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SPELEOGENESIS IN REGIONAL GEOLOGICAL EVOLUTION AND ITS ROLE IN KARST HYDROGEOLOGY AND GEOMORPHOLOGY

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THE PATTERN OF HYPOGENIC CAVES

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The hypogenic cave pattern reflects the speleogenetical processes. Processes vary according to the depth in the aquifer, involving mixing corrosion by convergent flux and with meteoric water, cooling, sulfur oxidation, carbon dioxide degassing, and condensation-corrosion. Cave patterns are: isolated geodes, 2D and 3D multistorey following joints and bedding planes, giant phreatic shaft, water table mazes, isolated chambers, upwardly dendritic spheres, water table cave, and smoking shafts.

1. Introduction

The development of caves by hypogenic processes (i.e. "hypogenic speleogenesis") corresponds to *the formation of caves by water that recharges the soluble formation from below, driven by hydrostatic pressure or other sources of energy, independent of recharge from the overlying or immediately adjacent surface* (Ford 2006). Hypogenic caves - often referred to as "thermal caves" or "sulfuric acid caves" – were often considered as an "exotic" side of the "normal" (i.e. meteoric) caves. Palmer (1991) estimated that about 10% caves have hypogenic origin. Recent studies (overview in Klimchouk 2007) have emphasized the specific hydrogeological background and shown that hypogenic caves are much more common than previously thought. The extreme diversity of settings (carbonic, sulfuric, thermal, cold, deep phreatic, shallow phreatic, vadose...) in different geological or geomorphological contexts produces a puzzling impression: each hypogenic cave seems to be unique, with few characteristics in common with the other hypogenic caves regarding their pattern.

2. Method

A data base of more than 350 hypogenic caves was constructed from the literature, comparing geological structure, hydrology, morphology of caves at different scales (wall features, passages morphology, and cave pattern), mineralogy, deposits... Field study of the most representative hypogenic caves, combined with the information in the literature, show that the apparent dissimilarity in shape can be overcome. Taking into account the diverse settings (hydrologic, geologic) and the speleogenetic processes, we obtain a conceptual model of a cave pattern, integrating all kinds of hypogenic caves (Fig. 1) (Audra 2007). Patterns are subdivided into two main types: deep phreatic systems generally developed in a confined aquifer by transverse speleogenesis (*sensu* Klimchouk 2000), and cave systems developed above the water table, where condensation-corrosion plays a paramount role.

3. Hypogenic Cave Patterns in Phreatic Condition

3.1 Isolated geodes

At depth, mixing allows complex dissolution and deposition processes. Large crystals (calcite, gypsum...) are deposited in slightly saturated water, together with diverse minerals (mainly metallic sulfides) (Fig. 2).

3.2 3D Multistorey maze caves

The rising hypogenic flow uses alternatively joints and bedding planes, producing a 3D maze cave, in a staircase pattern. Generally, the cave has a main trunk where hypogenic flow was rising, surrounded by 3D mazes, smaller in size (Fig. 3). In Monte Cucco Cave system (Italy), the sulfuric water was rising toward the top of the anticline, where impervious covers are breached, allowing the discharge of the karst aquifer. Contiguous vertical passages correspond to discrete hypogenic trunks, inclined galleries follow dip, horizontal passages and some cave entrances record past base level positions (Galdenzi & Menichetti 1995). In the Black Hills (South Dakota), Jewel and Wind Caves range among the largest maze cave of the world. There genesis is complex, involving several early phases (Palmer 2006). However, the pattern resulting from the main speleogenetical phase is simply a dense network of enlarged discontinuities, similar to the previous examples.

3.3 2D maze caves

If an aquitard is present, the cave develops below this impervious ceiling, as a 2D maze cave (Fig. 4). The passages are horizontal or inclined, according to the dip. The Denis Parisis system in the central part of Paris basin is horizontal.

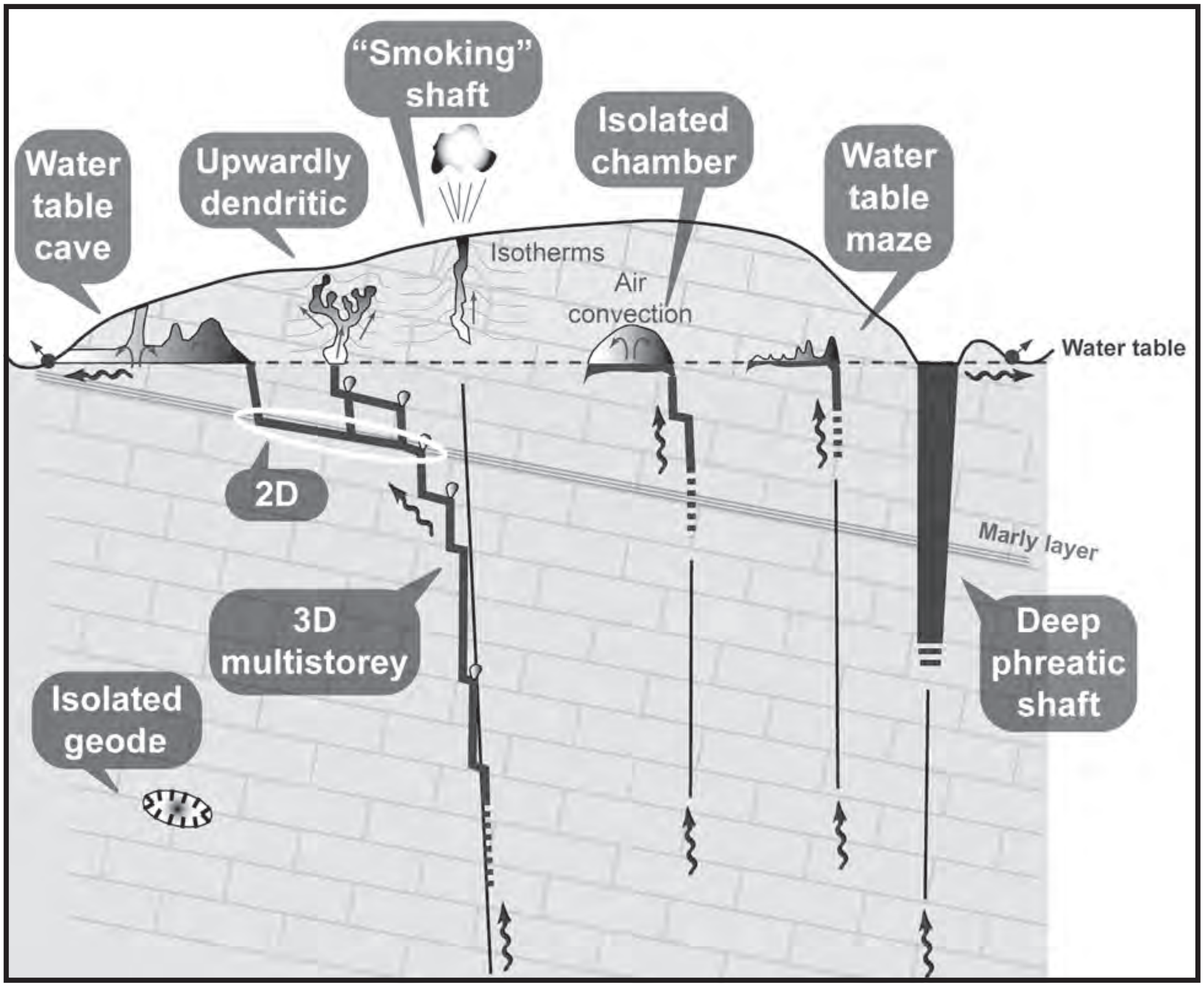

Figure 1: Conceptual model of the hypogenic cave patterns, according to the geological structure, the groundwater recharge, and the speleogenetic processes.

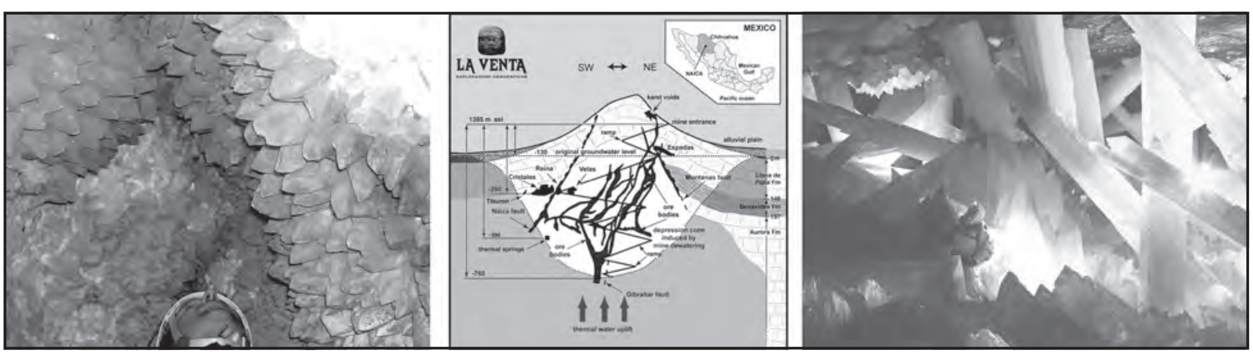

Figure 2: Isolated geodes. Left: geode lined with calcite spar, France. Center-right: cueva de los Cristales (Chihuahua, Mexico) was intersected and drained by the Naica mine (Bernabei et al. 2007). The gypsum swords in this cave are the largest crystals of the world.

In Monte Cucco, the Faggeto Tondo develops below the inclined marly cover (cave indicated as no. 2 in Fig. 3, right). The 2D maze cave is a subtype of 3D maze cave; some parts of 3D mazes locally develop as 2D mazes, when a less permeable stratum is present.

3.4 Deep phreatic shafts

In active tectonic areas, the combination of rising warm

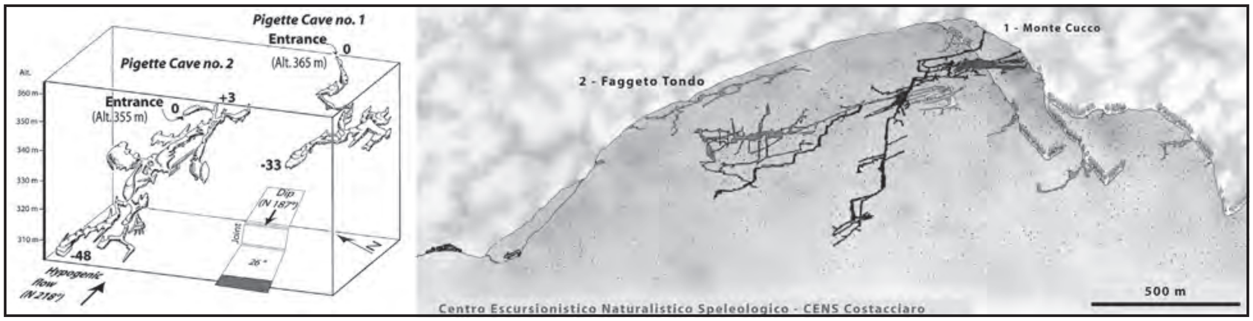

Figure 3: Left: perspective view of the Pigette Caves (France), a 3D multistorey maze cave originating in the phreatic zone by hypogenic upwelling, following structural weaknesses (inclined dip and vertical joints) (sketch by J.Y. Bigot). Right: Monte Cucco system (Italy), probably the deepest hypogene cave system of the world (- 923 m / 31 km), with large shafts of several hundred meters of depth and ramps inclined along the dip of the anticline (Cairoli et al. 1991).

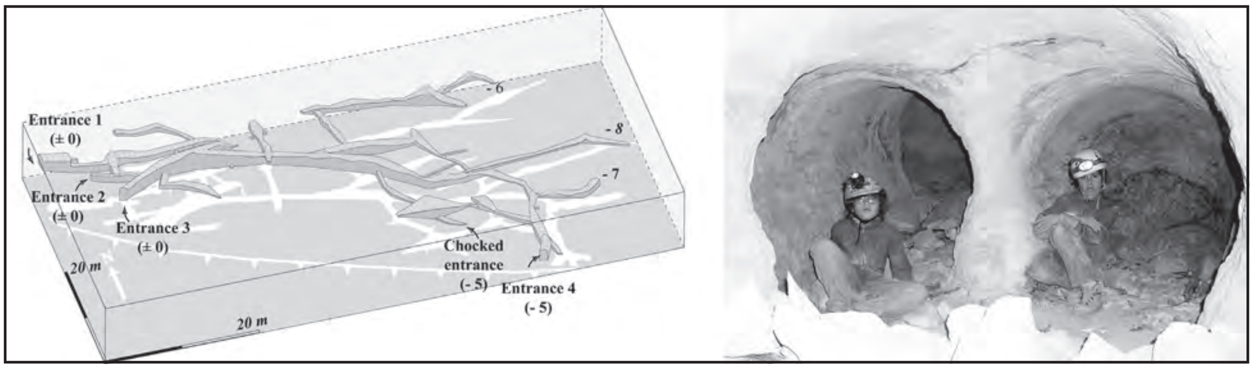

Figure 4: A sub-type of the 3D maze, the 2D maze confined under an inclined impervious roof. Grotte de Saint-Sébastien (France). The dip is towards the SE, water used to well up towards the left.

water, with CO_2 and H_2S outgassing concentrates speleogenetic processes along major fault lines, producing the deepest phreatic shafts of the world: pozzo del Merro, Italy (-392 m); El Zacaton, Mexico (-329 m, Fig. 5); Hranica propast, Czech republic (-267 m).

4. Hypogenic Cave Pattern Along or Above the Water Table

4.1 Upwardly dendritic caves

Above thermal water, condensation occurs at the ceiling

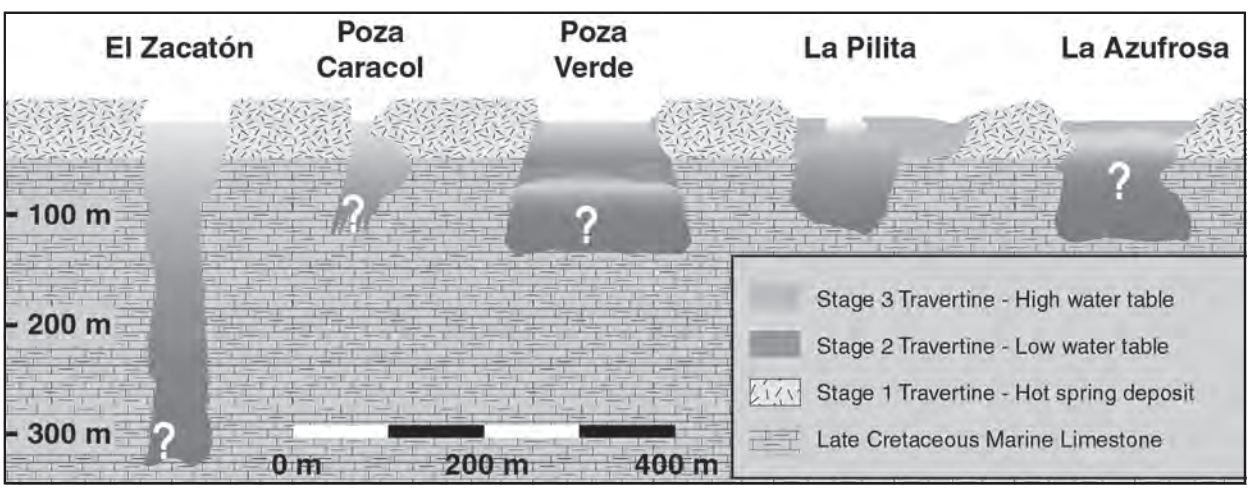

Figure 5: Deep phreatic shafts. Zacaton shaft is one of the numerous windows in the karst aquifer of Tamolipas area (Mexico), reaching a depth of 329 m. Investigation showed nearby volcanoes were the source of H2S. Microbial activity based on sulfur oxidation is present (Gary & Sharp 2006).

which is cooler. CO_2 and H_2S outgassing enhance aggressivity. By condensation-corrosion, cupolas develop upward as a dendritic pattern of stacked spheres (Audra et al. 2007). The development of two neighboring spheres will be divergent, toward the greatest potential heat transfer, because the rock in between the two spheres has less transfer potential and remains warm (Szunyogh 1990), giving the bush-like structure, as found in the Sátorkö-puszta Cave, Hungary (Fig. 6).

4.2 Isolated chambers

When strong degassing occurs, upwardly dendritic spheres enlarge and join together, eventually producing large isolated chambers (Fig. 7) (Audra et al. 2002). With a moderate thermal gradient and pCO_2, modeling shows that such volume can develop in a rather short time span, about 10 000 years (Lismonde 2003). From Israel occurrences, Frumkin & Fischhendler (2005) assign the origin of isolated chambers to phreatic convections.

4.3 Water table sulfuric acid caves

Above the water table, sulfuric vapors and thermal convections produce strong condensation-corrosion and replacement gypsum crusts (Egemeier 1981). The main drain develops headwards from springs (Fig. 8). Due to the sulfuric corrosion the cave has a low gradient (Fig. 9). Minor changes in base level cause the flow to migrate laterally making incipient mazes (fig. 9) (Audra 2007).

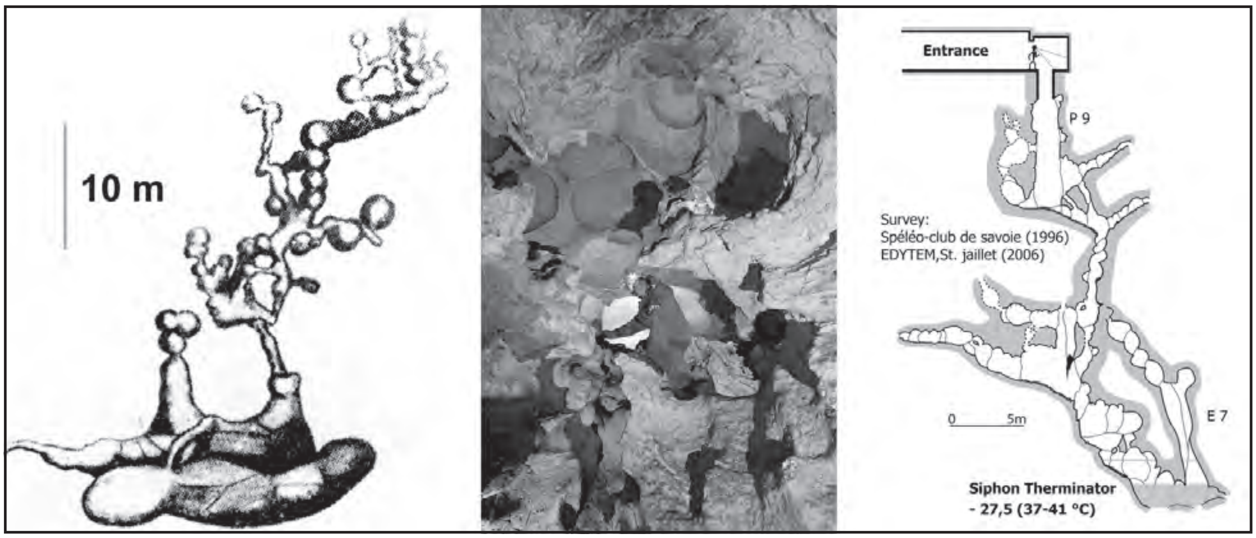

Figure 6: Upwardly dendritic caves. Left: Sátorkö-puszta Cave, Hungary, has been used to represent thermal speleogenesis. Upwardly dendritic spheres develop above a basal chamber (survey in Ford & Williams 1989). Center: stacked up spheres in Serpents Cave, France, which is close to Chevalley. Right: Chevalley shaft, France (Audra et al. 2007).

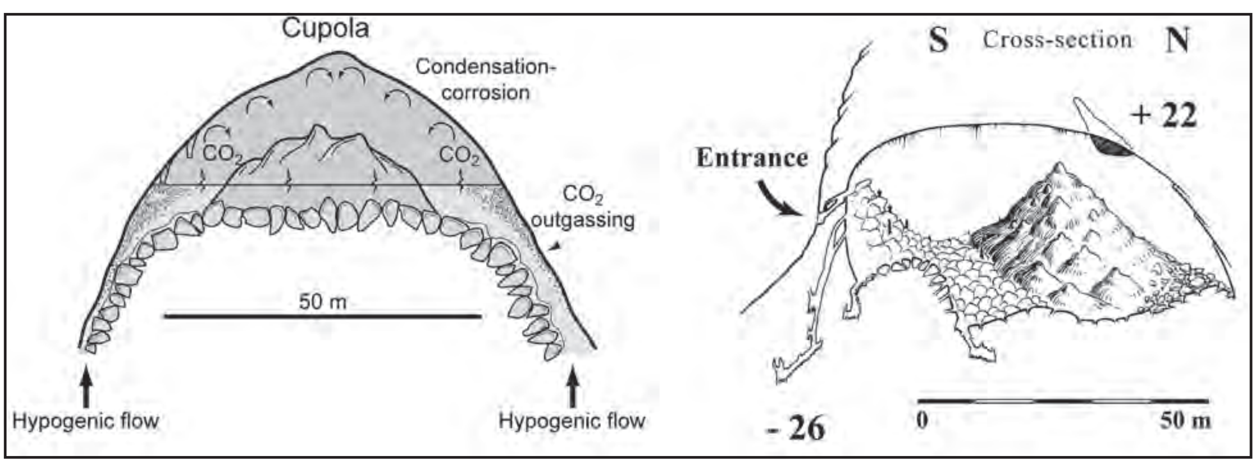

Figure 7: Isolated chambers. Thermal hypogene flow degasses at shallow depth, the thermal convections with CO2 (or H2S) gas enhance strong condensation-corrosion and the development of large isolated chambers. They tend toward a hemispherical shape. Simultaneously, a massive calcite deposit occurs in the lake, oversaturated after CO2 degassing; Champignons, France (sketches J.-Y. Bigot).

Condensation domes develop upward and may breach to the surface (Fig. 8). The most demonstrative water table sulfuric caves are Cueva de Villa Luz (Mexico), Chat Cave (France), Kane Caves (USA). Because of major base level lowering, successive horizontal cave levels develop: Frasassi Cave (Italy).

4.4 "Smoking" shafts in the vadose zone

Above thermal aquifers, the rock is significantly heated by the geothermal gradient. In winter the atmosphere of open shafts is unstable: the cold air sinks inside the shaft and expels the warm air out of the shaft which condenses, giving the impression that the shaft is smoking. The air flow follows ceiling channels where condensation-corrosion focuses. Eventually, it produces condensation ceiling cupolas and channels, which could lead to misinterpreting them as phreatic in origin (Vapeur Shaft, France; Nasser Schacht, Austria; Fumarollas and Vapor Shafts, Spain). The origin of the shaft is generally a mechanical fracture; the hypogenic role of the thermal gradient is indirect and limited to the etching of the wall features.

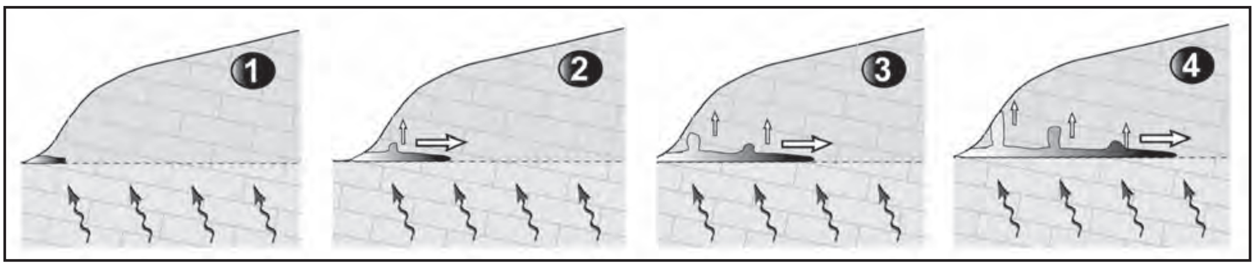

Figure 8: Water table Sulfuric cave. Headwards evolution by condensation-corrosion along the water table, supplied with major sulfuric upwelling along a fracture. Simultaneously, hydrothermalism lifts the hot air, condensation-corrosion occurs, bells and chimneys develop, some finally break through to the surface. The white arrows indicate the direction of cave development (inspired from Cueva de Villa Luz, Mexico).

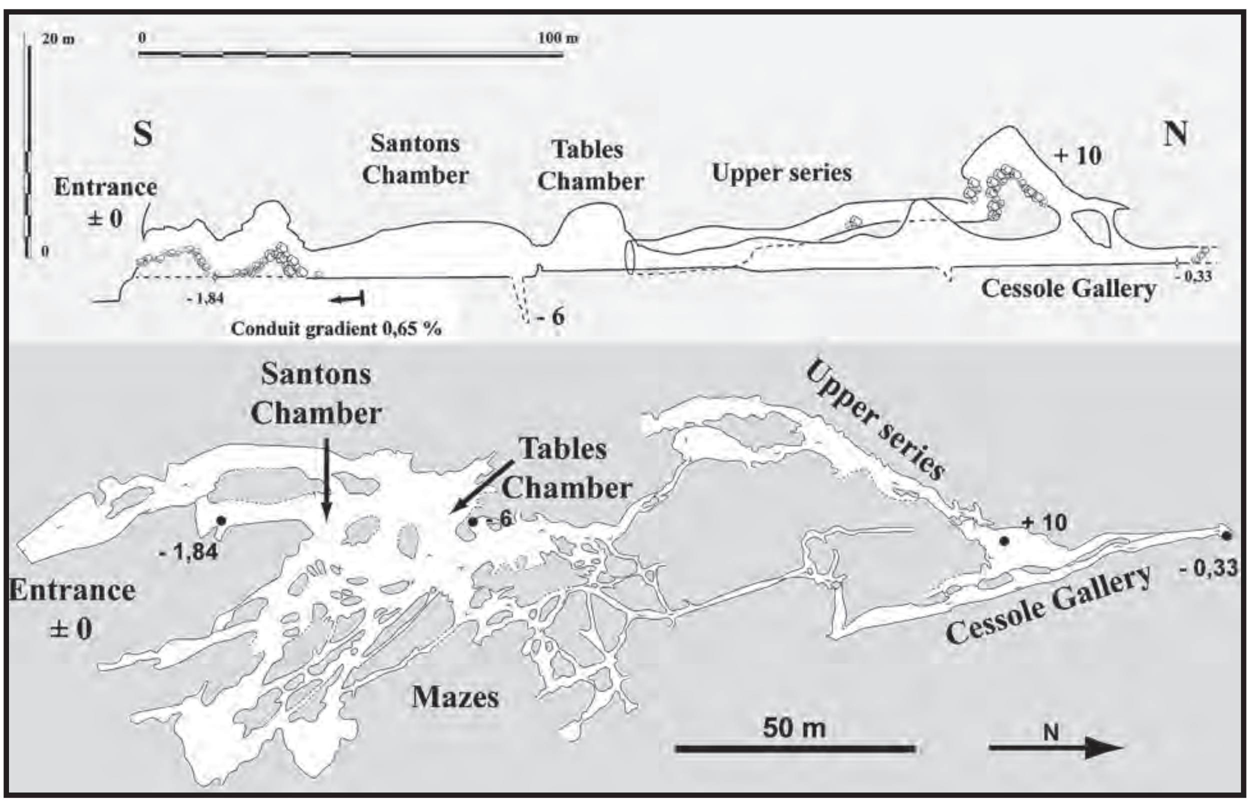

Figure 9: Chat Cave, France. The long profile with very low gradient (0.7%) results from the sulfuric flows. Incipient mazes beside the main drain result from lateral migration of the flow due to minor changes in base level (plan from M. Rousseau, profile Ph. Audra).

5. Conclusion

The diversity of hypogenic caves is now placed in a global model, explaining all kinds of patterns, depending on the geological structure, the groundwater recharge, and the speleogenetic processes. Beyond hypogenic caves developed at depth by mixing corrosion and rising flow, some hypogenic caves are developing in the atmosphere at -or above- the water table, mainly by condensation-corrosion, due to the combination of thermal convection, sulfuric and carbonic corrosion.

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