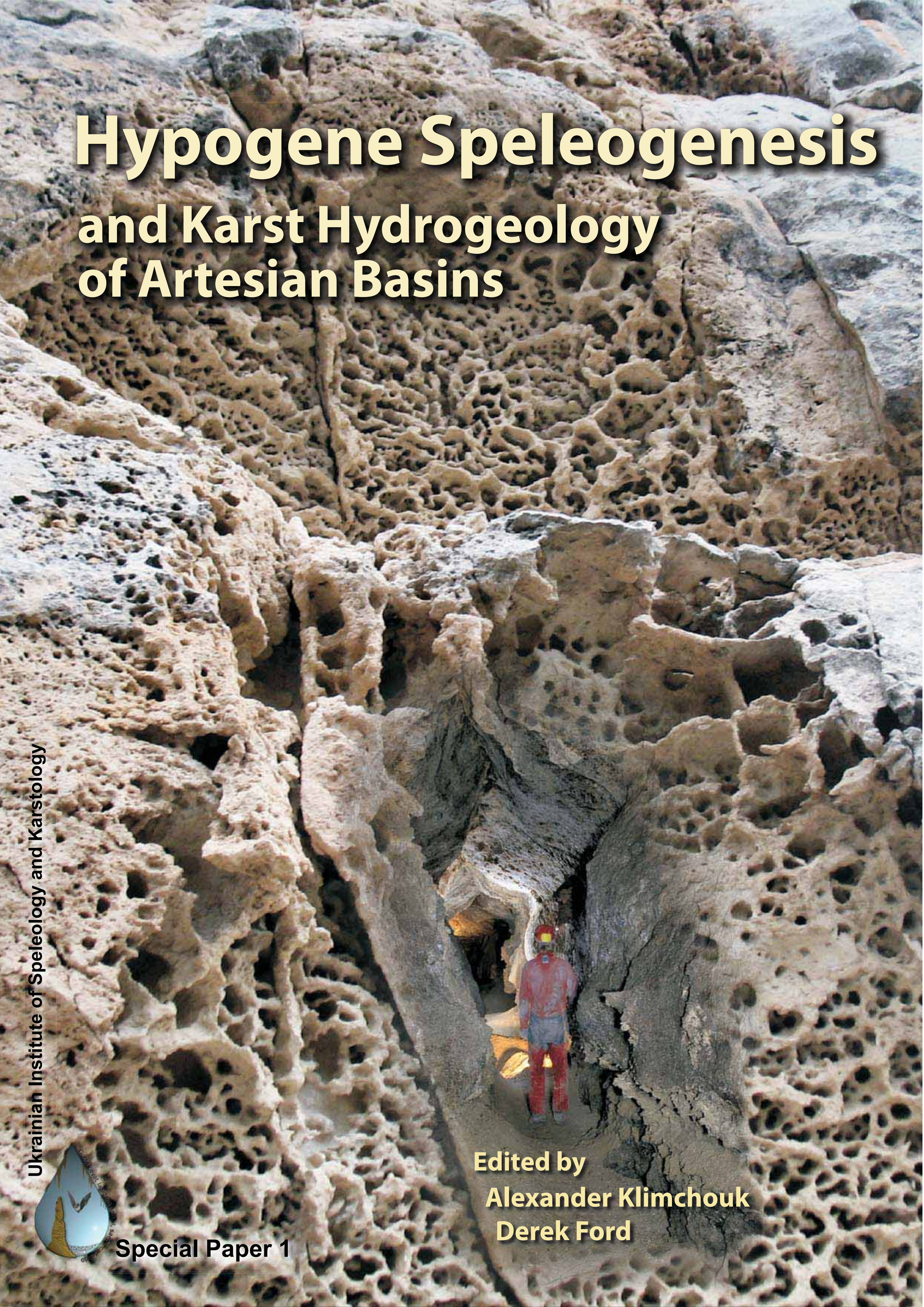

Hypogene Speleogenesis

and Karst Hydrogeology of Artesian Basins

Edited by
Alexander Klimchouk
Derek Ford

Ukrainian Institute of Speleology and Karstology

Special Paper 1

Hypogene Speleogenesis and Karst Hydrogeology of Artesian Basins

Proceedings of the conference held May 13 through 17, 2009 in Chernivtsi, Ukraine

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Front cover: Tafoni on a limestone escarpment in the Crimea Piedmont (background) and a passage in Slavka Cave, Western Ukraine (inset). Photos and collage by A.Klimchouk

Back cover: Hypogenic morphology in gypsum caves of the Western Ukraine. Photos and collage by A.Klimchouk

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CONTENTS

MORPHOLOGICAL INDICATORS OF SPELEOGENESIS: HYPOGENIC SPELEOGENS

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ABSTRACT

Hypogenic speleogenesis can be identified at different scales (basinal flow patterns at the regional scale, cave patterns at cave system scale, meso- and micromorphology in cave passages). We focus here on small scale features produced by both corrosion and deposition. In the phreatic zone, the corrosion features (speleogens) are a morphologic suite of rising flow forms, phreatic chimneys, bubble trails. At the water table are thermo-sulfuric discharge slots, notches with flat roofs. Above a thermal water table the forms reflect different types of condensation runoff: wall convection niches, wall niches, ceiling cupolas, ceiling spheres, channels, megascallops, domes, vents, wall partitions, weathered walls, boxwork, hieroglyphs, replacement pockets, corrosion tables, and features made by acid dripping, such as drip tubes, sulfuric karren and cups. Each type of feature is described and linked to its genetic process. Altogether, these features are used to identify the dominant processes of speleogenesis in hypogenic cave systems.

Hypogenic caves were recognized early, especially where thermal or sulfuric processes were active (Martel, 1935; Principi, 1931). However Socquet (1801) was one of the earliest modern contributors to speleogenetic knowledge, and probably the first to identify the role of sulfuric speleogenesis by condensation-corrosion due to thermal convection. More recent major contributions evidenced the role of sulfuric speleogenesis and hydrothermalism (e.g. Dublyansky, 2000; Egemeier, 1981; Forti, 1996; Galdenzi and Menichetti, 1995; Hill, 1987; Palmer and Palmer, 1989). However, most of these case-studies were often considered as "exotic", regarding the "normal" (i.e. epigenic) speleogenesis. Only recently, Klimchouk (2007) provided a global model, allowing the understanding of "hypogenic" speleogenesis and gathering the characteristics of hypogenic caves. Consequently, the number of caves where a hypogenic origin is recognized dramatically increased during the last years.

The hypogenic origin can be recognized at the regional scale (deep-seated karst in basins), at the scale of an individual cave system because of distinctive features in its pattern, by studying the morphology of the cave conduits, or at the local scale of wall features made by corrosion processes (i.e. speleogens). Such type of features depict the characteristics of local cave development, and by extension the characteristics of speleogenesis. The description and interpretation of hypogenic speleogens is generally scattered in the literature. The aim of this paper is to gather the most important hypogenic speleogens, considered here as indicators, and used for the identification and characterization of the hypogenic speleogenesis. Our knowledge is based on the compilation of about 350 caves from the literature, and the study of some of the most significant caves (Audra, 2007; Audra et al., 2002, 2006). In this paper, we focus on the speleogens (i.e. wall-scale corrosion features) as indicators of hypogenic speleogenesis; we exclude here solution feature at larger scale such as conduits and cave systems and depositional features (sediments).

Some of the features observed in the sulfuric caves are specifically caused by this strong acid. Some features are closely associated with hydrothermalism. Other features that are widespread in hypogene caves are created without sulfuric influence. The following typology mainly takes into account the type of runoff. In confined settings with slow phreatic flow, cave features are common to all types of hypogene processes, whether they are sulfuric or not (i.e. carbonic, hydrothermal…). In unconfined settings, condensation-corrosion processes take place above the water table. These aerial processes, enhanced by the oxidation of sulfides by the thermal convections, and by the microbial processes, result in a large variety of cave features. Some features are closely related to specific processes. Consequently, they are considered as valuable indicators of the sulfuric speleogenesis.

1. CORROSION FEATURES CREATED BY THE DEEP RISING FLOWS

In confined settings, hypogene caves developed under phreatic conditions by rising flow result in 3D mazes. These mazes are composed of the juxtaposition of rising flow paths, often misinterpreted as horizontal diffuse flow paths.

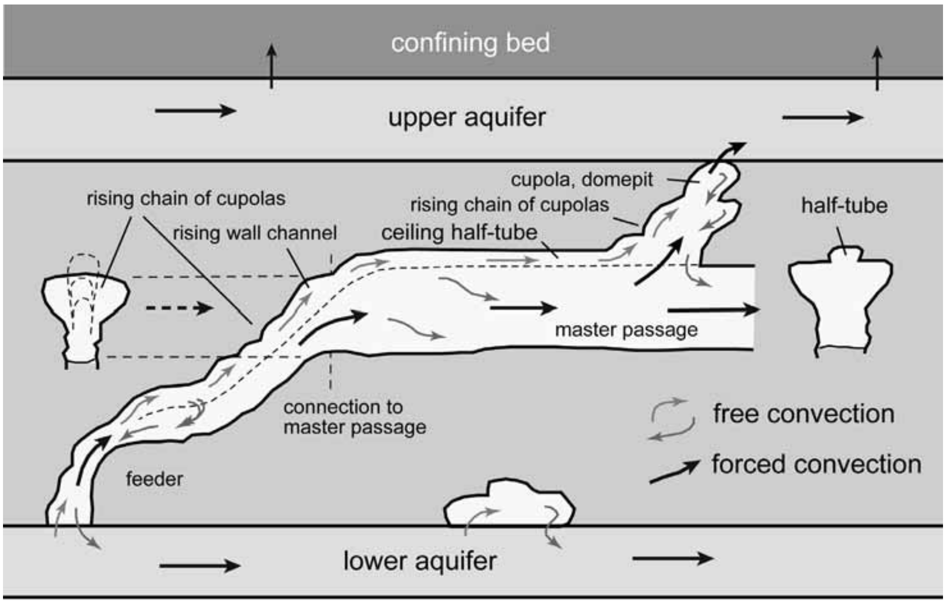


Figure 1. Morphologic features of rising flow (after Klimchouk, 2003). Water coming from the lower aquifer enters the karst cave through a "feeder", follows a rising master conduit, and passes into the upper aquifer through an "outlet". Characteristic morphologies are indicated (rising channels, cupolas), as well as the flows driven by natural or forced convection.

"Morphologic suite of rising flow" in phreatic confined caves

The prevalence of ascending flow is however attested by an association of characteristic features, the "morphologic suite of rising flow" (Klimchouk, 2007; Figure 1). At the bottom, a small crack or "feeder" supplies water from an underlying aquifer. In the same manner the conduit terminates with an "outlet" at the top, *i.e.* bells or blind chimneys at the contact with the overlying aquifer. The exchanges between these aquifers pass through small cracks or merely through beds of higher porosity. Between feeder and outlet, the ascending flows are attested by transitional features, *i.e.* rising channels and cupolas. The morphologic suite constitutes the basic pattern of any confined cave: it may be stretched vertically, repeated laterally and vertically, with a higher complexity to account for multiple lateral stories. The largest mazes of the world account on this origin, such as Optimisticeskaya in the Ukrainian gypsum, Jewel Cave in the Black Hills, or Lechuguilla in the Guadalupe Mountains.

Morphologic suites of rising flow are a characteristic of confined hypogene caves, which can be sulfuric or not. In unconfined settings involving sulfur oxidation, dissolution is predominant above the water table, with active condensation-corrosion processes. Consequently, when mixing allowing the oxidation of sulfides at depth is weak, phreatic dissolution remains limited. The corresponding features are represented in the early phase by small phreatic chimneys, and when a cave is already present, by discharge slots.

Phreatic chimneys of the early phase

In the early phase, narrow tubular chimneys develop along the major faults where deep water upwelling occurs. Thereafter, with the development of caves, these early chimneys become perched above the cave system such as at Grotte du Chat, France (Audra, 2007). In Cathedral-Wellington Cave they are cut by the cave system itself (Osborne, 2007).

Bubble trails

Bubble trails are rising solution channels cut in overhanging walls (Figure 2). Their development is due to carbon dioxide degassing (Chiesi and Forti, 1987), or to the oxidation of sulfur ore deposits (De Waele and Forti, 2006). During the rise of water in the phreatic zone, water degasses CO_2, typically to 15-30 m depths at the maximum. Bubble trails are produced by the continued corrosion along these unchanging routes. The carbon dioxide bubbles do not corrode by themselves, but they locally enhance the aggressivity of the adjacent water. They are present in carbonic caves (grotta Giusti, Italy), in sulfuric caves (grotte Frasassi, Italy); they are also known in some inactive caves (grotte de l'Adaouste, France; Ferenc-hegy barlang, Hungary).

Rising channel of thermal water

The OX 655 Shaft (French Pyrénées), which is believed to be hydrothermal in origin, has a wall channel with scallops indicating a rising flow (Figure 3). As a paragenetic origin is hardly possible, this feature could correspond to a plume of warm water rising along the wall of a phreatic chamber.

Thermo-sulfuric discharge slots

Where a sulfuric cave already exists, the thermo-sulfuric water discharges through discrete slots. These slots narrow at a shallow depth, since most of the corrosion occurs in the atmosphere (Figure 4). Slots providing a concentrated acidic discharge give rise to the development of large chambers (*infra*: "Domes"). Upstream of the terminal slot, the conduit has an abrupt dead end: the origin of the cave is not a horizontal meteoric flow, but corresponds actually to this slot discharging upwelling aggressive water. Such discharge slots are clearly visible in Kane Cave, Wyoming (Egemeier, 1981), in Grotte du Chat, France (Audra, 2007), in Grotte de Frasassi, Italy, and in Tirshawaka, Iraq.

Figure 2. Bubble trail made by rising carbonic bubbles below the water table where degassing occurs; Grotte di Frasassi, Italy (photo: S. Galdenzi)

Figure 3. Rising thermal water channel, possibly linked to a hydrothermal plume; OX 655 Shaft, France (photo: J.-Y. Bigot)

2. CORROSION AT THE EDGE OF SULFURIC POOLS

Notches with flat roof

When corrosion is renewed by significant upwelling, cave basins may be particularly corrosive due to the permanent condensation runoff feeding the pool with concentrated sulfuric acid. The aggressive water body causes lateral corrosion which is visible as a notch with flat roof, corresponding to the surface of the pool (Figure 5). These sulfuric notches are different from water table notches developed along calm rivers, where small oscillations of the water table create half-elliptical cross-sections (Audra, 2006).

3. CORROSION FEATURES RELATED TO THE CONDENSATION OF THERMAL CONVECTIONS

Part of the hypogenic speleogenesis occurs in thermal conditions, above thermal pools. Atmospheric convection enhances the processes of condensation-corrosion, resulting in a great variety of specific features.

Wall convection niches above thermal ponds

Juxtaposed convection cells appear at the rim of a thermal pool. Condensation-corrosion creates wall convection niches (Figure 6). Their form corresponds to a portion of a spheroid, slightly tilted towards the base and with a steep overhang at the top. Dimensions of the niches are homogeneous, and they are roughly aligned at the same level. They intersect in a blunted vertical edge. Their juxtaposition displays a series of hemispherical niches. When deeply incised into the wall, their coalescence tends to form a notch with shallow embedded niches (Figure 6, right).

Wall niches, ceiling cupolas, and ceiling spheres

Convection cells of bigger size can be found at walls and in roof cupolas, which intersect with clear edges (Figure 7). Condensation is more abundant at the cooler ceiling, so by positive feedback the cupolas develop upwards. They become embedded in the ceiling, finally creating spheres there. Condensation-corrosion caused by convection may be the main process of upwardly dendritic caves developed as stacked up spheres, a very peculiar type of the thermal cave (Audra *et al.*, 2007).

Condensation-corrosion channels, megascallops

In rooms with a high ceiling, thermal convection rises up overhanging walls towards the highest points (fissures, chimneys, outlets to the surface…). Guided by the shape of the wall, the convection process carves a condensation-corrosion channel, the shape of which corresponds to a section of a tube. Its depth can be more or less as deep as the half-tube (Figure 8). Turbulence in the convection creates megascallops (Forti *et al.*, 2006), which evolve as superimposed niches when deeply incised (Figure 8, left). The air flow may diverge, making a channel bifurcate (Figure 8, right). The base of the chimney can be at the thermal water table (Kraus-Höhle). In Eisensteinhöhle, the

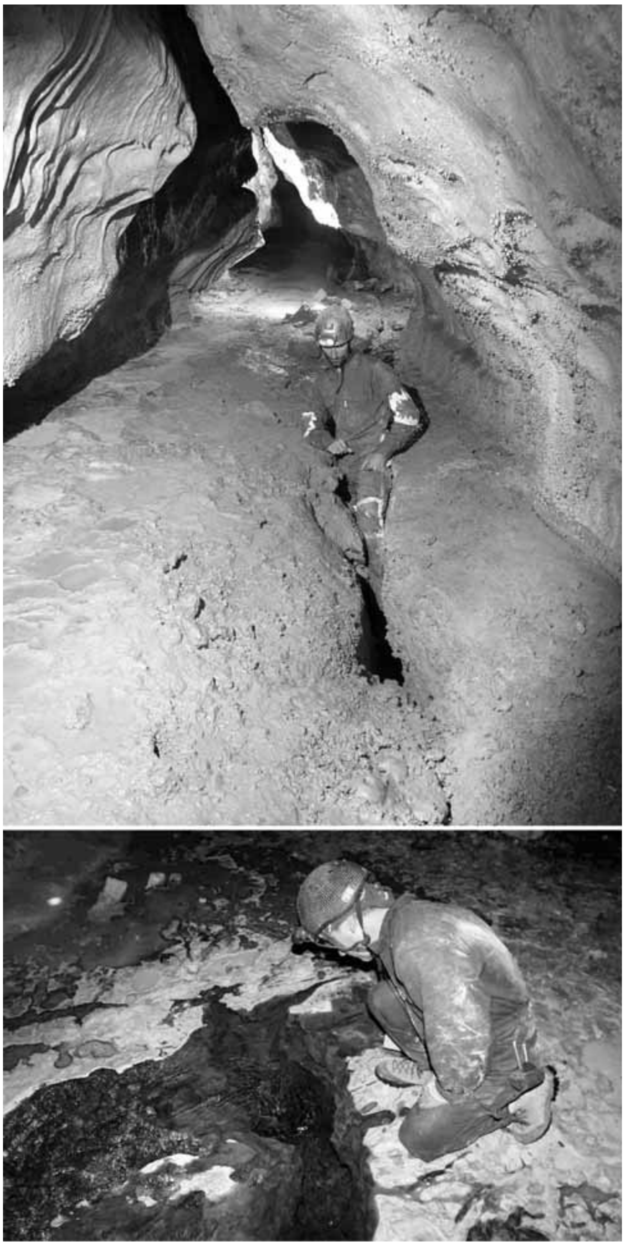


Figure 4. Thermo-sulfuric discharge slots. Upper: inactive slot at the upstream end of Grotte du Chat, France (photo: J.-Y. Bigot). Lower: active slot in Trshawaka, Iraq (photo: Zana Qasim Haider).

strong geothermal gradient is related to the presence of a more in-depth warm water body where the convection creates a channel, with subsiding, re-warming convection favoring evaporation along the wall and the growth of cave popcorn. In a karst covered with impermeable rocks the thermal gradient in confined caves is sufficient to create such channels with megascallops that connect different cave levels (Fairground in the show part of Wind Cave). Forti *et al.* (2006) mention such megascallops in a Mexican cave above guano deposits, whose exothermic mineralization provides steam, carbon dioxide, and heat forcing the convection!

Warm rivers systematically produce powerful convections, enhancing the development of condensation-corrosion channels (Figure 9). On the contrary, in areas with a low roof where the thermal gradient is lower the atmosphere is more stable and convection is attenuated, the ceilings remain flat (Figure 10). These convective processes explain the round shapes of cross-sections in cases without any initial phreatic flow.

Condensation domes

At the discharge slots, when the thermal gradient is high and the sulfuric outgassing is strong, powerful convection takes place, enhancing active condensation-corrosion at the ceiling, which develops upwards as a rounded dome, intensively corroded by boxwork (Figure 10).

Wall Partitions (Osborne, 2007)

Hypogenic caves develop predominantly from discrete infeeders. Convection favors the local expansion of early voids rather than longitudinal extension of a cave. Consequently, the expansion leads to the intersection and the integration of the early voids. Sharp-shaped partitions evidence the gradual removing of adjacent boundary walls and the subsequent integration of the voids. Depending on the shape of early voids, wall partitions appear as blades, pendants, biconcave pillars, pseudo-notches and half tubes, arches, projecting corners, *etc*. (Figure 11). From Wellington Cave (Australia) study, Osborne (2007) suggested an expansion by slow thermal phreatic convection. In Grotte du Chat, France (Figure 11), expansion is clearly related to atmospheric convection above thermal-sulfuric pools, making condensation-corrosion (Audra, 2007).

Vents

Some discrete points emitting moisture-saturated air produce tubes (called vents) that connect two galleries at different levels (Figure 12). The thermal water body, located at shallow depth, warms the air which then rises. Condensation occurs in the cooler vent, creating corrosion: the inner walls are clean. While emerging in the gallery, aerosols charged with carbonates in solution fall down by gravity. The air warms up and evaporation supports calcite deposition at the edge of the vent. A calcite rim may develop (Gouffre Chevalley, France; Jószef-hegy barlang, Hungary). Sometimes calcite popcorns develop by accretion of the aerosols.

Figure 5. Notch with flat roof carved in by lateral corrosion of a pool with sulfuric acid. Kraus-Höhle, Austria (photo: Ph. Audra).

Figure 6. Wall convection niches (photos: Ph. Audra). Left: at the edge of a thermal pool (Cueva de Villa Luz, Mexico). Centre and right: in a dry cave, above the level of an old thermal basin (Kraus-Höhle, Austria).

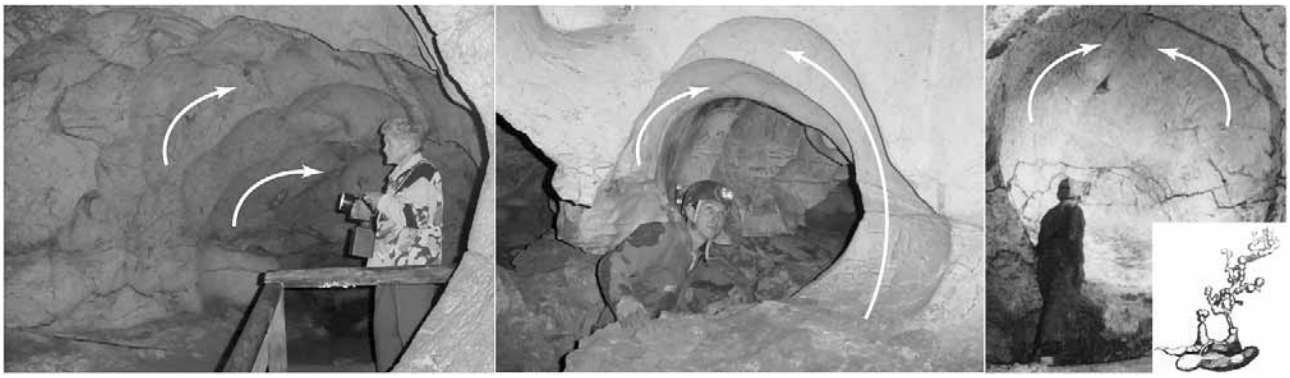


Figure 7. Convection cupolas. Left: large wall convection niches, Kraus-Höhle, Austria (photo: Ph. Audra). Center: ceiling cupolas, Grotte des Serpents, France (photo: Ph. Audra). Right: ceiling sphere in an upwardly dendritic cave made of stacked up spheres, Sátorkö-puszta barlang, Hungary (photo. from a tourist folder; 3D view after Ford and Williams 1989)

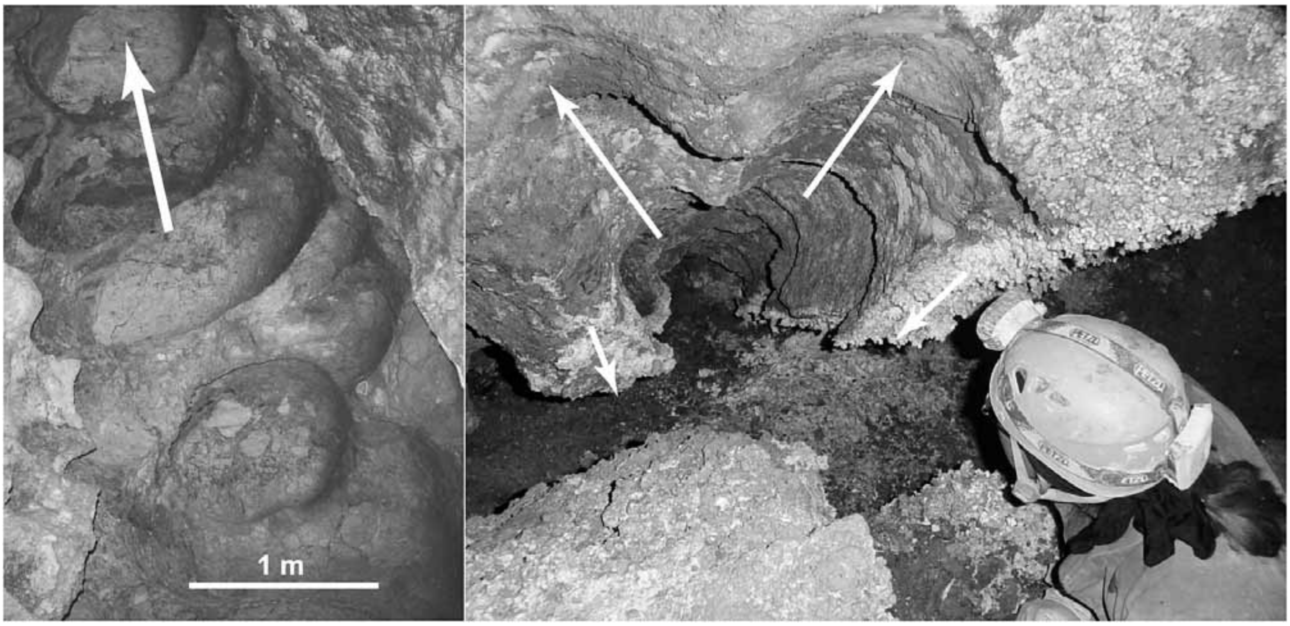


Figure 8. Condensation-corrosion channels (photos: Ph. Audra). Left: a condensation-corrosion channel in brecciated limestone with megascallops, viewed from the bottom, Kraus-Höhle, Austria. Right: divergent condensation-corrosion channels, viewed from top, with a rim of popcorn made by evaporation in the subsiding air, Eisensteinhöhle, Austria.

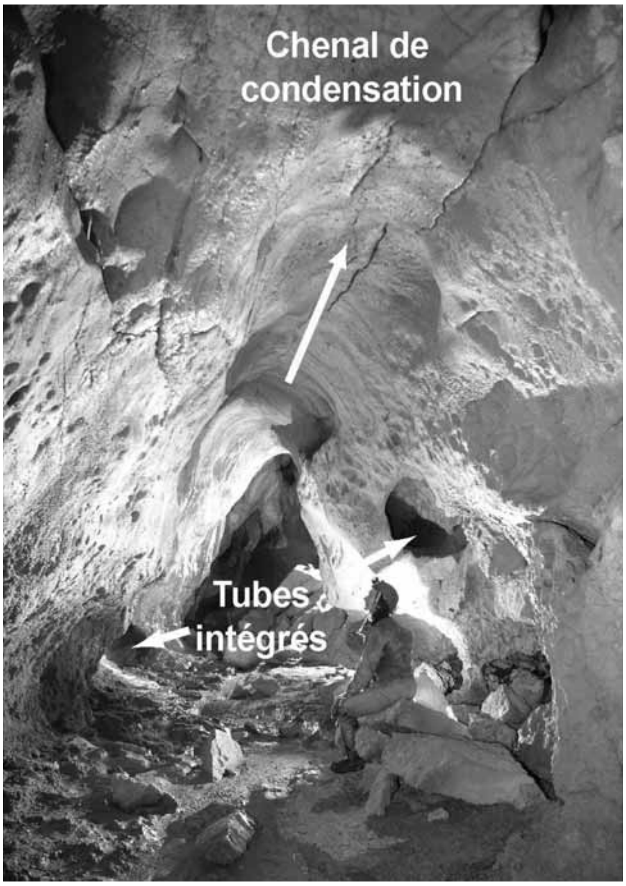


Figure 9. Condensation-corrosion channel at the ceiling above a thermal river. The incision of the channel is related to the warm, moist air flowing along the ceiling towards the highest bell holes, which themselves develop upwards by positive feedback (photo: J.-Y. Bigot).

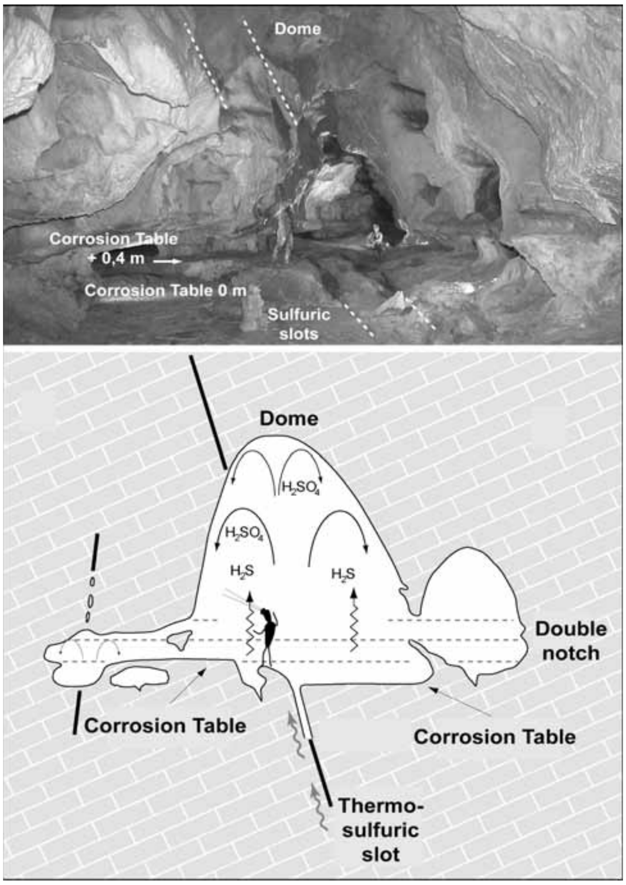


Figure 10. Condensation dome, Grotte du Chat, France. The tilted fissure, allowing the thermal upwelling is visible to the right of the first caver. This fissure initiated the dome's development, which then has developed upwards at the right of the fissure, showing the major role of the condensation above "hot spots" (photo: L. Mocochain).

Vents are features developed by atmospheric processes subsequent to the hydrothermal main phase. Popcorn marks a late stage of the thermal activity, when the water table has dropped a few meters but remains sufficiently high to produce a corrosive wet ascending draught. A vent is the result of a combination of corrosion and calcite deposition related to the distribution of condensation-corrosion and evaporation-precipitation (Audra *et al.*, 2007).

Weathered walls, boxwork, and wall hieroglyphs

In a massive limestone condensation-corrosion is diffuse. It produces an incomplete weathering distributed in a homogeneous way creating a weathered wall. When calcite veins are present, condensation-corrosion favors differential corrosion: the grains of the micritic cement are disjoined and eventually fall down by gravity, while the calcite veins made up of larger crystals remain and create a boxwork (Figure 13). In fissured rock, the cracks are widened as wall hieroglyphs.

In a thermal environment, condensation-corrosion is maximal at the ceiling, where the thermal gradient is higher. Consequently, boxwork is systematically present on the highest parts of conduits. At middle heights, the accumulated condensation runoff is significant and washes down small grains: the lowest part of the wall is smooth.

Replacement pockets

Replacement pockets are quasi-perfect hemispherical corrosion features embedded into the wall. They correspond to focused sulfuric corrosion, with simultaneous replacement of limestone by gypsum, which fills the pocket (Galdenzi and Maruoka, 2003). Gypsum in pockets absorbs the sulfuric acid and concentrates corrosion, allowing a progressive deepening (Figure 14). When the sulfuric activity stops, the gypsum falls off, leaving the pockets empty. Their inner surfaces are perfectly smooth and regular. The cave wall appears riddled with numerous pockets.

Their vertical distribution systematically reveals a preferential concentration between 1 and 2 m height, where condensation and evaporation are balanced: above this level, condensation runoff washes away the sulfates, while at the bottom evaporation generates large pockets with irregular forms. In addition, their density is higher around the slots discharging deep water where H_2S degassing occurs. Sometimes pockets appear downstream of the slots where turbulence finally induces degassing.

4. DRIPPING CORROSION FEATURES

Intense condensation above thermal pools induces acid drips which strongly corrode the rocks.

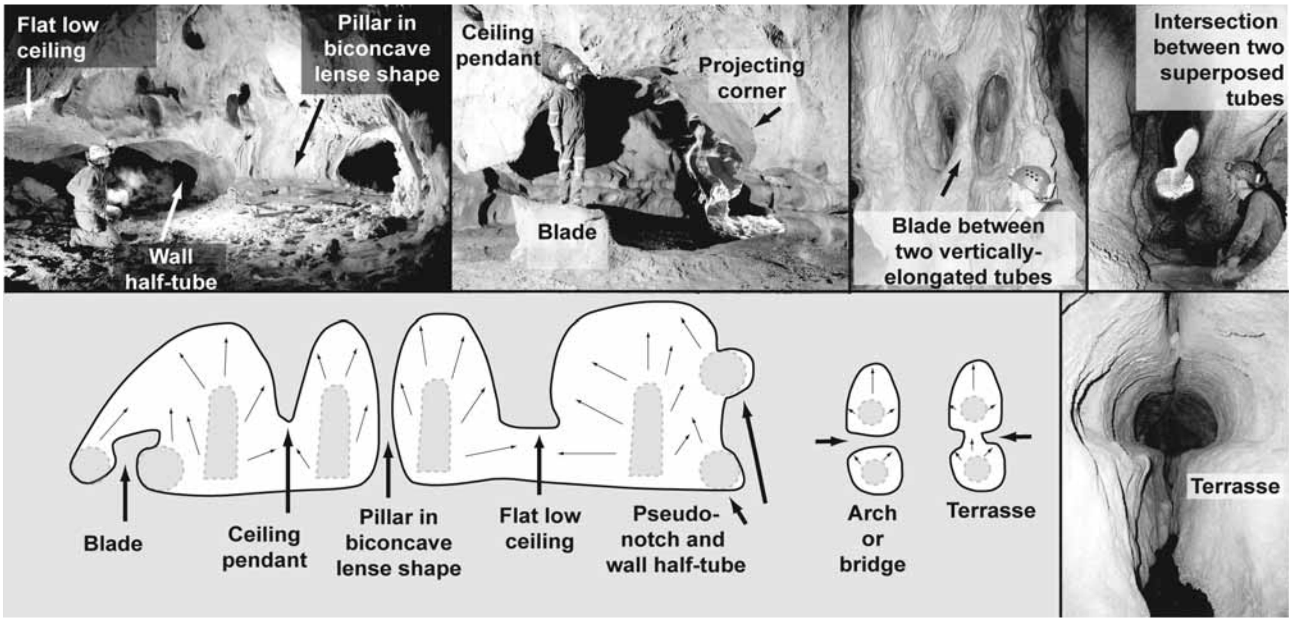


Figure 11. Wall partitions, Grotte du Chat, France. The expansion of early voids (light blue) by condensation-corrosion leads to their intersection; thin partitions remain thereafter. The arrows show the expansion from the early voids.

Drip tubes

Drip tubes are half-cylinders carved along walls which originally projected into the rock mass as a full tube with a round bottom (Figure 15). These drip features can appear only when water is exceptionally aggressive, or when the rock is soft like very soluble gypsum or particles of weathered limestone. In “normal” conditions, the water drops cannot penetrate into the rock, they only dissolve small grooves.

Sulfuric karren

In the vicinity of a zone of concentrated emission of H_2S, sulfo-oxidant microbes develop and take part in the formation of concentrated sulfuric acid. This strong acid drips from biofilms similar to “snots” (“mucolites”) whose pH is often lower than 1. Directly below the mucolites features develop due to extreme corrosion. In the dry zones, with little condensation runoff, the sulfuric acid remains concentrated and drippings carve sulfuric karren (Figure 16). The dry atmosphere allows the conservation of the replacement gypsum which partially covers the karren. These features are rare, they were only observed in the Grotte du Chat, France and in Lechuguilla Cave, New Mexico.

Sulfuric cups

In wet atmospheres, condensation water flows as a film which dilutes the sulfuric acid and corrodes sulfuric cups with smooth forms (Figure 17). The concentrated sulfuric acid can also flow as rills in water, creating a subaqueous cup with convergent grooves.

5. CONDENSATION SHEET-RUNOFF: CORROSION TABLES

The high thermal gradient between a thermal river and the ceiling and edges of a gallery generates abundant condensation. This condensation water returns towards the river, initially along the ceiling, then in a laminar flow on the lower surfaces. This condensation runoff levels corrosion tables (Figure 18). Planation by sulfuric acid makes a smooth glacis, where rocks of different hardness are uniformly worn down. Thereafter, these tables can be punched by sulfuric drips (Grotte des Serpents, France). Corrosion tables are known from the Grotte du Chat (France), in Kraus-Höhle (Austria), in Grotta di Frasassi (Italy), and in Cueva de Villa Luz (Mexico).

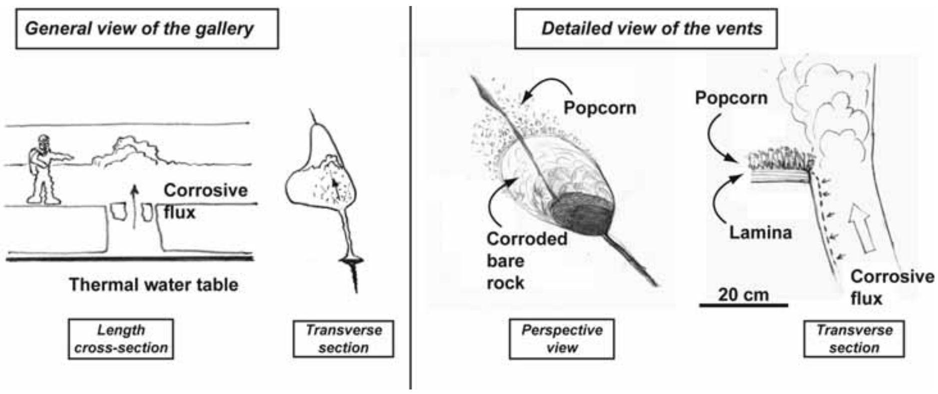


Figure 12. Diagrams of vent dynamics (J.-Y. Bigot). Left: relation between a subjacent thermal water body producing the uplifting of corrosive humid air and a main conduit where the subsiding aerosols deposit popcorn in the periphery of the vent. Right: corrosion inside the tube of the vent and popcorn deposition around the vent.

Figure 13. Boxwork covering the highest part of the conduit, resulting from diffuse condensation-corrosion. The middle part of the conduit, close to the caver's head, is smoothed by condensation runoff which erodes the small particles and produces a compact and regular surface. Grotte du Chat, France (photo: J.-Y. Bigot).

Figure 14. Replacement pockets after the transformation of limestone into gypsum. Upper left: pockets empty or filled with gypsum, Grotta de Faggetto Tondo, Italy (photo: S. Galdenzi). Upper right and lower: hemispherical replacement pockets carving the middle part of the wall. Close to the ground pockets are more irregular, Grotte du Chat, France (photos: J.-Y. Bigot)

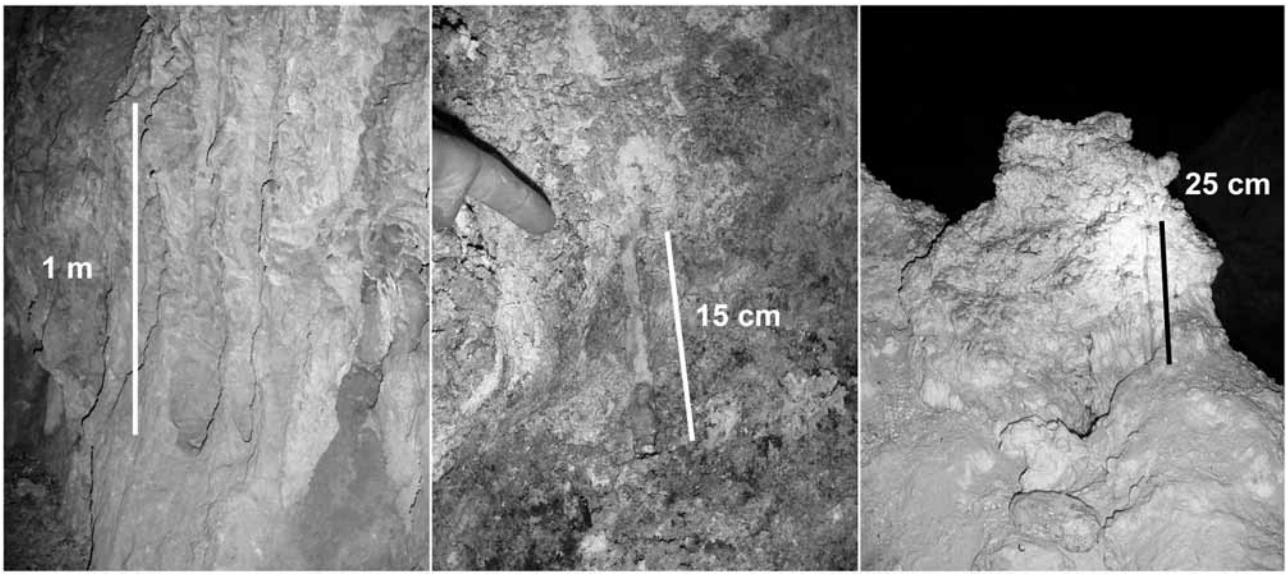


Figure 15. Drip tubes created by intense dissolution (photos: Ph. Audra). Left: in massive limestone, with a high-aggressive atmosphere at 10 % CO_2 (Zbrasov Cave, Czech Republic). Centre: in a limestone wall deeply weathered by sulfuric vapors (Gouffre Chevalley, France). Right: in very soluble gypsum (Kraus-Höhle, Austria).

The very small gradient of the corrosion tables, both across (1.6%) and along (1.3% - 0.1%), results from a balance between the agitation and the corrosion. The agitation generated by the slope allows degassing; subsequently, the corrosion attenuates when the profile tends towards the horizontal, eventually generating smaller

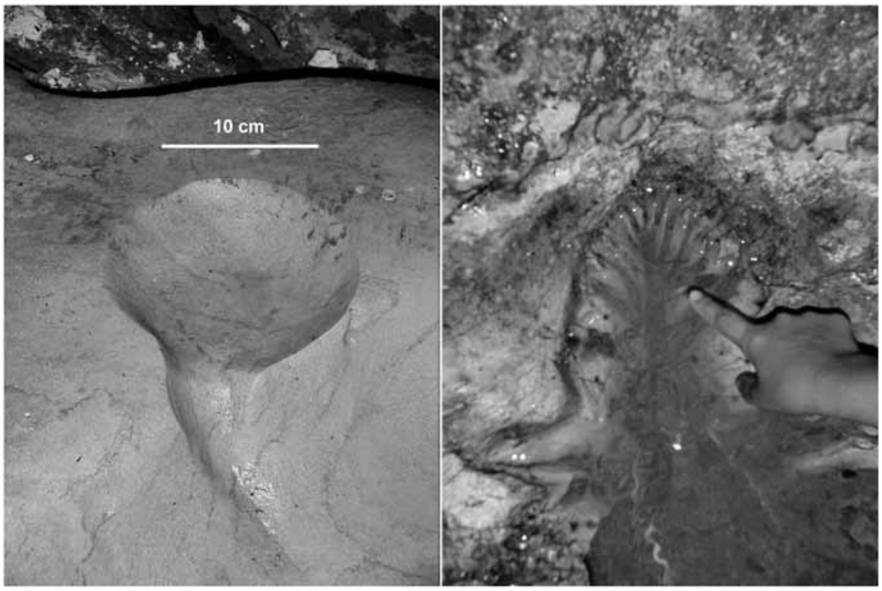


Figure 16. Sulfuric karren covered with replacement gypsum, Lechuguilla Cave, New Mexico (photo: A. N. Palmer).

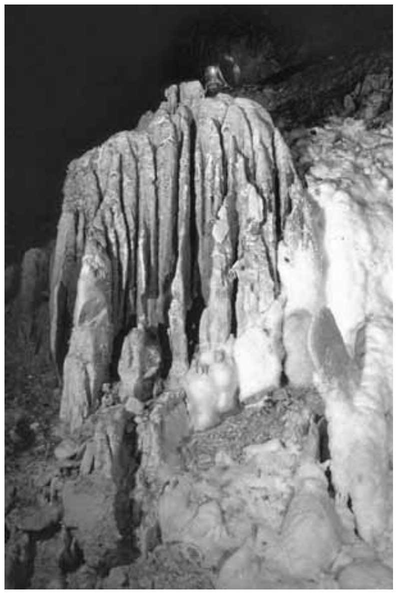
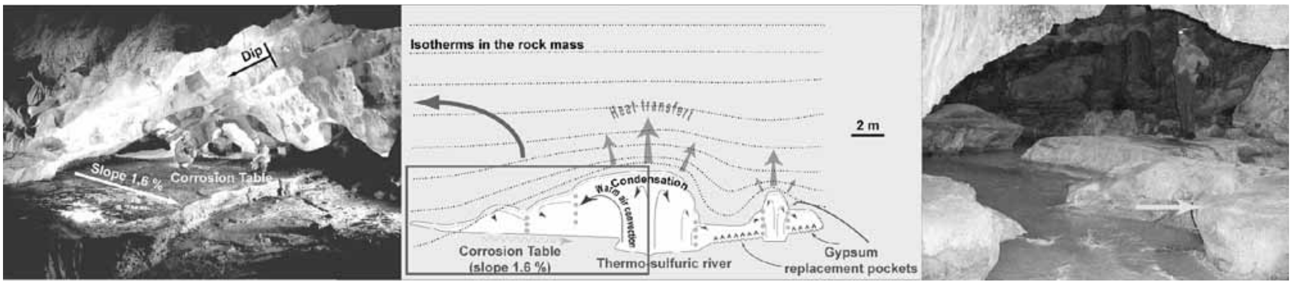


Figure 17. Sulfuric cups, Cueva de Villa Luz, Mexico (photo: Ph. Audra). Left: aerial feature smoothed by the diffuse flow of the condensation film. Right: at the edge of a lake, the seepages of concentrated sulfuric acid form grooves converging towards the center of a subaqueous cup.

Figure 18 (below)**.** Corrosion tables made by the laminar condensation runoff charged with sulfuric acid. The corrosion tables are surrounded by convection niches developed above the thermal river. Left and center Grotte du Chat, France (photo: J.-Y. Bigot). Right: Cueva de Villa Luz, Mexico (photo: Ph. Audra).



degassing (Egemeier, 1981). These graded long plains represent the base level position. They adjust with the lowest point of the base level by an entrenchment of the sulfuric river into the former level, which then becomes a perched corrosion table. In the Grotte du Chat twelve levels are recorded within only 6 m of elevation (Audra, 2007).

Like surface river networks, the longitudinal extension of corrosion tables is affected by turn points marking the upstream limit of upwards erosion by a reversal of the slope resulting from undercaptures. Lateral shifting of the drainage also corresponds to these vertical developments, which produce mazes parallel to the main conduit (Grotte du Chat, Cueva de Villa Luz).

CONCLUSION

It is well recognized that the presence of a single indicator is not conclusive for the hypogenic speleogenesis. The convergence of several evidences at different scales is generally required, including isotopes or fluid inclusion proofs.

Some indicators presented above have to be used carefully, since they may also be present in non-hypogenic setting. For instance, boxwork may be encountered in any environment where differential corrosion prevails, either in the phreatic zone or in the atmosphere, especially close to the entrances where moist exchange and condensation-corrosion are strong.

However, some speleogens are unequivocal and can be considered as reliable indicators of the hypogenic speleogenesis, including:

- in the phreatic zone: morphologic suites of rising flow, bubble trails;

- in sulfuric caves: notches with flat roof, corrosion tables, replacement pockets;

- in thermal environments: convection niches, corrosion features closely related to a local “hot spot” (corrosion channel above a thermal river, condensation domes…).

The above-mentioned speleogens category is not exhaustive and may be increased by further studies.

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