HYPOGENE SPELEOGENESIS AND SPELEOTHEMS OF SIMA DE LA HIGUERA CAVE (MURCIA, SOUTH-EASTERN SPAIN)

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Sima de la Higuera Cave (Pliego, south-eastern Spain) has been recently adapted for speleological use. Nevertheless, knowledge of the hypogenic origin of this cavity is still quite limited. The peculiar genetic mechanisms could provide added value if the cave is exploited for speleotourism. By studying geomorphological features and speleothem characteristics, it has been possible to deduce the predominant speleogenetic mechanism (whether hypogenic or epigenic) that controlled the evolution of this cave. The hypogenic mechanism that gave rise to this cavity was associated with upflow of CO_2-rich hydrothermal fluid from depth, and was unconnected to meteoric water seepage. In this paper we describe some of the geomorphological evidence and unusual speleothems in Sima de la Higuera Cave. Large scallops are found on the upper level (-74 m); these are related to the mechanism of hypogenic speleogenesis and generally indicate the direction of ascending flow. There are also corrosion crusts made of micritic calcite. In addition, bubble trails related to bubbles of rising CO_2 have been identified. Centimetric calcite spar speleothems frequently fill fractures in the host rock. Other typical hypogenic speleothems occur in this cave, including calcite raft cones, folia, cave clouds, tower coral and calcite raft deposits, all suggesting the influence of thermal water during the cave's formation. Furthermore, the first reported occurrence of calcite raft double-tower cones has been described in this cave; their origin is linked to water table oscillations in Paradise Chamber (-82 m). At the deepest level (-110 m), Mn-Fe oxyhydroxides occur as a black coating totally covering the cave walls, usually over subaerial "boxwork" formations. The wide variety of speleothems unconnected to meteoric water seepage make Sima de la Higuera Cave one of the most unusual hypogenic caves in Spain.

1. Introduction

Seepage of meteoric water in karstic terrains is the most common mechanism for cave development. However, besides this kind of cavity (epigenic caves), there is another type of genesis linked to rising hydrothermal fluids, usually rich in dissolved CO_2 and/or H_2S. These hypogenic caves form as a result of circulation of thermal water, usually from depth, and are unconnected with superficial flow (Palmer 2011). The term "hypogenic" does not refer specifically to extremely deep caves but rather to the origin of the fluids responsible for these caves' development (Klimchouk 2009). This kind of system is represented by around 5–10% of the cavities worldwide (Forti 1996; Forti et al. 2002).

Geomorphological features and specific speleothems are the most useful tools for identifying whether the origin of a cave was hypogenic or epigenic (Audra et al. 2002). The morphologies generated by hypogene mechanisms depend on the characteristics of the host rock, the temperature at which dissolution occurs, and the nature of the gases in solution. For instance, H_2S-rich thermal water gives rise to acid attack that is more efficient than corrosion produced exclusively by CO_2 (Forti et al. 2002). Furthermore, in H_2S-rich systems, the water-rock interaction frequently results in gypsum precipitation (Palmer and Palmer, 2012).

Other morphological features typical of hypogenic conditions are bubble trails, bell-shaped condensation-corrosion domes, scallops and widespread corrosion pockets (Forti 1996).

On the other hand, the speleothems and cave minerals formed under subaqueous conditions from a solution highly saturated in calcium carbonate can provide the evidence to support a hypogenic origin of caves. For example, speleothems such as large bisphenoidal calcite crystals (Lundberg et al. 2000), calcite raft cones (Audra et al. 2002), cave clouds and folia (Audra et al. 2009; Davis 2012), tower coral and calcite raft deposits (Hill and Forti 1997) all commonly occur in hypogenic caves.

In the current paper, we describe and examine the hypogenic geomorphological features of Sima de la Higuera Cave (Murcia, South-eastern Spain), which has been recently adapted for speleological use. Together with the mineralogical and geochemical characteristics of some of its speleothems, these have enabled a preliminary model of the evolution of this cave to be established.

2. Geological setting

Sima de la Higuera (Fig Tree Cave) is located in the Sierra de Espuña, in the municipal district of Pliego (Murcia Region). Its entrance lies 485 m a.s.l. and its mouth is crowned by a large fig tree that gives the cave its name. Speleological exploration of the cave began in 1997, although there is evidence that it was discovered earlier than this date (Club Cuatro Picos and Club Pliego Espuña 2001; Ferrer 2010). Its surveyed length is 5,500 m and its deepest part is 156 m below the cave entrance (82 m below the base of the entrance sinkhole) (Fig. 1B).

The cave lies in Oligo-Miocene detrital and marly limestone (Fig. 1A). The carbonate sequence is quite fractured due to NW-SE pressure that has given rise to a series of joints and faults that subsequently determined the cave's morphology, particularly its deeper levels. Significant hydrothermal springs currently arise in the vicinity of the cave, with temperatures ranging from 30 to 50 ºC.

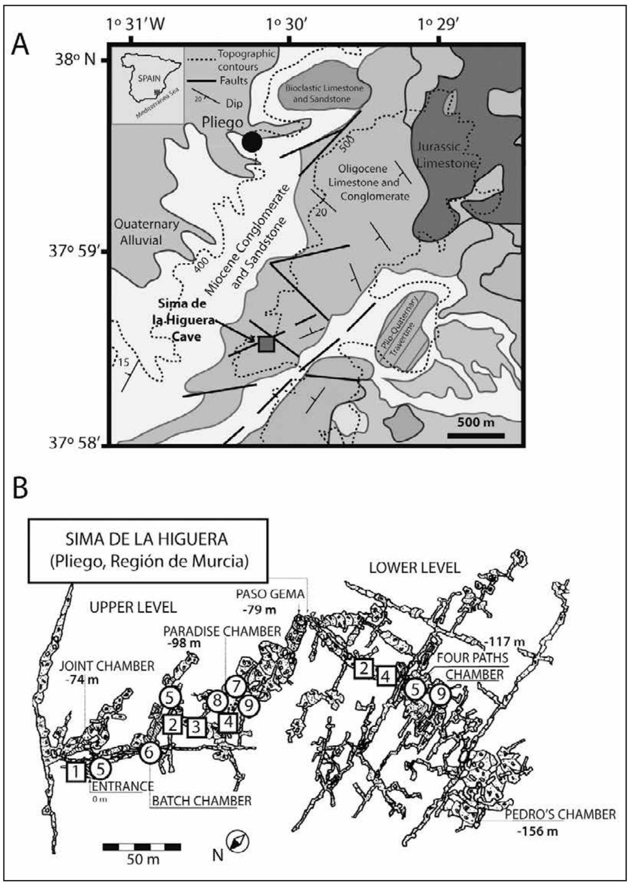

Figure 1. A. Location and geological setting of Sima de la Higuera Cave. Geological cartography modified from Kampschuur et al. (1972); B. Location of the main hypogenic geomorphological features (squares) and speleothem formations (circles) in Sima de la Higuera Cave (topography by the Cuatro Picos and Pliego-Espuña caving clubs (2001): 1. Scallops, corrosion domes and alteration crusts; 2. Bubble trails; 3. Bubble grooves on mammillary crusts; 4. Boxwork and ferromanganese coatings; 5. Calcite "spars" infilling fractures; 6. Tower coral; 7. Calcite raft cones; 8. Folia and cave clouds (mammillary crusts); 9. Piles of calcite rafts.

The cave contains strong evidence of a hypogenic origin. In this study, we use the term "hypogenic" as postulated by Palmer (2011), who suggested that hypogenic caves form due to the upward flow of deep-seated water, or by solutional aggressivity generated at depth below the ground surface. In Sima de la Higuera Cave the hypogene speleogenetic mechanisms are evidenced by the presence of different types of speleothems and geomorphological features typical of hypogenic caves, such as calcite raft cones, tower cones, cave clouds (mammillary crusts), folia, specific corrosion forms, cupola, condensation domes and scallops.

Further evidence comes from the fact the ambient cave temperature is higher than the annual mean outside temperature of 13.8 ºC. The current cave temperature oscillates between 18.6 ºC and 21.7 ºC, increasing slightly in the deeper parts, and this indicates a significant positive thermal anomaly. Relative humidity of the cave air is between 87.5 and 90 % (Club Cuatro Picos and Club Pliego Espuña 2001).

Although the evidence points to deep hydrothermal water flowing through the caves in the past, present-day water inflow is entirely from infiltration of meteoric water. There are only a few vadose speleothems generated from dripwater (stalactites, stalagmites, etc.) in the shallowest levels, around -74 m, and above the level of Bath Chamber.

3. Methodology

3.1. Inventory of speleological features and sampling

The speleothems and the speleogenetic forms of the Sima de la Higuera Cave were inventoried and photographed for classification and analysis. The locations of these features were included on the topographical map drawn by the Cuatro Picos and Pliego-Espuña caving clubs (2001).

The cave cones of the Paradise Chamber were inventoried and positioned relative to a topographic station located -85.2 m below the cave entrance. Distances were measured using a laser-distance meter Disto A3 of Leica Geosystems AG® and an upgrade kit (DistoX) which adds a 3-axis compass, clinometer and a Bluetooth connection. This wireless instrument was connected to a PDA device where data were stored. Calibration was performed using Palm OS software designed by Luc Leblanc and adapted for the topographical Auriga software.

A fragment of a dark-coloured "boxwork" blade (SHG) was taken from the roof of the Manganese Gallery, situated in one of the deeper levels of Sima de la Higuera Cave, at the -110 m level (Fig.2H, I). The sample comprised a mineral lamina, 5–10 mm thick with a sugary texture, whose outer surface was covered by dull greyish-blue deposits, rough in texture.

One sample of a calcite raft consisting of thin, brownish calcite laminae (CR-01) was collected from the Paradise Chamber (-85 m). Lastly, a sample of powdered raft calcite was taken from the Four Paths Chamber (-117 m) where the piles of white raft calcite reach up to 2 m high (CR-02) (Fig. 2E).

3.2. Analytical methodology

SEM microphotographs were taken using a HITACHI S-3500 instrument in high vacuum mode. The samples were previously dried and coated with graphite to increase electron transmissivity. The elemental chemistry was determined by EDX (Energy Dispersive X-ray Spectroscopy) microprobe at two points with different typology over the *boxwork* sample (Fig. 5).

Microanalyses employed the same instrument coupled to an Oxford INCA 7210 X-ray detector. The diameter of the beam was approximately 1 μm. (Table 1). Carbon concentration was not measured due to masking by the graphite coating. Quantitative chemical analysis of samples was done using X-ray fluorescence (wavelength dispersive XRF) with a BRUKER S4 Pioneer instrument.

A subsample of dark material of the boxwork from Manganese Gallery (CMN) was extracted using a needle for subsequent mineralogical analysis by XRD (X-Ray Diffraction). The mineralogy of the internal crystalline

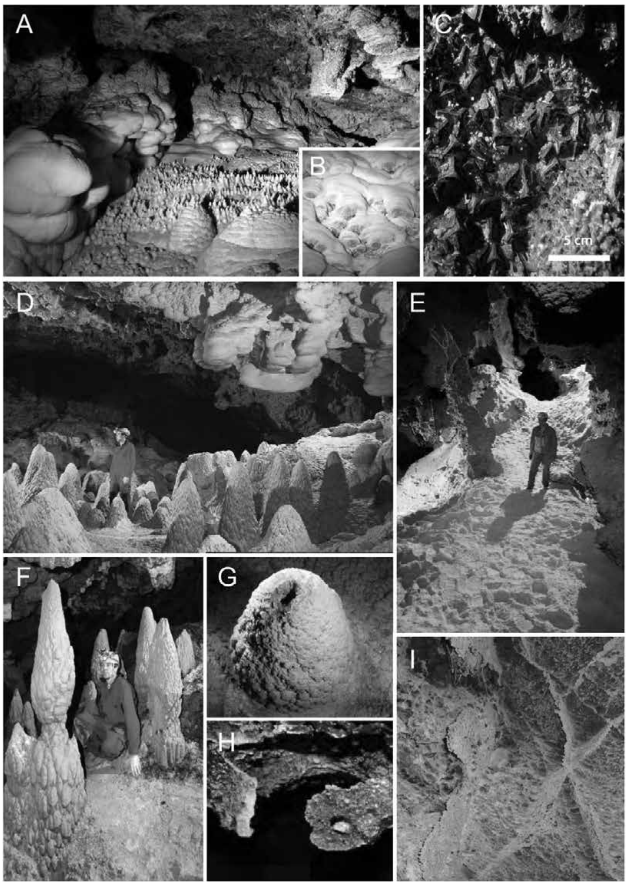

Figure 2. Speleothems linked to the hypogenic origin of Sima de la Higuera Cave. A. Tower coral (floor), cave clouds (wall) and folia (ceiling) in the Bath Chamber level; B. Folia; C. Calcite "spar" crystals coated with ferromanganese oxyhydroxides; D. Calcite raft cones and cave clouds in Ghost Chamber; E. Piles of calcite rafts in Four Paths Chamber; F. Double-tower raft cones in Paradise Chamber; G. "Volcano cone" in Ghost Chamber; H and I. Boxwork and ferromanganese coatings in Manganese Gallery (Photos: Víctor Ferrer).

laminae was also determined by XRD of a powdered sample. The calcite raft samples (CR-01 and CR-02) were crushed and analyzed by XRD. Mineral analysis using XRD used a BRUKER APEX CCD area detector. The geochemical and mineralogical analyses were performed in the Servicios Centrales de Investigation of the University of Almería (Spain).

4. Results

Observations led us to identify three zones with different morphological appearances in Sima de la Higuera Cave:

(1) The mouth of the cave gives access to a subvertical sinkhole 74 m deep, which is developed along the length of a diaclase running E-W, which finally opens out in Junction Chamber. This chamber and the galleries that communicate with it form one of the upper levels of the cave, which also run E-W. On this level appear several, small perched lakes (Coral Lake and Bath Chamber).

The temperature of the lake water is 19.8 ± 0.5 ºC, similar to the cave air (20.2 ±2.2 ºC), while pH (8.10), conductivity (550 µS/cm) and HCO_3^- concentration (220 mg/l) are typical of cave infiltration water. This fact suggests that the only water inflow to these lakes come from dripwater following infiltration of meteoric water through the carbonate rock overlying the cave. Dripstones like stalagmites and stalactites are scarce in this cave level; however, some examples can be observed around the lakes.

Typical features of phreatic speleogenesis such as scallops, cupolas and bell-shaped condensation domes appear in this area (Fig. 3A). Furthermore, dissolution forms like bubble trails (Fig. 3C) and alteration calcite crusts (Fig. 3B) are seen above the -85 m level.

(2) Beyond this point, the cave morphology changes considerably, with larger galleries and chambers, such as Ghost Chamber and Paradise Chamber, which occupy an intermediate level (-85 m).

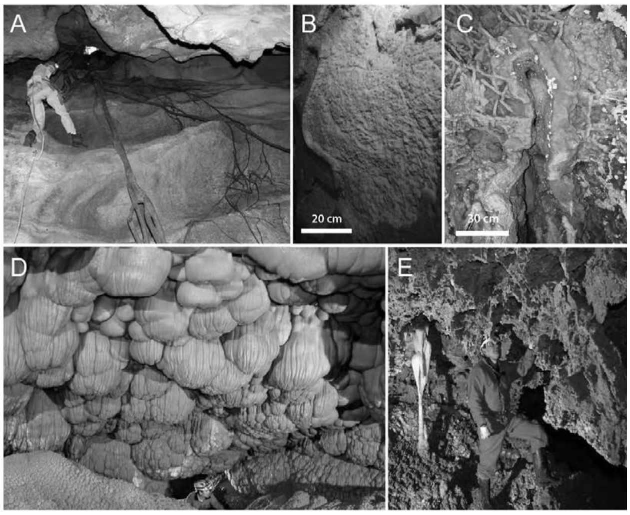

Figure 3. Features related to the hypogenic origin of Sima de la Higuera Cave: A. Scallop in the entrance shaft; B. Alteration calcite crusts; C. Bubble trails and boxwork; D. Bubble grooves on cave clouds in Ghost Chamber; E. Corrosion forms due to acid dissolution appear in several places inside the cave. (Photos: Víctor Ferrer).

This cave level accommodates speleothems such as calcite spars that fill fractures in the host rock, cave clouds, folia, tower coral and calcite raft cones (Fig. 2), all of them indicative of epiphreatic conditions during their precipitation.

Of particular note are the calcite raft cones present in Ghost Chamber. In Paradise Chamber, 92 cave cones have been inventoried (Fig. 5) displaying two different morphologies. Thirty-seven of them can be considered as tower cones (or simple-tower cones), whilst the remaining fifty-five cones have a notch in the middle and look like two cones, one superimposed over the other (Fig. 2F).

(3) Lastly, the deepest levels include labyrinthine galleries (three-dimensional "maze caves") that are smaller in size and typical of hypogenic caves (Klimchouk 2009). Features like *pendants*, related to phreatic dissolution-corrosion have been identified in this level. Boxwork formations and ferromanganesic deposits also appear, particularly in Manganese Gallery (-110 m level) (Gázquez et al. 2012) (Fig. 2H).

The SEM microphotographs enabled two visibly different zones to be identified (Fig. 4B). The first comprises sub-millimetric euhedral calcite crystals, some of which have a sphenoidal habit with well-defined faces and edges. The

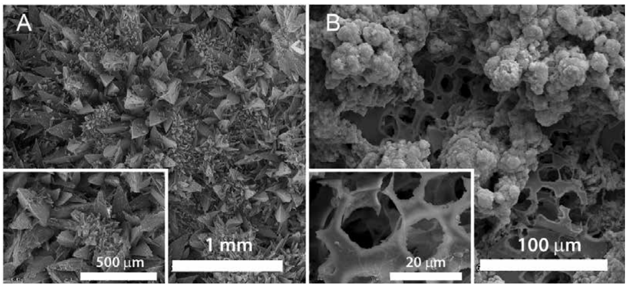

Figure 4. Secondary electron images of (A) calcite rafts from Four Paths Chamber and (B) ferromanganese coatings on the boxwork of Manganese Gallery.

Table 1. Elemental composition of the samples analyzed by X-ray fluorescence (XRF) and EDX microprobe. Analytical errors ranged from ±0.33‰ for oxygen to ±0.13‰ for aluminum. Errors for Fe and Mn were better than ±0.2‰ (n.a = not analyzed; n.d = non detected).

Elements (% wt)	CR-01^{XRF} (-117 m)	CR-02^{XRF} (-98 m)	CMNcal^{EDX} (-110 m)	CMNmn^{EDX} (-110 m)
Ca	52.8	51.8	38.1	2.3
O	22.2	22.4	50.8	34.8
C	n.a	n.a	n.a	n.a
Mg	0.111	0.110	n.d	0.7
Sr	0.0616	0.0603	n.d	n.d
Mn	0.0032	0.0051	2.1	38.2
Fe	0.0621	0.173	1.5	10.3
Si	0.324	0.778	0.7	2.4
Al	0.149	0.465	n.d	2.8
K	0.0341	0.104	n.d	n.d
P	0.261	0.0961	n.d	n.d
S	0.103	0.0918	n.d	n.d

calcite mineralogy of this lamina was confirmed using XRD. EDX analysis revealed traces of Mn, Fe and Si, in addition to Ca, C and O (CMNcal, Table 1).

Over this mineral lamina appear botryoidal structures. EDX analysis of their chemical composition indicated Mn concentrations of up to 38.2 % wt, and Fe of up to 10.3 % wt. Other elements like Na, Al and Si were present in quantities below 3 % wt.

The XRD analyses revealed that this patina is composed of todorokite ($NaMn_6O_{12}·3H_2O$) (22 %), pyrolusite (MnO_2) (16 %), in addition to the calcite (42 %) and amorphous phases (20 %), probably poorly crystalline Fe oxyhydroxides (CMNmn, Table 1).

Finally, the samples of calcite raft analyzed were composed exclusively of calcite, though the XRF analyses revealed traces of Si, Mg, P, S and other minor elements. The composition of samples taken from Paradise Chamber (CR-01) and Four Paths Chamber (CR-02) were similar (Table 1).

5. Discussion

5.1. Speleogenetic forms and dissolution-corrosion features

Sima de la Higuera Cave hosts a great number of morphological features and speleothems, indicating that its origin is not linked to seepage of meteoric water.

Typical features of hypogenic speleogenesis, such as white micritized rind and alteration crusts, appear in the upper levels and in the entrance sinkhole (Fig. 3B). The origin of these elements is usually connected to interactions between carbonate host rock and acid hydrothermal water (Palmer and Palmer 2012). Furthermore, forms typical of phreatic speleogenesis, such as the large scallop (Fig. 3A) identified along the diaclase that gives access to the main galleries, suggest slow upward flows during the speleogenetic stages. Besides, cupola and corrosion domes in the upper levels of the aquifer indicate interactions between the carbonate rock and the thermal water in its gaseous phase (due to lower hydrostatic pressure) here.

Bubble trails have been identified on the ceiling in the intermediate levels, for instance, around Bath Chamber (Fig. 3C). Such features also formed due to acid aggressivity of thermal water; however in this case, gases (CO_2 and/or H_2S) were released as bubbles that rose along preferential trails (Forti 1996) that eventually carved channels on the cave ceiling.

Other features related to rising CO_2 bubbles were observed on the ceiling of Ghost Chamber (-85 m). Grooves several centimeters deep appear on the mammillary crust (cave clouds) that covers the ceiling of this chamber (Fig. 3D). When this cave level was under water, CO_2 degassing caused bubble trails on the hemispherical surface of the cave clouds. The continuous trail of rising bubbles led to dissolution-corrosion of the calcite crusts.

Thermal water accessed the intermediate cave level mostly through a large fracture in the floor of Paradise Chamber (-98 m). This diaclase seems to have acted in the past as a feeder of deeper thermal water into this chamber.

The cave forms found below the level of Paradise Chamber differ substantially from those in the upper levels. The are no dissolution features due to CO_2 bubbles. Instead, "pendants", a cave form typical of phreatic dissolution, indicate a different mechanism of carbonate dissolution. The difference was determined by the different hydrostatic pressure of the solution containing the dissolved CO_2. As the thermal water flowed toward the upper levels, the hydrostatic pressure fell and the volume of the gaseous phase increased. As a result, larger bubbles formed and these followed preferential trails that carved vertical dissolution grooves and channels.

Other dissolution-corrosion forms, in this case generated under vadose conditions, appear in the lower cave levels. Dissolution-corrosion mechanisms affected the cave walls when the water table dropped and left the cave exposed. Wet CO_2-rich air entered from lower levels and condensed on the slightly cooler cave walls and ceiling. Dissolution of the host rock by the condensed water increased as a result of the high CO_2 partial pressure in the cave atmosphere (Sarbu and Lascu 1997). Current CO_2 levels in the cave reach 2000 ppm and may have been even higher in the past due to degassing of hydrothermal water below the cave galleries.

Dissolution-corrosion forms are particularly striking in Manganese Gallery (-110 m). Boxwork and ferromanganese coatings on the cave walls have been described (Fig. 2H, I) whose origin lie in (1) the precipitation of sparitic calcite veins in the fissures of the carbonate host rock when the cave was submerged in thermal water; and (2) the corrosion of carbonates by acid generated from CO_2 diffusion into the condensed water, and oxidation of reduced Fe-Mn under aerobic conditions. The acid attack preferentially dissolved the carbonate host rock (which has a microcrystalline structure), while the veins of sparitic calcite were more resistant to corrosion. As a result, the calcite blades now project into the cave in the form called *boxwork* (Gázquez et al. 2012).

On a microscopic scale, the Fe-Mn oxyhydroxides are botryoidal structures over a visibly altered sugary-textured calcite substrate (Fig. 4B). Oxidation of manganese and iron from the host rock gave rise to protons that acidified the medium, so lead to corrosion of the calcite beneath (Gázquez et al. 2012).

5.2. Hydrothermal speleothems

Sima de la Higuera Cave contains a wide variety of speleothems of subaqueous origin which were generated from a solution highly saturated in calcium carbonate. As a general rule, this type of speleothem precipitates out from hydrothermal solutions that have a high CO_2 content, frequently related to dissolution of the host rock during the genesis of the cave.

Nevertheless, some cases have been reported where subaqueous speleothems (calcite raft cones, folia, etc.) have been generated from cold water in epigenic caves (Davis 2012). Notwithstanding, the relatively high ambient temperature of Sima de la Higuera Cave (up to 6 ºC higher than the annual mean temperature outside the cave) clearly points to this cavity retaining residual heat from an earlier hypogenic stage.

Speleothems in Sima de la Higuera are not randomly distributed; rather, there is a gradation from the base of the cave towards shallower levels. This fact suggests that speleothem precipitation was controlled by the saturation state in calcite of the water, which in turn was conditioned by the hydrostatic pressure of the solution. Thus, crystallization of larger calcite crystals (Fig. 2C) was favoured in the lower cave levels, where slower CO_2 degassing caused low calcite supersaturation leading to slower calcite precipitation. As the hydrothermal fluid rose, CO_2 degassing intensified, resulting in other kinds of phreatic speleothems, such as cave clouds and folia (Fig. 2A, B) in the intermediate levels of Sima de la Higuera Cave. These type of speleothems usually form near the water surface (Audra et al. 2009; Davis 2012), where CO_2 degassing is more active and calcite precipitation faster than in the levels beneath. In some places, crusts of microcrystalline calcite cover the walls and ceiling of the intermediate levels (Fig. 2D).

More recently, the groundwater level gradually fell and the water table intercepted the intermediate cave levels. In such a situation, precipitation of calcite raft laminae was favoured on the water surface due to intense evaporation and CO_2 degassing. Significant temperature and pCO_2 differences between the thermal water and the cave atmosphere triggered rapid precipitation of calcite rafts.

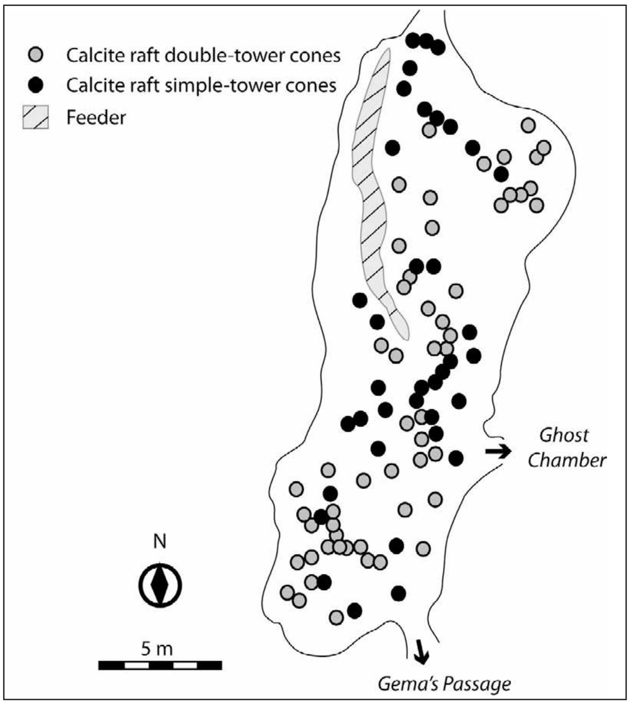

Figure 5. Spatial distribution of cave cones in Paradise Chamber of Sima de la Higuera Cave, distinguishing simple-tower cones (n=37, in black) and double-tower cones (n=55, in grey).

This process would have started in the upper levels; nowadays however, calcite raft deposits are scarce in this shallower level as they would have been eroded during subsequent vadose stages. By contrast, there are abundant calcite raft piles in deeper levels, like Paradise Chamber and Four Paths Chamber (Fig. 2E).

On a microscopic scale, the calcite rafts in Sima de la Higuera Cave display well-developed faceted crystals (Fig. 4A). This kind of *dogtooth* calcite crystal often precipitates at a low-medium temperature (Lundberg et al. 2000). A similar trace element composition of the calcite rafts at -82 and -110 m depth points to the precipitation of calcite laminae with similar characteristics.

When the weight of the crystalline laminae is greater than the surface tension can support, rafts of calcite sink and accumulate on the pool bottom. Since the drips fall consistently at one point over a long period, piles of rafts lamina accumulate on the pool bed forming a cone-shaped speleothem, dubbed cave cones (Hill and Forti 1997). In Sima de la Higuera Cave, cave cones are particularly significant in the Ghost and Paradise Chambers (Fig. 2D, F, G).

A new variety of cave raft cones has been recently discovered in Paradise Chamber, called "calcite raft double-tower cones" (Fig. 2F) (Gázquez and Calaforra 2012). They represent 60 % of the cave cones in this chamber (Fig. 5). The unusual shape of these speleothems is explained by an intermediate phase of rapid calcite precipitation of uncemented calcite rafts covering cave cones formed in previous stages. When conditions favouring slow calcite raft formation were restored, new cave cones were formed exactly on top of some of the earlier cones (Gázquez and Calaforra 2012).

The phreatic/epiphreatic conditions ceased when the water table definitively left the cave. Under the new vadose