Origin of double-tower raft cones in hypogenic caves

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ABSTRACT

In the present paper, we describe the genetic mechanism that causes the precipitation of raft cones in cave. These speleothems usually form in a hydrothermal and epiphreatic environment where dripwater, dripping repeatedly over the same spot, sinks calcite rafts that were floating on the water surface of a cave pool. In particular, the paper describes a new variety of raft cones that were recently discovered in the Paradise Chamber of the Sima de la Higuera Cave (Murcia, south-eastern Spain) based on their morphological and morphometric characteristics. These speleothems, dubbed “double-tower cones”, have a notch in the middle and look like two cones, one superimposed over the other. The genetic mechanism that gave rise to the double-tower cones must include an intermediate stage of rapid calcite raft precipitation, caused by a drop in the water table and by changes in cave ventilation leading to greater CO_2 degassing and evaporation over the surface of the thermal lake where these speleothems formed. Calcite rafts were deposited in Paradise

Chamber, completely covering many of the cones. Later, conditions for slower calcite raft precipitation were restored and some of the cones continued to grow at the same points. When the water table finally fell below the level of Paradise Chamber, the tower cones became exposed, as the incongruent deposits of calcite rafts were dissolved and mobilized to lower cave levels.

Keywords: cave cones, tower cones, raft calcite, hypogenic cave, Sima de la Higuera Cave

INTRODUCTION

Speleothems such as cave cones, folia, cave clouds, coral towers and calcite raft deposits, usually precipitate from thermal water in hypogenic (thermal) caves (Audra et al., 2002, 2009; Davis, 2000, 2012). The term “hypogenic” refers to karstic systems that form due to the upward flow of deep-seated water, usually thermal water, or by aggressive dissolution generated at depth below the ground surface (Palmer, 2011).

Of the hydrothermal speleothems, cave rafts are one of the most common in hypogenic caves. Cave rafts are thin, planar speleothems consisting of crystalline material, usually calcite or aragonite, which float on the surface of quiet cave pools and are supported by the surface tension of water (Hill and Forti, 1997). These thin sheets develop as the water becomes supersaturated as a result of CO_2 degassing and/or evaporation across the water surface.

Both evaporation and degassing are widespread mechanisms that occur in all kinds of caves; however, calcium carbonate precipitation is frequently faster in hypogenic caves due to the greater contrast between water and air temperatures, leading to high saturation of the solution. In hypogenic caves, calcium carbonate saturation of the solution is linked to the deep provenance of thermal water, rich in CO_2 and/or to H_2S-induced dissolution of the carbonate bedrock under hydrothermal conditions (Forti et al., 2002). Nevertheless, a few epigenic caves have been reported where speleothems related to highly saturated water precipitated not from thermal but from cold water. Such cases include the folia of Hurricane Crawl Cave, California (Davis, 2012) and the cave cones of Hölloch Cave, Switzerland (Wildberger, 1987) where saturation in calcite was due to CO_2 derived from soil activity and the vegetation cover over the cave.

When cave rafts form, the calcite crystals are usually disposed with the C axis in radial form around a nucleus that is generally made of organic mucilage (Pomar et al., 1975). When the weight of the crystalline lamina exceeds the supporting surface tension, the cave rafts sink and accumulate on the pool bottom. At other times, sudden sinking occurs when dripwater from the cave ceiling hits the floating lamina, disturbing its unstable buoyancy equilibrium.

When dripping is consistently over one point for a long time, piles of raft lamina accumulate on the pool bottom into cone-shaped speleothem, dubbed “cave cone” (Hill and Forti, 1997). In some places, cave cones have a hard consistency due to calcite cementation of the sunken rafts; though several examples have been reported where cones comprise only uncemented rafts (Lino, 1989).

Traditionally, only two different varieties of raft cones - volcano cones and tower cones - have been described in a large number of caves (Hill and Forti, 1997). “Volcano cones” form when the drip water becomes under saturated with respect to calcite and drills a vertical hole in the apices of the cones. This mechanism is only feasible when the cave cone emerges above the water surface or is exposed as the water level fell. Volcano cones have been found in a variety of caves, some of the most outstanding examples worldwide being discovered in Blue Lagoon Cave (South Africa), where a great many cave cones, including volcano types, lie on the flat bed of a dry pool some 300 m^2, called the “Volcano Plain” (Hill and Forti, 1997). Other examples of volcano cones have been reported in Gruta de las Maravillas Cave (SW Spain) (Martinez-Rosales et al., 2008) and Carlsbad Cavern (New Mexico) (Hill, 1987).

The other kind of well-known cone is the tower cone (also called “penitents”; Audra et al., 2002). These are usually taller and more steeply angled than the volcano cones. In some cases, the flank is steeper than 80º from the horizontal. There are superb examples of tower cones in the Guisti Cave (Italy) (Hill and Forti, 1997) and Lechuguilla Cave (New Mexico) (Davis, 2000), where some exceed three meters in height.

Recently, a new and unusual subtype of cave cone, dubbed “comet cone” by Polyak and Provencio (2005) was identified in Fort Stanton Cave (New Mexico). These consist of a 1-3 centimetres-high pile of powdered calcite raft with a tail, resembling the tail of a comet. Unlike conventional cave cones, these authors suggest that this rare type of cave cone formed in a more dynamic environment, like a subterranean stream.

In the present paper, a new and rare variety of cave cone speleothem is described, which has been recently discovered in the Sima de la Higuera Cave (Murcia, south-eastern Spain). The genetic mechanism that gave rise to these double-tower cones has been determined based on their morphology and morphometric characteristics.

GEOLOGICAL SETTING

The 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 some evidence that it was discovered earlier than this date (Club Cuatro Picos and Club Pliego Espuña, 2001; Ferrer, 2010). Its surveyed length is 5500 m and its deepest level lies 156 m below the cave entrance, or 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. This gave rise to a series of joints and faults (Rodríguez-Estrella, 1996) that subsequently determined the cave's morphology, particularly its deeper levels. Significant hydrothermal springs currently emerge in the vicinity of the cave, at temperatures of between 30 to 50 ºC. These include Mula and Archena springs, 10 and 20 km from the cave, respectively. The high heat flux is due to the relative thinning of the earth's crust and the presence of recent magmatic masses produced by volcanic eruptions over one million years ago (Pinuaga-Espejel et al., 2000).

The mouth of the cave leads to a sub-vertical sinkhole 74 m deep, which is developed along the length of a diaclase running E-W and which finally opens out in Junction Chamber (Sala de la Unión). This chamber, together with its communicating galleries, forms one of the upper levels of the cave, also running E-W. Several, small perched lakes (“Coral Lake” - Lago de los Corales, and “Bath Chamber” –Sala de la Bañera) appear on this level. Beyond this point, the cave morphology changes considerably, with larger galleries and chambers, such as the “Ghost Chamber” (Sala de los Fantasmas) and “Paradise Chamber” (-85 m level, Sala Paraíso), which occupy an intermediate level. It is here that the cave cones, subject of the present study, are found (Fig. 1B and C and Fig. 2). Lastly, the deepest levels include labyrinthine galleries (three-dimensional “maze caves”) that are smaller in size, where boxwork formations and ferromanganesic deposits appear (Manganese Chamber) (Gázquez et al., 2012).

The cave presents strong evidence of a hypogenic origin, as suggested by the presence of different types of speleothems and geomorphological features that are typically related to hypogenic caves, such as calcite raft cones, coral towers, cave clouds (mammillary crusts) and folia, specific corrosion forms, cupolas, condensation domes, scallops, etc. (Gázquez and Calaforra, 2012).

The ambient temperature inside the cave is higher than the outside annual mean temperature of 13.8 ºC. The current cave temperature oscillates between 18.6 ºC and 21.7 ºC, increasing slightly in the deeper parts, which 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 upper levels, around -74 m, and above the level of the Bath Chamber (Gázquez and Calaforra, 2012).

METHODOLOGY

The cave cones in Paradise Chamber were inventoried and positioned relative to a topographic station at -85.2 m below the cave entrance (Club Cuatro Picos and Club Pliego Espuña, 2001). The topographic point is located just at the chamber entrance, 0.5 m below the top of an elevated promontory that separates Paradise and Ghost Chambers (Fig. 1C).

Distances were measured using a laser-distance meter Disto A3 from Leica Geosystems AG® and an upgrade kit (DistoX) which adds a 3-axis compass, clinometer and Bluetooth connection (http://paperless.bheeb.ch/). The instrument was wirelessly connected to a PDA device where data were stored. The 2σ length error of the instrument was better than ± 1 mm for distances shorter than 10 meters and better than ± 3 mm for distances up to 30 meters; the angular error for inclination and direction was better than ± 0.3º. Calibration was performed using the Palm OS software designed by Luc Leblanc and adapted for the topographic Auriga software (www.speleo.qc.ca/auriga/).

Each raft cone was considered as an individual station, assigned with its own identification code (ID-code). At least two measurements were taken on each cone: base and apex. In the cases of double-tower cones, three measurements were made: base, notch and apex. The angular and length measurements for each transect were converted to Cartesian coordinates oriented to magnetic north (Fig. 3 and 4). The polygonal contour of the Paradise Chamber was also obtained by means of this method.

RESULTS

The Paradise Chamber of Sima de la Higuera Cave is 85 m deep. Its maximum length and width are 30 and 15 meters, respectively, and its surface area is around 500 m^2. The chamber's height ranges between 3 and 8 meters. Access to Paradise Chamber is through Ghost Chamber. A 2 m high promontory separates these two chambers.

92 cave cones were inventoried in Paradise Chamber. In terms of their morphology, 37 can be considered as tower cones (or simple-tower cones), whilst the remaining 55 boast morphologies not reported elsewhere. This peculiar calcite raft cone comprises a simple cone topped by a pineapple-shaped one; they have been named “double-tower cones” in the current paper (Fig. 2C and D). Both types of cave cone are distributed unevenly through the Paradise Chamber but are absent at the deepest part of the chamber (NW) (Fig. 4) where a crack in the cave floor connects with deeper cave levels. In

addition, three simple-tower cones in the Ghost Chamber were measured, near the entrance of Paradise Chamber.

The apices of all the cave cones are below the current chamber entrance level. The apex of the highest cone lies 0.24 m below the chamber entrance, while the apex of the lowest cone is 2.85 m beneath it. The highest double-tower cave cones (based on their apex level) are in the south-western sector of the chamber, whilst the shortest specimens are in the central and northern parts. As for the simple-tower cones, the apex of the highest specimen lies 0.56 m below the chamber entrance. This example forms part of a group of simple tower cones of similar height in the eastern-central sector of the chamber. The three cones measured in the Ghost Chamber lie around the same level, 0.9 m below the Paradise Chamber entrance (Fig. 3C, D).

The tallest simple-tower cones (measured from base to apex) are in the northern sector of Paradise Chamber, with a mean height of 1.68 ± 0.21 m (n=5). The remaining simple-tower cones have a mean height of 0.50 ± 0.21 m (n=32). In contrast, the tallest double-tower cones appear in the southern sector, with a mean height of 2.17 ± 0.20 m (n=13), whilst the remaining double-tower cones are 0.97 ± 0.37 m high (n=44).

With regard to the notch of the double-tower cones, their mean position relative to the chamber entrance level is 1.30 ± 0.17 m beneath it. The highest cone notches are in the south-western sector of the cave, whereas the lowest notches are in the eastern-central part. Together, the cave notches lie approximately on a slightly tilted plane (tilting 1.06 º north and 1.54 º east; Fig.

3A, B). Nevertheless, not all cone notches are arranged on this plane. In fact, some lie up to 1.94 m deep below the chamber entrance.

DISCUSSION

Hydrothermal origin of cave raft cones

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

As for Sima de la Higuera Cave, in addition to the presence of a great array of hydrothermal speleothems, the main evidence of its hypogenic and thermal origin is the current cave temperature, which oscillates around 20 ºC, increasing slightly in the deeper parts. This is considerably higher that the mean annual temperature on the ground surface and indicates the cave still stores residual heat from previous hypogenic phases. Furthermore, the location of the hydrothermal elements in the cross section of the cave (Fig. 1B) suggests an upflow of thermal water during its speleogenesis, as indicated in other hypogenic caves (Audra et al., 2009). In the lower levels, we find calcite spars filling cracks in the bedrock, boxwork, ferromanganesic coatings and piles of powdered calcite raft (Gázquez et al., 2012; Gázquez and Calaforra, 2012). On the intermediate level, where the Paradise Chamber is located, epiphreatic speleothems are found, such as the cave cones that are the subject of this study, along with cave clouds and folia. A 10-meter-long diaclase on the floor of the Paradise Chamber seems to have acted in the past as a feeder of deeper thermal water into this chamber.

Just above the chamber, bubble trails and corrosion grooves have been identified on older speleothems, related to intense CO_2 degassing of hydrothermal water (Audra et al., 2007). Finally, in the entrance pit are scallops, cupolas and alteration crusts, all features that are typical of phreatic (and sometimes thermal) conditions (Gázquez and Calaforra, 2012).

On the basis of all this climatic, speleothemic and geomorphological evidence, it can be postulated that the cave cones of the Sima de la Higuera Cave was precipitated from thermal water under epiphreatic conditions.

Genesis of the double-tower raft cones in Paradise Chamber

The first stage of precipitation of the tower cones in Paradise Chamber involved sinking of calcite rafts that had crystallized on the water surface. Thus, the cave level where the Paradise and Ghost Chambers are located (85 m deep) was a subterranean lake at this stage. Triphasic conditions (water-air-rock), would have favoured evaporation and CO_2 degassing, leading to supersaturation of the lake water in calcium carbonate and formation of calcite rafts at the water-air interface (Fig. 5A). This saturation mechanism was controlled by temperature differences between the water and the cave atmosphere producing convection currents in the air, as described extensively in other thermal caves (Cigna and Forti, 1986; Audra et al., 2007).

Simultaneously, water vapour condensed on the cooler walls and ceiling of the cave (Sarbu and Lascu, 1997; Audra et al., 2007). Accordingly, the upper part of the chamber displays features typical of condensation due to air convection, such as the acid corrosion forms related to CO_2 diffusion into condensed water (Sarbu and Lascu, 1997). In addition, condensation gave rise to dripping that returned water to the subterranean lake. Condensing water drops were directed toward preferential dripping points and, together with dripwater from meteoric seepage, the floating calcite rafts at these points were continuously impacted, causing them to sink and accumulate on the chamber bottom (Fig 5A). In this way, tower cones in the Paradise and Ghost Chambers were formed.

Later, a period of higher saturation in calcium carbonate of the solution occurred when environmental conditions in the cave changed. This rapid calcite precipitation could have occurred in response to a drop in phreatic level or, more probably, to an alteration in cave ventilation as a result of cave conduits breaking out at the ground surface. As a result, the rate of CO_2 exchange between the thermal water and the cave air changed and calcite precipitation was extremely accelerated. It is likely that the difference between water and air temperature increased during that period, leading to a higher rate of evaporation that also favoured rapid precipitation of calcite (Fig. 5B). Consequently, cementation of the unconsolidated calcite raft occurred, resulting in hardening of the cones (Fig. 5B). High saturation of the solution also led to rapid formation of calcite rafts on the water surface occurred at this cave level (Fig. 5B). Calcite rafts began to accumulate unevenly over the cave bottom, covering the majority of the cones generated during the previous stage.

Drier conditions at this cave level were produced by increased air circulation within the cave (which lowered the relative humidity of the cave atmosphere), slowed down the dripping or even stopped it completely. During this phase, therefore, the sinking of individual calcite rafts did not occur and the precipitation of cave cones was interrupted (Fig. 5B).

In a subsequent phase, the water level rose, dripping began again and a slower phase of calcite raft precipitation continued the sedimentation of the tower cones (Fig. 5C). However, dripping did not restart at every point so that, rather than restore the growth of some of the earlier cones, these were buried beneath a layer of raft calcite. Conversely, some cones were shallow enough that the sinking calcite rafts deposited another cone on top of the first, giving rise to double-tower cones. During this stage, the sunken calcite rafts (deposited during the previous stage and through which the tops of the previous cones protruded) were still uncemented. Therefore, their accumulation over the still present subhorizontal floor of unconsolidated calcite rafts allowed the evolution of a shallower-sided cone (Fig. 5C). The union between the two cones forms the narrowest part of these speleothems, which in this paper we have been dubbed “notch” (Fig. 2).

Alternatively, one might suppose that the notch in the double-tower cones originated in response to fluctuations of the water table at that particular level, dissolving and corroding the surface of simple-tower cones. However, the wide range in the position of the notches (up to 0.5 m) precludes such a mechanism being the cause of the peculiar shape of these speleothems. Further evidence ruling out groundwater fluctuations as the cause of the rare shape of these cave cones is the crusty aspect of the notches (Fig. 2C), since a corrosion-erosion mechanism linked to water table oscillations would have produced a smooth notch outline.

An explanation for the differences observed in the notch positions is that accumulation of calcite rafts during the previous stage of cone precipitation was unevenly distributed, due to the morphological characteristics of the chamber floor and its slight inclination towards the NE, similar to that also observed in the plane of the notch positions of the double-tower cones (Fig. 3).

Subsequently, conditions for fast calcite precipitation were restored, resulting in the cementation and hardening of the piled-up calcite raft (Fig. 5D). During this stage, massive precipitation of raft calcite also occurred as a consequence of the high saturation in calcium carbonate of the solution.

Finally, and probably in a recent period, the water level fell definitively and left this cave level dry. Under these conditions, the calcite rafts deposits in the Paradise Chamber and adjoining galleries were eroded, dissolved and carried away to lower cave levels through the crack in the chamber floor, which in previous stages had acted as the thermal water feed (Fig. 5E). This explanation is strongly supported by the presence of wide calcite rafts deposits particularly in the galleries around -130 m deep (like the Four Path Gallery), where piles of powdered calcite raft can reach more than 2 m high (Fig. 2G).

CONCLUSIONS

The current paper shows the evolutional mechanism involved in the genesis of cave raft cones. These speleothems are typical of hypogenic/thermal caves and were formed by the sinking of calcite rafts that were floating on the water surface of cave pools.

In particular, we deal with the origin of a peculiar subtype of cave cone, the double-tower raft cones, recently discovered in the Sima de la Higuera. Precipitation of calcite rafts occurred in Paradise Chamber due to evaporation and degassing of thermal water under epiphreatic conditions. Floating calcite rafts sank when water drips fell onto them; they accumulated into piles on the cave floor, resulting in tower cone formation. Subsequently, a phase of rapid calcite raft precipitation occurred as a result of evaporation and increased CO_2 degassing at this cave level; thus, cones precipitated during earlier stages were covered by a thick layer of calcite rafts.

Later, a further phase of cave cones formed over the earlier ones; however, dripping was restored only at some of the points and these are the places where double-tower raft cones formed. When the water table finally left Paradise Chamber, erosion and dissolution removed the calcite raft deposits, exposing the cave cones.

In conclusion, the multistage genesis of the cave cones of the Sima de la Higuera Cave highlights the fact that conditions for calcite precipitation in hypogenic caves can be subject to changes in the cave environment due to hydrogeological shifts. Therefore, further research into the hydrothermal minerals precipitated in caves should take into account that hypogenic systems can be more than dynamic than previously thought.

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