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Hypogenic caves in France. Speleogenesis and morphology of the cave systems

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Key-words. – Hypogenic caves, Speleogenesis, Hydrothermalism, Sulfuric corrosion, Maze cave, Condensation-corrosion, Sulfide ore.

Abstract. – Hypogenic caves develop by recharge from below, not directly influenced by seepage from the overlying land surface. Several processes of speleogenesis are combined, involving CO_2 or H_2S produced at depth. If the recharge from depth remains uniform, the growth of selected fissures is prevented, giving rise to maze cave systems with an upward development trend, which is defined as "transverse speleogenesis" [Klimchouk, 2003]. Hypogenic caves are much fewer than epigenic caves (i.e. developed downwards by meteoric water with aggressivity derived from soil). In France, as in the rest of the world, hypogenic caves were poorly recognized until recently because of their lower frequency, subsequent epigenic imprint often hiding the true origin, and the absence of a global conceptual model. However, about a hundred of hypogenic caves have been identified recently in France. The extreme diversity of hypogenic cave patterns and features is due to the variety of geological and topographic settings and types of flow.

Thermal caves are a sub-set of hypogenic caves. Active thermal caves are few and small (Mas d'En Caraman, Vallon du Salut). Often, thermal influences only occur as point thermal infeeders into epigenic caves (Mescla, Estramar). In addition to the higher temperature, they may be characterized by CO_2 (Madeleine) or H_2S degassing, by warm water flowing in ceiling channels, or by manganese deposits. The Giant Phreatic Shafts locate along regional active faultlines. They combine all characteristics (thermal, CO_2, H_2S), due to the fast rising of deep water. The Salins Spring has been explored by scuba diving down to –70 m. Such a hyperkarstification is responsible for the development of the deepest phreatic shafts of the world: pozzo del Merro, Italy (-392 m).

Inactive hypogenic caves may be recognized by their specific mineralization or by the presence of large calcite spar. Metallic deposits are due to the rising of deep waters that are warm, aggressive, and low in oxidation potential. Mixing with meteoric water generates Mississippi Valley Type (MVT) sulfidic ores. Iron deposits as massive bodies (Lagnes) or onto microbial media (Iboussières, Malacoste) making specific facies, such as "black tubes", iron flakes, and iron pool fingers. Other frequent minerals are Mn oxides and Pb sulfur. In such low thermal conditions, calcite deposits occur as large spar in geodes or as passage linings.

Other inactive hypogenic caves may also be recognized by characteristic patterns, such as mazes. The relatively constant recharge into confined karst aquifers suppresses fissure competition, so they enlarge at similar rates, producing a maze pattern. In horizontal beds, mazes extend centrifugally around the upwelling feeder. The juxtaposition of multiple discrete vertical feeders produces extended horizontal mazes. In gently tilted structures, 2D mazes extend below aquitards, or along bedding or more porous beds (Saint-Sébastien). In thick folded limestone the rising hypogenic flow alternatively follows joints and bedding planes, producing a 3D maze cave in a staircase pattern (Pigette). Isolated chambers are large cupola-like chambers fed by thermal slots. Thermal convection of air in a CO_2-rich atmosphere causes condensation-corrosion that quickly produces voids above the water table (Champignons Cave).

Sulfuric acid caves with replacement gypsum are produced by H_2S degassing in the cave atmosphere. H_2S oxidizes to H_2SO_4, which corrodes the carbonate rock and replaces it with gypsum. The strongest corrosion occurs above the water table, where sulfide degassing and thermal convection produce strong condensation-corrosion. Caves develop headward from springs and from thermo-sulfuric slots upward (Chevalley-Serpents System). The low-gradient main drains record base-level positions and even the slightest stages of water-table lowering (Chat Cave).

Hypogenic speleogenesis provides better understanding of the distribution of karst voids responsible for subsidence hazards and the emplacement of minerals and hydrocarbons.

Les cavités hypogènes en France. Processus de spéléogenèse et morphologie des réseaux karstiques

Mots-clés. – Cavités hypogènes, Spéléogenèse, Hydrothermalisme, Corrosion sulfurique, Réseau labyrinthe, Minerai sulfurique, Condensation-corrosion

Résumé. – Les cavités hypogènes se développent par recharge sous-jacente, sans influence directe des infiltrations en surface. Plusieurs processus de spéléogenèse se combinent, impliquant notamment le CO_2 ou l'H_2S issus des profondeurs. La recharge profonde constante empêche l'élargissement sélectif au profit de fissures préférentielles, produisant par conséquent des réseaux labyrinthiques se développant vers le haut, ce qui correspond à la « spéléogenèse transverse » [Klimchouk, 2003]. Au regard des cavités épigènes (qui se développent vers le bas sous l'effet des infiltrations

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d'eau météorique rendue agressive lors de la traversée des sols), les cavités hypogènes sont minoritaires. En France, tout comme dans le reste du monde, les cavités hypogènes restent peu reconnues, du fait de leur faible fréquence, de l'empreinte épigène postérieure pouvant masquer l'origine réelle, et du manque d'un modèle conceptuel global. Néanmoins, une centaine de cavités hypogène a récemment été identifiée. La diversité extrême des réseaux et des morphologies est due aux contextes géologiques et topographiques, ainsi qu'aux modalités d'écoulement.

Les grottes thermales sont un sous-type des cavités hypogènes. Les cavités actives sont rares et peu développées (sources du Mas d'En Caraman, du Vallon du Salut). Souvent, l'influence hypogène se limite à des arrivées thermales dans les cavités épigènes (sources de la Mescla, font Estramar). Hormis la température plus élevée, certaines émettent du CO_2 (grotte de la Madeleine) ou de l'H_2S, présentent des circulations chaudes en chenaux de plafond et des dépôts de manganèse. Les puits noyés géants se localisent sur les grands linéaments actifs. Ils combinent toutes ces caractéristiques (thermal, CO_2, H_2S) grâce aux remontées rapides d'eaux profondes. Une telle hyperkarstification est à l'origine des plus profonds puits noyés du monde: pozzo del Merro, Italie (-392 m). En France, la source de Salins a été reconnue en plongée jusqu'à 70 m de profondeur.

Lorsqu'elles sont devenues inactives, les cavités hypogènes peuvent s'identifier par la présence de minéralisations spécifiques ou par de grands cristaux de calcite. Les dépôts métalliques découlent des ascendances d'eaux profondes, chaudes, agressives et réduites. Le mélange avec les eaux météoriques est à l'origine des minerais de type Mississippi Valley (MVT). Le fer apparaît en amas massif (grotte de Lagnes) ou en dépôts vacuolaires sur support microbien (grotte des Iboussières, carrière de Malacoste), donnant des faciès particuliers, notamment les *black tubes* et *pool fingers*. Les autres minéraux fréquemment associés sont les oxydes de Mn et la galène. Dans ces conditions hypothermales, la calcite se dépose en grands cristaux couvrant les parois des conduits et les géodes.

Un autre critère d'identification est la forme caractéristique de réseau, en particulier le labyrinthe. La recharge constante des aquifères karstiques confinés ne permet pas la compétition entre fissures, qui de fait s'élargissent uniformément, donnant un labyrinthe. En structure horizontale, le labyrinthe s'étend de manière centrifuge autour du point d'alimentation hypogène. La juxtaposition d'alimentations hypogènes produit de grands labyrinthes horizontaux. En structures peu inclinées, les labyrinthes en 2D s'étendent sous un *aquitard*, ou bien le long de joint de strate ou d'un lit plus poreux (grotte de Saint-Sébastien). En région plissée, les écoulements hypogènes ascendants utilisent alternativement les joints de strate et les fissures, donnant un labyrinthe en forme d'escalier en 3D (grottes de Pigette). Les salles isolées sont de grands vides hémisphériques alimentés par des fissures thermales. Les convections thermiques dans une atmosphère riche en CO_2 favorisent la condensation-corrosion qui permet le développement rapide de tels vides, au-dessus de la zone noyée (grotte des Champignons).

Les grottes sulfuriques avec gypse de remplacement sont produites par le dégazage d'H_2S qui s'oxyde en H_2SO_4, lequel corrode le calcaire et le remplace par du gypse. Cette corrosion est intense au-dessus de la zone noyée où le dégazage sulfurique et les convections thermales produisent une puissante condensation-corrosion. Les cavités se développent de manière régressive à partir de l'émergence et en remontant à partir des points d'alimentation thermo-sulfuriques (réseau Chevalley-Serpents). Le conduit principal, de faible gradient, enregistre les positions successives du niveau de base, y compris les abaissements mineurs (grotte du Chat).

La spéléogenèse hypogène contribue à une meilleure compréhension de la distribution des vides karstiques responsables du risque de subsidence, des minéralisations associées, ainsi que des hydrocarbures.

INTRODUCTION

Definition

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. This gap results firstly from a previous lack of a global conceptual model and lots of hypogenic caves were misinterpreted as epigenic; secondly, due to tectonic uplifting, hypogenic caves developed at depth are progressively moved toward shallower depth, where epigenic processes may change their aspect, obscuring their true origin.

The hypogenic karst is thus the opposite of the "classical" epigenic karst, where surface water becoming aggressive while traversing the soil and produces karst networks by seepage, in which highly irregular recharge, physical characteristics, and chemical composition are typical. On the contrary, because of the deep origin of rising water, the hypogenic cave systems are independent of surface conditions, or at least not directly influenced by seepage. Consequently, the hydrologic characteristics (discharge, temperature, and mineralization) are more regular, especially where mixing with meteoric water is limited.

Speleogenesis processes

Most hypogenic speleogenesis occurs with the mixing of waters of different origin and thus of different physical and chemical characteristics [Palmer, 2000]: at depth in converging zones; at shallow depth or close to the discharge areas where deep water and meteoric water are mixing. In these conditions, the mixing produces chemical disequilibrium allowing dissolution, particularly when CO_2 concentrations differ in both solutions. The carbonic component originates from depth (mantle degassing, metamorphism, decaying of organic components). At depth, sulfates can be reduced by microbial activity to produce H_2S, which eventually oxidizes to H_2SO_4. Cooling of rising water theoretically boosts the solubility of calcite. Finally, dolomite solubility increases with the presence of sulfates by incongruent dissolution [Palmer, 2006].

Such a variety of processes (carbonic, sulfidic), of physical characteristics (thermal/cold), and of hydrogeological settings (deep seated, shallow phreatic, vadose), combined with the diversity of geologic and topographic settings, produce an outstanding diversity of hypogenic caves, ranging from entire cave systems, to wall features, and facies deposits [Audra, 2006, 2007].

Even though extremely diverse, the common denominator of hypogenic caves is to be "out of the ordinary", or at least to be very different from neighboring epigenic caves. Our investigations in France reinterpret the genesis of about hundred caves, which clearly appear to be hypogenic. We will focus here on about 35 caves, which are the most significant (fig. 1, tabl. I). If hypogenic caves generally remain far fewer than epigenic caves, some contexts occur where hypogenic cave are predominant.

In this paper, we describe hypogenic caves in France according to their main characteristics, such as hydrodynamics, unusual mineralization, peculiar cave patterns, or solution processes.

THE ACTIVE CAVES: THERMAL CAVES AND GIANT PHREATIC SHAFTS

Active thermal caves are few and small (Chevalley Shaft-Serpents Cave, *infra*). Additionally, in some epigenic caves fed by meteoric seepage, several thermal feeders are known: Mescla Cave (Alpes-Maritimes), Gourg de l'Antre Spring (Pyrénées-Orientales) [Salvayre, 1978]. Several thermal sumps have been explored over short distances (springs of Mas d'En Caraman and of Vallon du Salut). Along the shoreline of the Pyrénées-Orientales, at the Font Estramar Spring, less dense water originating from the "Warm gallery" flows along a ceiling channel and precipitates manganese [Brandt, 2003]. The grotte de la Madeleine, in the Gardiole plateau (Hérault), is known for CO_2 degassing. In the Alpes-de-Haute-Provence, the thermal springs of Sorine and of Salaou (which means "salty") exit from short caves in gypsum [Toro, 1988]. The Salins Spring (Savoy) is a giant phreatic shafts, explored by scuba diving down to –70 m (fig. 2) [Hobléa, 1999]. The sulfate and chloride content is characteristic of the Triassic evaporites.

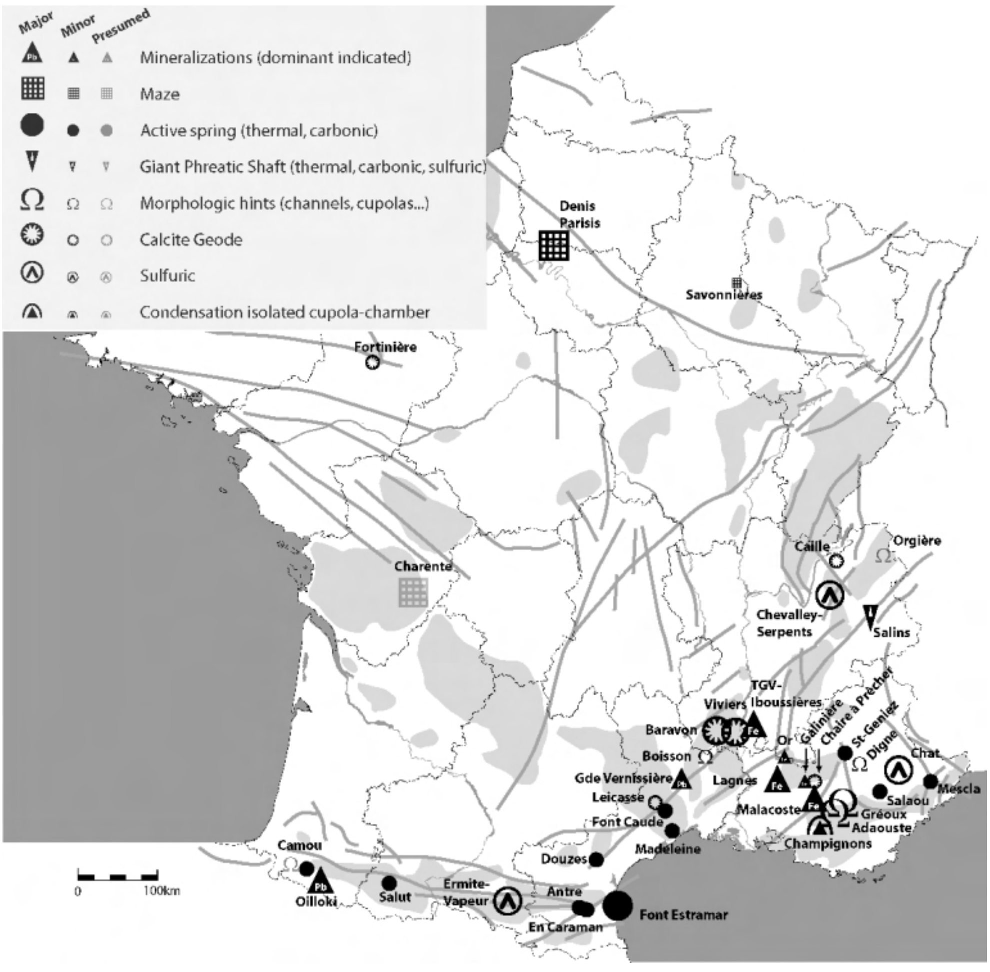

FIG. 1. – Distribution of hypogenic caves in France. Typology according to the predominant character. They cluster in orogenic belts, along large fault lines, and in some plateaus. Limestone karst outcrops are shown in grey surfaces, main fault in grey lines.

FIG. 1. – *Carte de répartition des cavités hypogènes en France, selon leur caractéristique prédominante. Elles se concentrent dans les régions orogéniques, le long des grands linéaments, et dans certaines régions de plateaux. Les régions karstiques figurent en surfaces grises, les principaux linéaments sont représentés par des traits gris.*

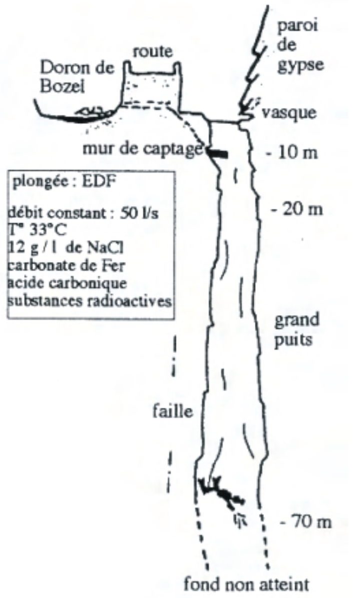

FIG. 2. – The Salins Spring, Savoy, a giant phreatic shaft, explored by scuba diving down to –70 m [Hobléa, 1999]. The recharge of giant phreatic shafts by deep upwelling occurs along regional fault lines. In volcanic area, the flow is generally associated with magmatic bodies.
FIG. 2. – *Source de Salins, Savoie, puits géant noyé reconnu jusqu'à – 70 m [Hobléa, 1999]. L'alimentation s'effectue par des remontées profondes le long de grandes failles. Dans les régions actives, les remontées sont généralement associées aux corps magmatiques.*

Fast upwelling along the Middle-Tarentaise fault causes high temperature, high load of dissolved carbonates, and radioactivity.

In active tectonic areas, rising warm waters degassing CO_2 and H_2S concentrate speleogenetic processes along major fault lines. Such intense karstification is responsible for the development of the deepest phreatic shafts of the world: pozzo del Merro, Italy (–392 m); El Zacaton, Mexico (–329 m,); Hranica Propast, Czech Republic (–267 m).

Caves with mineralization and spar

Deep waters, being warm, acid, and low in oxidation potential, pass through and weather endogenic and sedimentary rocks. Thus the water acquires a high load of dissolved minerals. At shallow depth, these dissolved species precipitate due to loss of CO_2 as it approaches the water table, to mixing with meteoric water, to oxidation of sulfides, and to the activity of chemiolithotrophic microbes (which gain their energy from oxidation of mineral compounds).

Metallic elements (Fe, Pb, Zn, Ag, Cu…) combine with sulfidic compounds to form Mississippi Valley Type (MVT) sulfidic ores, concentrations of which are sometimes of economic size [Audra and Hofmann, 2004]. Iron deposits form massive bodies (Lagnes Cave-mine, Vaucluse), wall crusts (Baume Galinière Cave, periphery of the Vaucluse plateau; Viviers Caves, Ardèche), coatings on microbial media (fig. 3), iron agglomerates as flakes (TGV Cave and Iboussières Cave; Malacoste quarry), or pool fingers around microbial filaments (Malacoste quarry). The channels cut by the Malacoste quarry show a segregation of Fe and Mn minerals, resulting from the evolution of the redox conditions along the hypogenic chimney. Examples where iron is widespread include the Oilloki Cave-mine (Pyrénées), which has been mined for galena [Audra, 2009], and the Grande Vernissière Mine (Cévennes), which contains masses of fluorite, barite, smithsonite, and galena.

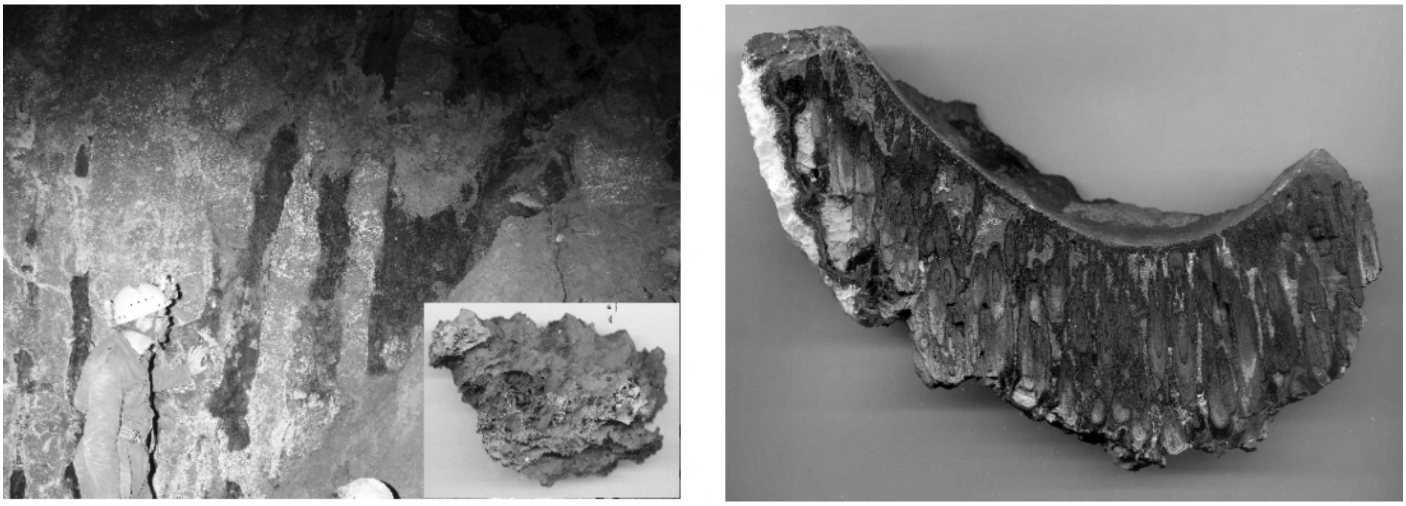

FIG. 3. – Iron mineralizations. Left: Iboussières Cave (Malataverne, Drôme): "black tubes" of iron oxides-hydroxides (goethite-hematite) lining wall channels (photo. J.-Y. Bigot). Inset: detail of iron oxides deposited as flakes on microbial media; sample width: 9 cm. Right: iron oxide pool fingers (goethite, hematite), deposited on microbial filaments handing from the ceiling; sample width: 11 cm (images Ph. Audra).
FIG. 3. – *Minéralisations ferreuses. Gauche : grotte des Iboussières (Malataverne, Drôme) : « tubes noirs » d'oxydes de fer (goethite-hématite) moulant des chenaux de paroi (photo. J.-Y. Bigot). En vignette, détail de fer déposé en copeaux sur support microbien, largeur de l'échantillon : 9 cm. Droite : baguettes (pool fingers) de fer (goethite, hématite), déposés sur filaments microbiens en plafond. Largeur de l'échantillon : 11 cm (images Ph. Audra).*

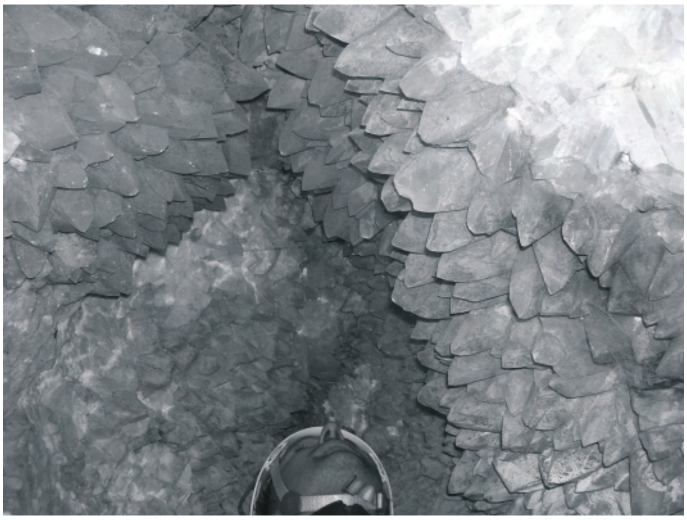

FIG. 4. – Geode lined with calcite spar. Cave in Ardèche, not located for conservation reasons (Photo. P. Deconinck).
FIG. 4. – *Géode de calcite en rhomboèdres trigonaux. Grotte en Ardèche, localisation non divulguée pour raison de conservation (Photo. P. Deconinck).*

Upwelling of deep water may induce CO_2 degassing, which leads to supersaturation with respect to calcite. Underwater calcite forms large spar crystals (fig. 4), or very seldom folia [Audra *et al*., 2009]. Most crystals are trigonal rhombohedra that originate from low-grade hydrothermal conditions [Dublyansky and Smirnov, 2005], as at Pont de la Caille, Viviers, Chaire à Prêcher, and Col de la Cardonille. Along the Cevennes Fault, fluid inclusions in calcite spar indicate crystallization temperatures higher than 70°C at the Baravon Cave (Ardèche) and 50 to 70°C in a geode cut by the Aven de la Leicasse (Larzac) [Häuselmann, unpubl.].

Wind Cave and Jewel Cave (Black Hills, USA) are show caves, which are famous for their calcite spar lining, associated in places with manganese deposits. These characteristics are due to the ponding of slightly thermal water by thick continental sediments that blocked former springs [Palmer and Palmer, 2000; Palmer *et al.*, 2009].

INACTIVE HYPOGENIC CAVES WITH CHARACTERISTIC PATTERNS: MAZES AND CUPOLA-CHAMBERS

The recharge of confined karst aquifers occurs through surrounding porous or fissured aquifers and by distant infiltration where the karst aquifer itself outcrops. Where discharge takes place, flow mainly concentrates along vertical joints that connect different aquifers [Klimchouk, 2007]. The limited hydraulic conductivity of the surrounding aquifers does not allow the discharge to increase as the karst fissures enlarge. The absence of competition prevents the convergence of the initial karst passages toward a main drain. Consequently, the entire fissure network is enlarged at the same rate, producing a maze pattern reflecting the joint pattern. In horizontal beds, mazes extend centrifugally around the upwelling feeder. The juxtaposition of several discrete vertical feeders produces extended horizontal mazes. It gives the false impression of horizontal flow through the whole karst aquifer, whereas flow is mainly vertical (except locally). This pattern is defined as “transverse speleogenesis” [Klimchouk, 2003]. It is thought that most of extended horizontal mazes owe their origin to transverse (i.e. vertical) speleogenesis. Consequently, the absence of feedback competition within karst fissures to produce a maze pattern is often an attribute of hypogenic speleogenesis.

In gently tilted structures, the structural discontinuities (less permeable stratum at the ceiling, open bedding-plane parting, or bed with higher porosity) allow the development of extended 2D mazes. Passages are horizontal or gently

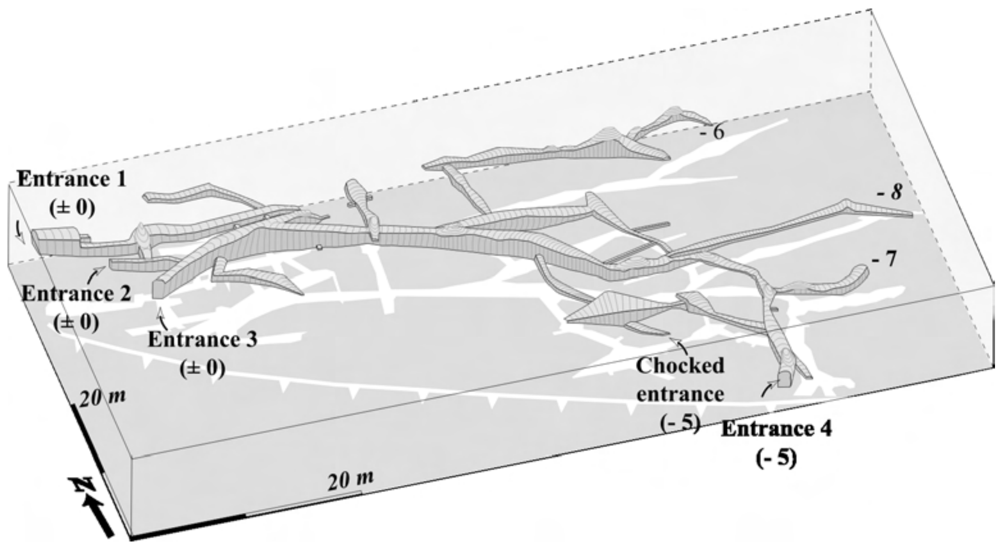

FIG. 5. – The cave of Saint-Sébastien (Gréoux-les-Bains, Alpes-de-Haute-Provence) is a 2D maze. It is an inclined planar maze confined below a marly ceiling. Dip is oriented toward the SE, the thermal water rose toward the NW (toward left on the sketch)
FIG. 5. – *La grotte de Saint-Sébastien (Gréoux-les-Bains, Alpes de Haute-Provence) présente un labyrinthe développé selon un plan en 2D, confiné sous un toit marneux incliné, de pendage SE, l’eau remontait vers le NW (à gauche).*

inclined along the dip. The Denis Parisis System in the Paris basin extends in a Ludian gypsum bed; the Saint-Sébastien cave has developed below a marly ceiling (fig. 5); the Baume des Pierres (close to Gréoux-les-Bains) follows an open parting between thick limestone beds. In Charente, the extended mazes (Fosse Mobile Shaft, *etc.*) could be of the same origin.

In thick folded limestone, rising flow alternatively follows joints and bedding planes, 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 of smaller size: Adaouste, Tranchée de la Barque, and Pigette Caves (fig. 6). Where only a short part of the cave is accessible, or where passages are not penetrable, the presence of ceiling channels where water was rising could indicate a hypogenic origin (Boisson quarry; Thermes Cave at Digne-les-Bains). However, these ceiling channels must not be misinterpreted as paragenetic [Audra, 2006].

Many isolated hypogenic chambers are huge voids at the regional scale. The cupola-like chambers are fed by thermal slots (fig. 7). They develop just above the water table: the thermal flux favors moist air convection in a CO_2-rich atmosphere originating from strong degassing. Gradually the condensation-corrosion enlarges the void above the water table, eventually producing large isolated chambers [Audra *et al.*, 2002]. Geochemical modeling shows that such a volume can develop in a rather short time span, about 10000 years, even with a moderate pCO_2 and thermal gradient [Lismonde, 2003]. Bakhardenskaya in Turkmenistan is a huge chamber open to the surface, extending down to a thermo-sulfuric lake. In this example, condensation-corrosion is enhanced by sulfuric acid, which replaces limestone walls by gypsum crusts [Dublyansky, 1980]. From another viewpoint, Frumkin and Fischhendler [2005] assign the origin of such isolated chambers to phreatic convections, on the basis of observations in Atarot Cave in Israel.

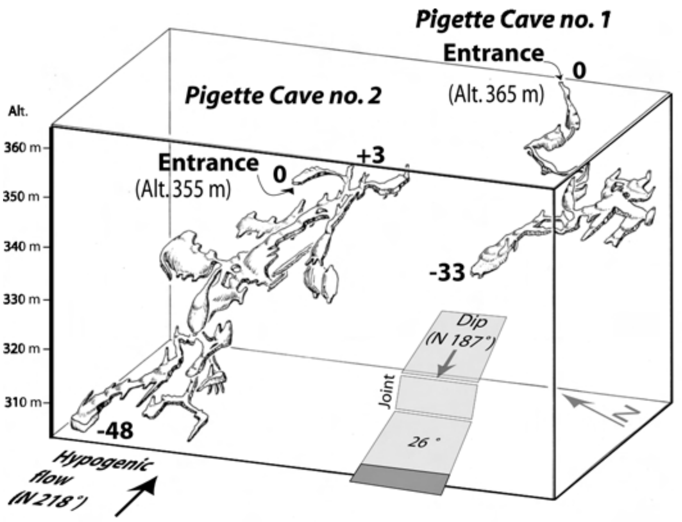

FIG. 6. – The Pigette Cave (Gréoux-les-Bains, Alpes-de-Haute-Provence) is a 3D maze. It developed in the shallow phreatic zone. Rising flow alternatively enlarged bedding planes and vertical joints, producing a staircase-like pattern.

FIG. 6. – *Les grottes de Pigette (Gréoux-les-Bains, Alpes de Haute-Provence) présentent un système développé sous le toit de la zone noyée par les remontées thermales, suivant les discontinuités structurales (pendage incliné, fractures verticales).*

SULFURIC ACID CAVES CONTAINING REPLACEMENT GYPSUM

Deep H_2S-rich waters can be aggressive with respect to limestone. At shallow depth, mixing with meteoric water allows oxidation to sulfuric acid (H_2SO_4) that corrodes the limestone. The strongest corrosion occurs above the water table, where sulfuric acid and thermal convection produce strong condensation-corrosion. Atmospheric corrosion produces gypsum after limestone, where the gypsum forms crusts on the cave walls [Egemeier, 1981]. Caves develop where atmospheric condensation-corrosion is possible, i.e. above the outlets for sulfide-rich water. Consequently, the main drain develops headward from the spring, while condensation domes above the sulfidic slots develop upward and may breach the surface (fig. 8) [Audra, 2007].

Due to the strong sulfuric acid corrosion, the flow produces a main drain with very low gradient (0.07% at Chat Cave). Minor changes in base level cause the flow to migrate laterally, to form incipient mazes [Audra, 2007].

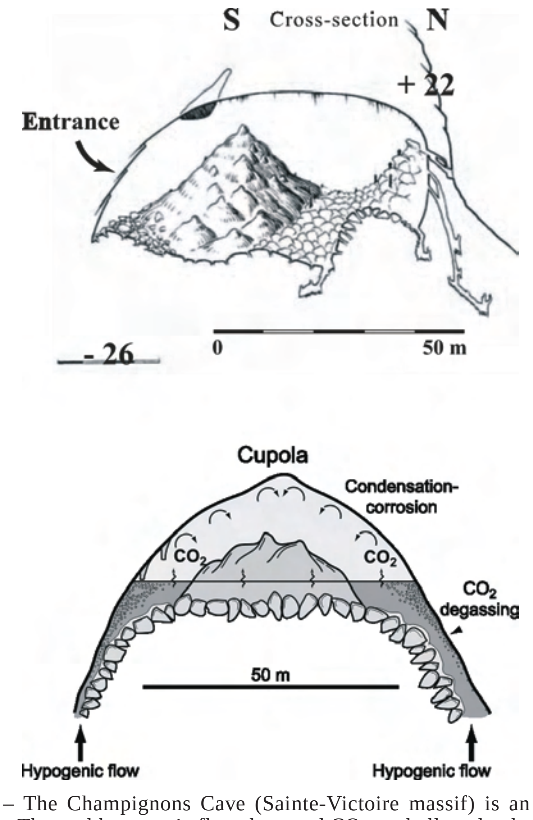

FIG. 7. – The Champignons Cave (Sainte-Victoire massif) is an isolated chamber. Thermal hypogenic flow degassed CO_2 at shallow depth. Thermal convection enhanced condensation-corrosion to develop a large isolated chamber more than 50 m wide, which tends toward a hemispherical shape. Simultaneously, massive calcite deposits occurred in the lake, which was supersaturated with calcite because of CO_2 degassing [Audra *et al.*, 2002; Lismonde, 2003].

FIG. 7. – *Dans la grotte des Champignons (Puyloubier, Bouches-du-Rhône), le flux hypogène thermal dégazait à proximité de la surface piézométrique, favorisant simultanément une corrosion dans les panaches thermaux et un dépôt de calcite dans le lac sursaturé par dégazage. Les convections thermiques dans l'atmosphère chargée en CO_2 favorisaient la condensation-corrosion et le développement d'une vaste salle-coupole de plus de 50 m de diamètre [Audra* et al.*, 2002 ; Lismonde, 2003].*

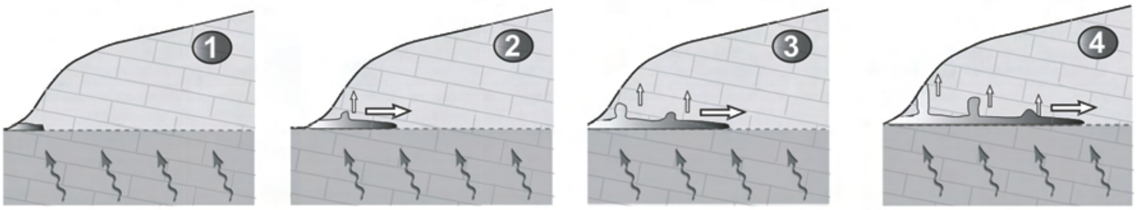

FIG. 8. – A water-table sulfuric acid cave. Headward evolution by condensation-corrosion along the water table, supplied by major sulfuric upwelling along a fracture. Simultaneously, hydrothermal conditions lift the hot air, condensation-corrosion occurs, bells and chimneys develop, and some finally break through to the surface. The white arrows indicate the direction of cave development (inspired by Villa Luz Cave, Mexico).
FIG. 8. – *Cavité sulfurique de surface piézométrique. Évolution régressive du conduit le long de la surface piézométrique, alimentée par des remontées sulfuriques le long d'une fracture. Simultanément, le thermalisme provoque des ascendances d'air chaud, de la condensation-corrosion, et la formation de cloches et cheminées pouvant déboucher en surface. Les flèches désignent la direction de développement des vides (inspiré de la grotte de Villa Luz, Tabasco, Mexique).*

Major base-level lowering makes successive horizontal cave levels. The clearest examples of water-table sulfuric caves are Villa Luz Cave (Mexico), Chat Cave (France), and Kane Caves (USA). The Frasassi Caves display cave levels that record past stages of base-level lowering [e. g. Galdenzi and Menichetti, 1995], whereas Villa Luz Cave displays a simpler pattern with a single level [e.g. Hose and Pisarowicz, 1999].

TABLE I. – Location and main characteristics of the most significant hypogenic caves in France.
TABL. I. – *Localisation et caractéristiques des principales cavités hypogènes en France.*

Cave	Commune	Département	Characteristics
Adaouste Cave	Jouques	Bouches-du-Rhône	3D thermal cave
Baravon Caves	Gras	Ardèche	Hydrothermal calcite spar (fluid inclusions 50-70 °C)
Baume des Pierres Cave	Quinson	Alpes-de-Haute-Provence	2D Maze
Baume Galinière Cave	Simiane-la-Rotonde	Alpes-de-Haute-Provence	Calcite spar, iron crusts
Boisson Quarry	Allègre-les-Fumades	Gard	Thermal ceiling channel
Caves	Viviers	Ardèche	Calcite spar
Chaire à Prêcher Geode	Oppedette,	Alpes-de-Haute-Provence	Calcite spar
Champignons Cave	Puyloubier	Bouches-du-Rhône	Isolated cupola chamber
Chat Cave	Daluis	Alpes-Maritimes	Sulfuric cave
Chevalley Shaft – Serpents Cave	Aix-les-Bains	Savoie	Active sulfuric caves
Col de la Cardonille Geodes	Saint-Bauzille-de-Putois	Hérault	Calcite spar
Denis Parisis Cave-System	Béthemont-la-Forêt	Val-d'Oise	Ludian gypsum
Font Estramar Spring	Salses	Pyrénées-Orientales	Thermal feeders, Mn
Fosse Mobile Shaft	Agris	Charente	Hypogenic (?) maze
Gourg de l'Antre Spring	Soulatgé	Aude	Thermal feeders in cold water
Grande Vernissière Mine	Durfort	Gard	Fluorite, baryte, smithsonite, galena
Iboussières Cave	Malataverne	Drôme	Fe microbial structure
Lagnes Mine-Cave	Lagnes	Vaucluse	Massive Fe
Leicasse Shaft	Saint-Maurice-Navacelles	Hérault	Hydrothermal calcite spar (fluid inclusions 50-70 °C)
Madeleine Cave	Villeneuve-lès-Maguelonne	Hérault	CO_2 degassing
Malacoste Quarry	Mirabeau	Vaucluse	Fe, Mn, Calcite spar
Mas d'En Caraman Spring	Paziols	Pyrénées-Orientales	Thermal spring (21,5 °C)
Mescla Cave	Malaucène	Alpes-Maritimes	Thermal feeders in cold water
Oilloki Mine-Cave	Sainte-Engrâce	Pyrénées-Atlantiques	Galena, Fe
Pigette Cave	Gréoux-les-Bains	Alpes-de-Haute-Provence	3D maze
Pont de la Caille Geodes	Cruseilles	Haute-Savoie	Calcite spar
Route du Razal Site	Vallon-Pont-d'Arc	Ardèche	Calcite spar
Saint-Sébastien Cave	Gréoux-les-Bains	Alpes-de-Haute-Provence	2D thermal maze, gypsum
Salaou Spring	Castellane	Alpes-de-Haute-Provence	Gypsum, sulfate-thermal (20 °C)
Salins Spring	Salins-les-Thermes	Savoie	Sulfuric giant shaft
Sorine Spring	Saint-Geniez	Alpes-de-Haute-Provence	Gypsum, sulfate-thermal (20 °C)
TGV Cave	Malataverne	Drôme	Fe microbial structure
Thermes Cave	Digne-les-Bains	Alpes-de-Haute-Provence	Thermal ceiling channel
Tranchée de la Barque Site	Jouques	Bouches-du-Rhône	Thermal ceiling channel
Vallon du Salut Spring	Bagnères-de-Bigorre	Hautes-Pyrénées	Thermal spring (17 °C)

In France, the Chevalley Shaft-Serpents Cave System (Aix-les-Bains, Savoy) is one of the rare active sulfuric acid caves, where upwardly dendritic cupolas develop by condensation-corrosion [Audra *et al.*, 2007]. The Chat Cave (Daluis, Alpes-Maritimes), even though no longer active, displays the most outstanding sulfuric acid features: replacement pockets at points of sulfuric acid corrosion, corrosion tables smoothed by sulfuric acid condensation, and condensation domes produced by corrosive convections [Audra, 2006].

CONCLUSION

"Classic" epigenic caves, the most numerous caves of all, develop downward by rapid flow whose aggressivity comes from biogenic acids. On the contrary, hypogenic caves develop along rising, slow-moving flows. Such flows are often but not systematically, thermal, highly mineralized, and low in oxygen. At shallow depth, cooling, mixing, change in redox condition, and degassing favor the deposition of metallic sulfur (Fe, Mn, Pb…) and calcite as spar linings. Microbial processes are also involved in both corrosion and deposition processes. Depending on the geologic setting and the type of flow, cave patterns display 3D mazes in the phreatic zone, 2D mazes where lithologic heterogeneity takes part, and giant phreatic shafts along main active faults. Above the water table, condensation-corrosion may produce caves when it is boosted by thermal convection and by degassing of H_2S and CO_2. Such an "atmospheric" (i.e. above the water table) speleogenesis is unusual, involving air convections and moisture instead of concentrated flowing water.

Hypogenic caves are located mainly along active faults, often discharge along impervious covers, and consequently at the boundaries of karst aquifer outcrops (fig. 1). Hypogenic caves are generally in the minority, but they can be in the majority where epigenic caves are rare (e.g., Middle Durance Valley). Past hypogenic activity is often marked by the presence of nearby still-active thermo-mineral springs. The criteria for identification and the hypogenic speleogenesis model [Klimchouk, 2007] highlight an increasing number of hypogenic caves that have been identified. Even though in the minority, these hypogenic caves are characterized by features rarely present in epigenic caves, such as MVT ore deposits, rare minerals or development of huge crystals, and specific cave features [Audra, 2006]. Four of the five longest cave systems in the world (surveyed over 200 km) are hypogenic (Jewel Cave; Optimisticeskaja; Wind Cave; Lechuguilla Cave), which clearly shows that hypogenic speleogenesis is not an exotic process.

Finally, hypogenic speleogenesis can help to better understand the geometry and the origin of economic deposits such as MVT ores [Piccini *et al.*, 2007], the distribution of porosity in basins where hydrocarbons may be stored [Hill, 1990], and the distribution of subsidence hazards [Klimchouk, 2005] (tabl. I).

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