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THE ROLE OF CONDENSATION-CORROSION IN THERMAL SPELEOGENESIS: STUDY OF A HYPOGENIC SULFIDIC CAVE IN AIX-LES-BAINS, FRANCE

VLOGA KONDENZNE KOROZIJE V TERMALNI SPELEOGENEZI: ŠTUDIJA HIPOGENE SULFIDNE JAME V AIX-LES-BAINS, FRANCIJA

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Philippe Audra, Fabien Hoblea, Jean-Yves Bigot & Jean-Claude Nobecourt: The role of condensation corrosion in thermal speleogenesis. Study of a hypogenic sulfidic cave in Aix-les-Bains, France

Condensation-corrosion is an active speleogenetical process in thermal caves where high thermal gradient drives air convection. Wall retreat rates are greater than in meteoric caves. Conversely, evaporation produces depositional processes by replacement of limestone by gypsum and by aerosol decantation leading to the formation of popcorns. The Chevalley Aven belongs to Aix-les-Bains thermal-sulfidic cave system. Condensation occurs at the contact of cool walls of large spheres; conversely, evaporation occurs at the output of the narrow passages where the air sinks down from the upper sphere. A weathered layer and biofilms are present where slow condensation occurs. Corrosion distribution varies according to thermal rock conductivity and causes the sphere to develop upwards, laterally, and divergent. This morphodynamic pattern favors the development of stacked spheres, isolated by narrow necks, and arranged in a bush-like pattern. This development is clearly active in the vadose zone above the thermal water table. We propose that some avens above water table hypogenic caves, like Villa Luz (Mexico), may be of condensation-corrosion origin instead of phreatic. Future development will collect physical and chemical data to calculate the condensation-corrosion budget and assess its role in cave development.

Key words: condensation-corrosion, thermal caves, sphere genesis, air convection, Aix-les-Bains thermal-sulfidic cave system, Chevalley Aven, France.

Izvleček UDK 551.435.8:551.3.053(44)

Philippe Audra, Fabien Hoblea, Jean-Yves Bigot & Jean-Claude Nobecourt: Vloga kondenzne korozije v termalni speleogenezi: študija hipogene sulfidne jame v Aix-les-Bains, Francija

Kondenzacijska korozija predstavlja aktivni speleogenetski proces v termalnih jamah, kjer kroženje zraka povzroča visok termalni gradient. Raztapljanje jamskih sten in stropa je v takšnih jamah večje, kot v vodnih jamah. Izhlapevanje povzroča tudi odlaganje, ki se vrši v obliki nadomeščanja apnenca s sadro in z usedanjem aerosola, kar vodi v tvorbo značilnih morfoloških oblik (popcorn). Brezno Chevalley sodi k termalno-sulfidnemu jamskemu sistemu Aix-les-Bains. Kondenzacija deluje na stiku toplega zraka s hladnimi jamskimi stenami, do izhlapevanja pa prihaja na izhodu ozkih jamskih prehodov. Prepereli sloji kamnine in prevleke biološkega izvora se pojavljajo na mestih, kjer je počasna kondenzacija. Porazdelitev korozijskega delovanja je odvisna od termalne prevodnosti kamnine in povzroča nastanek stropnih, stenskih in divergentnih krožnih oblik. Takšni morfodinamični vzorci omogočajo oblikovanje raznih kupol, ločenih z ožinami in vejasto razvrščenimi. Takšne morfološke oblike so značilne za vadozno cono. Nekatere zožitve nad vodno gladino v hipogenih jamah (npr. Villa Luz v Mehiki) so kondenzacijsko-korozijskega in ne freatičnega nastanka. Prihodnje raziskave fizikalno-kemičnih lastnosti bodo pokazale pomen vpliva kondenzacijsko-korozijskih procesov za razvoj jam.

Ključne besede: kondenzacijska korozija, termalne jame, sphere genesis, zračna cirkulacija, Aix-les-Bains thermalno-sulfidni jamski sistem, brezno Chevalley, Francija.

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INTRODUCTION

Convection and condensation-corrosion are generally considered as minor processes for cave development, producing only etching or smoothing of flow-induced features and conduits. However, some authors have put forward the importance of condensation-corrosion in specific conditions. Müller (1974) was among the first to relate spherical cupolas (called spheres in this paper) to air convection above thermal lakes, whereas Rudnicki (1978) had attributed them mainly to phreatic convection. Sphere development by condensation has been simulated numerically, focusing on the role of pressure changes connected to flooding in the epiphreatic zone (Mucke & al., 1983; Lismonde, 2000) or cooling of rising air above thermal lakes (Cigna & Forti, 1986; Szunyogh, 1990; Lismonde, 2003). Dublyansky & Dublyansky (2000) updated a review of worldwide contributions about condensation. Finally, Dreybrodt & al. (2005) recently performed a comprehensive modeling of this process within various boundary conditions. As a rule, most of these authors stated the efficiency of convection-condensation on speleogenesis only in specific conditions that are not widespread in meteoric caves, but more frequent in hypogenic caves such as thermal caves or caves with high carbonic or sulfidic atmospheres.

The study of Chevalley and Serpents Caves in Aix-les-Bains, France, clearly shows the importance of this process which is enhanced by sulfidic corrosion. Aix-les-Bains Caves, located in the Northern French Prealpes in Savoy, are still active and provide an outstanding picture of convection processes and related corrosion and deposition phenomena, particularly with gypsum replacement.

This paper presents the first results of a study of the morphology of the cave, the distribution of the deposits, and the distribution of condensation and evaporation zones, in order to make an assessment of the role of condensation-corrosion role in cave development. A second study is being undertaken to calculate the condensation-corrosion budget through the collection of physical and chemical data. The first part of this paper summarizes current knowledge about condensation-corrosion and the development of spheres. The second part examines condensation-corrosion and the resulting morphologies and deposits in Chevalley and Serpents Caves. Finally, we will discuss the respective role of the different speleogenetical processes.

CONDENSATION-CORROSION AND THE DEVELOPMENT OF SPHERES

SPELEOGENESIS BY SULFUR RELEASE AND SULFIDIC CAVES

Hypogenic caves formed from sulfur release producing sulfuric acid and limestone corrosion with replacement by gypsum were only recently identified (Morehouse, 1968; Egemeier, 1981). They have been particularly studied in the Guadalupe Mountains, USA (Hill, 1987), in the Frasassi Caves, Italy (Galdenzi & Menichetti, 1990; Forti, 1996), and in France (Audra & al., 2002; Audra & Hofmann, 2004; Audra & Häuselmann, 2004; Audra, 2005). The active participation of microbial processes was identified in Movile Cave, Romania (Sarbu & al., 1996), and in Villa Luz Cave, Mexico (Hose & Pisarowicz, 1999).

CONVECTION ABOVE A THERMAL LAKE

Air convection occurs when a thermal gradient exists between a lake heated by thermal flow and the upper part of the cave which is cooler. Evaporation from the thermal lake produces warm-moist air that rises, while cooler air sinks. Since the thermal gradient is maintained by heat transfer through the cooler rock mass toward the surface (Lismonde, 2003), permanent convection cells exchange heat and water between the different parts of the cave. The thermal flux is independent of the distance to the surface (Dreybrodt & al., 2005), but high gradients may be present close to topographic surfaces where meteoric seepage can cool the cave roof.

CONDENSATION ON COOL WALLS

Warm-moist rising air cools at the contact of the colder walls and ceilings producing condensation. Condensation, in turn, releases heat at the wall surface that lowers the thermal gradient itself (Dreybrodt & al., 2005). For vapor-saturated air, the condensation rate depends on the thermal gradient. Thus, maximal condensation rates appear when hot thermal water is present within a cave close to the surface, at the ceiling of the upper passages, and more generally in chambers which are relatively isolated by narrow passages from lowermost warmer places.

CORROSION OF THE ROCK WALLS

When condensation water quickly reaches equilibrium with carbon dioxide-rich cave atmosphere and residence time of contact between aggressive condensation water and limestone wall is sufficient, corrosion can occur (Dreybrodt & al., 2005). Such weathering of walls has been demonstrated in Movile Cave, Romania, where soft residue displays C-light isotopic ratios. This depleted carbon results from the solution of biogenic carbon dioxide (Sarbu & Lascu, 1997). Modeling of wall retreat within thermal conditions shows rates about one order of magnitude above those of meteoric karst, ranging from 2 to 20 cm / ka (Mucke & al., 1983; Cigna & Forti, 1986; Dreybrodt & al., 2005), thus allowing the possibility of cave development in a "reasonable" time-span. Modeling has also shown that in "normal" meteoric caves condensation-corrosion does not reach sufficient rates to be considered as a main speleogenetic process.

Consequently, condensation-corrosion represents a main process only in the following cases: 1/ when warm-moist air condenses in the entrance of a cold cave in summer; 2/ above thermal lakes where the thermal gradient is high; 3/ where CO_2 or H_2S-rich atmosphere gives a high aggressivity to the condensed water, even if this parameter is considerably less important than the condensation itself (Szunyogh, 1990). Condition 2 may combine with 3.

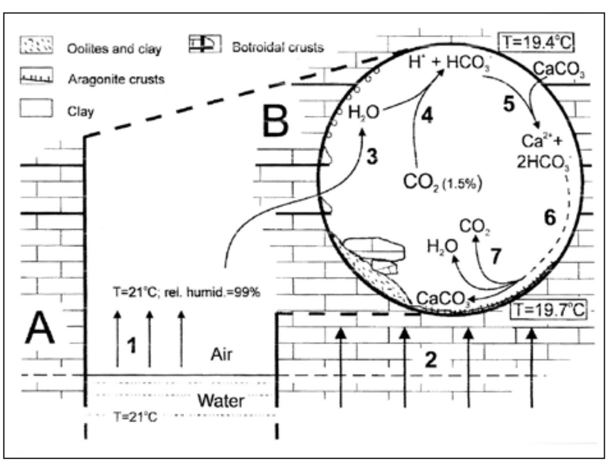

Fig. 1: Schematic profile view of Movile Cave (Sarbu & Lascu, 1997).

A. Lower passage; B. Upper dry passage

1. Evaporation of water at the surface of the lake

2. Thermal flux through the bedrock

3. Condensation of water vapor onto the colder cave walls and ceiling in the upper cave passage

4. Dissolution of CO_2 into the condensate and formation of carbonic acid.

5. Reaction between carbonic acid and the carbonate bedrock with formation of bicarbonate

6. Transport of bicarbonate along the walls

7. Precipitation of aragonite crusts and dissociation of bicarbonate

DEPOSITIONAL PROCESSES

Several types of depositional processes may occur separately or in combination: 1/ by evaporation of the condensed water at the base of walls where air is warmer; 2/ by replacement of limestone by gypsum when H_2S is released from thermal lakes; 3/ by decantation of aerosols building popcorns in the lowest part of passages (Dublyansky & Pashenko, 1997). Fig. 1 resumes the steps involved in condensation-corrosion.

SPHERE GENESIS BY CONVECTION AND CONDENSATION

The term sphere roughly corresponds to hemispheric or semi-spherical holes located in the ceiling. Spheres may develop by different processes, involving convection and sometimes additionally condensation: 1/ by pressure rise and condensation after flooding in the epiphreatic zone (Mucke & al., 1983; Lismonde, 1999); 2/ by mixing-corrosion in the phreatic zone (Bögli, 1964, 1978); 3/ by convection of water in the phreatic zone (Rudnicki, 1978); 4/ by air convection above thermal lakes (Müller, 1974; Szunyogh, 1990). Except for (1), these processes correspond to slow moving fluid (water or gas) and convection more or less directly connected to uprising water, conditions encountered more frequently in hypogenic cave systems (Osborne, 2004). We will initially consider step (4) alone, that is air convection above thermal lakes making almost perfect spheres.

The thermal conductivity of rock produces higher thermal gradients at the top of ceiling holes (Cigna & Forti, 1986; Szunyogh, 1990), thereby creating the great-

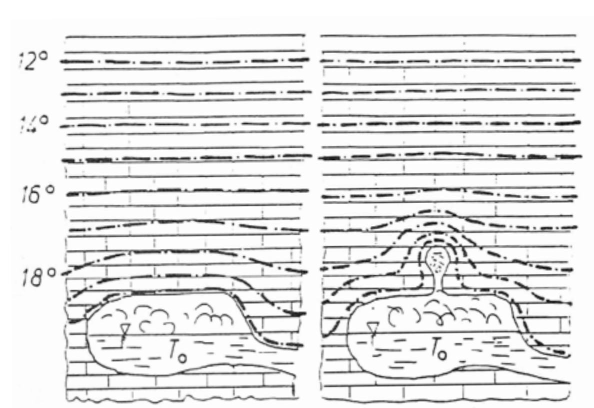

Fig. 2: Development of a sphere in the ceiling, where thermal gradient is the highest, by condensation-corrosion (Szunyogh, 1982).

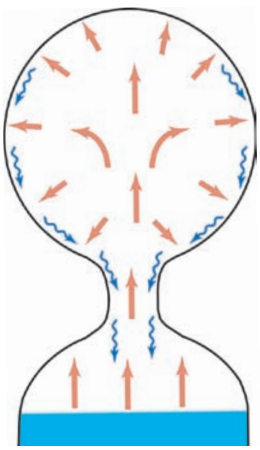

Fig. 3: Condensation occurs at the ceiling. Wall benefits from both condensation plus seepage. Evaporation plus saturated runoff occur at the bottom, thus preventing the expansion of the neck (from Szunyogh, 1990, redrawn).

est condensation and thus strongest corrosion: the sphere continues developing upward, where condensation is at the maximum, and laterally, where seepage occurs, since it is connected to the lower conduit by a narrow neck (Fig. 2, 3). Modeling shows that irregularity of the ceiling produces a new sphere development that fits within the previous one (Szunyogh, 1990). 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 (Fig. 4). Such a process explains the development of stacked up spheres arranged in a bush-like structure, as found in the Sátorkö-puszta Cave, Hungary (Fig. 5). The smooth ceiling results from the regular corrosion by a thin film of condensed water rather than discrete drips (Mucke & al., 1983); slow runoff of condensed water at the base of the sphere makes corrosion furrows, and calcite deposits as popcorn at the outlet of the sphere after evaporation (Cigna & Forti, 1986).

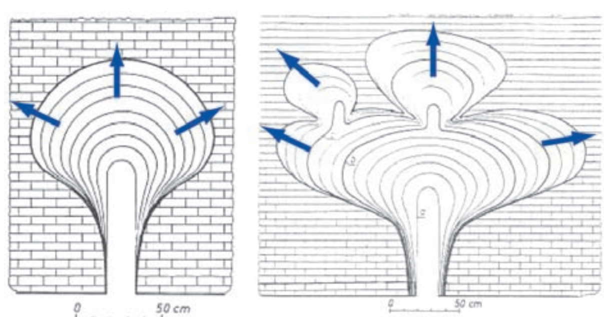

Fig. 4: Theoretical development of simple and complex spheres. Simple sphere develops upwards and laterally (left); an irregularity in the ceiling produces a new sphere development that fits within the previous one (right); two neighboring spheres diverge toward the greatest zone of heat transfer (right) (after Szunyogh, 1990, modified).

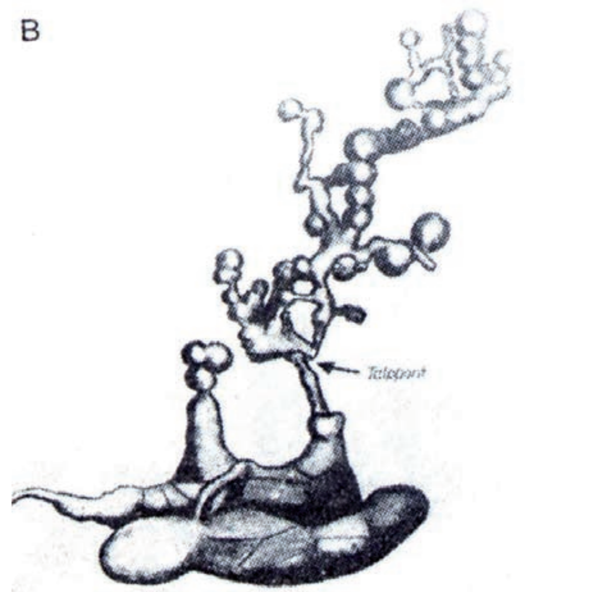

Fig. 5: 3D view of Sátorkö-puszta Cave, the bush-like pattern cave type, made of stacked up spheres (Müller & Sarvary, 1977).

AIX-LES-BAINS THERMAL-SULFIDIC CAVES (CHEVALLEY AVEN AND SERPENTS CAVE)

BUSH-LIKE SPHERES AND WATER TABLE PATTERN

Aix-les-Bains is a thermal resort in Savoy, located between the Bourget Lake shore and the foot of the Bauges massif in Northern French Prealps. Chevalley Aven and Serpents Cave belong to the same system (Fig. 6) (Hobléa, 1999; Gallino 2006). Chevalley Aven is made of stacked spheres arranged in a bush-like pattern (Sátorkö-puszta Cave type). Chevalley Aven rises from the thermal water table and does not break through the surface, and the present entrance is artificial. Serpents Cave is a water table cave, with spheres and avens at the ceiling. The active Alum thermal spring flows into the cave at the upstream end. The gallery is gently sloping downstream and is plugged at the end with till.

A SULFIDIC AND THERMAL UPWELLING FLOW

The discharge of the Alum spring ranges from 8 to 42 Ls^{-1}; the temperature oscillates seasonally between 33.5 and

46.6 °C on account of some mixing with meteoric component (Muralt, 2003). Water has a high concentration of calcium, sulfate, and secondary sodium, magnesium, and silica (Tab. 1). It degasses some H_2S and CO_2 and brings up microbial soft flakes. The temperature, high silica and salt content, and the presence of trace elements suggest a deep artesian flowpath (about 2000 m), confined under the Bourget Lake syncline, where Triassic evaporites are leached (Carfantan & al., 1998).

H_2S degassing seems less strong in Chevalley Aven, probably due to the standing water. On the contrary, the water flowing turbulently out from the Alum spring produces a stronger degassing, as is evidenced by the characteristic rotten egg smell, together with a thick coating of replacement gypsum and native sulfur covering walls around the spring pool (Audra *et. al.,* 2007). Martel (1935) was the first to identify the sulfidic origin of Serpents Cave.

THE CONVECTION CELLS IN CHEVALLEY AVEN (Fig. 7)

The aerial thermal gradient, between the pool at about 32 to 34 °C and the top of Chevalley Aven at 26 °C ranges from 0.2 to 0.3 °C/m, so, air convection cells occur. The distribution of air loops is controlled by the presence in the main passage of a cool dripping originating from both condensation and seepage. The cool airflow sinks into the main passage whereas the warm airflow rises from the thermal pool through lateral passages. The highest airflow velocity is about 15 cm/s in the narrow passages. Before 1996, water seepage originated from natural rainwater percolation through the soil. Since the building of the thermal Spa, seepage originates from leakage from the thermal pool. We present here the observations made in the small vent connecting the Lower Gallery and the Aixinoise gallery (Fig. 7). Preliminary measures were done the 10/26/2006 using a heated wire anemometer (Testo V1) which includes a digital thermometer. Device accuracy is 1 cm/s for air velocity and 0.1 °C for air temperature.

Physico-chemistry	***Values***	***Reference, if other than Muralt (2003)***
Temperature	33,5 – 46,6 °C	
Discharge	8 - 42 $L.s^{-1}$	
Conductivity	576 – 691 $\mu S.cm^{-1}$	Hobléa, 1999
pH	6,5	Hobléa, 1999
TDS	496 $mg.L^{-1}$	
$HCO3^-$	262 $mg.L^{-1}$	
$SO4^{--}$	60 - 230 $mg.L^{-1}$	
Cl^-	15 - 30 $mg.L^{-1}$	
Na^+	20 - 40 $mg.L^{-1}$	
Ca^{++}	100 - 150 $mg.L^{-1}$	
K^+	3 - 6 $mg.L^{-1}$	
Mg^{++}	10 - 25 $mg.L^{-1}$	
SiO_2	22 - 26 $mg.L^{-1}$	
H_2S	5 $mg.L^{-1}$	Iundt & al., 1987
Trace elements	Al, Fe, Mn, Pb, B, Sr, Sn, Sb, Ba, Li	Iundt & al., 1987

Tab. 1: Main physical and chemical data from the Alum spring, Serpents Cave, Aix-les-Bains (main data after Muralt, 2003).

STUDY OF CONDENSATION-CORROSION AND EVAPORATION-DEPOSITION PROCESSES OCCURRING INTO THE VENT (Fig. 8)

This vent is a narrow inaccessible passage about 3 m long. Temperature is 32.7 °C at the base, and 28.4 °C at the upper mouth. The air flow velocity is very low, about 1 cm/s or less. Warm air rises up through the vent and some sinking secondary loops appear at the contact of the cooler lateral walls of the central sphere. The accumulation of condensation produces runoff as a film along the sphere walls and dripping at the tip of downfacing pendants. Airflow is considered close to saturation regarding moisture. Consequently, cooling from rising air produces condensation in the narrow fissures, at

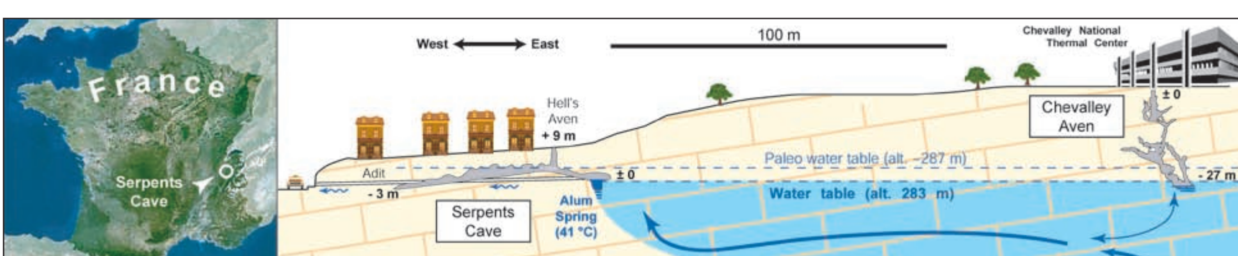

Fig. 6: Outline of Chevalley Aven and Serpents Cave, cross-section view (survey SC Savoy, EDYTEM). Serpents Cave is a water table cave, with spheres and avens at the ceiling. The active Alum thermal spring flows into the cave at the upstream end. Chevalley Aven is made of stacked up spheres arranged in a bush-like pattern and reaches the thermal water table. The "paleowater table" corresponds to the water level before the digging of the adit in 1859.

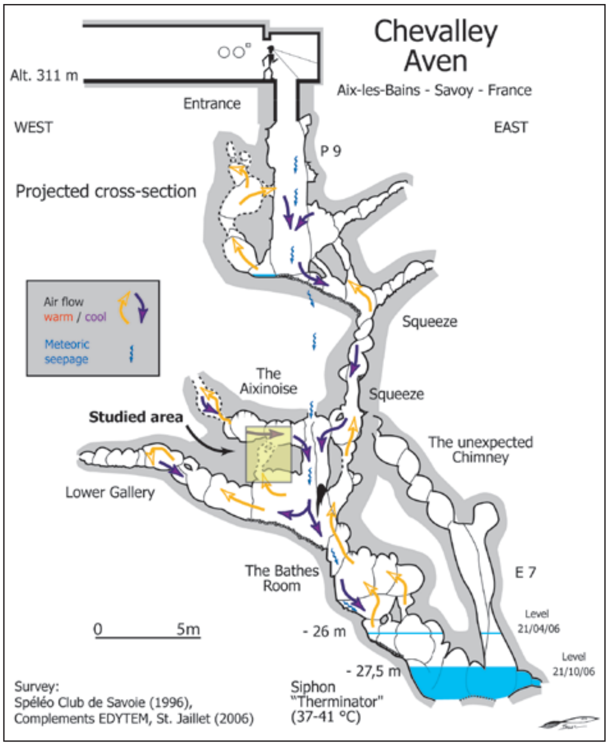

Fig. 7: Chevalley Aven cross-section. Air convection is shown, together with present water seepage originating from leakage of the thermal swimming pool located above. Before the building of the new thermal center in 1996, this water seepage was provided by natural rainwater infiltration through the soil.

the ceiling, and on the walls of the central sphere which is covered with condensation drips; conversely, cool air that sinks from an uppermost chimney warms up and produces evaporation at the upper mouth of the vent, which is dry. At the upper part of the lowermost neck evaporation also occurs from secondary convection cells in the central sphere.

The corrosion rate depends on condensation; thus corrosion occurs mainly on the ceiling and walls of the sphere that is gradually enlarged. The sphere ceiling and the upper part of the walls display a regular and smooth cupola shape made of a weathered limestone layer, 2-3 cm in thickness, where boxwork veins protrude. The condensation film dissolves the limestone micrite cement, dissociates the sparite grains, and progresses deepwards into the host rock as an incomplete weathering front (Zupan-Hajna, 2003). Along the walls of the sphere, the runoff from the accumulation of condensation dissolves the walls; consequently, no weathered material subsists over the lower rockwalls. At the base of the sphere, the condensation flow becomes saturated, and calcite deposits as small transparent crystals in a soft and wet paste.

Sulfate produced by replacement corrosion on the limestone wall is also washed down by condensation runoff. This process has also been noticed in Frasassi (Cigna & Forti, 1986). Runoff arriving at the base of the sphere becomes saturated with gypsum. Evaporation onto the "calcite grains wet paste" causes microcrystalline gypsum to deposit in a thin crust. Dripping from the top of the sphere may re-dissolve the gypsum that re-deposits downward into the narrow passage as gypsum flowstones, stalactites and columns made of massive gypsum crystals.

Biofilms coat most of walls, except: where intense condensation or runoff washes the walls; or where evaporation prevents the microbial development that needs permanent moisture.

Evaporation dries up the upper lip of the vent. Water is attracted by capillarity toward this dry zone that maintains a continuous recharge of dissolved species of carbonate. The evaporation allows calcite precipitation as a rim, similar to a small drapery, shaped by both airflow and evaporation (Fig. 9). Such cave features are characteristic of caves having a high thermal gradient and develop at the upper mouth of chimneys connecting cave levels where convection airflow cells occur. They may develop in the following situations:

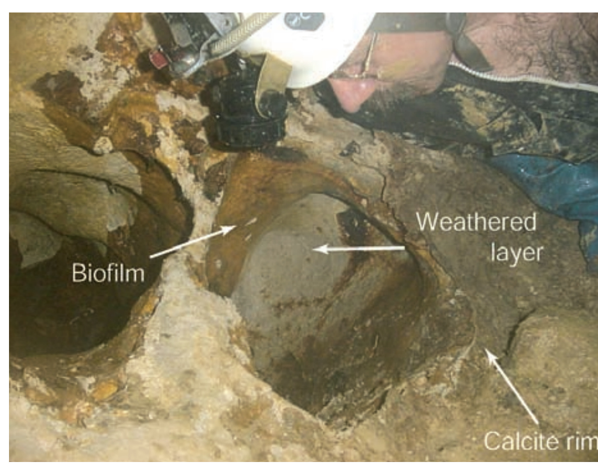

Fig. 9: Twin upper vents at the bottom of the Aixinoise gallery (photo. Ph. Audra).

1- in avens above a thermal water table located at depth, such as József-Hegy barlang, Budapest (auth. obs.);

2- where impervious layers covering karst prevent meteoric seepage that may homogenize temperatures throughout the cave profile (Wind Cave, Black Hills);

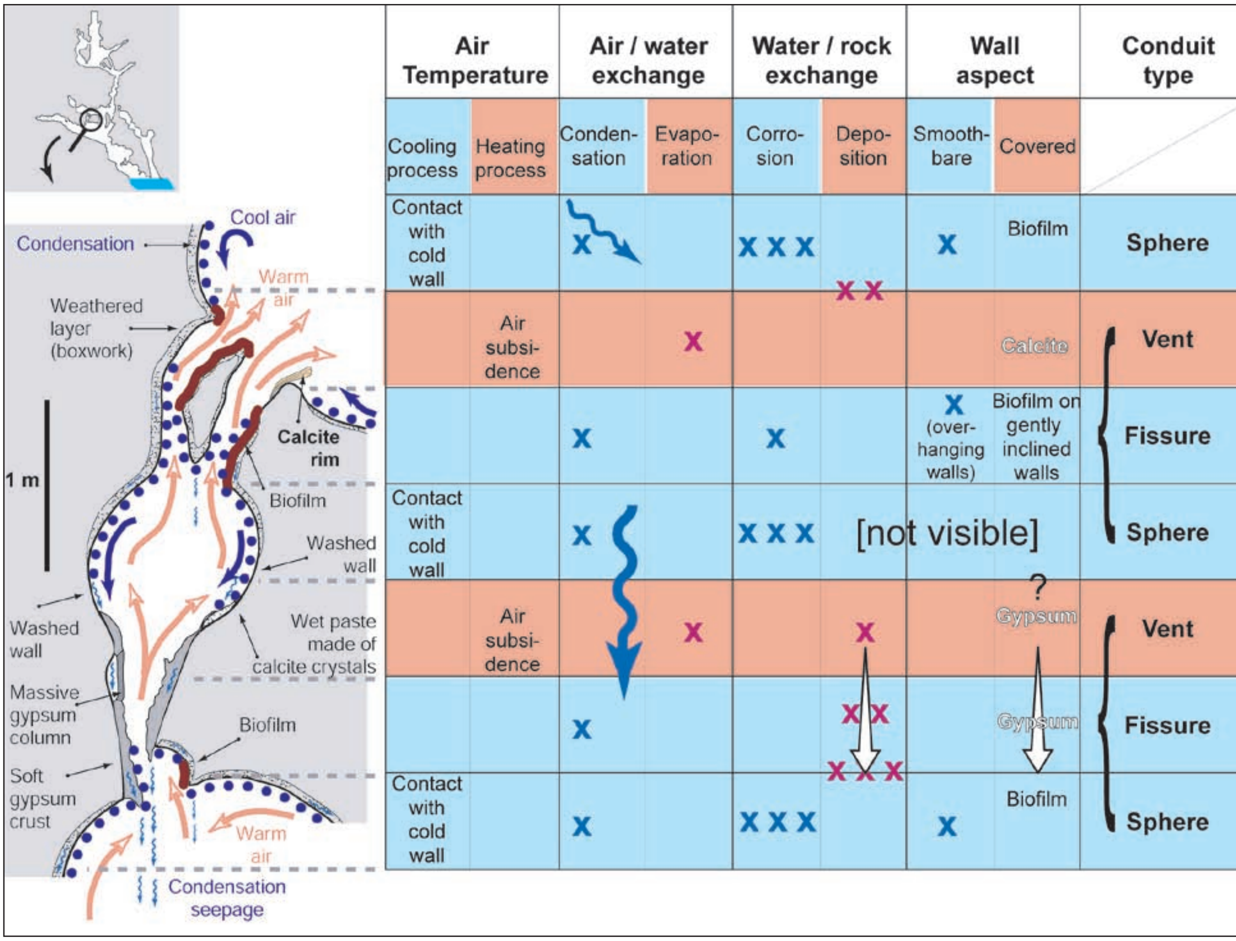

Fig. 8: Overview of the condensation-corrosion and evaporation-deposition processes. See text for details.

3- in arid areas for the same reason (Endless Cave, Guadalupe Mountains; see photography in Hill & Forti, 1997, p. 91);

4- in tropical caves where strong humidity and temperature gradients may exist between active galleries fed by surface seepage and galleries where strong airflow between entrances dries walls (NT2 Cave System, Kammouan, Laos; auth. obs.)

THE VENT, A CAVE FEATURE COMBINING CONDENSATION / EVAPORATION PLUS CORROSION / DEPOSITION PROCESSES

Figure 8 shows that the morphological setting strongly influences the distribution of processes.

- The upper mouth of the vent opens above the bottom of the uppermost sphere: the condensation water of the uppermost sphere flows away in another direction. Consequently, the vent collects its own condensation only that becomes visible in the lowest part of the narrow where clear surfaces covered with a weathered layer are visible.

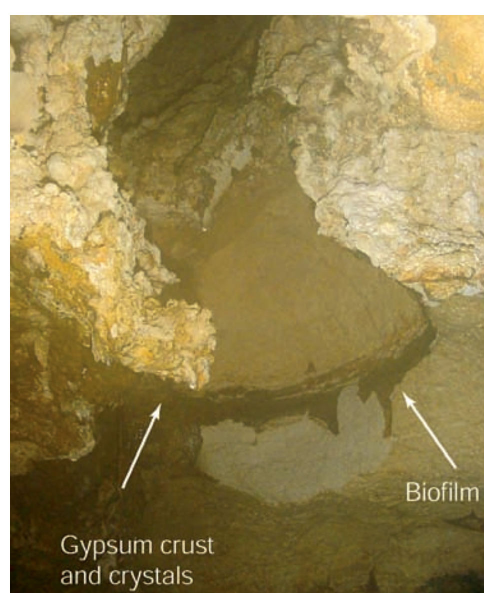

Fig. 10: The vent viewed from below, in the Lower Gallery; width of the vent is about 20 cm (photo. Ph. Audra).

- The lowermost vent located below the central sphere acts as a funnel that collects condensation from the upper narrow, from the central sphere that is the main runoff provider, and from its own condensation occurring in the lowermost part. Consequently, condensation runoff is important. Thus, by an overtopping effect, condensation runoff transfers the processes normally occurring at the base of the central sphere downwards. Instead of evaporating slowly, condensation water with high sulfate content flows downward into the narrow where it finally evaporates and where it deposits secondary gypsum as speleothems made of massive crystals. These gypsum deposits develop downward till they arrive at the ceiling of the lowermost sphere, where condensation and corrosion are predominant (Fig. 10).

Thus, a calcite rim may line the upper mouth of a vent if it is located above the drainage point of the upper sphere; on the contrary, condensation runoff washes and transports dissolved minerals downwards, to the lower narrow.

DISCUSSION

A POSITIVE FEEDBACK DEVELOPS SPHERES IN BUSH PATTERN

The distribution of corrosion and deposition processes produces a morphodynamic evolution according to the size of the conduits:

- spheres, where condensation-corrosion is high, evolve faster and tend to enlarge;

- narrow passages evolve slowly due to the small amount of condensed water collected, by neutralization of the condensation runoff after some distance, or evaporation.

Thus, a positive feedback tends to enlarge the wider places that evolve to form a spherical shape, whereas narrows remain small. Such a morphodynamic tends towards the development of stacked up spheres arranged in a bush-like pattern that are isolated by narrow necks.

THE ORIGIN OF SPHERES IN BUSH PATTERN REMAINS ENIGMATIC

The accurate observation of condensation-corrosion and evaporation-deposition processes clearly demonstrates that aerologic convections tend to exaggerate the difference in size of the voids located in the vadose zone just above thermal water table, and finally may develop as spheres in bush pattern and avens.

However, the origin of the Chevalley Aven is still obscure:

- did it develop exclusively from this aerologic convection process by hollowing into massive rock?

- did an older phreatic lift exist, that was drained by base level lowering and which evolved afterwards under aerologic conditions? And in this case, could a phreatic origin have initiated the development of the spheres? Flooding from meteoric invasions is also evoked as a contribution to the aven genesis, which would have enhanced mixing-corrosion processes typical of "transitional karst" (Hobléa, 1999; Dublyansky, 1997).

If the origin of the proto-cave is still under debate, we propose that a major part of the cave volume, if not the entire cave, could develop under aerologic conditions involving condensation-corrosion by a progressive upward propagation of voids into the rock mass which finally produces spheres in bush pattern. Similarly, in Movile Cave, condensation-corrosion is considered to be the main process of current wall retreat for air-filled passages above the water table (Sarbu & Lascu, 1997).

IMPLICATION FOR THE UNDERSTANDING OF HYPOGENIC WATER TABLE CAVES (VILLA LUZ, SERPENTS CAVE)

The Villa Luz Cave (Tabasco, Mexico) is similar to Serpents Cave, since it has an active water table cave with sulfidic springs upstream. Numerous avens are present, some being blind, some having broken through the surface as skylights. These avens are considered as phreatic lifts (due to their spectacular scallops showing rising flow) older than the drainage of the cave and the development of the main gallery (Hose & Pisarowicz, 1999). However, Villa Luz is a typical water table cave, clearly connected to the bottom of a small local valley and displaying a low gradient free surface flow. The avens starting from this water table gallery and developing upward cannot be older than the gallery itself. Consequently, they must have developed simultaneously to the main water table gallery (or later), thus not in phreatic conditions. The "phreatic scallops" that have been taken as indicators of upflowing, in fact would result from corrosive convection in the warm sulfidic atmosphere. Such airflow would produce features very similar to the scallops. Some of the avens still contain huge masses of replacement gypsum made of the accumulation of gypsum crust detached from walls. Other avens have breached through the surface, allowing the meteoric infiltration to wash away the gypsum deposits (Palmer, 2003).

In Serpents Cave, the Hell's Aven, which is the natural entrance, probably has a similar origin, that is to say a breakthrough surface of an aven made by corrosive "air" convections. However, and contrary to Villa Luz, the Hell's Aven is located just above the Alum spring (fig. 6); in this case, there remains the possibility that the aven could be an older phreatic lift drained after a base level lowering (Hobléa, 1999).

CONCLUSION

Observation of condensation and evaporation areas, corrosional morphologies, and of the distribution of the deposits have shown the strong relationship between condensation and corrosion, and conversely between evaporation and deposition. Moreover, the distribution of the condensation and evaporation processes strongly depends on the morphology of the cave. Condensation-corrosion tends to enlarge the largest voids, leading finally to a pattern of stacked spheres. These first conclusions, based on the study of cave features, indicate the possibility of speleogenesis mainly through condensation-corrosion. This hypothesis is currently under investigation. We are collecting data (temperature, airflow speed, pCO_2 and pH_2S, chemistry of condensate water), in order to calculate a budget of condensation rates and corrosion volumes which will be compared to the cave dimensions.

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