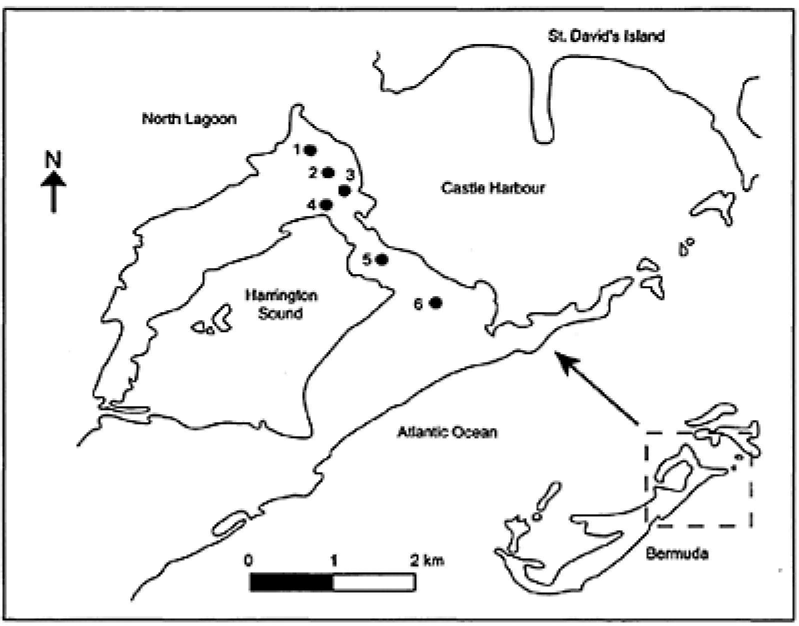
Coral-reef derived limestone, first deposited as coastal sand dunes, caps most of present-day Bermuda. Approximately one million years ago, limestone caves began forming during glacial periods when sea level was as much as 100 m lower (Palmer, Palmer & Queen, 1977). Later, as postglacial sea levels rose, encroaching sea water drowned large portions of the caves. Continuing collapse of overlying rock into the large solutionally formed voids created the irregular chambers and fissure entrances that are commonly seen in Bermuda's caves. Extensive networks of submerged passageways, developed primarily at depths between 17 and 20 m below present sea level, interconnect otherwise isolated cave pools. These passages, only accessible to divers, are well covered at all depths with impressive stalactites and stalagmites, confirming that the caves must have been dry and air-filled for much of their history.

The sea-level, brackish pools located in the interior and/or entrances of Bermuda's caves are classified as anchialine habitats. The term anchialine was coined by Holthuis

(1973) to describe “pools with no surface connection to the sea, containing salt or brackish water, which fluctuates with the tides.” Bermuda’s cave pools have a thin, brackish layer at the surface, overlying fully marine waters at depth (Sket & Iliffe, 1980; Iliffe, Hart & Manning, 1983). In the caves bordering Harrington Sound, subterranean waters tidally exchange with the sea through coastal springs. Caves farther inland typically contain slowly moving or near-stagnant waters. The input of food in most caves is primarily derived from the sea itself, although chemosynthethic bacteria may provide an additional source of organic matter to the anchialine cave ecosystem (Pohlman, Cifuentes & Iliffe, 2000).

Even on a small island like Bermuda, caves are not evenly distributed. Most of Bermuda’s 150 known caves are located in the Walsingham district, a kilometre-wide isthmus separating Castle Harbour and Harrington Sound (see map). This part of Bermuda consists of hilly, wooded terrain underlain by highly karstified limestone containing numerous caves and dolines. While most of these caves initially appear to be relatively small and end in tidal saltwater pools, diving explorations have shown them to be highly integrated. The caves consists of large, subsealevel chambers, floored with breakdown and profusely decorated with speleothems. The Walsingham Caves consists of two larger and mostly underwater cave systems, Walsingham (1300 m long with seven known entrances) and Palm (500 m long with five entrances), plus many smaller caves.

Bermuda’s anchialine caves, especially the Walsingham Caves, are inhabited by an unexpectedly high diversity of unique and previously unknown marine invertebrates. Included among this fauna are extremely ancient relict organisms that can be



Walsingham Caves, Bermuda:
Location of the Walsingham caves district, Bermuda.

legitimately referred to as "living fossils". As examples, the copepod *Erebonectes* is one of the most primitive of known calanoids, while the *Antrisocopia* agrees in many ways with the description of a theoretical ancestral copepod. Some of Bermuda's cave-dwelling species have close affinities with Old World cave and groundwater fauna, and probably colonized the subterranean habitats on Bermuda early in the island's history when the Atlantic was much narrower. The amphipod genus *Pseudoniphargus,* which has two species in Bermuda caves, was previously known only from caves and groundwater around the Mediterranean, the Azores, and the Canary Islands. Other animals inhabiting Bermuda caves have close relatives occurring in caves on other isolated oceanic islands from both the Atlantic and Pacific. The misophrioid copepod *Speleophriopsis* includes cave species from Palau, Bermuda, and the Balearic Islands. Finally, some animals are closely related to deep-sea species. The order Mictacea, for example, includes cave species from Bermuda and the Bahamas, plus deep-sea species from the Atlantic and Indo-Pacific. Thus, Bermuda's cave species are providing important clues about the evolution and dispersal of present oceanic species.

Belying the considerable age of both caves and the obligate cave-dwelling organisms that inhabit them, this environment is one of the rarest and most delicate on Earth. The potential impact of human activity on caves is profound—over time, even just visiting of caves can result in irreparable damage. The four primary threats to Bermuda caves are: (1) construction and quarrying activities, (2) water pollution, (3) dumping and littering, and (4) vandalism (Iliffe, 1979). Quarrying has destroyed numerous significant caves, particularly at Government Quarry in the Walsingham district. Construction of luxury town homes directly on top of Church and Bitumen Caves may destroy their endangered anchialine fauna. The Karst Waters Institute twice named these two caves to their list of the Top Ten Most Endangered Karst Ecosystems on Earth. The anchialine pool of Bassett's Cave, once said to be the longest and geologically most instructive cave in Bermuda (Nelson, 1840), was used by the United States Navy as a cesspit for disposal of raw sewage and waste fuel oil. Many of Bermuda's caves have been used as dumping sites. The bulldozing of large piles of partially burned rubbish into the anchialine pool of Government Quarry Cave resulted in depletion of dissolved oxygen and anaerobic production of hydrogen sulfide. Groundwater circulation transmitted this pollution to at least five other caves as much as half a kilometre or more away (Iliffe, Jickells & Brewer, 1984). In these polluted caves, all stygobitic species have disappeared. Since many of Bermuda's cave species are endemic and are often restricted to only one cave or cave system, pollution or destruction of these habitats can result in the extinction of entire species. Finally, few of Bermuda's larger caves have escaped the effects of vandals maliciously breaking and removing fragile stalactites and stalagmites or defacing cave walls with their names.

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See also **Anchialine Habitats; Marine Cave Habitats**

Works Cited

Baillie, J. & Groombridge, B. (editors) 1996. *1996 IUCN Red List of Threatened Animals,* Gland, Switzerland: IUCN and Washington, DC: Conservation International

Holthuis, L.B. 1973. Caridean shrimp found in land locked saltwater pools at four Indo-West Pacific localities (Sinai Peninsula, Funafuti Atoll, Maui and Hawaii Islands), with the description of one new genus and four new species. *Zoologische Verhandelingen,* 128:1–48

Iliffe, T.M. 1979. Bermuda's caves: a non-renewable resource. *Environmental Conservation,* 6:181–86

Iliffe, T.M. 1994. Bermuda. In *Encyclopaedia Biospeologica,* vol. 1, edited by V.Decu & C.Juberthie, Moulis and Bucharest: Société de Biospéleologie

Iliffe, T.M., Hart, C.W. Jr & Manning, R.B. 1983. Biogeography and the caves of Bermuda. *Nature,* 302:141–42

Iliffe, T.M., Jickells, T.D. & Brewer, M.S. 1984. Organic pollution of an inland marine cave from Bermuda. *Marine Environmental Research,* 12:173–89

Nelson, R.J. 1840. On the geology of the Bermudas. *Geological Society of London Transactions, Series 2,* 5:103–23

Palmer, A.N., Palmer, M.V. & Queen, J.M. 1977. Geology and origin of the caves of Bermuda. In *Proceedings of the 7th International Congress of Speleology,* edited by T.Ford, Sheffield

Pohlman, J.W., Cifuentes, L. & Iliffe, T.M. 2000. Food web dynamics and biochemistry of anchialine caves: a stable isotope approach. In *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F.Humphreys, Amsterdam and New York: Elsevier

Sket, B. & Iliffe, T.M. 1980. Cave fauna of Bermuda. *Internationale Revue der Gesamten Hydrobiologie,* 65:871–82

Further Reading

Iliffe, T.M. 1992. Anchialine cave biology. In *The Natural History of Biospeleology,* edited by A.I.Camacho, Madrid: Museo Nacional de Ciencias Naturales

Review article on anchialine biodiversity, biogeography and evolution

Iliffe, T.M. 2000. Anchialine cave ecology. In *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F. Humphreys, Amsterdam and New York: Elsevier This review article contains water quality and tide data from Bermuda caves, as well as information on anchialine habitat, ecology, biodiversity, and evolution.

Sterrer, W. 1992. *Bermuda's Marine Life,* Bermuda: Bermuda Natural History Museum and Bermuda Zoological Society A well-illustrated introductory guide to 225 marine species, including bacteria, plants, invertebrates, fishes, reptiles, birds, and mammals.

Useful Websites

Anchialine Caves and Cave Biology, http://www.cavebiology.com/. This website contains detailed information on the anchialine caves and cave fauna of Bermuda, the Bahamas, and the Yucatan Peninsula.

WATER TRACING

Water tracing can be defined as the use of natural or induced properties to label a body of water, allowing detection of that water at some point downstream, thereby gaining understanding of the character of the flow path followed by the water. In karst environments, water tracing finds particular value in defining the path followed by inaccessible underground streams. The primary application for this is in catchment definition and related water and land use management, but it finds applications amongst hydrogeologists for clarifying conduit network structure, and is increasingly used in litigation concerning karst groundwater rights or contamination. The following review is intended to present the primary elements of karst water tracing, but particular attention should be paid to the legal and ethical issues associated with tracing public and private water supplies.

Tracers

Natural tracing exploits existing properties of water, whereas artificial tracing implies deliberate alteration of the water. Tracers can be classified as physical, chemical, isotopic, and biological, each with its corresponding analytical method. Physical traces may be natural or artificial physical impulses (e.g. flood or dam release pulses; Ashton, 1966; Williams, 1977) or changes in temperature or turbidity. In general, flood impulses travel faster than the water originally comprising the flood, especially in closed conduits. Microscopic inert particles (e.g. *Lycopodium* spores) are a specialized form of physical tracer, sometimes used to simulate transmission of bacteria. Chemical tracers can be simple ionic soluble materials like salt, or specialized fluorescent dyes like uranine (fluorescein sodium) or Rhodamine WT (e.g. Smart & Laidlaw, 1977). Stable and radioactive isotopes are highly detectable and may vary naturally, or in response to a deliberate injection. The isotopes of water (^{2}H, ^{3}H, ^{18}O) are particularly valuable, as they can be considered to mimic water most effectively. Biological tracers are often present inadvertently, as in the detection of coliform bacteria in wells. However, artificial bacteriophages have been used (Kennedy, 2000), and DNA-based tracing is now possible (Sabir *et al.*, 2000).

Natural tracing includes any natural chemical species, such as dissolved calcium, but more particularly refers to the stable isotopes of the oxygen and hydrogen in water, sulfur, carbon and chlorine, and the radioactive isotopes of hydrogen and carbon. These environmental isotopes are widely used in groundwater studies, but their success depends on the existence and consistency of marked contrasts in source composition. In contrast, artificial tracing allows greater control on the magnitude of the tracer signal and the specificity of the site to be traced, and is widely used in karst hydrogeology.

Apart from the issue of mimicking the movement of water as closely as possible, tracer selection depends on practical issues of cost, danger, sensitivity of analysis, characteristics of background (naturally occurring) concentrations, ease of handling and risk of contamination, and ability to discriminate a range of tracers at one time. Fluorescent dyes are the predominant tracer used at present. There are a number of “safe” dyes (e.g. uranine, eosine) which can be detected at the parts per trillion level, although they suffer to some extent from retardation, photo-decay and variable background (e.g.

Käss, 1998). Analytical sensitivity should not be the primary criterion in tracer selection; it is important to consider all aspects of tracer performance.

Applications and Relevance

Tracing in karst is most widely used in "point-to-point" mode, to define the trajectory taken by underground water. Typically, this implies the identification of the destination spring of a sinking stream. Successful establishment of a rapid link between a sinking stream and a spring means that there is a conduit link between the point of injection and the point of recovery. A series of point-to-point tracer tests can be used to establish a regional network of underground flow routes analagous to the network of a surface river system. Most karst systems are dendritic systems with a number of tributaries feeding one trunk conduit. However, parallel conduits and distributary systems, where a single conduit feeds a number of springs, are also found, e.g. the Mendips in the United Kingdom (Atkinson, 1977) and Central Kentucky karst (Quinlan & Ewers, 1989). Replication of tracer tests under different flow conditions may show different flow routing, often arising from adoption of underground overflow routes by the floodwater. Monitoring the time required for a tracer to reappear generates travel time and, with an estimate of (linear) distance, groundwater velocity. Conduit velocities in karst conduits are usually between 100 m d^{-1} and 10 km d^{-1} with averages of 1700 m d^{-1} (Worthington, Davies & Ford, 2000). There have been many successful traces over distances as great as several tens of kilometres.

Tracing provides a major tool in the hydrogeological characterization of karst aquifers for water resource studies. Defining the regional network allows the catchment areas associated with springs or wells to be determined, permitting appropriate land use management to be developed. A major feature of karst land use schemes is pre-emptive definition of contaminant trajectories; the velocity of karst groundwater in conduits is so rapid that it does not permit reaction in the event of contamination. The way in which a tracer is modified, in passing through the aquifer from the initial spike injected, provides an analogy to the dilution and dispersion of potential contaminants. In addition, tracing also allows systematic tracking of the source of contaminants appearing in karst springs or wells. Effective tracing provides unequivocal evidence of groundwater trajectories. Flow rates revealed by tracing may be orders of magnitude faster, and contaminant concentrations much higher, than predicted by conventional groundwater models. In mantled karst, tracing may be quite challenging, and recourse to borehole injection methods may be necessary.

Approaches

A variety of styles of tracing are available. The simplest methods are inexpensive, but may be aesthetically unacceptable, and yield less compelling information than more sophisticated methods. Qualitative tracing involves nothing more than the identification of the tracer in the water. Visual detection generally requires high concentrations of tracer and is considered unacceptable for ecological, aesthetic, and legal reasons. Normally, a water sample should be analysed to confirm the presence of tracer. Qualitative tracing provides point-to-point and associated routing and catchment information. Semi-quantitative tracing involves defining the concentration of the tracer in the water over time. The resulting time-concentration breakthrough curve provides unequivocal evidence of the tracer, and can be used in determining characteristics of the traced route. Quantitative tracing combines concentration measurements with flow determinations, permitting the compilation of mass-breakthrough curves. The area under the mass-breakthrough curve indicates the total mass of tracer collected at a site. Comparison of this value to the mass of tracer injected allows definition of tracer recovery. This may be used to identify the presence of other flow routes, but can also arise from more insidious loss of the tracer by decay or adsorption on surfaces.

Injection

Successful injection of tracer requires total and immediate dissolution or dispersion in the receiving water. Clean injection is easier with liquids than powders, and may require use of an injection hose and flushing with a large volume of water to deliver the tracer effectively. In addition to streams, tracer may be injected into boreholes, closed depressions, fissures, or spread on the ground surface, with increasing likelihood of failure or massive loss of tracer as the tracer is increasingly removed from major conduits in the karst. In general, the mass injected should allow a coherent signal above background fluctuations, but should not compromise safety or aesthetics. The quantity of tracer for a conduit trace can be based on calculations (Field, 2003; Worthington & Smart, 2003). Traces using wells or on the ground surface will typically require much larger quantities.

Sampling and Sample Analysis

Personal detection of a tracer by eye, smell or taste is simplest, but provides the least coherent information. Convenient integrative sampling of fluorescent dyes is possible with granular activated charcoal packets (fluocapteurs) deployed in a range of sites and replaced at intervals of hours to weeks. The dyes are eluted from the charcoal with an alkaline-alcohol mixture, but the resulting mix of compounds may prevent coherent interpretation. Discrete water samples can be collected manually or by automatic water samplers. While laborious, this allows construction of time-concentration curves at the resolution of the sampling interval. Continuous sampling and analysis provides the most detailed and immediate tracer data, but increases the field logistic costs. Examples include *in situ* detection of common salt tracer with a conductivity meter and detection of fluorescent dyes using a field fluorometer. The sampling method is selected based upon the tracer used, the application and the resources available.

The mode of analysis depends on the same considerations. Thus fluorescent dyes can be detected visually, with a colorimeter, a filter fluorometer or a spectrofluorometer, with increasing discrimination and sensitivity. Good protocol demands the development of analytical standards, replicates, and a range of controls in the laboratory and in the field.

Interpretation

Point-to-point tracing provides simple positive and negative tracer results that can be interpreted to generate the “hydrogeography” of an aquifer showing linkages, networks and variable routing. In practice, this is often complicated by equivocal or inconsistent results and dependence on flow conditions in the aquifer. Features such as crossovers, convergence, divergence, and conditional routing may be identified. Catchments may be defined by aggregating and interpolating the traced routes to a particular destination.

Again, results may be disjointed, fuzzy, or variable, compared to the discrete catchments associated with surface rivers.

Tracer travel times can be converted to “linear” velocities using the distance between the injection and sampling points. Velocity is an indicator of relative conduit openness. The relationship of velocity to discharge can demonstrate whether the conduit is predominantly closed (water filled), giving a velocitydischarge power function with an exponent of 1; an open channel will yield a power function with an exponent <1. This is because changes in discharge may only be accomplished by varying the velocity in a closed conduit, whereas an open channel may also vary in cross-sectional area. If the power function has an exponent >1, either the data are corrupt, or there has been a routing switch involving multiple conduits.

Time concentration and mass curves allow more sophisticated analysis of the hydraulics and behaviour of the tracer. Tracer concentration typically declines more gradually than it rises, because of storage in backwater areas (dead zones) or adsorption of the tracer. Compound peaks can arise from multiple routes or unsteady flow effects (temporary dilution or redirection of the tracer). A well-defined breakthrough curve can be used to define time to peak, mean travel time, and a dispersion coefficient for the conduit. If 100% recovery of tracer is assumed, then the ratio of the mass injected to the area under the time concentration curve provides the discharge from the system. A rapidly developing field is the computer analysis of tracer breakthrough curves to allow determination of parameters (average properties) of the traced system; for example, the conduit roughness, dispersion coefficient, and dead zone volume (e.g. Field & Pinsky, 2000).

Practice and Ethics of (Dye) Tracing

Effective groundwater tracing requires maximizing the likelihood of a correct positive while respecting the impact that the tracing may have on people and the environment. Loss of a tracer leaves uncertainty as to the explanation. In some cases tracer is held in storage until a subsequent flood, in other cases failure to monitor the correct site or delayed or infrequent sampling may be the cause. The resulting ambiguity means that the particular tracer may not be used again with confidence in that area. False positive results are similarly confounding, although the error may not be apparent. The main cause of false positives is misinterpreted background or contamination. Background arises from substances that can be mistaken for the tracer; an example is the fluorescence arising from organic matter that can be mistaken as a tracer dye. Contamination arises from the presence of the tracer from sources other than the trace. This can arise from environmental presence or release of the tracer, for example the green fluorescent dye uranine is widely used in antifreeze fluids, and is ubiquitous in industrialized regions. Autocontamination occurs when the operator transfers tracer to the samples, a particular problem with activated charcoal and powdered dyes. A false positive can also arise from uncoordinated tracing in the same region.

Maximizing the likelihood of a correct positive trace requires knowledge of the site, good protocol, and experience. Once regional geology, hydrology, and local knowledge have been compiled, it is best to undertake a simple, even self-evident trace as a proof of practice. More sophisticated tracing can thus be built on local experience.

There is much sensitivity to the deliberate contamination of water supplies, not only for aesthetics and health, but because labelled water may not be usable. For example, colorimetric determination of residual chlorine in drinking water is difficult in heavily dyed water. Future tolerance and support of tracing rests on local experience. In much of the world, tracing is regulated, not only to prevent unnecessary or ill-conceived tracing with inappropriate materials, but also to ensure that the results of bona fide tracer tests are duly reported and archived.

Where tracing is undertaken as an aspect of litigation, then particularly stringent protocols must be adopted. The appropriate procedures depend on the regional and legal context and are best left for professional practitioners. One particularly difficult issue is demonstrating that the tracer detected is indeed the material injected. Most tracers are not unique, and background and contamination can occur in any trace. A time-concentration curve provides less equivocal evidence than a positive charcoal detector, but a fully quantitative mass recovery is more compelling.

Conclusion

Tracing remains the primary tool of the karst hydrogeologist, and it provides essential information on groundwater flow. However, it is not the only tool available, and it is much more effective when employed along with appropriate hydrochemical, geological and hydrological techniques.

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Works Cited

Ashton, K. 1966. The analyses of flow data from karst drainage systems. *Transactions of the Cave Research Group of Great Britain,* 7(2):161–203

Atkinson, T.C. 1977. Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *Journal of Hydrology,* 35:93–110

Field, M.S. & Pinsky, P.F. 2000. A two-region nonequilibrium model for solute transport in solution conduits in karst aquifers. *Journal of Contaminant Hydrology,* 44:329–51

Field, M.S. 2003. A review of some tracer design equations for tracer-mass estimation and sample-collection frequency. *Environmental Geology,* 43:867–881

Worthington, S.R.H., and Smart, C.C., 2003, Empirical determination of tracer mass for sink to springs tests in karst. In: *Proceedings of the ninth multidisciplinary conference on sinkholes and the engineering and environmental impacts of karst* (Ed. B. Beck). American Society of Civil Engineers, Reston, Virginia., pages 287–295

Käss, W. 1998. *Tracer Techniques in Geohydrology,* Rotterdam: Balkema (original German edition published 1992)

Kennedy, K.G. 2000. Bacteriophages as particle migration indicators in subsurface environments. In *Tracers and Modelling in Hydrogeology,* edited by A.Dassargues, Wallingford, Oxfordshire: IAHS

Quinlan, J.F. & Ewers, R.O. 1989. Subsurface drainage in the Mammoth Cave area. In *Karst Hydrology: Concepts from the Mammoth Cave Area,* edited by W.B.White & E.L.White, New York: Van Nostrand Reinhold

Sabir, L., Haldorsen, S., Torgersen, J., Aleström, P., Gaut, S., Pedersen, T.S., Colleuille, H. & Kitterød, N.-O. 2000. Synthetic DNA tracers: Examples of their application in water related studies. In *Tracers and Modelling in Hydrogeology,* edited by A. Dassargues, Wallingford, Oxfordshire: IAHS

Smart, P.L. & Laidlaw, I.M.S. 1977. An evaluation of some fluorescent dyes for water tracing. *Water Resources Research,* 13: 15–33
Williams, P.W. 1977. Hydrology of the Waikoropupu Springs: A major tidal karst resurgence in northwest Nelson, (New Zealand). *Journal of Hydrology,* 35:73–92
Worthington, S.R.H., Davies, G.J. & Ford, D.C. 2000. Matrix, fracture and channel components of storage and flow in a Paleozoic limestone aquifer. In *Groundwater Flow and Contaminant Transport in Carbonate Aquifers,* edited by C. Wicks & I.Sasowsky, Rotterdam: Balkema

WATER TRACING: HISTORY

The use of tracers to determine karst groundwater flow reportedly began in 10 AD when Philippus used chaff to trace the spring that is the source of the Jordon River (Whiston, 1957). Mayer used chaff and sawdust as tracers in southwest Germany during the 17th century, and Hagler used salt (sodium chloride) to trace a sinking stream to the water supply spring for Lausen, Switzerland in an experiment to find the source of a typhoid epidemic in 1872 (Käss, 1998). Three tons of sodium chloride were used in 1899 to trace the sinking at Malham Tarn in Yorkshire, England (Ford & Williams, 1989).

Fluorescein dye, discovered in 1871 and combined with salt to increase its fluorescence and solubility, was first used by Knop to trace the stream sinks of the upper Danube River to Aach Spring in Germany in 1877 (Knop, 1878). Visual observation of the green dye, sodium fluorescein (uranine, CI Acid Yellow 73), at springs was used as the primary karst tracing technique until the late 1950s. There were, however, problems associated with the visual detection method, including: (1) large quantities are required for detection and low dye concentrations may be missed; (2) springs and downstream water become visually impaired; (3) a large amount of labour is necessary for monitoring; and (4) dye may resurge at a spring or springs not monitored.

A major breakthrough solving most of the above problems occurred when Dunn (1957) demonstrated that sodium fluorescein could be adsorbed by granular activated coconut charcoal and then eluted from the charcoal by a solution of potassium hydroxide in ethanol. With this technique, granular charcoal packets in a wire or fibreglass screen mesh are placed in all springs where injected dye could possibly resurge. These charcoal packets (called dye receptors or fluocapteurs) are exchanged at regular intervals and then, after being eluted, dye extracted from the charcoal can be observed with a bright light. Visual detection of the dye in the charcoal elutant is possible even though it is not visually detectable in the resurgent water since dye adsorbs onto the charcoal and accumulates, resulting in higher concentrations as the dye cloud flows past.

In the early 1970s, Smart and Brown (1973) demonstrated that rhodamine WT (CI Acid Red 388), a red dye, could also be adsorbed onto charcoal granules and eluted with a solution of ammonium hydroxide, 1–propanol, and distilled water. The technique of detecting sodium fluorescein and rhodamine WT on charcoal dye receptors resulted in numerous dye traces performed by researchers in Europe and North America. However, trace results remained unreliable when insufficient dye was injected. Background fluctuation was also a problem, and interpretation under a bright light was very subjective.

The next dye tracer technique breakthrough was the use of a fluorometer for analysis, an instrument that quantitatively measures dye concentrations in water samples and charcoal elutant (Käss, 1967; Wilson, 1968). When fluorescent materials are irradiated, they emit light, and the emitted or fluoresced light always has a longer wavelength than that which is absorbed during irradiation. The fact that each fluorescent dye exhibits its own combination of excitation and emission spectra when analysed by a fluorometer, greatly increased the detectability and objectivity in the detection of fluorescent dyes.

Glover (1972) introduced the use of commercial optical brighteners to trace groundwater. Small bundles of surgical quality cotton, not treated with any brightening agent, are used as receptors and changed at regular intervals. Adsorbed dye is visually detected by its characteristic light blue fluorescence when observed under an ultraviolet light. Eight fluorescent dyes that could be detected using charcoal or cotton dye receptors were evaluated by Smart and Laidlaw (1977), and by the mid-1970s numerous dye traces were being performed, primarily using three dyes, often injected simultaneously at three different locations: sodium fluorescein, rhodamine WT, and optical brightener.

At the same time that these powerful dye tracer techniques were being developed in the mid 1970s, Lambert (1976) and Quinlan and Ray (1981) demonstrated that the water table could be contoured in karst aquifers by measuring the water level elevation in uncased water wells in the Bowling Green and Mammoth Cave, Kentucky, United States areas. A combination of dye tracing and potentiometric surface investigations permitted the delineation of karst groundwater basins and the approximation of the actual flow routes of subsurface streams through karst aquifers.

Technological advances in the late 1980s brought karst researchers the scanning spectrofluorophotometer, an instrument that provides the lowest detection limits and the most reliable dye analysis. A synchronous scan is performed with the excitation and emission monochrometers kept at a fixed wavelength separation during the scan. The emission spectra from the synchronous scan is then displayed on a computer monitor. Scanning spectrofluorophotometers allow four to six dyes to be injected simultaneously and then detected in water and charcoal elutant samples. The dyes usually used, because of less overlap between spectra, are: (1) tinopal CBS-X (CI Fluorescent Brightener 351); (2) sodium fluorescein (CI Acid Yellow 73); (3) eosine (CI Acid Red 87); and (4) sulphorhodamine B (CI Acid Red 52). Use of the spectrofluorophotometer permits dye detection for several dyes at concentrations of about 1 part per trillion, and if charcoal dye receptors are used to accumulate and concentrate the dye, it can be detected in the elutant even though it never reached a concentration of 1 part per trillion in the water that flowed past the receptor.

Dye tracing has evolved from a simple visual research tool for determining the resurgence for a sinking stream to a highly technical one used to provide definitive results concerning groundwater flow in karst aquifers for regulatory purposes. Dye traces and potentiometric surface mapping combined with geologic information about stratigraphy and structure usually permit the construction of a site conceptual hydrogeological model. This type of investigation is often required by groundwater regulatory agencies in the United States as part of a groundwater monitoring and remediation plan for karst aquifers. It is therefore imperative that dye traces be performed following strict adherence to procedures and protocols (Crawford & Roach, 2001). The author estimates that 6000 to 8000 dye traces have been performed to trace karst groundwater flow in the United States since 1970. Most of them have been performed by private consulting firms to determine the flow of contaminated groundwater or to establish groundwater flow for monitoring purposes.

Other Tracers

Spores of the Canadian club moss, *Lycopodium clavatum* L., were used for groundwater tracing by Mayr (1953) and further developed by Maurin and Zötl (1959) and Dechant (1959). Lycopodium spores, with an average diameter of only 33 µm, are usually dyed, often with fluorescent dyes, previous to injection. With spores dyed different colours, four to six simultaneous traces can be performed. Nylon plankton nets with a sieve opening of 25 µm are used to collect the spores at emergent springs, and analysis is performed by counting the spores under a microscope. Numerous spore drift traces were performed in the alpine karst and German Uplands of Europe. However, problems associated with the time and expense of dyeing the spores, potential spore contamination influencing the results, siltation of the plankton nets, and time and potential operator error in identifying and counting the spores under a microscope, have resulted in spore drift tracing being largely replaced by the superior fluorometric techniques (Smart *et al.*, 1986).

Fluorescent microspheres are occasionally being used as tracers, but they tend to have the same problems as the spore drift technique. However, since they are similar in size and have similar transport behaviour as bacteria, they are sometimes used for hygienic evaluations. Bacteria and other micro-organisms have also been used as well as bacteriophages, but the considerable amount of work involved in their preparation, handling, and examination have limited their use.

Salts, such as sodium chloride and lithium and potassium chlorides have been used as tracers as well as non-fluorescent dyes, but the large quantities required have limited their use (Brown *et al.*, 1972). Radioactive isotopes have been used, and for some species the public health disadvantages may be overcome by post-sampling activation analysis, but very specialized facilities are required (Kruger, 1971). Radioactive isotope tracers tend to be costly and hazardous, and they need skilled handling by personnel supported by atomic laboratories.

An additional method of tracing karst waters that does not require the use of tracer substances is known as flood pulse analysis. The pulse may result from a natural event such as a storm or the melting of snow/glacier ice, or it may be created artificially by the breaching of a small temporary dam or by opening the sluice gates on a permanent structure (Ashton, 1966). Flood pulses were used successfully in 1879 as part of a series of notable early experiments to trace the source of the River Aire in Yorkshire, England (see summary in Smith & Atkinson, 1977). These traces are rarely used, but they do serve to provide point-to-point connections for karst aquifers where dye tracing is difficult, such as confined karst aquifers that discharge at artesian springs. For example, Williams (1977) showed that pressure pulses produced by release from a hydroelectric dam in the Takaka Valley, New Zealand, took only 9–11 hours to travel over 20 km through a marble aquifer to an artesian spring. Tritium measurements at the spring suggest a minimum flow through time of 2–4 years (Stewart & Down, 1982).

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Works Cited

Ashton, K. 1966. The analyses of flow data from karst drainage systems. *Transactions of the Cave Research Group of Great Britain,* 7(2):161–203
Brown, R.H., Konoplyantsev, A.A., Ineson, J. & Kovalevsky, V.S. (editors) 1972. *Groundwater Studies: An International Guide for Research and Practice,* Paris: UNESCO
Dechant, M. 1959. Das Anfärben von Lycopodiumsporen. *Steirische Beiträge zür Hydrologeologie,* 11:145–49
Dunn, J.R. 1957. Stream tracing: Mid-Appalachian region, *National Speleological Society Bulletin,* 2:7
Ford, D.C. & Williams, P.W. 1989. *Karst Geomorphology and Hydrology,* London and Boston: Unwin Hyman
Glover, R.R. 1972. Optical brighteners—a new water tracing reagent. *Transactions of the Cave Research Group of Great Britain,* 14(2):84–88
Käss, W. 1967. Erfahrungen mit Uranin bei Farbversachen. *Steirische Beiträge zür Hydrologeologie,* 18/19:123–340
Käss, W. 1998. *Tracing Technique in Geohydrology,* Rotterdam: Balkema (originally published in German, 1992)
Knop, A. 1878. Über die hydrographischen Beziehungen zwischen der Donau und der Aachquelle im badischen Oberlande. *Neues Jahrbuch für Mineralogie,* 350–63
Kruger, P. 1971. *Principles of Activation Analysis,* New York: Wiley
Lambert, T. Wm. 1976. *Water in a Limestone Terrane in the Bowling Green Area, Warren County, Kentucky,* Kentucky Geological Survey, Report of Investigations 17, Series 10, 43
Maurin, V. & Zötl, J. 1959. Die Untersuchung der Zusammendhänge unterirdischer Wässer mit besonderer Berücksichtigung der Karstvarhältnisse. *Steirische Beiträge zür Hydrologeologie,* 11:5–184
Mayr, A. 1953. Blütenpollen und pflanzliche Sporen als Mittel zur Untersuchung von Quellen und Karstwässern. *Anzeiger der Österreichische Akademie der Wissenschaften, Mathom—naturwiss. Klass,* 90:94–98
Quinlan, J.F. & Ray, J.A. 1981. *Groundwater Basins in the Mammoth Cave Region, Kentucky,* map, Mammoth Cave, Kentucky: Friends of the Karst
Smart, P.L. & Brown, M.C. 1973. The use of activated carbon for the detection of the tracer dye Rhodamine WT. *Proceedings of the 6th International Speleological Congress,* Praha: Academica, vol. 4: 285–92
Smart, P.L. & Laidlaw, I.M.S. 1977. An evaluation of some fluorescent dyes for water tracing. *Water Resources Research,* 13: 15–23
Smart, P.L., Atkinson, T.C., Laidlaw, I.M.S., Newson, M.D. & Trudgill, S.T. 1986. Comparison of the results of quantitative and non-quantitative tracer tests for determination of karst conduit networks: An example from the Traligill basin, Scotland. *Earth Surface Processes and Landforms,* 11:249–61
Smith, D.I. & Atkinson, T.C. 1977. Underground flow in cavernous limestone with special reference to the Malham area. *Field Studies,* 4:597–616
Stewart, M.K. & Downes, C.J. Isotopic hydrology of Waikoropupu Springs, New Zealand. In *Isotopic Studies of Hydrologic Processes,* edited by E.C.Perry & C.W.Montgomery, DeKalb, Illinois: Northern Illinois University Press
Whiston, W. 1957. *The Life and Works of Flavius Josephus,* Philadelphia: Winston
Williams, P.W. 1977. Hydrology of the Waikoropupu Springs: A major tidal karst resurgence in northwest Nelson (New Zealand). *Journal of Hydrology,* 35:73–92

Wilson, J.F. 1968. Fluorometric procedures for dye tracing. In *Techniques of Water-Resources Investigations,* Book 3, Chapter A12, Washington: United States Geological Survey

Further Reading

Crawford, N.C. & Roach, S.D. 2001. *Karst Groundwater Investigation Research Procedures,* Bowling Green, Kentucky: Crawford Hydrology Laboratory, Center for Cave and Karst Studies, Department of Geography and Geology, Western Kentucky University, http://www.dyetracing.com/

Käss, W. 1998. *Tracing Technique in Geohydrology,* Rotterdam: Balkema

WILDERNESS

There are two widely different definitions of wilderness—the legal and the social. At the legal extreme, wilderness can be narrowly defined as "an area of undeveloped land which retains its primeval character and influence, which appears to have been affected primarily by the forces of nature, and with the nearly undetectable imprint of man's work substantially unnoticeable" (Wilderness Society, 1984, p.27). The United States Wilderness Act of 1964, Section 2(c), recognizes a wilderness "as an area where the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain" (Lera, 2001). At the social extreme, it is whatever people perceive natural wilderness to be—potentially the entire universe.

Wilderness Management

In theory there are two alternatives to actually managing a wilderness. Firstly, all use could be prohibited. However, most wilderness philosophy believes that wild places should be used and enjoyed. Secondly, a *laissez-faire* attitude could be adapted, which is also in violation of the wilderness philosophy requiring protection and perpetuation (preservation), and would likely ensure that most wilderness would vanish. The focus clearly should be on preserving the natural integrity of the wilderness environment, while still providing for human use and enjoyment, without needless restrictions to protect the area.

The many benefits derived from wilderness depend on the preservation of its undisturbed natural integrity. "Wilderness", "National Park", and "World Heritage Site" may seem to be mutually contradicting terms. If wilderness areas were to be simply placed off-limits to human use, they would probably remain natural and unimpaired as they have for centuries. However, wilderness is a multiple-use human resource, addressing needs for: watershed protection, scientific research, habitat for threatened or endangered plant and animal species (as well as game and non-game fish and wildlife), and many types of non-motorized recreation. Without some sort of monitoring and control, many outstanding wilderness areas would begin to lose those very values for which they were designated. Wilderness management, therefore, is not the management of the physical and biological resources themselves, but of the human use of those resources. Some wilderness managers find themselves forced to manage resources, as invasive species have no respect for human-defined boundaries.

Major Issues Facing Cave Wilderness

Several issues must be resolved when caves are considered for wilderness designation. Each significant cave needs to be inventoried for its unique list of wilderness values, uses of the land above the cave and impacts of those uses, definition of appropriate wilderness boundaries, and an established methodology to manage the cave wilderness. Cave wilderness boundaries should be defined in a more flexible manner than surface wilderness boundaries, as caves are best measured linearly rather than areally. The surface area under which a cave lies may be known at the time of wilderness designation, but allowances must be made to include additional cave passages within the wilderness area as they are explored, even if they extend under land managed by different agencies.

Cave features are very different from surface features and require a different management approach. However, the public's use of a cave wilderness for recreation, research, education, or inspiration are analogous to similar uses of surface land wilderness areas. Determining the cave's carrying capacity or limits of acceptable change will be a key—and difficult—issue in developing cave wilderness management guidelines. The problem is exacerbated by the fact that whereas on the surface the environment is largely self-renewing—given adequate control over visitor numbers and behaviour—the same is not true of caves. In areas with increasing pressures on recreational resources, the successful management of cave wilderness areas is of particular importance. The welfare of such resources should not be neglected—irrespective of location or political motivation—because of the nature and number of impacts that may occur, many of them irreversible. Any wilderness disturbance must be carefully planned and controlled in order to optimize the resource.

Defining the Boundaries of Underground Wilderness

The US Federal Cave Resource Protection Act provides the opportunity to begin wilderness assessment for all significant caves on federal lands (Lera, 2000). In 2001, the National Park Service defined their authority over cave wilderness, as:

> …all cave passages located totally within a surface wilderness boundary will be managed as wilderness. Caves that have entrances within wilderness, but contain passages that may extend outside the surface wilderness boundary, will be managed as wilderness. Caves that have multiple entrances located both within, and exterior to, the surface wilderness boundary, will be managed consistent with the surface boundary; those portions of a cave within a wilderness boundary will be managed as wilderness. (National Park Service, 2001)

Lechuguilla Cave, New Mexico, for example, is located within the boundaries of the Carlsbad Caverns Wilderness Area, and is managed as wilderness by the National Park Service.

Karst ecosystems may be disturbed either directly through physical intrusion into, or direct interference with, the cavern environment (e.g. effluent disposal), or indirectly through the alteration of the natural surface overlying the cave and of the entire water catchment area of the cave. The disturbance of underground wilderness areas in karst ecosystems is a complex process, which varies in significance according to the nature of the impact. Where disturbance is totally uncontrolled, it is the most detrimental and therefore least desirable. Landscape management of karst ecosystems will protect and preserve cave wilderness. There are several cave World Heritage Sites but not all would qualify as true wilderness. Perhaps the best example is the Nahanni Karst in Canada (see separate entry). The Tasmanian Wilderness World Heritage Area (see Australia entry) has a number of caves within its boundaries, but they are managed to the full spectrum of levels—from major tourist caves to totally unvisited and unmanaged caves. The Caves of the Aggtelek and Slovak Karst World Heritage site (see separate entry) is similar in that it contains major tourist caves and is also affected by tourism and quarrying.

As Frank Elger observed, "Ecosystems are not only complex, but more complex than we think." (Elger, 1977, p.3). With this in mind, we should be cautious about consciously manipulating the last of our true wilderness—the underground wilderness.

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See also **Conservation: Protected Areas; Ramsar Sites; World Heritage Sites**

Works Cited

Elger, F.E. 1977. *The Nature of Vegetation, its Management and Mismanagement: An Introduction to Vegetation Science,* Norfolk, Connecticut: Aton Forest Publishers

Lera, T.M. 2000. *A Summary of Legislation and Organizations Involved in the Preservation of Caves and Bats,* available at http://www.caves.org/section/ccms/bat2k/index.htm

Lera, T.M. 2001. Can underground wilderness remain a reality? *NSS News,* 59(3):64–66

National Park Service. 2001. Wilderness preservation and management: 6.3.11.2 Caves. In *2001 NPS Management Policies,* Washington DC: National Park Service, Department of the Interior; available at www.nps.gov/refdesk/mp/index.html

Wilderness Society. 1984. *The Wilderness Act Handbook,* Washington, DC: Wilderness Society

Further Reading

Agee, J.K. & Johnson, D.R. (editors) 1989. *Ecosystem Management for Parks and Wilderness,* Seattle: University of Washington Press

Green, M.J.B. & Paine, J. 1997. State of the world's protected areas at the end of the twentieth century. Paper presented at the *IUCN World Commission Symposium on Protected Areas in the 21st Century: From Islands to Networks, 24–29 November 1997, Albany, Australia* (unpublished; available at http://wcpa.iucn.org/pubs/pdfs/AlbanyConfReport.pdf)

Hendee, J.C., Stankey, G.H. & Lucas, R.C. 1991. *Wilderness Management,* 2nd edition, Golden, Colorado: North American Press

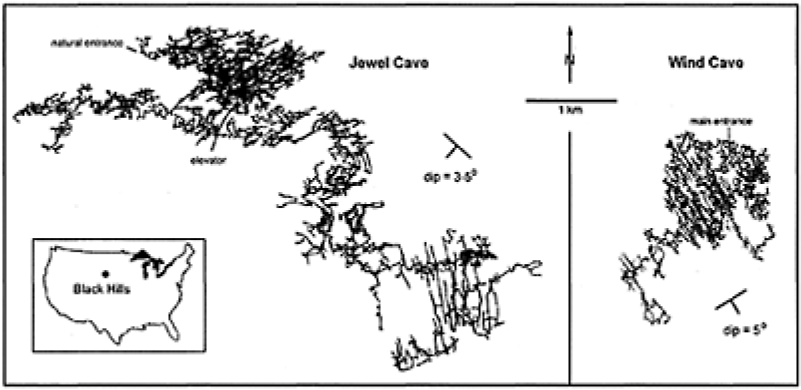
Willers, W.B. (editor) 1999. *Unmanaged Landscapes: Voices for Untamed Nature,* Washington, DC: Island Press

World Conservation Monitoring Centre and the IUCN Commission on National Parks and Protected Areas. 1994. *1993 United Nations List of National Parks and Protected Areas*, Gland, Switzerland and Cambridge: IUCN
World Conservation Monitoring Centre and the IUCN Commission on National Parks and Protected Areas. 1998. *1997 United Nations List of Protected Areas*, Gland, Switzerland and Cambridge: IUCN

WIND AND JEWEL CAVES, UNITED STATES

Caves of the Black Hills, South Dakota, are complex, multitiered network mazes, with an unusually complex history, spanning 300 million years (Palmer & Palmer, 1989). The Black Hills uplift is an elongate structural dome with a core of Precambrian igneous and metamorphic rocks, with dipping sedimentary rocks exposed along its flanks. Dips are typically 3–5 degrees, but in local areas are much steeper. Caves and karst are located almost exclusively in the Mississippian (lower Carboniferous) Madison Limestone, which has an average thickness of 100–150 m. The two largest caves, Jewel and Wind Caves, are among the world's longest, with 205 and 173 km of surveyed passages, respectively (Figure 1). The cave areas are located in a dry climate, with rainfall averaging about 450–500 mm yr^{-1}, and surface karst is limited to a few scattered dolines and sinking streams.

The Madison originally contained substantial sulfate deposits (Sando, 1985). While the formation was still exposed at and near sea level, early diagenetic changes included dissolution, mobilization, reduction, and calcite replacement of the original sulfates (Palmer & Palmer, 1995). Early voids, up to two metres in diameter, formed as the result of sulfate reduction to hydrogen sulfide, which oxidized as it rose into higher strata to form sulfuric acid. Near the end of the Mississippian Period (*c.* 300 million years ago) the Madison was exposed to surface karst development, which produced dolines and fissures, and some additional cave passages in the upper strata. Sands and clays of the Pennsylvanian (late Carboniferous) Minnelusa Formation filled all the dolines and most early cave passages. Deep burial, by as much as two kilometres of mainly detrital sediments, continued through the Cretaceous Period. Uplift of the Black Hills during the Laramide Orogeny (late Cretaceous—early Tertiary) exposed the Madison to erosion, and the onset of rapid groundwater flow during the early Tertiary formed the present caves. The present caves mainly follow earlier voids and diagenetically altered zones of Mississippian age. The conspicuous fracture pattern, extending radially outward from the centre of the Black Hills uplift, seems to indicate a post-Laramide age—but the diagenetic and paleokarst features follow those same trends, indicating that the Black Hills represented an active positive area, even during the Carboniferous. This resulted from reactivation of Precambrian structures during the early Carboniferous Antler Orogeny of western North America (Palmer & Palmer, 1989).



Wind and Jewel Caves, United States: Figure 1: Plan-view maps of Jewel Cave and Wind Cave, South Dakota. Jewel Cave is located in the southwestern flank of the Black Hills, and Wind Cave is located 30 km away in the southeastern flank. Based on maps by National Park Service staff and others.

Sandwiched between sandstones and shales, the Madison is one of the foremost artesian aquifers of the United States. Most groundwater flow feeds springs by rising along fractures in the overlying Minnelusa Formation. However, the caves reach the water table in only a few places and give no indication of extending indefinitely downdip into artesian regions. The caves do not extend to the bottom of the Madison, and in only a few places do they reach the base of the overlying Minnelusa Formation (mainly sandstone and shale).

The uppermost cave passages are irregular rooms that form a crudely planar zone, slightly discordant to the strata. Lower passages are mainly tall fissures following joints and minor faults (Figure 2; see also photograph in Speleogenesis: Deep-Seated and Unconfined). Intermediate levels are located within prominently bedded strata and consist of low, wide, rambling passages. The abundant cave tiers, at least six in places, are sub-parallel to the strata and show no horizontal levels (note contrast with Carlsbad Cavern and Lechuguilla Cave in New Mexico). Although a few passages contain small trickles of running water, there is no indication that discrete cave streams have contributed significantly to cave origin. Except for exhumed cave relics and sinking streams, surface karst is very scant, and the caves do not

Wind and Jewel Caves, United States: Figure 2: Tour route in Jewel Cave, showing irregular passage pattern, paleokarst remnants in ceiling, calcite wall coating, and sediments rich in manganese oxides (lower right wall). (Photo by Art Palmer)

appear to be related to present hydrologic patterns. Entrances are accidental intersections of the caves by surface erosion. Sediments consist mainly of sand and clay from redistribution of paleofills. Manganese oxides are common in Jewel Cave, either derived from paleofill or precipitated by oxidation from rising anoxic water.

Displacement of continuous rock spans indicates that some of the faults have been reactivated after cave development. Many cave passages intersect filled paleokarst voids as much as 100m below the top of the Madison, exposing bright red and yellow sand and clay that is only partly indurated. All of Jewel Cave, and the lower half of Wind Cave, possess a lining of calcite spar crystals up to 15 cm thick, except where removed by later dissolution or collapse.

The exact cave origin is unclear. Various authors have used the caves as examples of either artesian or thermal cave development. However, the layout of the caves makes it clear that mixing between waters of differing chemistry was responsible (Palmer & Palmer, 1989). Three sources are feasible: groundwater entering as sinking streams in the outcrop belt; rising thermal water from adjacent basins or from thermal convection; and diffuse infiltration through the overlying Minnelusa Formation. The fact that the caves are mostly concentrated beneath thin caps of sandstone, suggests that diffuse infiltration may have been more important than is generally recognized. Mixing of any of these three sources, which would differ in carbon dioxide content, would produce solutionally aggressive fluids. Widespread calcite wall coatings postdate cave development (Figure 2). They may represent stagnant thermal conditions, owing to blockage of springs around the perimeter of the Black Hills by the Oligocene White River Group. This group once extended over most of the cave region, and its remnants still persist in lowlands around the caves. The position of these remnants indicates that the present topography around the caves has not changed significantly from the late Eocene. Maximum cave enlargement is most likely of PaleoceneEocene age.

The present caves contain abundant evidence of their lengthy geologic history (Palmer & Palmer, 1995). Early diagenetic features include bedded breccias and breccia dykes, H_2S-related porosity, calcite replacement of primary sulfates, rinds of quartz, calcite, and secondary dolomite, calcite veins, and intense alteration of bedrock to a porous quartz-rich mass between calcite veins. Deep-burial deposits include clear scalenohedral calcite void coatings and euhedral quartz crystals. Boxwork in the caves, especially Wind Cave, is the result of exposure and weathering of early diagenetic zones, in which sulfuric acid altered clay-rich bedrock to a removable mass, while not affecting the early veins of gypsum, which were later replaced by calcite. The boxwork seen today is a combination of the relatively resistant calcite veins protruding from the highly weathered intervening bedrock. Early diagenetic alteration zones in the bedrock have been turned into friable, powdery fluff or sandy material, that is easily removed by gravity and by water during periodic water-table rises.

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See also **Paleokarst; Speleogenesis: Deep-seated and Confined Settings**

Works Cited

Palmer, A.N. & Palmer, M.V. 1989. Geologic history of the Black Hills caves, South Dakota. *National Speleological Society Bulletin,* 51:72–99

Palmer, A.N. & Palmer, M.V. 1995. The Kaskaskia paleokarst of the Northern Rocky Mountains and Black Hills, northwestern U.S.A. *Carbonates and Evaporites,* 10(2):148–160

Sando, W.J. 1988. Madison Limestone (Mississippian) paleokarst: a geologic synthesis. In *Paleokarst,* edited by N.P.James & P.W. Choquette, New York and London: Springer

Further Reading

Bakalowicz, M.J., Ford, D.C., Miller, T.E., Palmer, A.N. & Palmer, M.V. 1987. Thermal genesis of dissolution caves in the Black Hills, South Dakota. *Geological Society of America Bulletin,* 99: 729–38

Conn, H. & Conn, J. 1977. *The Jewel Cave Adventure: Fifty Miles of Discovery under South Dakota,* Teaneck, New Jersey: Zephyrus Press

Deal, D.E. 1968. Origin and secondary mineralization of caves in the Black Hills of South Dakota, U.S.A. *Proceedings of the 4th International Congress of Speleology, Ljubljana, 1965,* vol. 3, Speleological Society of Yugoslavia

Ford, D.C., Lundberg, J., Palmer, A.N., Palmer, M.V., Schwarcz, H.P. & Dreybrodt, W. 1993. Uranium-series dating of the draining of an aquifer: The example of Wind Cave, Black Hills, South Dakota. *Geological Society of America Bulletin,* 105:241–50

Howard, A.D. 1964. Model for cavern development under artesian ground water flow, with special reference to the Black Hills. *National Speleological Society Bulletin,* 26:7–16

WORLD HERITAGE SITES

In the 1950s, international concern over the potential destruction of the Abu Simbel temples in Egypt by a proposed reservoir led to a massive campaign under the auspices of UNESCO resulting in reassembly of the temples on another site. Further international campaigns led to international cooperation in the protection of other cultural monuments, and in due course UNESCO, with the support of the International Council on Monuments and Sites (ICOMOS), prepared a draft convention on the protection of cultural heritage. Meanwhile, international concerns over the protection of outstanding examples of natural heritage were also mounting. The 1965 White House Conference, a meeting of the International Union for Conservation of Nature (IUCN) in 1968, and the 1972 UN Conference on the Human Environment all called for the establishment of a World Heritage Trust. It was seen that this would lead to international cooperation to protect the world's superb natural and scenic areas and historic sites for the present and the future of the entire world citizenry. In 1972 the UN General Conference brought together these two strands of concern, and agreed upon a Convention Concerning the Protection of the World Cultural and Natural Heritage. Basically, this convention provided for: the identification of such sites and their inscription upon a register; the responsibility of the state party for continuing protection of site integrity and provision of access by all peoples; and international support as necessary in restoration and protection of sites.

Criteria for assessment of nominated sites have been separately developed for natural and cultural heritage. Those for natural heritage are that the sites should (from Operational Guidelines for the Implementation of the World Heritage Convention):

1. be outstanding examples representing major stages of earth's history, including the record of life, significant ongoing geological processes in the development of land forms, or significant geomorphic or physiographic features; or
2. be outstanding examples representing significant ongoing ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals; or
3. contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance; or
4. contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of outstanding universal value from the point of view of science or conservation.

Cultural heritage criteria demand that the site should:

1. represent a masterpiece of human creative genius; or
2. exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning, or landscape design; or
3. bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared; or
4. be an outstanding example of a type of building or architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history; or
5. be an outstanding example of a traditional human settlement or land-use which is representative of a culture (or cultures), especially when it has become vulnerable under the impact of irreversible change; or
6. be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance (the Committee considers that this criterion should justify inclusion in the List of sites only in exceptional circumstances and in conjunction with other criteria cultural or natural)

Furthermore, and in relation to both natural and cultural heritage, each site is expected to meet a series of conditions in respect to integrity. It is sufficient here to summarize those that relate to natural heritage as an example:

1. boundary issues, to ensure that the whole of any one phenomenon is included (e.g., the watershed of a karst area), and that the size is sufficient to demonstrate the totality of any one process or to genuinely protect an ecosystem, and generally, to provide for an adequate buffer zone around the area of universal value, either within or external to the boundary of the site
2. protection issues, to ensure adequate long-term legislative, regulatory, or institutional protection

3. management issues, including the development and implementation of an adequate plan of management.

Underlying all of the detail is the fundamental assumption that a World Heritage site will truly be of universal value, not simply of national importance. This is increasingly tending to be seen, at least in relation to natural heritage, as going hand-in-hand with the notion of representation, and demanding a degree of unique character in any one site. The process by which a site comes to be recognized usually commences with local or international concern being expressed, leading to a nomination being prepared and forwarded to UNESCO by the host government (usually referred to as the State Party). This leads in turn to assessment by IUCN (for natural heritage), or ICOMOS (cultural site), or both (mixed sites). The recommendations aris ing from the assessment are then placed before the annual meeting of the World Heritage Committee for decision.

The Table lists the karst sites that were inscribed as World Heritage as of July 2002. Many karst sites are of both natural and cultural value, but as the Table shows, only a small number have been assessed and designated as mixed sites, even though at least some probably should have been. Furthermore, on at least one occasion, both the nomination and assessment processes were based entirely upon surface features and biodiversity and totally failed to recognize that a large part of the site was karst. In others, although the site was recognized as including karst, no account was taken of the subterranean sector with its own biodiversity. Thus a number of the important karst sites included in the register of properties were not inscribed as a result of karst phenomena, even though these may be of outstanding importance.

World Heritage Sites: Karst sites currently inscribed as World Heritage. (N=Natural heritage, C=Cultural heritage, M=Mixed sites, *=site has a separate entry in this encyclopedia.)

Australia	
The Tasmanian Wilderness	M
Riversleigh & Naracoorte fossil mammal sites	N
Shark Bay	N
Greater Blue Mountains	N
Lord Howe Island	N
Bulgaria	
Pirin National Park	N
Canada	
Nahanni National Park	N*
Rocky Mountain Parks	N
China	

Huanglong	N*
Jiuzhaigou Valley	N*
Wulingyuan	N
Zhoukoudian	C
Croatia	
Plitvice Lakes National Park	N*
Cuba	
Desembarco del Granma National Park	N
Viñales Valley	C
Alejandro de Humboldt National Park	N
France	
Caves of the Vézère	C*
France & Spain	
Pyrenees-Mount Perdu	M
Hungary & Slovakia	
Aggtelek and Slovak Karst	N*
Indonesia	
Lorentz National Park (Irian Jaya)	N
Lao PDR	
Luang Prabang	C
Madagascar	
Tsingy Bemaraha	N
Malaysia	
Gunung Mulu National Park	N*
Mexico	
Chichen Itza	C
Sian Ka’an	N
New Zealand	
Te Wahipounamu	N
Philippines	
Puerto-Princesa Subterranean River National Park	N
Russia	

Western Caucasus	N
Solomon Islands	
East Rennell	N
Slovenia	
Škocjan Caves	N*
South Africa	
The Fossil Hominid Sites of Sterkfontein, Swartkrans, Kromdraai, and Environs	C
Spain	
Altamira Cave	C*
Atapuerca Caves	C*
Sweden	
Södra Ölands Odlingslandskap	C
Thailand	
Thungyai-Huai Kha Khaeng wildlife sanctuary	N
Turkey	
Pamukkale	M*
United Kingdom (Pitcairn Islands)	
Henderson Island	N
United States	
Grand Canyon National Park	N*
Mammoth Cave National Park	N*
Carlsbad Caverns National Park	N*
Venezuela	
Canaima National Park	N
Vietnam	
Ha Long Bay	N*
Yugoslavia (Montenegro)	
Durmitor National Park	N

N.B. Mogao Caves, Longmen Grottoes, Ajanta Caves, Ellora Caves and the Cave of Sokkuram are also inscribed on the WHS list but they are artificially excavated sites.

Thus there are special problems in the assessment and full recognition of karst. These arise in part from the organizational relationship between natural and cultural heritage, but much more from the emphasis upon biodiversity and lack of awareness of the special nature of karst. Indeed, karst has received little recognition, partly because it is commonly assumed to be a permanent characteristic of any landscape and not threatened, and partly because of the disciplinary focus on biological sciences. Similarly, much of the important, remarkably diverse, and often endemic invertebrate fauna of karst areas remains unrecognized in assessment because it lacks fur or feathers.

Many karst areas have a potential capacity to meet the natural heritage criteria simply because the very nature of karst embodies these characteristics. One of the special features of karst is the dynamic and complex interaction of the various elements that comprise it and more attention might well be paid during assessment to the extent to which any one site visibly demonstrates this. Perhaps one of the most difficult special problems related to karst is the extent to which many karst areas which have been, or might be, recognized as world heritage are only a very small component of the total karst system, sharing both the watershed area and the drainage system of the whole. This means that the karst area is often impacted by activities external to the management boundary and sometimes occurring a considerable distance from the site. Sediment and chemical pollution may be transmitted through the groundwater system over very long distances. In particular, agriculture, viticulture, and similar land uses commonly lead to eutrophication (or enrichment) of the groundwater. In turn this often leads to algal blooms in exposed waters and to a variety of impacts on aquatic fauna. Although it is unlikely that an adequately managed World Heritage area will in itself generate undesirable downstream impacts, it is possible that this may happen. For instance, if a natural water flow had been altered to better serve downstream agriculture and the natural flow was restored to better meet World Heritage standards of integrity then this may well be seen as a highly undesirable impact by those affected.

The continuing management of a karst World Heritage site provides significant challenges. Currently, there is a considerable rise of interest in effective monitoring and assessment of both environmental changes and visitor experience (Hamilton-Smith, 2000; Hamilton-Smith & Ramsay, 2001; Kranjc, 2002). One aspect of this problem is that in making some of the great caves of World Heritage areas accessible to the public as tourist caves, often outmoded systems of infrastructure and display are still in use, or even still being developed. One of the current challenges which is currently receiving examination with a view to developing guidelines is the strategies and methods for effective presentation of World Heritage values in karst to the public.

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See also **Ramsar Sites**

Works Cited

Hamilton-Smith, E. 2000. Managing for environmental and social sustainability at Jenolan Caves, New South Wales, Australia. In *Essays in the Ecology and Conservation of Karst,* edited by I. Barany-Kevei & J.Gunn, special issue of *Acta Geographica Szegedensis,* 36:144–52

Hamilton-Smith, E. & Ramsay, A. 2001. Social and environmental evaluation at Jenolan Caves, New South Wales. *Evaluation Journal of Australia,* n.s., 1:60–65

Kranjc, A. (editor) 2002. Proceedings of the meeting on monitoring of karst areas. *Acta Carsologica,* 31(1)

Further Reading

Wong, T., Hamilton-Smith, E., Chape, S. & Friederich, H. (editors) 2002. *Proceedings of the Asia-Pacific Forum on Karst Ecosystems and World Heritage,* available at http://www.heritage.gov.au/apfp/pubs/Karst-full.pdf
World Heritage Centre at http://www.unesco.org/whc/
World Conservation Monitoring Centre at http://www.unepwcmc.org/
International Union for Conservation of Nature at http://www.iucn.org/
International Council on Monuments and Sites at http://www.icomos.org/

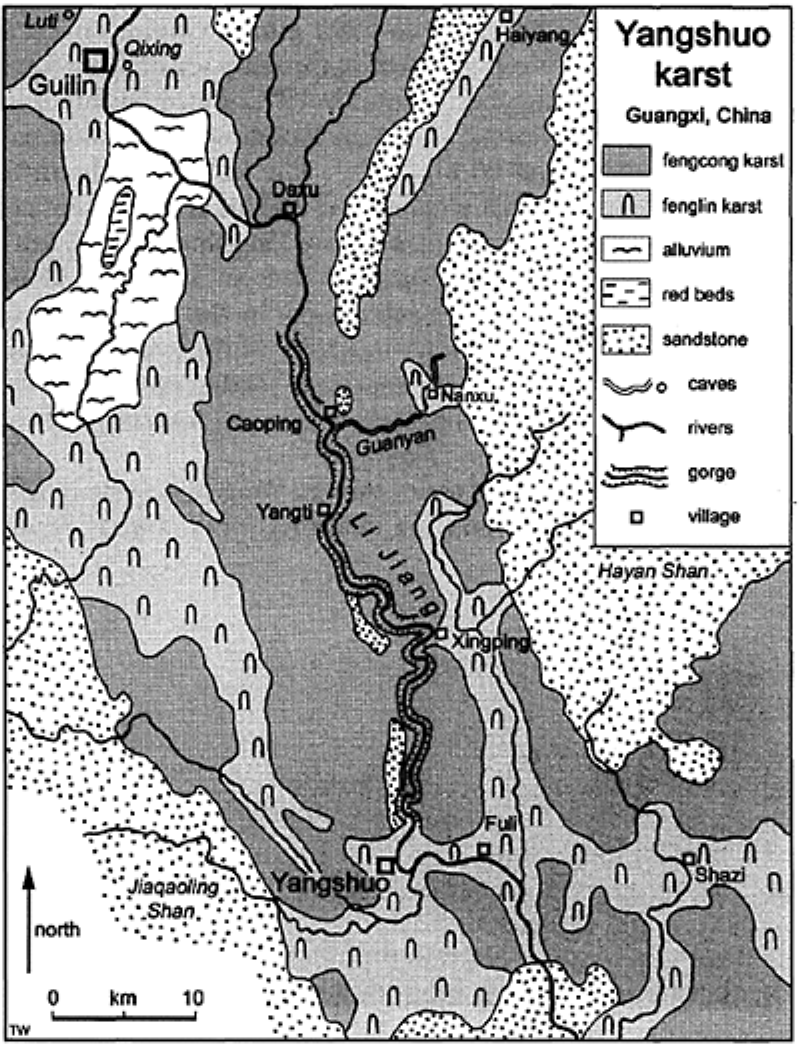
Y

YANGSHUO KARST, CHINA

Located some 60 km south of Guilin, in the province of Guangxi, southern China, Yangshuo is a small town at the centre of the most spectacular tower karst for which Guilin and Guangxi are famous. The terrain is a classic example of one of the four relief types of tropical karst defined by Balazs (1971). The Yangshuo type is characterized by a peak base diameter that is less than 1.5 times its height. The other three types have lower hill profiles, with base/height ratios of 1.5–3.0 (Organos type, from Cuba), 3–8 (Sewu type, from Indonesia), and more than 8 (Tual type, from Indonesia). These differences appear to be dependent on lithological features, as well as on their geomorphological evolution. The Yangshuo type is developed on hard and compact Devonian carbonates, while the others are on younger and more porous carbonate rocks.

Geologically, Yangshuo is at the southern end of a 90 km long, north—south, arcuate synclinal structure, protruding to the west near Guilin (Figure 1). Basement rocks crop out on all sides around the Guilin-Yangshuo basin, at 1936 m Haiyan Mountain to the east, at 1215 m Jiaqiao Mountain to the west, and at 2142 m Yuecheng Mountain to the north. Overlaying the basement, above a strong angular unconformity of Caledonian orogeny, are upper Paleozoic and Mesozoic rocks, with some scattered Tertiary outliers. The main carbonate rocks are 4600 m thick, ranging from middle Devonian to lower Carboniferous age. These occur in the central part of the synclinorium and form the basis of the tower karst formation from Yangshuo to Guilin. The thickly bedded, pure limestone of the Devonian Rongxian Formation, 400 m thick, is especially important for the development of the finest karst landforms.

The main Pleistocene deposits are poorly sorted boulder beds, that appear as many low mounds on the dissolutional karst plain. Most of the cobbles are sandstone or quartzite, derived from the lower Paleozoic outcrops, with a general diameter of 100–300 mm, though boulders up to 1 m are not unusual. Whether these are moraines, fluvioglacial deposits, or debris-flow deposits, remains controversial. Holocene alluvial deposits form terraces alongside the modern Li Jiang (Li River), through the central part of the basin. These are well-sorted gravels, covered by silty sand, with a total thickness of about 10 m, but may be thicker over buried karstic depressions. Recent drilling for the many bridge sites on the Li Jiang have revealed a trough, 30–50 m



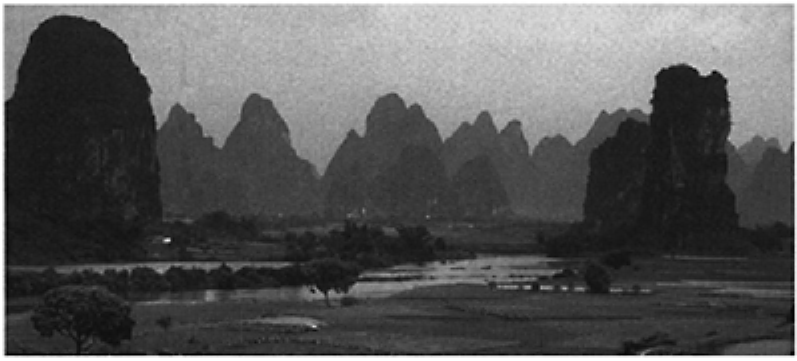
Yangshuo Karst, China: Figure 1. Outline map of the geomorphology of the karst between Yangshuo and Guilin.

Yangshuo Karst, China: Figure 2. The panorama of steep limestone cones and towers breached by the Li Jiang, that are seen on the justly famous boat trip between Guilin and Yangshuo. (Photo by John Gunn)

deep, infilled by Pleistocene boulder beds under the Holocene alluvium. This trough is considered to be a feature incised during Quaternary stages of lower sea levels, and may be associated with some of the cave development in the karst aquifer beneath the dissolutional plain.

Influenced by the Asian monsoon circulation, Yangshuo's climate is characterized by wet summers with frequent storms, but dry autumns and winters. Annual mean precipitation ranges from 1570 mm at Yangshuo to 1990 mm at Guilin, but 62% of the total rainfall is concentrated in the rainy season from April to August. Mean temperatures are 18–19°C. Based on data from many years of monitoring, the mean limestone denudation rate in the karst is around 90 mm ka^{-1}. The Li Jiang is the main drainage system with its base level at 103 m at Yangshuo and 141 m at Guilin. The catchment above Yangshuo is 5520 km^2, giving an annual mean discharge of 215 $m^3 s^{-1}$, with flood peaks at 6330 $m^3 s^{-1}$. Carbonate rocks in the central part of the catchment cover 3464 km^2, or 62.8% of the total. Allogenic water from the non-carbonate outcrops washes down into the karst basin and plays an important role in the formation of the fenglin karst of the region (Figure 2).

There are two types of tower karst in Yangshuo—the fenglin (peak forest; Figure 3) and the fengcong (peak cluster; Figure



Yangshuo Karst, China: Figure 3.
The classic landscape of fenglin tower karst just to the southeast of Yangshuo. (Photo by Tony Waltham)

Yangshuo Karst, China: Figure 4.
Clustered towers and steep cones form the fengcong karst to the west of Caoping. (Photo by Tony Waltham)

4). The fengcong is defined as groups of rocky hills or peaks rising from shared limestone foot-slopes. Closed depressions lie between the peaks, so the landscape is sometimes described as "peak cluster depression". The fenglin is defined as limestone towers or peaks that are isolated from each other by flat limestone surfaces, which are generally covered by a thin layer of loose sediment. The peaks are usually completely surrounded by a karst plain, so the landscape may be called a "peak forest plain". The relative heights of the peak surface are generally 30–80 m above the plain in the middle of the basin, but rise to 300–500 m in the mountainous regions of the fengcong.

The profiles of the peaks are columnar towers where the limestone is gently dipped in the trough of the syncline, but form steep, broken escarpments on both flanks of the fold, where the dip is steeper. No strict zonal distribution of the fenglin and fengcong can be established, either in plan or profile, though this was claimed by Zhongjian (1935) and Gellert (1962) for the fenglin karst at Baisha, 10 km northwest of Yangshuo. The two types are mixed in their areal distribution (Figure 1). However, it is evident that most of the fenglin towers occur in those areas where they are subjected to strong lateral erosion by allogenic rivers, either the Li Jiang or its tributaries. In contrast, the fengcong hills lie beyond the zones of allogenic fluvial erosion, as in areas west of Guilin and in blocks on both sides of the Li Jiang gorge between Caoping and Yangshuo (Figure 1).

About 600 caves have been recorded within the area. Caves in the fenglin are generally short because of the limited size of the limestone towers. Within a population of 80 of the isolated peaks, only 24 have caves totalling more than 200 m. Most of these are foot caves with inflow from the alluvial plains indicated by the scallops on their walls. Cave development plays a significant role in the recession of cliffs around the peaks, and therefore in the formation of the fenglin landscape.

Caves in the fengcong karst are generally longer. There are more than 23 stream caves, each with a length of more than 1 km, on both sides of the Li Jiang gorge. Those on the eastern side receive allogenic recharge from Haiyang Mountain and discharge into the Li Jiang. The longest known caves are in the Guanyan system, east of Caoping, which has a catchment of 80 km^2 and flows of 0.3–8 $m^3 s^{-1}$. A total length of 10 530 m of passages have been mapped (Waltham, 1986), but the central section of active phreatic passages has not yet been explored. The resurgence end of the caves has already been opened for tourists, who cruise on an underground stream from a boat dock on the Li Jiang. Other tourist caves in the area include the well-decorated Luti Dong (Reed Flute Cave), the 1300 m long Qixing Dong (Seven Star Cave) with its large abandoned phreatic passages, and some small caves around Yangshuo. Many caves have fossils of the Pleistocene Ailuropoda-Stegodon fauna, as well as archaeological relics.

Dating and stable isotopic studies of a 1200 mm tall stalagmite from Panlong Cave, 30 km northwest of Yangshuo, revealed paleoclimatic changes over the past 36 ka that included the last glaciation, the Younger Dryas and the Holocene optimum, while an analysis of the clay beneath stalagmites in Shuinan Cave showed paleoclimatic change during the Jaramillo subchron at 1.0–0.9 Ma (Li *et al.*, 1998). A paleomagnetic study of flowstone from a cave on Tunnel Hill, indicated a maximum lowering rate for the karst plain and the Li Jiang of 23 mm ka^{-1} (Williams, 1987).

The initiation and early evolution of the Yangshuo tower karst is unclear. Late Cretaceous Atopochara plant fossils are found both in the Red Beds on the floor of the basin and in many small patches of red breccia scattered on peaks 300–600 m higher. This correlation shows that the Cretaceous Red Beds used to cover a remarkable area, and the fenglin karst could only develop after their removal. It appears that much of the modern landscape may have evolved through the Quaternary, after the Asia monsoon became seasonal (Yuan, 1987).

Karst dominates the environment in the Guilin-Yangshuo basin, and groundwater abstraction from the karst aquifer is increasing, especially as tourism grows. Daily extraction is about 150 000 m^3. Karst collapses happen frequently, especially in those areas where groundwater is overpumped from limestone beneath alluvial soils. Local records include 148 incidents of collapse, with the earliest dating back to 1498 AD in the Ming Dynasty. Drilling of new wells is now controlled by municipal, environmental, and water protection regulations.

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Works Cited

Balazs, D. 1971. Relief types of tropical karst areas. Presented at European Regional Conference of *IGU Symposium on Karst Morphogenesis*

Li B., Hauge, F. & Lovlie, R. 1998. Paleomagnetic record from Shuinan cave sediments, Guilin, and its bearing on paleoclimatic changes. *Journal of Geomechanics,* 4(4):50–57

Gellert, J.F. 1962. Der Tropenkarst in Sud-China im Rahmen der Gebirgsformung des Landes. *Verhandlungen des Deutschen Geographentages,* 33:376–84

Waltham, A.C. (editor). 1986. *China Caves '85: The First Anglo-Chinese Project in the Caves of South China,* London: Royal Geographical Society

Williams, P.W. 1987. Geomorphic inheritance and the development of tower karst. *Earth Surface Processes and Landforms,* 12:453–65

Yuan D. 1987. New observations on tower karst. In *International Geomorphology,* vol. 2, edited by V.Gardiner, New York: Wiley

Zhongjian Y & Chardin, T. 1935. Cenozoic geology of Guangxi and Guangdong. *Bulletin of the Geological Society of China,* 14(2): 179

Further Reading

Silar, J. 1965. Development of tower karst of China and North Vietnam. *National Speleological Society Bulletin,* 27(2):35–46

Sweeting, M.M. 1995. *Karst in China: Its Geomorphology and Environment,* Berlin: Springer

Williams, P.W., Lyons, R.G. & Wang X. 1986. Interpretation of the paleomagnetism of cave sediments from a karst tower in Guilin. *Carsologica Sinica,* 5(2):119–25

Yuan D. (editor) 1991. *Karst of China,* Beijing: Geological Publishing House

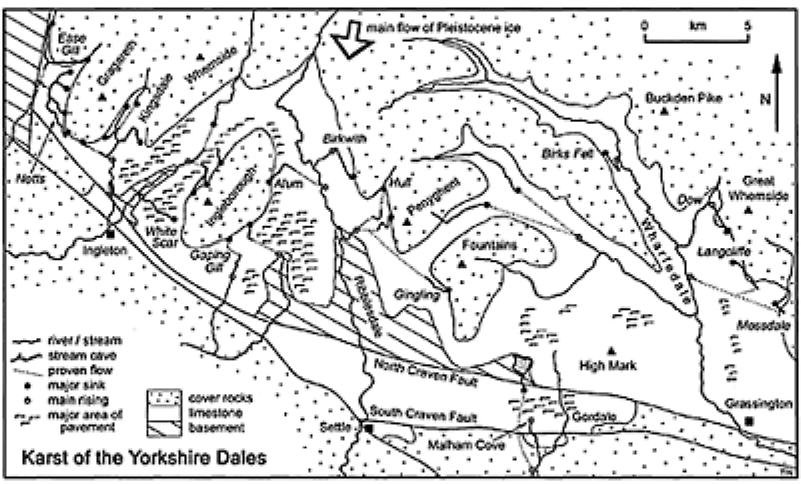
Zhu X. 1988. *Guilin Karst,* Shanghai: Scientific and Technical Publishers

YORKSHIRE DALES, ENGLAND

The central part of England's Pennine Hills is better known as the Yorkshire Dales, after the deep glaciated valleys (dales) running through it, and this is also the name of the National Park that contains the finest glaciokarst landscapes in Britain.

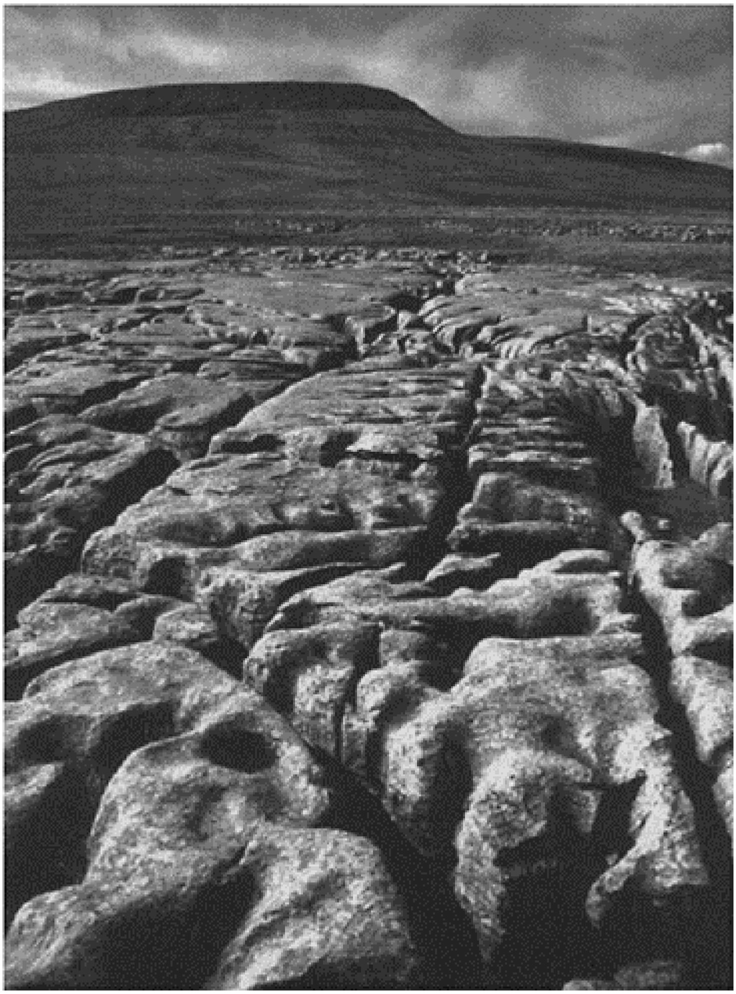
The Lower Carboniferous Great Scar Limestone is nearly 200 m thick, and lies with a very gentle northerly dip on an impermeable basement. The dales descend gently from the north, in the direction of Pleistocene ice flow, so that some cut through the entire thickness of limestone. Between the dales, hills that rise 150 m above the limestone are formed of shales (with thin limestones and sandstones), and provide allogenic streams draining onto the limestone. The broken carbonate platform is known as the Craven Uplands, and is truncated to the south by the Craven Faults, where the limestone is downthrown to depth beneath the Craven Lowlands further south. Between the shale caps, the dale floors and the faults, the total area of limestone outcrop is about 320 km^2 (Figure 1). Erosive Devensian glaciation followed earlier stages of Pleistocene ice cover, and stripped much of the limestone to clean bare outcrops that constitute excellent glaciokarst. During interglacial stages, the karst matured with extensive cave development in a mainly temperate climate. The conspicuous elements of the glaciokarst are extensive limestone pavements, thousands of dolines and some deep meltwater gorges.

Perhaps the best-known karst occupies the limestone benches that surround Ingleborough Hill (Figure 2 and see also photo in Floral Resources entry). Devensian ice flowed along both sides of the hill, leaving limestone pavements that are terraced on strong beds of limestone and separated by ice-plucked scars. The pavements are dominated by postglacial rundkarren, rounded beneath a cover of lichen, feeding into deep grikes (kluftkarren). Away from the pavements, the limestone is covered by glacial till, which is thickest and most extensive in the southwestern lee of the hill. The till is pocked by hundreds of suffosion dolines, locally known as shakeholes, most of which drain into narrow fissures in the underlying limestone. Larger potholes (vertical shafts up to 10 m across and 100 m deep) are scattered across the karst. Some are active stream sinks fed by streams off the shale. Others, located along interglacial positions of the retreating shale margin, are almost dry, and many are widened by wall collapse. They include Gaping Gill (see photo in Valleys in Karst), which still takes Fell Beck down its 95 m deep shaft



Yorkshire Dales, England: Figure 1.
Main features of the geology, karst,

and glacial geomorphology of the Yorkshire Dales, with the major underground drainage routes through known cave passages or proven by dye tracing.



Yorkshire Dales, England: Figure 2. Limestone pavements on the glacially stripped top surface of the limestone, with the summit mass of Ingleborough formed of shales and sandstones in the background. (Photo by Tony Waltham)

through the roof of the main chamber. A complex of 18 km of active and abandoned caves, mostly phreatic, link beneath the meltwater gorge of Trow Gill and drain to the Ingleborough Cave resurgence.

East of Ingleborough, the glaciokarst above Malham also has extensive pavements, but is noted more for its entrenched proglacial meltwater features. The Watlowes dry valley ends at the lip of the 80 m high cliff of Malham Cove. The width of the cove

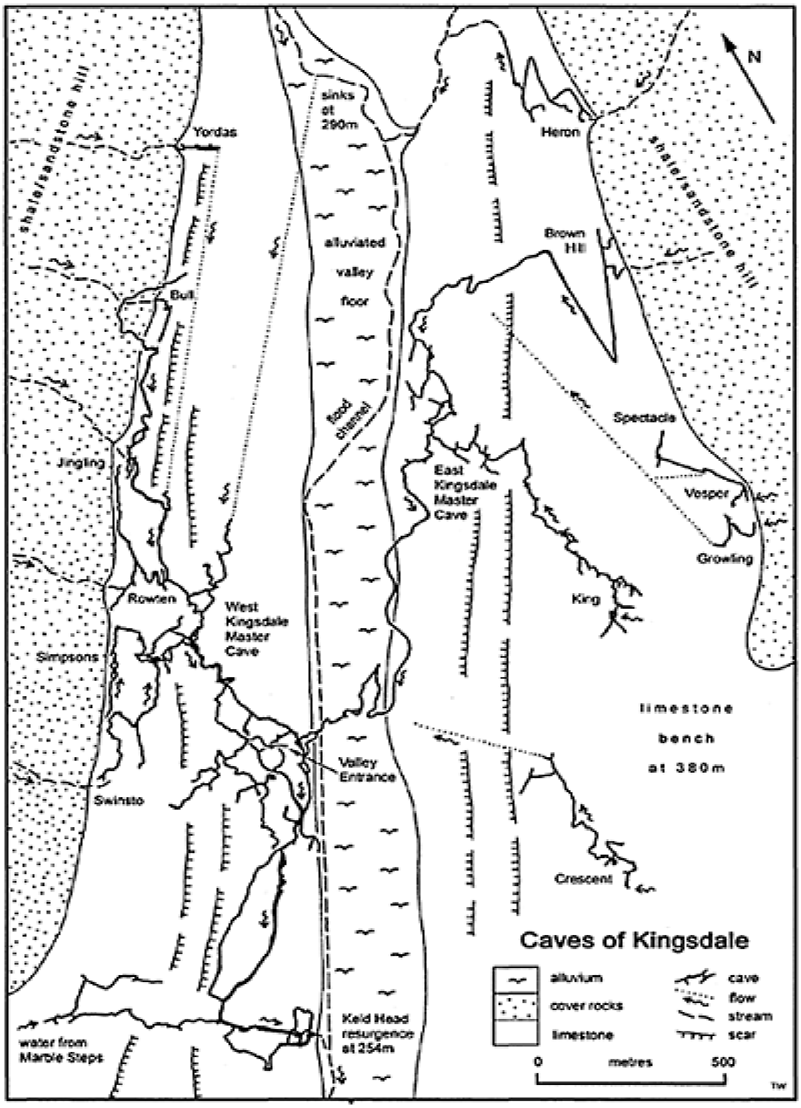
Yorkshire Dales, England: Figure 3. Stalagmites stand on banks of clastic sediment in the abandoned phreatic tunnel that leads to Gour Hall, Pippikin Pot, in the Ease Gill Cave System. (Photo by Tony Waltham)

suggests that it may have originated by glacial plucking, before its modification as a meltwater cascade. The adjacent Gordale carries a tufa-depositing, underfit stream, and deepens between cliffs over 100 m high at its mouth in the fault scarp, where it leaves the Craven Uplands. East of Malham, the High Mark plateau is a polygonal karst with gently rounded dolines 200–800 m across, which appear to have been overridden by the Devensian ice.

Over 1400 caves are known in the Yorkshire Dales, with 50 of them having more than 1000 m of passage. A total of 330 km of cave passages have been mapped, but the deepest cave reaches only 211 m. The typical Dales cave has a vadose streamway only a few metres high and wide, cut beneath a bedding plane or thin shale bed; it drains roughly downdip, to the north (see photo in Morphology of Caves). Its meandering canyon is interrupted by vertical waterfall shafts on major joints, where the cave drops to lower bed horizons. Some caves are tall rifts along the joints. At the level of the resurgence, the cave continues as a phreatic tube, looping down joints and up the bedding planes, towards the south, against the dip. Swinsto Hole is the type example (Waltham *et al.*, 1981), with a kilometre of streamway leading into a kilometre of flooded tube, explored the whole way from sink to resurgence.

Swinsto is also typical in that its modern drainage route intersects and invades segments of older passages. These include large phreatic tunnels, now well above the water table, partly choked with mud and partly decorated with stalactites and stalagmites (Figure 3). They were interglacial and preglacial trunk conduits, abandoned when new resurgences were established at the lowest outlets where the deepening dales crossed the Craven Faults. In many caves, fragments of these old passages survive. Some can be traced back to abandoned sinks, which are now the larger, partly-collapsed dolines and potholes away from the shale margins, and others are truncated in the walls of the glaciated dales. Stalagmites dated from some of the old caves, show periodic deposition during interglacial stages of the Pleistocene (Gascoyne & Ford, 1984). Sequential levels of passage abandonment, dated by their oldest stalagmites, indicate the drainage of the karst as the dales were excavated. The lower half of their depth has been achieved within the last 400 000 years. Valley deepening can be broadly correlated with shale margin retreat during stripping of the limestone benches, as the karst evolved through alternating stages of fluvial and glacial erosion that must reach back into the early Pleistocene.

West of Ingleborough, Gragareth Hill has more than 100 km of mapped cave passages beneath its largely till-covered limestone flanks. The longest single cave system is currently Ease Gill, with 75 km of mapped passages extending under both sides of the normally dry valley of the same name. On the north side, numerous, down-dip, canyon streamways capture flows from various parts of the Ease Gill stream, and feed them all into a parallel master cave, then up-dip to a flooded resurgence back in the same valley. The main drain lies beneath a large abandoned passage, parts of which are very well decorated. On the south side, caves drain from sinks on the high-level shale margin of Gragareth. The modern drains are descending vadose canyon tributaries into the long, low-level, vadose Lost Johns Master Cave just above resurgence level. A parallel, old, phreatic master cave, with equally numerous inlets in Notts Pot, now carries an underfit stream in a floor canyon and is a relict feature of the interglacial karst drainage. On the eastern flank of Gragareth, the Kingsdale caves collect inlet streams from both sides of the valley (Figure 4). Both Swinsto Hole and King Pot demonstrate the northerly downdip vadose drainage before turning south in the phreas. The flooded tube carrying the King Pot drainage passes beneath the valley floor and continues, without air space, to the resurgence where it is truncated in the side of the glaciated dale.



Yorkshire Dales, England: Figure 4. Known passages in the Kingsdale Cave System, Yorkshire (compiled from surveys by various caving clubs).

Mossdale and Langcliffe are two distinctive caves that lie east of Malham. Each has 10 km of passages formed within the Brigantian Middle Limestone, a band just 30 m thick within the clastic sequence above the Great Scar Limestone. The small stream passages have angular courses that switch between two steps of joint rifts with sandstone floors. They trend downdip until they can break through into the underlying Great Scar Limestone by descending faults that cut through the sandstones and shales. Only in Langcliffe Pot has the breakthrough point yet been reached by exploration.

Nearly all the karst and caves lie within the Yorkshire Dales National Park. Tourism sustains many of the villages in the dales, and the white limestone scars attract hill walkers. The upland is grazed by sheep that maintain the open aspect of the grassland fells, by keeping down new trees and shrubs. Aggregate quarries are a localized threat to the limestone, but most of the spectacular glaciokarst remains in good condition.

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Works Cited

Gascoyne, M. & Ford, D.C. 1984. Uranium series dating of speleothems: Results from the Yorkshire Dales and implications for cave development and Quaternary climates. *Cave Science,* 11: 65–85

Waltham, A.C., Brook, D.B., Statham. O.W. & Yeadon, T.G. 1981. Swinsto Hole, Kingsdale: A type example of cave development in the limestone of northern England. *Geographical Journal* 147:350–53

Further Reading

Gascoyne, M., Schwarz, H.P. & Ford, D.C. 1983. Uranium series ages of speleothems from northwest England: Correlation with Quaternary climate, *Philosophical Transactions of the Royal Society of London,* B301:143–64

Waltham, A.C. 1970. Cave development in the limestone of the Ingleborough district. *Geographical Journal,* 136:574–85

Waltham, A.C. 1990. Geomorphic evolution of the Ingleborough karst. *Cave Science,* 17:9–18

Waltham, A.C., Simms, M.J., Farrant, A.R. & Goldie, H.S. 1997. *Karst and Caves of Great Britain,* London and New York: Chapman and Hall

YUCATÁN PHREAS, MEXICO

The Yucatan Peninsula is a low-lying limestone platform, extending over 75 000 km^2, between the Caribbean Sea and the Gulf of Mexico. The limestone ranges in age from Paleocene in the interior, to Quaternary on the coastal margins. There are numerous roughly circular cenotes (dolines; from the Maya word d'zonot meaning a well) that lead to the water table. Cenotes in the interior are steep walled with large chambers, extending below the water table to depths in excess of 60 m, on the perimeter of central piles of rock breakdown. These rarely lead to more than 500 m of accessible passage, exploration being impeded by silt, breakdown rock, and the depth limits of scuba diving. In contrast, cave diving explorations, which accelerated in the mid-1980s along the Caribbean coast, have identified at least 91 horizontally extensive submerged cave systems, with a combined length greater than 500 km and an average maximum depth of −16m (see Table). Among these are the three longest flooded cave systems in the world and 13 other systems more than 5 km long, firmly establishing this region as the leading site for explored underwater cave systems.

The peninsula is underlain by a density-stratified aquifer, with a thin freshwater lens recharged by rapid infiltration of rainwater. The shallow underlying saline water flows coastward, in response to mixing and entrainment by freshwater outflow above the halocline interface. There is a compensatory influx of deeper saline water from the coastal margins. Unlike the blind flank margin cave development in island karst settings (see separate entry, Speleogenesis: Coastal and Oceanic Settings), channel networks have been explored here to distances 12 km inland from the Caribbean coast. The channel networks drain to coastal springs that are often located at the headward end of coastal inlets known as caletas. Quantitative dye tracing, conducted over 5 km in Sistema Nohoch Nah Chich, showed that 99.7% of

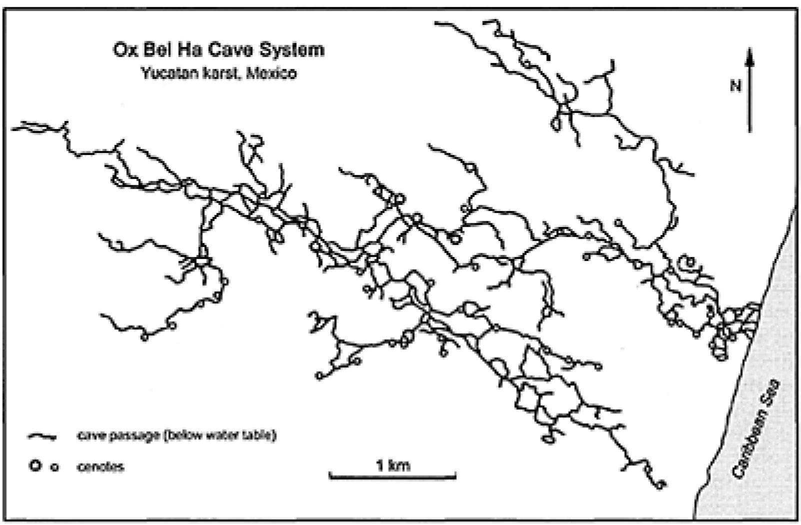
Yucatan Phreas, Mexico: Summary of completely submerged cave systems longer than 10 km of the Yucatan Peninsula. Yaxchen and Aerolito are discontinuous and the passages are broken by several open cenotes.

Sistema/Cueva	Length (km)	Max Depth (m)	Number of cenotes
Ox Bel Ha	107.1	33.5	60
Nohoch Nah Chich	61.0	73.6	n/a
Dos Ojos	56.7	119.1	24
Sac Actun	24.0	25.0	22
Naranjal	21.1	34.7	8
Aerolito	19.5	23.5	3
Yaxchen	18.3	22.3	40
Ponderosa	15.0	16.5	18
Nohoch Kiin	13.9	19.8	12

the freshwater flow occurs in the cave channels (Worthington, Ford & Beddows, 2000). As a consequence of the extensive cavernous porosity, the aquifer is highly transmissive, such that 40% of the Caribbean microtide (30 cm amplitude) is transmitted to cenotes 5 km from the coast. The hydraulic gradient is also extremely flat (7–10 mm km^{-1}) as measured in the northwest of the peninsula by Marín and Perry (1994). No coastal cave passages have yet been reported along the north or west coastlines. However, very large springs at the intersection of the “Ring of Cenotes”, a concentration of cenotes that overlies the deeply buried Chicxulub Cretaceous—Tertiary impact crater (Perry *et al.*, 1995), attest that the peninsula is highly karstified throughout.

The caves formed at some time(s) before our present sealevel high stand, as indicated by the great abundance of drowned vadose speleothems. Many of the shallow passages are now wholly within the freshwater lens or intersected by the halocline which is found at −8 m at Cenote Car Wash (in Sistema Aktun Ha), 9 km from the coast, and at shallower depths as the coast is approached. Mixing corrosion is thought to be an important speleogenic process in these horizontally extensive sys tems but bacterially mediated reactions, associated with hydrogen sulfide layers, may also enhance dissolution (Stoessell, Moore & Coke, 1993). Good examples of vertically extensive fracture-guided passages are found predominantly within 2 km of the coastal zone, such as in Sistemas Abejas and Aak Kimin. The deep pit cenotes of the peninsula interior, combined with deeper tiers of passage completely in the saline zone along the Caribbean coast, such as at The Pit (−119 m in Sistema Dos Ojos), the Blue Abyss (−74 m in Sistema Nohoch Nah Chich), and Sistema Aak Kimin (−69 m), indicate that extensive cavernous development occurred at lower sea levels. It may extend to the 120 m Quaternary sea minimum, or deeper in the older buried limestones.

Sistema Ox Bel Ha (Maya for “Three Paths of Water”) is characterized by inter-linked northwest-southeast parallel main passages, with an average depth of 15 m, and four near-shore springs that connect to the Caribbean Sea (Figure 1). Exploration of Sistema Esmerelda (the precursor to Ox Bel Ha) only began in May 1998. The poetic name “Three Paths of Water” was adopted because of the connection with Sistema Chikin Ha, and an anticipated southern link to Sistema Yaxchen. Promising



Yucatan Phreas, Mexico: Figure 1. Outline map of the known underwater cave passages of Ox Bel Ha, the longest of the caves beneath the

Yucatan karst of Mexico (cave map by Grupo de Exploracion Ox Bel Ha).

Yucatan Phreas, Mexico: Figure 2. A diver passes subaerial calcite deposits in one of the flooded phreatic passages near Cenote of the Sun (in Sistema Naranjal). (Photo by Jill Heinerth)

leads northwest towards Sistema Naranjal (20 km long) are being explored by the Grupo de Exploración Ox Bel Ha.

Sistema Nohoch Nah Chich (Maya for "Giant Bird House"), with its main entrance 3 km from the coast, was first dived in 1987. The Cedam cave diving team effectively used jungle camps to survey the amazingly decorated upstream passages, generally more than 5 m wide, filled with crystal-clear fresh water at depths of less than 10 m. Exploration downstream, under the paleo-beach ridge, encountered restricted passages that were highly unstable with low visibility. Nonetheless, Sistema Nohoch Nah Chich was explored from 6 km inland, through to the Caribbean Sea via the near-shore spring at Cenote Manati/Tankah/Casa, and was the longest underwater cave system in the world, until displaced by Sistema Ox Bel Ha in 2000. Many leads exist, including the potential to locate a more northerly discharge point identified by the divergence of 50% of the flow at 3 km inland. Most tantalizing is the potential connection with Sistema Dos Ojos, which lies as little as 200 m away at one point.

Sistema Dos Ojos (Spanish for “Two Eyes”) was first dived through the “two eyed” double collapse cenote in 1986. Exploration increased in the early 1990s, with expeditions that have resulted in the survey of 56.7 km of passage and the notable discovery of The Pit in 1994. Ongoing exploration has found The Pit Cenote to be the deepest known site in the Caribbean coast caves, at a depth of 119m. At present it is not certain which coastal spring is fed by Sistema Dos Ojos, but a portion of flow is likely to exit via Caleta Xel-Ha.

Many cave passages are known to contain Maya pottery, fire pits, carvings and human remains below the present water table, highlighting the long-standing cultural and religious importance of these sites to the indigenous Maya. At present, the cenotes and caletas are used extensively for recreational water activities and are favoured locations for small and large-scale tourism developments and nature parks, such as Caleta Xel-Ha, Caleta XCaret, and Gran Cenote. The population of the Yucatan Peninsula is also wholly dependent on the freshwater lens for drinking water. However, there is justified concern that groundwater resources and the anchialine cave habitat (known to host at least 37 stygobitic species) may be degraded by disposal wells that pump sewage effluent into the saline zone, while cess pits and garbage dumps leach into the freshwater lens from above. It is certain that almost all water (including contaminants) will eventually pass through the cave systems to be discharged onto the sensitive barrier reef system. The phenomenal growth of Cancun and other coastal resorts demands that regional and multidisciplinary understanding of the aquifer is developed in order to maintain quality and achieve sustainable use of groundwater resources. It is hoped that ongoing cave diving exploration will continue to raise awareness and concern for the sub-aquatic environment, and therefore assist in conservation.

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See also **Blue Holes of Bahamas; Caribbean Islands; Diving in Caves; Speleogenesis: Coastal and Oceanic Settings**

Works Cited

Marín, L.E. & Perry, E.C. 1994. The hydrogeology and contamination potential of northwestern Yucatan, Mexico. *Geofisica Internacional*, 33(4):619–23

Perry, E., Marín, L., McClain, J. & Velázquez, G. 1995. Ring of cenotes (sinkholes), northwest Yucatan, Mexico: Its hydrogeologic characteristics and possible association with the Chicxulub impact crater. *Geology*, 23(1):17–20

Stoessell, R.K., Moore, Y.H. & Coke, J.G. 1993. The occurrence and effect of sulfate reduction and sulfide oxidation on coastal limestone dissolution in Yucatan cenotes. *Ground Water*, 31(4): 566–75

Worthington, S.R.H., Ford, D.C. & Beddows, P.A. 2000. Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution. In *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer and W. Dreybrodt, Huntsville, Alabama: National Speleological Society

Further Reading

Back, W., Hanshaw, B.B., Herman, J.S. & Van Driel, J.N. 1986. Differential dissolution of a Pleistocene reef in the ground-water mixing zone of coastal Yucatan, Mexico. *Geology*, 14(2):137–40

Barton, H. 2000. The Pit. *Underwater Speleology*, 27(3):10–17

Gerrard, S. 2000. *The Cenotes of the Riviera Maya*, Tallahassee, Florida: Rose Printing

Martin, J.B., Wicks, C.M. & Sasowsky, I.D. (editors) 2002. *Hydrogeology and Biology of Post-Paleozoic Carbonate Aquifers*, Charlestown, West Virginia: Karst Waters Institute

Matthes, A.W. 2001. Yucatan Deep Speleological Dive Team: Proyecto de investigacion de Cenotes y Grutas Yucatan 2000. *Underwater Speleology*, 28(1):6–8

Phillips, B.A. 2001. The exploration of Sistema Ox Bel Ha. *Underwater Speleology*, 28(4):4–8

www.caves.org/project/qrss/ Official site of the Quintana Roo Speleological Survey (QRSS) with statistics on the long and deep cave systems on the Caribbean coast, Yucatan Peninsula

www.mexicocavediving.com/is the official webpage of the Grupo de Exploracion Ox Bel Ha

www.cavebiology.org/Anchialine Caves and Cave Fauna of the World webpage contains a very useful summary of Yucatan Peninsula biospeleology

NOTES ON CONTRIBUTORS

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Interstitial Habitats (Aquatic)

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Forests on Karst; Tourist Caves: Algae and Lampenflora

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Professor, Department of Paleontology, Natural History Museum, London, UK. Author of *Owls, Caves, and Fossils: Predation, Preservation, and Accumulation of Small Mammal Bones in Caves* (1990). Contributor to *Miocene Hominoid Fossils: Functional and Phylogenetic Implications,* edited by D.Begun (1997) and to the journals *Journal of Zoology, Nature, Philosophical Transactions of the Royal Society of London, Science*.

Paleontology: Animal Remains in Caves

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Departement de géographie, Université Nice-Sophia-Antipolis, Nice, France. Contributor to *Cave and Karst Science, Journal of Cave and Karst Studies, Karstologia*.

Dent de Crolles Cave System, France; Nakanai Caves, Papua

New Guinea; Vercors, France

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America, South; America, South: History; Bambuí Karst, Brazil; Boa Vista, Toca da Boa Vista, Brazil; Quartzite Caves of South America

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Clima Sotterraneo (1995); *Grotte e Forre: Tecniche Speciali* (1997); *Il Fondo di Piaggia Bella* (1999). Former President, Società Speleologica Italiana. Member of the steering board and of the scientific board of Associazione La Venta, devoted to underground exploration all over the world.

Antarctica

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Altamira Cave, Spain: Archaeology; Ardèche Caves, France: Archaeology; Art in Caves; Art: Cave Art in Europe; Atapuerca Caves, Spain: Archaeology; Vézère Caves, France: Archaeology

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Bauxite Deposits in Karst

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Assistant Professor, Department of History and Ethnology, Democritus University of Thrace, Greece, and Director, Department of Speleology, Anaximandrian Institute of Human Evolution, Voula, Greece. Author of *The Palaeontology of Cythera Island* (1988). Contributor to *Bulletin de la Société Spéléologique de Grèce, Journal of*

Archaeological Science, Journal of Human Evolution, Proceedings of the Royal Society, Science, and *The Anatomical Record*.

Europe, Mediterranean: Archaeological and Paleontological Caves; Shanidar Cave, Iraq

Beddows, Patricia A.

PhD student, School of Geographical Sciences, University of Bristol, UK. Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.Ford, A.Palmer & W.Dreybrodt (2000).

Yucatan Phreas, Mexico

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President, International Federation of Rock Art Organisations (IFRAO), Melbourne, Australia. Author of *Rock Art Science: The Scientific Study of Paleoart* (2001). Co-author of *Indian Rock Art and its Global Context* (1997); *Nale Tasih: Eine Floβfahrt in die Steinzeit* (1999). Contributor to *Rock Art and Posterity: Conserving, Managing and Recording Rock Art,* edited by C.Pearson & B.K.Swartz (1991); *Ancient Images, Ancient Thought: The Archaeology of Ideology,* edited by S.Goldsmith, S.Garvie, D.Selin & J.Smith (1992); *Preservation of Rock Art,* edited by A.Thorn & J.Brunet (1996); *Indian Archaeology in Retrospect, Vol. 1, Prehistory,* edited by S.Settar & Ravi Korisettar (2000). Contributor to many journals, including *Anthropologie, Antiquity, Cambridge Archaeological Journal, Current Anthropology, Helictite, Journal of World Prehistory, Studies in Speleology*. Editor of *Rock Art Research,* the *A URA Newsletter* and *CARA Newsletter,* editor of *the AURA Occasional Monographs;* editor-in-chief of the *IFRAO-Brepols Rock Art Series*.

Art in Caves: History; Art: Cave Art in Australasia

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Salukkan Kallang, Indonesia: Biospeleology

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Ramsar Sites

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Retired from governmental management of the quality control of pharmaceuticals, Switzerland. Author of *Revision of the Genus Bythiospeum (Mollusca Prosobranchia Hydrobiidae) of France* (1990). Contributor to *Proceedings of the 12th International Congress of Speleology* (1997); *Fauna Helvetica 2: Mollusca. Atlas der Mollusken der Schweiz und Liechensteins* (1998); and to the journals *Documents Malacologiques* and *Revue Suisse de Zoologie*. Former Editor of *Speleological Abstracts* (1975–97).

Mollusca

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Plitvice Lakes, Croatia; Poljes; Ponors

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Director, Cave and Karst Research Program, New Mexico Institute of Mining and Technology. Editor of *Astrobiology Journal and* four proceedings volumes. Contributor to *Encyclopedia of Environmental Microbiology* (2001) and to *Chemical Geology, Journal of Cave and Karst Studies, NSS News.*

Biofilms; Extraterrestrial Caves

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Contributor to *Speleogenesis: Evolution of Karst Aquifers*, edited by A. Klimchouk, D.Ford, A.Palmer & W.Dreybrodt (2000), and to the journals *Cave and Karst Science, Cave Science, Earth Surface Processes and Landforms* as well as many geochemical journals.

Microbial Processes in Caves; Sulfide Minerals in Karst

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Crustacea: Isopoda, aquatic Organisms: Classification

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Research Hydrologist, Appalachian Farming Systems Research Center, US Department of Agriculture, Agricultural Research Service, Beaver, West Virginia, USA. Contributor to *Agricultural and Forest Meteorology, Earth Surface Processes and Landforms, Journal of the American Water Resources Association, Soil Science*.

Groundwater Pollution: Dispersed; Soils on Carbonate Karst; Soil Erosion and Sedimentation

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Professor, Department of Anthropology, California State University at Los Angeles, USA. Co-editor of *In the Maw of the Earth Monster: Studies of Mesoamerican Ritual Cave Use* (in press). Contributor to *Archaeology of Ancient Mexico and Central America: An Encyclopedia,* edited by S.T.Evans & D.L.Webster (2001) and to the journals *Archaeology Magazine, American Antiquity, Journal of Cave and Karst Studies*.

America, Central: Archaeological Caves

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Crustacea: Copepoda

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Music about and in Caves

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Professor, Department of Geography, University of Georgia, Athens, Georgia, USA. Contributor to *Evolution of Environments and Hominidae in the African Western Rift Valley,* edited by N.T.Boaz (1990); *Quaternary Deserts and Climatic Change,* edited by A.S. Alsharhan, K.W.Glennie, G.L.Whittle & C.G.St.C.Kendall (1998); *Paleoenvironmental Reconstrution in the Arid Lands,* edited by A.K.Singhvi & E.Derbyshire (1999); and to the journals *Holocene, Journal of Archaeological Science, Palaeogeography, Paleoclimatology and Palaeoecology, Zeitschrift für Geomorphologie.*

Africa, Sub-Saharan

Brooks, Simon

UK. Co-editor of *Caving in the Abode of the Clouds; The Caves and Karst of Meghalaya, N.E. India* (1994); *Caving in the Abode of the Clouds, Part 2: The Caves and Karst of Meghalaya, North East India* (1998). Contributor to *Caves and Caving, Descent, International Caver, Stalactite, Speleologia.*

Indian Subcontinent

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Amphibia: Proteus

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Littoral Caves

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Crustacea: Syncarida

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Food Resources

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Britain and Ireland: Archaeological Caves

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Cockpit Country Cone Karst, Jamaica

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Adaptation: Morphological (External); Speciation

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International Journal of Speleology. Contributor to *Karst Terrains: Environmental Changes and Human Impact,* edited by P.Williams (1993); *Cave Minerals of the World,* edited by C.A.Hill & P.Forti (2nd edition, 1997), and to the proceedings of national and international speleological congresses, and the journals *Environmental Geology, International Journal of Speleology, Le Grotte d'Italia, NSS News, VIA*. Honorary Member, National Speleological Society, USA.

Climate of Caves

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China: Archaeological Caves

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Insecta: Pterygota

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Crustacea: Isopoda (Aquatic); Crustacea: Syncarida; Interstitial Habitats (Aquatic)

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Senior researcher, Department of Geospeleology, "Emil Racovita" Institute of Speleology. Bucharest, Romania. Co-author of *Karst of Southwestern Romania* (1996); *Sisteme carstice majore din zona Resita-Moldova Noua* [Major karstic systems from Resita-Moldova Noua area] (1996). Editor of *The Great Romanian Caves Atlas* (in preparation). Contributor to *Bulletin Speleogic, International Caver, Journal of Quaternary Science, Theoretical and Applied Karstology*. Managing Editor, *Theoretical and Applied Karstology,* and former Editor, *Speleotex*.

Europe, Balkans and Carpathians

Cordingley, John

British Cave Rescue Council Diving Officer and UK Cave Diver (CDG Qualified), UK. Author of *The Peak Cavern System, A Cavers' Guide* (1986); "Peak Cavern, a climb beyond The Far Sump" in *The Last Adventure,* edited by A.Thomas (1989); *The Peak District Sump Index 1994; The Peak District Sump Index Update 1997*. Co-editor of *The Cave Diving Group Manual 1990*. Contributor to *Cave and Karst Science, Compass Points (Journal of the BCRA Cave Survey Group), UIS International Cave Diving Magazine,* and a large number of contributions on cave exploration to the major British caving journals over 25 years.

Diving in Caves

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Professor, Center for Cave and Karst Studies, Applied Research and Technology Program of Distinction, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky, USA. Author of over 200 articles and technical reports dealing primarily with groundwater contamination of karst aquifers. Co-author of *Living with Karst* (2001). Honorary Member, National Speleological Society, USA.

Water Tracing: History

Crothers, George M.

Director, William S.Webb Museum of Anthropology and Assistant Professor, Department of Anthropology, University of Kentucky, Lexington, Kentucky, USA. Contributor to *Caving Basics: A Comprehensive Guide for Beginning Cavers,* edited by G.T.Rea (3rd edition, 1992); *Formation Processes in Archaeological Context,* edited by P.Goldberg, D.T.Nash & M.D.Petraglia (1993); *Fleeting Identities: Perishable Material Culture in Archaeological Research,* edited by P.B.Drooker (2001); *The Woodland Southeast,* edited by D.G.Anderson & R.C.Mainfort (2002); and to the journals *Journal of Archaeological Science, Missouri Cave and Karst Conservancy Digest, NSS Bulletin, Tennessee Anthropologist*.

America, North: Archaeological Caves

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Adaptation: Genetics

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Grand Canyon, United States

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Owner, Speleobooks, Schoharie, New York, USA. Co-editor of *Guide to Speleological Literature of the English Language 1794–1996* (1998).

Accidents and Rescue

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America, Central; Aves (Birds); Cockpit Country Cone Karst, Jamaica; Cone Karst; Military Uses of Caves; Morphometry; Tower Karst

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Insecta: Coleoptera; Interstitial Habitats (Terrestrial)

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Asia, Southeast: Biospeleology; Insecta: Apterygota; Salukkan Kallang, Indonesia: Biospeleology

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Faculty of Earth and Life Sciences, Vrije University, Netherlands. Contributor to *Environmental Geology*.

Pamukkale, Turkey

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Aquifer-Stream Relations, edited by J.van Brahana (1998); *Hydrogeology and Engineering Geology of Sinkholes and Karst, 1999,* edited by B.F.Beck, A.J.Pettit & J.G.Herring (1999); *Groundwater in the Celtic Regions,* edited by N.S.Robins & B.D.R.Misstear (2000); *Oxford Companion to the Earth,* edited by P.L.Hancock & B.J.Skinner (2000). Co-editor and author of articles in *Karst Hydrogeology and Human Activity: Impacts, Consequences and Implications* (1999). Contributor to *Environmental Geology, Proceedings of the Geological Association.*

Burren Glaciokarst, Eire; Groundwater Protection

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Professor, Institute of Experimental Physics, University of Bremen, Germany. Author of *Processes in Karst Systems: Physics, Chemistry and Geology* (1988). Co-editor of *Speleogenesis: Evolution of Karst Aquifers* (2000). Contributor to *Global Karst Correlation,* edited by Yuan Daoxian (1998); *Karst Modeling* (1999) and to the journals *Cave and Karst Science, Chemical Geology, Environmental Geology, Geochimica et Cosmochimica Acta,* and *Zeitschrift für Geomorphologie*.

Carbonate Minerals: Precipitation; Dissolution: Carbonate Rocks; Dissolution: Evaporite Rocks; Erosion Rates: Theoretical Models; Speleogenesis: Computer Models

Dublyansky, Victor

Professor, Department of Geology, Perm State University, Russia. Author of *Karst Caves and Shafts of the Crimea Mountains* (1977, in Russian); *Karst Caves of the Ukraine* (1980, in Russian); *Hydrogeology of Karst in Alpean Folded Zone of Southern USSR* (1984, in Russian); *Karst and Groundwaters of the Mountain Massifs of the Western Caucasus* (1985, in Russian); *Microclimate of Karst Caves in the Crimean Mountains* (1989, in Russian); *An Intriguing Speleology* (2000, in Russian). Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.Klimchouk, D.Ford, A.Palmer & W. Dreybrodt (2000), and to the journals *Journal of Cave and Karst Studies, Studies in Speleology*.

Crimea, Ukraine

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Asia, Southeast: History

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Groundwater Protection

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China: Archaeological Caves

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Exploring Caves

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Department of Prehistoric Archaeology, University of Aarhus, Denmark. Author of *Change and Continuity in a Prehistoric Hunter-Gatherer Society: A Study of Cultural Adaptation in Late Glacial-Early Postglacial Southwestern Germany* (1991). Co-editor of *Humans at the End of the Ice Age: The Archaeology of the Pleistocene-Holocene Boundary* (1996); *As the World Warmed: Human Adaptations across the Pleistocene-Holocene Boundary* (1998). Contributor to *The Human Use of Caves*, edited by C.Bonsall & C.Tolan-Smith (1997).

Europe, Central: Archaeological Caves

Fairchild, Ian

Professor of Earth Surface Processes and Dean of Natural Sciences, School of Earth Sciences and Geography, Keele University, UK. Over 100 published contributions, including to the journals *Chemical Geology, Geochimica Cosmochimica Acta, Journal of the Geological Society, London, Science*.

Chemistry of Natural Karst Waters

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British Geological Survey, Keyworth, Nottingham, UK. Author of *Walks around the Caves and Karst of the Mendip Hills* (1999) and co-author of *Karst and Caves of Great Britain* (1997). Contributor to *Cave and Karst Science, Geology, Proceedings of the University of Bristol Spelaeological Society*.

Draenen, Ogof Draenen, Wales; Mendip Hills, England; Paleoenvironments: Clastic Sediments; Paragenesis

Filippov, Andrej G.

Formerly, East Siberian Research Institute of Geology, Geophysics and Mineral Resources, Irkutsk, Russia.

Mineral Deposits in Karst; Siberia Caves, Russia

Finlayson, Clive

Director of the Gibraltar Museum, Gibraltar and co-director of the Gibraltar Caves Research Project. Author of *Birds of the Strait of Gibraltar* (1992). Co-editor of *Neanderthals on the Edge: 150th Anniversary Conference of the Forbes's Quarry Discovery, Gibraltar* (2000) and *Gibraltar during the Quaternary* (2000). Contributor to *Neanderthals on the Edge* (2000) and *Studies in Honour of DA.E. Garrod*, edited by R.Charles & W.Davis (1998) and to the journal *Antiquity*.

Gibraltar Caves: Archaeology

Ford, Derek (Adviser)

Emeritus Professor, School of Geography and Geology, McMaster University, Hamilton, Ontario, and Adjunct Professor of Earth Sciences, University of Waterloo, Canada. Co-author of *Karst Geomorphology and Hydrology* (1989): Co-editor of *Paleokarst: A World Regional and Systematic Review* (1989); *Geomorphology sans frontierès* (1995); *Speleogenesis; Evolution of Karst Aquifers* (2000); *Present State and Future Trends of Karst Studies* (2001). Contributor to many journals including most recently *Bulletin d'Hydrogeologie, Chemical Geology, Quaternary Research*. Honorary Member, National Speleological Society, USA.

Aggtelek and Slovak Karst, Hungary-Slovakia; Bear Rock Karst, Canada; Canada; Carbonate Karst; Castleguard Cave, Canada; Karst; Nahanni Karst, Canada; Paleoenvironments: Speleothems; Solution Breccias; Speleogenesis: Unconfined Settings

Forti, Paolo

Professor of Geomorphology and Speleology, University of Bologna, Italy. Co-author of *Le cavita' naturali dell'Iglesiente* (1982); *I cristalli di gesso del Bolognese* (1983); *La cavita' naturali della Repubblica di San Marino* (1983); *Cave Minerals of the World* (1986; 2nd edition 1997). Editor or co-editor of *L'idrogeolia del bacino minerario dell'Iglesiente* (1983); *Morfologie Carsiche e Speleogenesi—diapositive didattiche* (1993); *Grotte marine d'Italia* (1994); *Volcanospeleology* (1998); *Karst Geomorphology* (1999). Contributor of articles to *Karst Terrains: Environmental Changes and Human Impact*, edited by P. Williams (1991); *La Vena del Gesso,* edited by U.Bagnaresi *et al.* (1994); *Il lago del Fucino e il suo emissario,* edited by E.Burri & G. Tavano (1994); *Gypsum Karst of the World,* edited by A.Klimchouk *et al.* (1997). Contributor to *Atmospheric Environment, International Journal of Speleology, Marine Geology, NSS Bulletin, Tectonophysics*.

Books on Caves; Frasassi Caves, Italy; Journals on Caves; Paleotectonics from Speleothems; Speleothems: Carbonate

Frankland, John

MD, Lancaster, UK. Cave rescue doctor for the busiest cave rescue team in the world (the Cave Rescue Organization in Yorkshire, England) for 30 years. Co-author of *Race Against Time* (1988), a detailed history of the Cave Rescue Organization's first 50 years.

Accidents and Rescue

Frumkin, Amos

Senior Lecturer in Geography and Director of Cave Research Center, Department of Geography, The Hebrew University of Jerusalem, Israel. Contributor to *Salt Tectonics,* edited by I.Alsop, L., D.Blundell & I.Davison (1996); *Cave Minerals of the World,* edited by C.A.Hill & P.Forti (1997) and to the journals *Earth Surface Processes and Landforms, Israel Journal of Earth Sciences, Journal of Caves and Karst Studies, Quaternary Research, The Holocene*.

Sedom Salt Karst, Israel

Gabrovšek, Franci

Researcher, Karst Research Institute, The Scientific Research Center of the Slovenian Academy of Sciences and Arts, Slovenia. Author of *Evolution of Karst Aquifers: From Simple Principles to Complex Models* (2000), and contributor to *South China Karst,* edited by Chen Xiaoping *et al.* (1998); *Speleogenesis: Evolution of Karst Aquifers,* edited by A.Klimchouk, D.Ford, A.Palmer & W.Dreybrodt (2000). Editor of *Evolution of Karst: From Prekarst to Cessation* (2002). Contributor to *International Caver, Proceedings of the 12th International Congress of Speleology*.

Kanin Massif, Slovenia-Italy

Galdenzi, Sandro

Instituto Italiano di Speleologia, Ancona, Italy. Co-editor *Il carsismodella Gola di Frasassi* (1990). Contributor to *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F.Humphreys (2000) *and Journal of Cave and Karst Studies, Environmental Geology*.

Frasassi Caves, Italy

Gauchon, Christophe

Maitre de Conferences, Agrégé de Géographie, Laboratoire de Géographie de l'Université de Savoie, France. Author of *Des Cavernes et des Hommes* (1997). Contributor to *Spelunca*. Editorial board member of *Karstologia*. Secretary of karst phenomena Commission (French National Committee of Geography).

France: History

Gebauer, Daniel

Author of *Caves of India and Nepal* (1983); *Kurnool 1984* (1985); *Speleological Bibliography of South Asia* (1996); *Unexplored Caves and Limestone Areas of Arunachal Pradesh, Assam, Manipur, Mizoram and Tripur (North-east India)* (1997); *Caves of Mizoram (North-east India)* (1999). Contributor to the journals *British Caving, Caves and Caving, Grottes et Gouffres, International Caver, International Journal of Speleology, Spelunca,* and *Stalactite*.

Indian Subcontinent

Gibson, David

Consultant Electronic Design Engineer (self-employed). Technical Editor of the BCRA's *Cave Radio & Electronics Group Journal*. Contributor to *Advanced Signal Processing for Communication Systems,* edited by T.Wysocki, M.Darnell & B.Honary (2002), and to the journals *Cave and Karst Science, Cave Radio & Electronics Group Journal, Compass Points, Electronics World*.

Communications in Caves; Radiolocation

Gillieson, David (Adviser)

Professor of Geography and Head of School, School of Tropical Environment Studies and Geography, James Cook University, Cairns, Australia. Author of *Caves: Processes, Development and Management* (1996) and co-author of *Guidelines for Cave and Karst Protected Areas* (1997). Contributor to *Global Karst Correlation,* edited by Yuan

Daoxian (1998); *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications,* edited by D. Drew & H.Hötzl (1999); *Oxford Companion to the Earth Sciences,* edited by B.Skinner & I.Stewart (2000); *Australia Underground,* edited by E.Hamilton-Smith & B.Finlayson (2003). Contributor to *Earth Surface Processes and Landforms, Environmental Geology, International Journal of Speleology, Proceedings of the Linnean Society of New South Wales,* and *Zeitschrift für Geomorphologie*.

Asia, Southeast Islands; Chillagoe and Mitchell-Palmer Karsts, Australia; Floral Resources; Nullarbor Karst, Australia; Sediments: Allochthonous Clastic

Ginés, Àngel

Associate Professor of Ecology, Department of Biology, Universitat de les Illes Balears, Palma de Mallorca. Co-editor of *El carst I les coves de Mallorca* (1995); *Karren Landforms* (1996). Contributor to *Late Quaternary Sea-level Changes in Spain,* edited by C.Zazo (1987); *El karst en España,* edited by J.J.Durán & J.López-Martínez (1989); *The Natural History of Biospeleology,* edited by A.I. Camacho (1992); *Environmental Effects on Karst Terrains,* edited by I.Bárány-Kevei (1995); *Karst and Agriculture of the World,* special issue of *International Journal of Speleology* (1999), and to the journals *Acta Carsologica, Endins, Earth Surface Processes and Landforms, Geodinamica Acta, Quaternary Science Reviews*.

Europe, Mediterranean; Karren

Glover, Ian

Institute of Archaeology, University College London, UK. Author of *Archaeology in Eastern Timor, 1966–67* (1986); *Early Trade Between India and Southeast Asia—A Link in the Development of a World Trading System* (1990). Contributor to *South Asian Archaeology,* edited by N. Hammond (1973); *Early South-East Asia: Essays in Archaeology, Historical Geography,* edited by R.Smith & W.Watson (1979); and to the journal *World Archaeology*. Dr Glover has excavated many caves in Indonesia.

Asia, Southeast: Archaeological Caves

Goldie, Helen

Department of Geography, University of Durham, UK. Contributor to *Karst and Caves of Great Britain,* edited by A.C.Waltham, M.J. Simms, A.R.Farrant & H.S.Goldie (1997), and to the journals *Acta Geographica Szegediensis, Cave and Karst Science, Environmental Geology,* and *Zeitschrift für Geomorphologie*.

Ornamental Uses of Limestone

Grimes, Ken G.

Consultant geologist, Regolith Mapping, Australia. Co-author of *Field Guidebook to Karst and Volcanic Features in Southeast South Australia and Western Victoria* (1999). Contributor to *Australian Cave and Karst Management Association Journal, Cave and Karst Science, Environmental Geology, Helictite, Memoirs of the Queensland Museum*. Editor of *Helictite:* The Journal of Australasian Speleological Research.

Syngenetic Karst

Günay, Gültekin

International Research and Application Center for Karst Water, Hacettepe University, Ankara, Turkey. Co-editor of *Karst Water Resources* (1996); *Karst Waters and Environmental Impacts* (1997). Contributor to many journals including *Cave and Karst Science, Environmental Geology, Journal of Hydrology*.

Pamukkale, Turkey; Turkey

Gunn, John (Editor)

Professor, Limestone Research Group, Department of Geography, University of Huddersfield, UK. Co-author of *Caves and Karst of the Peak District* (1990); *The Reclamation of Limestone Quarries using Landform Replication* (1997). Co-editor of *Karst Hydrology* (1998); *Essays in the Ecology and Conservation of Karst* (2000) and Editor, *An Introduction to British Limestone Karst Environments* (1994). Authored over 80 papers in journals and edited books. Chairman of the International Geographical Union's Karst Commission for the period 2000–2004. Joint Editor of *Cave and Karst Science*, Editorial Advisory Board member of *Environmental Geology*.

Erosion Rates: Field Measurement; Fluviokarst; France, Southern Massif Central; Limestone as a Mineral Resource; Peak District, England; Quarrying of Limestone; Radon in Caves; Turkey; Valleys in Karst

Halliday, William R. (Adviser)

Nashville, Tennessee, USA. Author of *Adventure is Underground* (1959); *Caves of California* (1962); *Caves of Washington* (1963); *Depths of the Earth* (1966); *American Caves and Caving* (1974), and contributor to *Mount St. Helens Five Years Later*, edited by S.A.C. Keller (1986). Editor of *Proceedings, 1972 International Symposium on Vulcanospeleology and its Extraterrestrial Applications* (1972); *Selected Caves of the Pacific Northwest: Guidebook of the 1972 National Speleological Society Convention* (1972); *Proceedings, 1982 Third International Symposium on Vulcanospeleology* (1982); *Introduction to Hawaii Caves: Field Guide for the 6th International Symposium on Vulcanospeleology* (1991). Contributor to *Geological Newsletter, GP Magazine, NSS Bulletin/Journal of Cave and Karst Science, Science, Studies in Speleology*. Honorary President, Commission on Volcanic Caves, International Union of Speleology. Honorary Member, National Speleological Society, USA.

America, North: History; Caves in History: The Eastern Mediterranean; Crevice Caves; Disease; Hawaii Lava Tube Caves, United States; Piping Caves and Badlands Pseudokarst; Pseudokarst; Talus Caves; Volcanic Caves; Vulcanospeleology: History

Hamilton-Smith, Elery (Adviser)

Chair, IUCN/WCPA Task Force on Cave and Karst Protection. Adjunct Professor, Cave and Karst Management, Charles Sturt University, New South Wales, Australia. Fellow of both the Australian Speleological Federation and the Australasian Cave and Karst Management Association. Co-author of *South-east Karst Province of South Australia* (1993); *Guidelines for Cave and Karst Protection* (1997); *Karst Management Considerations for the Cape Range Karst Province Western Australia* (1998). Co-editor of *Proceedings of the Asia-Pacific Forum on Karst Ecosystems and World Heritage* (2002). Contributor to *Essays in the Ecology and Conservation of Karst*, edited by I.Barany-Kevei & J.Gunn (2000); *Subterranean Ecosystems*, edited by H.Wilkens &

D.Culver (2000) and to the journals *Evaluation Journal of Australia, Helictite, Natura Croatica*.

Conservation: Protected Areas; Karst Resources and Values; Organic Resources in Caves; Tourism and Caves: History; Tourist Caves; World Heritage Sites

Häuselmann, Philipp

PhD student, Institute of Geography, University of Fribourg, Switzerland, and Postdoctoral fellow, Earth and Atmospheric Sciences, Purdue University, USA. Co-editor of *Speleogenesis in the Alpine Belt* (2001). Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.Klimchouk *et al.* (2000); *Speleogenesis in the Alpine Belt,* edited by P.Häuselmann & M.Monbaron (2001), and to the journals *Al Ouat'Ouate, Etudes de Géographie Physique, Geodinamica Acta, Jahrbuch vom Thuner- und Brienzersee, Stalactite*.

Siebenhengste, Switzerland

Hervant, Frédéric

Hydrobiologie et Écologie souterraines, Université Claude-Bernard Lyon I, France. Contributor to *Aquatic Sciences, Archiv für Hydrobiologie, Hydrobiologia, Journal of Experimental Biology, Mémoires de Biospéologie*.

Adaptation: Physiological

Hildreth-Werker, Val

Hillsboro, New Mexico, USA. Co-editor of *Cave Conservation and Restoration* (2003), Co-Chair of the Conservation Division for the National Speleological Society.

Restoration of Caves and Speleothem Repair

Hill, Carol A.

Adjunct Professor, Geology Department, University of New Mexico, Albuquerque, USA. Author of *Cave Minerals* (1976), *Geology of Carlsbad Cavern* (1987), and *Geology of the Delaware Basin* (1996). Co-editor of *Cave Minerals of the World* (1986; 2nd edition 1997). Contributor to *American Association of Petroleum Geologists Bulletin, Environmental Geology, Journal of Cave and Karst Studies, Journal of Geology,* and *Science*.

Minerals in Caves; Speleothems: Evaporite

Hobbs, Horton H., III

Professor, Department of Biology, Wittenberg University, Springfield, Ohio, USA. Co-author of *The Crayfishes and Shrimp (Palaemonidae, Cambaridae) of Wisconsin* (1988). Editor of *A Study of Environmental Factors in Harrison s Cave, Barbados, West Indies* (1995). Contributor to *Biodiversity of the Southeastern United States: Aquatic Communities,* edited by C.T.Hackney, S.M.Adams & W.H.Martin (1992); *Conservation and Protection of the Biota of Karst,* edited by I.D.Sasowsky, D.W.Fong & E.L.White (1997); *Encyclopedia Biospeologica,* edited by C.Juberthie & V.Decu (1998); *Subterranean Ecosystems,* edited by H.Wilkens & D.Culver (2000); *Ecology and Classification of North American Freshwater Invertebrates,* edited by J.A.Thorp & A.P.Covich (2nd edition, 2001); and to the journals *American Zoologist, Conservation*

Biology, Crustaceana, Hydrobiologia, International Journal of Speleology, Journal of Crustacean Biology, Smithsonian Contributions to Zoology. Honorary Member, National Speleological Society, USA.

Crustacea; Crustacea Decapoda

Holsinger, John R.

Professor of Biological Sciences, Old Dominion University, Norfolk, Virginia, USA. Author of *The Freshwater Amphipod Crustaceans (Gammaridae) of North America* (1972); *Descriptions of Virginia Caves* (1975), and contributor to *Stygofauna Mundi*, edited by L. Botosaneanu (1986); *Encyclopedia Biospeologica* (vol. 1), edited by C. Juberthie & V.Decu (1994); *Subterranean Ecosystems,* edited by H. Wilkens & D.Culver (2000). Co-editor of *Biogeography of Subterranean Crustaceans* (1994). Contributor to *Hydrobiologia, Journal of Natural History, Proceedings of the Biological Society of Washington, Proceedings of the 12th International Congress of Speleology*. Honorary Member, National Speleological Society, USA.

Crustacea: Amphipoda

Hope, Jeanette

River Junction Research, New South Wales, Australia.

Australia: Archaeological and Paleontological Caves

Hose, Louise D.

Director, National Cave and Karst Research Institute, Carlsbad, New Mexico, USA. Author of articles in *Encyclopedia of Environmental Issues,* edited by C.W.Allin (2000); *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.Ford, A. Palmer & W.Dreybrodt (2000); *Caves: Exploring Hidden Realms,* edited by M.J.Taylor (2001). Contributor to *Astrobiology, Chemical Geology, Geology, Journal of Cave and Karst Studies, NSS Bulletin, Revista Mexicana de Ciencias Geológias*. Editor *of Journal of Cave and Karst Studies (1996-).*

Golondrinas and the Giant Shafts of Mexico; Huautla Cave System, Mexico; Selma Plateau Caves, Oman; Villa Luz, Cueva de, Mexico

Howarth, Francis G.

L.A.Bishop Chair of Zoology, Department of Natural Sciences, Bernice P.Bishop Museum, Honolulu, Hawaii, USA. Author of *Hawaiian Insects and their Kin* (1992). Co-editor of *Balancing Nature: Addressing the Impact of Importing Non-native Biological Control Agents, An International Perspective* (2001). Contributor to *The Unity of Evolutionary Biology,* edited by E.C.Dudley (1991); *The Conservation of Insects and their Habitats* (1991); *Problem Snake Management: The Habu and Brown Treesnake,* edited by G.Rodda, Y.Sawai. Chzar & H.Tanaka (1999); *Encyclopedia of Biodiversity,* edited by S.Levin (2000); *Measures of Success in Biological Control,* edited by G.M.Gurr & S.D.Wratten (2000), and contributor to the journals *American Naturalist, Bioscience, Evolution, International Journal of Speleology, Mémoires de Biospéologie, Science,* and *Trends in Ecology and Evolution.*

Hawaiian Islands: Biospeleology

Howes, Chris

Freelance author and photographer, Cardiff, UK. Author of *Cave Photography: A Practical Guide* (1987); *To Photograph Darkness: The History of Underground and Flash Photography* (1989); *Images Below: A Manual of Underground and Flash Photography* (1997); *The Spice of Life: Biodiversity and the Extinction Crisis* (1997); *Radical Sports: Caving* (2002). Editor of *Descent*, the magazine of underground exploration. Contributor to *A Man Deep in Mendip*, edited by J. Savory (1989); *On Caves and Cameras*, edited by N.Thompson (2002), and to the journals *Cave Science, New Scientist, Proceedings of the University of Bristol Spelaeological Society*. Peter M.Hauer Spelean History Award (1993). Tratman Award for Speleological Literature (1997). Giles Barker Award for excellence in cave photography (1997). Spelean Arts and Letters Award for contributions to underground photography (1998). Outdoor Writers' Guild Award for Photographic Excellence (1998).

Films in Caves; Photographing Caves

Hoyt, John

Aquifer Sciences Program Manager, Edwards Aquifer Authority, San Antonio, Texas, USA.

Edwards Aquifer and the Texas Karst, United States; Groundwater Pollution: Point Sources

Humphreys, William Frank

Senior Curator, Terrestrial Invertebrate Zoology, Western Australian Museum, Australia. Editor or co-editor of *The Biogeography of Cape Range, Western Australia* (1993); *Proceedings of the XII International Congress of Arachnology* (1993); *Subterranean Ecosystems* (2000); *Subterranean Biology in Australia 2000* (2001). Author of articles in the above volumes and in *Encyclopedia Biospeleologica* vol. 3 (2001); *The Biology of Hypogean Fishes*, edited by A.Romero (2001): *Australia Underground: A Tribute to Joe Jennings* (2002). Contributor to *Comparative Biochemistry and Physiology, Crustaceana, Journal of Animal Ecology, Journal of Crustacean Biology, Journal of Zoology, Mémoires de Biospéologie, Nature, Zoological Journal of the Linnean Society, London*.

Australia: Biospeleology

Hunt, Chris

Senior Research Associate, Division of Geographical Sciences, University of Huddersfield, UK. Contributor to *Archaeometry, Cave and Karst Science, Journal of Archaeological Science, Journal of Arid Environments, Proceedings of the Prehistoric Society*.

Palynology

Iliffe, Thomas M.

Associate Professor, Department of Marine Biology, Texas A&M University at Galveston, USA. Contributor to *Galápagos Marine Invertebrates*, edited by M.J.James (1991); *Diversidad Biológica en la Reserva de la Biosfera de Sian Ka'an, Quintana Roo, Mexico*, edited by D.Navarro & E.Suárez-Morales (vol. 2, 1992); *Natural History of*

Biospeleology, edited by A.Camacho (1992); *Encyclopaedia Biospeologica,* edited by C.Juberthie & V.Decu (vol. 1, 1994); *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F. Humphreys (2000); and to many journals including *Acta Carsologica, Crustacean Research, Crustaceana, Hydrobiologia, Internationale Revue der Gesamten Hydrobiologie, International Journal of Speleology, Mémoires de Biospéologie, Nature, Science, Stygologia.*

Walsingham Caves, Bermuda: Biospeleology

James, Julia

Emeritus Professor, School of Chemistry, University of Sydney, New South Wales, Australia. Contributor to many caves and karst science books, journals, and conference proceedings.

Accidents and Rescue; Carbon Dioxide-enriched Cave Air; Condensation Corrosion; Tourist Caves: Air Quality

Jeannin, Pierre-Yves

Hydrogeologist, Centre d'Hydrogeologie in Neuchâtel and Director of the Swiss Institute for Speleology and Karst Studies, La Chaux-de-Fonds, Switzerland. Co-editor *Modelling in Karst Systems* (1998). Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.C.Ford, A.N.Palmer & W.Dreybrodt (2000) and to many journals including *Cave and Karst Science, Environmental Geology, Ground Water, Stalactite, Water Resources Research.*

Hölloch, Switzerland; Siebenhengste, Switzerland

Johnson, Steve

Senior Hydrogeologist, Edwards Aquifer Authority, San Antonio, Texas, USA.

Edwards Aquifer and the Texas Karst, United States

Juberthie, Christian

Past Director of CNRS Laboratory, Laboratoire souterrain du CNRS, Moulis, France. Coeditor of *Encyclopaedia Biospeologica* (3 vols, 1994, 1997, 2001). Editor-in-chief *Mémoires de Biospéologie.*

France: Biospeleology

Judson, David

Architect and surveyor who surveyed one of Britain's longest caves, Dan-yr-Ogof (1967–1977), was a founder member of the British Cave Research Association (BCRA) in 1973 and the co-founder of the Ghar Parau Foundation, the speleological equivalent of the Mount Everest Foundation (1974). He is currently Insurance Manager of BCRA and Legal and Insurance Officer of the National Caving Association.

Britain and Ireland: History

Kambesis, Patricia

Graduate student (karst geology), Department of Geography and Geology, Hoffman Environmental Research Institute, Western Kentucky University, Bowling Green, Kentucky, USA. Co-author of *Deep Secrets: The Discovery and Exploration of*

Lechuguilla Cave (1999). Editor of *Association for Mexican Cave Studies Report* (1990). Contributor to *Lechuguilla: Jewel of the Underground,* edited by M.R. Taylor (1991), and to the journal *Clay and Clay Minerals*.

Encantado, Sistema del Rio, Puerto Rico

Kashima, Naruhiko

Professor Emeritus, Ehime University and part-time instructor Junior College, Matsuyama Shinonome Gakuen, Ehime, Japan. Co-author of *A Primer of Speleology* (1981, in Japanese); *Karst* (1996, in Japanese). Editor of *A Guidebook for the Nature of Ehime* (1997). Contributor to *Annals of the Speleological Research Institute of Japan, International Journal of Speleology, Journal of the Speleological Society of Japan*.

Akiyoshi-dai, Japan; Cheju-do Lava Caves, South Korea

Kiernan, Kevin

Research Associate, School of Geography and Environmental Studies, University of Tasmania, Australia. Author of *Lake Pedder* (1986); *The Management of Soluble Rock Landscapes: An Australian Perspective* (1988); *Caves, Karst and Management at Mole Creek, Tasmania* (1989); *An Atlas of Tasmanian Karst* (1995); *The Conservation of Coastal Landforms* (1996); *The Conservation of Landforms of Glacial Origin* (1997). Contributor to *The South-West Book,* edited by H.Gee & J.Fenton (1978); *Caves of Northwest Thailand,* edited by J.R.Dunkley & J.B.Brush (1986); *Hydrogeology of Selected Karst Regions,* edited by W.Back, J.Herman & H.Paloc (1992); *Archaeology of Aboriginal Australia,* edited by T.Murray (1998) and to the journals *Australian Archaeology, Australian Journal of Earth Sciences, Cave and Karst Management in Australia, Helictite, Journal of the Sydney Speleological Society, Nature,* and *Zeitschrift für Geomorphologie*.

Australia; Religious Sites

Klimchouk, Alexander (Adviser)

Department of Hydrogeological Problems, Institute of Geological Sciences, National Academy of Science, Kiev, Ukraine. Co-editor of *Gypsum Karst of the World* (1996) and *Speleogenesis: Evolution of Karst Aquifers* (2000). Author of more than 180 papers on geospeleology and karstology, including more than 70 papers published in major international geoscience and speleological journals and proceedings. Vice-President of the International Union of Speleology (IUS) and President of the UIS Commission on Karst Hydrogeology and Speleogenesis. Honorary Member, National Speleological Society, USA.

Asia, Central; Caucasus, Georgia; Caves; Evaporite Karst; Krubera Cave, Georgia; Morphometry of Caves; Russia and Ukraine; Soviet Union: History; Speleogenesis; Speleogenesis: Deep-Seated and Confined Settings; Ukraine Gypsum Caves and Karst

Knez, Martin

Scientific researcher, Karst Research Institute, Scientific Research Center of the Slovenian Academy of Sciences and Arts, Postojna, Slovenia. Author of *The Bedding-Plane Impact on Development of Karst Cave: An Example of Velika Dolina* (1996) and co-author of *Minerals in the Slovene Karst Caves* (1992). Co-editor of *South China Karst*

(1998). Contributor to *Slovene Classical Karst,* edited by A. Kranjc (1997); *Field Guide of Karst in Slovenia,* edited by A.Kranjc (1997); *Global Karst Correlation,* edited by Yuan Daoxian (1998); *South China Karst,* edited by Chen Xiaoping *et al.* (1998), and to the journals *Acta Carsologia, Annales, Carbonates and Evaporites, Environmental Geology, International Journal of Speleology, Materials and Geoenvironment,* and *Zeitschrift für Geomorphologie*.

Highways on Karst

Kogovšek, Janja

Professional Adviser, Karst Research Institute ZRC SAZU, Postojna, Slovenia. Co-editor of *South China Karst* (1998). Contributor to *Kras: Slovene Classical* Karst, edited by A. Kranjc (1997); *Karst Hydrogeological Investigations in South-western Slovenia,* special issue *of Acta Carsologica* (1997); *Global Karst Correlation,* edited by Yuan Daoxian (1998); *South China Karst,* edited by Chen Xiaoping *et al.* (1998), and to the journals *Acta Carsologia, Acta Geologica Sinica, Environmental Geology,* and *International Journal of Speleology*.

Postojna Planina Cave System, Slovenia

Kranjc, Andrej

Scientific Adviser, Karst Research Institute, ZRC SAZU, Ljubljana, Slovenia. Author of *Recent Fluvial Cave Sediments, Their Origin and Role in Speleogenesis* (1989); co-author of *Proteus, The Mysterious Ruler of Karst Darkness* (1993). Editor of *Kras: Slovene Classical Karst* (1997). Contributor to *Encyclopaedia Biospeologica,* edited by C. Juberthie & V.Decu (1994); *Enciklopedija Slovenije,* edited by M. Javornik *et al.* (1996); *Global Karst Correlation,* edited by Yuan Daoxian & Liu Zaihua (1998); *Karst Hydrogeology and Human Activitioes: Impacts, Consequences and Implications,* edited by D. Drew & H.Hötzl (1999), and to the journals *Acta Carsologica, Cave and Karst Science, International Journal of Speleology, Slovensky Kras.* Editorial board member of *Acta Carsologica, Acta Geographica, Annales, Karstologia, Kras I Speleologia, Slovensky Kras*.

Dinaric Karst; Kras, Slovenia

Kryštufek, Boris

Associate Professor and Senior Curator, Department of Vertebrates, Slovene Museum of Natural History, Ljubljana, and Institute for Biodiversity Studies, Scientific and Research Centre of the Republican Slovenia, Koper, Slovenia. Author of *Mammals of Slovenia* (1991); *Fundamentals of Conservation Biology* (1999); *Mammals of Turkey and Cyprus* (2001). Co-editor of the *Atlas of European Mammals* (1999); *Key to Vertebrates of Slovenia* (1999). Contributor to *European Bat Research 1987,* edited by V.Hanának, I.Horáček & J.Gaisler (1988); *Wild Sheep and Goats and their Relatives. Status Survey and Conservation Action Plan for Caprinae,* edited by D.M.Shackleton (1997); *Mousterian Bone Flutes and Other Finds from Divje Babe I Cave Site in Slovenia,* edited by I. Turk (1997); *Prague Studies in Mammalogy,* edited by I.Horáček & V.Vohralik (1992); *Mustelids in a Modern World: Management and Conservation Aspects of Small Carnivore:human Interactions,* edited by H.I.Griffiths (2000); and to the journals *Folia*

Zoologica, Journal of Biogeography, Journal of Zoology, Mammalian Biology, Mammalia, Myotis.

Chiroptera (Bats)

Kueny, Jeff

Department of Geography, University of Wisconsin-Milwaukee, USA. Contributor to *Journal of Cave and Karst Studies, Caribbean Geography*.

America, Central; Military Uses of Caves

LaMoreaux, E.Philip

Senior Hydrogeologist, P.E. LaMoreaux & Associates, Inc, Tuscaloosa, Alabama, USA. Author or co-author of *Hydrology of Limestone Terranes; Annotated Bibliography of Carbonate Rocks* (1970); *Hydrogeology and Management of Hazardous Waste by Deep Well Disposal* (1989); *Environmental Hydrogeology* (1997). Co-editor of *Guide to the Hydrology of Carbonate Rocks* (1984); *Hydrology of Limestone Terranes; Annotated Bibliography of Carbonate Rocks* (vol. 3, 1988; vol. 4, 1989, vol. 5, 1993); *Springs and Bottled Waters of the World: Ancient History, Source, Occurrence, Quality and Use* (2001). Contributor to *Sinkholes: Their Geology, Engineering, and Environmental Impact: Proceedings of the First Multidisciplinary Conference on Sinkholes* (1984); *Karst Hydrogeology and Karst Environment Protection: Proceedings of the 21st Congress of the IAH* (1988); *Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Sinkholes and Karst* (1989); *Selected Papers on Aquifer Overexploitation: from the 23rd International Congress of IAH* (1991); *Proceedings of the International Conference On Karst-Fractured Aquifers: Vulnerability and Sustainability* (1996) and to the journals *Bulletin of the Association of Engineering Geologists, Geotimes, Journal of Hydrology, KWI Conduit, Professional Geologist*. Editor-in-Chief, *Journal of Environmental Geology*.

Karst Hydrology: History

Lascu, Cristian

Geologist, “Emil Racoviță” Speleological Institute, Cluj, Romania.

Movile Cave, Romania

Latham, Alf G.

Lecturer in Archaeological Science, School of Archaeology, Classics and Oriental Studies, University of Liverpool, UK. Contributor to *Uranium Series Disequilibrium: Applications to Earth, Marine and Environmental Sciences,* edited by Ivanovich & Harmon (1992); *Geoarchaeology: Exploration, Environments, Resources* (1999); *The Cenozoic of Southern Africa,* edited by T.C.Partridge & R.R.Maud (2000); *Handbook of Archaeological Sciences,* edited by D.R.Brothwell & A.M.Pollard (2001), and to the journals *Archaeometry* and *Cave Archaeology and Palaeontology Research Archive*.

Africa, South: Archaeological Caves; Carmel Caves, Israel: Archaeology; Dating Methods: Archaeological

Lauritzen, Stein-Erik

Geologisk Institutt, University of Bergen, Norway. Editor of *Climate Change: The Karst Record* (1997). Contributor to *Acta Carsologica, International Journal of Speleology, Journal of Cave and Karst Studies, Theoretical and Applied Karstology*. Honorary Member, National Speleological Society, USA.

Stripe Karst

Lavoie, Kathleen H.

Professor of Biology and Dean, Faculty of Arts and Science, Plattsburgh State University of New York. Co-author of *Introduction to Speleology* (2002). Contributor to *A Guide to Speleological Literature of the English Language 1794–1996,* edited by D.E. Northup, E.D.Mobley, K.L.Ingham III & W.W.Mixon (1998); *Subterranean Ecosystems,* edited by H.Wilkens, D.C.Culver & W.F. Humphreys (2000), and to the journals *American Midland Naturalist, Astrobiology Journal, Comparative Biochemistry and Physiology, Geomicrobiology Journal, Journal of the Helminthological Society of Washington, Journal of Mammology,* and *Microbial Ecology*.

Microorganisms in Caves

Lera, Thomas

Falls Church, Virginia, USA. Author of *Bats in Philately* (1995). Contributor to the journals *American Philatelist, Journal of Cave and Karst Studies, Journal of Spelean History, NSS News, Scott Stamp Monthly*. Editor of *The Underground Post* and Contributing Editor to *Speleophilately International*. Former conservation editor of *NSS Bulletin*.

Stamps and Postcards; Wilderness

Llona, Ana C.Pinto

Laboratorio de Prehistoria, Asturias, Spain. Co-author of *Taphonomy and Palaeoecology of Bears from N. Spain* (2002).

Paleontology: Animal Remains in Caves

Longley, Glenn

Director, Edwards Aquifer Research and Data Center and Professor of Aquatic Biology, Southwest Texas State University, San Marcos, Texas, USA. Author of articles on the salamander and blindcat in *The New Handbook of Texas* (1996). Contributor to *Copeia, Malacologia, Proceedings of the Biological Society of Washington, Smithsonian Contributions to Zoology*.

Edwards Aquifer, United States: Biospeleology

Loucks, Robert G.

Bureau of Economic Geology, John A. and Katherine G.Jackson School of Geosciences, University of Texas, Austin, USA. Co-editor of *Silicilastic Diagenesis and Fluid Flow: Concepts and Applications* (1996); *Carbonate Sequence Stratigraphy: Recent Advances and Applications* (1993). Contributor to *Clastic Diagenesis,* edited by D.A. McDonald & R.C.Surdam (1984); *Carbonate Sequence Stratigraphy,* edited by R.G.Loucks & R.Sarg (1993); *Petroleum Geology of North Africa,* edited by D.S.MacGregor, R.T.J.Moody & D.D.Clark-Lowes (1998); *Modern and Ancient*

Carbonate Eolianites: Sedimentology, Sequence Stratigraphy, and Diagenesis, edited by F.E. Abegg, P.M.Harris & D.D.Loope (2001); and to the journals *American Association of Petroleum Geologists Bulletin, Gulf Coast Association of Geological Societies Transactions, and Journal of Applied Geophysics.* Associate editor for the *American Association of Petroleum Geologists Bulletin*.

Hydrocarbons in Karst

Lowe, David J. (Adviser)

Field geologist and, lately, geoscientific data project manager, British Geological Survey, Keyworth, Nottingham, UK. Joint author of *Dictionary of Karst and Caves* (1995, revised 2002). Co-editor of *Gypsum Karst of the World* (1996), and *Implications of Speleological Studies for Karst Subsidence Hazard Assessment* (2003). Joint Editor of *Cave and Karst Science.* Editorial Board member for *International Journal of Speleology, Naše jame, Theoretical and Applied Karstology,* and the *Virtual Journal of Speleogenesis and Evolution of Karst Aquifers.* Contributor to *Limestones and Caves of Wales* (1989), *Speleogenesis: Evolution of Karst Aquifers* (2000), *Paviland Cave and the 'Red Lady'* (2000) and to the journals *Acta Carsologica, Cave Science*. Visiting Research Fellow, Limestone Research Group, University of Huddersfield, UK; Research Associate, Karst Research Institute, Postojna, Slovenia.

Geoscientists; Inception of Caves; Speleogenesis Theories: Post-1890

Lundberg, Joyce

Department of Geography and Environmental Sciences, Carleton University, Canada. Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.Ford, A.Palmer & W.Dreybrodt (2000) and to the journals *Cave and Karst Science, Journal of Cave and Karst Science, Palaeogeography, Palaeoclimatology, Palaeoecology, Quaternary Research, The Holocene.*

Coastal Karst

Maire, Richard

Directeur de recherches au CNRS, Université Bordeaux, France. Author of *La haute montagne calcaire* (1990). Co-editor *Karsts de Chine Centrale* (1995). Editor-in-chief *Karstologia*.

Patagonia Marble Karst, Chile; Pierre Saint-Martin, France-Spain

Martens, Koen

Researcher, Department of Freshwater Biology, Royal Belgian Institute of Natural Sciences and Guest Professor, University of Ghent, Belgium. Co-editor of *Speciation in Ancient Lakes* (1994); *The Evolutionary Ecology of Reproductive Modes in Non-marine Ostracoda* (1994); *Evolutionary Biology and Ecology of Ostracoda* (2000). Editor of *Sex and Parthenogenesis: Evolutionary Ecology of Reproductive Modes in Non-marine Ostracods* (1998). Contributor to *Crustaceana, Heredity, Hydrobiologia, Journal of Evolutionary Biology, Oecologia, Proceedings of the Royal Society, London, Zoological Journal of the Linnean Society*. Member of the editorial board of *Hydrobiologia, Phegea*.

Crustacea: Ostracoda

Martini, Jacques

Formerly, Council for Geoscience (former Geological Survey), Pretoria, South Africa; currently retired in France. Contributor to *Speleogenesis: Evolution of Karst Aquifers*, edited by A.Klimchouk *et al.* (2000), and to the journals *Annals of the Geological Survey of South Africa, Karstologia, South African Speleological Society Bulletin*. Honorary life member of the Société Suisse de Spéléologie and of the South African Spelaeological Association.

Dissolution: Silicate Rocks; Silicate Karst

Mathieu, Jacques

Hydrobiologie et Écologie souterraines, Université Claude-Bernard Lyon I, France. Co-editor *Groundwater/Surface Water Ecotones: Biological and Hydrological Interactions and Management Options* (1997). Contributor to *Groundwater Ecology*, edited by J.Gibert, D. Danielopol & J.Stanford (1994) and to the journals *Archiv für Hydrobiologie, Hydrobiologia, Mémoires de Biospéologie, Stygologia.*

Adaptation: Physiological

Mauriès, Jean-Paul

Laboratoire de Zoologie-Arthropodes, Museum National d'Histoire Naturelle de Paris, Paris, France. Co-editor *Acta Myriapodologica (Mémoires du Museum National d'Histoire Naturelle)* (1996).

Myriapoda

McFarlane, Donald A.

Associate Professor, Keck Science Center, The Claremont Colleges, Claremont, California, USA. Contributor to *Jamaica Underground: The Caves, Sinkholes and Rivers of the Island,* edited by A.G.Fincham (1997); *Extinctions in Near Time: Causes, Contexts and Consequences,* edited by R.D.E.MacPhee (1999), and to the journals *Biogeochemistry, Caribbean Journal of Science, Cave and Karst Science, Journal of Cave and Karst Studies,* and *Quaternary Research.*

Guano

Messana, Giuseppe

Senior Researcher, CNR—Istituto per lo Studio degli Ecosistemi Sezione di Firenze, (formerly Centro di Studio per la Faunistica ed Ecologia Tropicali), Firenze, Italy. Contributor to *Encyclopaedia Biospeleologica, Archiv fur Hydrobiologie, Crustaceana, Italian Journal of Zoology, Mémoires de Biospéologie, Tropical Zoology*. President of Société de Biospéologie. Editor of the journal *Tropical Zoology*.

Africa: Biospeleology

Meyer-Rochow, Victor Benno

Professor of Biology, Faculty of Engineering and Science, International University of Bremen, Germany. Author of *The New Zealand Glow-Worm* (1990). Contributor to *The Compound Eye and Vision of Insects,* edited by G.A.Horridge (1975); *Mechanisms and Phylogeny of Mineralization in Biological Systems,* edited by S.Suga & H.Nakahara (1991); *Atlas of Arthropod and Sensory Receptors,* edited by E.Eguchi & Y.Tominaga

(1999); *Sensory Biology of Jawed Fishes*, edited by B.J Kapoor & T.J.Hara (2001); and to the journals *Biologist, Invertebrate Biology Journal of Insect Physiology, Physiology and Behaviour, Proceedings of the Royal Society of London*. Editorial board member of *Invertebrate Biology, Acta Neurobiologiae Experimentalis,* and *Entomologica Fennica*.

Adaptation: Eyes

Michie, Neville

Freelance Cave Scientist, New South Wales, Australia. Contributor to several Conference Proceedings and to the journal *Helictite*.

Tourist Caves: Airborne Debris

Middleton, Gregory

Manager Integrated Policies and Strategies, Resource Management and Conservation Division, Department of Primary Industries, Water and Environment, State of Tasmania, Hobart, Tasmania, Australia. Author or co-author of *Timor Caves,* NSW (1973); *Wilderness Caves of the Gordon-Franklin River System, Tasmania* (1979); *Oliver Trickett: Doyen of Australia's Cave Surveyors* (1991). Editor or co-editor of *Bungonia Caves* (1972); *Cave Management in Australasia II* (1997). Contributor to *Bungonia Caves* (1972), *Encyclopedia Biospeologica,* vol. 3, edited by C.Juberthie (2001), and to *Australasian Cave and Karst Management Association Journal, Journal of Spelean History, Journal of the Sydney Speleological Society, International Journal of Speleology, Proceedings of the 7th International Congress of Speleology, Proceedings of the 12th International Congress of Speleology Studies in Speleology*. Editor of *Australian Speleo Abstracts* (1970–79).

Australia: History; Madagascar

Mihevc, Andrej

Lecturer and researcher at Karst Research Institute, Postojna, Slovenia. Author of *Notranjska A-Z: prirocnik za popotnika in poslovega človeka* (1999); *Speleogeneza Divaškega krasa* (2001). Co-editor of *South China Karst* (1998). Contributor to *Karst Hydrogeological Investigations in South-western Slovenia,* special issue of *Acta Carsologica* (1997); *Global Karst Correlation,* edited by Yuan Daoxian (1998); *South China Karst* (1998); *Geografski atlas Slovenije: drzava v prostoru in casu,* edited by J.Fridl *et al*. (1998), and to the journals *Acta Carsologica, Environmental Geology, Geografia Fisica e Dinamica Quaternaria, Geografski Vestnik, International Journal of Speleology, Kras i Speleologia*.

Škocjanske Jama, Slovenia

Milanović, Petar

Professor emeritus, Yugoslavia. Author of *Karst Hydrogeology* (1981); *Geological Engineering in Karst* (2000) and contributor to *Karst Hydrogeology and Water Resources* (1979); *Hydrogeology of the Dinaric Karst* (1984); *Karst Waters and Environmental Impacts* (1997) and to the journals *Environmental Geology, Episodes, Journal of Hydrology, Journal of International Geoscience*.

Dams and Reservoirs on Karst; Dinaride Poljes; Tunnelling and Underground Dams in Karst

Miller, Rebecca

Archaeologist in the Université de Liège, Service de Préhistoire, Liège, Belgium.

Belgium: Archaeological Caves

Moldovan, Oana

Institutul de Speologie "Emil Racovitza", Cluj, Romania. Contributor to *Mémoires de Biospéologie*.

Adaptation: Morphological (Internal); Biodiversity in Terrestrial Cave Habitats

Mouret, Claude

France. President of Speleological Federation of European Community, member of the Bureau of International Union of Speleology and Vice-President of French Federation of Speleology (former President). Author of more than 200 articles on karst and caves and of a book on French karst. Guest author in congresses on Southeast Asia. Invited author for an Encyclopedia on Asian Caves. Editor of 5 books on karst and caves, including a review of Southeast Asian caves, a dictionary of Speleology and a study on caves and karst conservation. Contributor to *Spelunca and Karstologia Bulletins and Memoirs*.

Asia, Southeast; Burials in Caves; Khammouan, Laos-Vietnam

Mueller, Bill

Department of Geography, University of Wisconsin-Milwaukee, USA. Contributor to *Journal of the Wisconsin Society for Ornithology*.

Aves (Birds)

Mylroie, John

Professor of Geology, Department of Geosciences, Mississippi State University, USA. Co-author of *A Field Trip Guidebook of Lighthouse Cave, San Salvador Island, Bahamas* (1994); *Geology and Karst of San Salvador Island, Bahamas: A Field Trip Guidebook* (1994); *Field Guide to Sites of Geological Interest, Western New Providence Island, Bahamas* (1996); *Geomorphology and Quaternary Geology of the Inner Part of the Sognefjord Area and an Introduction to the Caves and Karst of Dummdalen* (1996); *The Geology of South Andros Island, Bahamas* (1998). Editor of *Western Kentucky Speleological Survey Annual Report* (1984); *Field Guide to the Karst Geology of San Salvador Island, Bahamas* (1988); *Proceedings of the Fourth Symposium on the Geology of the Bahamas* (1989); *Karst Landsforms and Caves of Nordland, North Norway* (1996); *Proceedings of the Ninth Symposium on the Geology of the Bahamas and other Carbonate Regions* (1999). Contributor of articles to *Unconformities and Porosity in Carbonate Strata,* edited by D.A.Budd *et al.* (1995); *Climatic Change: The Karst Record,* edited by S.-E.Lauritzen (1996); *Geology and Hydrogeology of Carbonate Islands,* edited by H.L.Vacher & T.M. Quinn (1997); *Speleogenesis: Evolution of Karst Aquifers,* edited by A. Klimchouk *et al.* (2000). Contributor to *American Scientist, Carbonates and Evaporites, Cave and Karst Science, Climate Research, Earth Surface Processes and Landforms, Geology, NSS Bulletin/Journal of Cave and Karst Studies*.

Blue Holes of Bahamas; Mona, Puerto Rico; Speleogenesis: Coastal and Oceanic Settings

Nader, Fadi

PhD student at the physico-chemical geology lab, Katholieke Universiteit Leuven, Belgium. Former General Secretary, Spéléo-Club du Liban. Adjunct Secretary, International Union of Speleology (UIS). Contributor to *International Caver Magazine, Caves and Caving, Al Ouat'Ouate (SCL bulletin).*

Jeita Cave, Lebanon

Northup, Diana E.

Associate Professor, Centennial Science and Engineering Library, and Associate, Museum of Southwestern Biology, University of New Mexico, Albuquerque, New Mexico, USA. Co-editor and compiler of *A Guide to Speleological Literature of the English Language 1794–1996(1998).* Contributor to *Astrobiology Journal, Geomicrobiology Journal, Journal of Cave and Karst Studies, American Midland Naturalist,* and *Comparative Biochemistry and Physiology*.

Microorganisms in Caves

Olson, Rick

Ecologist, Division of Science and Resources Management, Mammoth Cave National Park, Kentucky, USA. Co-author of *Living With Karst, A Fragile Foundation* (2001). Contributor to *Restoration and Conservation of Caves,* edited by V.Hildreth-Werker & J.Werker (2003).

Mammoth Cave, United States: Biospeleology

Onac, Bogdan P.

Professor, Department of Mineralogy, University of Cluj and Speleological Institute "Emil Racovita", Cluj, Romania. Author of *Speleothems from Caves in Padurea Craiului Mountains: A Mineralogic, Crystallographic and Paleoclimatic Study* (1998); *Geology of Karst Terrains* (2000); *Scarisoara Glacier Cave* (2000). Editor of *Quaternary Studies in Romania: Achievements and Perspectives* (2000); *Karst Studies and Problems: 2000 and Beyond* (2000). Contributor to *Cave Minerals of the World,* edited by C.A.Hill & P.Forti (2nd edition, 1997); *Karst Processes and the Global Carbon Cycle,* edited by Yuan Daoxian (2001); and to the journals *Cave and Karst Science, European Journal of Mineralogy, Journal of Quaternary Science, Quaternary Research, Theoretical and Applied Karstology*.

Europe, Balkans and Carpathians

Oromí, Pedro

Titular Professor of Animal Biology, Department of Animal Biology, University of La Laguna, Tenerife, Canary Islands, Spain. Author of *Los Apiónidos de las Islas Canarias* (1986); *Islas Galápagos: volcán, mar y vida en evolución* (1992); *Catálogo Espeleológico de Tenerife* (1995); and *Catalogue of the Coleoptera of the Canary Islands* (2000). Editor of *La Cueva del Viento* (1995); and *Proceedings of 7th International Symposium on Vulcanospeleology* (1996). Contributor to *The Unity of Evolutionary Biology,* edited by E.C.Dudley (1991); *The Natural History of Biospeleology,* edited by A.I.Camacho (1992); *Encyclopaedia Biospeologica,* edited by C.Juberthie & V.Decu (1994 and 1998); and contributor to the journals *Evolution, Journal of Evolutionary*

Biology, Mémoires de Biospéologie, Proceedings of the Royal Society of London, Trends in Ecology and Evolution.

Canary Islands: Biospeleology

Osborne, Armstrong

School of Development and Learning, University of Sydney, New South Wales, Australia. Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.Ford, A.Palmer & W.Dreybrodt (2000); *Evolution of Karst: From Prekarst to Cessation,* edited by F.Gabrovšek (2002), and to *Acta Carsologica, Australian Journal of Earth Sciences, Cave and Karst Science, Helictite*.

Paleokarst

Otte, Marcel

Université de Liège, Service de Préhistoire, Liège, Belgium.

Belgium: Archaeological Caves

Palmer, Arthur (Adviser)

Professor of Hydrology and Director of Water Resources Program, Earth Sciences Department, State University of New York, Oneonta, New York, USA. SUNY Distinguished Teaching Professor of Hydrology, Geochemistry, and Geophysics. Author of *Geology of Wind Cave, Wind Cave National Park, South Dakota* (1981); A *Geologic Guide to Mammoth Cave National Park* (1981); *Jewel Cave—a Gift from the Past* (1984, revised 1995); *Wind Cave: An Ancient World beneath the Hills* (1988, revised 1995). Co-editor of *Karst Modeling* (1999) and *Speleogenesis: Evolution of Karst Aquifers* (2000). Contributor to *Acta Carsologica, American Association of Petroleum Geologists Memoirs, Carbonates and Evaporites, Geological Society of America, Journal of Cave and Karst Studies*. Honorary Member, National Speleological Society, USA.

Carlsbad Cavern and Lechuguilla Cave, United States; Hydraulics of Caves; Mammoth Cave Region, United States; Patterns of Caves; United States of America; Wind and Jewel Caves, United States

Pavuza, Rudolf

Karst- und Höhlenkundl. Abteilung Naturhistorisches Museum, Vienna, Austria.

Calcareous Alps, Austria

Pentecost, Allan

School of Health and Life Sciences, King's College London, UK. Contributor to *The Ecology of Cyanobacteria*, edited by B.A. Whitton & M.A.Potts (2000), and to the journals *Cave and Karst Science, Geology Today, Geomicrobiology Journal, Proceedings of the Geological Association, Quaternary Science Review*.

Entrance Habitats; Huanglong and Jiuzhaigou, China; Travertine

Perritaz, Luc

Researcher, Institute of Geography, University of Fribourg, Switzerland. Contributor to *Karstologia, Zeitschrift für Geomorphologie*.

Africa, North

Price, Liz

Kuala Lumpur, Malaysia. Author of Malaysian cave bibliography (up to 1997) (1998); *Caves and Karst of Peninsular Malaysia* (2001).

Asia, Southeast: Archaeological Caves

Proudlove, Graham

Department of Zoology, The Manchester Museum, Manchester University, UK. Contributor to *Caving Practice and Equipment*, edited by D.Judson (1991); *Mapping Subterranean Biodiversity*, edited by D.C.Culver, L.Deharveng, J.Gibert & I.D.Sasowsky (2001); *A Cave and Mine Conservation Audit for the Masson Hill Area* (2001); and to the journals *Caves and Caving, Journal of the Craven Pothole Club*.

Pisces (Fish); Britain and Ireland: Biospeleology

Raeisi, Ezzat

Department of Geology, Shiraz University, Iran. Contributor to *Carbonates and Evaporites, Cave and Karst Science, Journal of Cave and Karst Studies, Iranian Journal of Science and Technology, Journal of Engineering*.

Iran

Reddell, James R.

Curator of arthropods, Texas Memorial Museum, University of Texas at Austin, USA. Author of many papers on caves, cave fauna, and conservation. Editor of *Studies on the Cave and Endogean Fauna of North America* (3 vols, 1986–2001). 2001 NSS Science Award for lifetime contributions to speleology.

America, Central and Caribbean Islands: Biospeleology

Ribera, Carles

Facultat de Biologia, University of Barcelona, Spain. Author of more than 50 contributions on cavernicolous spiders.

Arachnida; Arachnida: Acari; Arachnida: Aranae; Arachnida: Minor Groups

Rodríguez-Vidal, Joaquin

Department of Geology, University of Huelva, Spain.

Gibraltar Caves: Archaeology

Roje-Bonacci, Tanja

Civil Engineering Faculty, University of Split, Croatia.

Plitvice Lakes, Croatia

Romero, Aldemaro

Director and Associate Professor, Environmental Studies Program, Biology Department, Macalester College, St Paul, Minnesota, USA. Author of *Manual de Ciencias Ambientales* (1992); *Canaima* (1992); *Venezuela: Mágico pais de la biodiversidad* (1993); *Vida Verde* (1994); *How to Build an Environmental Academic Program* (2002). Editor of *The Biology of Hypogean Fishes* (2001), and *Environmental Issues in Latin America* (2002). Contributor of articles to *El Manejo de los Ambientes y*

Recursos Costeros en America Latina y el Caribe (1990); *La gerencia de los 90* (1991); *Voices from the Environmental Movement: Perspectives for a New Era,* edited by D.Snow (1992); *Ambiente y Desarrollo Urbano* (1992). Contributor to *Biodiversity, Copeia, Environmental Biology of Fishes, Journal of Spelean History, NSS Bulletin, NSS News*.

Adaptation: Behavioral Biospeleologists; Evolution of Hypogean Fauna; Pisces: Amblyopsidae

Rossi, Carlos

Professor, Departamento de Petrologia y Geoquimica, Universidad Complutense de Madrid, Spain. Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.Klimchouk *et al.* (2000); *Quartz Cement in Sandstone Reservoirs,* edited by R.Worden & S.Morad (2000). Contributor to *AAPG Bulletin, Journal of Geochemical Exploration, Journal of Marine and Petroleum Geology, Journal of Sedimentary Research, Revista de la Sociedad Geológica de España*.

Picos de Europa, Spain

Sabol, Martin

Assistant Professor, Department of Geology and Paleontology, Comenius University in Bratislava, Slovakia. Contributor to *Mineralia Slovaca, Slovak Geological Magazine, Slovenský Kras—Acta Carsologica Slovaca*.

Aggtelek Caves, Hungary-Slovakia: Archaeology

Sambugar, Beatrice

Associate researcher, Museum of Natural History, Verona, Italy. Contributor to *Checklist delle specie della fauna italiana,* edited by A. Minelli, S.Ruffo & S.LaPosta (1995), and to the journals *Annales de Limnologie, Hydrobiologia, Journal of Zoology, Mémoires de Biospéologie*.

Annelida

Sasowsky, Ira D.

Associate Professor, Department of Geology, University of Akron, Ohio, USA. Co-editor of *Breakthroughs in Karst Geomicrobiology and Redox Geochemistry* (1994); *Conservation and Protection of the Biota of Karst* (1997); *Karst Modeling* (1999); *Groundwater Flow and Contaminant Transport in Carbonate Aquifers* (2000). Contributor to *Clays and Clay Minerals, Geology, Geomorphology, Journal of Hydrology, Quaternary Research, Water Research, Water Resources Research.*

Sediments: Autochthonous Clastic

Sauro, Ugo

Associate Professor of Physical Geography, Department of Geography, University of Padova, Italy. Co-editor of *Le Grotte del Veneto: paesaggi carsici e grotte del Veneto* (1989); *Proceedings of the International Conference on Environmental Changes in Karst Areas* (1991); *Altopiani Ampezzani: geologia, geomorfologia, speleologia* (1995); *Gypsum Karst of the World* (1996). Contributor to *Environmental Geology, Geomorphology, Zeitschrift für Geomorphologie.*

Asiago Plateau, Italy

Sbordoni, Valerio

Department of Biology, Tor Vergata University, Roma, Italy. Editor-in-chief *International Journal of Speleology*. Author of many journal papers on evolutionary genetics and population biology, subterranean fauna, and Antarctic fauna. Contributor to *Encyclopedia Biospeologica,* edited by C.Juberthie & V.Decu (1998); *Subterranean Ecosystems,* edited by H.Wilkens *et al.* (2000).

Insecta: Pterygota

Schindel, Geary

Chief Technical Officer, Edwards Aquifer Authority, San Antonio, Texas, USA. Author of several papers on karst, groundwater, and tracer testing.

Edwards Aquifer and the Texas Karst, United States; Groundwater Pollution: Point-Source; Groundwater Pollution: Remediation

Šebela, Stanka

Higher scientific researcher at Karst Research Institute ZRC SAZU, Postojna, Slovenia. Author of *Tectonic Structure of Postojnska Jama Cave System* (in Slovenian and English, 1998). Co-editor of *South China Karst* (1998). Contributor to *Kras: Slovene Classical Karst,* edited by A. Kranjc (1997); *Karst Hydrogeological Investigations in South-western Slovenia,* special issue of *Acta Carsologica* (1997); *Global Karst Correlation,* edited by Yuan Daoxian (1998); *South China Karst,* edited by Chen Xiaoping *et al.* (1998), and to the journals *Acta Carsologia, Acta Geologica Sinica, Environmental Geology, Geological Journal, International Journal of Speleology, Studia Carsologica*.

Postojna—Planina Cave System, Slovenia

Self, Charles Anthony

UK. Chairman, Genetic Mineralogy working group, Mineralogy Commission, Union International de Spéléologie. Editor of *Caves of County Clare* (1991). Contributor to *Cave Science, Cave Geology, Cave and Karst Science, Geofluids, Proceedings of the University of Bristol Spelaeological Society*.

Cupp-Coutunn Cave, Turkmenistan

Senior, Kevin

Graduated in Geology and Physical Geography but has worked for IBM for most of his life. Member of numerous British caving expeditions to Spain, Uzbeckistan, Irian Jaya, Laos, and China.

Di Feng Dong, China

Shaw, Trevor (Adviser)

Honorary Research Fellow, Karst Research Institute, Postojna, Slovenia. Author of *History of Cave Science: The Exploration and Study of Limestone Caves, to 1900* (2nd edition, 1992); *Foreign Travellers in the Slovene Karst, 1537–1900* (2000). Contributor of articles to *Festschrift Lurgrotte 1894–1994,* edited by R.Benischke (1994); *Jamaica*

Underground, edited by A.G.Fincham (1997); *Cave Minerals of the World,* edited by C.A Hill & P.Forti (2nd edition, 1997); *L'Homme qui voyageait pour les gouffres,* edited by D. André & H.Duthu (1999); *Speleogenesis: Evolution of Karst Aquifers,* edited by A.Klimchouk *et al.* (2000). Contributor to many journals, including *Acta Carsologica, Cave and Karst Science, Helictite, International Caver, Journal of Caves and Karst Studies, Journal of Spelean History, Naše jame, Slovensky Kras, Studies in Speleology.* Honorary Member, National Speleological Society, USA; Peter M. Hauer Spelean History Award, 1985; Petrbok Medal of the Česká Speleologická Spolecnost, 1994. Editorial Board member of *Acta Carsologica,* and Advisory Board member of *International Journal of Speleology.*

Archaeologists; Asia, Northeast: History; Caribbean Islands: History; Cerknica Polje, Slovenia: History; Exploration Societies; Speleogenesis Theories: Early; Speleologists; Speleothem Studies: History

Shopov, Y.Yavor

Senior Research Assistant, University Center for Space Research, University of Sofia, Bulgaria. Author of articles in *ESR Dating and Dosimetry,* edited by M.Ikeya & T.Myki (1985); *Climatic Change: The Karst Record,* edited by S.-E.Lauritzen (1996); *Cave Minerals of the World,* edited by C.A.Hill & P.Forti (2nd edition, 1997); *Global Karst Correlation,* edited by Yuan Daoxian & L.Zaihua (1998); *Encyclopedia "World of the Earth Sciences",* edited by L. Lerner & B.Lerner (2002). Contributor to *Acta Crystallographica, Annales Geophysicae, Geology.* Editor-in-chief of *Solar Eclipse Journal* (1999–), and editorial board member of *Theoretical and Applied Karstology* (2000–). President of the Royal Society of Bulgaria.

Dating of Karst Landforms; Sediments: Biogenic; Speleothems: Luminescence

Shrewsbury, Carolina

International SpeleoArt coordinator (originally based in the UK, now the USA). Contributor to *Illuminations* (publication of the NSS Arts and Letters Section), *Journal of the Sydney Speleological Society, Stalactite, Underground Photographer.*

Art Showing Caves

Simek, Jan

Professor, Department of Anthropology, University of Tennessee, USA. Author of *A K-Means Approach to the Analysis of Spatial Structure in Upper Paleolithic Habitation Sites* (1984). Co-editor of *Cave Archaeology in the Eastern Woodlands,* special issue of *Midcontinental Journal of Archaeology* (2001). Contributor to *American Antiquity, Antiquity, Journal of Archaeological Science, Journal of Human Evolution, Southeastern Archaeology.*

Archaeology of Caves: History

Sket, Boris (Adviser)

Professor, Department of Biology, Biotechnical Faculty, University of Ljubljana, Slovenia. Author of *Subterranean Life in Karst* (in Slovenian, 1979), and articles in *Fauna of Slovenia,* edited by F. Bernot *et al.* (1998), *Handbuch der Reptilien und Amphibien Europas,* edited by K.Grossenbacher & B.Thiesmeier (1999). Editor or co-editor of *Manual for Cavers* (in Slovenian, 1964); *Identification Keys for Animals of Yugoslavia* (in Slovenian, series: 1967–68); *Fauna of Slovenia* (in Slovenian, in preparation). Editor for biology and biotechnical topics for *Lexicon* (in Slovenian, 1973, 1976, 1985, 1988). Contributor to *Archiv für Hydrobiologie, Biodiversity and Conservation, Journal of Biogeography, Journal of Zoology, Proceedings of the Biological Society of Washington, Trends in Ecology and Evolution*. Editorial Board member of *Mémoires de Biospéologie,* Advisory Board member of *International Journal of Speleology,* Associate Board member of *Stygologia,* Associate Editor of *Zootaxa*.

Anchialine Habitats; Biodiversity in Hypogean Waters; Biology of Caves; Dinaric Karst: Biospeleology; Invertebrates: Minor Groups; Postojna-Planina Cave System, Slovenia: Biospeleology; Subterranean Habitats; Thermal Water Habitats; Vjetrenica, Bosnia-Herzegovina: Biospeleology

Slabe, Tadej

Higher scientific researcher, Karst Research Institute, Postojna, Slovenia. Author of *Cave Rocky Relief and its Speleogenetical Significance* (1995). Co-editor of *South China Karst* (1998). Contributor to *Kras: Slovene Classical Karst,* edited by A. Kranjc (1997); *Global Karst Correlation,* edited by Yuan Daoxian (1998); *South China Karst,* edited by Chen Xiaoping *et al.* (1998), and to the journals *Acta Carsologia, Annales, Atti mem. Comm. Grotte Eugenio Bpegan, Environmental Geology, International Journal of Speleology*.

Morphology of Caves

Smart, Chris

Associate Professor and Graduate Chair, Department of Geography, University of Western Ontario, Canada. Author of a number of papers on karst modelling, karst groundwater, and tracing, specializing in alpine and glaciated terrain, most recently in *Earth Surface Processes and Landforms, Environmental Geology, Hydrological Processes, Theoretical and Applied Karstology*.

Alpine Karst; Glaciated and Glacierized Karst; Glacier Caves and Glacier Pseudokarst; Groundwater in Karst; Groundwater in Karst: Borehole Hydrology; Groundwater in Karst: Conceptual Models; Groundwater in Karst: Mathematical Models; Karst Water Resources; Springs; Water Tracing

Smith, Marion O.

Retired; former Assistant Editor, *The Papers of Andrew Johnson,* University of Tennessee, Knoxville, Tennessee, USA. Author of *The Exploration and Survey of Ellison's Cave* (1977); *Letters from TAG, 1966–1969* (1992); *Saltpeter Mining in East Tennessee* (1990). Contributor to *Civil War History, Florida Historical Quarterly, Georgia Historical Quarterly, Journal of Spelean History, Tennessee Historical Quarterly*.

Gunpowder

Song Linhua

Professor, Institute of Geography, Chinese Academy of Sciences, Beijing, China. Co-editor of *The Pinnacle Karst of Stone Forest, Lunan, Yunnan, China, An Example of a*

Sub-jacent Karst (1986); *Karst Landscape and Cave Tourism* (1993) and *Stone Forest: A Treasure of Natural Heritage* (1997). Author of many papers including in the journals *Acta Carsologica, Acta Geologica Sinica, Cave Science, Studies in Speleology*.
Hongshui River Fengcong Karst, China

Spötl, Christoph
Institut für Geologie und Paläontologie, Universität Innsbruck, Austria.
Spannagel Cave, Austria

Steward, Paul Jay
Production control and material specialist for Lockheed Martin, USA. Author of *Tales of Dirt, Danger and Darkness* (1998). Contributor to *American Caves, Central Jersey Caver, Illuminations* (publication of the NSS Arts and Letters Section), *NSS News*.
Caves in Fiction

Stierman, Donald J.
Associate Professor of Geophysics, Department of Earth, Ecological and Environment Sciences, University of Toledo, Toledo, Ohio, USA. Contributor to *Bulletin of the Seismological Society of America, Environmental Geology, Geoarchaeology, Journal of Geophysical Research, Pure and Applied Geophysics, Science, Tectonophysics*.
Geophysical Detection of Caves and Karstic Voids

Stoch, Fabio
Consultant and associate researcher, Museums of Natural History of Verona, Udine, and Trieste, Italy. Author of several book chapters on karstic environments, including in *Studies in Crenobiology: The Biology of Sprigs and Springbrooks,* edited by L.Botosaneanu (1997); *Ponds and Pond Landscapes in Europe,* edited by J.Boothby (1999). Editor of *Grotte e fenomeno carsico* [Caves and Karst Phenomena] (2001). Contributor to several journals, including *Annales de Limnologie, Belgian Journal of Entomology, Crustaceana, Hydrobiologia, Mémoires de Biospéologie, Memorie dell'Istituto Italiano di Speleologia*.
Colonization

Stone, Andrea
Professor, Department of Art History, University of Wisconsin-Milwaukee, USA. Author of *Images from the Underworld: Naj Tunich and the Tradition of Maya Cave Painting* (1995). Editor of *Heart of Creation: The Mesoamerican World and the Legacy of Linda Schele* (2002). Contributor to *Time and Space: Dating and Spatial Considerations in Rock Art Research,* edited by J.Steinbring *et al.* (1993); *The Human Use of Caves,* edited by C.Bonsall & C.Tolan-Smith (1997); and to *Journal of Cave and Karst Studies*.
Art: Cave Art in the Americas

Taiti, Stefano
CNR Researcher, Istituto per lo Studio degli Ecosistemi, Firenze, Italy. Contributor to *Proceedings of the Second Symposium on the Biology of Terrestrial Isopods* (1989) and

to the journals *Fauna of Arabia, Invertebrate Taxonomy, Journal of Natural History, Mémoires de Biospéologie, Zoological Journal of the Linnean Society*. Co-Editor of *Tropical Zoology*.

Crustacea: Isopoda: Oniscidea

Tarhule-Lips, Roosmarijn

Lecturer, Department of Geography, University of Oklahoma, USA. Contributor to *Cave and Karst Science, Journal of Cave and Karst Studies, Journal of Physical Geography*.

Caribbean Islands

Tao Tang

Department of Geography and Planning, State University of New York, College at Buffalo, USA. Contributor to *Earth Surface Processes and Landforms, Middle States Geographer, Chinese Journal of Geographic Studies*.

Tower Karst

Taylor, Steven J.

Associate research scientist, Center for Biodiversity, Illinois Natural History Survey, Champaign, Illinois, USA. Contributor to *Annals of the Entomological Society of America, Entomological News, Florida Entomologist, Great Lakes Entomologist, Journal of Cave and Karst Studies.* Associate editor for life sciences, *Journal of Cave and Karst Studies*.

America, North: Biospeleology

Tercafs, Raymond

Senior Research Associate of the Belgian Fund for Scientific Research, Institute of Zoology, Department of Animal Physiology, University of Liege, Belgium. Author or co-author of *Atlas de la vie souterraine: Les Animaux cavernicoles* (1972); entry on Biospéleologie in *Encyclopedia Universalis* (1974). Contributor to *The Natural History of Biospeleology,* edited by A.Camacho (1992); *Encyclopedia Biospeologica,* edited by C.Juberthie & V.Decu (1994, 2001), and to the journals *Annales de Spéléologie, Ecological Modelling, Environmental Conservation, International Journal of Speleology, Mémoires de Biospéologie*.

Conservation: Cave Biota

Thurgate, Mia

Karst Resources Manager, Karst Resources Department, Jenolan Caves Reserve Trust, New South Wales, Australia. Contributor to *Acta Geographica Szegedensis, Records of the Western Australian Museum Supplement, Stalactite*.

Monitoring

Tolan-Smith, Chris

Senior lecturer, Department of Archaeology, University of Newcastle upon Tyne, UK. Author of *Late Stone Age Hunters of the British Isles* (1992); *Landscape Archaeology in Tyneside* (1997); *The Caves of Mid-Argyll: An Archaeology of Human Use* (2001). Co-editor of *The Human Use of Caves* (1997). Contributor to *Contributions to the Mesolithic in Europe*, edited by P.M.Vermeersch & P.Van Meer (1990); *The Late Glacial in North-West Europe*, edited by N.Barton *et al.* (1991); *The Neolithic in No-Mans Land*, edited by P. Frodsham (1996); *Proceedings of the Berlin INQUA Symposium on Human Adaptations across the Pleistocene-Holocene Transition*, edited by L.G.Strauss & B.V.Eriksen (1998); *14C and Archaeology Acts of the 3rd International Symposium*, edited by J.Evin *et al.* (1999); and to the journals *Archaeologica Cambrensis, Proceedings of the Prehistoric Society, Scottish Studies*.

Folklore and Mythology; Human Occupation of Caves

Tooth, Anna F.

Hydrologist with The Environment Agency, Worthing, West Sussex, UK. Contributor to *Journal of the Geological Society, London, Chemical Geology*.

Chemistry of Natural Karst Waters

Trajano, Eleonora

Associate Professor, Departamento de Zoologia, Instituto de Biociências, Universidade de São Paulo, Brazil. Contributor to *Encyclopedia Biospeologica*, edited by C.Juberthie & V.Decu (1994); *Subterranean Ecosystems*, edited by H.Wilkens *et al.* (2000); *Fundação e a Produção Florestal do Estado de São Paulo* (2001), and to many journals including *Biological Rhythm Research, Biotropica, Entomologia, Environmental Biology of Fishes, Mémoires de Biospéologie, Revista Brasileira de Entomologia, Revista Brasileira de Zoologia*.

America, South: Biospeleology

Trimmel, Hubert

Professor and retired Director of the Department of Karst and Cave Science, Museum of Natural History, Vienna, Austria. Lecturer, Institutes of Geography of the Universities of Salzburg and Vienna. Author of *Höhlenkunde* (1968). Editor of *Speläologisches Fachwörterbuch* (1965) and of the quarterly bulletin *Die Höhle* (1953–). Honorary President of the International Union of Speleology and of the Federation of Austrian Speleologists. Honorary member of the speleological federations of Germany, Hungary, and Italy.

Europe, Alpine; Europe, Central: History

Tyc, Andrzej

Researcher, University of Silesia, Department of Geomorphology, Sosnowiec, Poland. Author of *Guide des terrains choisis des Sudety et Haut-Plateau de Silesie-Cracovie* (1987); *Anthropogenic Impact on Karst Processes in the Silesian-Cracow Upland* (1997, in Polish); *Development of Natural Processes on the Bratsk Reservoir's Banks* (2000, in Russian). Co-editor *Limestone Exploitation in Landscape Parks* (1998). Contributor to *Karst et evolution climatiques*, edited by J.N.Salomon & R.Maire (1992); *Karst Hydrogeology and Human Activities: Impacts, Consequences and Implications*, edited by D. Drew & H.Hötzl (1999); *Essays in the Ecology and Conservation of Karst*, edited by I.Barany-Kevei & J.Gunn (2000); and to the journals *Acta Carsologica, Acta*

Geographica, Annales Societatis Geologorum Poloniae, Kras i Speleologia, Studia Carsologica.

Cuba; Europe, Central

Vakhrushev, Boris

Dean of Geography Faculty and Manager of Speleology and Karst laboratory, Tavrichesky National University, Crimea, Ukraine. Co-author of *Karst and Groundwaters of the Mountain Massifs of the Western Caucasus* (1985).

Crimea, Ukraine

Veni, George

Hydrogeologist, owner of George Veni and Associates, San Antonio, Texas, and Adjunct Professor for Center for Cave and Karst Studies, Western Kentucky University, Bowling Green, Kentucky, USA. Author of *Caves of Bexar County* (1988) and *Geomorphology, Hydrology, Geochemistry, and Evolution of the Karstic Lower Glen Rose Aquifer, South-central, Texas* (1997). Editor or co-editor of *Caves and Karst of Texas* (1994); *Speleology in Brazil* (special issue *of Journal of Cave and Karst Studies,* 1996); *Living with Karst* (2001). Contributor *to Images from the Underworld: Naj Tunich and the Tradition of Maya Cave Paintings,* edited by A.Stone (1995); *Cave Minerals of the World,* edited by C.A.Hill & P.Forti (2nd edition, 1997); *Conservation and Restoration of Caves,* edited by V. Hildreth-Werker & J.Werker (2003), and to the journals *Environmental Geology and Water Science, European Journal of Mineralogy, Geoarchaeology, Journal of Cave and Karst Studies.*

Belize River Caves; Environmental Impact Assessment

Viles, Heather

School of Geography and the Environment, University of Oxford, UK. Editor of *Biogeomorphology* (1988). Editorial board member of *Zeitschrift für Geomorphologie*. Contributor to *Cave and Karst Science, Earth Surface Processes and Landforms, Progress in Physical Geography*. Biokarstification; Phytokarst

Waltham, Tony (Adviser)

Senior Lecturer in Engineering Geology, Department of Civil Engineering, Nottingham Trent University, UK. Author of *Caves* (1974); *The World of Caves* (1976); *Catastrophe: the Violent Earth* (1978); *Caves, Crags and Gorges* (1984); *Yorkshire Dales National Park* (1987); *Ground Subsidence* (1989); *Foundations of Engineering Geology* (1994, revised 2002). Co-author of *Caves of Mulu* (1978); *China Caves 1985* (1986); *The Underground Atlas* (1986); *Xingwen* (1993); *Karst and Caves of Great Britain* (1997). Editor of *Limestones and Caves of Northwest England* (1974). Contributor to *Quarterly Journal of Engineering Geology, Cave and Karst Science, Zeitschrift für Geomorphologie, Proceedings of Geologists' Association*. Editorial Board Member for *Geology Today, Mercian Geologist*. President of British Cave Research Association.

Asia, Northeast; Asia, Southwest; China; Construction on Karst; Europe, North; Ha Long Bay, Vietnam; Mulu, Sarawak; Pinega Gypsum Caves, Russia; Sewu Cone Karst, Java; Shilin Stone Forests, China; Yorkshire Dales, England

Webb, Rauleigh

Australia. Speleologist, Computer Systems Analyst (self-employed). State Cave Recorder and Map Curator for Western Australia. Webmaster for Western Australian Speleological Group (WASG) and Australasian Cave and Karst Management (ACKMA). Numerous publications at both Australian Speleological Federation (ASF) and ACKMA Conference.

Recreational Caving

Weber, Axel

Zoologisches Institut und Zoologisches Museum, Universität Hamburg, Germany. Contributor to *Encyclopedia Biospeologica*, edited by C.Juberthie & V.Decu (1998); *Subterranean Ecosystems*, edited by H.Wilkens & D.Culver (2000); and to the journals *Copeia*, *Mémoires de Biospéologie*.

Amphibia

Werker, Jim C.

Hillsboro, New Mexico, USA. Co-editor of *Cave Conservation and Restoration* (2003), Co-Chair of the Conservation Division for the National Speleological Society.

Restoration of Caves and Speleothem Repair

Wildberger, Andres

Swiss Institute for Speleology and Karst Studies, La Chaux-de-Fonds, Switzerland. Co-author *Karst and Caves of Switzerland* (1997).

Hölloch, Switzerland

Williams, Paul (Adviser)

Professor of Geomorphology, School of Geography & Environmental Science, University of Auckland, New Zealand. Co-author of *Karst Geomorphology and Hydrology* (1989). Editor of *Karst Terrains: Environmental Change and Human Impact* (1993). Editorial board member of *Earth Surface Processes and Landforms* and *Zeitschrift für Geomorphologie*. Member of the World Commission on Protected Areas (WPCA) of the International Union for the Conservation of Nature (IUCN). Honorary Member, National Speleological Society, US.

Dolines; Kaijende Arête and Pinnacle Karst, Papua New Guinea; Karst Evolution; New Zealand

Wood, Paul (Adviser)

Department of Geography, University of Loughborough, Loughborough, UK. Contributor to *Aquatic Conservation: Marine and Freshwater Ecosystems*, *Archiv für Hydrobiologie, Biological Conservation, Cave and Karst Science, Hydrobiologia.*

Britain and Ireland: Biospeleology; Subterranean Ecology

Wookey

Software designer, Cambridge, UK. Contributor to *Caves and Caving*. Editor, *Cave Radio and Electronics Journal*.

Surveying Caves

Worthington, Stephen R.H.

Principal hydrogeologist, Worthington Groundwater, Dundas, Ontario, Canada. Contributor to *Speleogenesis: Evolution of Karst Aquifers,* edited by A.B.Klimchouk, D.Ford, A.Palmer & W. Dreybrodt (2000), and to the journals *Earth Surface Processes and Landforms, Environmental Geology, Environmental Monitoring and Assessment, Geology*.

Appalachian Karst, United States; Groundwater in Karst; Groundwater in Karst: Borehole Hydrology; Groundwater in Karst: Conceptual Models; Groundwater in Karst: Mathematical Models; Karst Water Resources; Sof Omar, Ethiopia; Springs; Water Tracing

Yuan Daoxian

Research professor and former director, Institute of Karst Geology, Chinese Academy of Geological Science, Guilin, China. Author of *Glossary of Karstology* (in Chinese, with English indices, 1988); *The Science of Karst Environment* (in Chinese, with English summary, 1988). Editor of *Karst of China* (1991); *Environmental Geology* (1997); *Global Karst Correlation* (1998). Contributor to *Hydrogeology of Selected Karst Regions,* edited by W.Back & H.Paloc (1992); *Karst Terrains: Environmental Change and Human Impact,* edited by P.W.Williams (1993), and to the journals *Carsologica Sinica, Environmental Geology, Journal of Hydrology, Journal of the Speleological Society of Japan, Zeitschrift für Geomorphologie*. Member of Editorial Advisory Board for *Environmental Geology*. President of Commission on Karst Geology, Geological Society of China.

Yangshuo Karst, China

Yonge, Charles J.

President of Alberta Karst Consulting, and Adjunct Professor, Department of Physics & Astronomy, University of Calgary, Alberta. Author of *Under Grotto Mountain: Rats Nest Cave* (2001). Contributor to *Boreas, Cave and Karst Science, Cave Science, Chemical Geology (Isotope Geoscience Section), Journal of Hydrology, Nature, Proceedings of the National Academy of Sciences.*

Ice in Caves

Zander, C.Dieter

Professor, Zoologisches Institut and Museum, University of Hamburg, Germany. Author of *Parasit-Wirt-Beziehungen. Einführung in die ökologische Parasitologie* (1997). Contributor to *Biology of Benthic Organisms,* edited by B.F.Keegan & O.Ceidigh (1977); *Biology and Ecology of Shallow Coastal Waters,* edited by A. Eleftheriou *et al.* (1996); *Das Mittelmeer, Fauna, Flora, Ökologie,* edited by R.Hofrichter (2001), and to the journals *Helgoländer Meeresuntersuchungen, Mémoires de Biospéologie, Mitteilungen aus dem Hamburger Zoologischen Museum und Instituts, Zeitschrift für Zoologische Systematik und Evolutionsforschung.*

Marine Cave Habitats

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