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Morphological and mineralogical evidence for ancient bat presence in Cova des Pas de Vallgornera (Llucmajor, Mallorca, Western Mediterranean)

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Abstract: Cova des Pas de Vallgornera is a unique karst cave located at the Llucmajor coastal platform that stands out not only because of its length, more than 78 km, but also for its particular morphological suite, richness and variety of speleothems and mineral infillings. Although the mineralogy of speleothems and minerals related to hypogene morphologies has been studied and described, the existence of minerals derived from guano deposits was still poorly investigated. The cave hosted bat colonies until the collapse of its natural entrances, circa 2.4 My ago, since then until its discovery in 1968, the cave remained sealed. These particular environmental conditions, kept along millennia, helped the interaction of guano-related leachates with the bedrock and clay deposits provoking dissolution and mineral precipitation. Moreover, thanks to the discovery of guano-associated cave minerals, it has also been possible to determine the presence of morphologies related to ancient guano deposits. In this paper, we report on features caused by bat's biomechanical erosion, bat claws and bat thumb marks and the influence of geobiological modifications caused by guano deposits on stalagmites and fallen boulders, haystack-shaped stalagmites, stalagmites covered in niches and crypto-corrosion features on fallen boulders. In addition, an array of guano-related minerals is reported, being phosphates the most abundant mineral group identified, underlining the broad presence of fluorapatite from all the studied sites. Among the oxides and hydroxides, nordstrandite, gibbsite and todorokite are especially common. Finally, connections between microclimatic conditions in the cave and the location of bat roosting and breeding sites are discussed.

Keywords: littoral karstic cave, bats, scratches, guano deposits, phosphates, microclimate, ichnofossils

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INTRODUCTION

Cova des Pas de Vallgornera is located on the coast of Mallorca island, Western Mediterranean, and is an extensive maze cave partially drowned by brackish phreatic waters. With over 78 km it is the longest cave on the island (Merino et al., 2014a; Ginés et al., 2017). The cave lies in the natural area of Migjorn, in southern Mallorca, a coastal karstic region forming a tabular platform built by an Upper Miocene (Tortonian-Messinian) reef limestones sequence.

The speleogenesis of the cave is quite complex and is associated to three main drivers: dissolution in the freshwater-seawater mixing zone, the influence of surface recharge, and finally hypogene processes

(Ginés et al., 2009, 2014, 2017). The presence at the *Galeria del Tragus* of an important fossiliferous site containing among others, well-preserved remains of an extinct and endemic mammal (goat) attributed to *Myotragus* aff. *kopperi* helps to shed some light on the chronology of the deposit and thus, the sealing and isolation of the cave. In this sense, the absence of more modern species of *Myotragus* suggests that the collapse and sealing of the ancient natural entrances occurred around 2.4 My ago (Bover et al., 2014). Furthermore, some bat bones were also discovered at this site, proving that bats inhabited the cave before and until the collapse of the natural entrances. Currently, no natural entrances exist, being accessed by a single man-drilled well. Therefore, at present, the

cave does not host bat colonies and thus is deprived of recent bat guano deposits.

Guano related morphologies and the resulting mineral assemblages have been described by many authors from caves worldwide that at present have open entrances and contain current or ancient bat guano deposits: Tarhule-Lips & Ford (1998), Onac & Veres (2003), Marinacea et al. (2004), Onac et al. (2005, 2009), Bird et al. (2007), Lundberg & McFarlane (2008, 2015), Wurster et al. (2010, 2015), Serra-Cobo et al. (2011, 2015), Giurgiu & Tămaş (2013), Pogson et al. (2014), Puşcaş et al. (2014), Audra et al. (2016, 2017, 2019), McFarlane & Lundberg (2018), Dandurand et al. (2019), etc. Nevertheless, Cova des Pas de Vallgornera represents a peculiar and uncommon site, it hosted bat colonies for an uncertain period of time, leaving their imprints and guano deposits until the entrances collapsed around 2.4 My ago. Since that moment and until its discovery, the cave did not experience major geomorphological changes allowing the preservation of bat-derived morphologies. Moreover, its special underground environmental conditions, temperature, relative humidity, CO₂ concentration among others, favoured the precipitation of a variety of minerals associated with guano deposits. This paper describes bat-derived features and morphologies related to guano deposits found in the cave. Some of them can be classified as ichnofossils, being represented by bat scratches (bat claws and bat thumb marks) present in lenticular cross-section niches and ovoid-shaped alcoves, whereas crypto-corrosion features originated on stalagmites and rock blocks are also described. Besides, guano-associated minerals have been identified and are also reported. Finally, the relationship between the microclimatic conditions that prevailed in the cave while it was inhabited by bats and the choice of roosting and breeding sites is discussed.

METHODS

First of all, a thorough search for bat claws and thumb marks was carried out not only at the already known places displaying bat scratches but also all around the cave system. Simultaneously, morphologies exhibiting marks (ovoid-shaped alcoves, lenticular niches) were identified as well as those displaying unusual crypto-corrosion features. The morphometry, depth and length of marks and thickness of the walls' weathered layer, were measured using a graduated ruler.

In order to evaluate and demonstrate the presence of guano-related cave minerals, more than 70 samples of minerals and weathering products were collected from all the studied sites. Particular interest was devoted to sample earthy materials accumulated on ovoid-shaped alcoves, lenticular cross-section niches, wall ledges, crypto-corrosion features and walls. Samples were collected with the permission of the Direcció General d'Espais Naturals i Biodiversitat del Govern Balear.

Mineralogy was determined by X-ray diffraction on raw powder unoriented samples using a Bruker D8 Advance analytical X-ray system at the Universitat de

les Illes Balears (Serveis Científico-Tècnics), with CuK α radiation at 40 kV/40mA and 3-70° (2-theta), step 0.02°, time per step 1s, conditions. Semi-quantitative mineral calculations based on the obtained peak areas were carried out using the Diffraction EVA 4.1 software. Selected samples were analysed by EDX (Bruker X-Falsh Detector 4020) and/or observed by Scanning Electron Microscope (SEM, Hitachi S-3400N).

GENERAL AND MORPHOGENETIC SETTINGS

Cova des Pas de Vallgornera is an outstanding karst cave located at the Llucmajor coastal platform that stretches along the southern part of Mallorca Island and develops in flat-lying Upper Miocene reef carbonates (Merino et al., 2014a; Ginés et al., 2014, 2017). The cave is roughly disposed in three main tiers; the studied and sampled locations are all of them placed in the passages of the upper tier that forms the northernmost landward part of the cave (Fig. 1).

The morphology of the cave system is very diverse showing a rich assortment of solutional features of different characteristics, together with a remarkable crystalline decoration characterized by great speleothem diversity (Merino et al., 2014b). From the point of view of its planimetric pattern, the Cova des Pas de Vallgornera exhibits two well-differentiated settings (Ginés et al., 2014). On one hand, spongework mazes and collapse chambers form the seaward sections of the cave, developed in the very porous reef-front facies of the Upper Miocene carbonates; on the other hand, an important network of joint-guided passages characterises the innermost landward parts, which were excavated in the less permeable back-reef facies (Fig. 1).

Regarding the morphogenesis of this complex karst cave, three speleogenetic pathways are envisaged (Ginés et al., 2009, 2014, 2017). Besides the coastal mixing processes occurring in the littoral limestone areas, a basal hypogene recharge linked to the geothermal phenomena existing in the Llucmajor area has been documented (López & Mateos, 2006; López, 2007; Onac et al., 2014). Finally, a noticeable meteoric recharge, evidenced by means of thick detritic deposits related to an ancient blocked entrance, should be mentioned. The chronology of the main speleogenetic processes falls back, at least, to mid-Pliocene times, on the basis of the vertebrate palaeontological remains recovered in the innermost sectors of the cave.

PRESENCE OF BAT-RELATED FEATURES

Bat claws and thumb scratches were first identified on the walls of *Galeria d'en Pau* (Fig. 1) and one of the passages that communicates the former gallery with *Galeria del Gran Canyó*. Currently, these peculiar morphologies have also been observed at the following sites: a gallery aligned to the SE of *Galeria del Gran Canyó*, a passage situated parallel to *Galeria del Tragus*, in the **Sector Nord**, and at the *Jacuzzi*, a vast rimstone pool that temporarily dams up fresh water, located to the NE branch of *Galeria de les Columnes*.

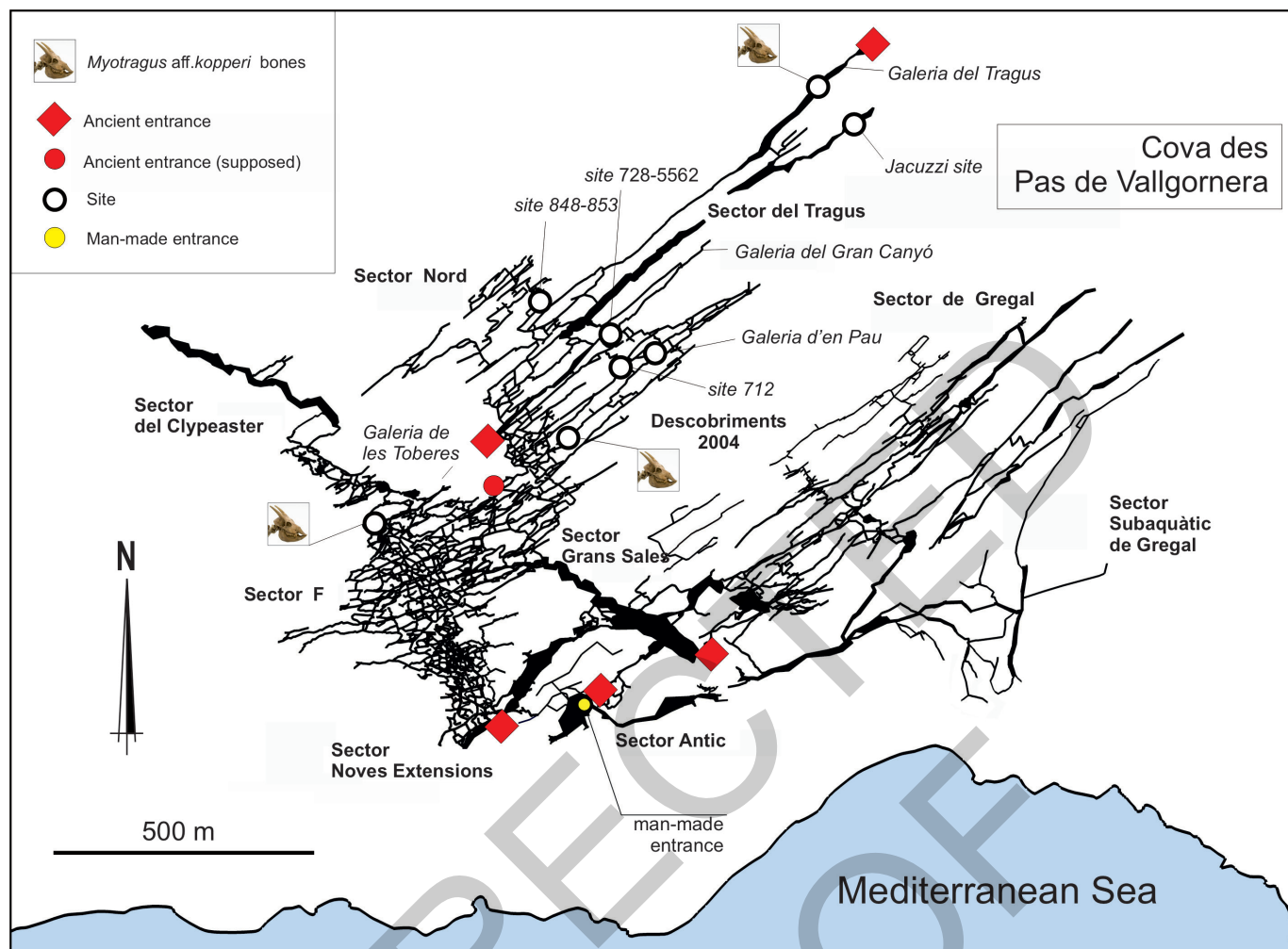


Fig. 1. Survey of Cova des Pas de Vallgornera showing the distribution of the described sites, as well as the ancient and currently sealed entrances.

It must be stressed that nowadays there is no open entrance to the cave, neither bat colonies in it. Although no natural access exists, the existence of small holes and cracks that allow a certain air exchange with the outside cannot be completely ruled out. The only accessible entrance is a 6-m deep drilled cesspit, which is sealed with a special gate. The excavation of this well in 1968, led to the discovery of the cave (Merino et al., 2014a).

In order to identify the different described locations containing distinctive morphologies within the cave, they have been named using the suitable gallery name or survey station numbers for those passages without specific names.

Locations with bat related morphologies

Galeria d'en Pau site. Along the *Galeria d'en Pau*, a section of about 25 m in length presents bat-related morphologies, mainly composed of bat claws and thumb marks covering walls and ceiling affected by weathering processes. This segment of the gallery (Fig. 2A), whose walls are affected by a weathering process up to 1 mm in depth, shows a marked ceiling channel exhibiting abundant bat scratches.

Site 712. The passage that connects *Galeria d'en Pau* with *Galeria del Gran Canyó*, displays about 40 m of its length marked with bat-related morphologies: claws and thumb marks, being narrower than *Galeria d'en Pau* (Fig. 2B). Walls are quite weathered, showing an increasing alteration and thickness to the NE of

the gallery, thickness also varies from 1 mm in the upper half section up to 4 mm in the ceiling. This site contains some interesting examples of ovoid-shaped alcoves and lenticular cross-section niches.

Site 728-5562. Another area with bat scratches is a corridor aligned to the *Galeria del Gran Canyó* that starts at a junction and runs to the SW for roughly 90 m. The upper half of the weathered walls and ceiling are covered with abundant light brown to brown multicoloured deposits that overlay an altered rock layer with a fluctuating thickness between 1 mm and 30 mm, decreasing from NE to the SW (Fig. 2C). In a marginal small corridor, the ceiling shows a deep altered layer of 30 mm in thickness, while on the walls it reaches up to 10 mm.

Site 848-853. Two passages parallel to the SW section of *Galeria del Tragus* also present bat-related morphologies. The first one (Fig. 3A), exhibits bat scratches along 25 m, walls are profusely cracked and deeply weathered (Fig. 3B). The upper half of the gallery shows an altered rock layer that ranges from 10 to 30 mm in depth, which in turn is overlain by a thin brownish to yellowish brown multicoloured deposit.

The second gallery, parallel to the former one, shows bat scratches along 30 m. Ceiling and walls of the upper third of passage are strongly altered, showing layers of weathered rock up to 50 mm in thickness; this deep weathering causes the fall of the thickest sheets (Fig. 3C).

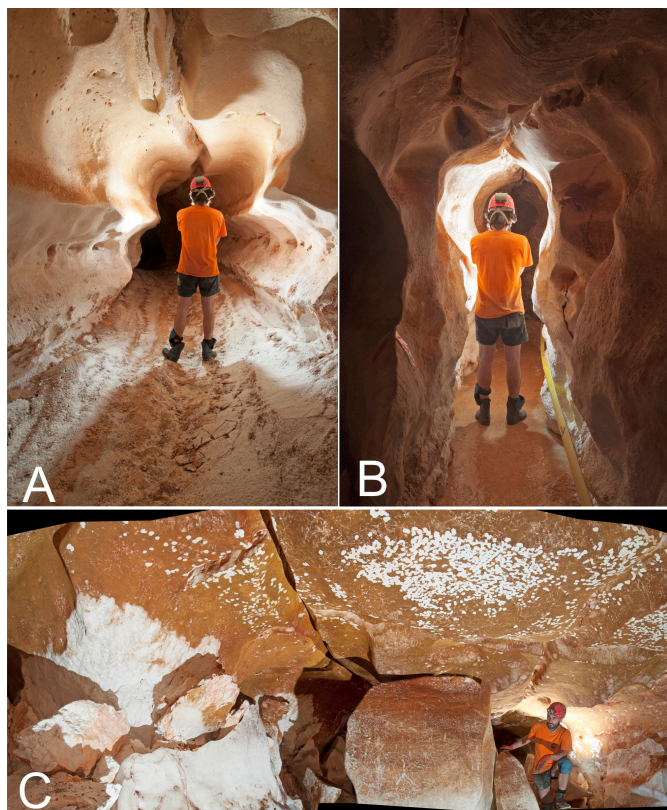


Fig. 2. A) Cross-section at *Galeria d'en Pau* showing its peculiar shape. Almost two thirds of the lower section of the gallery are coated with a white mineral crust thicker at the bottom and thinning upwards. The upper section shows some bat scratches on the wall and ceiling; B) *Site 712*. Tight passage between *Galeria d'en Pau* and *Galeria del Gran Canyó* whose walls and ceiling exhibit abundant bat scratches in the upper half of the gallery. The ceiling has a layer of weathered rock 4 mm thick, while its thickness decreases to the walls; C) *Site 728-5562*. Panoramic photo of the junction at the beginning of the corridor aligned to the *Galeria del Gran Canyó*. Walls and ceiling are covered with a thick brown yellowish multicoloured deposit where clear bat scratches are displayed. The boulder roughly in the center of the photo exhibits profuse scratches all around it, which attests that this rock was already in place while bats were using the cave as a shelter. On the contrary, the white slabs on the left occurred subsequently to the sealing of the cave because of the lack of marks on them.

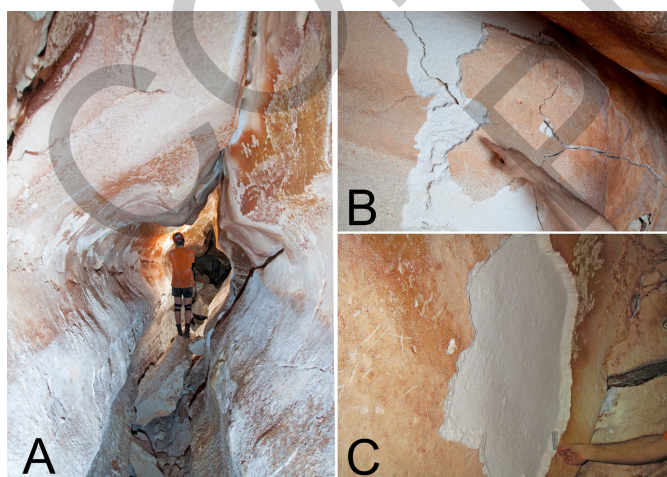


Fig. 3. A) Structurally controlled rectilinear passage at *site 848-853*. The lower half section is varnished with a white mineral crust mainly composed of calcite, while the upper section is cracked and altered, with weathered layers of up to 30 mm in thickness. Brownish to yellowish multicoloured deposits are clearly seen along the gallery; B) *Site 848*. Cracked wall displaying a thick altered layer of rock overlain by a thin multicoloured coating which in turn shows bat marks; C) *Site 848-853*. Stretch of wall exhibiting an extremely weathered process that penetrates deep into the bedrock. The detached 50 mm altered layer allows showing the white bedrock surface devoid of bat scratches, whereas the rest of the stained surface displays different bat-related marks.

Jacuzzi site. This is the richest area containing bat scratches that are also among the best preserved. It is located to the NE branch of *Galeria de les Columnes*, parallel to *Galeria del Tragus*. The *Jacuzzi* is a 140-m long passage, with an average width of 8 m; it can be divided into two different parts. The first one shows a massive accumulation of collapsed roof rocks and wall slabs; the ceiling and some walls are covered with light-brown to yellowish multicoloured deposits (Fig. 4A). A section of the ceiling, about 4 m above the gallery, displays a large concentration of bat thumb marks (Fig. 4B). The second one is formed by a huge two-terraced rimstone pool (Fig. 4C).



Fig. 4. A) First section of the *Jacuzzi site*. Massive accumulation of boulders floors the passage after breakdown processes that happened before the cave was sealed. Brownish deposits can be seen covering fallen rocks; the left-hand wall displays multicoloured deposits, exhibiting patches of white bedrock surfaces where the weathered layer has fallen down; B) Flat ceiling utterly covered mainly in bat thumb marks, differences in colour highlight the profusion of scratches, general setting; C) Marks in detail. *Jacuzzi site*; D) Last section of the first rimstone dam at the *Jacuzzi site*. Right at the center of the photo, the second and deep rimstone dam can be clearly seen. The gallery is coated and ringed with a yellowish band of calcite crystals that completely seals it, allowing the accumulation of fresh water. Ceiling and walls present an irregular surface with some speleothems.

DESCRIPTION OF BAT-DERIVED FEATURES AND DEPOSITS

The peculiar morphologies associated to the presence of bats in Cova des Pas de Vallgornera can be organised into two categories, depending on the mechanism of alteration and its effect: (1) features caused by biomechanical erosion affecting walls and ceilings and (2) guano-related features (Audra et al., 2016, 2017, 2019).

As a consequence of the long-term cave evolution since it was isolated from the surface and of the deep alteration processes that have acted and still act in the cave, it is perfectly plausible that some of these morphologies were displayed in other areas, being currently obscured by weathering processes, coated by mineral crusts, or destroyed by collapse episodes.

Biomechanical erosion

Mechanical erosion morphologies are by far, the most abundant and conspicuous in the cave; they have been observed in all of the known and described sites (Tables 1, 2). The identified and reported morphologies are: bat scratches (bat claws and bat thumb marks) along walls and ceilings, or concentrated in lenticular niches and ovoid-shaped alcoves. The genesis of the last two mentioned features is not related directly to bat activity, but bats benefited from the pre-existence of voids and pockets to use them as shelters causing erosion and, in the case of ovoid-shaped alcoves, producing clear modifications. These pre-existent corrosion morphologies, that exist in other areas with no bat presence recorded, are the result of complex corrosion processes linked to the mixing

zone between fresh meteoric water and sea water, in the coastal fringe of carbonate terrains (Gràcia et al., 2009a, 2009b).

Bat claws and thumb marks

Apparently, these trace fossils have not been described in detail before. Audra et al. (2016, 2017) refer to bat claws as a mechanical weathering agent acting when bats cling to the walls using their claws. The only comments we have found in the published literature of anything comparable is by Tarhule-Lips and Ford (1998) who briefly mention the lack of claw marks on the walls of bell holes. Two types of marks can be differentiated, the ones left by bat thumbs (Fig. 5A) and the ones left by bat claws (Fig. 5B-D). As far as claw marks, they are formed by two more or less parallel rectilinear marks composed each of them, by up to 5 parallel grooves (Fig. 6A); on some occasions and due to the thickness of altered bedrock, it is not possible to distinguish any groove, being replaced by a blurred mark that also exists for thumb marks (Fig. 6C). They proliferate on walls and mainly on ceiling channels where they become longer when the channel is wider. This morphology is also abundant near cracks or wall ledges where bats tried to hang (Fig. 6D). In places, it is possible to distinguish both feet claws from the same individual making a distinctive v-shaped mark (Fig. 6E). Marks left by bat thumbs (Fig. 6B) are caused when bats flutter around trying to grasp at walls or ceiling using their thumbs, they are formed by a single, more or less curvilinear, uneven groove. In general, grooves are more obvious when they affect an altered surficial layer that shows some differences in color with the layer below.

Table 1. Measurements of thumb and claw marks taken at each of the locations.

	Location	L max (mm)	L min (mm)	Width (mm)	Thickness of altered layer (mm)	V-shaped	L average (mm)
Thumb marks	Galeria d'en Pau	190	60	1-2	1-2	----	125.0
	Site 712	130	35	1-2	1-2	----	82.5
	Site 728	110	35	1-2	1-2	----	72.5
	Site 5562	150	60	1-2	1-2	----	105.0
	Site 848	110	50	1-2	2-30	----	80.0
	Site 853	110	30	1-2	2-20	----	70.0
	Jacuzzi beginning	190	40	1-2	4-10	-----	115.0
	Jacuzzi center	170	50	1-2	2-50	-----	110.0
	Jacuzzi back	180	20	1-2	1-2	-----	100.0
Claws marks	Galeria d'en Pau	95	40	10	1-2	yes	67.5
	Site 712	70	35	10	1-2	yes	52.5
	Site 728	50	30	10	1-2	yes	40.0
	Site 5562	90	40	10	1-2	yes	65.0
	Site 848	85	45	10	2-30	yes	65.0
	Site 853	80	35	10	2-20	yes	57.5
	Jacuzzi beginning	90	40	10	4-10	yes	65.0
	Jacuzzi center	80	40	10	2-50	yes	60.0
	Jacuzzi back	90	40	10	1-2	yes	65.0

Table 2. Dimensions of lenticular and ovoid shape features identified at each of the locations, along with thickness of altered rock layer and deposits.

	Location	Width (mm)	Depth (mm)	Height (mm)	Thickness of altered layer (mm)			Deposit thickness (mm)
					lateral	at the back	ceiling	
Lenticular shape	Galeria d'en Pau	-----	-----	-----	-----	-----	-----	-----
	Site 712	899	542	398	5	3	15	10
	Site 728	-----	-----	-----	-----	-----	-----	-----
	Site 5562	421	314	170	5	10	20	5
	Site 848	-----	-----	-----	-----	-----	-----	-----
	Site 853	-----	-----	-----	-----	-----	-----	-----
	Jacuzzi beginning	506	287	229	5-7	0	7	5
	Jacuzzi center	-----	-----	-----	-----	-----	-----	-----
	Jacuzzi back	662	838	233	1-2	0	12	2
Ovoid shape	Galeria d'en Pau	459	391	574	10	15	30	2
	Site 712	296	523	773	20	25	30	2
	Site 728	-----	-----	-----	-----	-----	-----	-----
	Site 5562	326	293	965	30	20	30	20
	Site 848	636	474	595	15	20	30	2
	Site 853	-----	-----	-----	-----	-----	-----	-----
	Jacuzzi beginning	-----	-----	-----	-----	-----	-----	-----
	Jacuzzi center	-----	-----	-----	-----	-----	-----	-----
	Jacuzzi back	-----	-----	-----	-----	-----	-----	-----

Features present in lenticular cross-section niches and ovoid-shaped alcoves

Lenticular-shaped niches are elliptical concavities of centimetric order which develop on bedding planes or horizontal levels where a change in the bedrock's lithology occurs; Gràcia et al. (2009a) call these features wall pockets. They can be found in main galleries and lateral sinuses. The upper half of this morphology is devoid of sediments, while the ceiling and walls exhibit mainly bat claw marks; the lower section has a sloping floor covered by a thin layer of sediments composed of different minerals and particles of rock (Fig. 7A).

Ovoid-shaped alcoves develop on minor vertical joints that previously presented some voids or

concavities that facilitated the use of these features as roosting sites. This morphology displays an ovoid cross-section, which is commonly culminated in its highest part by an open conical cap (Fig. 7B). The former inception cavity was altered and highly modified by bat claws and bat thumbs when bats fluttered around while trying to cling to walls or ceiling surface, causing an important mechanical erosion and the fall of rock fragments that accumulate on an inclining surface at the bottom of this structure (Fig. 7C). Finally, a positive influence of condensation-corrosion processes caused by bat breathing and heating cannot be excluded in the weathering of the rock surface.

Morphologies related to guano deposits

All of these morphologies have been exclusively identified at the *Jacuzzi site*, encompassing features originated on stalagmites: haystack-shaped structures and stalagmites covered in niches; and crypto-corrosion morphologies developed on fallen rocks and boulders.

Features originated on stalagmites

The haystack-shaped stalagmites exhibit smooth and corroded surfaces that allow to see the inner crystallized structure; some of them are quite hemispherical, being between 0.5 and 0.7 m in diameter (Fig. 8A). They are developed mainly on a huge boulder that in turn, is covered by highly corroded flowstones that show several stages of calcite precipitation.

One stalagmite carved by niches has also been identified at the *Jacuzzi site*, being located in the central area. It displays a particularly corroded side with some alveoli embedded in the upper third, the rest of the formation that is not coated by vadose

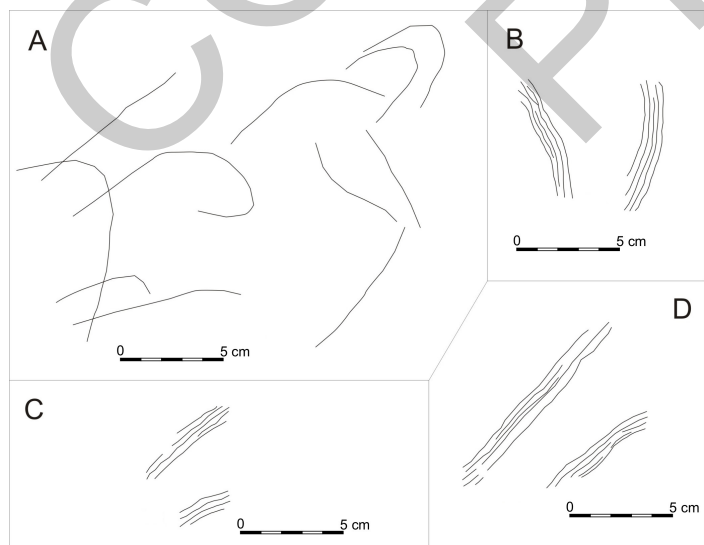


Fig. 5. Sketch showing the main bat scratches trend; A) Different curvilinear and arbitrary bat thumb marks; B) Characteristic V-shaped mark left by bat claws displaying clear and parallel 5 grooves; C and D) Uneven bat claw marks of different length showing a more parallel pattern between claws and the distinctive small grooves.

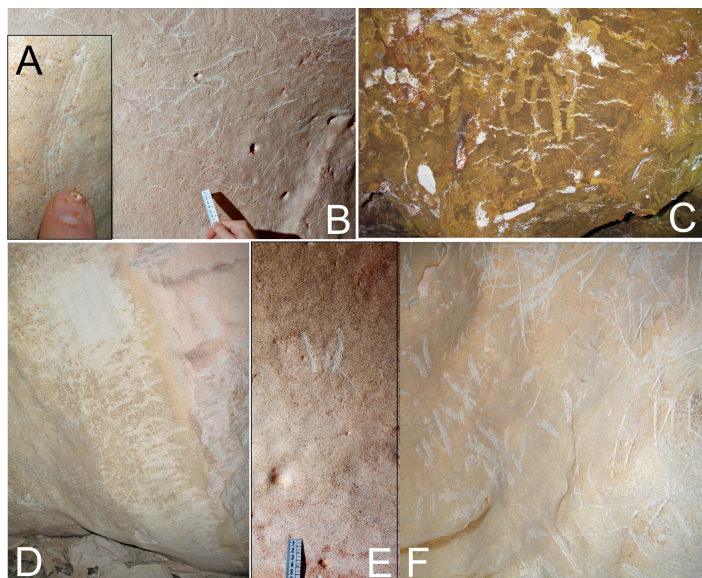


Fig. 6. A) Bat claw mark showing 5 clear parallel grooves on the wall of site 853; B) Assemblage of curvilinear bat thumb marks covering a wall at *Galeria d'en Pau*. Scale in centimetres; C) Blurred claw marks on a boulder wall covered with colourful deposits that contain among others minerals, fluorapatite and nordstrandite. Site 728. Width of the photo is 35 cm; D) Tilted fallen slab, formerly part of a cracked wall. The upper third band of the tilted rock shows a heavily marked surface, where it is possible to observe a profusion of claw marks and numerous thumb marks below. The white spot situated at the upper part of the photo exhibits an area covered in claw marks. *Jacuzzi site*. Width of the photo is 1 m; E) Peculiar V-shaped morphology produced when a bat tried to cling to the wall with its claws and failed to do it, leaving these visible scratches, *Galeria d'en Pau*; F) V-shaped morphologies at the *Jacuzzi site*. Scale in centimetres.

crystallizations exhibits massive abraded layers (slice-shaped) of calcite, some of them protruding from the main body (Fig. 8B).

Crypto-corrosion features

Smooth elongated grooves have been recognized on tilted fallen limestone boulders, reaching up to 2 m in length, about 4 cm width and 2 cm deep. They are carved quite parallel to each other, showing a more complex upper area with smoother interconnected incuts; grooves get more marked and deeper to the bottom of the boulder. It is possible to observe curved grooves caused by a shift in the surface direction (Fig. 8C).

Juxtaposed morphologies also occur, being composed of small rills, up to 20 cm in length, intermingled with concave voids that would resemble guano pots (Audra et al., 2016). As in the previously described features of this site, the substantial calcite crystallization that took place as a consequence of the large accumulation of water, covered and disguised all patterns situated below the reached maximum level of the rimstone pool (Fig. 9).

Some boulders show more conspicuous gutter-shaped morphologies that might also be related to these features, but due to the intricate morphological variety of patterns that carve the bedrock, the evidence is perhaps not conclusive.

Guano-associated cave minerals

The cave mineral assemblage of the analysed samples is composed predominantly of calcite and silicates (Table 3), containing occasionally phosphates,

oxides and hydroxides (Tables 4, 5). Most samples are mixtures of 3 or more minerals.

Deposits found covering boulders, rock shelves, alcoves and niches have a paste-like consistency and feel slippery and somehow greasy to touch, with colours ranging from light brown to black, whereas multicoloured deposits exhibit a fluffy and porous structure that forms thin mats on walls and ceilings of passages. Many of these deposits are yellowish brown, but they may also be pinkish or black. A total of 34 samples yielded phosphates, whereas supplied some atypical oxides and hydroxides (most of these mineral assemblages associated with detrital material, quartz, goethite, muscovite, kaolinite, etc.). The most abundant phosphate occurrence is fluorapatite, which has been identified at all investigated sites, followed by hydroxylapatite. The existence of uncommon phosphate minerals, like kribergite, wyllieite, and qingheite, is suspected but not yet confirmed. The presence of Al-hydroxides (nordstrandite, gibbsite) and Mn-oxide (todorokite) is also reported.

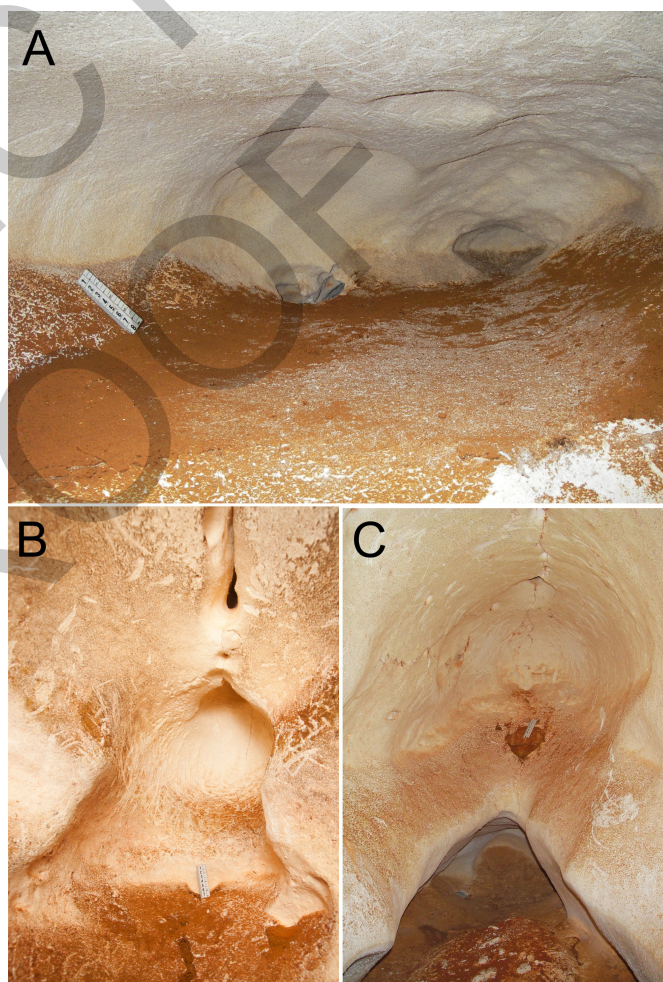


Fig. 7. A) Lenticular cross-section niche whose walls and ceiling exhibit abundant bat marks. The floor presents a brownish paste deposit that contains fluorapatite. Scale in centimetres. *Jacuzzi site*. Scale in centimetres; B) Characteristic ovoid-shaped alcove located at Site 712. The altered layer is totally eroded away from walls by bat thumbs and claws, while at the bottom of this morphology, hydroxylapatite has been identified intermingled with brown clay material. Scale in centimetres; C) Ovoid-shaped alcove at *Galeria d'en Pau*, showing bat thumb and claw marks along its walls and ceiling. The brownish deposit right in the center of the photo contains, among other minerals, fluorapatite. Below the slit, an evident accumulation of bedrock particles and some clayey materials can be seen. Rule for scale is 8 cm.

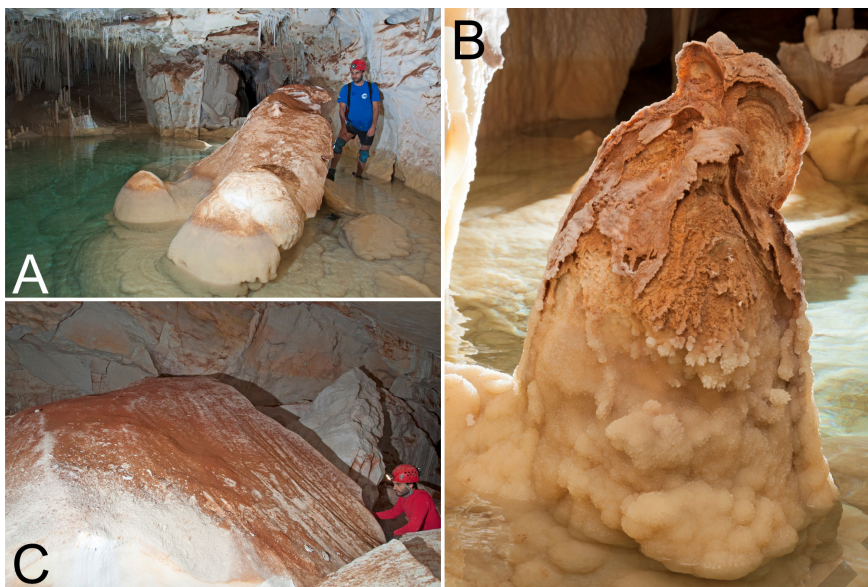


Fig. 8. A) Haystack-shaped stalagmites developed on a fallen boulder located in a massive rimstone dam at the *Jacuzzi site*. Fluorapatite has been identified in the brownish deposit that covers the surface of the boulder. A pool spar crystallized band lines the whole pool and marks the upper water level reached by percolating water; B) Stalagmite displaying deep organic corrosion processes that causes the formation of small niches, exposing its inner structure. Spar crystallizations obscure most of the stalagmite surface, making infeasible the examination of the whole formation. *Jacuzzi site*. Scale: diameter at the base of the stalagmite is 50 cm; C) Elongated grooves that resemble rinnenkarren features, developed on a tilted fallen boulder located at the beginning of the *Jacuzzi site*. The brownish deposit that covers most of the rock is enriched in fluorapatite.

Although gypsum is one of the most common minerals related to bat guano deposits, it has only been reported at *Galeria d'en Pau*.

DISCUSSION

Caves containing guano-related features and associated minerals currently host (or have hosted) bat colonies that have permitted the accumulation of important guano deposits and caused a biogenically-mediated corrosion and the resulting mineral assemblages. All of these caves share a common denominator, they have present-day open entrances that allow access not only to bats but also to cavers and researchers, at the same time they all have current or relict bat guano deposits.

In this sense, Cova des Pas de Vallgornera represents a unique and exceptional site, inhabited by bats for an uncertain period of time, leaving their imprint and guano deposits until it was naturally blocked, circa 2.4 My ago (Bover et al., 2014, Ginés et al., 2014). During the Quaternary, the studied areas did not undergo major geomorphological changes: the long-term stability of the underground environment has allowed the preservation of bat-derived features (Fig. 10).

Nevertheless, flooding of the cave as a consequence of global glacio-eustatic variations that affected the

phosphates and minerals mostly by dissolution).

Although currently there are no recognizable guano traces in the cave, its former presence can be inferred from several mineral species identified, mainly belonging to the chemical group of phosphates (fluorapatite, hydroxylapatite). The special underground environmental conditions that prevailed over the centuries, temperature, high relative humidity, CO₂ concentration, lack of outside influences, limited percolating water, permitted not only the precipitation of a variety of minerals, but also their evolution to more stable mineral species under these conditions.



Fig. 9. Juxtaposed morphologies which might be related to guano deposits at the back of the *Jacuzzi site*. A) Boulder whose surface could have been altered due to guano accumulation. The black deposit is composed of fluorapatite and clayey materials; B) Boulder exhibiting a quite uneven surface which could have been reworked by guano deposits. Small rills and concave features can clearly be distinguished.

Table 3. List of clay minerals and carbonates (no fluorine content) found at each location.

Location	Sample	Mineral/Series	Associated mineral/series	Color	Other minerals/Series
Galeria d'en Pau	VL-M286	Calcite	Goethite	Brown	Quartz, Kaolinite
Site 712	VL-M245	Calcite	Muscovite/Illite	Brown	Kaolinite
	VL-M246	Calcite	Illite/ Montmorillonite	Black	Kaolinite
	VL-M247	Calcite	Kaolinite	Brown	Quartz
	VL-M288	Muscovite/Illite	Goethite	Brown	
Site 728	VL-M248	Calcite	Kaolinite	Yellow-Brown	
	VL-M289	Calcite	none	Yellow-Green	
Site 5562	VL-M249	Goethite	Kaolinite	Yellow-Brown	
	VL-M251	Muscovite/Illite	Goethite	Brown	
	VL-M252	Calcite	Goethite	Black	
	VL-M253	Goethite	Kaolinite	Brown	Muscovite/Illite
	VL-M290	Calcite	Illite	Brown	Kaolinite
Site 848	VL-M254	Calcite	Kaolinite	Brown	Muscovite/Illite
	VL-M255	Calcite	none	Light Brown	
Site 853	VL-M259	Illite	Calcite	Reddish	Kaolinite/Illite
	VL-M260	Calcite	none	Yellow-Brown	
	VL-M261	Calcite	none	Brown	
	VL-M262	Illite	Kaolinite	Brown-Reddish	
	VL-M291	Illite	Kaolinite	Reddish	
	VL-M292	none	none		just Fluorapatite and Nordstrandite
Jacuzzi back	VL-M196	Quartz	Calcite	Black	Muscovite/Illite
	VL-M209	Quartz	none	Black	
	VL-M210	Calcite	Quartz	Black	
	VL-M263	Goethite	Muscovite/Illite	Brown	Quartz, Kaolinite
	VL-M264	Dolomite	Quartz	Black	
	VL-M265	Calcite	Quartz	Black	
	VL-M266	Calcite	none	Black-Brown	
	VL-M267	Goethite	Quartz	Brown	
	VL-M268	Goethite	Montmorillonite	Brown	
	VL-M271	Calcite	none	Black	
	VL-M272	Calcite	Quartz	Brown	
Jacuzzi center	VL-M197	none	none		just Fluorapatite and Kribergite
	VL-M198	Calcite	none	Pinkish	
	VL-M206	Calcite	none	Pinkish	
	VL-M207	Calcite	none	Pinkish	
	VL-M215	Calcite	Muscovite/Illite	Ochre	Kaolinite
	VL-M220	Calcite	none	Brown	
	VL-M221	Calcite	none	Brown	
Jacuzzi beginning	VL-M280	Illite	none	Pinkish	
	VL-M281	Calcite	none	Orange	
	VL-M283	Illite	Kaolinite	Brown	

On the contrary, this environmental scenario would have prevented the widespread preservation of other guano-related minerals like gypsum because of their high solubility (Onac & Vereş, 2003; Onac et al., 2005; Puşcaş et al., 2014), occurring only in small quantities at *Galeria d'En Pau*.

Microclimatic constraints

The distribution of the studied and described locations containing bat-related features was not a

random choice for bats; actually, they can shed some light on the microclimatic conditions that prevailed at that time in certain areas within the cave. In fact, all bat-derived morphologies caused by biomechanical erosion are present where walls and ceilings display a layer of weathered rock, with various thickness. This demonstrates that, by the time bats inhabited the cave, weathering processes were already active and had a key role in facilitating the biomechanical erosion produced by bats.

The area where the cave is located has an average annual temperature of approximately 18°C (López, 2007), therefore the cave should have roughly the same ambient temperature. On the contrary, the Lluçmajor area presents geothermal activity whose origin is the shallowest aquifer of the Lluçmajor platform and the Campos Basin. A deep investigation drilling, 700 m deep,

revealed water temperatures up to 70°C at the deepest section (López et al., 2004; Mateos et al., 2005; López, 2007). Boop et al. (2014) reported mean air temperatures at *Sector Antic* of 19.50°C, whilst mean phreatic water temperature was 19.68°C. At *Sector del Tragus*, a remote section within the cave, we have detected phreatic water and air temperatures of 20.40°C (unpublished).

Table 4. List of more significant mineral species identified at each of the locations, describing the site where it was deposited and its colour.

Location	Sample	Mineral	Associated mineral	Color	Location
Galeria d'en Pau	VL-M242	Gypsum	none	Translucent	on passage floor
	VL-M286	Fluorapatite	none	Brown	at the base ovoid-shaped feature
Site 712	VL-M245	Hydroxylapatite	none	Brown	at the base ovoid-shaped feature
	VL-M246	Hydroxylapatite	Wyllieite	Brown	multicolored on the ceiling
	VL-M247	Hydroxylapatite	Fluorapatite	Brown	on floor lenticular shaped feature
	VL-M288	Fluorapatite	none	Brown	on floor lenticular shaped feature
Site 728	VL-M248	Fluorapatite	none	Yellow-Brown	multicolored on boulder's wall
	VL-M289	Fluorapatite	Nordstrandite/ Gibbsite	Yellow-Green	multicolored on the ceiling
Site 5562	VL-M249	Fluorapatite	none	Yellow-Brown	on lateral terrace
	VL-M251	Fluorapatite	none	Brown	at bottom juxtaposed feature
	VL-M252	Fluorapatite	none	Black	multicolored on wall upper part
	VL-M253	Fluorapatite	none	Brown	on floor lenticular shaped feature
	VL-M290	Fluorapatite	none	Brown	on floor lateral passage
Site 848	VL-M254	Nordstrandite	none	Brown	at the base ovoid-shaped feature
	VL-M255	Fluorapatite	Qingheite	Light Brown	multicolored on wall upper part
Site 853	VL-M259	Nordstrandite	none	Reddish	on boulder
	VL-M260	Fluorapatite	Qingheite	Yellow-Brown	multicolored on the ceiling
	VL-M261	Hydroxylapatite	none	Brown	on lateral shelf
	VL-M262	Fluorapatite	Nordstrandite	Brown-Reddish	on lateral shelf
	VL-M291	Nordstrandite	none	Reddish	on boulder
	VL-M292	Nordstrandite	Fluorapatite	Brown	on boulder under previous sample
Jacuzzi back	VL-M196	Hydroxylapatite	none	Black	on boulder (fallen boulder)
	VL-M209	Hydroxylapatite	Chromceladonite	Black	on lateral shelf under calcite layer
	VL-M210	Hydroxylapatite	none	Black	on lateral shelf under calcite layer
	VL-M263	Hydroxylapatite	none	Brown	on lateral shelf
	VL-M264	Fluorapatite	Fluorapatite	Black	on lateral shelf under calcite layer
	VL-M265	Hydroxylapatite	none	Black	on lateral shelf under calcite layer
	VL-M266	Nordstrandite	Todorokite/ Birnessite	Black-Brown	on boulder, at lateral passage
	VL-M267	Todorokite	none	Brown	on boulder, at lateral passage
	VL-M268	Fluorapatite	none	Brown	on lateral terrace, at lateral passage
	VL-M271	Fluorapatite	none	Black	on boulder in the middle upper gour
	VL-M272	Fluorapatite	none	Brown	on boulder, right side "cylinders"
Jacuzzi center	VL-M197	Fluorapatite	Kribergite	Ochre	multicolored on wall upper part
	VL-M198	Fluorapatite	none	Pinkish	multicolored on wall layer under
	VL-M206	Fluorapatite	none	Pinkish	multicolored on the ceiling
	VL-M207	Fluorapatite	none	Pinkish	multicolored on the ceiling
	VL-M215	Fluorapatite	none	Ochre	on boulder (fallen) haystack boulder
	VL-M220	Fluorapatite	none	Brown	multicolored on the ceiling
	VL-M221	Hydroxylapatite	none	Brown	on boulder below ceiling
Jacuzzi beginning	VL-M280	Nordstrandite	none	Pinkish	on boulder
	VL-M281	Nordstrandite	none	Orange	on boulder
	VL-M283	Fluorapatite	none	Brown	on boulder with crypto-lapiaz

All of these data show an anomalous difference of between +1.68°C and +2.40°C, higher than would be expected, strongly suggesting a feeble ongoing geothermal influence in the cave. It is probable that this environmental geothermal-driven situation was already prevailing at the time when the cave was used as roosting and breeding shelter, consequently providing a suitable cave environment for bats.

Bats inhabiting temperate zones are known to make migratory movements, changing roosting sites on a seasonal basis, trying to reach suitable cave environments for each season (McNab, 1982; Baudinette et al., 1994; Rodrigues & Palmeirin, 2008). In this respect and taking into consideration these higher than normal mean temperatures in the cave, it is possible that it was not used as hibernation site, but as spring-maternity and/or maternity-mating roost instead (Rodrigues & Palmeirin, 2008). These authors suggest that warmer hibernaculum temperature is advantageous for pregnant bat females to allow embryos to develop; furthermore, the newly born bats require even higher temperatures to stimulate fast growth.

Bats prefer isolated breeding and nursery roosts whose requirements are rather precise in terms of temperature and humidity, avoiding unstable environmental areas affected by airflows or close to cave entrances, among others (Ransome, 1990). Apart from the artificial access to the cave, five ancient entrances have been identified so far, two of them in the studied area within the innermost sectors of the cave; both of them are today naturally sealed from

the external surface (Fig. 1). The first one is located at the north-easternmost section of *Galeria del Tragus*, (Fig 1) and the other situated to the south-westernmost point of *Galeria del Gran Canyó*, both of them on a NE-SW axis, approximately one kilometre away from each other. The most significant ancient entrance, from a chronological point of view, is the one located at the end of *Galeria del Tragus*, due to the discovery of a rich, well-preserved fossiliferous deposit of vertebrate remains (Bover et al., 2014), that include some Chiroptera bones attributed to *Rhinolophus* aff. *mehelyi* and *Pipistrellus* sp. The finding, among other mammal bones, of fossil remains belonging to the extinct and endemic goat *Myotragus* aff. *kopperi*, and the absence of more modern species of this genus, suggests that the chronology of the collapse of this natural entrance occurred during the Early Pleistocene, circa 2.4 My ago, or even before (Bover et al., 2014). The other ancient entrances have not yet provided clear geochronological data in order to determine whether they collapsed sooner or later than the Early Pleistocene; nevertheless, the remains of two other individuals also belonging to *Myotragus* aff. *kopperi* have been clearly identified, one of them at *Galeria d'en Pau*, and the other at a remote area within Sector F (Fig 1). All of this and the lack of more modern *Myotragus* species, especially *Myotragus balearicus* which is common in many caves in Mallorca, might indicate that all of them collapsed around the same period of time. This means the cave belonged to a closed cave system from the Early Pleistocene onward, until its discovery in 1968.

Table 5. Identified guano-derived mineral species and their chemical formulae.

Chemical Group	Mineral	Chemical formula
Sulfates	Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$
Phosphates	Fluorapatite	$\text{Ca}_5(\text{PO}_4)_3\text{F}$
	Hydroxylapatite	$\text{Ca}_5(\text{PO}_4)_3(\text{OH})$
	Wyllieite	$(\text{Na}, \text{Ca}, \text{Mn}^{2+})(\text{Mn}^{2+}, \text{Fe}^{2+})(\text{Fe}^{2+}, \text{Fe}^{3+}, \text{Mg})\text{Al}(\text{PO}_4)_3$
	Qingheite	$\text{Na}_2(\text{Mn}^{2+}, \text{Mg}, \text{Fe}^{2+})(\text{Al}, \text{Fe}^{3+})(\text{PO}_4)_3$
	Kribergite	$\text{Al}_5(\text{PO}_4)_3(\text{SO}_4)(\text{OH})_4 \cdot 4(\text{H}_2\text{O})$
Oxides /Hydroxides	Birnessite	$\text{Na}_4\text{Mn}_{14}\text{O}_{27} \cdot 9\text{H}_2\text{O}$
	Nordstrandite	$\text{Al}(\text{OH})_3$
	Gibbsite	$\text{Al}(\text{OH})_3$
	Todorokite	$(\text{Mn}^{2+}, \text{Ca}, \text{Mg})\text{Mn}_3^{4+}\text{O}_7 \cdot \text{H}_2\text{O}$
Silicates	Chromceladonite	$\text{K Cr Mg}(\text{Si}_4\text{O}_{10})(\text{OH})_2$

The mass of air inside the cave is not stagnant: important air movements have been documented in the cave, not only at the access hatch, but also when the access door is sealed while researchers are inside. On this latter situation, a soft measured breeze at a speed of 1 m/s, at a narrowing, was able to cause soda straw stalactites to vibrate. For a period of 18 months a wind measurement programme was carried out at the cave entrance. The results showed changes in airflow direction, from outflow to inflow or vice-versa, with distinct time delays between one situation and the other, this happening every day, with airflow velocities ranging from 1 up to 6 m/s.

The variation of airflow direction and airflow speed are a response of the cave system to air pressure

differences between the cave microclimate and the outside atmosphere. These key factors would point out to classify the cave as a barometric cave from a speleoclimatologic point of view, with air flowing into the same direction simultaneously at all entrances of the cave due to barometric influences (Conn, 1966; Pflitsch & Piaseck, 2003; Pflitsch et al., 2010). In addition, these authors also conclude that equilibrium between the outside pressure and the pressure inside the cave hardly ever lasts too long, causing an almost constant airflow.

This permanent airflow configuration and the influence of outside temperature and humidity changes would have obliged bats to choose specific sites to roost and breed.

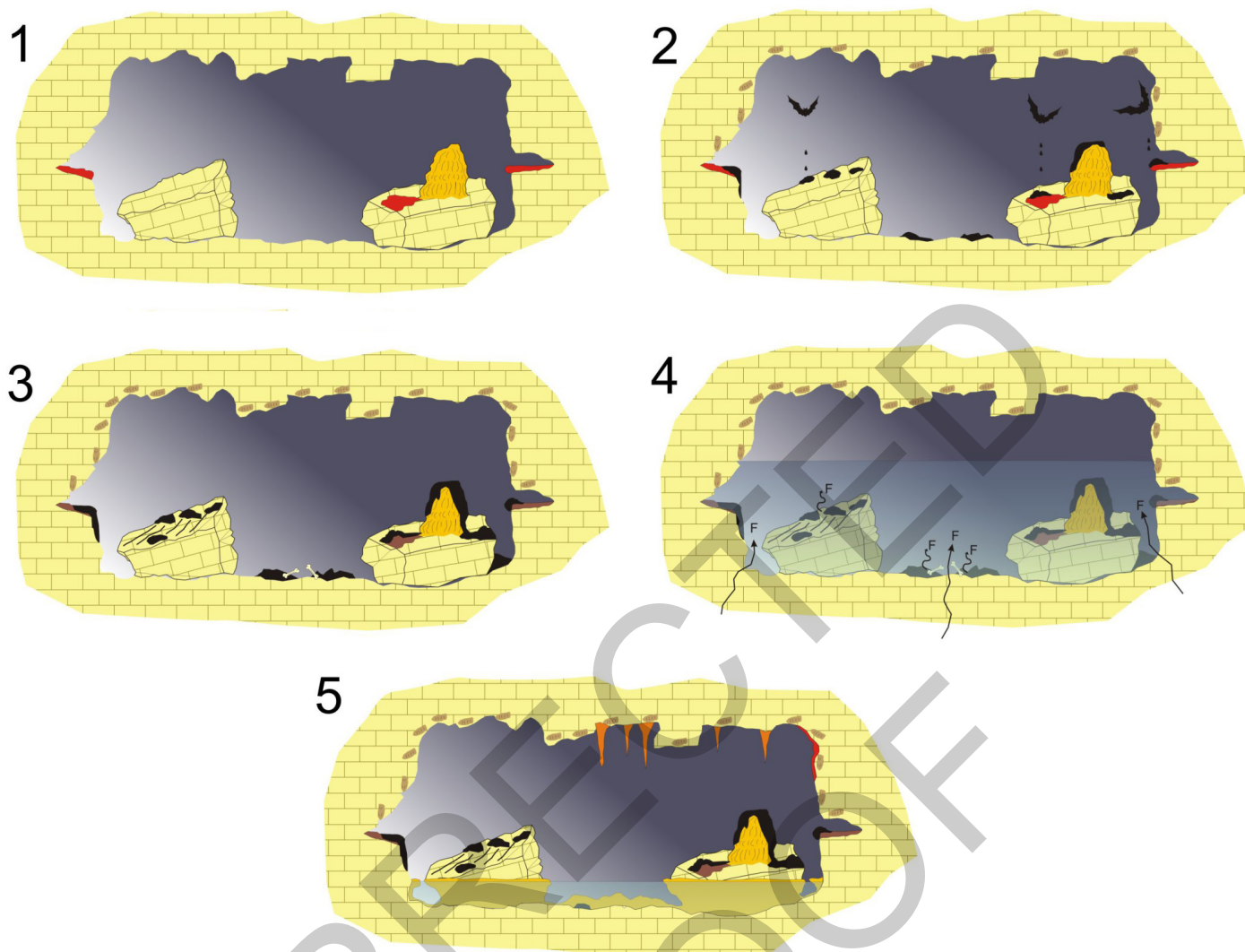


Fig. 10. 1) Situation after the main speleogenetic processes and before being inhabited by bats (in red colour, clays); 2) Bats use the cave as a roosting and breeding site. Accumulation of guano deposits and biomechanical erosion. Decomposition of guano starts in a moist environment causing acidic leachates that react with the bedrock and clayey deposits precipitating phosphates and other cave minerals; 3) Simultaneously, the acidic conditions carve elongated grooves on fallen boulders and cause important corrosion features on stalagmites. After the sealing of the main entrances of the cave, bats disappear; accumulation of bat bones that are dissolved by the highly aggressive leachates that release among other products fluorine; 4) During Pleistocene sea high-stands the cave is partially drowned interspersing hypogene episodes that carry fluorine that reacts with already precipitated phosphates; 5) When the phreatic level drops as a consequence of sea low-stands, the upper tier of the cave, where these passages are located, dries out. Carbonate precipitation processes start as a result of seeping vadose water, provoking the deposition of a calcite band that lines the bottom of the gallery, allowing the formation of freshwater ponds.

All sites with bat-related morphologies and guano-associated minerals, discovered so far, are not situated in the main galleries of this sector, *Galería del Gran Canyó* and *Galería del Tragus*, but at a certain distance away and at well-protected locations within them. Bats are sensitive to changes in their environment, therefore they choose small alcoves (lenticular-shaped niches and ovoid-shaped morphologies) to be more isolated and at more stable climatic conditions. At the time when most of the entrances remained open, the microclimatic conditions inside the cave could have been quite extreme during episodes of great and quick atmospheric pressure changes. The presence of calcified splashes on walls of a tight sector in *Galería del Tragus* is strongly suggestive of an ancient inward powerful draught of air (Fig. 11). The moving air mass would have circulated relatively smoothly from the massive ancient entrance, located at the end of this gallery, through the vast first hundredths of meters of the passage until reaching the beginning of the narrowing. At this point, the air would have

accelerated, gaining strength and being capable of causing spatter-shaped morphologies where walls were covered in pasty altered bedrock.

Morphologies associated to guano deposits

The genesis of these morphologies is a consequence of the accumulation of bat feces on the bedrock or on stalagmites; at these spots corrosion takes place under the guano surface at the rock-guano interface etching out these features (Audra et al., 2016, 2017, 2019).

Other possible corrosive processes that could have been involved in shaping these morphologies, could be ruled out for the following reasons. Firstly, all of these morphologies have been exclusively identified at the *Jacuzzi site*. Secondly, the section of the gallery that exhibits these features presents walls and ceiling covered with abundant bat claws and thumb marks. At the same time, the ceiling directly above these peculiar features does not normally have visible dripping points or stalactites. Thirdly, most of the



Fig. 11. Calcified splashes oriented by strong airflow covering a wall surface at a narrowing at *Galeria del Tragus*. The radial organization of elongated spatters developing on concave areas is quite obvious.

described bat-related morphologies show phosphate deposits on them (crypto-corrosion features). In the case of the stalagmite carved by niches, the process is highly likely to have been complemented by condensation-corrosion under vadose conditions (Audra et al., 2016, 2017, 2019).

Mechanical erosion features

The existence of bat-derived features (bat claws and thumb marks) caused by biomechanical erosion on walls and ceilings, could possibly be explained because their surfaces were already affected by deep weathering processes which would be related to condensation-corrosion processes. The latter happening when the temperature of the cave walls is below the dew point of the cave air; water condensates and reaches an equilibrium with the partial pressure of CO_2 of the cave atmosphere, provoking an aggressive solution that is able to dissolve limestone (Dreybrodt et al., 2005). During the period the cave entrances remained opened and bats inhabited in there, the already mentioned air movements (cold winter air from the surface) would have increased the condensation-corrosion rate causing a strong and faster weathering that affected walls and ceilings, allowing bat biomechanical erosion. Eventually, the progressive closing of the cave entrances would have reduced the tendency for further condensation to lower levels, fossilizing bat scratches.

Table 1 shows the measurements obtained from each of the described morphologies, maximum and minimum figures of claw and thumb marks are on average calculated on 6 samples for each of them. The layer of altered bedrock thickness can be quite variable ranging from 1-2 mm (*Galeria d'En Pau*, site 712, site 728-5562) up to 50 mm (site 848-853, *Jacuzzi site*). At the same time, it greatly varies along the section of the galleries: the upper half shows an increase of up to 50 mm in thickness, whilst the lower half is in most of the occurrences covered by a calcite coating.

As for thumb marks length, they range from 20 mm up to 190 mm, being more abundant on walls. The width of each of the claw marks is always constant, 10 mm, with lengths ranging from 30 up to 95 mm.

The mechanical erosion caused by bat claws and to a lesser extent bat thumbs, will depend on the characteristics and degree of alteration of the bedrock.

Seemingly, there is a direct connection between the degree of bedrock alteration, the thickness of the weathered layer, and the existence of, on the one hand, well-preserved clear grooves or, on the other, blurred marks (whether they are claws or thumb marks). Generally, well-marked and distinctive grooves are present with layers of altered rock between 1-10 mm in depth. On some occasions, when bats tried to clutch at walls, they were capable of causing significant mechanical erosion that virtually deprived the wall or ceiling of altered material (Fig. 7B).

Allegedly, the degree of bedrock weathering also facilitates the configuration of ovoid-shaped alcoves that are concentrated at locations where the altered bedrock sheet ranges from 10 to 30 mm (Table 2).

The inclination angle of the floor of ovoid-shaped alcoves and lenticular-shaped niches determines the deposit bulkiness that accumulates, being much higher at the latter due to their quite horizontal floor (Table 2). Although being classified as ovoid-shaped feature, the one described from site 5562, exhibits a more bell-shaped form, surrounded by other corrosion features, which could explain the presence of an anomalous thicker deposit.

Mineralogy

The occurrences of nordstrandite, gibbsite and todorokite are not new in the cave; they were firstly identified in the mineral deposits that are distributed on vent's roof and walls, at different locations of *Sector Nord*, *Galeria del Tragus*, *Galeria de les Toberes*, etc. (Merino et al., 2009; Fornós et al., 2011). The mineral assemblage of these extremely fluffy and porous materials is composed as well of strontianite, celestine, barite, chamosite and jacobsonite, which along with the abundance of vertical feeders or vents, suggests a hypogene (thermal water related) basal recharge at various times during the evolution of the cave (Ginés et al., 2014, 2017; Onac et al., 2014).

The new discovered occurrences of nordstrandite (Table 4) exhibit a thin pinkish to reddish, brown to orange coloured coating, whereas gibbsite and todorokite are intermingled with other minerals, including phosphates, occurring as brown to black deposits. Specifically, at one locality, nordstrandite is accompanied by todorokite, birnessite, and calcite, or by illite, calcite, kaolinite, or quartz at others (Tables 3, 4). A thin layer of nordstrandite, illite and kaolinite is overlaying a nordstrandite and fluorapatite deposit that covers a fallen boulder. The vast majority of these mineral assemblages are deposited on fallen boulders or rock shelves (Table 4), but nordstrandite has also been identified at the bottom of an ovoid-shaped feature, along with calcite, kaolinite and muscovite-illite. Only one occurrence of nordstrandite intermixed with fluorapatite, gibbsite, and calcite has been identified in a multicoloured ceiling deposit. The characteristics of the spots where these minerals mixtures occur, horizontal surfaces, or bat-related features, would reveal a certain connection

with bats and guano deposits. Polyak (1998) and Polyak and Provencio (2001) identify, among others, nordstrandite, gibbsite and todorokite as a possible speleogenetic by-product formed as a consequence of the reaction between H_2SO_4 bearing waters and clay minerals (bedrock in the case of todorokite) with the participation of microorganisms and their by-products. Cova des Pas de Vallgornera does not present a H_2SO_4 speleogenetic vector along its evolution, being utterly devoid of H_2SO_4 speleogenetic features.

In this sense, and taking these points into consideration, the origin of the new occurrences of nordstrandite, gibbsite, and todorokite could be related with acidic leachings, specifically sulfuric acid, released from guano decomposition (boosted by microbial action) reacting with aluminium-rich clays to generate these aluminium hydroxides, or with the limestone bedrock enriched in manganese by earlier ascending hypogene flows (Merino et al., 2009; Fornós et al., 2010; Ginés et al., 2014, 2017; Onac et al., 2014), in the case of the hydrous manganese oxide.

As stated before, phosphates are the largest group of minerals reported in this article. After having taken and analysed more than 290 samples from all around the cave (including the 70 collected at the studied sites), only a total of 34 samples yielded phosphates. So far, phosphates have been only identified at places where bat-derived features and morphologies associated to guano deposits are present, being fluorapatite by far the most abundant. The widespread occurrence of fluorapatite would indicate that the agent providing fluorine would be present at all sites and with a proper concentration as to react with other minerals. Fluorapatite is associated with fossil bone and teeth deposits (Hill & Forti, 1997; McFarlane & Lundberg, 2018), with bat urine reacting with calcite crusts (Hill & Forti, 1997; Onac & Veres, 2003), with bat guano deposits or with the existence of traces of fluorite in the bedrock (Hill & Forti, 1997). The cave is developed in the carbonate rocks appertaining to the Reef Complex Unit (Pomar, 1991), with an age ranging from Upper Tortonian to Lower Messinian (Pomar et al., 1996; Fornós et al., 2002). The bedrock is predominantly composed of calcarenites (calcite 98.27%, dolomite 1.73%), which locally presents some dolomitization (dolomite 98.2%, calcite 1.3%, quartz 0.5%). This would rule out the influence of existing fluorite in the bedrock as F^- provider. Currently, the only known important fossil bone deposit is situated at *Galeria del Tragus* relatively far away from the *Jacuzzi* site and far from the rest of locations; two bat species belonging to *Rhinolophus* and *Pipistrellus* genera were recovered from that deposit (Bover et al., 2014). In spite of the fact that the accumulation of bat bones during the use of the cave as breeding and nursery sites is likely, no bone remains have been found in any of the locations with bat-related morphologies. The wet environment of the cave would have caused a quick guano decomposition, provoking acidic conditions and the dissolution of bat bones, consequently supplying fluorine. Bat urine and guano accumulations could have also supplied part of the F^- necessary to form fluorapatite or hydroxylapatite. However, we cannot

exclude the influence of another agents that could have also been involved in the contribution of fluorine.

The cave gathers morphological and mineralogical evidences of deep hypogene recharge episodes (Ginés et al., 2009, 2014; Merino et al., 2009, 2011; Fornós et al., 2010, 2011; Onac et al., 2014) linked to the geothermal anomalies existing in the Lluçmajor platform (López et al., 2006; López, 2007). In addition, current chemical analysis of the Lluçmajor aquifer showed significant concentrations of F^- . López (2007) carried out an extensive campaign of water sampling from drilled wells within the area; 9 samples out of the 21 studied yielded F^- concentrations above 200 $\mu\text{g/L}$, whereas 3 of the 9 indicated concentrations of 1080, 1170, and 1966 $\mu\text{g/L}$. These ascending hypogene solutions might have also acted as F^- carrier, reacting with already precipitated phosphates to produce fluorapatite.

A common secondary mineral associated with guano deposits is gypsum, but due to its high solubility, the moisture conditions present in the cave, the extensive vadose water accumulations fed by seeping waters, and the repeated inundation of the cave during the high-stand Pleistocene periods, most of the gypsum would have been removed. The only occurrence of gypsum is located at *Galeria d'en Pau* where it forms small saccharoid deposits.

CONCLUSIONS

The cave provided shelter for bat colonies until it was sealed by the collapse of its natural entrances around 2.4 My ago, it is highly likely it remained isolated from the outside until it was discovered in 1968. At present, it does not harbour any bat colonies.

The impact of ancient bat colonies in Cova des Pas de Vallgornera can be inferred by the discovery of the following ichnofossils, as well as morphologies related to guano deposits and associated cave minerals:

- bat claws and bat thumbs marks,
- morphologies present in lenticular cross-section niches and ovoid-shaped alcoves,
- haystack-shaped stalagmites and stalagmites covered in niches,
- crypto-corrosion features (flutes),
- guano-derived cave minerals (fluorapatite, hydroxylapatite).

All of this makes the cave an outstanding and unique site for cave mineralogy associated to guano-derived minerals and related morphologies. At the same time, the location of these bat-derived features along with the study of the microclimatic conditions that prevailed and prevail in the cave provide palaeoenvironmental information and can be used as indicators of bat ethology.

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