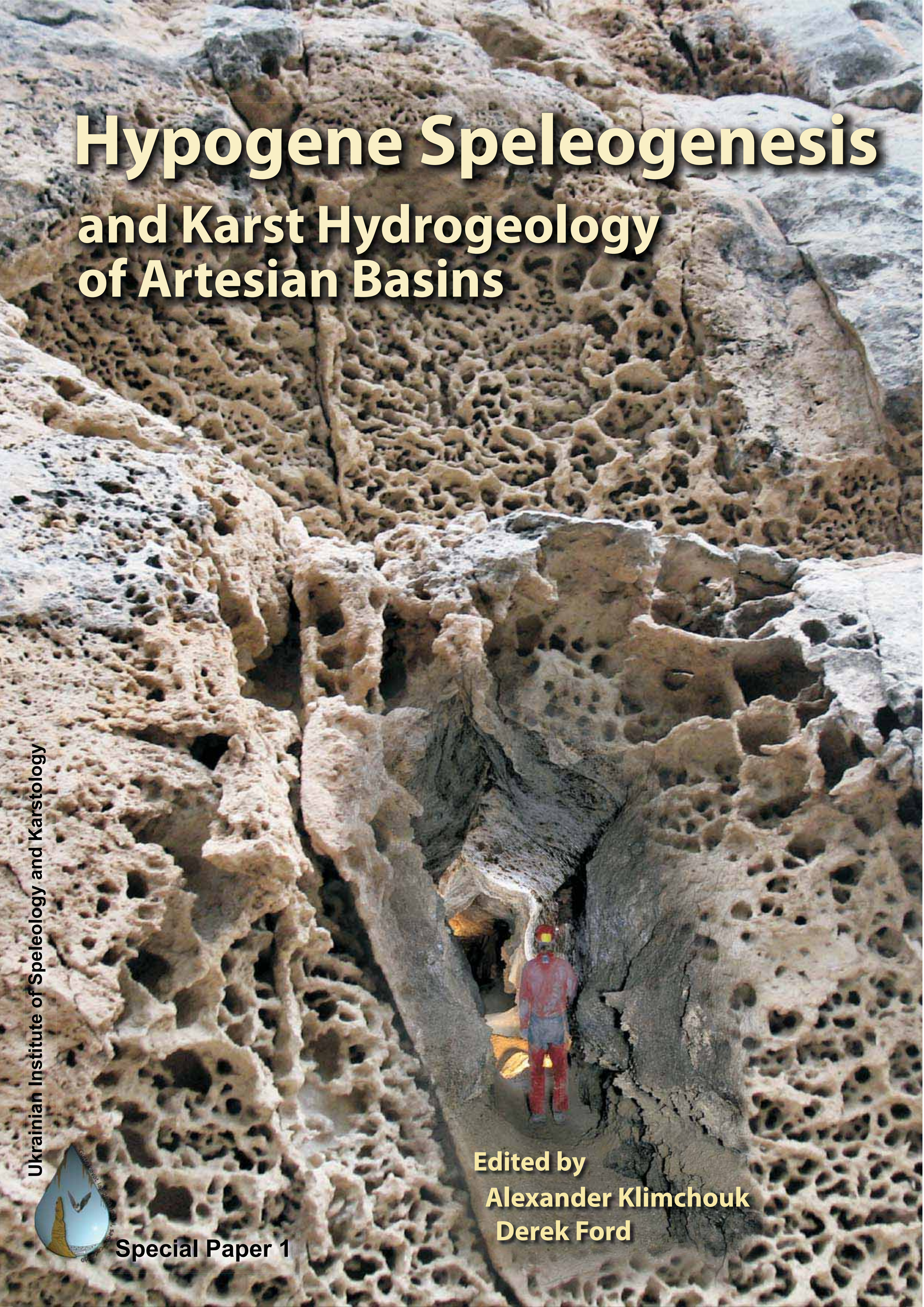
Hypogene Speleogenesis

and Karst Hydrogeology of Artesian Basins



Edited by
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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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Special Paper 1

Simferopol

2009

УДК 556
ББК 26.22
Г 505

Recommended citation for this volume:

Klimchouk, A.B. and Ford, D.C. (eds.). 2009. Hypogene Speleogenesis and Karst Hydrogeology of Artesian Basins. Ukrainian Institute of Speleology and Karstology, Special Paper 1, Simferopol, 280 pp.

ISBN 978-966-2178-38-8

The volume contains papers presented during the International Conference held May 13 through 17, 2009 in Chernivtsi, Ukraine.

Published by:
Ukrainian Institute of Speleology and Karstology,
4 Vernadsky Prospect, Simferopol 95007, Ukraine
http://institute.speleoukraine.net
institute@speleoukraine.net

Дизайн обкладинки: О.Б.Климчук
Cover design: A.B.Klimchouk
Оригінал-макет: О.Б.Климчук, А.М.Гребнєв
Master copy: A.B.Klimchouk, A.N.Grebnev
Компьютерна верстка: А.М.Гребнєв
Computer layout: A.N.Grebnev

Надруковано в типографії СПД Харітонов О.О., Сімферополь, АР Крим, Україна
Printed by SPD Kharitonov A.A., Simferopol, AR Crimea, Ukraine

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

ISBN 978-966-2178-38-8

Здано до набору 17.04.2009. Підписано до друку 22.04.2009. Формат 60х84/8. Папір офсетний №1.
Друк офсетний. Ум. друк. арк. 37,0. Тираж 300 прим. Зам. № 3/052

Ukrainian Institute of Speleology and Karstology, Ukraine
Vernadsky Tavrichesky National University, Ukraine
Fed'kovich Chernivtsy National University, Ukraine
Institute of Geological Sciences, Ukraine
National Cave and Karst Research Institute, USA
Karst Water Institute, USA
Silesian University, Poland
Katowice Section of the Polish Geographic Society, Poland
Ukrainian Speleological Association, Ukraine

With support of:
Union International of Speleology (UIS),
UIS Commission on Karst Hydrogeology and Speleogenesis
International Geoscience Program 513
"Global Study of Karst Aquifers and Water Resources" (UNESCO)
International Year of Planet Earth (UNESCO-IUGS)

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CONTENTS

HYPOGENE CAVE PATTERNS

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ABSTRACT

The hypogenic cave pattern reflects the speleogenetic processes incvolved. 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 multistory systems following joints and bedding planes, Giant phreatic shaft, Water table mazes, Isolated chambers, Upwardly dendritic spheres, Water table cave, 'Smoking' shafts.

The development of caves by hypogene 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" - 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 in terms of their patterns.

METHODS

A data base of more than 350 hypogene caves was compiled 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 (Figure 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.

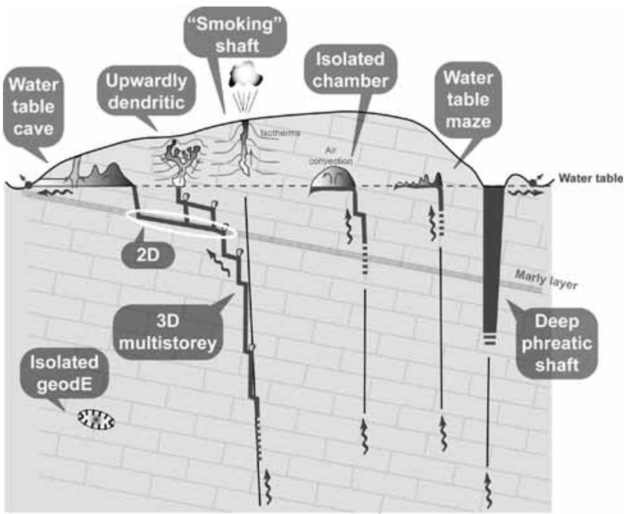

Figure 1. Conceptual model of the hypogenic cave patterns, according to the geological structure, the groundwater recharge, and the speleogenetic processes.

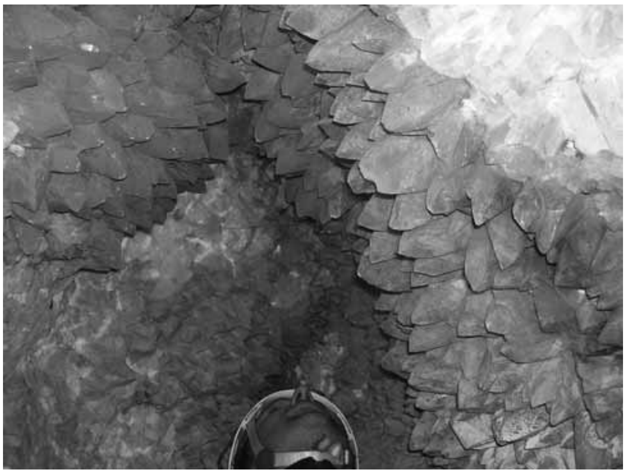

Figure 2. Geode lined with calcite spar, crystallized as sharp rhombohedrons. Cave in Ardèche, France (photo. P. Deconinck)

1. HYPOGENIC CAVE PATTERN IN PHREATIC CONDITION

Isolated geodes

At depth, mixing allows complex dissolution and deposition processes. Isolated voids are created and large crystals (calcite, gypsum...) may be deposited in them (from slightly saturated water), together with diverse other minerals,mainly metallic sulfides (Figures 2 and 3).

3D multi-storey maze cave

The rising hypogenic flow uses joints and bedding planes alternatively, producing a 3D maze cave in a staircase pattern. Generally, the cave displays a main trunk where hypogenic flow was rising, surrounded by 3D mazes, smaller in size (Figure 4). In the Monte Cucco Cave system (Italy), the sulfuric water was rising toward the top of an anticline, where an impervious cover was breached, allowing discharge of the karst aquifer (Figure 5). Contiguous vertical passages correspond to discrete hypogenic trunks, inclined galleries follow dip, horizontal passages and some cave entrances record past base level positions (Galdenzi and Menichetti, 1995). In the Black Hills (South Dakota), Jewel and Wind Caves range among the largest maze caves of the world (Figure 6). Their genesis is complex, involving several early phases (Palmer, 2006), however the pattern resulting from the main speleogenetic phase is simply a dense network of enlarged discontinuities, similar to the previous examples.

2D maze caves

If an aquitard is present, the cave develops below this impervious ceiling as a 2D maze cave (Figure 7). The passages are horizontal or inclined in accordance with the dip. The Denis Parisis system in the central part of the Paris Basin is horizontal. In Monte Cucco, the Faggeto Tondo develops below the inclined marly cover (cave indicated as no. 2 in Figure 5). 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.

Deep phreatic shafts

In active tectonic areas, the combination of rising warm 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); Hranica propast, Czech republic (-267 m).

2. HYPOGENIC CAVE PATTERNS ALONG OR ABOVE THE WATER TABLE

Upwardly dendritic caves

Above thermal water, condensation occurs at the ceiling which is cooler. CO_2 and H_2S outgassing enhance aggressiveness. 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

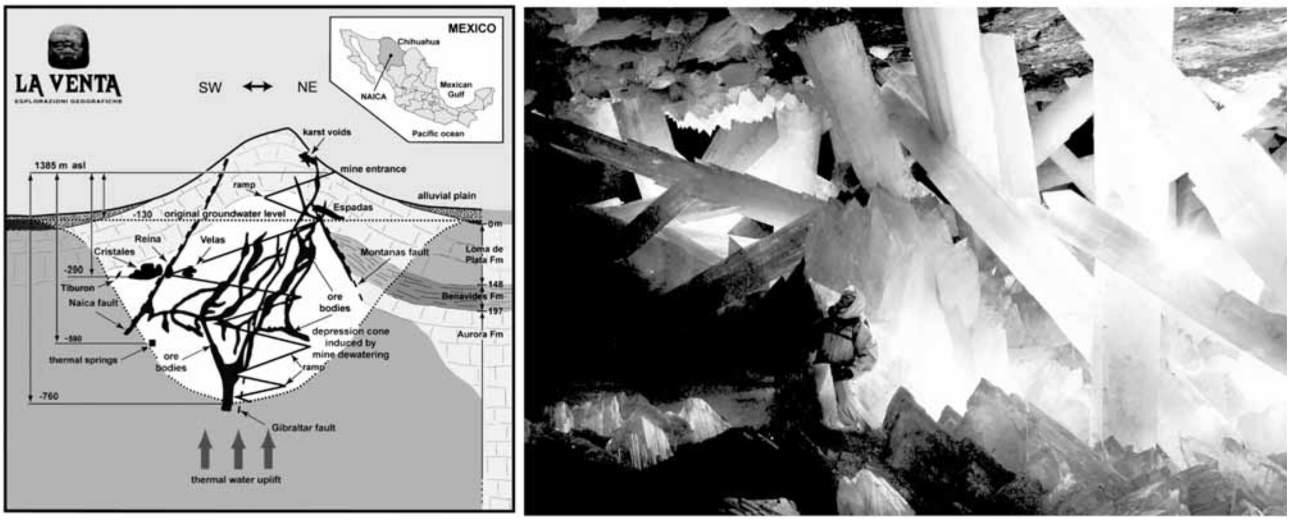

Figure 3, Cueva de los Cristales (Chihuahua, Mexico) was intersected and drained by the Naica mine (Bernabei *et al.*, 2007). The gypsum swords in this cave are the largest crystals known in the world (photo. R. Tedeschi arkif Speleoresearch & Films and La Venta Exploring team)

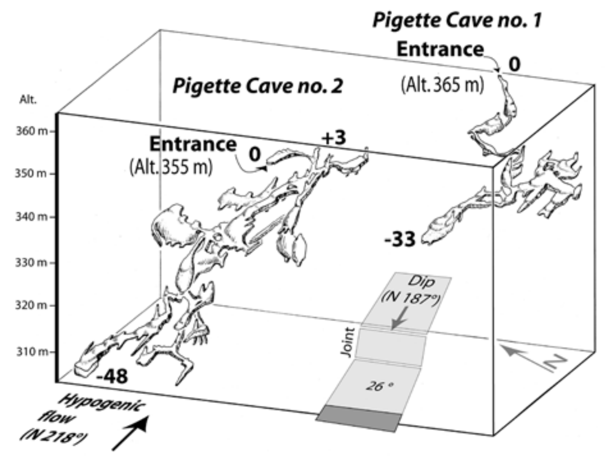

Figure 4. Perspective view of the Pigette Caves (France), a 3D multistorey maze cave originating in the phreatic zone by hypogenic upwelling, following structural weaknesses (inclined dip and vertical joints) (sketch by J.-Y. Bigot)

less transfer potential and remains warm (SZUNYOGH 1990), giving the bush-like structure, as found in the Sátorkő-puszta Cave, Hungary (Figure 9).

Isolated chambers

When strong degassing occurs, upwardly dendritic spheres enlarge and join together, eventually producing large isolated chambers (Figure 9; AUDRA *et al.*, 2002). Taking into account moderate thermal gradient and pCO_2, modeling has shown that such volumes can develop in a rather short time span, about 10 000 years (LISMONDE, 2003). From occurrences in Israel, FRUMKIN AND FISCHHENDLER (2005) assign the origin of isolated chambers to phreatic convections.

Water table sulfuric cave

Above the water table, sulfuric vapors and thermal convection cells produce strong condensation-corrosion and replacement gypsum crusts (EGEMEIER, 1981). The main drain develops headwards from springs (Figure 11). Due to the sulfuric corrosion the long profile displays only a tiny gradient (Figure 12). Minor changes in base level cause the flow to migrate laterally, making incipient mazes (Figure 12) (AUDRA, 2007). Condensation domes develop upward and may breach the surface (Figure 11). The most illustrative water table sulfuric caves are Cueva de Villa Luz (Mexico), Chat Cave (France), Kane Caves (USA). In case of major base level lowering, successive horizontal cave levels develop: Frasassi Cave (Italy).

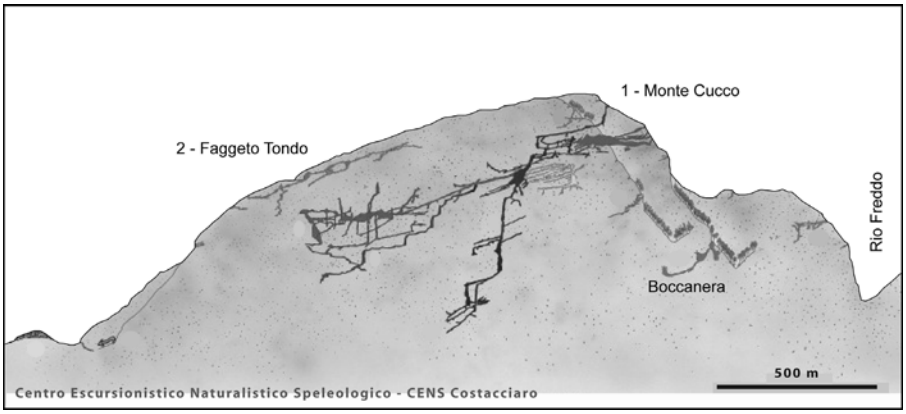

Figure 5. Monte Cucco System (Italy), probably the deepest known hypogene cave system of the world (- 923 m / 31 km), with large shafts of several hundred meters of depth and ramps inclined along the dip of the anticline (CAIROLI *et al.*, 1991)

«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: cold air sinks into the shaft, expelling its warm air and creating condensation, 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 can 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 (Figure 13); the hypogenic role through thermal gradient is indirect and limited to the etching of the wall features.

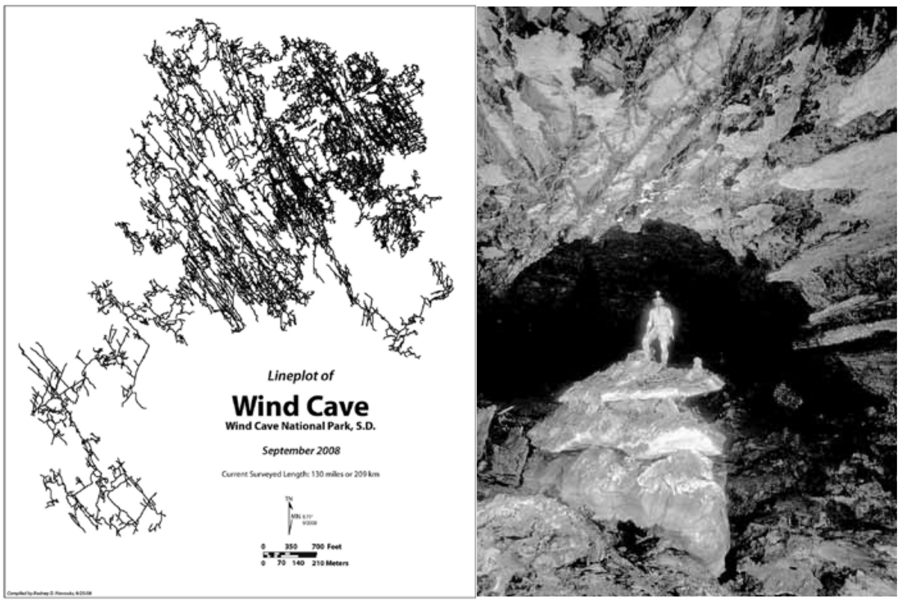

Figure 6. Wind Cave (USA), 209 km of passages in a 3D maze cave (map compiled by R. Horrocks; photo. A. Palmer).

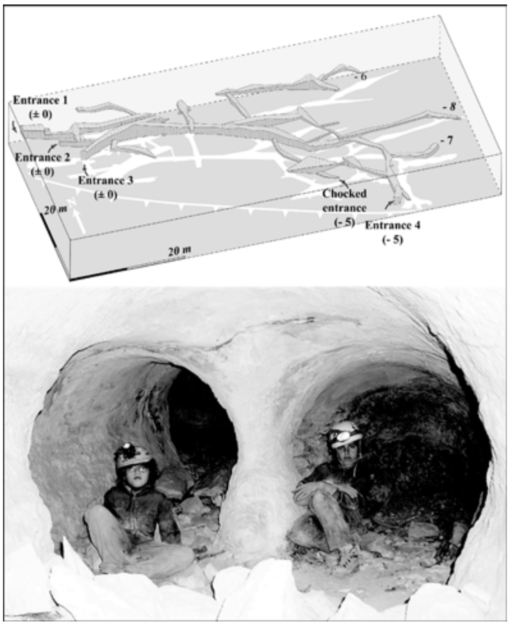

Figure 7. A sub-type of the 3D maze, the 2D maze confined under an inclined impervious roof. Grotte de Saint-Sébastien (France). The dip is towards the SE, water used to well up towards the left (sketch Ph. Audra, photo. J.-Y. Bigot)

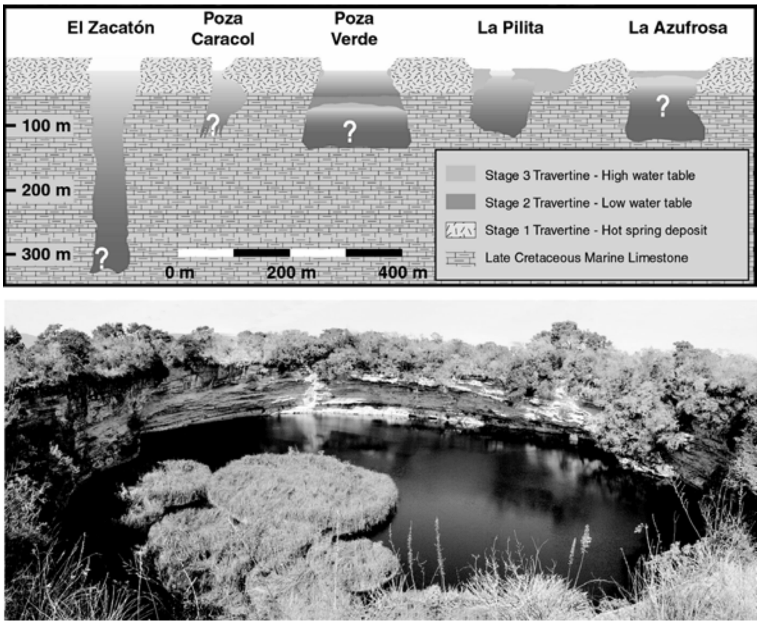

Figure 8. Deep phreatic shafts. Zacaton shaft is one of the numerous windows in the karst aquifer of the Tamaulipas area (Mexico), reaching a depth of 329 m (Photo A. Palmer). Investigation showed nearby volcanoes were the source of H_2S. Microbial activity based on sulfur oxidation is present (Gary and Sharp 2006)

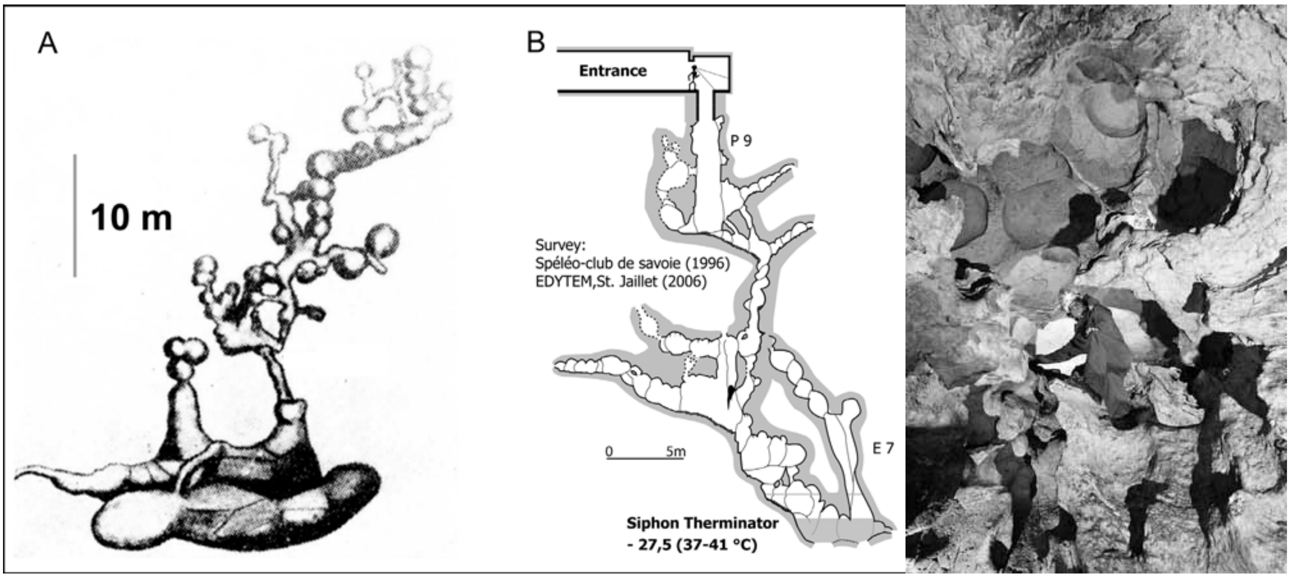

Figure 9. Upwardly dendritic caves. Left: Sátorkö-puszta Cave, Hungary, has been used to represent thermal speleogenesis. Upwardly dendritic spheres develop above a basal chamber (survey in Ford and Williams 1989). Center: Chevalley shaft, France (Audra *et al.*, 2007). Right: stacked up spheres in Serpents Cave, France, which is close to Chevalley (photo. S. Jaillet)

CONCLUSIONS

The diversity of hypogenic caves is now placed in a global model, explaining all of the kinds of patterns encountered, stressing their dependence on geological structure, groundwater recharge, and the particular speleogenetic processes at work. In addition to hypogenic caves developed at depth by mixing corrosion and rising flow, some hypogenic caves develop in the atmosphere at -or above- the water table, mainly by condensation-corrosion, due to the combination of thermal convection, sulfuric and carbonic corrosion.

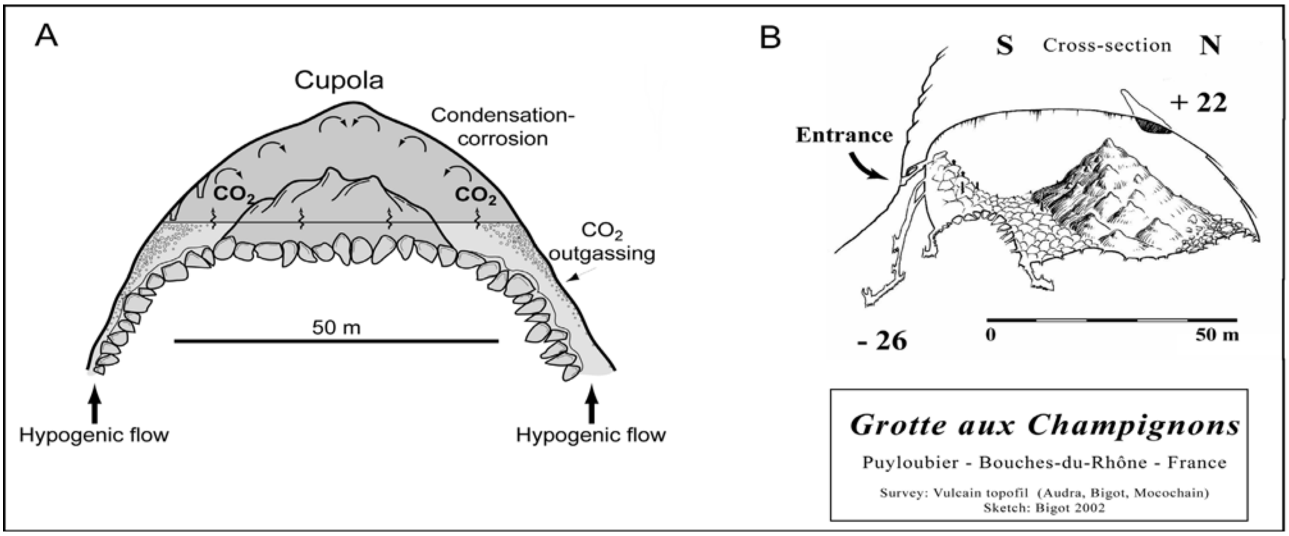

Figure 10. Isolated chambers. Thermal hypogene flow degasses at shallow depth, thermal convection with CO_2 (or H_2S) gas enhances strong condensation-corrosion and the development of large isolated chambers. They tend toward a hemispherical shape. Simultaneously, a massive calcite deposit occurs in the lake, oversaturated after CO_2 degassing; Champignons, France (sketches J.-Y. Bigot)

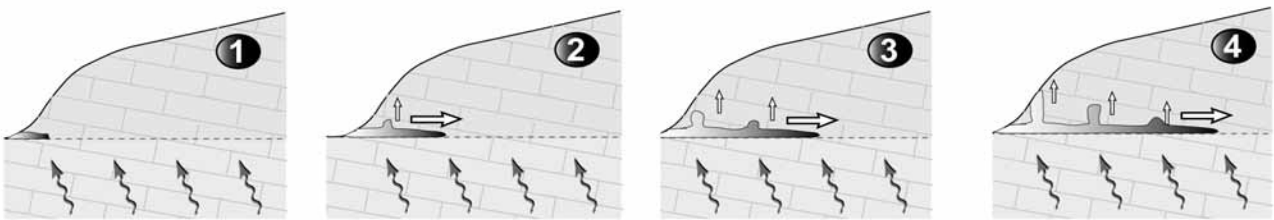

Figure 11. Water table Sulfuric cave. Headwards evolution by condensation-corrosion along the water table, supplied with major sulfuric upwelling along a fracture. Simultaneously, thermal water heats the air to induce convection, condensation-corrosion occurs, bells and chimneys develop, some finally break through to the surface. The white arrows indicate the direction of cave development (inspired from Cueva de Villa Luz, Mexico)

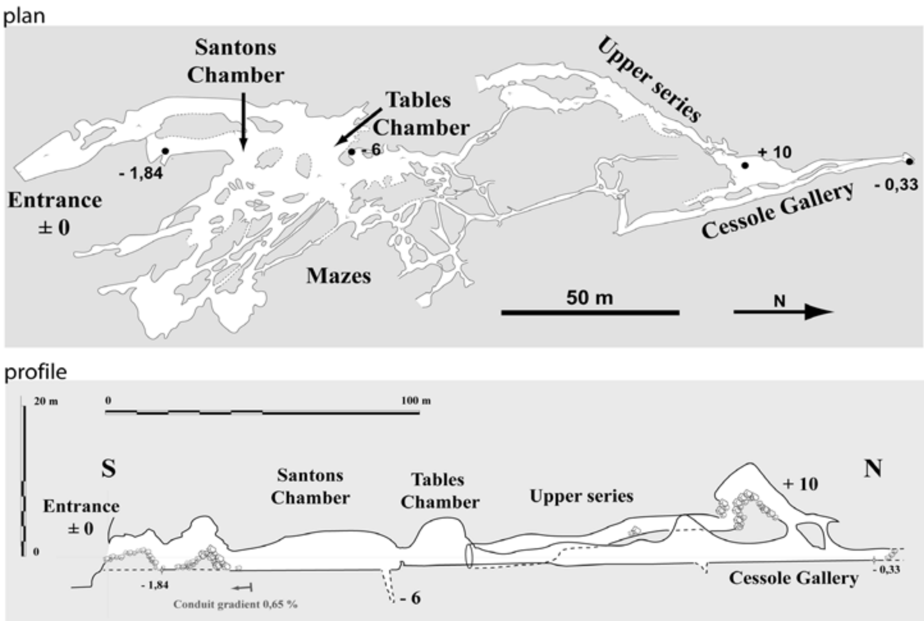

Figure 12. Chat Cave, France. The long profile with a very low gradient (0.7%) results from the sulfuric acidic water flow (plan from M. Rousseau, profile Ph. Audra)

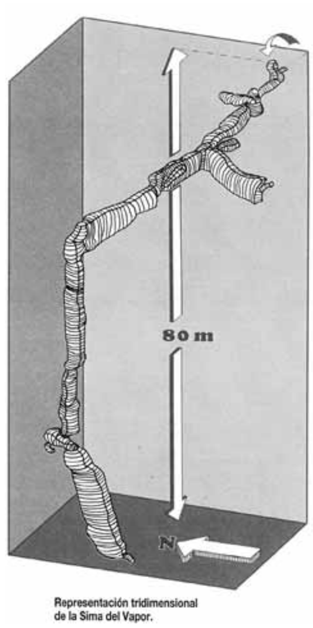

Figure 13. Sima del Vapor, Spain. The temperature of the air at bottom is 41 °C, giving rise to convective airflow in winter, with a condensation plume outside (survey Cuatro Picos, Cartagena)

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