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HYPOGENIC MORPHOLOGIES AND SPELEOTHEMS IN CAVES IN THE MURCIA REGION, SOUTHEASTERN SPAIN

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Abstract
Evidence for hypogenic speleogenesis has been detected in nine caves within a radius of 60 km in the Murcia Region (SE Spain), in many cases revealing active speleogenetic mechanisms that are rarely observed in hypogene cavities elsewhere in the world. Processes related to ancient and current hydrothermal activity, the discordance of permeability structures in the adjacent beds, and the spatial arrangement of the regional hydrogeology have given rise to networks of maze patterns and typical subaqueous hypogenic morphologies. These include spongework mazes, rising wall channels and shafts, feeders, bubble trails, solution pockets, scallops, zenithal ceiling tubes, and cupolas. Carbonic speleogenesis is responsible for the formation of most of these cave features; however, evidence of sulphuric acid speleogenesis (SAS) has been observed in Cueva del Puerto and Sima del Pulpo, which host massive secondary gypsum deposits. Speleothems typically linked to hydrothermal water upwelling and CO_2 degassing close to the water table are present in most of these cavities, including folia, calcite spar crystals, cave clouds, tower cones, calcite rafts and several types of cave raft cones. Other morphologies related to subaerial hypogenic speleogenesis, such as micritized bedrock crusts, ferromanganese coatings, and boxwork, have been observed in several caves, including Sima de la Higuera. The wide variety of hypogenic speleogenesis indicators and speleothems whose genesis is unconnected to meteoric water seepage reveals that the hydrothermal field of the Murcia Region hosts one of the densest active hypogenic subterranean networks in the world.

Introduction
The Murcia Region is located in southeastern Spain. Its climate is characterized by low annual mean rainfall (<500 mm/yr) and annual mean temperatures of ~18^{o}C. Despite limited surface water resources, this region hosts extensive karstic aquifers that have been historically exploited for agricultural purposes. Groundwater overexploitation over the past 50 years has produced a dramatic lowering of the water table on a regional scale, which has allowed access to several phreatic caves that were previously flooded (Ros et al., 2011; 2014a,b). Many aquifers in this region are hydrothermal, with temperature exceeding 40^{o}C.

Some of these caves show marked hypogenic morphologies, suggesting hypogenic/thermal mechanisms were involved during certain stages of their formation. Most hypogenic caves form as a result of circulation of thermal water, usually from depth, and are unconnected with surface water flows (Palmer, 2011). The term "hypogenic" does not refer specifically to extremely deep caves but rather to the origin of the fluids responsible for the development of these caves (Klimchouk, 2009).This kind of system is represented in over 5–10% of the cavities worldwide (Forti, 1996; Forti et al., 2002).

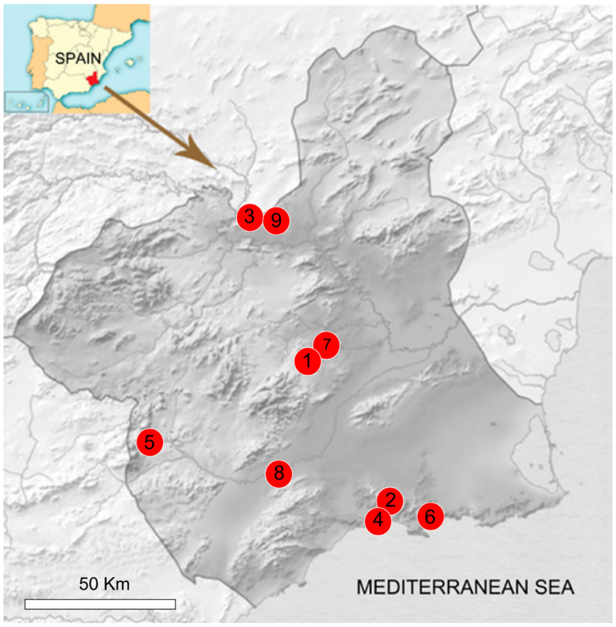

Figure 1.
Location of the main hypogenic caves in Murcia Region.
(1) Sima de la Higuera, (2) Sima Destapada, (3) Cueva del Puerto, (4) Cueva del Agua, Cartagena, (5) Cueva de Luchena, (6) Cueva del gigante, (7) Sima del Almez, (8) Cueva del Agua, Lorca, (9) Sima del Pulpo.

The lack of relationship between subterranean morphologies and seepage water from the surface can serve as a criterion for identifying hypogenic caves. However, relict or fossil hypogenic features can be easily masked by sediment accumulation or epigenic elements, especially in humid climates. These traits have motivated the search for recognizable signatures of hypogenic speleogenesis that allow clear identification of this kind of cave. Recent studies have proposed a series of indicators to flag hypogenic caves, including morphological features and characteristic speleothems (Klimchouk, 2007; Osborne, 2004; Armstrong and Osborne, 2005; Audra, 2009).

In the Murcia Region, these distinctive patterns are widespread in many caves that have recently been suggested as having a hypogenic origin (Gázquez et al., 2012; Gázquez and Calaforra, 2013). In the present study, we selected nine caves for preliminary description and morphological analysis: Sima de la Higuera, Sima Destapada, Cueva del Puerto, Cueva del Agua-Cartagena, Cueva de Luchena, Cueva del Gigante, Sima del Almez, Cueva del Agua-Lorca, and Sima del Pulpo.

Evidence for Morphologic Suite of Rising Flow (MSRF) and Hypogenic Morphologies

The model of *morphologic suite of rising flow* (MSRF) was initially proposed by Klimchouk (2007) and has been widely applied to characterize hypogenic caves. This includes a set of so-called hypogenic patterns that result from water upwelling, usually thermal fluids. These features can be split into three categories: (1) inlet of ascending flow into the system (feeders), usually located at the bottom of chambers and master passages; (2) transition wall and ceiling features that connect the cave levels with upper passages (usually ceiling domes, channels, and solution pockets); and (3) upward leakage structures (outputs), typically located on the ceilings of upper cave levels.

Feeders are very abundant in the context of the hypogenic caves in Murcia. For example, in Sima de la Higuera, a 10-m-long diaclase along the floor of Paradise Chamber seems to have acted in the past as a feeder of deeper thermal water into this cave level (-98m).

In Sima Destapada, 50-m-deep pits connect the intermediate emergent cave levels with the hydrothermal aquifer (~30^{o}C) at -221m depth from the cave entrance (Figure 2). Also, blind shafts (without man-size access to the lower level) are found in the floor of upper galleries that probably acted as feeders in the past. Transitional features connect passages and chambers at different depths. For example, in Cueva del Puerto, several 100-m-deep subvertical fractures connect the Chamber of the Desert (~-80 m) with the shallower Chamber of the Blocks (~-40 m) (Figure 3). In this cave, the hydrothermal flow to the system occurred through a 100-m-long diaclase located 114 m below the current cave mouth. Likewise, in Cueva del Agua-Lorca, the recent lowering of the water table has allowed access to several vertical shafts that acted as feeders in the past.

The hydrothermal dissolution of the host rock occurred preferentially along fractures, giving rise to labyrinthine passages (three-dimensional “maze caves”) that are typical of hypogenic caves and which are especially well-developed in Sima de la Higuera and Cueva del Puerto. In places, dissolution of this wall has left pillars where some of the galleries have partly disappeared and been incorporated into bigger chambers. Sima Destapada, Cueva del Almez and Cueva del Puerto display multiple examples of these morphologies (Figure 4). Features related to phreatic

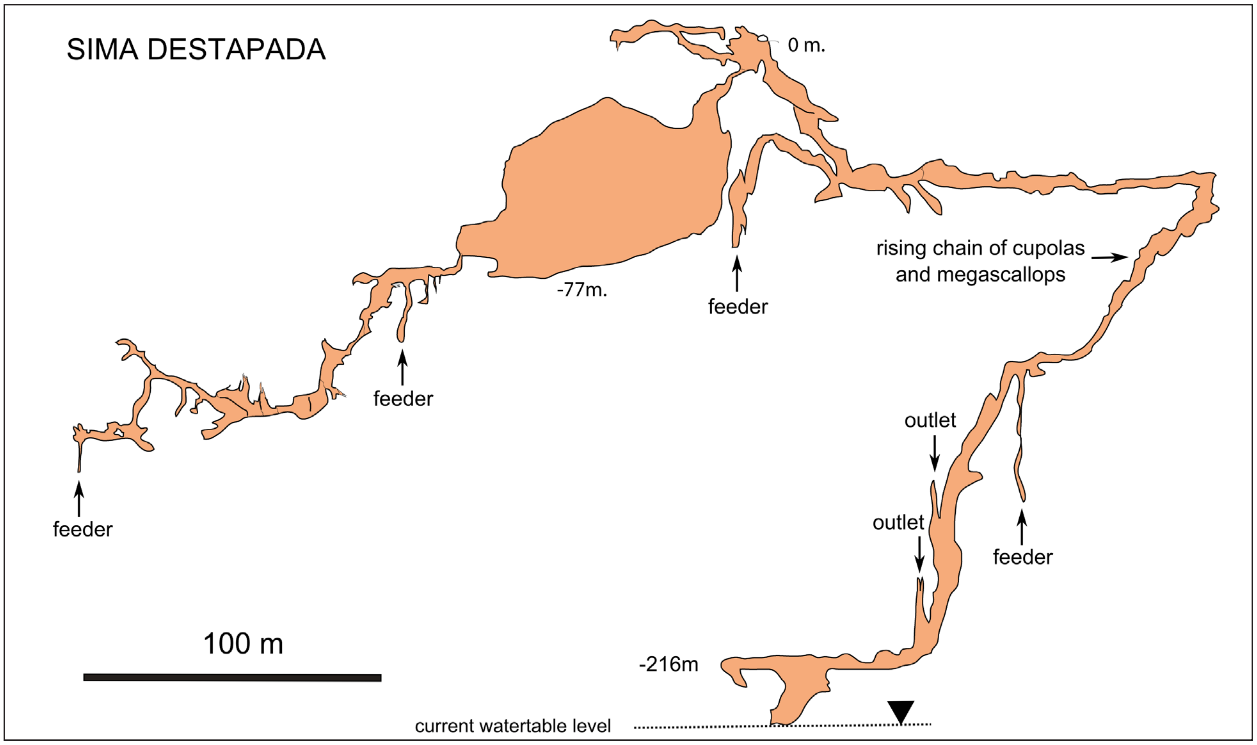

Figure 2.
Topographic profile of Sima Destapada and its main hypogenic morphologies.

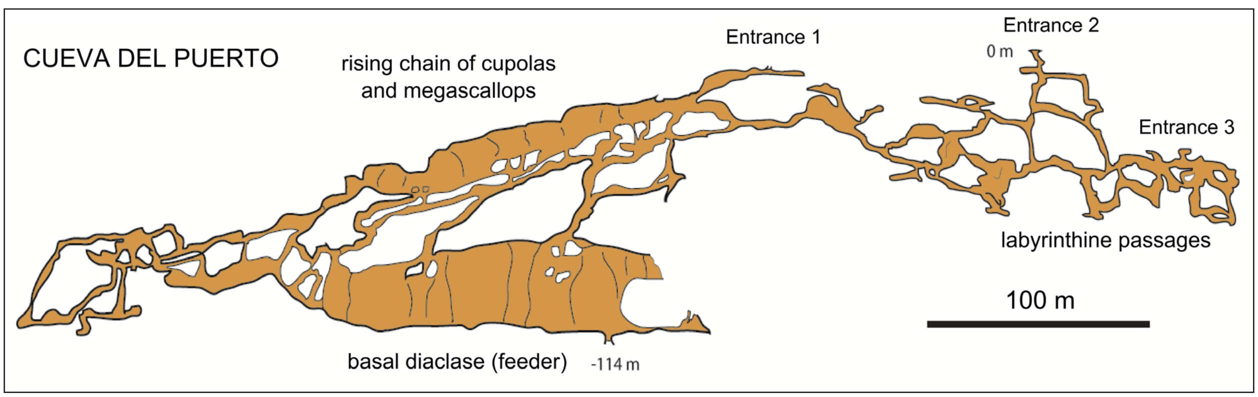

Figure 3.
Topographic profile of Cueva del Puerto and its main hypogenic morphologies.

dissolution-corrosion, like pendants, have been identified in Sima de la Higuera and Sima Destapada (Figure 4A). In Sima Destapada, Cueva del Puerto and Cueva del Almez, linear half-tube structures with smooth surfaces (ceiling half-tubes) are evidence of water flows that dissolved the carbonate host rock (Figure 4B). Sometimes, the CO_2 bubbles followed an ascending path, producing vertical dissolution channels.

These dissolution features are well exhibited in Sima de la Higuera, for example (Fig. 4C).

The ascending flow of thermal water carved the carbonate host rock, giving rise to typical dissolution patterns related to the slow movement of water, including scallops and phreatic domes that are especially well exhibited in Sima la Higuera (Figure 4D), Cueva del Gigante (Figure 4E) and Cueva del Puerto. Rising

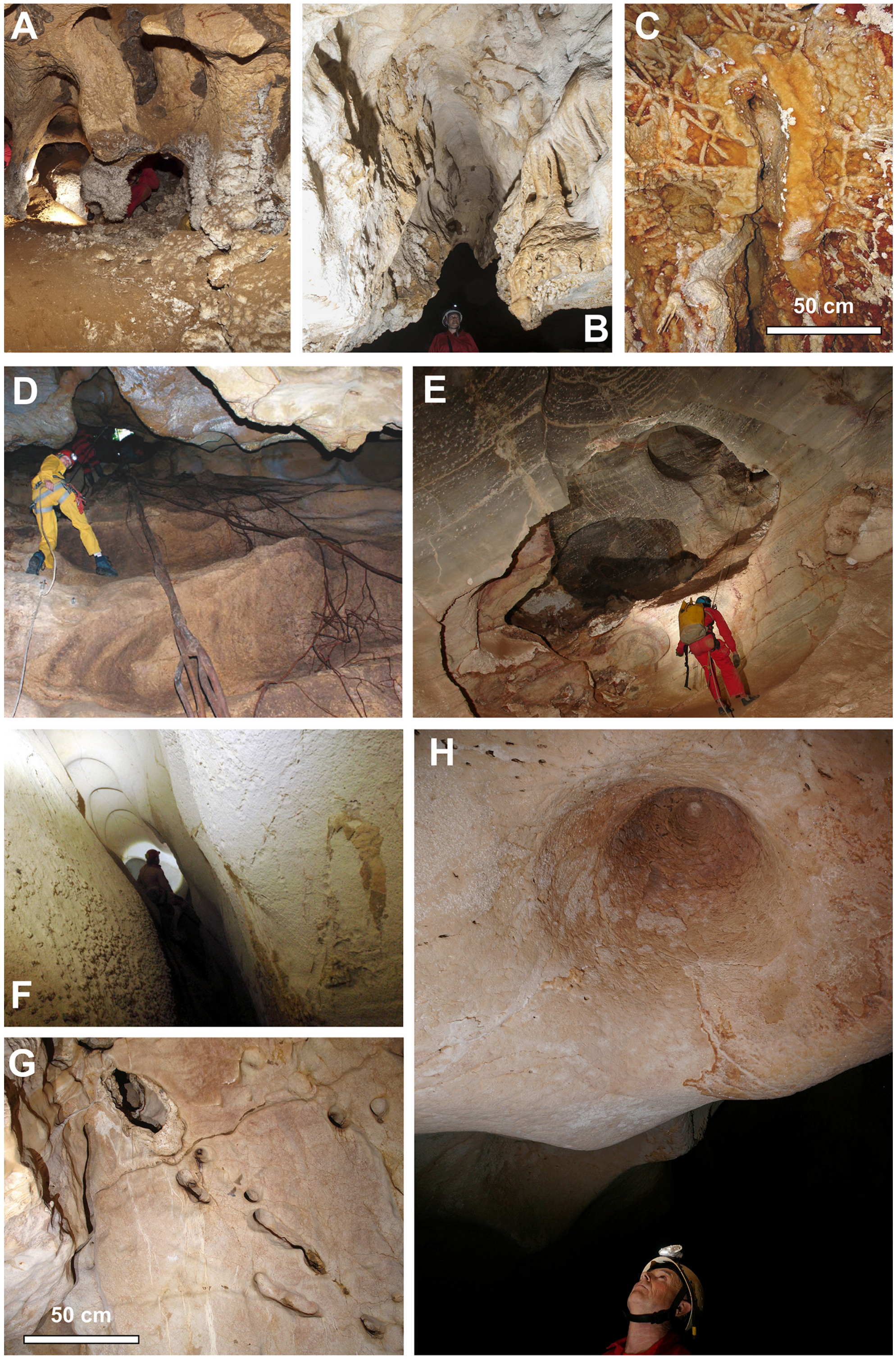

Figure 4.
Hypogenic morphologies in caves in the Murcia Region. (A) Pendants in Sima Destapada; (B) Ceiling half-tubes in Sima del Almez; (C) Bubble trails in Sima de la Higuera; (D)Mega-scallops in Sima de la Higuera; (E)Mega-scallops in Cueva del Gigante; (F) Rising chain of cupolas in Cueva de Luchena; (G) Solution pocket in Sima del Almez; (H) Cupola in Cueva del Puerto. (Photos: Andrés Ros, Llamusí, A, B, E, G, H. Victor Ferrer and C, D, Antonio Gónzalez F)

chains of ascending cupolas have been observed in Cueva de Luchena (Figure 4F). On occasions, the accumulation of air bubbles on the cave ceiling under phreatic conditions generated solution pockets and corrosion cupola, usually attributed to a condensation-corrosion mechanism resulting from the high content of CO_2 from water degassing (Cigna and Forti, 1986). These features are splendidly displayed in Sima del Almez (Figure 4G) and Cueva del Puerto (Figure 4H). Even more interesting is that this mechanism is still active in the flooded passages of Cueva del Agua, Cartagena, where small hemispherical air chambers 20 cm in diameter can be found between the host rock and the hydrothermal water at the depth of -14 m.

Table 1.
Hypogenic features in caves in the Murcia Region.

	Higuera	Destapada	Puerto	Agua-Cartagena	Luchena	Gigante	Agua-Lorca	Almez	Pulpo
Location	Pliego	Cartagena	Calasparra	Cartagena	Lorca	Cartagena	Lorca	Pliego	Cieza
Length (m)	5,500	3,400	4,389	2,560	561	610	546	220	4,780
Air temperature (ºC)	21º	29º	20º	30º	n.m	21º	21º	n.m	n.m
Hypogenic morphologies									
Maze caves	X	X	X	X	X	X	X		
Chimneys	X	X	X		X	X	X		
Bubble trails	X			X			X	X	X
Scallops	X	X	X	X	X		X	X	X
Zenithal tubes		X	X	X	X	X	X	X	X
Ceiling pockets	X	X	X		X	X	X	X	
Cupola and domes	X	X	X		X	X			
Feeders	X	X	X	X	X		X	X	X
Pendants	X	X	X	X			X		X
Blind ascending passages	X	X	X	X	X				X
Boxwork	X	X	X			X	X		
Micritic crusts	X								
Hypogenic speleothems									
Cave cones	X						X		
Coral towers	X								
Cave clouds	X								X
Calcite spars	X	X	X				X		X
Folia	X								X
Calcite rafts	X	X	X				X		X
Ferromanganese crusts	X	X	X	X		X	X		X
Gypsum crusts			X						X
Gypsum chandeliers									
Gypsum fibres and flowers			X						X
Calcite crusts				X		X			

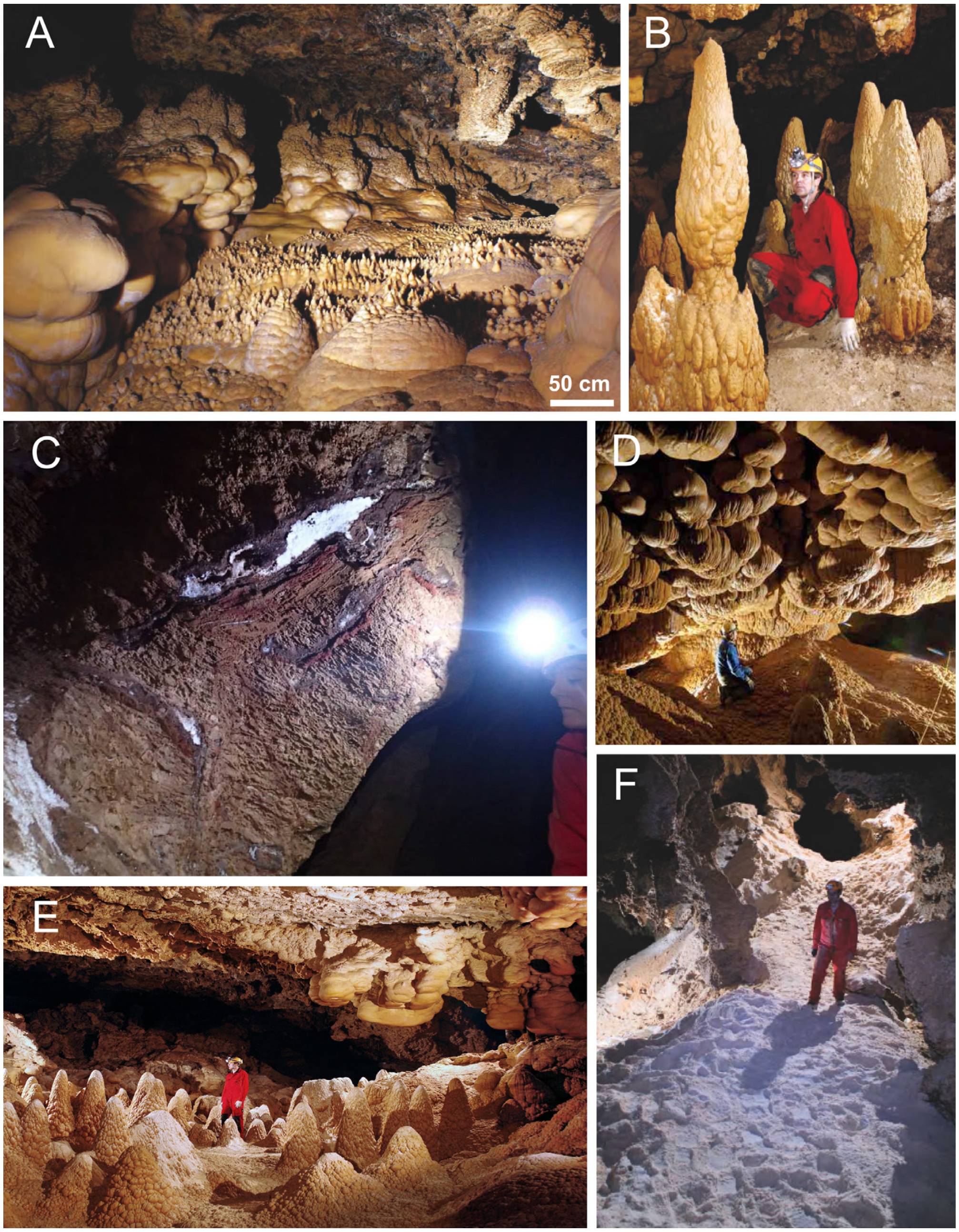

Figure 5.
Hypogenic speleothems in caves in the Murcia Region. (A) Coral towers, folia and cave clouds in Sima de la Higuera; (B) Double-tower cones in Sima de la Higuera; (C) Hydrothermal calcite infill in Cueva del Agua-Cartagena; (D) Cave clouds in Sima de la Higuera; (E) Cave cones in Sima de la Higuera; (F) Piles of calcite rafts in Sima de la Higuera (Photos: A, B, E, and F by Víctor Ferrer; D by Andrés Ros and J.L. Llamusí)

In caves where the current water table is tens of meters below the lower accessible levels, the action of subaerial hypogenic speleogenesis is especially evident. For example, in Cueva del Gigante, Cueva del Puerto, Sima de la Higuera, and Sima Destapada, many corrosion cupolas show strongly foliated micritized surfaces, whose alteration could be related to condensation-corrosion mechanisms due to the diffusion of CO_2 into condensation water under subaerial conditions (Palmer and Palmer, 2012).

Speleothems with a Hypogenic Origin

The presence of speleothems formed under subaqueous conditions from a solution that was highly saturated in calcium carbonate can provide evidence of the hypogenic origin of caves. In the caves in Murcia Region, a wide variety of speleothems usually related to hydrothermal flows has been identified. It is worth mentioning that most of these caves still show positive thermal anomalies with respect to the mean external temperature (~18ºC) (Table 1). This provides further evidence of the hypogenic/hydrothermal origin of these cavities.

Of these caves, Sima de la Higuera hosts most of the typical speleothems described for hypogenic caves, including calcite spars that fill fractures in the host rock, cave clouds, folia, tower coral, and calcite raft cones (Figure 5). All these speleothems are usually precipitated under phreatic or epiphreatic conditions, with water that is highly saturated in calcium carbonate, typical of hydrothermal environment. Nevertheless, it is worth mentioning that the presence of these types of speleothem is not restricted to hydrothermal caves but has also been described in non-thermal, epigenic caves (D'Angeli et al., 2015), where high saturation in calcite is reached due to elevated production from plants, as well as intense CO_2 degassing and evaporation in the cave.

Interestingly, in the Paradise Chamber (-85 m) of Sima de la Higuera, 92 cave cones have been inventoried. Roughly 40% can be considered as tower cones (or simple-tower cones), whilst the remaining 60% have a notch in the middle and look like two cones, one superimposed over the other (Figure 5B and E). The genetic mechanism of the double-tower cones includes the typical sinking of calcite rafts by dripwater and an intermediate stage of rapid precipitation of a calcite raft, caused by a drop in the water table and changes in cave ventilation; this leads to greater CO_2 degassing and evaporation over the surface of the thermal lake where these speleothems formed (Gázquez and Calaforra, 2013). Today, calcite raft deposits are scarce in this shallower level (above -82m) but they do appear at the depth of the Paradise Chamber of Sima de la Higuera, and are especially abundant in deeper passages, such as the Four Paths Chamber (-117 m) (Figure 5F), where abundant calcite raft piles are found (Gázquez and Calaforra, 2013). Likewise, Cueva del Puerto, Sima Destapada, and Sima del Pulpo display vast deposits of calcite rafts that suggest intense CO_2 degassing, typical of hydrothermal water.

Other speleothems formed by the sinking of calcite rafts in shallow (~20 cm) pools have been observed in Sima la Higuera and Sima Destapada, such as coral towers (Figure 5A). The Sima de la Higuera also shows outstanding examples of folia, which usually form under subaqueous conditions near the water surface as a result of CO_2 degassing. Folia are also present in Sima del Pulpo. On most occasions, these speleothems appear at the same level as other speleothems of hydrothermal origin, including cave clouds and calcite crusts (Figure 5A). Sima de la Higuera and Sima del Pulpo host relevant examples of these types of crust speleothems. Calcite infilling of cracks in the host rock, sometimes in the form of spars, can be found in Sima de la Higuera and Cueva del Agua-Cartagena (Figure 5C).
In addition to carbonate speleothems, gypsum is present in Cueva del Puerto and Sima del Pulpo. In these caves, gypsum appears as crusts and gypsum flowers. The origin of sulphates is probably linked to sulphuric acid speleogenesis (SAS) as has been described in many other caves worldwide (e.g., Palmer and Palmer, 2012; Audra et al., 2015).

Conclusions

Signs of hypogenic mechanisms have been detected in nine caves in the Murcia Region. CO_2-based hydrothermal mechanisms are proposed for the formation of Sima de la Higuera, Sima Destapada, Cueva del Agua-Cartagena, Cueva de Luchena, Cueva del Gigante, Sima del Alméz, and Cueva del Agua-Lorca. By contrast, Cueva del Puerto and Sima del Pulpo, where massive deposits of gypsum have been identified, were likely generated by SAS mechanisms. The wide range of hypogenic speleogenesis indicators and hydrothermal speleothems reveals that the hydrothermal field of the Murcia Region hosts one of the densest active hypogenic subterranean networks in the world.

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José L. Carcelén, Antonio Latorre, José Soto, Andrés Marín, José David Lisón, José Florencio, Jesús López, and David Bayón. More information about these caves can be found at www.cuevashipogenicasdemurcia.es.

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