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Technical Note

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Fossil Vertebrate Database from Cova des Pas de Vallgornera (Llucmajor, Mallorca)
GUEST EDITORIAL

Cova des Pas de Vallgornera: an exceptional coastal karst cave in the Western Mediterranean basin

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Mallorca Island represents an European benchmark with respect to coastal karst and Quaternary investigations (Ginés et al., 2012). As an exponent of the early explorations, E.A. Martel discovered in 1896 important extensions in Coves del Drac when crossing the brackish pools of an outstanding littoral karst phenomenon that nowadays is the most visited show cave in Europe. The relevance and amount of coastal karst studies in Mallorca were growing during the 20th century, but explorations recently conducted in Cova des Pas de Vallgornera (CPV), particularly from 2004 till today, led to a tremendous increase in the knowledge of Mallorcan karst. With over 74 km of surveyed passages and chambers, including more than 17 km of underwater conduits, CPV is the longest cave of the Balearic Archipelago. The cave was accidentally discovered on 1968 when building a touristic hotel in the southern coast of the island. Since then, and thanks to the involvement of many cavers and, more recently of speleo-divers, the present surveyed length continues to grow and there is no foreseeable end in sight, particularly in the underwater extensions.

The cave develops in Upper Miocene reef limestones whose progradation built an extensive tabular platform (90 km long and up to 20 km wide) that has been intensely karstified, especially near the littoral where an interesting eogenetic coastal karst (Vacher & Mylroie, 2002) is widely developed (Ginés et al., 2007; Lace & Mylroie, 2013). In fact, the cave pattern of CPV and their morphological features suggest the necessity of shifting from a carbonate island karst model towards a Carbonate Coast Karst Model. In our case, the speleogenesis of CPV includes besides coastal mixing processes other hydrogeological inputs, as for example, the existence of a deep-seated geothermal recharge. The diverse speleogenetic pathways invoked in this particular case, bring up again an unsolved terminological problem: what must be considered a hypogenic process? (Palmer, 2007; Klimchouk, 2007). Throughout all the papers included in this issue, the authors have used this term exclusively when referring to uprising waters from depth, independently of the source of aggressiveness; therefore, simple coastal mixing processes are not termed hypogenic in order to better identify the speleogenetic factors involved.

CONTRIBUTIONS IN THIS VOLUME

The collection of papers gathered in the present issue covers a broad range of topics, aiming to document the current scientific knowledge on the Cova des Pas de Vallgornera.

The first article of this issue includes an historical introduction to the exploration of the cave. Signed by the most involved explorers, both in the air-filled passages and underwater extensions, the paper by Merino et al. makes an accurate and concise description of the cave system, illustrated with a couple of topographical surveys corresponding to the different stages in its exploration; some comments on the future prospects regarding research and exploration are also addressed. The paper ends with information about the legal situation of the cave in relation with its protection and management status.

The geological aspects and the speleogenesis of the cave are tackled by Ginés et al. in an extensive paper that highlights the role played by the sedimentological characteristics of the bedrock over the cave patterns and passages morphology. On the basis of different morphological informations as well as data from cave deposits with vertebrate fauna, the authors revise the complex implication of different agents that have been involved in the speleogenesis, such as: coastal
mixing dissolution, drainage of meteoric diffuse recharge, and hypogene basal recharge related to local geothermal phenomena. The paper ends with a geochronological timeline of the cave evolution that takes into consideration the role played by the sea level fluctuations since the mid-Pliocene.

A third paper by Merino et al., deals with the typologies and distribution of the speleothems within this eogenetic cave system. The authors discuss the role played by the factors that control their distribution, e.g., the lithological characteristics (mainly textural variations), the hydrogeology, and other speleogenetic aspects. Special attention is devoted to the description of several speleothem types not found in any other cave in Mallorca; these are documented by spectacular images that contribute to their description. Particular attention is addressed to the phreatic overgrowths on speleothems (POS) that precisely record the Holocene and Pleistocene sea levels (Tuccimei et al., 2006; Dorale et al., 2010; Giné et al., 2012).

Onac et al., while describing the mineral assemblages present in the cave, reinforce the role of the three speleogenetic pathways that have configured the present pattern and morphological features of the cave, i.e. the sea coast mixing, the meteoric recharge, and the ascending warm groundwater. Their interaction produces certain unusual minerals (barite, celestine, nordstrandite, etc.) completely different when compared to other cave minerals in the island, which are clearly dominated by carbonates. Several of the not common minerals were found within or nearby clear hypogenic morphologies although none of them are sulfuric acid by-products.

The detrital sedimentary infilling is covered by the paper of Fornós et al. Although sediments have not a conspicuous presence along the cave, they represent a good example of the complex sedimentation processes that can take place in those coastal karst environments. Autochthonous carbonate materials (detached rock particles, calcite rafts, etc.) intermix with allochthonous infillings carried into the cave through small surface openings (soil infiltration) or larger entrances that allow direct deposition of eolian sands and a rich paleontological content. Presence of Mn- and Fe-rich in the sediments of the underwater passages give new insights into the sedimentary processes involved during the cave evolution.

Two different papers account for the paleontological content of the sediments present in CPV. The paper of Bover et al., brings good paleontological and chronological data on the vertebrate remains discovered in the Galeria del Tragus, once an entrance facies sedimentary deposit related to an ancient opening. The exceptional preservation state shown by these Early Pleistocene fossils had allowed the characterization of its faunal assemblage, which otherwise is poorly documented till now in the Balearics. Paleontological data are supplemented by a fossil vertebrate database paper (Díaz et al.) including three endemic mammals, two taxa of Chiroptera, sixteen taxa of birds, one Reptilian taxon and one Amphibian from the Early Pleistocene.

Geochemical and isotopic studies on phreatic waters are covered in the paper of Boop et al. This study deals with the geochemical factors that controls the precipitation of calcite or aragonite in the uppermost part of the brackish pools giving way to POS that have important implications for sea level history. The authors compare the degassing of $CO_2$ in two Mallorcan caves (CPV and Coves del Drac), where different POS mineralogies are present, and discuss the relation with the air cave ventilation and the salinity values resulting from mixing waters.

Microbiology topic is present with two different papers. Busquets et al. report the species diversity of the microbial communities found along three cave pools of this anchialine environment (mainly Gammaproteobacteria and Actinobacteria). Their biogeochemical role in precipitating calcite and controlling the variability of crystal habit and growth according to different species is highlighted. Menning et al., describe the species richness and the relative abundance of Achaeae, Bacteria, and microbial eukaryotes by means of quantitative PCR. The vertical profiles investigated in CPV as well as in three different pools of Coves del Drac (a touristic cave), report results that highlight the importance of the anthropic influence in the touristic cave as well as reinforce the similarities in the microbiological presence for both caves.

FUTURE PROSPECTS AND ACKNOWLEDGEMENTS

Most of the current research lines, namely, morphological, mineralogical, sedimentological, geochronological, geochemical, or microbiological are represented in the 10 papers included in this issue. Nevertheless, the potential for new investigations remains wide open because just the general trends of every field have been outlined. To begin with, most of the physical parameters of the cave atmosphere and waters remain largely unpublished; such studies are in progress along with their spatial distribution and seasonal variation. Furthermore, corrosion studies due to condensation processes are now being explored, as well as several aspects concerning the deposition of Fe-Mn sediments, radon concentration, terrestrial and anchialine fauna, etc. These are only a few of many other research topics that are currently under way.

Some other important topics remain only partially solved, as is establishing the overall chronological framework of the processes that have acted in the development of the cave. Future investigations on this topic will contribute to a better knowledge of the evolution of littoral karst systems in the Balearics, supplying additional insights to the broadening interpretation of coastal karst phenomena in complex geologic settings.

Most of the research projects developed in CPV have been performed as collaborative tasks involving cavers from the Federació Balear d’Espeleologia together with Mallorcan scientific institutions as the Universitat de les Illes Balears (UIB) or IMEDEA.
(CSIC-UIB), sometimes in collaboration with other foreign universities (Università di Roma Tre, University of South Florida, or Babes-Bolyai University in Cluj).

It must be specifically highlighted the tasks carried out by many individuals from a number of speleo-clubs grouped in the Federació Balear d’Espeleologia who through their continuous and anonymous work have improved the knowledge of this exceptional cave system; their support during the scientific field-trips has been decisive.

Thanks are due to the editors of the International Journal of Speleology who have supported the publication of this special issue from the very first moment. Particularly, we are very grateful to Dr. Bogdan P. Onac (Editor-in-Chief) for his continuous assistance in the preparation of this volume, to all reviewers (mostly anonymous) for their expertise that have improved the final versions of the papers, and last but not least, the University of South Florida Libraries production team for professionally typesetting the manuscripts.

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We are especially indebted to the regional authorities from Conselleria d’Agricultura, Medi Ambient i Territori from Govern de les Illes Balears, who granted permission to carry on explorations and research activities in CPV.

Nowadays the cave is protected by the regional environmental authority and was declared a Site of Community Importance (Natura 2000 Network, ECC). The exploration for new extensions, especially in the flooded passages has not yet finished. It is our hope that the results expressed in the present issue will encourage new generations to pursue, not only with the exploration but with the scientific research, which surely will increase the knowledge on coastal karst thanks to the enormous investigation potential shown by the Cova des Pas de Vallgornera.

REFERENCES


The Cova des Pas de Vallgornera lies in the Llucmajor municipality, in southern Mallorca, and is the longest cave in the Balearic Islands. Currently its surveyed length is over 74,000 m, including more than 17,000 m of underwater extensions. The cave was discovered accidentally in 1968, but it was in 2004 when a major breakthrough shed light on its real extension and importance. The cave roughly shows two tiers of passages, apart from the underwater extensions, the first one is between 7 and 11 m above the mean sea level, the second one is about at the water table level. The importance of the cave is not only related to its extension, but also to the presence of a wide variety of speleothems and outstanding solutional morphologies that evidence a complex evolution. The cave is under the protection of Conselleria de Medi Ambient, Govern de les Illes Balears (the Regional Environmental Authority) and was declared Site of Community Importance, within the Natura 2000 Network.

Abstract: The Cova des Pas de Vallgornera lies in the Llucmajor municipality, in southern Mallorca, and is the longest cave in the Balearic Islands. Currently its surveyed length is over 74,000 m, including more than 17,000 m of underwater extensions. The cave was discovered accidentally in 1968, but it was in 2004 when a major breakthrough shed light on its real extension and importance. The cave roughly shows two tiers of passages, apart from the underwater extensions, the first one is between 7 and 11 m above the mean sea level, the second one is about at the water table level. The importance of the cave is not only related to its extension, but also to the presence of a wide variety of speleothems and outstanding solutional morphologies that evidence a complex evolution. The cave is under the protection of Conselleria de Medi Ambient, Govern de les Illes Balears (the Regional Environmental Authority) and was declared Site of Community Importance, within the Natura 2000 Network.

Keywords: Cova des Pas de Vallgornera; Mallorca; history; description; exploration


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INTRODUCTION

The cave was discovered on April the 26th, 1968 while drilling a cesspit for the sewage of a hotel that was being built in the area. During the following days, a representative from the Llucmajor local Council along with a photographer undertook the first visit to the cave. Two days later, the news about the discovery were published on the front page of the Diario de Mallorca newspaper.

Local caving groups: Centro de Actividades Espeleológicas, Grup Espeleològic EST and Speleo Club Mallorca began the exploration of the cave. Later, in 1970, a group of Belgian cavers from Groupe Speleo Namur Cinquè undertook the first survey of the cave. Between 1991 and 1992, cavers from Grup Espeleològic EST and Secció d’espeleologia de l’ANEM completed the exploration of the cave, yielding about 2 km of cave passages. In 1994 an important breakthrough came when cavers from Grup Espeleològic EST enlarged a tight passage that led the explorers to new galleries and chambers. The survey and exploration of the newly discovered part started in 1994 and was completed in 1999; at that time the cave was 6.4 km long including some extensive pools. From 2002 members of Grup Espeleo Llubí and Secció d'Espeleologia de l'ANEM faced the challenge of investigating a slight draught of air at one remote chamber. In 2004 Grup Espeleo Llubí achieved a major breakthrough when a draughting slot was discovered, leading the explorers into the biggest known chamber in the cave so far. The discovery fueled the fires and the cavers begun the exploration of a maze of passageways and chambers. Along the way, cavers from Secció d’espeleologia de Voltors and Grup Espeleològic EST joined the team that is still exploring, surveying and studying this impressive and complex cave; important underwater extensions are currently being explored and surveyed by cave divers from Grup Nord de Mallorca and lately also Grup Espeleo Llubí.

The cave is located in the Llucmajor municipality in southern Mallorca, being developed in the natural area of Migjorn (coordinates UTM/WGS84, 489120; 4.357.510). A great deal of galleries and chambers lies beneath the Vallgornera housing estate (east of Cala...
Pi), while the northernmost sections are developed under farm land (Fig. 1). This littoral karstic region is formed by a tabular platform built up by a Tortonian-Messinian reefal limestones sequence. With over 74,000 m of surveyed passages and chambers, it is the longest cave of the island and one of the most important in Spain (Fig. 2).

The cave is formed by a series of breakdown chambers which are interconnected with each other by a network of passages situated at different levels. In spite of the labyrinthine pattern of the cavern, it is possible to recognize several rectilinear main passages that run relatively parallel from SW to NE. Some of them are close to one kilometre in length, being structurally controlled by major joints. The lower part of the cave is occupied by brackish water pools, whose surfaces rise or fall with tidal fluctuations of the sea level. The system has two tiers of passageways clearly

Fig. 1. a) Location of Mallorca Island within the Western Mediterranean sea; b) The red square shows the situation of the cave in the Southern region of Migjorn; c) Plan pattern of Cova des Pas de Vallgornera overlapping an aerial view of the area (ortophoto PNOA-2008).

COVA DES PAS DE VALLGORNERA

Fig. 2. Map of the cave with the main sectors described. While the Sector Antic and Noves Extensions contain longitudinal sections, there is a lack of them in Descobriments 2004 due to the impossibility to construct a reasonable longitudinal section in this maze of long and in general, narrow galleries.
differentiated: the first one is located approximately at the current water table level, whereas the second one is situated between 7 and 11 m above the brackish waters. Moreover, underwater explorations have revealed the presence of a vast series of galleries below the present-day water table level.

The importance of the cave is not only related to the extension attained by the cave, but also the finding of rare types of speleothems, fossil remains, Quaternary sand deposits, and conspicuous corrosion morphologies. All this has prompted the local authorities (Conselleria de Medi Ambient, Govern de les Illes Balears) to protect the cave and access to it is now severely restricted.

HISTORY

Exploration has taken place in three different stages, corresponding to those of the breakthroughs.

Sector Antic (1968-1992)
Between 1968 and 1969 local caving clubs, Centro de Actividades Espeleológicas, Grup Espeleològic EST and Speleo Club Mallorca, began the explorations (Fig. 3). Subsequently, the hotel proprietor, a Belgian citizen at that time, contacted a group of Belgian cavers from Groupe Spéléo Namur-Ciney and commissioned them to explore and survey the cave with the aim of considering the possibility of opening it as a show-cave (Collignon, 1982). However the report, based on that information, was negative and plans were abandoned.

As a result of a meeting held between cavers from Grup Espeleològic EST and Secció d’Espeleologia de l’ANEM in 1990, it was decided to begin an comprehensive survey and study of the cave. The task began in 1991 and was finished by the end of 1992, yielding about 2 kilometres of surveyed passages, the so-called Sector Antic (Merino, 1993). The exploration of underwater passages began in 1991 when divers from Cas Triton explored and surveyed the submerged galleries located in this sector.

Noves Extensions (1994-1999)
On July the 2nd 1994, an important breakthrough came when, Miquel Barceló and Pedro Riera from Grup Espeleològic EST enlarged a tight passage that led the explorers into a series of new galleries and chambers (Fig. 2). Early in the winter of that year, the survey of the new discoveries started and continued for some months in 1995, but some problems within the survey team and later the sealing of the cave entrance by the local Authority caused a temporary interruption to the work in the cave.

After several meetings held between the Federació Balear d’Espeleologia and the Conselleria de Medi Ambient along with the Llucmajor Council, the issue was addressed and the decision of protecting the cave was taken. A small locked and gated hut was built over the entrance. Eventually, the last leg of the survey task was restarted on July the 4th, 1998, being finished on November the 27th, 1999. Furthermore, between 1995 and 2001 members of Grup Nord de Mallorca carried out several visits to the cave exploring and surveying submerged passages of the fresh discovered galleries. At that time the cave was 6.4 km long including some extensive brackish pools. That sector was named Noves Extensions (Merino, 2000).

Descobriments 2004 (2004-2013)
Cavers from Grup Espeleològic Llubi (GELL) and Secció d’Espeleologia de l’ANEM kept visiting the cave with the aim, among others, of continuing studies at the remote spots of the cavern. From 2002 exploration was focused on an area extending from the innermost part of Llac de Na Gemma and Sala de Na Bàrbara (in the Noves Extensions sector), where a slight draught fluctuated in intensity and direction. Because of that, a thorough control of the air pressure and water table level changes were established. As a first result, some new narrow galleries and a small chamber with a pond were found at the northern section of Sala de Na Bàrbara.

2004 was an important year in the history of Cova des Pas de Vallgornera. After a massive series of explorations that took place throughout 2003 and the beginning of 2004, in June it was possible to follow the air flow. Consequently, a draughting slot was found and widened by the explorers who gained access to a series of small passages and tight rifts that seemed to get narrower preventing them from progressing.

After spending several hours exploring between boulders, Guiem Mulet squeezed through a tight slot that led him to the beginning of the Sala Que No Té Nom. Speechless, he crawled back to join Toni Mulet and Tony Merino to tell them of the fresh discovery. The three highly excited cavers explored the vast chamber, the largest found in the cave so far, hardly believing what lay beyond.

Since then exploration and survey tasks have been taking place without a break. With the ambitious aim of fulfilling the project, different local caving clubs, including Secció d’Espeleologia Voltors, Grup Espeleològic EST, and cave divers from Grup Nord de Mallorca worked together with Grup Espeleològic Llubi. Cova des Pas de Vallgornera undoubtedly became one of the most jaw-dropping cave in Spain, due to its surveyed length over 74,000 m so far (Merino et al., 2006, 2007, 2008, 2009, 2011). In 2007 cave divers from Grup Nord de Mallorca joined in and started the exploration of the
underwater extensions situated in the newly discovered sector, called **Descobriments 2004**. The group of divers found considerable prolongations with long galleries and chambers that present important accumulation of sediments, well-decorated passages, etc. In just three years, from 2007 to 2009, the group devoted more than 140 visits to the cave, exploring and surveying more than 10,000 m of underwater passages, photo documenting their discoveries (Gràcia et al., 2009). At the beginning of 2012 cave divers from Grup Espeleo Llubi also started to explore and survey different submerged areas. Since the first exploration in the **Descobriments 2004** series and because of the great deal of passages and their complexity, the need to set up an underground camp became clear. The purpose was to be able to spend two or more days in the cave and at the same time improving the well-deserved rest period. As a result of the cave unique features and the need of swimming across long ponds cavers had to face a logistic problem that eventually was overcome. Once all the equipment had been hauled to a previous chosen spot at the Sala Que No Té Nom, the camp was definitely established (Fig. 4).

As far as the survey task, new challenges were taken up; the main problem was how to keep surveying without losing the broad overview on the already mapped labyrinth of passages and chambers. The pencil-and-notebook traditional system along with notes and sketches became ineffective due to the cave’s size and complexity. Therefore the use of PDA’s and lap-tops was undertaken, besides the disto laser measuring device brought about a significant change to the routine, not only because of the higher level of performance achieved, but mainly for conservation reasons. Those devices greatly simplified the instrument readings and at the same time the disto laser prevented cavers from being too close to formations. Nevertheless, when surveying while swimming in partially drowned passages or extensive ponds most of the electronic gadgets were useless; then the pencil, water-proof notebook, and tape were again required.

**DESCRIPTION OF THE CAVE**

The cave can be clearly divided into three well-differentiated units, related to the temporal evolution of the discoveries: the so-called **Sector Antic**, the **Noves Extensions** and finally, the **Descobriments 2004** series. The connection between these three units corresponds to tight constrictions that previously isolated them, which needed the clearance of some speleothems to allow the exploration. In order to attain a proper description of the cave, up to 10 sectors have been distinguished (Fig. 2) most of them corresponding to individualized sectors within the **Descobriments 2004** series.

**Sector Antic**

The **Sector Antic** (Merino, 1993) is formed by a breakdown chamber, Sala d’Entrada, which is gained through the only known entrance to the cave, a 6 metres deep man-made well. Extensive flowstones cover and cement most of the large accumulations of boulders of different sizes that make up the floor. The chamber is lavishly decorated with stalactites, stalagmites and groups of columns that cause a slight compartmentalization. A gour situated to the East side of the chamber shows the way to the Pista Americana, which is reached after negotiating a boulder choke and climbing down a steep slope. The Pista Americana is floored with large boulders and small brackish ponds, up to 5 m in length, occupy the right-hand side of the passage, which is scarcely decorated. The way leads on and opens into a chamber, Sala del Moonmilk, deriving its name from the abundance of these deposits that covers the area. Close to the end of this uneven, low-roofed chamber, an opening in the floor allows descending through the boulders in Via Max, a passage that contains similar features.

Back to the Sala d’Entrada, and towards the NW sector, a downslope constricted passage gives access to the drowned section of **Sector Antic** and the galleries that constitute the **Noves Extensions** (Merino, 2000).

**Noves Extensions**

The passages of **Noves Extensions** sector, located at the current water table elevation, can be divided into two clearly differentiated sectors: the Lakes series and the Lower Maze. The former one contains the impressive pool of Llac de Na Gemma which is more than 200 m long and constantly varies in width (reaching a maximum of 40 m), narrowing towards the end because of flowstones and boulders leading into Sala de Na Bàrbara. The first third of Llac de Na Gemma is gorgeously ornamented with soda straw forests and assemblages of stalactites covered in helicites that reach the water table; war club stalactites occur at some points. This richness in formations vanishes in a matter of few meters after which the bare ceiling and walls only show corrosion morphologies. The latter, the Lower Maze, is formed by a framework of small passages whose walls and roof are covered with solutional Sculpturings and groups of speleothems (Fig. 5) as it can be clearly seen in Galeria d’Enmig and Galeria de Llevant.

**Descobriments 2004**

Finally, the **Descobriments 2004** series is where the cave reaches its longer and notable dimensions (Merino et al., 2006, 2007, 2008, 2011). Roughly speaking, the new galleries and chambers discovered

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![Fig. 4. During the early stages of exploration at Descobriments 2004, a camp was set at Sala Que No Té Nom in order to make easier the long exploration week-ends easier (photo by Tony Merino).](image-url)
in Cova des Pas de Vallgornera are neatly organized in two different tiers, besides the underwater extensions. The first one is located at the water table level or slightly above it. At points where the roof and walls have collapsed, passages and chambers of different sizes occur, some of them impressively large, like Sala Que No Té Nom, which has an area exceeding 11,000 square meters. The second, the upper tier, situated between 7 and 11 m above the water table, is characterized by networks of rectilinear passages creating complex labyrinths (Fig. 6). In these series up to eight new sectors can be distinguished: Sector de les Grans Sales, Sector de Gregal, Sector Subaquàtic de Gregal, Sector F, Sector del Clypeaster, Sector del Tragus, Sector Nord and Sector dels Privilegiats.

**Sector de les Grans Sales**

The first one, whose name refers to the great chambers included in it, is located to the northeastern part of Noves Extensions and Sector Antic passages. It consists of an assemblage of breakdown chambers heading in a northwest-southeast direction, ringed by phreatic water pools. Sala Que No Té Nom (Fig. 7) is gained from a subaerial small passage that begins at Sala de Na Bàrbara -the last chamber of Noves Extensions series- or diving from the NE aquatic section of Sector Antic. The existence of large boulders that floor the chambers is the common denominator to all of them. Speleothems are rather scarce and corrosion processes significantly affect some of them. As a consequence of boulder settling, some flowstones that cover the floors, are cracked and broken. Sala Que No Té Nom, with a length of 230 m and an average width of 46 m, is so far, the largest breakdown chamber in the cave and could be considered the “hub” of the cave from where most of the passages are distributed. The water table is reached at both sides of the chamber’s central axis through down slopes composed of rocks and boulders. The Llac Quadrat, which is about 65 m long and with a maximum width of 20 m, has the same features but is totally drowned by phreatic waters; the bottom of this massive brackish lake is formed by a large accumulation of boulders. This point is the access way to Sala Blanca and to other sectors of the cave (Sector de Gregal and Sector Subaquàtic de Gregal).

The already described Sala Que No Té Nom continues to the NW through Galeria dels Espeleotemes, which is remarkable for its dimensions and abundance of speleothems Galeria dels Espeleotemes is the connection with the innermost sectors of the cave.

**Sector de Gregal and Sector Subaquàtic de Gregal**

These two sectors, located at the water table level or below it, spread out in NE trend from the Sala Que No
The southern section consists of shorter passageways extending in variable directions, being currently still explored. Finally, several aquatic breakdown chambers are scattered within this area, being only reachable by means of diving equipment; Sala Jaume Damians and Sala de la Fadrina Vella are the largest so far (Fig. 9).

**Sector F**

It includes a network of small interconnected passages, of an average width of 2 m and 3 m in height, normally located at the cave’s upper tier. It is developed to the SW zone that lies between Sala Que No Té Nom - Galeria dels Espeleotemes and Sector del Clypeaster. In spite of the fact that this sector is above the Lower Maze of Noves Extensions, it has not been possible to link them so far. Areas with corrosion patterns alternate with others where a wide range of speleothems have been deposited. It is characterized by a maze of galleries of diverse sizes. Some sections present regular and flat floors covered by flowstones, while other joint-controlled passages are uneven and tight. In general, when the gallery is wide the floor is often level. Walls and ceiling can quite often be totally covered in moonmilk, alternatively well-decorated spots with varied speleothems also exist. Extensive}

**Té Nom and Llac Quadrat area.** Both stand out because of their dimensions. In Sector de Gregal some of the most important galleries are Galeria del Quilòmetre (Fig. 8), with a length of 1000 m, and Galeria dels Perduts which is 750 m long. The majority of these long passages are flooded by brackish phreatic waters; the large accumulation of boulders, caused by breakdown processes, constantly force cavers to enter and leave water. Abundant solutional ascending grooves and channels are conspicuous on the walls of some of these passages. At the same time, along the SE side of this area different collapse chambers are present, like Sala de la Fradina Vella and Sala de la Menorquina. The beginning of the last third of Galeria del Quilòmetre is marked by another rounded-shape chamber, Plaça de Toros. This breakdown chamber, 40 m long and 20 m in width, is formed by a boulders cone rising 8 m above the water table. Scattered among the main galleries, labyrinths formed by smaller passages occur. Finally, Galeria d’en Navarrete, which is 450 m in length, must be mentioned, not only because of the abundant corrosion morphologies that cover walls and ceiling, but also for the notable accrual of mud deposits piled up in the middle of the passages.

The underwater sector, **Sector Subaquàtic de Gregal,** is a massive assemblage of totally flooded passages, with only a few aquatic galleries located around the water table, as well as some breakdown chambers. Its passages reach outstanding length and head in northeast-southwest direction; Galeria Miquel Àngel Barceló, Galeria Grup Nord de Mallorca and Galeria Collonuda must be underlined. The first one is quite parallel to Galeria del Quilòmetre, trending SW to NE; its width is variable, between 1.5 to 7 m, reaching a depth of 8 m.

Galeria Grup Nord de Mallorca is a structurally controlled passage with a length of 700 m that ends at a collapsed area where the flat ceiling allows the exposure of marly strata. Along the passage, various types of morphologies are present, corrosion features are prominent while speleothems are scarce.

With a roughly N-S trend, Galeria Collonuda is a massive gallery that can be divided into two areas, depending on the passage direction. The first, heading N, is practically deprived of any branches, while the

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**Fig. 8.** Galeria del Quilòmetre, located at the Sector de Gregal, is one of the longest passages in the cave, totally flooded by phreatic brackish waters. At some spots a wide range of speleothems are present (photo by Tony Merino).

**Fig. 9.** Rectilinear structurally controlled passage located in the underwater extensions of Sector Subaquàtic de Gregal. Although devoid of formations, this gallery shows some corrosion morphologies in its upper section. Many of the underwater passages present a similar morphological setting to that of the upper tier of the cave (photo by Miquel Àngel Perelló).
gours, most of them totally filled with water, are ringed with calcite crystals.

**Sector del Clypeaster**

This section is a network of maze-like galleries located not only at the water table, but also at the upper level that extends to the NW-most side of the cave; a variety of solutional sculptureings cover the walls, while speleothems are very few. Some medium-sized breakdown chambers are interspersed, as Sala del Compás, Sala Fosca and Sala de la Forca. Generally, these chambers are floored with large boulders, covered with thin flowstone layers that are cracked, as a consequence of settling phenomena. *Galeria Voltors* must be highlighted as a paradigm of solutional passage. *Galeria de les Toveres* is the link passage between the northern part of **Sector F** (at the upper tier) and *Galeria dels Clypeasters* spreading near the water table. The presence of copious cave rims developed along the floor is what makes it distinctive. *Galeria dels Clypeasters* is a 2 m wide aquatic passage that stands out due to the existence of well-preserved sea urchin fossil remains that come out of its walls.

Finally, *Galeria Voltors*, a 500m-long passageway, utterly devoid of speleothems, is impressively affected by outstanding corrosion features (Fig. 10); the floor, roof and walls show massive spongework morphologies.

**Sector del Tragus**

This part of the cave is one of the most extensive and larger sectors within the *Descobriments 2004* series; it is formed by an intricate maze where a set of rectilinear passages that run parallel from southwest to northeast can be distinguished. The sector is reached through the labyrinth developed to the NW area of *Galeria dels Espeleotemes* (**Sector de les Grans Sales**) and is situated both at the upper tier and the phreatic level. Some galleries are close to one kilometre in length, being structurally controlled by major joints. *Galeria del Tragus* and *Galeria del GELL* are pointed out because of their outstanding dimensions and beauty, whereas *Galeria d’en Pau*, *Línia 200*, *Galeria del Gran Canyó*, and *Galeria de les Columnes* are also worth mentioning for the beautifully decorated areas and abundance of speleothems.

*Galeria d’en Pau*, with a total length of over 800 m, is the connection between **Sector F** and **Sector del Tragus**, harbouring an important variety of long gours that contain significant amounts of fresh water. The heterogeneity of solutional morphologies and speleothems is quite remarkable.

On the contrary, *Línia 200*, presents a string of dry gours ringed with fragile crescent shelfstones. At the same time, bedding planes have been dissolved creating flat niches where various formations have been deposited.

*Galeria del Gran Canyó* is 600 m in length and can be divided into two different parts: the first one, located to the NE, is characterized by a narrow passage floored by massive boulders, with few speleothems, those present being affected by corrosion processes; most of the walls are covered in moonmilk. The second section is situated to the SW, forming a subrectangular-shaped gallery that reaches up to 10 m in width and 7 m in height, is mostly drowned by phreatic water. A clear joint throughout the ceiling has helped the development and deposition of huge assemblages of draperies that along with long soda straws, stalactites, stalagmites and flowstones decorate the passage. Substantial accumulations of mud deposits, both at the bottom of the lake and above it, are exhibited at the furthest end of this section of *Galeria del Gran Canyó*.

*Galeria del GELL* has a length of 260 m and, as a consequence of mechanical readjustment processes that affect the ceiling and walls, the floor of the first third of the gallery is covered by huge breakdown boulders that extend to the middle section where the water table is reached. Finally, the last part of this passage is ornamented with a wide sort of formations and spectacular gours.

*Galeria del Tragus* is 930 m in length, being the longest in this sector and can be properly organized into two different parts. The one situated to the SW has modest dimensions, 3 m height and 2 m in width; boulders of diverse sizes are scattered along the area, as well as speleothems, some of them corroded. After a narrow and small well-decorated section, the water table is gained. At this point the square-shaped gallery increases its proportions, reaching up to 12 m in width and 10 m height, being decorated with some large stalagmites (Fig. 11). The rest of the gallery keeps its size and is floored by a significant accumulation of allochthonous mud and sand deposits that contain among others, well-preserved fossil remains of a vertebrate belonging to the *Myotragus* genus, an extinct goat endemic to the Mallorca and Menorca islands.

*Galeria de les Columnes*, is located parallel to the SE side of *Galeria del Tragus*. This magnificent medium-sized passage, 340 long, 20 m wide and 9 m in height, is composed of two branches. The one to the SW is floored by a large accumulation of boulders totally covered by uneven and impressive flowstones that, at the same time, are the foundations for the massive columns and stalagmites that decorate the gallery. The branch to the NE is longer and at the beginning a true speleothems forest containing gours, stalactites, stalagmites, flowstones etc, must be crossed. Then a boulders-covered section leads to a huge gour that temporarily damps up fresh water.

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Fig. 10. *Galeria de Voltors*. This 500 m long passage is entirely covered in massive spongework that affect roof, walls and floor (photo by Tony Merino).
passages are poorly decorated, the coralloids are one of the most abundant speleothems. At the same time, flat ceilings covered by massive spongeworks are succeeded by structurally controlled passages with clear fractures. The most notable dimensions are gained at junction points, with widths close to 20 m. *Galeria Negra* should be emphasized due to the presence of cave rims and a large accumulation of black muddy deposits (Fig. 12). As it was mentioned, this sector approaches the current coast line but exploration was eventually thwarted at low ceiling and small passages that could not be passed.

**SCIENTIFIC RESEARCH**

Regarding scientific research, significant works have been performed over the last decade particularly on morphological, mineralogical, and geochronological issues (Dorale et al., 2010; Fornós et al., 2011; Ginés et al. 2009a, 2009b; Merino et al., 2009a, 2011; Tuccimei et al., 2010). Nevertheless, the potential for future in depth investigations is enormous because only the general trends are outlined in every field of research that has been undertaken.

Some of the research projects developed in the cave are conducted in collaboration with local scientific institutions, like Universitat de les Illes Balears or Institut Mediterrani d’Estudis Avançats (Fornós et al., 2010, 2011; Ginés et al., 2008, 2009a, 2009b; Merino et al., 2009a, 2009b; Merino & Fornós, 2010a, 2010b), as well as with international researchers from foreign universities (Dorale et al., 2010; Tuccimei et al., 2010).

**FUTURE PROSPECTS**

It is fascinating to look at how the potential of the cave has grown within only the space of 9 years. In 2004 the cave had an extension of only 6.4 km, and currently its length is over 74 km. Exploration continues at a moderate pace, mainly at underwater level, but has slowed considerably since the end of 2008, when nearly every day of surveying yielded between 1 and 2 km of new passages.

At the upper tiers exploration and survey have been focused on *Sector F*, aimed at completing the survey...
of this massive maze area. A few isolated corners may remain to be explored, but the overall extent of galleries has been realized. In addition, a particular expedition was organized to thoroughly explore Galeria Voltors, situated at the farthest northwest side of the cave. Quite surprisingly, only a few new passages were discovered. Sector Nord series offer some potential for new discoveries, since the survey is not utterly finished.

But the underwater extensions are where the cave’s prospective is highly promising. Firstly, the vast Sector Subaquàtic de Gregal with its notorious passages remains partially unexplored and many galleries are due to be surveyed. Secondly, between Galeria del Quilòmetre and Sector de Gregal a fresh challenging area of underwater passages is being explored. Some of the narrow and small passages are negotiated with the aim of trying to reach the void area existing towards the northwestern side of the cave (Sector del Tragus). Besides, a new and extremely demanding series of subaquatic galleries have been discovered at Gran Canyó area, where cave divers require the logistic support of other cavers to haul the bulky diving equipment. Finally, no further exploration prospects seem to exist at the subaquatic maze located to the southern and eastern side of Pista Americana (Sector dels Privilegiats), where exploration has been taken to the accessible limits.

Given the intricacies and complexity of the cave, there is every chance that a continued effort and dedication will undoubtedly reveal new discoveries, both in the upper passages and close to the phreatic level as well as along the underwater extensions.

**CAVE PROTECTION**

The cave is under the protection of Conselleria de Medi Ambient, Govern Balear (the Regional Authority). In July 2000 it was listed as Area of Community Interest by the Govern de les Illes Balears (the Regional Authority), and in March 2006 was declared and registered with code ESS310049, belonging to the Natura 2000 Network (Council Directive, 92/43/EEC).

Since the latter date, the Regional Authority had 6 years to work out a Management Plan and submit it to the ECC. This document should be drawn up in order to establish targets and management guidelines not only for the cave, but also for the territorial boundaries where it lies. In case of having been approved, the legal entity of Area of Community Interest would have been changed to Special Conservation Zone. Subsequently, and thanks to the efforts made by the Federació Balear d’Espeleologia and the Conselleria de Medi Ambient, on March 11, 2011, an Agreement of the Regional Council was published with the aim of starting the procedure to declare the cave a Natural Monument. Due to diverse problems and political changes of the regional governments, neither the natural monument, nor the management plan have been accomplished. Nevertheless, since 2007, the Federació Balear d’Espeleologia, along with the Universitat de les Illes Balears, have made all possible effort to help working out the project. Currently, the only protective measures officially taken are the already mentioned declaration of Area of Community Interest and the installation and maintenance of a gate and alarm system. In the light of the results of this situation, a massive effort should be made to fulfill the comprehensive protection project.

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The flank margin model of cave evolution, based on the well-known examples from the Bahamas archipelago, was later complemented and enlarged in the form of the CIKM (Carbonate Island Karst Model) which was an important attempt taking into account the great diversity of geological settings present in limestone islands (Mylroie & Carew, 2000). This initial theoretical approach has been repeatedly improved on the basis of world-wide island locations, leading to updates of the CIKM as shown in Jenson et al. (2006) and Mylroie & Mylroie (2007); nevertheless, the complexity of situations observed in the littoral karst areas all over the world is far enough larger than those reflected in these last versions of CIKM. Regarding this fact, several recent papers deal with extensive cave forming processes that don’t strictly fit within the flank margin model of cave evolution or the CIKM.

**INTRODUCTION**

Coastal karst is a research field of growing interest as evidenced by the recently edited book by Lace & Mylroie (2013) as well as by specific scientific meetings like the Island Karst Symposium, coordinated by J.E. Mylroie and A. Ginés and held in 2009 at Kerrville (Texas) during the 15th International Congress of Speleology. Going back to the last decades of the past century, the late J.N. Jennings (1985) devoted a whole chapter of his fundamental book to Coast and Karst just when the geochemical and geomorphologic implications of the littoral mixing zones were put forward (Plummer, 1975; Back et al., 1984); subsequently, a new paradigm about speleogenesis in coastal settings was formulated through the flank margin cave model (Mylroie & Carew, 1990) defining a new cave type fully specific to the carbonate islands.

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for example those occurring in continental settings as Florida, USA (Florea et al., 2007; Gulley et al., 2013) or the Yucatan Peninsula, Mexico (Beddows, 2004; Smart et al., 2006; Kambesis & Coke, 2013).

Since the middle of the 19th century until today, a significant number of coastal caves have been reported and studied in the the Upper Miocene eogenetic carbonate rocks of southern Mallorca (Ginés & Ginés, 2007; Ginés et al., 2013). The explorations performed during the last decade in Cova des Pas de Vallgornera (Llucmajor municipality) have lead to the discovery of important extensions (Merino et al., 2011b), today totaling over 74 km of development. Nowadays it is the most important endokarst phenomenon in the Balearic archipelago, being undoubtedly one of the more remarkable littoral caves in the Western Mediterranean basin. The cave certainly stands out regarding its unusual morphological suite, and provides an excellent illustration on how lithology influences the pattern and morphology of the cave (Ginés et al., 2009a). These geologic and morphogenetic aspects will be dealt with thoroughly in the present paper, according to the current knowledge about karstification in coastal environments. The main proposed goal is to elucidate the complex speleogenetic mechanisms leading to the formation of this special littoral cave, which until now have only been hinted in previous publications (Ginés et al., 2009b; Fornós et al., 2010a).

**GEOLOGIC AND GEOGRAPHIC SETTING**

The island of Mallorca is located in the middle of the complex geological frame of the Western Mediterranean Sea, being the largest (<3,667 km²) and the most central island of the Balearic archipelago. Generally speaking, these islands are characterized by folded and thrusted Mesozoic, Paleogene and Middle Miocene rocks that are flanked by down-dropped areas covered with only slightly deformed Upper Miocene to Pleistocene sedimentary rocks.

From a physiographical point of view the archipelago is the eastern emergent part of the so-called Balearic Promontory: the north-eastward extension of the Betic Range External Zone, a thickened continental crustal unit forming the NE continuation of the Alpine Betic thrust and fold belt, built during the Middle Miocene (Gelabert et al., 1992).

The stratigraphic sequence that crops out in Mallorca is continuous, practically without interruption, from the Carboniferous to the present-day (Fornós et al., 2002). The carbonate lithologies, occurring almost continuously since the Middle Triassic to the present (Fornós & Gelabert, 1995), are the scene of a remarkable wide range of exo- and endokarstic morphologies.

The island’s sedimentary deposits experienced extension and thinning during Mesozoic times. Subsequently, they were affected during the Cenozoic by two tectonic phases that shaped the present physiography of Mallorca. The first one was a compression and thrusting phase lasting from the Paleogene to the Middle Miocene. The second phase was an extensive one that took place during the Upper Miocene. This extension phase has generated a structure characterized by horsts and grabens, which are not older than Langhian (Middle Miocene) and are bounded by Upper Miocene normal faults (Gelabert et al., 1992).

The horsts originated two more or less parallel mountain ranges, orientated NE–SW (Serra de Tramuntana and Serres de Llevant), along with a series of small hills located in between (Serres Centrals) (Fig. 1). The grabens developed on the foreland of these ranges are filled with sediments of Middle Miocene to Quaternary age, that are unaffected by tectonics. The differentiation between ranges and plains is not always so clear; occasionally their limits are angular discordances, where structures produced during the Mesozoic (normal faults) or in the Lower Cenozoic (mainly thrusts) are buried by Tertiary and Quaternary deposits (Gelabert et al., 1992).

It is important for the purpose of this work to note that, resulting from the mid-Miocene major compressional events, a number of paleo-islands remained individualized (the horsts). The islands were covered by an epicontinental sea that favored the development of a coral reef environment around the uplifted areas. Upper Miocene carbonate platforms grew in shallow submerged areas around all Balearic paleo-islands, but most extensively on their southern margins (Pomar, 1991). Specifically, in the southern margin of Mallorca (the Llucmajor Platform) a thick slab of carbonate deposits built up, creating a structural post-orogenic platform that stretches around the central and eastern folded ranges (Fig. 1). These deposits include a Late Tortonian-Early Messinian Reef Complex (Pomar et al., 1996), where most of the littoral caves in the island occur.

At the end of the Miocene, during the Messinian, the Mediterranean experienced an extreme recession, which left the Balearics completely exposed. Following the Lower Pliocene transgression, sea level covered the lowland areas of Mallorca (the Neogene basins), whereas the folded areas (ranges) remained emerged. Finally, the Pleistocene glacial cycles led to sea-level rises interspersed with important regressions that are well-recorded along the coasts of the island (Butzer and Cuerda, 1962; Ginés et al., 2012).

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**Fig. 1. Simplified geologic map of Mallorca Island indicating the major physiographical units and the karst locations mentioned in the text.**

1) Font Santa de Sant Joan; 2) Pou de Can Carro; 3) Cova de sa Guitarreta; 4) Cova Nova de Son Lluís.
Geology and speleogenesis of Cova des Pas de Vallgornera, Mallorca

Additional geographic data

As a general geomorphologic overview (Fig. 2), the southern part of the Llucmajor Platform corresponds to a gently domed structure of Upper Miocene sedimentary rocks forming a rather tabular relief, which corresponds, as has been said, to the southward progradation of a reefal unit over the prerogamic basement. Some authors (Pomar & Ward, 1994) have suggested the presence of a strike-slip fault (SW–NE) with a hectometric dextral displacement; nevertheless, it seems more probable that the gently domed appearance corresponds to a SW–NE antiform structure created by a series of listric normal faults (Gelabert, 1998; Fornós et al., 2002). The area where the cave is located has a gentle slope in a southeast direction coincident with the meridional anticlinal flank (Fig. 2).

A poorly developed fluvial system is incised over the carbonate platform, consisting nowadays in dry valleys with only ephemeral discharge after heavy precipitation; the most important of these creeks is Torrent de Garonda, located to the northeast of the cave area. The fluvial network is tightly controlled by relevant fractures and related joints (Fig. 2), that are evident as well in the outline of some coastal cliffs. The surficial drainage system becomes more deeply incised when approaching the coastline, and therefore *calas* are formed. These macroforms are characteristic coastal embayments (Gómez-Pujol et al., 2013) related to steep-sided dry valleys that were deeply incised on carbonate plateaus during low sea stands; subsequently, they became drowned after the post-glacial sea level rise.

Vertical shoreline cliffs higher than 25 m are dominant in the Vallgornera site (Fig. 3), and are only interrupted by the already described indentations (*calas*), which are intercalated within a less articulated coast. Apart from the littoral cliffs, the gentle slope trend of the Vallgornera area is interrupted by a clear change in slope that approximately follows the 25-30 m contour lines (Fig. 2); this altimetric irregularity corresponds to a rather steep
talus associated with the presence of a Messinian coastal paleo-cliff, as discussed later in the paper.

Regarding the climate, Mallorca enjoys the typical Mediterranean climate characterized by its hot and dry summers, whereas winters are mild and relatively wet. The mean annual temperature in the area is 17°C, with mean winter and summer values of 10°C and 25°C, respectively. Mean annual precipitation is less than 400 mm in the southern part of the Llucmajor Platform, with most rain occurring in the autumn (Guijarro, 1995).
The landscape supports typical Mediterranean vegetation where bushes are dominant but interspersed with rainfed-cultivated areas existing in these arid lowlands.
The dominant main winds come from the north and west and sea breezes are very common during summer time. The wave regime over the coastal areas is characterized by a mean significant wave height greater than 1 m during autumn-winter months and 0.3 m approx. during the spring-summer seasons (Cañellas et al., 2007). The tidal range is almost negligible (the spring tidal range not exceeding 0.25 m), although changes in atmospheric pressure and wind stress can account for considerable fluctuations in sea water levels (Gómez-Pujol et al., 2007), but with a maximum fluctuation range less than 1 m.

**LITHOSTRATIGRAPHY OF THE LLUCMAJOR PLATFORM**

In broad terms, the post-orogenic platform developed along the eastern and southern coasts of Mallorca is formed in an Upper Miocene to Quaternary sequence, synthetically represented in Fig. 4. The Upper Miocene carbonates consist of three sedimentary units: the *Heterostegina* calcisiltites at the base, considered to be Lower Tortonian (not outcropping in the studied area); the middle unit or *Reef Complex* that is Upper Tortonian-Lower Messinian in age (Pomar et al., 1996); and the upper unit or *Terminal Complex* which is assigned to the Messinian, and is tentatively considered to be a third-order depositional sequence (Pomar & Ward, 1994). Plioene and Pleistocene deposits include beach-rock, eolianites, and paleosols.

In more detail, the sea cliffs close to Cova des Pas de Vallgornera display a set of lithostratigraphic sequences, which are quite variable according to its W-E location along the shoreline (Fig. 5). A detailed lithological description of the different units is necessary in order to interpret the morphologies and pattern of the cave system as well as its evolution.

At the base of the studied sequences, the Upper Miocene limestones belonging to the Reef Complex (Pomar, 1991) crop out all along the littoral cliff (Fig. 5). These deposits vary in thickness along the coastline due to the intra and post Messinian erosive periods that had affected them; inland, they represent the unique unit where the cave system develops. This unit consists in a series of progradational (towards the SW) reef-rimmed platforms that present different facies associations, characterized in this area by well-differentiated reef front and back reef deposits. Their architecture shows complex accretional geometric relationships related to the high-frequency oscillations in relative sea level (Pomar, 1991). The lithofacies that compose this carbonate Reef Complex –defined mainly on the basis of lithology, texture and constituents– plays an important role in the development of the cave morphology (see below). In that sense, three main types of lithofacies can be described (Fig. 4) according to Pomar et al. (1996). The reef core or reef front has a classical framestone texture due to the growth of the coral colonies (almost exclusively *Porites* sp.); these rock deposits have a massive appearance. Intermixed with the coral colonies there are abundant bioclastic sediments composed mainly by mollusks, bryozaons and red algae. The elevated primary porosity, which favors rudstone and grainstone textures, brings to these lithofacies a great permeability. Landward (towards the NE), these lithofacies interfinger with flat-lying lagoon deposits composed of partly dolomitized packstone, grainstone and, especially, wackestones textures. The outer lagoon is dominated by the coarsest facies and includes the sporadic presence of poorly developed patch reefs. The sediments are mainly composed of foraminifers, equinoids and red algae fragments. Farther inland the lagoon sediments become mudstones to wackestones (the inner lagoon) with peloidal sands that include abundant foraminifers and whole mollusks. The sediments, which are slightly dolomitized, show a conspicuous thin horizontal lamination. The muddy texture of this lithofacies gives these deposits a very low permeability.

An important erosion and karstification surface over the Reef Complex was followed by a transgressive sequence known as the Terminal Complex (Esteban, 1979) later defined by Formós and Pomar (1984) as the Santanyí Limestones (Fig. 4). They correspond to a series of more or less restricted coastal environments and oolitic sand shoals with stromatolites (Pomar et al., 1996). In this area, it reaches a maximum thickness of around 10 m and consists of two main units. The marly lower one has a very pronounced stratification due to the alternation of miliolid packstones and grainstones, with vertical root traces and abundant accumulations of *Ostreaea* sp. (mangrove swamps) that usually end in thin laminated criptalgal boundstones and mudstones.
The backshore gives way to eolian sedimentation. Grainstones composed of medium-sized bioclastic sand display the typical eolian cross-bedding.

On top, a Middle Pleistocene eolian system (Nielsen et al., 2004) unconformably overlies both the Upper Miocene limestones and/or the Pliocene deposits (Fig. 3). It consists of a succession of interbedded greyish red eolian carbonates and darker red colluvial deposits up to 10 m thick (Figs. 5 and 6). The eolian sediments form part of an extensively eolian system that extended more than 15 km inland, covering today a large part of the Llucmajor Platform. It decreases in thickness towards the southeast agreeing with the data obtained from the cross-bedding that indicate sand transport towards the

Overlying the major Messinian erosion surface, a Pliocene regressive sequence fills the remaining reef-rimmed basins above the Upper Miocene sequence (Pomar, 1991). Never more than 10 m thick in this area (Figs. 5 and 6), and increasing to the southeast towards the basin depocenter, these deposits represent the westernmost margin of sedimentation in the Campos basin (see location in Fig. 1) during the Pliocene transgression (Colom, 1985). This regressive sequence has two main units that correspond to a coastal and shallow restricted marine environment at the base that evolves to an eolian deposition. The basal contact of the lower unit contains transgressive lag deposits composed of calcarenites with abundant mollusk macrofauna deposited on a soft, burrowed surface. These calcarenitic shoreface deposits, including an alternance of rudstones and floatstones with large bivalves and many trace fossils, have horizontal laminated bedding sometimes with slightly eroded layers. This evolves to a more hydrodynamic sequence with conspicuous medium-sized cross-bedded structures. Abundant low angle cross-bedding and wave ripples with abundant trace fossils characterize the foreshore environment. Gradually,

**Fig. 5.** Lithostratigraphic columns obtained along the sea cliffs of the Vallgornera area with the representation of main joint and fracture orientations.

**Fig. 6.** Interpretative sketches of the stratigraphic sequence observable between sites 2 and 3 of Fig. 5. The yellow arrow in the top picture points to some Reef Complex blocks fallen from a coastal paleo cliff and embedded within the Pliocene deposits. Small patches of the Messinian Terminal Complex (marked in the lower sketch) occur today at the base of this erosive paleo cliff.
east and southeast. Located at the top of the coastal cliff and truncating the Neogene sequence, the sedimentary eolian system could be classified as a cliff-top depositional system (Nielsen et al., 2004) although characterized by eolian transport across the cliff edge. Locally, at some entrances of the coastline, part of the cliff base is covered by Upper Pleistocene eolianites considered as cliff-front dunes (Clemmensen et al., 1997).

**GEOTHERMAL ACTIVITY IN SOUTHERN MALLORCA**

Geothermal phenomena, in the form of thermal springs discharging underground waters with temperatures higher than the annual average, are present in Mallorca although scarcely studied until now. Since ancient times (documented in the XV century), one spring was well-known in the southern part of the island, the Font Santa de Sant Joan (Fig. 1), where a health resort was built in the middle of the nineteenth century to exploit the hot water (37°C). Nevertheless, this fact was not addressed by the scientific community until three decades ago, when the Instituto Geológico y Minero de España (IGME) conducted in 1984 a preliminary study of geothermal activity in the eastern part of Spain, including the Balearic Islands. As a result of these investigations, abundant wells with anomalous temperatures were documented in the Llucmajor area (IGME, 1984).

From an hydrogeologic and geochemical point of view, the geothermal activity originates in the shallowest aquifer of the Llucmajor Platform and Campos Basin (see location in Fig. 1), located in the Upper Miocene limestones and calcarenites, where nowadays more than 24 exploitation wells have recorded anomalous temperatures (López, 2007). The water table is about 125 m below the elevation datum of Llucmajor village, and the water temperature is near 50°C (López et al., 2004; López & Mateos, 2006; López, 2007). Geochemical analysis clearly separates the calcium-sulfate thermal waters from the calcium-bicarbonate and chloride waters, characteristic of the natural composition of the shallow Upper Miocene aquifers in the rest of the island, although mixing of both in different degrees can be observed depending on the well location and depth (Mateos et al., 2005; López, 2007). The isotopic analyses of these thermal waters reveal their deep origin; there is no influence of sea water intrusion, as is demonstrated by the chloride/oxygen-18 ratio (López, 2007). Furthermore, the dissolved gases analyses indicate a sharp methane anomaly in the hottest waters, which may be due to the hydrocarbon traces in the deep Mesozoic basement deposits (Mateos et al., 2005; López, 2007). The data distribution of temperature, sulfates, silica, fluorine and lithium –recognized as geothermal indicators– suggest the existence of important SW-NE faults, as observed in seismic profiles (Mateos et al., 2005), which would allow the preferential flow direction of the thermal water from depth to the Upper Miocene aquifer. In the perpendicular direction a slow diffusion of geothermal indicators is observed.

Deep exploratory drilling (700 m) performed in the Llucmajor Platform revealed the presence of two different aquifers: the shallowest corresponding to the Upper Miocene calcarenites and the deepest corresponding to the Paleogene mélange and carbonate conglomerates and sandstones. The latter shows an increase in temperature reaching at the deepest part 70°C (López et al., 2004; Mateos et al., 2005; López, 2007). Probably, these carbonate aquifers are fed by hot waters ascending, along SW-NE faults, from a deeper aquifer at an estimated temperature close to 90°C (López, 2007).

The geological setting where this geothermal activity takes place is part of the alpine belt that links the Balearics with the Betic Range, located at the southeast of the Iberian Peninsula. The carbonate lithologies, deposited almost continuously since the Middle Triassic, have been extensively affected by a complex compressive tectonic phase active from the Paleogene to the Middle Miocene. This compressive phase occurred within the context of the Western Mediterranean plate tectonics (Gelabert et al., 1992), which generated an environment suitable for the existence of geothermal anomalies. In that sense, thick carbonate deposits at great depths are present that can act as geothermal reservoirs (Mateos et al., 2005). Moreover, the southern part of Mallorca has been affected by Neogene normal faults (Gelabert et al., 1992; Sábat et al., 2011), having a SW–NE trend, which produced relative uplift of the Llucmajor area and also caused the subsidence of the Campos basin (Fig. 1) at the southern end of the island. These graben-type structures were produced during the post-orogenic main extensional phase (Tortonian-Messinian); the faults delimitating these structures, or some vertical fractures subparallel to them (Ginés et al., 2008), permit hydraulic communication between the Mesozoic carbonate reservoirs and the Upper Miocene aquifer, where thermal anomalies are observed today.

More recently, feeble geothermal activity also has been evidenced during the systematic study of caves in the southern sector of the Mallorcan karst. In this respect, Merino et al. (2011a) reported anomalous high temperatures of the phreatic waters in Cova de sa Guitarreta (27.1°C) and Pou de Can Carro (23.6°C); both caves are located in the eastern edge of the Llucmajor Platform (Fig. 1), close to the Campos subsidence basin, their deepest passages reaching the water table of the Upper Miocene aquifer. The high temperatures together with specific morphological features, particularly from Cova des Pas de Vallgornera (Merino & Fornós, 2010), have allowed to postulate the involvement of geothermal hypogene processes in the formation of this special cave system (Ginés et al., 2009b), as will be discussed in the next sections. Finally, it is worth mentioning the existence of another possible hypogenic cave (Cova Nova de Son Lluís; Ginés & Ginés, 2006) located in the Mesozoic hills corresponding to the northeastern margin of the Llucmajor Platform (Fig. 1); this cave would support the existence of geothermally mediated speleogenesis affecting the folded basement that forms the Serres Centrals Range.

**MORPHOGENETIC INTERPRETATION OF THE CAVE**

Cova des Pas de Vallgornera is composed of a huge assemblage of passages and chambers quite
heterogeneous from the morphogenetic point of view, with a surveyed length exceeding 74 km. Its artificial entrance is located 400 m away from the coastline (Fig. 7), with some galleries almost reaching the coastal cliffs (less than 50 m away) but without a negotiable connection to the Mediterranean Sea; the maximum inland penetration is around 1.5 km. The area containing the cave is approximately 2.5 km², giving a passage density value close to 30 km/km². This figure is higher than the values reported from other extensive cave systems in coastal settings, like Quintana Roo, Mexico (6.5 to 19 km/km²), but substantially lower than densities of passages from some hypogenic caves both in limestone or gypsum (300 km/km²) according to the values supplied by Smart et al. (2006).

Most of the cave development occurs near the water table, which is linked to the current sea level, whereas there are also extensive passages located both above and below present sea level (Merino et al., 2011b). Underwater extensions are significant (Gràcia et al., 2009a) totaling nowadays over 17 km of galleries. A detailed description of the cave is available in the paper by Merino et al. (2014) also included in this issue. Several morphologic aspects will be treated now in order to contribute later on to the speleogenetic interpretation of this cavern. The location of the main sectors and galleries of the cave has been compiled in Fig. 7 with the aim of providing a helpful tool that can facilitate this discussion.

**Main morphological trends**

The general morphology of the cave is rather variegated, its most prominent characteristic being the coexistence of collapse chambers together with extensive arrays of phreatic solutional galleries. The topographical arrangement of these two-fold categories of passages shows evident regularities in a first look, mainly consisting in a remarkable abundance of collapse features in the sections of the cave closer to the coastline. This really relevant fact is related to the spatial distribution of the Upper Miocene reef front facies (Ginés et al., 2008) as will be in depth discussed later on.

Referring to the solutional galleries, the dominant morphologies are spongework mazes and passages that are developed particularly in the south-western seaward sectors of the cave. On the other hand, in the inland north-eastern sections, the presence of shallow phreatic solutional conduits is the rule. These conduits, which characterize the inner part of the cave, formed along prominent SW-NE fractures (Fig. 7) and are markedly horizontal and without vertical loopings.

In whatever case, it is worth remarking that solutional sculpturing does not include true scallops, with...
the dominant morphologies being different kinds of centimetric to even metric dissolution pockets, in many cases arranged along bevels and notch-like features. The diversity of dissolution forms is quite important, being the subject of detailed descriptions in Gràcia et al. (2009b, 2009c). Special mention should be made about the presence of solutional ascending features, pointing towards the participation of hypogene processes in the genesis of the cave (Fornós et al., 2011).

Finally, the present-day appearance of Cova des Pas de Vallgornera is characterized by a large number of speleothems that are widespread all along its different sections. The diversity of speleothems is really impressive, including underwater crystallizations related to Upper Pleistocene and Holocene sea-stands (Dorale et al., 2010; Tuccimei et al., 2010); these phreatic carbonate deposits provide clear evidence about the control that sea level has exercised during the entire evolution of the cave and, in particular, on the most recent geomorphological events recorded inside it.

**Cave patterns and lithologic variability**

In broad terms, the plan pattern of this cavern fits into the wide category of maze caves, according to the systematization established by Palmer (1991, 2007). However the maze pattern of the cave is not homogeneous, showing a two-fold configuration already cited when referring to its general morphological trends. In this respect a clear dichotomy arises again between the seaward part of the cave system, where spongiform-ramiform patterns are dominant, and the inland sectors consisting in a crude labyrinth of structurally controlled passages developed in a SW-NE direction (Fig. 8).

The above-mentioned distribution of the cave patterns is related to the architecture and lithological variability (both laterally and vertically) of the Upper Miocene Reef Complex, as has been postulated in some previous papers (Ginés et al., 2008, 2009a). The different depositional environments represented within the Reef Complex determine well-defined morphogenetic assemblages as a function of the lithological and hydrological characteristics of the bedrock in this eogenetic coastal karst. So, a first clear differentiation could be envisaged concerning the morphogenetic suite observable in the south-western seaward part of the system –excavated in the reef front facies– as opposed to the inland inner sectors developed in the less permeable back reef facies (Fig. 8).

Starting with the south-western part of the cave (which comprises the following sections: Sector Antic, Sector Noves Extensions, Sector F, Sector Grans Sales and Sector del Clydeaster; all of them depicted in Fig. 7), the plan is predominantly labyrinthine but there are many collapse chambers interspersed within a general spongiform array of passages (Palmer, 2007); it is not possible to recognize any kind of structural network pattern in the above mentioned sectors. The passages of this part are medium-sized (in the order of a few meters maximum) and were formed in the very porous and permeable reef front facies, where spongework solutional features occur together with rather generalized breakdown processes. The coastal phreatic mixing has greatly increased the porosity of the rock by dissolving the coral structures, which are ubiquitous in these sectors of the cave, thereby causing spectacular differential dissolution phenomena (Fig. 9). The preferential dissolution of coral constructions has favored the collapse processes, so abundant in the seaward south-western sectors of the cave. The resulting plan pattern is a spongiform maze ranging in places to a rather ramiform pattern (Palmer, 2007) owing to the presence of extensive breakdown chambers that are scattered within these cave sections, being normally accessible through narrow collapse constrictions. Special note should be taken of Galeria Voltors, a paradigmatic example of speleogenesis totally conditioned by the reef barrier topography (Figs. 7 and 8). This unique passage develops over 500 m in the NW direction due to the solutional phreatic excavation of the coral barrier, with a mean width exceeding 10 m; the gallery lacks any structural guidance and follows a wandering course rigidly adapted to the reef front architecture.

On the other hand, a quite different situation takes place in the extensive assemblage of passages developing more than 1 km inland towards NE (which includes the following sections: Sector Nord, Sector Tragus, Sector de Gregal and Sector Subaquàtic de Gregal). The width of the galleries range from less than a meter to more than 10 m particularly when breakdown processes have enlarged them, as for example in Galeria GELL and Gran Canyó. These inner passages are developed in the back reef deposits (Fig. 10), specifically in the outer lagoon facies of the Upper Miocene Reef Complex (Pomar et al., 1996). These back reef carbonates are very massive and less permeable than the reef front facies, owing to their lower porosity and more calcisilitic character. The extensive array of passages existing in the outer lagoon facies are joint-controlled phreatic galleries excavated along major SW-NE fractures (Fig. 8), that run parallel to the extensional faults responsible for the Campos subsidence basin located to the SE of the cave area (Fig. 1). The pattern of the passages corresponding to the outer lagoon facies may be defined as an irregular 2D maze, with a clear SW-NE alignment. This structural trend is determinant regarding the results obtained through the statistical treatment of passage orientations: almost 42% of the total length of the segments from the topographical survey is oriented in the range N40-70°E (Fig. 11). Finally, it must be mentioned that the long galleries forming the inland sectors of the cave, display from time to time some breakdown chambers where coral patches are interspersed within the back reef carbonates. The Plaça de Toros, located along Galeria del Quilòmetre, is a clear example of these local collapse phenomena associated with the dissolution of isolated coral structures.

Another important lithological change occurs toward the north-eastern ends of the long passages that integrate the inner part of the cave system (Fig. 8). In this sense, the termination of the main galleries corresponding to Sector Tragus and Sector de Gregal seems to be explained by the appearance of deposits attributed to the inner lagoon facies, within
In the terminal passages of the above-referred sectors, the rock becomes less massive, with calcisiltitic and marly materials disposed in beds whose thickness is decimetric to metric. In the current state of exploration, all the major passages trending inland to the NE (including the underwater ones, as for instance Galería M.A. Barceló) have abrupt endings at a distance of around 1 km away from the deduced location of the Upper Tortonian reef barrier (Fig. 8).

Some comments must be made about another relevant geological unconformity, related to the outcropping of the so-called Terminal Complex (Messinian) as well as the Plio-Quaternary beach and dune deposits. These materials are only present near the coastline cliffs, being laterally attached to an erosive paleociff affecting the Upper Miocene carbonates which form the Reef Complex (Figs. 5 and 8). This unconformity is rather coincident with the southern limits of the cave system, where the conduits from Sector Subaquàtic de Gregal turn towards the south and almost reach the coastline (Fig. 8). Probably the littoral breaching of these Messinian to Plio-Quaternary materials has played some hydrological role in the configuration of the network of passages developed within the carbonates of the Reef Complex, favoring its bending towards the south because of the sea cliff retreat and consequent erosion of these deposits that have acted as an aquitard.

As a brief recapitulation of the lithological constraints, three diverse morphogenetic settings can be individualized which are conditioned by the sedimentological and textural characteristics of the Upper Miocene Reef Complex (Pomar et al., 1996). In the terminal passages of the above referred sectors the rock becomes less massive, with calcisiltitic and marly materials disposed in beds whose thickness is decimetric to metric. In the current state of exploration, all the major passages trending inland to the NE (including the underwater ones, as for instance Galería M.A. Barceló) have abrupt endings at a distance of around 1 km away from the deduced location of the Upper Tortonian reef barrier (Fig. 8).

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As a brief recapitulation of the lithological constraints, three diverse morphogenetic settings can be individualized which are conditioned by the sedimentological and textural characteristics of the
Upper Miocene Reef Complex (Ginés et al., 2008, 2009a; Fornós et al., 2010a). It is possible to distinguish: 1) the very porous and permeable reef front facies, with framestone and rudstone textures, where spongework passages and breakdown passages are the rule; 2) the massive calcarenitic and/or calcisiltitic outer lagoon facies, with variable wackestone, packstone and grainstone textures, where joint-guided NW-SE conduits are dominant; and 3) the inner lagoon facies, that are well-bedded as well as increasingly calcisiltitic and marly (wackestone textures) and represent the inland limit of the cave passages. These three lithological settings are arranged more or less parallel from SW to NE, reflecting the architecture of the Upper Miocene Reef Complex (Fig. 8). The described distribution of the different facies also shows some vertical variations linked to the sedimentological history of the whole Reef Complex. For example, part of the Sector F upper maze is located in the back reef facies (with packstone textures) corresponding to a depositional sequence later than the main reef constructions, located at lower elevations and hosting some sections of the cave system developed close to the present-day water table. The whole cave has been formed in the different facies of the Upper Tortonian-Lower Messinian Reef Complex, without penetrating the more recent deposits outcropping along the littoral fringe (Messinian Terminal Complex and Plio-Quaternary littoral sediments).

Development of the cave in its vertical dimension

Looking at the disposition of passages in Cova des Pas de Vallgornera concerning their elevation, it is possible to distinguish roughly two main tiers of galleries and chambers developed respectively above or close to the current water table, the later including an extensive array of underwater extensions. This relatively simple configuration comprising two principal tiers appears substantially modified by breakdown processes that produce the disorganization of the initial solutional voids through the enlargement and upwards migration of the passages.

In general terms, within the air-filled part of the cave system it is clearly individualized a lower tier of solutional galleries and collapse chambers, located at the water table or slightly above it; this water table story is outstanding due to the presence of very extensive brackish pools of unusual beauty. On the other hand an upper tier, mainly consisting in several maze areas, develops at elevations between +7 and +11 m above the current sea level, although its altimetric disposition is far from being uniform. This upper story includes some collapse-enlarged passages, but not as abundant as those
in the lower tier. A simplified graphical overview of the elevation at which the floors of the passages are located is quite illustrative (Fig. 12), showing a general distribution of the highest mazes and galleries in the NW half of the cave. As opposite, the lower tier of passages running close to the water table is located in the SE part of the cave system, together with the extensive underwater sections that reach maximum depths of ~8 m below the sea level.

It must be also mentioned that a superposition of the two main tiers occurs at some spots of the cave. Particularly, in the southern limits of the system the lower maze (corresponding to the Noves Extensions sector) runs below an extensive area of the Sector F upper story (Fig. 12), but there is no a direct connection between these two superposed mazes. In a similar way, in the area leading to Sector del Clypeaster, the upper maze is connected to a net of narrow corridors developed at the water table that allows access to the spectacular reef front gallery constituted by Galeria Voltors.

The altimetric distribution of the passages shows some additional particularities, for example the progressive descent of the northernmost Galeria del Tragus in the NE direction before reaching the water table (Fig. 12), or the important ascending trend of Galeria Voltors towards its NW end, where an elevation near +30 m a.s.l. is attained.

With the aim of better illustrating the elevation of the inner sectors of the cave, a transverse schematic profile of the back reef passages is depicted in Fig. 13; the profile has been constructed projecting on a NW-SE vertical plane the elevation data from the survey taken from the main passages in Sector Tragus, Sector de Grgal and Sector Subaquàtic de Grgal.

In this sketch, the vertical scale is greatly exaggerated (elevations ranging only from ~8 to +15 m a.s.l.) with respect to the horizontal axis of the profile, which is 1,200 m long. The vertical dimension of the galleries is real, but their widths are not drawn to scale for a more useful representation. The color-code used for elevation intervals in this drawing is similar to that in Fig. 12.

It is clear that the northernmost back reef passages (those from Sector Tragus) are higher than the conduits developed to the SE (Sector de Grgal and Sector Subaqutìc de Grgal), with some disturbances introduced by the involvement of collapse processes. As a general trend resulting from the observation of Fig. 13, two principal tiers of back reef galleries can be distinguished, the lowest of them being also present in some recently explored underwater passages existing towards the north in the vicinity of Gran Canyó and Galeria GELL.

In spite of this more or less evident disposition in two principal tiers –the highest +7 to +11 m mazes on one hand, and the water table and underwater sections on the other hand– it is yet not possible to discuss about

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**Fig. 12. Simplified survey of Cova des Pas de Vallgomera depicting the elevation distribution of passages and chambers. Notice the existence of two main tiers, the upper one located several meters above sea level (orange, red and dark grey colors), and the lower developed close to or below the current coastal water table (green and blue colors). Detailed explanations are supplied in the text (section on the vertical arrangement of the cave system)-**
clear levels of passages on the basis of any lithological or erosional evidence. Additionally, it must be taken into account that the sea-controlled base level has fluctuated extensively from Messinian times to present, so it is difficult to make any precise morphogenetic and/or geochronological reconstruction, considering furthermore the assumed pre-Quaternary age of speleogenesis (see the later discussion on this matter in next paragraphs). Therefore, geomorphologic interpretations like that proposed by Florea et al. (2007) for underwater cave systems in Florida are valid in a broad sense (i.e. sea level controls the speleogenetic processes) but can hardly supply more precise data, at least in our case. Moreover, and contributing to the complex situation in Cova des Pas de Vallgornera, the elevation of the Pliocene and Quaternary shoreline deposits (already discussed when presenting the lithostratigraphy of the area) supplies evidence on Plio-Quaternary tectonic disturbances that could have ultimately affected the altimetric distribution of the cave passages.

**Solutional features and their diagnostic significance**

Although a thorough discussion of dissolution morphologies is not the target of this section, some comments must be made about those features that could be relevant when trying to ascertain the processes involved in the cave genesis. Besides the profusion of spongework and other morphologies typically ascribed to coastal mixing environments (Mylroie & Mylroie, 2009), there are in Cova des Pas de Vallgornera some assemblages of dissolution features that can be considered diagnostic regarding the specificity of their forming mechanisms; these features fall into two broad categories, not specifically related to karstification in coastal environments. So, whereas the seaward part of the cave—developed in the porous reef front facies—is dominated by a suite of forms quite common in the littoral caves of Mallorca (Gràcia et al., 2009c, 2011a) the inland part of the system contains some solutional features, which must be highlighted because they do not fit the general morphogenetic frame of karst in the south-eastern coast of the island, as documented in several papers (Ginés & Ginés, 2007; Gràcia et al., 2011b; Ginés et al., 2013).

A first group of forms provided with a clear diagnostic signification are the abundant solutional conduits (in the back reef facies) whose morphological suite denotes an effective and concentrated drainage corresponding to ancient water table positions, obviously sea level controlled. These conduits show well-developed solution notches, usually with their lower sides beveled by wall facets (Fig. 10). Many of these notch-like morphologies are integrated by a string of decimetric to metric horizontal pockets that suggest rather slow flow, but without the presence of small-scale flow features like scallops. Certainly, the presence of solutional galleries in the coastal karst of Mallorca is relatively frequent in those sectors of underwater caves not affected by generalized breakdown phenomena—as happens in other localities like Cova des Coll and Cova de sa Gleda— but usually these passages are integrated in a general spongework pattern (Gràcia et al. 2005, 2010), lacking clear evidence of a substantial dynamic flow through the conduits.

Fig. 13. Transverse schematic profile of the back reef passages. The vertical dimension of the galleries is real (but exaggerated with respect to the horizontal axis of the profile) whereas their widths are not scaled for a more clear representation. Note the lower elevation of the south-eastern passages and the existence of some underwater galleries also close to Gran Canyó and Galeria GELL (additional explanations in the text).
any elevation within the inland back reef passages, from underwater galleries to the upper maze areas located more than +7 m a.s.l.; they are very abundant and conspicuous, for example, in Galeria del Quilomètre and the passages leading to it. These kinds of rising channels are integrated within a more extensive suite of forms including cupolas, feeder-like vertical hollows, blind galleries, etc. (Fornós et al., 2011; Merino et al., 2011a), pointing towards an involvement of hypogenic processes linked to the geothermal anomalies in the area (López & Mateos, 2006; López, 2007). There is no evidence for the involvement of H₂S in the genesis of the system, CO₂-rich deep recharge and/or the cooling of thermal waters being the most probable sources of aggressiveness explaining these rising features.

Sediments and their distribution

Detrital sedimentation is not a relevant phenomenon in the whole cave system. Clayey and silty sediments are scarce, but do occur in the galleries of the innermost part of the cave as patchy accumulations rarely exceeding 20 cm in thickness, both in the air-filled and underwater passages. The allochthonous sediments are similar to those previously described in Mallorcan coastal caves (Fornós et al., 2009), frequently being a mixed sedimentation including carbonate particles detached from the walls, together with clay and silt deposits derived from the infiltration of soil materials to the underlying voids. Despite the general scarcity of detrital infillings, a particularly different situation occurs in the northernmost end of the cave (the so-called Galeria del Tragus; see location in Fig. 7) where an important sequence of sediments is present, which hosts a very rich paleontological deposit. A detailed overview of sedimentary processes acting in the cave is supplied by Fornós et al. (2014).

On the one hand, the clayey sedimentation is not very widespread and it seems to be preferentially deposited in some secondary passages, like for instance Galeria Navarrete (Fig. 7), which exhibits the thickest accumulation of this kind of deposit (nearly 40 cm). This distribution is probably related to a rather substantial flow in the main drainage conduits, so preventing the accumulation of sediments that are preferentially deposited in the secondary routes of the minor lateral galleries.

On the other hand, the already referred sequence in Galeria del Tragus is completely different (Fornós et al., 2010b). It is a 2.5 m thick accumulation of sands and silty deposits of allochthonous origin that host very interesting osteological remains (Bover et al., 2014), linked to the existence of an ancient entrance to the cave system. The extension of these deposits, filling up more than 200 m of Galeria del Tragus, points towards important episodes of surficial recharge perhaps related to some sinks from major surface ravines, like Torrent de Garonda running some hundred meters to the north.

Although completely different, both types of sediments suggest a noteworthy participation of the meteoric recharge in the formation of the innermost passages of the cave. However, the involvement of other active genetic processes is not excluded.

**SPELEOGENETIC APPROACH**

Coastal caves in the Upper Miocene rocks of south and eastern Mallorca have been attributed historically to different genetic mechanisms: marine erosion (Martel, 1896), erosive action of underground rivers (Maheu, 1912; Faura y Sans, 1926; Darder, 1930) or, more recently, phreatic dissolution voids affected by collapse processes (Ginés & Ginés, 1977). Nowadays there is a wide consensus about the formation of caves in this area as a result of coastal mixing dissolution and extensive breakdown, in a geomorphic setting fully controlled by sea level history (Ginés & Ginés, 1992, 2007, 2011; Gràcia et al., 2011b). However the resulting caves, in the Mallorcan case, don’t fit strictly the flank margin model of cave evolution (Mylroie & Carew, 1990), which is internationally adopted as the current paradigm in littoral speleogenesis. In fact, the geologic setting of Mallorca is rather similar to the complex island category of the Carbonate Island Karst Model (Mylroie & Mylroie, 2007) that considers a complicated situation regarding lithologic and tectonic constraints. In the case of Cova des Pas de Vallgornera, the speleogenetic interpretation becomes even more complex, among other circumstances, because of the great length of the cave system together with its noticeable morphological diversity favored by the local geology; namely, the differences in hydrologic behavior between the distinct reef facies.

**Involved speleogenetic mechanisms**

Dealing with the aforementioned diversity of underground landscapes, the south-western seaward sectors of the cave are characterized by a morphological assemblage that could be compatible with dissolution in the coastal mixing zone, as has been invoked when studying the abundant littoral caves from the Migjorn region of Mallorca Island (Ginés & Ginés, 2007; Gràcia et al., 2011a; Ginés et al., 2013). In these seaward
sections of the cave system, a boost of aggressiveness associated with the mixing of fresh- and sea-water (Plummer, 1975; Back et al., 1984) has presumably led to the preferential dissolution of coral constructions, within the Upper Miocene eogenetic carbonates, creating a profusion of voids arranged in a roughly spongiform maze pattern (Palmer, 2007). The pervasive spongework sculpturing seems to be the result of a diffuse-flow phreatic dissolution acting on these extremely porous and permeable reef front facies. In addition, collapse processes have also been determinant from the morphogenetic point of view, causing the disorganization of the solutional voids that were formed by mixing dissolution in the more lithologically favorable parts of the littoral fringe. The geochemical aggressiveness linked to the coastal mixing zone must be responsible as well for the removal of a substantial part of the rock blocks produced by breakdown mechanisms. In this respect some other Mallorcan caves, like Cova de sa Gleda (in Manacor), exhibit solutional features carved at the current halocline which have cut across the rock walls and even the submerged vadose speleothems (Gràcia et al., 2010, 2011a), but in Cova des Pas de Vallgornera there is no clear evidence of dissolution being active in the current mixing zone.

With a completely different morphology, the inland sectors of the cave system consist of long conduits forming an irregular network maze developed along prominent joints and fractures. These even kilometric passages correspond to speleogenetic processes that happened in shallow phreatic conditions, within a coastal aquifer effectively drained by a couple of rather parallel master conduits excavated in the back reef carbonates (outer lagoon facies, according to Pomar et al., 1996). As mentioned in previous sections, small-scale solutional forms indicative of a highly dynamic hydrological flow (i.e. scallops) are not present. Although the presence of well-developed drainage galleries is not the rule when talking about eogenetic karstification (Vacher & Mylroie, 2002), the existence of real solutional conduits has been reported in cases like Florida (Moore et al., 2010) where dissolution by meteoric waters is capable of forming drainage systems, favored by the action of aggressive waters even at the rock matrix scale.

The elongated 2D maze pattern of the inner sectors of the cave seems to integrate a poorly organized drainage system, related to a diffuse recharge occurring directly over the moderate to highly permeable rocks of the Upper Miocene Reef Complex. In spite of the diffuse authigenic recharge and the current low rainfall (approx. 400 mm/yr), some important recharge episodes have presumably occurred in wetter Plio-Quaternary events, evidenced by locally important sediment accumulations existing in the cave (Fornós et al., 2010b). The presence of Torrent de Garonda, a creek that runs relatively close to the northern end of Galeria del Tragus, could have contributed to the meteoric recharge of the aquifer through losses from this episodic water course.

Finally, it must be remarked the presence of solutional ascending channels in the inland sectors of the cave, together with some other morphologies –feeder-like vertical hollows, cupolas, dead-end passages, etc.– of a plausible hypogene origin (Ginés et al., 2009b; Fornós et al., 2011), in the sense formulated by Klimchouk (2007, 2009). Other possible evidence of hypogene karstification consists in crusts and other precipitates rich in Mn and Fe, as well as a peculiar assemblage of uncommon minerals (celistine, strontianite, barite, nordstrandite, etc.) existing as post-drainage deposits close to the vents located in the floor of some passages (Merino et al., 2009; Fornós et al., 2010a; Onac et al., 2014). The above described phenomena could be explained by a deep hypogenic recharge from the Mesozoic basement, linked to the geothermal anomalies associated with the extensional faults limiting the western edge of the Campos subsidence basin (Fig. 1); this basal recharge is supported by the non-functional hypogene features described in this cave as well as isolated geothermal evidence from other cavities and wells of the surrounding area (López & Mateos, 2006; Merino et al., 2011a).

The genetic complexity illustrated by Cova des Pas de Vallgornera is depicted in Fig. 15, where the interaction of three speleogenetic agents is postulated: 1) phreatic dissolution in the coastal mixing zone, 2) epigenic karstification related to the underground drainage of meteoric precipitations, and 3) deep hypogenic recharge linked to the geothermal anomalies documented in the area. The participation of these three agents is strongly controlled by lateral and vertical variations in permeability, within an unconfined littoral aquifer, as a consequence of the internal architecture of the Upper Miocene reef. The resulting cave system displays a clear drainage functionality through conduits in the less permeable back reef facies, whereas in the highly permeable front reef facies the groundwater flow takes place basically through the primary porosity of the rock, enhanced by the coastal geochemical aggressiveness. This panorama shows little resemblance to the flank margin cave paradigm (Mylroie & Carew, 1990) whereas, however, has important similarities with the Quintana Roo caves from Yucatan Peninsula, as documented in Smart et al. (2006), with the particularity of the possible hypogene influence reported in the Mallorcan case, and even in the Yucatan Platform (Thomas, 2010). As argued by Smart et al. (2006), the extension of the catchment area acts as a limiting factor that forces the switch from one model to the other, a fact also observable in the Balearic archipelago where typical flank margin caves are exclusively well-represented in the small island of Formentera (Ginés et al., 2008) whose area is only 83 km².

**Base level position and evolution of the cave**

A relevant problem to our discussion is the position of the base level that controlled the main speleogenetic phases of the system. Logically, the base level elevation responsible for the cave formation has been tightly controlled by the sea-level changes, including the poorly known Pliocene sea stands as well as the Quaternary glacioeustatic fluctuations (Dwyer & Chandler, 2009; Miller et al. 2011). Within this context the temporal evolution of the cave genesis is difficult to establish, owing to the extreme fluctuations in base level elevation mirroring the Mediterranean sea level history (Butzer & Cuerva, 1962; Zazo, 1999; Ginés et al., 2012); the resulting trend is characterized by a succession of long-
lasting regressive events which are intercalated among other events with relatively high sea levels (interglacials and interstadials) sometimes similar or even higher than the current one. Obviously, the formation of Cova des Pas de Vallgornera as a whole must correspond to some high sea stands, which have determined the position of the water table at the moment of the solutinal excavation of its main tiers of passages. Difficulties arise when trying to determine a more or less precise chronology for these principal speleogenetic phases.

As previously stated, the inland sectors of the cave system are arranged in two main tiers, disposed respectively close or slightly below the current sea level and between +7 to +11 m above it (Fig. 13). There is no solid evidence to establish if these labyrinthine tiers are synchronous in origin and subsequently affected by tectonics or, as opposite, the genesis of the main tiers is diachronic and controlled by Plio-Quaternary sea level fluctuations. Supporting the first possibility, it is necessary to remember that Pliocene and Quaternary shoreline deposits are located along the coastal cliffs of the area at very variable elevations, ranging from close to the sea level to more than 15 m above. This situation suggests the extension towards the north of this regressive basin (Fig. 15).

The proposed arguments could support the hypothesis that considers the lower tier of passages (including Sector Subaquàtic de Gregal and Sector de Gregal) to be younger than the upper northern tier (Sector Tragus), because the latter is not affected by the southward trend presumably associated with the Pleistocene sea cliff retreat. Furthermore, the presence of small underwater passages developed below the main galleries of Gran Canyó suggests the extension towards the north of this lower tier of galleries (Fig. 13), so casting doubt on the first possibility consisting in the existence of a unique speleogenetic horizon deformed and compartmented by tectonic movements. Whatever evolutionary hypothesis is considered, the approximate chronology of speleogenesis is difficult to estimate solely on the basis of morphological evidences. Thus, indirect or direct geochronological data on some cave infillings need to be obtained.

Age of speleogenesis

The chronological key helping to reconstruct the morphogenetic evolution of the cave relies on the paleontological deposit that is located in the northernmost end of Galeria del Tragus (Fig. 7). This huge gallery contains a thick detrital infilling (Fornós et al., 2010b) plentiful of osteological remains of Plio-Quaternary fauna. Endemic species of mammals evolved in an isolated insular environment are well represented, including abundant skeletons and skulls of the Myotragus genus, a bovid which arrived in Mallorca and Menorca in Messinian times (Bover et al., 2008, 2010). The specimens recovered inside the cave correspond to archaic intermediate forms (Fornós et al., 2010b) placed between Myotragus antiquus and Myotragus kopperi, with an age around 2.4-2.6 Ma. These macromammal remains are accompanied by other osteological materials, documented in depth by Bover...
et al. (2014). Several paleontological remains are found in anatomic connection, indicating that some animals entered alive into the cave and without any substantial water or gravity transportation.

The paleontological deposit of *Galeria del Tragus* is decisive regarding the chronology of Cova des Pas de Vallgornera, because it fixes a *terminus ante quem* (a minimum age for speleogenesis) for the solutional excavation of the passages. So, it is possible to conclude that at the very beginning of the Pleistocene (about 2.4 Ma) the galleries of this sector were already formed; their dimensions and general morphology were quite similar to the present-day ones. These data constrain the genesis of the main passages to Pliocene times, falling back at least to some high sea levels that occurred during the mid-Pliocene.

The proposed evolutionary history of the cave is schematically represented in Fig. 16, based upon the scarce chronological and morphological data that are solid enough. The sequence envisages an important Pliocene speleogenetic phase, with perhaps some additional cave horizons being formed later on during the Upper Pliocene and Lower Pleistocene. Afterwards, in the earliest Pleistocene times, a crucial benchmark is recorded, consisting in the deposition of a thick allochthonous infilling which contains archaic *Myotragus* remains, whose emplacement is related to the existence of an ancient entrance to the cave system. This ancient access, as some others in which surface Quaternary materials have penetrated (for example in the southeast end of Sector Grans Sales), is nowadays blocked.

Over the entire Pleistocene, the cave evolution was thoroughly affected by the glacioeustatic fluctuations of sea level, which have favored the development of breakdown phenomena and especially the deposition of vadose speleothems, many of them nowadays drowned by brackish waters. Speleothem formation was intense during the Middle Pleistocene according to the datings supplied by Hodge (2004). Finally, the most recent sea level high stands are well-recorded in the cave as phreatic speleothem overgrowths, corresponding to the Last Interglacial event and to the Holocene rise in sea level (Dorale et al., 2010; Tuccimei et al., 2010).

**CONCLUSIONS: A COMPLEX SPELEOGENETIC MODEL**

Explorations in Cova des Pas de Vallgornera stands out as an exceptional discovery within the current knowledge of the karstification in the southern littoral of Mallorca. Its length exceeds 74 km, being the most important cave system in the island and hosting a unique morphological suite among the coastal karst in the Balearic Archipelago.

The cave clearly illustrates the crucial role of lithology as the main factor controlling the pattern and morphologies of its different sectors. Basically, a sharp dichotomy arises between the passages developed in the reef front facies being dominated by spongework features and affected by ubiquitous collapse phenomena, and the back reef galleries that form a maze composed of rather parallel master conduits excavated along important SW-NE fractures. This dichotomy is related to the great differences in porosity and permeability existing both laterally and vertically within the Upper Miocene carbonates, due to the Reef Complex facies architecture.

This cave contains evidence pointing towards a complex speleogenesis that includes, besides coastal mixing dissolution, a noticeable meteoric diffuse recharge and, furthermore, a hypogenic meteoric dissolution associated with the geothermal phenomena documented in the nearby area.

The principal speleogenetic phases extend back at least to some high sea-stand that occurred in mid-Pliocene times, on the basis of the paleontological vertebrate remains recovered from the cave. The disposition of the cave in two main tiers, relatively individualized both in plan and in elevation, is...
probably the result of speleogenetic phases correlated to different Plio-Quaternary high sea-stands. The southward trend of the lower tier seems to be related to the erosional retreat of the coastal cliffs, therefore being younger than the higher passages and mazes. During the whole Pleistocene, the morphological evolution of the cave was fully controlled by the glacioeustatic fluctuations of the Mediterranean Sea, with extensive deposition of speleothems in passages, which are nowadays drowned.

In spite of its coastal character, it is not possible to fit this kind of large and complex cave system within the flank margin cave category; alternatively, Cova des Pas de Vallengornera shares a lot in common with some continental littoral settings, for example the Quintana Roo caves in the Yucatan Peninsula, as documented by Smart et al. (2006). With our current knowledge of coastal karst it seems necessary to reformulate the Carbonate Island Karst Model (CIKM), shifting towards a Carbonate Coast Karst Model that will take into account the examples coming from larger islands and/or continental areas. This enlarged model should incorporate among other variables those controlling the amount of discharge through the coastal drainage system, namely the climate and especially the extension of the catchment area.

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Geology and speleogenesis of Cova des Pas de Vallgornera, Mallorca


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Speleothems in Cova des Pas de Vallgornera: their distribution and characteristics within an extensive coastal cave from the eogenetic karst of southern Mallorca (Western Mediterranean)

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Abstract: The abundance and variety of speleothems are undoubtedly among the remarkable features of Cova des Pas de Vallgornera, the longest cave system in Mallorca Island developed in the eogenetic karst of its southern coast. Due to the monotonous carbonate lithology of the area, most of the speleothems are composed of calcite and in a few cases aragonite, although other minerals are also represented (e.g., gypsum, celestine, barite). However, in spite of the rather common mineralogy of the speleothems, its distribution results strongly mediated by the lithologic and textural variability linked to the architecture of the Upper Miocene reefal rocks. Apart from a vast majority of speleothem typologies that are ubiquitous all along the cave system, some particular types are restricted to specific sections of the cave. In its landward inner passages, formed in the low permeability back reef facies, a great variety of speleothems associated to perched freshwater accumulations stands out, as well as some non frequent crystallizations like for example cave rims. On the other hand, the seaward part of the cave (developed in the very porous reef front facies) hosts conspicuous phreatic overgrowths on speleothems (POS), which are discussed to show their applications to constrain sea level changes. The factors controlling the distribution of speleothems found in Cova des Pas de Vallgornera are discussed along the paper, focusing the attention on the lithologic, hydrogeologic, and speleogenetic conditionings; at the same time some uncommon speleothems, not found in any other cave in Mallorca, are also documented from this locality. Finally, a cognizant effort has been undertaken to illustrate with photographs the most remarkable speleothem types represented in the cave.

Keywords: speleothems, carbonate crystallizations, phreatic overgrowths, coastal karst, southern Mallorca

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INTRODUCTION

The importance of Cova des Pas de Vallgornera is not only related to the extension attained by the cave itself (over 74 km of development), but also for the exceptional richness, striking variety, and abundance of speleothems. This wide exhibition of carbonate crystallizations is a common occurrence in Mallorcan karst areas (Ginés, 1995; Merino et al., 2011), but certainly this cave represents an exceptional case regarding this topic. As early as 2000, with the discovery and exploration of the Noves Extensions series (Fig. 1), this peculiar profusion and exhibition of speleothems was first highlighted (Merino, 2000). But it is not until the unexpected exploration breakthrough of 2004, when the hitherto unknown Descobriments 2004 series are discovered, that a full awareness for the spectacular display of speleothems is built (Merino et al., 2006). The discovery of abundant rimstone dams (gours) hosting a great number of other subaqueous types like shelfstones, cave rafts, cave cups, pool spar and, for instance, the existence of large areas of the cave covered in numerous capillary crystallizations—like filiform and vermiform helictites—were showing
a well-organized distribution of certain groups of speleothems. The finding of uncommon typologies, like cave rims, cave bubbles, pool fingers, and U-loops (to mention just a few of them) greatly enlarged the types of speleothems represented in Cova des Pas de Vallgornera (Merino, 2007b, 2008; Merino & Fornós, 2010a), converting this cave in a unique locality within the Mallorca’s endokarst.

Owing to the littoral character of the cave system, a special mention must be addressed to phreatic overgrowths on speleothems (POS). These carbonate encrustations have grown at the current sea-controlled water table (Tuccimei et al., 2010), recording in the same way ancient sea level positions (Dorale et al., 2010; Ginés et al., 2012b). The data supplied by the coastal phreatic speleothems from this cave are discussed in order to constrain sea level history during Pleistocene. Apart from the POS investigations, the only geochronological and paleoclimatological data produced on speleothems from this cave are those supplied by Hodge (2004), who studied three stalagmites whose chronology ranges from Middle Pleistocene to Holocene.

Regarding non-carbonate crystallizations, besides the scarce gypsum cave flowers reported in the cave (Merino, 2007b), detailed observations on cave rims shed light on a variety of unexpected minerals related to this particular morphological feature; strontianite, celestone, barite, and nordstrandite were identified (Merino et al., 2009), in a morphogenetic setting that points towards the actuation of hypogenic processes (Klimchouk, 2007).

Classifications of speleothems have been usually established on the basis of its morphology and/or the genetic mechanisms involved (Sweeting, 1973; White, 1976; Gillieson, 1996; Hill & Forti, 1997; Ford & Williams, 2007; Palmer, 2007). So, it is a common practice to systematize these deposits according to the characteristics of the water-flow that precipitates them; in this respect, speleothems formed by dripping waters, flowing waters and capillary or seepage waters are distinguished together with subaqueous crystallizations. All these categories are very well-represented in this exceptional cave by means of a great diversity of speleothem types, but their enumeration or even description is not the goal of this paper. In a more interpretative way, we will focus on the localization pattern of speleothems within the cave and on the factors that explain how they are distributed.

Commonly, all kinds of speleothems are present throughout the cave, but not in a rambling way. The lithologic and textural characteristics of the rock where the cave is located along with the proximity to the coastline and the complexity of the involved speleogenetic processes (Ginés et al., 2009a, 2009b), determine the presence and abundance of certain speleothems in specific sections of the cave system. The distribution of the speleothem typologies within Cova des Pas de Vallgonrera will be the main target of this paper, together with the documentation of the most striking and/or uncommon crystallizations reported from this cave. In order to locate and identify the different sectors, main galleries, and chambers, a comprehensive article including a detailed description of the cave is also published in this issue (Merino et al., 2014). The totality of photographs included in the paper has been performed by one of the authors (AM) with the helpful collaboration of cavers from several clubs integrated within the Federació Balear d’Espeleologia.

**FACTORS THAT CONTROL THE DISTRIBUTION OF SPELEOTHEMS IN THE STUDIED CAVE**

Mallorca is a mid-latitude island (39°N) located in a bioclimatic setting typically Mediterranean, with an annual average temperature of 16.6°C and a mean precipitation value near 600 mm/yr (Guijarro, 1995); rainfall is markedly seasonal, showing its maximum in the autumn. The natural vegetation in the south of the island is dominated by semi-arid shrubberies and scarce forests that grow on thin calcareous soils. In general terms the present-day bioclimatic context favors the processes that generate speleothems, a situation that is extensive to the whole Mediterranean area. Furthermore, due to its position in the middle of the Western Mediterranean basin, Mallorca was not severely affected by the glacial periods during the Pleistocene (Ginés et al., 2012a), when the climate conditions were mostly mild but with important variation in precipitations. Although Th/U datings of stalagmites or flowstones from Mallorca are scarce (Hodge, 2004; Ginés et al., 2011), the deposition of speleothems during the cooler Pleistocene events is clearly documented by the presence of abundant speleothems, formed during low-stand sea levels, that are nowadays submerged in the present-day brackish pools of coastal caves like Cova des Pas de Vallgonrera.

Apart from climate dependent controls, the formation of speleothems is also conditioned by the lithologic and textural characteristics of the rocks where the cave is located. Regarding their hydrogeological behavior, the Upper Miocene reefal carbonates that form the southern part of the island (Fornós et al., 2002) are an example of eogenetic karst, as defined by Vacher & Mylroie (2002). The diagenetically immature limestone rocks, hosting the coastal karst areas of southern Mallorca, are characterized in general by high porosity and permeability values that certainly have some influences on the speleothem formation processes.

Another important factor, in this case intrinsic to the cave, is the great development attained by Cova des Pas de Vallgonrera, with over 74 km of known passages and chambers. The very important extension of the cave system allows the existence of a great diversity of depositional environments, related to strictly topographic or morphogenetic conditionings, as well as to the wide textural variability of the rock as a function of the diverse facies observable within the Upper Miocene reef architecture (Pomar et al., 1996).

Centering our attention on lithology, two well-individualized parts of the cave can be distinguished on the basis of the rock facies where their passages...
are developed (Fig. 1). In this way, a very clear duality arises between the seaward sectors of the system and the inner landward passages (Ginés et al., 2009a). On the one hand, the sections of the cave closest to the coast-line (Sector Antic, Sector Noves Extensions, Sector Grans Sales and Sector del Clupeaster) are located in the reef front facies characterized by a very high primary porosity, along with an important secondary one linked to the dissolution of the aragonitic coral constructions. Within these reef front rocks, the spongework passages are dominant together with interspersed collapse chambers, all of them situated close to the water table corresponding to the present-day sea level. As opposite, the inner galleries are developed in the back reef carbonates, specifically in the outer lagoon facies (Pomar et al., 1996); in these less permeable rocks, that show a low primary porosity if compared with the reef front facies, the joint-controlled galleries are the rule, many of them forming an upper tier located +7 to +11 m a.s.l. The back reef part of the cave (Fig. 1) includes basically the sections located towards the northeast (Sector Tragus, Sector Nord, Sector de Gregal and Sector Subaquatic de Gregal); the upper tier maze (Sector F) is also developed in the back reef carbonates, owing to the existence of vertical facies variations controlled by the tridimensional reef architecture (Ginés et al., 2014). The substantial differences in porosity and permeability associated to the lithologic and textural variability of the Upper Miocene rocks are responsible for the morphogenetic duality referred above, which is discussed in depth by Ginés et al. (2014). This duality is also evident when explaining the speleothems distribution within the cave, as will be reviewed later on. The relative abundance of speleothems in connection with the distribution of rock facies within the cave is shown in the Table 1.

Yet it is possible to establish another important hydrological dichotomy concerning the characteristics of the water masses present in Cova des Pas de Vallgornera. The extensive brackish pools are distributed all along the cave, particularly in the sectors located closer to the coast-line, being evident that they are sea-controlled as tides and barometric sea level fluctuations can be observed. On the other hand, large extensions of passages forming the upper tier, in the inner part of the cave, are occupied by remarkable freshwater bodies. This fact seems to be related to the low permeability of the back reef facies, where the passage’s floors easily become impervious due to carbonate deposition and significant perched freshwater masses occur, forming extensive gours. This additional dichotomy, in some manner rather coincident with the lithologic duality, has a clear repercussion on the characteristics of the subaqueous speleothems formed in each case.

A last factor that must be taken into account deals with some particular morphogenetic aspects of the inner passages. The complex speleogenetic mechanisms that formed the cave system include...
Table 1. Relative abundance of speleothems in connection with the distribution of facies within the cave. (XXXX: abundant; XXX: frequent; XX: occasional; X: rare).

<table>
<thead>
<tr>
<th>Speleothem</th>
<th>Back reef facies</th>
<th>Reef front facies</th>
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<tbody>
<tr>
<td>Dripping and flowing water speleothems</td>
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<tr>
<td>Stalactites</td>
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<td>Soda straw</td>
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<td>Stalagmites</td>
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<td>Conulites</td>
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<td>Draperies</td>
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<td>Capillary speleothems and botryoidal forms</td>
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<td>Helicitites</td>
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<td>Antler helicitites</td>
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<td>Frostwork</td>
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<td>Shields</td>
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<td>Vermiculations</td>
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<td>Sandiscles</td>
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<td>Cave flowers</td>
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<td>Variable subaerial speleothems</td>
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<td>Rimstone dams</td>
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<td>Pool spar</td>
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<td>Cave rafts</td>
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<td>Cave bubbles</td>
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<td>Shelfstones</td>
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<td>Pool fingers</td>
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<tr>
<td>Phreatic speleothems</td>
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<td>POS†</td>
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<td>Cave clouds</td>
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<td>Tower corals</td>
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</table>

*Phreatic Overgrowths on Speleothems

Within this category fall those speleothems that are more or less evenly distributed all along the cave system or show only a small variability regarding their spatial distribution. The vast majority of dripping and flowing water speleothems is ascribed to this category, together with several eccentric or erratic speleothems precipitated from capillary-fed waters.

In order to avoid terminology problems (for instance, the use of more or less local speleothem denominations or the utilization of terms coming from different sources) we have adopted the speleothems nomenclature used in Hill & Forti (1997), considering this work the most comprehensive and updated effort on this topic.

Dripping and flowing water speleothems

Undoubtedly, stalactites, stalagmites, and columns are probably the most common speleothems in the cave. Those of reduced size are mainly present in small-scale passages where they can fill/block their entire section. Sectors like Gran Sales and Tragus where ceilings are 5 m high or higher, allow the growth of longer stalactites and columns; stalagmites and columns in these sectors can reach massive dimensions (e.g., Sala de les Columnes). Besides, totem-pole stalagmites of waxen-texture are also present. As a result of the textural characteristics of the Upper Miocene limestones, there is an abundance of soda straw stalactites particularly in the very porous reef front facies (Fig. 2). So, owing to the high primary porosity of the whole rock, magnificent closely spaced clusters of soda straw forests cover almost completely the ceiling of many passages and chambers; the length of straw stalactites vary from a few centimeters to nearly 4 m. In the passages of the inner part of the cave, stalactites and dripping water types are usually arranged along joints and fractures.

Depending on the surface unevenness of ceilings and overhanging walls, draperies can develop complex curves and twists, being often translucent revealing bands of different colors and shape. Draperies are found all over the cave, from the small-size passages of Sector F, to the large galleries that form the Sector del Tragus where the high ceiling allows the growth of long assemblages of them. At some areas, draperies severely affected by decalcification processes show a whitish altered shape (Fig. 3); in many cases, their occurrence is related to dissolution by condensation waters.

Flowstones cover large extensions in the cave, and as a result of the great variety of situations in which this chemical precipitation takes place, a wide range of forms can occur. Depending on where flowstones are deposited, they can be put into two groups, the forms covering walls and those flooring a suite of features produced by a deep hypogenic recharge (Ginés et al., 2009b; Merino & Fornós, 2010b; Fornós et al., 2011). Some of these feeder-like features allow the presence—in specific spots of the cave—of uncommon speleothems and crystallizations (Merino et al., 2009) that grow on these vent morphologies like, for example, most of the dripping and flowing water speleothems are ascribed to this category, together with several eccentric or erratic speleothems precipitated from capillary-fed waters.

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passages of Sector del Tragus (Galería del Gell, Galería del Quilòmetre, and Galeria del Tragus) must be noted (Fig. 4). The presence of these conspicuous yellowish flowstones seems to be restricted to the landward part of the cave, probably due to the existence of well-developed organic soils at the surface, situation that does not occur over the sectors closer to the coastline.

Erratic speleothems

Certainly helictites, represented by very diverse varieties, are one of the most common speleothems in the cave and can be found covering floors, walls, columns and stalactites. Clustered bunches of helictites also occur at small spots or rock shelves. The length of helictites varies greatly, from 2 mm up to 25 cm, being translucent, white or caramel-colored. Although they are especially abundant and variegated in the reef front carbonates (seaward part of the cave), in some passages of the inner sectors are quite spectacular, being frequently associated to cracks affecting flowstones that cover the passage’s floors (Fig. 5). In the Gran Canyó Gallery (Sector del Tragus), filiform and vermiform helictites covering a rock shelf and its adjacent walls have been reported (Merino, 2006), being present as well in many other spots of the cave. An uncommon variety are the antler helictites, each the thickness of a pencil, protruding like a spear from a coating floor near Sector F (Fig. 6).
vertical oval shield, 2 m high and 20 cm thick, exists in Noves Extensions, showing the shape of a wall and partially blocking an aquatic passage.

In general terms, subaerial coralloids and botryoidal speleothems are exceptionally well-displayed in Sector Noves Extensions, Sector F, and Sector del Clypeaster, all developed in the high porous calcarenites of front reef facies, being present as well in almost all the other sectors of the cave. This kind of speleothems are formed by capillary waters seeping through the pores and minute fissures of the rock, without excluding the interaction with other mechanisms like dripping water splash and evaporation processes; all of them are responsible for a wide range of morphologies. The most common varieties are the branched globular and the grapes-like shaped coralloids. They range in size from a few millimeters up to 2 cm and are usually white or yellowish in color, with the latter ones having a waxen appearance (Merino, 2006). This kind of speleothem grows on walls, floor, on isolated boulders, or even on flowstones and stalagmites (Fig. 7).

Other deposits and minerals
Moonmilk is present in nearly all sectors of the cave; Sala del Moonmilk, Galeria del Quilòmetre, Galeria Navarrete, Sala que No Té Nom, and Sector F are the areas where these deposits reach a wider distribution. Moonmilk occurs as a soft plastic and pasty coating growing over walls, ceiling and

Shields are not abundant but a few exemplars are distributed throughout the whole cave. They are composed of two parallel medallions of calcite separated by a thin fissure; through this internal crack a capillary seepage occurs, depositing calcite both sides and allowing the formation to grow vertically or at an oblique angle. Shields are commonly oval to circular, rarely exceeding 1 m in diameter, and quite often have other formations such as draperies or small stalagmites growing from them. A remarkable
boulders. When wet it contains a high percentage of water (Sector F), on the contrary dry moonmilk is powdery, resembling chalk powder (Sala del Moonmilk, Galeria del Quilòmetre, Galeria Navarrete). It is composed of calcite and usually white in colour but at many locations presents a thin multicolored layer of corrosion residues, exhibiting changes in color from yellowish, greenish, and greyish to red. The thickness ranges from a typically 2-4 cm to an exceptional 13 cm documented at the highest section of Sala que No Té Nom. These almost ubiquitous deposits may be originated as a result of particular physico-chemical conditions that lead to the degradation of bedrock, with the possible influence of biological processes caused by microorganisms (Hill & Forti, 1997). This fact could be supported by the presence of the already mentioned corrosion residues that might be end-products of microbially assisted dissolution and leaching of the rock (Northup et al., 2000, 2003; Spilde et al., 2005, 2006; Barton et al., 2007).

Composed of calcium sulfate, cave flowers are scarce in comparison with calcite speleothems (Merino, 2007a). They have been located in three different and distant areas of the cave. Firstly, at Sector del Clypeaster, few centimeters above the current water table level, secondly at Sector del Tragus and finally, at Sector F, the last two locations at the upper tier. These gypsum speleothems occur as thin translucent crust covering walls, as helical shaped formations and mainly as tiny flowers (Fig. 8). Cave flowers are commonly whitish in color, ranging from 2-3 mm up to 10 mm in length. They consist of variable number of crystalline fibrous petals that grow from a common center; these branching and curving bunches of parallel crystals show disparate lengths and thicknesses. This asymmetry seems to be caused by an unsteady growth. The genesis is likely to be controlled by seepage processes involving calcium sulfate solutions reaching walls and floors in the cave. A good example of this, would be the gypsum flowers and small crusts developed on a boulder partially submerged in the brackish waters at the Sector del Clypeaster.

**Fig. 8. Tiny cave flower composed of gypsum growing on the surface of a semi submerged boulder. Different calcium sulfate deposits can be seen around the area.**

**SPELEOTHEMS WITHIN THE BACK REEF CARBONATES (LANDWARD SECTIONS OF THE CAVE)**

Many speleothem types and subtypes are exclusively represented in the inner galleries corresponding to the landward part of the cave system, which are developed in the back reef limestones characterized by a relatively low permeability (Ginés et al., 2009a, 2014). In some cases, their presence is not related to any lithologic or morphogenetic factor: it is exclusively the result of unusual speleothems growing in a particular spot of the cave, but without clear conditionings that explain their distribution. In some other typologies there is an evident connection between speleothem types and specific factors that determine their existence; this is the case of subaqueous speleothems precipitated in perched freshwater bodies existing almost exclusively in the upper tier of the landward passages. The distribution of the most characteristic speleothems that differentiate the two different lithologic units distinguished within the cave system is shown in Fig. 9.

**Dripping water speleothems**

Several subtypes of conulites are mainly found at the inner passages like Galeria del Tragus, where the massive accumulation of sediments and the height of the passage allow the growth of this speleothem. Typically, a conulite is a conical or cylindrical shell caused by dripping water and developed in soft material; the same water that excavates the hollow tube, splashes over it and coats a thin layer of calcite. The relatively calcisiltitic character of the back reef carbonates (outer lagoon facies, according to Pomar et al., 1996) could explain their development, linked to the silty residues resulting from the rock dissolution.

A variety of this formation, called bird-bath conulite occurs as an isolated speleothem or in groups of several individuals where sandy, silty and moonmilk deposits are present (Merino, 2006). Bowl-shaped, it is coated by a thick calcium carbonate layer that on the one hand, prevents the dripping water from seeping, and on the other allows to retain water for long periods of time. A radial structure caused by water splashes is noted; the range of them is related to the height between the dripping point and the floor, the higher the gallery, the wider the diameter of the speleothem.

Another peculiar kind of conulite developed on moonmilk has been discovered in Galeria del Quilòmetre, within the Sector de Gregal. It closely resembles the typical bird-bath conulite’s morphology, but it does not contain water and a hollow tube of some centimeters in depth is present. A white vertical, gutter-shaped structure consisting of what appears to be moonmilk, grows over the hollow tube’s mouth (Fig. 10). This unique speleothem is 8 cm in height, about 2 cm across its top and has a wall thickness of less than 0.5 cm. The genesis could be related both to the materials that form the substratum and to the deposits that are washed away by dripping water.
Capillary speleothems

Apart from subaerial coralloids and other botryoidal forms that are ubiquitous, **frostwork** is another speleothem with a similar genesis but composed of delicate white needles of aragonite (Merino, 2007a). It is quite scarce and has been found in *Sector F* growing on white popcorns (Fig. 11). Occasionally the frostwork is formed by calcite as a consequence of a recrystallization process from aragonite while keeping the original needle-like shape (Palmer, 2007).
Vadose subaqueous speleothems

They are probably the most exceptional and one of the more varied categories of speleothems in the landward inner passages of Cova des Pas de Vallgornera. The richness of forms is favored, on the one hand, by the relative low permeability of the back reef facies that allows the accumulation of significant freshwater bodies on the floors of many galleries. On the other, the abundance of these temporary reservoirs of perched waters, distributed mainly along the sectors located at the upper tier (especially in Sector del Tragus and the maze of passages of Sector F), provides the right depositional environment for the development of numerous and variegated subaqueous formations. The following types have been described: rimstone dams (gours), pool spar, cave rafts, raft cones, cave bubbles, shelfstones, crescent shelfstones, candlesticks, coke tables, cave cups, pool fingers, and cave pearls (Merino, 2006).

Not only are rimstone dams (gours) the most abundant speleothems of this kind, but they also harbor the vast majority of the other types related to precipitation in this freshwater bodies. In Cova des Pas de Vallgornera, rimstone dams are mainly developed on gently sloping floors of ancient phreatic galleries currently located in the vadose zone. Most of them are lined with pool spar crystals of different sizes (Fig. 12). They are translucent, sometimes amber or yellowish in color, sharp-tipped calcite crystals that cover the whole pool sealing it and creating a perched pool. They have also been developed below shelfstones, growing on stalactites or on any formation submerged in pools.

As a consequence of the degassing of carbon dioxide at the pools surface, small calcite crystals form, floating by surface tension and joining together to create cave rafts. Floating rafts are normally small in size, with a thickness of about 1 millimeter or even thinner, whereas larger and thicker rafts are found attached to the pools walls or mostly sunk lying broken at the bottom of pools. Those thicker rafts show two different sides, the upper one is smooth and flat, whereas the lower one in contact with the water is coarse and covered by small calcite crystals. It is quite common to find dry pools with their shores and bottom covered in thin rafts. In spite of the fact that cave rafts are abundant, raft cones are generally rare in Cova des Pas de Vallgornera; only modest cone-shaped piles have been found below drip points in passages from Sector del Tragus and Sector F.

One of the weirdest speleothems associated to rimstone dams observed in the cave are cave bubbles. They have been observed only in a small pool located at Sector del Clypeaster, (Merino, 2007a) and can be described as a hollow calcite concretion floating on a quiet and shallow pool. The precipitation takes place around a bubble of gas; they are ovoid or even close to hexagonal in shape, reaching 5 mm in diameter. The assemblage of cave bubbles is formed by hundreds of individuals that coalesce, most of them adhered to the side of the pool, others floating in the middle of

Fig. 12. Noteworthy rimstone dam located at the upper tier of the cave containing a wide range of other vadose subaqueous speleothems. A unique crescent shelfstones and lotus rimstones association rings the pool, these speleothems are formed by translucent crystalline calcite. Below the water surface, a calcite deposit coats the whole pool, sealing it and allowing the accumulation of freshwater.
A delicate and conspicuous kind of shelfstones are *cave cups*, which are spread in many shallow rimstone dams throughout the cave. They look like smooth concave dishes; some are round or elongated in shape, white translucent to yellowish in color (Fig. 15). The size ranges from 1 cm up to 20 cm. The upper part of the cup is usually smooth, whereas small calcite crystals cover the lower one. They always form on the floor of cave pools, or as an eave-like projection from the water body (Fig. 13). The bubbles morphology is quite uniform, being their dimensions controlled by the concretion size. Clusters of cave bubbles are clearly separated one from each other by tiny gaps filled with water, while others show a higher concentration of individuals with the interstices filled with calcite (Fig. 14). At the same time, at the edge of those groups of bubbles, a cloud of what seem minute calcite crystals exists. Caves bubbles were located in a rimstone dam situated in a small alcove protected from air movements and without drips and were associated with other speleothems, like shelfstones and cave rafts, indicating highly saturated conditions. This special environment is necessary for the development of this fragile speleothem.

Because of carbonate precipitation taking place just at the water surface, a great number of rimstones are ringed by flat deposits of calcite attached as a projection or shelving to the edge of cave pools. These crystallizations, known generally as *shelfstones*, show a thickness that varies from a few millimeters up to several centimeters; it is quite common to find rimstone pools completely covered by shelfstones that show a decreasing of thickness to the centre of the pool. The diversity of forms associated to the rimstone pools’ surface is enormous in general, and this is particularly evident in Cova des Pas de Vallgornera. So, for instance, *crescent shelfstones* of different dimensions are also present in many cave pools; this rounded speleothem is caused by the interaction between dripping water and the pool itself. Therefore, the more stalactites or dripping points above the pool the more abundant crescent shelfstones are. Another variety of shelfstone present in the cave is the *candlestick* that forms surrounding small columns. One of the most outstanding and unique speleothems that occurs in the cave is the *coke table*. They are similar to a water lily-pad in shape, like a large plate that is close to 1 m in diameter and have been developed from a protruded half-submerged point inside a pool. They are quite flat and relatively smooth on the upper part, whereas the lower part is rough and formed by an aligned series of calcite macrocrystals. Similarly, others are developed around submerged stalactites tips.

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**Fig. 13.** A small rimstone dam harboring a myriad of minute cave bubbles.

**Fig. 14.** Cave bubbles in detail. Different individuals coalesce showing a quite uniform dimensions and morphology. A constellation of what seems to be tiny calcite crystals is surrounding the group of cave bubbles.

**Fig. 15.** Small-scale cave cups resembling smooth concave dishes. They are dry inside, in spite of the fact that the water level in the pool is just around the edge of the cups. The growing process of this speleothem is clearly exhibited by means of the tiny calcite rafts surrounding the cups and adhering to them.
the wall of those pools. The former are attached to the floor by a peduncle that would be the cup's apex; the latter have grown from the pool's walls and are stuck to them. Generally, cave cups size is determined by the pools depth, the deeper the pool, the larger the cave cups. Cave cups growing on the tip of calcite crystals or around a stalactite fragment in its center have been spotted in very shallow pools; these materials could be interpreted as acting as centers of precipitation for the speleothems to grow.

Also formed in shallow water accumulations, cave pearls are quite scarce, the only known locations being in Sector del Tragus and at the Galeria del Quilòmetre, normally associated with high ceilings and being developed in small pockets where water drips (Merino, 2008). They are round in shape like balls or elongated like rods when their origin is related to broken formations. The largest accumulation of cave pearls is in a series of micro rimstone dams, where they cover most of the surface, ranging from 1 to 3 mm in diameter.

Finally, pool fingers have only been located in an active pool, 9 m long 0.7 m in width and about 0.3 m deep, situated at the upper tier of the cave in Sector F. The pool is totally coated by pool spars and ringed with shelfstones and crescent shelfstones (Fig. 16). Pool fingers (Davis et al., 1990; Hill & Forti, 1997; Palmer, 2007) resemble tiny stalactites formed subaqueously that are translucent and whitish in color, being developed on pool spars that cover the walls of the rimstone dam. They are elliptical in cross-section and with a diameter between 1 to 3 mm; their length range from 1 to 30 mm. Those pool fingers that currently have their tips submerged show a slight overgrowth.

Moreover, very fine U-loops connecting fingers have been spotted (Merino & Fornós, 2010a). These curved structures (Davis, 2000) are composed of small-sized calcite crystals that form bridges between adjacent fingers. Contrary to the existing pool fingers found in the caves of the Guadalupe mountains where microscopic bacteria filaments have been identified (Northup et al., 2000; Melin et al., 2001), those from Cova de Pas de Vallgornera, do not show any filaments or microbial remains after being studied with SEM (Merino & Fornós, 2010a).

Phreatic crystallizations

In the northernmost passage of the cave (Galeria del Tragus), the walls and floor of a relatively long stretch are coated by aragonitic mammillaries, forming rounded bulges that can be described as cave clouds. The coating is only a few centimeters thick and its upper limit determine a horizontal line, corresponding presumably to an ancient stabilization of the water table, approximately two meters above the passage's floor and 7 m above the current sea level. The phreatic character of these subaqueous deposits seems evident, taking into account their mineralogy (aragonite) and morphology (lack of shelfstone crystallizations that could point towards perched freshwater bodies). The lower sections of this aragonitic coating are affected by short and tiny upward rising solutional channels of likely hypogenic origin (Klimchouk, 2007). Although it is not clear if this mammillary coating was sea level controlled, it is obvious that lacks the characteristic shape related to the fluctuating tide-controlled water table, as will be described below when dealing with the phreatic overgrowths on speleothems (POS) existing in the seaward part of the cave system.

Within this aragonitic drained pool some exemplars of tower coral have been reported (Merino, 2006). This speleothem is quite scarce in the cave, and has only been located in the Galeria del Tragus so far (Fig. 17). Generally, the tower coral consist in groups of pinnacles that grow assembled on the floor and on boulders. The pinaciles are mainly found on the flatter areas of the passage where the surface inclination allows the accumulation of calcium carbonate. These speleothems grow upward being conical, small-tower-shaped, with uneven walls, being white or brown colored. Its dimensions range from a few centimeters up to 6 cm in height, and 3 cm in diameter; they are vertically oriented but if a drip occurs while growing it can cause the tower to be more irregular and to incline away from the vertical orientation. In cross-section the coral tower shows an aragonite radial structure being coated by a tough calcite outer layer. The genesis of this speleothem is related to the shallower areas of former ponds, corresponding to an ancient stabilization of the water table.

![Fig. 16. Group of pool fingers hanging from the walls of an active rimstone dam. The whole pool is lined with pool spar.](image1)

![Fig. 17. Cluster of subaqueous Tower-Coral showing its typical conical small-tower shape. In cross-section this speleothem exhibits an aragonitic radial structure.](image2)
Cave rims

Until very recently, this speleothem was unknown in Mallorca (Merino, 2006), being very well-represented in the inner sectors of Cova des Pas de Vallgornera. **Cave rims** have been located along the floor of **Sector F, Sector Nord, Sector del Traguas (Galeria de les Toberes, Galeria d’en Pau, and Galeria del Traguas)** and more recently in some underwater areas as for example **Gran Canyó Gallery** (Merino, 2006) and **Sector dels Privilegiats**, not ruling out the possibility of having a wider distribution throughout the underwater extensions. Cave rim morphology resembles a shell, being both sides of these projections strikingly different (Fig. 18). While the outside is rough and coralline, the inside is smooth, like the inside of the tube below the rim. Small and whitish crystallizations on the rim’s edge have been noted. Rims occur around the lips of some rather vertical holes and cracks on the galleries’ floor, referred as vents (Merino et al., 2009). White in color they reach a thickness of between 1 and 4 cm. In addition to that, the nearby areas of the vents are normally rich in other mineral deposits such as gypsum precipitates, celestine crystals, white mineral aggregates composed of huntite and small Christmas tree-like aragonite (Merino et al., 2009; Onac et al., 2014). In general, the passages where this morphology has been found are small in size. It appears reasonably certain that these speleothems are mainly located in the upper maze area of this multi-storied cave, just above another tier, which is close to the current water table. Moist airflow from the lower tier to the upper one can cause the development of these rims, along with a combination of dissolution, weathering and deposition (Palmer, 2007).

The cave rims are developed on the upper top of rather vertical vents that presumably have acted as feeders (Klimchouk, 2007), related to a hypogenic basal recharge associated to geothermal phenomena (Ginés et al., 2009b, 2014; Merino & Fornós, 2010b; Fornós et al., 2011). Thus, the distribution of this type of speleothem is not exclusively connected with the already mentioned lithologic factors, but also with speleogenetic constraints as, for example, the existence of specific hypogene features.

Other deposits

Associated with moonmilk coatings, **vermiculations** have also been found mainly at **Galeria del Quilòmetre** (Fig. 19). These formations cover ceilings and walls; they consist of irregular, thin, discontinuous deposits composed of brownish weathering residues (Merino, 2008). They range from a few millimeters up to 2 cm in length, reaching about 2-3 mm in thickness. Narrow white bands surround the colored deposits. Depending on the shape, they could be classified between leopard’s spots and hieroglyphic vermiculations (Hill & Forti, 1997). The origin of vermiculations in Cova des Pas de Vallgornera could be controlled by the presence of colored corrosion residues that are present over walls and ceilings covered with a moonmilk substrate. In an early stage, these weathering residues are adhered to a damp moonmilk substrate. Later, as a consequence of a change in the local climatic conditions of the cave, the moonmilk deposits dry out, causing them to shrink and therefore crack. Fissures provoke the falling of affected colored deposits and isolate the distinctive morphologies.

Another common formations related to the presence of moonmilk are **sandsicles** (Fig. 20) (Merino, 2007a). This tuisked-shape speleothem is developed at the edge of flowstones or even on large boulders; they...
Speleothems in Cova des Pas de Vallgornera

wide extensions of its walls are fully covered by dense groups of vermiform and filiform helictites, which grow intermixed forming gorgeous and almost unbelievable assemblages (Fig. 21). Some of the walls that delimitate the Llac de na Gemma pool are really remarkable regarding the abundance and variety of tiny helictites.

Although not remarkable for its abundance, some drip cones of popcorn show a colorful shape and are mainly located in Sector del Clypeaster (Fig. 22) and the maze areas leading to it. In spite of the fact that they resemble hollow stalagmites, they are not classified as dripping water speleothems. Drip cones of popcorn are commonly formed where condensation water falls from points in the ceiling right above (Palmer, 2007). The highly aggressive subsaturated water dissolves the rock that forms the ceiling, provoking the development of a channel-like structure that concentrates the water drips to certain points. Small areas of the ceiling rock surrounded by those channels are fragile, soft and in some cases with a butter-like touch, being completely soaked in water. Provided the drips are undersaturated in calcite, no deposits form under the hitting point, on the contrary the growth of popcorn takes place as a result of evaporation processes around the affected area. When as a consequence of weathering, the dripping range up to 10 cm in length and color varies from dark brown to ochre. Sandsicles are composed of calcium carbonate and seem to be originated where ceilings and walls are covered in moonmilk, dry moonmilk powder or moonmilk-rich solutions that fall down or drip onto sloping flowstones. When the dense solution reaches the edge, impregnates it and begins to dry out depositing this tooth-like projections. The textural characteristics of the back reef facies seem to favor their presence owing to the silty material that results from the bedrock degradation.

SPELEOTHEMS WITHIN THE REEF FRONT FACIES (SEAWARD SECTIONS OF THE CAVE)

Most of the southwestern sectors of the cave develop within the Upper Miocene reef front, a rock facies that stands out by its very important primary porosity that configures a high permeability medium that becomes enhanced, moreover, by the dissolution of coral constructions. The high porosity of these carbonates, even at a matrix scale, is responsible for the particular occurrence of some speleothem types, like for example soda straw stalactites which cover large expanses of the cave ceilings but without being arranged along rock fractures (Fig. 2). Other kinds of crystallizations, like for instance the erratic features in general, are specially well-developed in these reef front limestones thanks to the capillary waters feeding the speleothems through the rock porosity. Additionally, the location of this lithologic unit in the seaward part of the cave constitutes an adequate hydrological and geochemical scenario where the precipitation of phreatic overgrowths on speleothems occurs (Ginés et al., 2013). The spatial distribution of these coastal subaqueous carbonate encrustations appears depicted in Fig. 9, being restricted to the brackish phreatic pools closer to the coastline.

Erratic speleothems

In spite of being previously referred as a ubiquitous speleothem, helictites are really very abundant and remarkable in the reef front carbonates, owing to the small-scale porosity of the rock. In this part of the cave, like for example in Sector Noves Extensions, wide extensions of its walls are fully covered by dense groups of vermiform and filiform helictites, which grow intermixed forming gorgeous and almost unbelievable assemblages (Fig. 21). Some of the walls that delimitate the Llac de na Gemma pool are really remarkable regarding the abundance and variety of tiny helictites.
Holocene POS datings

A bulky carbonate overgrowth covering a small stalactite at present-day sea level was sampled and studied to constrain Holocene sea level in Western Mediterranean. Once sectioned, the longitudinal view clearly showed the difference between the vadose speleothem (stalactite) and the phreatic precipitate (Fig. 25). The encrustation was a globular precipitate with a thickness of 0.5-2 cm, composed of 20 µm wide and 1 mm long acicular aragonite crystals with flat orthorhombic terminations, arranged in 0.3-1 mm thick successive growth bands of radial fan crystals. Five subsamples were drilled from the POS and dated by U-Th using ICP-MS (Inductively-Coupled Plasma Mass Spectrometry) (Fig. 25). They are characterized by high U contents ranging from 7 to 9 ppm, $^{234}$U/$^{238}$U activity ratios approaching the value of 1.5 and very high $^{230}$Th/$^{232}$Th activity ratios (always higher than 70). These data are evidence for very clean aragonite crystals forming from brackish water. The ages of subsamples 2, 4, and 5 (Fig. 25), drilled along the direction of the growth axis, are stratigraphically consistent, ranging from about 1.84 ± 0.02 to 0.61 ± 0.01 ka. Two samples (1 and 3) from the innermost growth layer are undistinguishable from subsample 2, giving ages around 2.0 ka. This demonstrates that the chemical system remained closed since deposition and no leaching or preferential dissolution occurred. It is worth noting that the extent of speleothem precipitation generally represents a minimum time interval for sea stand at that elevation, since the chemical properties of cave water can change.
The same POS was also dated using AMS $^{14}$C method (Tuccimei et al., 2011), but $^{14}$C ages were consistently 2.3-2.4 ka older than the corresponding U-Th data, as shown by values of percent dead carbon proportions of $24.61 \pm 0.25$ and by high and correlated abundances of trace elements in the inner stalactite. This is due to the long residence time of groundwater in epikarst and soil, where the water interaction with soil and bedrock is responsible for the dissolution of $^{14}$C-free limestone and the following incorporation in the precipitate. Better results were obtained for POS from other caves in Mallorca (Cova de Cala Varques A) where the residence time of water infiltration through the soil and epikarst is short and the interaction with soil and bedrock is limited. In these cases the so-called “reservoir” effect is negligible and $^{14}$C and U-Th ages corresponds within the error range (Tuccimei et al., 2011).

POS: a tool to constrain sea level history

ICP-MS U-Th dating of late Holocene speleothem overgrowths forming at present-day sea level in Cova des Pas de Vallgornera and other coastal caves (Tuccimei et al., 2012; 2013) indicates that in the study region sea level reached the present level about 4,000 years ago. U-Th records were compared with the predicted curve of relative sea level change, due to glacial isostatic adjustment (GIA). SELEN was used for this purpose, a software for solving the “sea level equation”, the law that governs the sea level variations associated with the melting of the Pleistocene ice sheets (Spada & Stocchi, 2007). The modeling shows that Mallorca largely tracks the eustatic sea level curve, but the predicted present-
day rate of relative sea level change due to GIA (Mitrovica & Milne, 2002) indicates that GIA alone does not explain data, but another mechanism has to be additionally invoked. A minor tectonic uplift (about 1 m) of the island in the last few thousand years could explain the observed discrepancy.

Older POS, now located at 1.5 and 2.6 m above present sea level, were U-series dated (Table 2), showing that western Mediterranean relative sea level was ~1 meter above modern sea level about 81 ka ago during marine isotope stage (MIS) 5a and about 2.6 m higher during MIS 5e (Dorale et al., 2010). The latter data are consistent with other estimates for MIS 5e in Mallorca (Tuccimei et al., 2006; Ginés et al., 2013) and other sites from around the world. The record of MIS 5a sea level, slightly higher than at present and only slightly lower than the MIS 5e, seemingly conflicts with the eustatic sea-level curve of far-field sites and corroborate an alternative view that MIS 5a was at least as ice-free as the present (Dorale et al., 2010).

### CONCLUSIONS

Cova des Pas de Vallgornera hosts a noteworthy richness in speleothems that represents one of the most important issues concerning the natural heritage values of this unique cave. The abundance and diversity of crystallizations is overwhelming throughout the cave system; they are mainly composed of calcite and to a lesser extent aragonite, along with gypsum, celestine, strontianite, nordstrandite, barite, and some other 19 minerals identified so far in this cave (Onac et al., 2014). Some typologies of speleothems hitherto unknown in Mallorca have been reported, like for instance cave rims, pool fingers and U-loops.

The arrangement of speleothems is influenced by the eogenetic character of the coastal karst from southern Mallorca, which provides depositional environments, generally marked by a quite high primary porosity. This fact has a clear repercussion on how some typologies (i.e., soda straw stalactites or helictites, for example) extensively cover the ceilings and walls of the passages and chambers.

Speleothems’ distribution within the cave system is strongly conditioned by the lithologic and textural variability of the Upper Miocene reeval rocks that build up the southern coast of the island. Additionally to these geologic conditionings, other factors become involved in the distribution of some speleothem typologies as, for instance, the existence of particular morphogenetic features in specific sectors of the cave. A last factor is a merely topographic one, consisting in the existence of two main tiers developed respectively close to the current water table or around 7 to 11 m above it.

The referred factors determine the existence of a sharp dichotomy that allows us to consider two well-differentiated sections within the cave system, regarding the distribution of speleothems. So, in the inner landward passages, the crystallizations formed in the perched freshwater bodies existing in the upper maze are remarkable, favored by the relatively low permeability of the Upper Miocene back reef facies. Cave rims are also abundant in some passages located in the back reef carbonates, being developed on feeder-like vents of hypogene origin.

On the other hand, the seaward sectors of the cave correspond to the very porous reef front facies, where the most distinctive deposits are the phreatic overgrowths on speleothems (POS) that record stabilizations of the water table, which are sea level controlled. These carbonate encrustations have supplied valuable data on sea level during the Upper Pleistocene and Holocene.

Research on speleothems is a promising field in Cova des Pas de Vallgornera since this paper is exclusively an overview of the current knowledge on that matter. Much more work should be devoted in the future to some uncommon speleothem types represented in the cave, their mineralogy, and especially, to the paleoclimate information that could be obtained both from stalagmites and from diverse phreatic overgrowths and mammillaries that have not been studied yet.

---

### Table 2. U-series data of Phreatic Overgrowths on Speleothems (POS) from Cova de Pas de Vallgornera.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Height m (a.s.l.)</th>
<th>U (ppb)</th>
<th>(^{230})U / (^{238})U</th>
<th>(^{234})Th / (^{238})U</th>
<th>(^{230})Th / (^{238})U</th>
<th>Age (ka ± 2σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL-D3-1</td>
<td>±0</td>
<td>8829</td>
<td>1.480 ± 0.002</td>
<td>271 ± 2</td>
<td>0.0202 ± 0.0002</td>
<td>1.9 ± 0.01</td>
</tr>
<tr>
<td>VL-D3-2</td>
<td>±0</td>
<td>7396</td>
<td>1.478 ± 0.002</td>
<td>69.3 ± 0.4</td>
<td>0.0250 ± 0.0002</td>
<td>1.8 ± 0.02</td>
</tr>
<tr>
<td>VL-D3-3</td>
<td>±0</td>
<td>8139</td>
<td>1.475 ± 0.001</td>
<td>510 ± 3</td>
<td>0.0264 ± 0.0002</td>
<td>2.0 ± 0.01</td>
</tr>
<tr>
<td>VL-D3-4</td>
<td>±0</td>
<td>8217</td>
<td>1.487 ± 0.001</td>
<td>457 ± 3</td>
<td>0.0183 ± 0.0001</td>
<td>1.4 ± 0.01</td>
</tr>
<tr>
<td>VL-D3-5</td>
<td>±0</td>
<td>8015</td>
<td>1.503 ± 0.002</td>
<td>145 ± 1</td>
<td>0.0084 ± 0.0002</td>
<td>0.6 ± 0.01</td>
</tr>
<tr>
<td>VL-D1</td>
<td>±0</td>
<td>7640 ± 180</td>
<td>1.510 ± 0.010</td>
<td>71 ± 18</td>
<td>0.010 ± 0.010</td>
<td>0</td>
</tr>
<tr>
<td>CPV-1</td>
<td>±1.6</td>
<td>156 ± 30</td>
<td>1.325 ± 0.019</td>
<td>1.408 ± 0.024</td>
<td>31537</td>
<td>80.1 ± 0.5</td>
</tr>
<tr>
<td>CPV-2</td>
<td>±1.6</td>
<td>144 ± 28</td>
<td>1.329 ± 0.021</td>
<td>1.413 ± 0.026</td>
<td>34757</td>
<td>80.1 ± 0.5</td>
</tr>
<tr>
<td>CPV-8</td>
<td>±1.6</td>
<td>119 ± 18</td>
<td>1.391 ± 0.016</td>
<td>1.492 ± 0.020</td>
<td>1812</td>
<td>81.0 ± 0.5</td>
</tr>
<tr>
<td>CPV-6</td>
<td>±2.6</td>
<td>108 ± 20</td>
<td>1.141 ± 0.013</td>
<td>1.198 ± 0.018</td>
<td>1892</td>
<td>120.6 ± 0.9</td>
</tr>
<tr>
<td>CPV-89</td>
<td>±2.6</td>
<td>122 ± 14</td>
<td>1.173 ± 0.012</td>
<td>1.240 ± 0.017</td>
<td>1151</td>
<td>116.2 ± 0.6</td>
</tr>
<tr>
<td>VL-D2</td>
<td>±2.6</td>
<td>250 ± 10</td>
<td>1.220 ± 0.020</td>
<td>1.310 ± 0.030</td>
<td>157 ± 47</td>
<td>120.4 ± 7.0</td>
</tr>
</tbody>
</table>

Notes:
- a data from Tuccimei et al. (2010)
- b data from Dorale et al. (2010)
- c data from Pazzelli (1999)
ACKNOWLEDGEMENTS

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Spada G. & Stocchi P., 2007 – *SELEN: a Fortran 90 program for solving the “Sea Level Equation”*. Computers & Geosciences, **33**: 538-562. [http://dx.doi.org/10.1016/j.cageo.2006.08.006](http://dx.doi.org/10.1016/j.cageo.2006.08.006)


INTRODUCTION

Distinguishing hypogenic (source of aggressiveness stem beneath surface; groundwater recharge mainly follows ascending paths) from epigenic (dissolution caused by acids originating from surface or near-surface processes; meteoric recharge by diffuse or floodwater flow) caves is not always straightforward. This is mainly because the hydrologic settings under which they form are responsible, sometimes, for rather similar cave patterns (mazes, solution pockets, passageways, chambers; Ford & Williams, 2007; Palmer, 2007, 2011; Klimchouk, 2009). The most common cave patterns displayed by hypogenic caves (i.e., sulfuric acid or thermal) includes spongework and network mazes, irregular chambers, and vertical to sub-vertical rising conduits. A suite of morphologies generated by rising flow (i.e., feeders, wall and ceiling features, etc.) appears to be indicative for hypogenic basal recharge (Klimchouk, 2009). Throughout this paper, a feeder represents a connecting karst conduit (between two or more levels of the cave) viewed in the direction of ascending flow. Instead, when using the term vent we refer to the aperture of feeders in floor passages (i.e., the outlet where the water and/or hot air was/is emerging), around which a mineral rim commonly occur.

Apart from these very peculiar large- and small-scale cave morphologies attributed to rising flow, a growing body of mineralogical studies indicates the existence of a clear relationship between various hypogene speleogenetic pathways and the minerals hosted within those respective caves (Hill & Forti, 1997 and references therein; Onac & Forti, 2011a, b). By far, the most...
complex, although expected, mineral assemblages were described from sulfuric acid caves (Hill, 1987; Polyak & Provencio, 2001; Onac et al., 2007, 2009, 2011, 2013; Plan et al., 2012; Audra et al., 2013; Puçaç et al., 2013; Sauro et al., 2014). The reason for this situation is the presence of sulfuric acid produced by oxidation/hydrolysis of H₂S-rich solutions that react with cave sediments and bedrock to form primary or secondary speleogenetic by-products (Polyak & Provencio, 2011).

The leading speleogenetic processes responsible for producing the so-called thermal caves are mixing (thermal and meteoric water), cooling (thermal water becomes more aggressive as it cools while rising to surface), and condensation corrosion (Dublyansky, 2000, 2012). Although less abundant and diverse when compared to the sulfuric acid caves, the mineralogy of thermal cavities has certain characteristics; among them, the presence of tabular barite and celestine crystals, as well as quartz, opal, or chalcedony that coat or even replace cave bedrock walls (Takácsné Bolner, 1989; Leél-Össy et al., 2011).

Cave development in the coastal zone is complex and often occurs during multiple sea-level changes (Mylroie, 2013; van Hengstum et al., 2014). The primary mechanism in control of forming these caves is the dissolution caused by mixing of two water bodies (fresh and salt) with contrasting temperature, chemistry, salinity, or CO₂ content (Herman et al., 1985; Mylroie & Carew, 1990). This particular type of caves form in shallow or deep coastal mixing zones and are characterized by spongework or crude ramifying passages. The littalor caves of Mallorca also features breakdown chambers and rectilinear karst conduits (Ginés et al., 2013, 2014). In general, the sea coast mixing caves have a narrow range of minerals composing their speleothems. Although the bedrock composition is monotonous, there are a few exceptional littoral caves that host very interesting and unusual mineral assemblages (Onac et al., 2001, 2008, 2014; Merino et al., 2009; Fornós et al., 2011). What ultimately controls the mineral diversity in these caves, is the particular geochemical environment of the mixing zone, where the carbonate bedrock is exposed to brackish groundwater.

Most of the studies investigating cave minerals rely on traditional X-ray diffraction (XRD), scanning electron imaging, X-ray fluorescence (XRF), and chemical composition inspection using microprobe, energy-dispersive X-ray spectroscopy (EDS), or inductively coupled plasma mass spectrometry (ICP-MS) techniques. The use of δ¹³S in tracing the source of S in cave minerals was pioneered by Hill (1981) and Kirkland (1982), whereas van Everdingen et al. (1985) first investigated the δ¹⁸O in sulfates to show the origin of O (meteoric H₂O or atmospheric O₂). Over the last decade, stable isotope analyses (mainly δ¹³C, δ¹⁸O, δ³⁴S) on cave minerals come to be a routine investigation in distinguishing between different speleogenetic pathways (Dublyansky, 1997; Onac et al., 2007, 2009, 2011; Palmer & Palmer, 2012; Temovski et al., 2013; Sauro et al., 2014a, b).

The present paper reports on the CPV mineral inventory, discusses the origin of the unusual species with respect to their occurrence within the cave (i.e., Sector F, Tragus and Nord sectors), and makes an attempt to link the mineral assemblages to various speleogenetic pathways identified and discussed by Ginés et al. (2014).

**GEOLOGIC AND KARST SETTINGS**

Cova de Pas de Vallgornera is the most significant (morphologically, scientifically, and length-wise) karst feature of Mallorca (Merino et al., 2011, 2014a, b; Ginés et al., 2014). Its artificial entrance opens on the southern coast of the island and gives access to an extensive 2-D spongework maze and fracture-controlled angular passages, currently exceeding 74 km of development (for cave location see Fig. 1 in Merino et al., 2014a). There is a clear relationship between geologic setting and cave patterns in that the 2-D spongework passages and collapse chambers develop in the more porous reef front facies of Upper Miocene age, whereas the angular galleries are typical for the outer lagoon facies (calcarenites and calcisiltites; Fig. 1) (Ginés et al., 2014). As highlighted in this paper, a similar relationship holds true for the mineral assemblages. For additional information on the geologic and karst settings of this cave, readers are directed to the publications of Ginés & Ginés (2007), Ginés et al. (2009), Fornós et al. (2011), Merino et al. (2011), as well as those included in this special issue of the International Journal of Speleology.

The geothermal studies conducted over the last decade in Mallorca pointed out the existence of at least two aquifers with anomalous temperatures in the vicinity of CPV (Mateos et al., 2005). The major thermal aquifer is hosted at depth in limestone and breccia of Lower Jurassic age (López, 2008; Fig. 1). Pools with thermal waters (23 to 27°C) are presently known in the lowermost parts of Cova de sa Guitarreta and Pou de Can Carro, two vertical caves located just few km NE of CPV (Merino et al., 2011). The water pooling in these caves is related to the shallow unconfined aquifer hosted within the Reef...
Minerals in Cova des Pas de Vallgonera

University of South Florida using a Bruker Analytical X-Ray System, Inc. D8 Endeavor XRD. Samples were scanned from 5° to 75° 2θ with a step increment of 0.02°, a scan speed of 0.5 sec/step (analytical conditions: 50 kV, 40 mA, CuKα radiation, line source filtered with a Ni foil). Mineral identification and abundance was evaluated quantitatively (in few samples) by measuring the integrated intensity of the strongest peak in each phase and then, using the reference intensity ratio (RIR) these intensity values were converted into weight percent (Hubbard & Snyder, 1998). The overall results based on XRD identification are tabulated in Table 1.

SAMPLES AND METHODS

More than 100 mineral samples were collected over the last six years during exploration and survey expeditions or at times of dedicated mineralogical cave trips. Samples were acquired mainly from the landward passages of Tragus and Nord sectors (71), but also from the seaward upper maze of Sector F (37) (Fig. 2), both developed within back reef facies limestone. The sampling activities focused on speleothems associated with hypogene-related features, such as vents and rims (Fig. 3a, b) or within feeders (Fig. 3c) located along the above mentioned sections of the cave.

All investigated samples (108) on which this paper relies, received a thorough macroscopic characterization at the time of collection in the cave and were later examined under the binocular microscope. The identification of minerals is primarily based on X-ray diffraction (XRD). The samples were all air-dried in the laboratory, and clay and other detritus was then removed. An agate mortar was employed for grinding the handpicked subsamples down to a fine powder (less than 38 µm in size particles) before running them on a Siemens D5000 diffractometer (Serveis Cientificotècnics, University of Balearic Islands in Palma de Mallorca, Spain) equipped with a diffracted-beam graphite monochromator and operated at 40 kV and 30 mA. Digitally recorded patterns were collected between 3 and 80° 2θ (step size of 0.04° 2θ and count rate of 2 to 4 second/step) and analyzed using EVA software (version 8.0). Silicon (NBS 640b) was used as the internal standard. Additional mineralogical analyses were performed in the Department of Chemistry, University of South Florida using a Bruker Analytical X-Ray System, Inc. D8 Endeavor XRD. Samples were scanned from 5° to 75° 2θ with a step increment of 0.02°, a scan speed of 0.5 sec/step (analytical conditions: 50 kV, 40 mA, CuKα radiation, line source filtered with a Ni foil). Mineral identification and abundance was evaluated quantitatively (in few samples) by measuring the integrated intensity of the strongest peak in each phase and then, using the reference intensity ratio (RIR) these intensity values were converted into weight percent (Hubbard & Snyder, 1998). The overall results based on XRD identification are tabulated in Table 1.

For scanning electron microscope (SEM) observations, freshly fractured speleothem fragments or hand-picked aggregates were gold-coated for better results while performing the semi-quantitative chemical analyses. SEM investigations were made at the University of Balearic Islands on a Hitachi Complex, in which hot water from the deep thermal aquifer migrates along a NE-SW fracture (Mateos et al., 2005).

Fig. 2. Location of the mineral samples on the map of CPV. The two orange lines across Tragus Gallery define the cross-section in Fig. 3.

Fig. 3. Cross-section along Tragus Gallery showing the position of floor feeders (vents); a-b) vents (holes in the floor connecting different cave levels; scale bar = 10 cm) and rims (the projecting white mineral fringe); c) multicolored ceiling deposit above a complex vent.
S-3400N using a backscattered electron detector (BSE) for atomic-number contrast imaging. The operation parameters were high-vacuum, 15 kV, 5 to 10 nA, and a defocussed electron-beam diameter of 30 µm. Further chemical analyses on bedrock samples were conducted in the Center for Geochemical Research (School of Geosciences, University of South Florida) using a Perkin Elmer Elan DRC II Quadrupole Inductively Coupled Plasma Mass Spectrometer.

The δ34S ratios of 11 samples representing S-bearing minerals (barite, celestine, and epsomite) were measured on a Delta V Isotope Ratio Mass Spectrometer (IRMS) coupled with an Elemental Analyzer Costech ECS 4100 at the School of Geosciences Stable Isotope Lab (University of South Florida) following the method described in Grassineau et al. (2001). The results reported in standard δ-notation were normalized to CDT (Cañon Diablo Troilite) using δ34S values of four IAEA standards (IAEA, International Atomic Energy Agency, S-2 and S-3 for sulfides and SO-5 and SO-6 for sulfates). The reproducibility between replicate standards in each run was better than ±0.12‰.

### RESULTS AND DISCUSSION

Twenty-six minerals were identified throughout the cave (Table 1); the highest diversity (20 species) is around or inside typical hypogene features (although not all minerals are necessary related to a hypogene speleogenetic phase) occurring within back reef limestone in the Tragus and Nord sectors (see Fig. 3). In the upper maze of Sector F (seaward part) which also develops on back reef facies only 13 minerals occur. At all these locations they form either speleothems that are unrelated to hypogene features; or developed in Tragus and Nord sectors whereas only 146 minerals identified, their crystal morphology, and the

<table>
<thead>
<tr>
<th>Mineral and Chemical formula</th>
<th>Sector F</th>
<th>Tragus and Nord sectors</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hypogene</td>
<td>Hypogene</td>
<td>Vadose</td>
</tr>
<tr>
<td>Ankerite, CaFe²⁺[Mg(CO₃)]₂</td>
<td>6</td>
<td>3</td>
<td>3</td>
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<td>1</td>
</tr>
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<td>1</td>
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<td>-</td>
<td>-</td>
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<td>8</td>
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<td>-</td>
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</tr>
<tr>
<td>Todorkite, (Na₂Ca₅Ba₃Sr₆)(Mn₃MgAl₆O₂₄)·3H₂O</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

1 According to the official IMA-CNMCN list of minerals (http://pubsites.uws.edu.au/ima-cnmnc/imalist.htm).
2 hw: hot water; v: vadose; bw: bedrock weathering; bb: bedrock/brackish water interface; ± m: microbial.
3 According to Rieder et al. (1998).
relationship between various species at each location, we distinguish three groups: 1) minerals related to hypogene speleogenetic processes, 2) minerals precipitated at the bedrock/brackish water interface, and 3) minerals of vadose/epiphreatic origin, typical for low-temperature epigene caves. A few species (e.g., aragonite, celestine, barite, gypsum, todorokite, etc.) belong to either group 1 and 3 or 2 and 3, but only aragonite and gypsum precipitate under all three minerogenic settings. The most abundant or peculiar minerals of these groups are characterized below; those having multiple origins are presented only under one of the genetic categories.

**Minerals related to hypogene speleogenetic processes**

In CPV, the minerals framed within this category are related to: i) either direct subaerial precipitation of dissolved species transported per ascensum by warm solutions (hw in Table 1) or ii) replacement/weathering of the bedrock (bw) due to corrosion when warm, humid air originating from these warm waters condensed onto the cold cave walls. This latter process might be enhanced/controlled by microbial activity (bw [†m]). Although there are no documented thermal water pools per se in CPV, the abundance of vents (characterized by rich mineral assemblages) suggests hypogean (thermal water-related) basal recharge was common in many parts of the cave at various times during its evolution (Ginés et al., 2009; Fornés et al., 2011; Ginés et al., 2014).

**Barite & Celestine**

Barite occurs as patchy crusts (few centimeters across) covering either bedrock or other coatings in and around hypogean features located in Sector F. At these locations barite appears as tabular after {001} closely associated with dolomite (Fig. 4a) and prismatic (after [010] and [100]) or bladed crystals (sometimes massive aggregates) along with acicular aragonite (Fig. 4b). It was also found precipitated on top of calcite and/or ankerite aggregates (see discussion under ankerite entry).

Celestine appears as bouquets of sub-centimeter long colorless to light blue shaded crystals (Fig. 4c) in eight occurrences, all related to hypogean features hosted within cave passages developed in Tragus and Nord sectors. SEM investigation reveals euhedral to subhedral equant prismatic crystals formed by the development of {011}, {001}, and {210}; another crystal habit observed is pyramidal with {122}, {011}, or {102} (Fig. 4d, e).

There is only one location in the Tragus Gallery (Aragonite Tub section) where the two minerals are closely associated and were precipitated over and in between ~1 million year old (Polyak, pers. comm.) aragonite needles (Fig. 4f). Based on the relationship between the two sulfates and their host mineral (aragonite) and considering that barite and celestine form a solid solution, we believe they precipitated from per ascensum migrating strontium- and barite-bearing hot groundwater after the thick aragonite crust covered the cave passage at this particular location. Considering the average δ³⁴S values obtained on these two sulfates (+21.6‰ for barite (n = 3) and +21.7‰ for celestine (n = 5), respectively) it is obvious that it derived from dissolution of primary marine sulfate (average δ³⁴S values of Miocene seawater sulfate is ~22‰; Paytan et al., 1998) interbedded or existing within limestones and is not a by-product of sulfuric acid speleogenesis.

**Chamosite**

Chamosite is a monoclinal mineral of the chlorite group first time identified in a cave environment. It occurs within the red fluffy ceiling deposit above a vent on Tragus Gallery. It is closely associated with quartz, hematite, braunite, kaolinite, and montmorillonite. It was identified by means of XRD (peak at 7.05Å that vanished after digesting the sample in concentrated HCl) and subsequently confirmed by SEM-EDS microchemical analyses. The crystals are tabular {001} arranged in the shape of sheafs (Fig. 5), < 100 µm across and are flattened on (001).

Vallgornera is an unusual occurrence of chamosite and the following two scenarios seem plausible to explain its presence: i) authigenically formed under slightly acidic to slightly alkaline conditions (pH 5 to 8). Under this model, hot air-condensing above feeders liberate (by corrosion) Fe²⁺, Fe³⁺, Al³⁺, and silica from the carbonate rock, which then co-precipitate with the subsequent formation of chamosite. Hence it is “secondary” in origin, thus a true cave mineral; ii) chamosite might have been a primary mineral in the carbonate rock (Akande & Mücke, 1993) and became exposed by various weathering processes (including bacterial activity) that affected the bedrock. If so, chamosite would not be a true cave mineral.
other authors considered its occurrence in caves as diagnostic for hypogene speleogenesis (Merino et al., 2009; Fornós et al., 2011).

The sample in which nordstrandite was positively identified consists of a millimeter-size thick brown film, collected from the ceiling of Tragus Gallery, above a feeder. The SEM observations reveal clay mineral aggregates and radiating clusters of tabular to prismatic crystals of nordstrandite, terminated by sharp, clear pyramidal faces (Fig. 7). The size of the crystals does not exceed 50-60 µm and they show perfect cleavage after {110}.

Given the environmental conditions from which nordstrandite was previously reported (outside the cave; Wall et al., 1962; Hathaway et al., 1965; Milton et al., 1975), its precipitation in CPV is a matter of conjecture. Based on the relationship between nordstrandite and the other minerals/deposits at the sampled location in the Tragus Gallery, it appears to be a late-stage precipitate. The exact chain of reactions that led to its deposition is still unclear. A carbonization mechanism, similar to the one proposed by Lipin (2001) seems reasonable, although it is difficult to imagine a limestone cave environment with pH above 13. However, nordstrandite was also obtained experimentally at lower pH (7.5 to 9) but under specific ionic concentrations and temperatures (Van Nordstrand et al., 1956). Not having such information for the CPV nordstrandite, we assume a combination of the two models cited above, with aluminous solutions transported into the cave by the hypogene hot waters or with Al$^{3+}$ sourced from either limestone bedrock or clay minerals already present in the cave.

**Strontianite**

During one of the visits in CPV, a fragment of bedrock (within a rim around a vent) on which two distinct, transparent and translucent minerals occurred as tiny crystals was sampled. The XRD investigation clearly identified dolomite as well as the presence of celestine and gypsum (by their characteristic peaks). The BSE imaging and micro-chemical analysis confirmed these three minerals, but in addition, we noticed spiky, radiating clusters of long (60 to 80 µm) prismatic crystals [001] growing on top of botryoidal aggregates of dolomite (Fig. 8). The EDS micro-analyses revealed the presence of only three elements: Sr, C, and O that make up strontianite.

Due to some geochemical constraints (e.g., temperature- and CO$_2$ partial pressure-dependent solubility, ion activity, Sr/Ca ratios, and pH; Helz & Holland, 1965; Busenberg et al., 1984) in the SrCO$_3$·CO$_2$·H$_2$O system, strontianite is an uncommon mineral in nature. There are only three reported cave occurrences from Sima de las Fumarolas, Spain (Fernández-Rubio et al., 1975), a small, nameless cave in the Terrace...
Minerals in Cova des Pas de Vallgornera

geochemical conditions under which aragonite, calcite, and gypsum speleothems are deposited in littoral caves at or a few centimeters below and above the present brackish water table are well documented and will not be discussed here (Bottrell et al., 1991; Onac et al., 2001, 2005; Csoma et al., 2006; Ginés et al., 2012). The phreatic overgrowths on speleothems (POS) used to reconstruct past sea-level positions (Vesica et al., 2000; Dorale et al., 2010; Tuccimei et al., 2010; Ginés et al., 2012) fall into this category as calcite and/or aragonite encrustations are precipitated over preexisting vadose speleothems from brackish waters. Dolomite is discussed along with the vadose minerals, thus ankerite and epsomite are the highlights of this group.

Ankerite

Ankerite was positively identified (XRD and SEM-EDS) in millimeter-size microcrystalline crusts of various colors, from white to yellowish-brown or dark brown. Eight of the samples come from cave passages rich in hypogene features, whereas the other 4 samples were collected at vadose sites. Similar to dolomite, ankerite forms rhombohedral crystals {1011} (Fig. 9a) or pseudo-octahedral (Fig. 9b). Dissolution features (pits) are frequent on many crystal faces; another characteristic of the rhombohedral ankerite crystals is the stepped morphology along their edges and at corners (Fig. 9a). In sample VL-M101, ankerite is intergrown with calcite and closely associates with aragonite crystals elongated in the direction of [001] and flattened on (110) (Fig. 9b). Bright white prismatic barite crystals were observed under SEM (Fig. 9b). Given their relationship with the other mineral phases, it certainly precipitated in a late stage after calcite/ankerite were already deposited.

Apart from XRD, staining techniques, and chemical analysis, ankerite in sedimentary environments is commonly investigated using stable isotope geochemistry. However, oxygen isotope fractionation between water and ankerite at low-temperatures is poorly constrained (Zheng, 1999). Multiple oxygen and carbon isotopic analyses were performed on nine samples of both hypogene- and vadose-related speleothems collected above vents in Sector F and Tragus Gallery and along other vadose passages. The isotopic composition (δ¹³C and δ¹⁸O) of these samples is listed in Table 2. Plotted in Fig. 10 the data show two distinct populations with significantly different δ¹³C values (~10‰), whereas the δ¹⁸O values are within 2‰. The ankerite crusts precipitated in conjunction with known hypogenic features group as Population 1, which is characterized by relatively high δ¹³C (1.97 to 2.04‰) and δ¹⁸O values between -4.71 and -4.65‰ (Fig. 10). The bedrock samples plot very close to this population. Population 2 includes ankerite crusts sampled along vadose passages, and has low δ¹³C (-7.91 to -7.87‰) and δ¹⁸O values (-6.47 to -6.22‰), comparable with other carbonate speleothems precipitated from low-temperature meteoric solutions in other carbonate caves worldwide.

The oxygen isotopic composition of meteoric and sea water nearby the cave is -5.6‰ (Araguas-
Fig. 9. BSE images of rhombohedral ankerite showing stepped morphology at edges and corners (a) and close up of needle-like aragonite and tabular barite crystals growing upon intimately associated calcite and ankerite (b).

Fig. 10. Plot of carbon (δ13C) and oxygen (δ18O) isotopic composition of two cave ankerite populations and limestone bedrock. Data for modern meteoric (Araguas-Araguas & Díaz Teijeiro, 2005), brackish, and Mediterranean sea waters (Boop et al., 2014) are also represented.

Araguas & Díaz-Teijeiro (2005) and +1.5‰ (Boop et al., 2014), respectively. The average δ13C value of the limestone bedrock is -3.5‰ whereas the δ13C value is +2.0‰. Combining this information with our isotope data, it is reasonable to consider the ankerite within Population 1 as being deposited at the bedrock/brackish water interface. At these locations the reaction between the brackish water supplying Mg2+ and the carbonate bedrock is responsible for its precipitation. The iron is probably derived from ferric oxides deposited in limestones. This idea is supported by the fact that all three samples of Population 1 have almost similar δ13C values with the limestone, indicating that the source of carbon is likely the carbonate bedrock. Instead, the isotopic signature of samples in Population 2 clearly suggest that soil pool represents the main source of carbon.

Table 2. Oxygen and carbon isotope values of bedrock limestone and ankerite speleothems from CPV.

<table>
<thead>
<tr>
<th>Location and Sample code</th>
<th>δ18O (‰)</th>
<th>δ13C (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector F (limestone)</td>
<td>-2.51</td>
<td>2.04</td>
</tr>
<tr>
<td>Sector Arctic (limestone)</td>
<td>-2.53</td>
<td>2.02</td>
</tr>
<tr>
<td>Sector F (VL-M96)</td>
<td>-6.22</td>
<td>-7.91</td>
</tr>
<tr>
<td>Sector F (VL-M101)</td>
<td>-6.47</td>
<td>-7.87</td>
</tr>
<tr>
<td>Tragus Gallery (limestone)</td>
<td>-2.47</td>
<td>2.0</td>
</tr>
<tr>
<td>Tragus Gallery (VL-M26)</td>
<td>-6.31</td>
<td>-7.88</td>
</tr>
<tr>
<td>Tragus Gallery (VL-M55)</td>
<td>-4.65</td>
<td>1.95</td>
</tr>
<tr>
<td>Tragus Gallery (VL-M57)</td>
<td>-4.7</td>
<td>1.96</td>
</tr>
<tr>
<td>Tragus Gallery (VL-M57a)</td>
<td>-4.71</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Epsomite

The observations presented here are based on a single occurrence of epsomite, in sample VL-M030 recovered from the Tragus Gallery, more specifically, at the Aragonite Tub. The mineral occurs as a sub-millimeter thin, dull white to slightly yellowish fibrous crust closely associated with aragonite. Calcite was also identified in this sample by means of XRD. The precipitation and preservation of epsomite is highly dependent on temperature and relative humidity (RH).

Considering the stability field of epsomite provided by Hill & Forti (1997) and Posern & Kaps (2008) and the topoclimatic conditions within the Aragonite Tub (T = 20.4°C and ~90% RH), its occurrence in CPV is not surprising.

Our hypothesis regarding the presence of epsomite in CPV is as follows: according with Berner (1975), Fischbeck & Müller (1971) and De Choudens-Sánchez & González (2009), from a parent solution with Mg/Ca between 2.9 and 4.4, aragonite is the main calcium carbonate mineral (calcite may also form) that will precipitate. The only way to suppress aragonite deposition, but form epsomite, is to increase the molar ratios SO42-/CO32- to ≥ 1 while the solution remains enriched meteoric solutions (Mg2+ originates from sea spray or is leached from the carbonate bedrock) percolating through the epikarst and the Upper Miocene limestone.
one of the high sea stands and both Mg\(^{2+}\) and SO\(_4\)\(^{2-}\) come from the cave brackish water (evaporation of capillary pore waters), then it is with certainty that the mineral belongs to this genetic group.

**Minerals precipitated under vadose conditions**

This category includes the most common cave minerals; such are calcite, aragonite, gypsum, or huntite, precipitated throughout the cave (v in Table 1) by flowing, dripping, seeping, or pooling water (Hill & Forti, 1997). These minerals are also present in the composition of speleothems in and around hypogene features (feeders, vents, cupolas) but at such locations they were deposited from cold meteoric waters in a late minerogenic stage. The precipitation of some minerals occurring in the highly weathered bedrock skin is likely controlled by microbial activity (bw ± (m) in Table 1).

**Clay minerals**

Abundant colorful “corrosion” residues coat floors, walls, and ceilings in many parts of CPV (Figs. 3c and 11a, b). This “mineral skin” is several centimeters in thickness and its texture progressively changes from a very fluffy, low-density layer (mm to cm thick) in the outer-most part to a soft, but denser one represented by weathered bedrock. Similar cave deposits were described in the literature under various names, such as okher (Maltsev, 1997) or speleosol (Spilde et al., 2006). Apparently, these materials are active biological media, rich in reworked and bacteria-mediated secondary minerals (Korshunov & Semikholenykh, 1994; Northup & Lavoie, 2001; Polyak & Provencio, 2001; Spilde et al., 2005; Barton & Northup, 2007). They are home of a variety of oxides and hydroxides of iron, manganese, and aluminum, as well as certain clay minerals. Apart from kaolinite, montmorillonite, and illite (Fig. 11c), the following mineral species were identified in the multicolored deposits of CPV: romanèchite, todorokite, goethite, hematite, gibbsite, and quartz.

To date, there are no dedicated studies to investigate the geomicrobiology and mineralogy of these residues in CPV. The clay minerals-rich “corrosion” residues are very common nearby vents (26 out 33 samples total) where they form abundant accumulations on both ceilings and walls. Many other passages in the cave (more or less ventilated) display rich multicolored deposits. Regardless to their location within the cave, these weathering residues appear to be the result of a combination of condensation-corrosion that is significantly enhanced by biochemical breakdown of the bedrock. The idea that microorganisms are involved in this process is supported by SEM images that show bacterial filaments and other microbial structures (Fig. 11d).

**Dolomite**

Although a common rock in ancient sedimentary deposits, dolomite is relatively rare in the recent ones and even rarer as mineral in low temperature environments (Tucker, 2001). The reason for this situation is attributed to a number of factors including Mg/Ca ratio, kinetics, temperature, pH, presence of sulfates, etc. (see Roberts et al., 2013 and references therein). Only a handful of cave locations are known and well documented with respect to the presence of dolomite speleothems (Thrailkill, 1968; Martini, 1987; Hill & Forti, 1997; Polyak & Güven, 2000; Alonso-Zarza & Martin-Pérez, 2008).

Macroscopically, the dolomite in CPV occurs as white to gray sub-millimeter thin crusts precipitated on either side of rims around vents. Sometimes dolomite microcrystals are deposited upon aragonite crystals or gypsum coatings. In one sample (VL-M38) dolomite and huntite are closely associated. Typically, the dolomite occurs near hypogene features (18), but it was also found in 5 locations that are characterized by exuberant vadose precipitates.

A detailed morphological investigation by SEM reveals that commonly, dolomite forms isolated or coalescing spheroidal aggregates of various sizes (30 µm to 0.5 mm across; Fig. 12a, b), which internally consist of individual rhombic crystals (Fig. 12c). Notable are the bacterial filaments (Fig. 12d) and what appears to be mucus strands (Fig. 12e) that covers or bridges dolomite crystals in many of the investigated samples.

Considering the morphology of crystals and mineral assemblages with which dolomite is associated in CPV, the following precipitation scenarios are proposed:

1. Locations where dolomite occurs with aragonite and/or huntite. After calcite and aragonite were deposited out of dissolved inorganic carbon (DIC)-rich vadose solutions, these become enriched in Mg\(^{2+}\) and will precipitate huntite and then dolomite. Huntite and dolomite have similar structures, but huntite will always precipitate before dolomite because of its open structure (low-density phase; Graf & Bradley, 1962; Dollase & Reeder, 1986) that favors enhanced magnesium dehydration (Lippmann, 1973). Another possible way in which dolomite may have formed under this scenario is considering that either aragonite or huntite acted as precursors. An argument for such a process is the presence in some samples of micro-aggregates consisting

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**Fig. 11.** a-b) Multicolored fluffy residue coating consisting of Fe and/or Mn oxides and hydroxides, clay minerals, calcite, and quartz silt; c) Feathery crystals of illite; d) SEM image reveals microbial structures within a sample of multicolored residual material.
of euhedral to subhedral dolomite crystals, tentatively interpreted as representing totally replaced huntite (Fig. 12a, b). A similar dolomite occurrence was described from Castañar Cave in Spain (Alonso-Zarza & Martín-Pérez, 2008).

2. Locations where dolomite is associated with gypsum. A high-resolution SEM examination of sample VL-M22 shows dissolution pockets on the surface of gypsum that are filled with crystals of dolomite (Fig. 12f). Vadose fluids could simply cause corrosion of gypsum, but at the same time, it might be the result of microbial boring activity (Douglas & Yang, 2002). Regardless the origin of the micro-dissolution features on the gypsum crystal faces, the dolomite filling them appears to be microbially mediated. This hypothesis is supported by SEM imagery that shows the presence of organic structures, binding or coating part of the dolomite crystals. Such examples are known from modern settings in Brazil and Spain (Vasconcelos et al., 1995; Sanz-Montero et al., 2006) as well as from laboratory experiments (Warthmann et al., 2000).

3. Locations where dolomite is only associated with calcite: The presence of the dolomite along with calcite in speleothems from CPV may suggest its precipitation from DIC-rich meteoric waters mixed with Mg-rich groundwaters. The source of magnesium could be twofold: 1) the extensive bodies of brackish water in CPV or/and 2) dissolution of magnesium from the bedrock.

Knowing that abiogenic precipitation of modern dolomite is limited in low-temperature environments, and because the SEM observations on dolomite samples reveal biological structures, we argue, without any dedicated microbiological investigations that precipitation of dolomite in CPV is bio-induced.

Huntite

Eleven samples collected in the close proximity of vents in all three sectors of the cave tested positive for huntite. The mineral occurs as dull white, fine-grained earthy deposits or moonmilk, as well as small spheres (Fig. 13a). SEM imaging reveals huntite is intimately associated with aragonite and dolomite (Fig. 13b, c). Inspecting at higher magnification the globular aggregates of huntite, we noticed that at their surface the platy rhombooidal crystals are visible (Fig. 13b inset).

Without exception, all huntite deposits occur near well-ventilated areas (in connection with the floor feeders), confirming its precipitation by evaporative concentration of magnesium-rich percolating solutions (mainly) and carbon dioxide loss. An interesting observation is that none of the common magnesium carbonates were identified in CPV. Because the precipitation of nesquehonite requires very high CO$_2$ partial pressure (P$_{CO_2}$) its absence is easy to explain (Lippmann, 1973). However, although the stability field of hydromagnesite overlaps the one of cave environment in terms of relative humidity, evaporation, and P$_{CO_2}$ (Hill & Forti, 1997; White, 1997), the mineral is not forming in CPV. The reason might be twofold: the P$_{CO_2}$ is still too high or, more likely, the Mg/Ca ratio is below the critical threshold (16) at which hydromagnesite forms (Fischbeck & Müller, 1971).

On the theoretical curve of the evolution of cave water in the CaCO$_3$-MgCO$_3$-H$_2$O system, huntite lies between aragonite and hydromagnesite. Thus, the presence of huntite and aragonite association at various locations within CPV confirms the depositional sequence of carbonate minerals proposed by Lippmann (1973). It also directly relates the two minerals with a late vadose speleogenesis phase. Diagenetic mechanisms similar to those invoked by Martínez-Pérez et al. (2012)
in Castañar Cave (Spain) could be a viable alternative for huntite precipitation as well.

Romanèchite

Earlier known as psilomelan (now an obsolete term), romanèchite is a barium-containing manganese oxide, commonly occurring in caves in the composition of soft or hard dark brown to black ferromanganese coatings, crusts, nodules, and earthy deposits (Hill & Forti, 1997; Onac et al., 1997; White et al., 2009; Gázquez et al., 2011). The sample analyzed (VL-M05) was collected near the end of the Galeria d’en Pau, where it occurs as black earthy masses. Apart from this location, ferromanganese deposits are widespread in CPV both in sediment sequences (Fornós et al., 2014) and as wall and ceiling deposits (Fornós et al., 2011).

Romanèchite crystals observed under SEM in our sample are either thin bladed or short acicular forming fibrous crusts (Fig. 14). The SEM imaging combined with mineral specific spot EDX analysis indicates that romanèchite is intergrown with hematite (also identified by means of XRD) and various clay minerals (Fig. 14, inset). This assemblage documents an intense subaerial weathering process, relating the presence of this mineral with a vadose phase in the cave evolution. Without further investigations it is difficult to precisely infer the precipitation conditions for romanèchite. However, the literature dealing with cave ferromanganese deposits and their mineral constituents, considers the enrichment in Mn$^{2+}$ and Fe$^{2+}$ a result of microbial alteration of the bedrock (Spilde et al., 2005, Spilde, 2006). Considering this scenario, the Mn$^{3+}$ and Mn$^{4+}$ in the CPV romanèchite are probably a product of Mn$^{2+}$ oxidation (a microbially mediated) in oxic, subaerial conditions. The barium is probably supplied by the carbonate bedrock in which concentrations of up to 1.5% were found (Fornós et al., 2011).

CONCLUSIONS AND IMPLICATIONS FOR SPELEOGENETIC DIAGNOSIS

The excitement about investigating the minerals of Cova des Pas de Vallgornera came from the fact that the most diverse assemblages group around typical hypogene features occurring in Tragus and Nord sectors (21 species) as well as in Sector F (13). Only after detailed studies we learned that not all these minerals were precipitated in conjunction with a hypogenic phase. Considering the textural relationship between the minerals of a given assemblage, and noticing the absence of only hypogene or non-hypogene mineral associations, we concluded that their precipitation is a result of several mineral-forming events. Given the spatial distribution of cave minerals throughout CPV, we argue that particular mineral associations are also related to different speleogenetic phases (seacoast mixing, ascending thermal groundwater, and meteoric recharge) in the cave evolution.

The minerogenic role of ascending thermal waters in the Mallorcan karst is somehow different from the classical one documented in caves under Budapest (Hungary). At certain locations the hot waters rising from depth are responsible for the precipitation of an abundant and diverse suite of carbonates and sulfates (gypsum, barite, and celestine), along with some exotic minerals (e.g., fluorite, quartz, etc.; Dubilyansky, 1995; Leél-Ossy et al., 2011). In contrast, in CPV the minerals are not deposited directly from deep-seated thermal groundwaters, but instead, they are a product of the interaction between mineralized warm brackish waters and the carbonate bedrock or preexisting minerals. Thus, most minerals (e.g., aragonite, barite, celestine, jacobsite, todorokite, etc.) were precipitated inside feeders while the solutions moved upward and in the near vicinity of vents (floor, wall, or ceiling).
In addition, the rising hot air released by these waters is responsible for complex replacement and condensation-corrosion processes acting upon bedrock. The result is a fluffy colorful organo-mineral thick skin, rich in clay minerals, Fe and/or Mn oxides and hydroxides (goethite, hematite, romanéchite, todorokite), charmosite, and quartz silt. Traces of microbial activity observed under SEM suggest microorganisms may play a significant role in the precipitation of certain minerals in CPV.

Ankerite, aragonite, calcite, dolomite, epsomite, and gypsum are the only minerals in the composition of speleothems occurring nearby (above, at, and below) the brackish water table. Apart from sea-controlled calcite and aragonite phreatic overgrowths on speleothems (POS), which are widespread in CPV, all the other minerals occur as crusts, coatings, and minute crystals. All are precipitated from cold, Ca\(^{2+}\), Mg\(^{2+}\), and SO\(_4\)\(^{2-}\)-rich brackish waters.

The mineralogy of speleothems deposited from low-temperature, downward-circulating meteoric waters is dominated by calcite. Gypsum, aragonite, dolomite, and ankerite are the other important mineral species associated with a late-stage, vadose cave evolution. Some less frequent minerals were also identified in the composition of other vadose speleothems (Table 1).

Although barite, celestine, todorokite, gibbsite, and nordstrandite were earlier associated with sulfuric acid speleogenesis (Polyak & Provencio, 2001; Onac et al., 2009), none of these or any of the other investigated cave minerals in CPV are actually speleogenetic by-products. This observation is supported by our stable isotope (\(^{6}^{13}\)C, \(^{18}\)O, and \(^{87}\)S) investigations.

Here we show that combining mineralogical mapping throughout CPV with precise mineral phase identification and textural relationship analysis is an efficient way to understand various mineral-forming events and their link to particular speleogenetic pathways. In this vein, stable isotope studies provide strong evidences that further help deciphering both the mineral origin and cave genetic history.

**ACKNOWLEDGEMENTS**

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Cave deposits and sedimentary processes in Cova des Pas de Vallgornera (Mallorca, Western Mediterranean)

Joan J. Fornós, Joaquín Ginés, Francesc Gràcia, Antoni Merino, Lluís Gómez-Pujol, and Pere Bover

Abstract: The Cova des Pas de Vallgornera is an important and protected coastal cave, located in the southern part of the island of Mallorca, that outstands due to its length and the complex processes involved in its speleogenesis. Although sediments are not the main topic of interest, their presence as well as their paleontological contents are valuable evidence for paleoclimatic and chronological reconstructions of the cave morphogenesis. The sedimentary infilling is characterized by a scarce presence of clastic sedimentation, mainly composed of silts and clays, which can only be found at some minor passages in the innermost parts of the cave. It corresponds to a clayey sedimentation mainly derived from the soil infiltration that can be found mixed with carbonate particles detached from the cave walls. A particularly different situation occurs in the northernmost end of the cave where an important sequence of silty sands are present, hosting a very rich paleontological deposit. The objective of this paper is to describe the detrital deposits present in the cave by means of the integration of sedimentological, chemical, and mineralogical data, which will aim to provide a better understanding of the processes that have occurred during the system’s speleogenetic evolution.

Keywords: cave detrital sediments; coastal karst; mixing zone; Mn-Fe-rich deposits; Mallorca

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INTRODUCTION

The Mallorcan coastal landscapes, especially those related with the Upper Miocene carbonates that crop out in the south and southeast parts of the island, are characterized by the frequent existence of littoral karst caves (Ginés & Ginés, 2011). The presence of sediments in these cave environments has been highlighted in the last years by several papers including those describing recently discovered caves with important underwater extensions (Gràcia et al., 2003, 2005, 2006, 2007, among others), those discussing the speleogenetic processes (Ginés & Ginés, 2007; Ginés et al., 2009a) and those characterizing the different types of sediments and processes that are present in these littoral areas (Fornós et al., 2009b, 2010).

In the above mentioned papers different types of sediments and genetic processes have been described as being the dominant mechanisms in producing the allochthonous in fillings that were carried into the caves mainly through surface entrances. The most frequent types are reddish-brown fine sediments mostly transported into the cave by surface runoff as in the case of Cova des Coll or Cova Genovesa (Gràcia et al., 2003, 2005), or by eolian processes as in the case of Cova de s’Onix (Ginés et al., 2007), Cova de sa Font (Egozcue, 1971), Cova de sa Bassa Blanca (Ginés & Ginés, 1974), among others, or mixed eolian and runoff deposits as is the case of Galeria del Tragus in Cova des Pas de Vallgornera (Fornós et al., 2010). Autogenic processes have also been suggested for Cova de sa Gleda (Gràcia et al., 2007) and in the Pirata-Pont-Piqueta system (Gràcia et al., 2006; Fornós et
started in the Paleogene (the Alpine orogeny) attaining its maximum during the Middle Miocene (Gelabert et al., 1992; Sàbat et al., 2011). Following this compressive phase, a period of extension occurred during the Upper Miocene, creating a series of horsts and grabens. From a physiographical perspective the horsts consist of two subparallel mountain ranges orientated NE-SW, along with a series of small hills located in between. The grabens developed on the foreland of these ranges and were filled by sediments of Middle Miocene to Quaternary age (Fornós et al., 2002). All the Neogene deposits onlap the irregular alpine folded and thrust basement composed by Mesozoic dolomites and limestones with minor marl intercalations (Pomar et al., 1996).

During the Upper Miocene, the folded areas (the previously cited horsts) remained above sea level whereas a surrounding epicontinental sea covered the rest of the current island. Climate and sea temperature during the Tortonian-Messinian favored the development and progradation of a coral reef environment resulting in a thick slab (70 m than occasionally exceed 120 m) of alternating calcilutites and very porous calcarenites with a complex geometry (Pomar, 1991). This carbonate platform is delimited by the presence of an important erosive surface with paleokarst features due to the extreme recession that the Mediterranean experienced during the Late Messinian. Above this erosive surface, the reef platform ends with a series of Late Messinian carbonate tabular deposits, which correspond to a sand shoal environment with oolitic sand bars and mangrove facies. In physiographical terms the Upper Miocene carbonate platform constitutes the post-orogenic tableau that surrounds the folded relief of southeastern Mallorca. This physiographical unit, which is rich in karst phenomena, is where the cavity under study was developed. The Pleistocene marine transgressions only covered the lowland areas of the island of Mallorca and in terms of cave development are envisaged as the main speleogenetic phases in Cova des Pas de Vallgornera, according to Ginés et al. (2014). The Pleistocene glacial cycles imply the succession of high sea-stands and sea level recessions of up to -135 m (Butzer and Cuerda, 1962) that complete the geological history of the area leading to the deposition of a sequence of marine and eolian sediments (Fornós et al., 2002, 2009a; Ginés et al., 2012).

A detailed description of the geology of the Vallgornera area can be obtained in Ginés et al. (2014).

**Cova des Pas de Vallgornera**

**Regional and geological setting**

The studied cave is developed in Upper Miocene limestones and calcarenites that crop out along the southern and eastern areas of Mallorca. The landscape surrounding the cave is characterized by a flat surface, which is the result of progradation during the Upper Miocene times of a well-developed carbonate platform deposited in a reef environment (Pomar, 1991). This flat surface is shaped by significant karst phenomena, including Miocene paleokarst features, littoral karren, fluvio-karst, and poor development of a terra rossa soil that host a “garriga” shrub-land type vegetation characteristic of the Mediterranean climate with low rainfall (Ginés et al., 2012).

The conspicuous horizontal topography of this carbonate platform is only cut by ravines. Scarce ephemeral streams form deep entrances at the coastline (bights or coves) result of the quaternary fluvial incision during glacial low-stands and the posterior flooding and sediment infill related to highstand interglacial periods. The flat surface contrasts, at the coastline, with the prominent vertical cliffs, more than 20 m height, that characterize most of the coastline (Gómez-Pujol et al., 2013) and where a Neogene (Upper Miocene reef calcarenites) to Quaternary sequence (mainly composed of eolianites) can be clearly observed.

From a geological point of view, the island of Mallorca is included in the complex geological setting of the western Mediterranean. Their geomorphological appearance derives from the compressive phase that started in the Paleogene (the Alpine orogeny) attaining

**Cave location and description**

The Cova des Pas de Vallgornera is located in the Marina de Llucmajor (Migjorn region, southeastern Mallorca), near the touristic bight of Cala Pi (coordinates UTM/WGS84: 489,120; 4,357,510). The artificial entrance of the cave is located 25 m above the sea level and some 0.5 km from the coast (Fig. 1). The cave consists of a complex network of breakdown chambers and joint guided phreatic passages developed forming two main tiers (Merino et al., 2014a). At present, over 74 km of passages have been surveyed, including over 17 km of underwater passages (Gràcia et al., 2009).
Cave deposits and sedimentary processes in a Western Mediterranean cave

The cave pattern is quite variable, being controlled by the textural and lithological characteristics of the carbonate substrate (due to the different sedimentary sub-environments of the Miocene reef) where the cave system is developed (Ginés et al., 2009b, 2014).

Besides the dominant labyrinthine pattern in its southwestern section, it is conspicuous that the presence of rectilinear main passages form the inner part of the cave running relatively parallel from SW to NE. These galleries are structurally controlled by major joints.

The lower parts of the cave are occupied by brackish pools, whose surfaces rise or fall with tidal and/or barometric fluctuations of the sea level. The underwater explorations have revealed the presence of a vast series of galleries below the present-day water table. These flooded passages change the dominant NE-SW direction to N-S near the coastline (Sector dels Privilegiats in Fig. 1).

The presence of spectacular speleothems and solution morphologies is a notable aspect of this cave. Among a great miscellany of vadose speleothems (Merino et al., 2014b), noticeable carbonate precipitation linked to the current water-table (POS: phreatic overgrowths on speleothems, Ginés et al., 2012) occurs in pools at the present sea-level. Relict phreatic overgrowths occur at former water-table levels which were in turn controlled by Quaternary sea-level oscillations (Tuccimei et al., 2006). The dominant deposits of calcite and aragonite associated with these vadose and epiphreatic speleothems contrast with the presence of less common mineralogies, including celestine, strontianite, barite among others (Merino et al., 2009; Onac et al., 2014) present in the form of weathering crusts as well as other precipitates rich in Fe and Mn. These deposits seem related to hypogenic processes (in the sense of Klimchouk, 2009) that have occurred during some phases in the speleogenetic evolution of the cave, explained by a deep recharge through extensional faults from the Mesozoic basement; this deep-seated recharge yielded abundant solutional features in the cave walls as sharp ascending solutional grooves, rounded rising channels developed from lateral feeding points, cupolas, etc. (Ginés et al., 2009a, 2014; Fornós et al., 2011).

A small part of the cave floors are covered by muddy and/or sandy sediments that, in a wide sense, are marked by two well differentiated characteristics. Two dominant types of sediment are present: fine red siliciclastic muds and yellowish carbonate-dominated mud and sand. The mixture of both materials is also frequent as well as the accumulation of debris due to the collapse of roof and cave walls. The underwater passages are characterized by the presence of Fe and Mn-rich sediments.

The speleogenesis of the system corresponds, besides the drainage of meteoric diffuse recharge, to
the mixing processes between continental and marine waters, which affected the Miocene calcarenites and provoked an important void creation, particularly in the very porous reef front carbonates (Ginés et al., 2014). Subsequently, breakdown processes were induced by the glacioeustatic sea level falls generating large block accumulations along with spectacular speleothem ornamentation that decorates almost the entire cave. The recognition of a series of non-functional hypogene features (Ginés et al., 2009a; Merino et al., 2011) brings a third speleogenetic agent, the hypogene basal recharge related to local geothermal phenomena (López & Mateos, 2006) that was also involved in the genesis of this coastal cave system.

**METHODS**

To characterize the sediments present in the galleries of Cova des Pas de Vallgornera standard sedimentological and geochemical analyses were carried out on all the collected samples.

Sediment samples were collected when available in different sectors of the cave (Fig. 1). In Galeria d’en Pau six samples were collected at the floor surface, while in Galeria del Tragus seven more samples were collected in the different profiles of the sediment accumulation exposures.

Additionally, a series of three push cores (Table 1) were obtained by scuba-divers in the underwater passages of Sector dels Privilegiats. Cores were drilled by forcing a PVC pipe, 5 cm in diameter and 50 cm long, until the bedrock was reached. Furthermore, in the air-filled passages of Galeria Navarrete two more cores were taken. Cores obtained were bagged, sealed, numbered, and brought back to the Earth Sciences Department of the Universitat de les Illes Balears, where they were opened, longitudinally sectioned, photographed and sampled in stratigraphic order according to the different observed levels (18 subsamples for the underwater cores and 11 in the case of the cores from the air-filled galleries). Presence of sedimentary structures, such as laminations, and other general observations were annotated for all the cases.

A total of 42 samples were processed in the laboratory where each sediment sample was air-dried for 24 h prior to analysis. After the color was determined by means of the MUNSELL® soil color chart, grain-size, mineralogy, geochemistry, and organic matter were determined.

As all sediments showed <2 mm-particle size, grain size analysis was made using a Malvern Mastersizer 2000. Elemental particle parameters were calculated using the Gradistat ver. 8 software (Blott & Pye, 2001). Cumulative curves, frequency histograms, and statistical parameters such as mean, sorting, kurtosis and skewness were obtained following the geometric graphical method of Folk & Ward (1957).

Randomly oriented powders of the bulk samples of sediments were used for the mineralogical analysis. After sample pre-treatment with H₂O₂ to remove organic matter, mineralogy of sediments was determined with a Siemens D-5000 X-ray diffractometer using Cu Kα radiation. The pressed powder diffraction patterns were recorded from 3° to 65° 2θ in steps of 0.03°, 0.3-s counting time per step, at 25°C room temperature, and logged to data files for analysis.

Phase determination and semi-quantitative analysis were made by the X-Powder ver.2010.01.09 Pro software using the DifData database (Downs & Hall-Wallace, 2003).

All samples were observed by SEM (Hitachi E S-3400N) and analyzed by EDX (Bruker X-Falsh Detector 4020) for their bulk sediment geochemistry. Major elements in their oxidized state (such as MgO, SiO₂, CaO, MnO, FeO, K₂O, Al₂O₃, SO₃, TiO₂, P₂O₅ and Na₂O) were determined as a percentage weight composition.

To estimate the organic matter content, the samples were weighted after drying at 105°C, then heated at 360°C for 2 hours and weighed again. The final value was reported as % LOI (Schulte & Hopkins, 1996).

**SEDIMENT CHARACTERISTICS WITHIN THE CAVE SYSTEM**

The Cova des Pas de Vallgornera has slight differences in the sediment characteristics as well as in processes involved when compared with other previously described caves within the littoral karst of the Mallorca Island (Gràcia et al., 2003, 2005, 2007; Fornós et al., 2009b). Most Mallorcan caves have natural entrances created by breakdown and collapse intersecting the surface, allowing the ingress of external sediments. In the present case, the cave does not currently have any natural entrance although in the past several entrances may have existed as revealed by the presence of vertebrate paleontological remains (Bover et al., 2014). As a consequence, significant allochthonous detrital sedimentation is not currently a relevant phenomenon in any section of the cave system. The muddy sediments are scarce, but present in the galleries of the innermost part of the cave as patchy accumulations few centimeters
in thickness, both in the terrestrial and underwater passages. The autochthonous sediments are similar to those previously described in Mallorcan coastal caves (Fornós et al., 2009b), frequently featuring a mixed sedimentation that includes carbonate particles of rock detached from the walls, together with the scarce allochthonous clay and silt deposits derived from the infiltration of soil materials to the underlying voids.

In the next paragraphs we describe the sediments existing in four different areas of the cave, where their presence is conspicuous and illustrative of the represented sedimentary facies as well as the processes that act or have acted in the cave along its speleogenetic evolution.

**Sediments in Sector dels Privilegiats**

Galleries and conduits that form the Sector dels Privilegiats (Fig. 1) correspond to the underwater passages nearest to the sea. Despite the general lack of sediments characteristic of most galleries and chambers of the cave, in some parts of these passages extensive sedimentary accumulations can be observed. Three sediment cores (Fig. 2), located in a SW-NE section of one of the nearest parallel galleries to the coastline, were obtained reaching a maximum thickness of 35 cm. Due to the difficulties during the sampling procedures as well as the absence of clear sediments exposures it has been impossible to know the real thickness of these extensive but irregular deposits.

In general they are composed by abundant but isolated rock fragments embedded in a dark silty sand matrix. The color of sediments (Table 2) ranges from dark reddish brown (5YR3/2) to brownish yellow (10YR6/6). The sand is the predominant texture with a mean greater than 50% while the mud represents around 40%.

The organic content (LOI) of these underwater sediments is the highest of all collected sediments in the entire cave, reaching a maximum of 10.27% in core PV-02 and a minimum on top of all cores (lowest value of 4.03%). The mean for the entire sampled cores in this area is around 6%.

One of the main differences with the rest of the cave sediments, reflected in their color, corresponds to their chemical composition (Table 3). They are rich in Fe-Mn sediments. FeO is the dominant oxide composition with mean values slightly higher than 45% that range from 14.62 to 72.13% and the MnO composition has a mean near to 11%, with values ranging from 5.96 to 18.56% (Table 4).

Clay minerals dominate the sediment composition, representing more than 40%. The main phyllosilicates, kaolinite (near 23%) and illite (around 13%) are in the highest proportion, although other minerals (e.g. montmorillonite and palygorskite) are also present. Goethite represents 15% and the elevated proportion (near 20%) of amorphous material can be correlated with the presence of Mn-oxides and hydroxides not detected in the XRD analysis due to their low crystallinity.

Grain size, as commented before, corresponds to a muddy sand. All the samples show similar values and no sequence trend can be observed on them. Silt represents near the 40%, and clay has values around 3.5%. The sand fraction is dominated by medium to very fine textures. The sediments of Sector dels Privilegiats show the poorest sorting (Table 5) of all the sediments represented in the cave.

Sediment accumulation in this sector represents a complex mixing of sediments with different mineralogies and chemistry that suggests a complex convergence of sedimentary processes. Besides the fine material infiltrated from the soil during
flooding episodes (layers with elevated concentration of quartz, feldspars, and clay minerals as kaolinite or palygorskite, mainly derived from dust rains as observed by Fiol et al., 2005 and Muhs et al., 2010)

Table 2. Cave sediments sample description, grain size distribution and LOI.

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Description</th>
<th>% gravel</th>
<th>% sand</th>
<th>% mud</th>
<th>% LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galería del Tragus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-22-1</td>
<td>7YR7/4 - Pink clayey silt</td>
<td>0</td>
<td>33.9</td>
<td>66.1</td>
<td>3.3</td>
</tr>
<tr>
<td>20-22-2</td>
<td>7YR8/6 - Reddish yellow clayey silt</td>
<td>0</td>
<td>31.9</td>
<td>68.1</td>
<td>2.19</td>
</tr>
<tr>
<td>20-22-3</td>
<td>5YR5/6 - Yellowish red sand</td>
<td>0</td>
<td>84.9</td>
<td>15.1</td>
<td>0.63</td>
</tr>
<tr>
<td>20-22-4</td>
<td>7YR6/4 - Light brown silty sand</td>
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<td>64.9</td>
<td>35.1</td>
<td>1.41</td>
</tr>
<tr>
<td>VLM115</td>
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<td>0</td>
<td>74.4</td>
<td>25.6</td>
<td>1.61</td>
</tr>
<tr>
<td>VLM117</td>
<td>5YR5/6 - Yellowish red silty sand</td>
<td>0</td>
<td>15.8</td>
<td>84.2</td>
<td>1.2</td>
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<td>Sector dels Privilegiats (underwater)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV-01a</td>
<td>5YR6/3 - Carbonate cust</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PV-01b</td>
<td>5YR2.5/1 - Black silty sand</td>
<td>0</td>
<td>57.1</td>
<td>42.9</td>
<td>4.03</td>
</tr>
<tr>
<td>PV-01c</td>
<td>5YR3/1 - Dark grey silty sand</td>
<td>0</td>
<td>64.6</td>
<td>35.4</td>
<td>5.66</td>
</tr>
<tr>
<td>PV-01d</td>
<td>5YR3/2 - Dark reddish brown sandy silt</td>
<td>0</td>
<td>53.3</td>
<td>46.7</td>
<td>3.8</td>
</tr>
<tr>
<td>PV-01e</td>
<td>5YR2.5/2 - Dark reddish brown sandy silt</td>
<td>0</td>
<td>48.1</td>
<td>51.9</td>
<td>5.25</td>
</tr>
<tr>
<td>PV-01f</td>
<td>5YR5/6 - Yellowish red silty sand</td>
<td>0</td>
<td>50.2</td>
<td>49.8</td>
<td>4.16</td>
</tr>
<tr>
<td>PV-02a</td>
<td>5YR5/4 - Carbonate silt</td>
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<td>-</td>
<td>-</td>
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<td>PV-02b</td>
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<td>38.8</td>
<td>4.61</td>
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<td>PV-02c</td>
<td>5YR5/8 - Brown silty sand</td>
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<td>59</td>
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<td>10.1</td>
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<td>65</td>
<td>35</td>
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<td>-</td>
<td>-</td>
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<td>PV-03b</td>
<td>10YR3/2 - Dark grayish brown sandy silt</td>
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<td>6.76</td>
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<tr>
<td>PV-04a</td>
<td>5YR6/3 - Carbonate cust</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>PV-04b</td>
<td>2.5YR4/8 - Dark red clayey silt</td>
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<td>1.07</td>
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<td>Galería de Pau</td>
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<tr>
<td>PV-06</td>
<td>2.5YR3/4 - 10R4/8 Dusky red sands and silts</td>
<td>0</td>
<td>64.5</td>
<td>35.5</td>
<td>3.77</td>
</tr>
<tr>
<td>PV-07</td>
<td>2.5YR3/3 - Dusky red silty sand</td>
<td>0</td>
<td>59.6</td>
<td>40.4</td>
<td>5.49</td>
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<tr>
<td>PV-08</td>
<td>5YR2.5/1 - Black cemented silt</td>
<td>-</td>
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</tr>
<tr>
<td>PV-09</td>
<td>10YR8/3 - Pale brown cemented sand</td>
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<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>PV-10</td>
<td>5YR5/8 - Reddish yellow cemented silty sand</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PV-11</td>
<td>7.5YR7/8 - Reddish yellow sands</td>
<td>-</td>
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</table>

Sediments in Galería Navarrete

The most important accumulation of muddy detrital red sediments is found at Galería Navarrete. Although accumulations of around 20 cm in thickness are the most common, others reaching nearly 40 cm can be observed thanks to the sediment cores made on their floor (Fig. 2). Mineralogical composition of sediments is characterized by the main presence of silicic minerals and the scarcity of carbonates (Table 4). The beds on top of the deposits exhibit abundant mud cracks showing a black Fe-Mn rich patina on them (Fig. 4).

From the detailed observation of sediment cores, a thin horizontal plane-parallel lamination less than 1 mm thick can be observed due to small changes in color and small grain size differences. The sedimentary accumulation is made up of well sorted fine-grained detrital sediments, predominantly silts with subordinate very fine sands. They show a color that ranges from dark red (2.5YR4/6) in the siltiest levels to red (2.5YR5/6) when very fine sand predominates. Globally, the grain size is mainly composed of a silt fraction representing around 50% of the total, whereas the fine to very fine sands represent nearly 38%. The clay fraction does not reach the 6%. Although the percentages of sand and mud vary along the sampled cores (Table 2), it seems quite evident that the upper levels of the sequence have a mean grain size slightly inferior to the lower ones. The complete deposit shows a fining upwards sequence and a poor sorting. All the statistical parameters related with the grain size can be viewed on Table 5.

The organic content of the sediments is the smallest of all collected samples in the entire cave, reaching these submerged passages, processes of wall corrosion and detachment of carbonate particles that may attain gravel size, are evident especially in core PV-01. Their deposition shows a characteristic longitudinal accumulation of sediments along the floor of the phreatic conduits (Fig. 3), following the projection of the cave walls. Mud cracks are evident on top of most of these deposits, as well as a carbonate crust deposited during an air-filled period.

Fig. 3. Longitudinal accumulation of grains detached from the cave walls and presence of mud cracks through the phreatic conduits of Sector dels Privilegiats (photo: Jaume Pocovi).
reaching a maximum of 1.34% in the top level and a minimum of 0.11% at the base. The mean for the entire column is 0.61%.

Mineral composition of sediments (Table 4) is dominated by quartz with a mean of 61.9% and feldspars (18.3%), the carbonates, mainly Mg-calcite, are poorly represented barely reaching the 6% (mean of 2.4%). Total clay minerals are around the 14% mostly represented by illite and kaolinite. Locally there are more silty intercalations with illite being more than 10%. Analysis of major chemical elements (Table 3) corroborates the aforementioned mineralogy.

The sediments here are interpreted as classical slackwater sediments, characteristic of maze caves (Bosch & White, 2004), deposited in very low flow velocities. Moreover, the autochthonous muddy sedimentation is not very common through the whole cave. This is probably due to the high purity of the Upper Miocene limestone with less than 1% insoluble residue (Fornós et al., 2009b). In the case of Cova des Pas de Vallgornera, the host rock is extremely pure (in lagoon facies the impurities represent 0.38% and in the reef front facies less than 0.1%, being their main chemical constituents SiO\textsubscript{2} 40%; Al\textsubscript{2}O\textsubscript{3} 17.5% and Fe\textsubscript{2}O\textsubscript{3} 13.5%).

<table>
<thead>
<tr>
<th>Sample</th>
<th>MgO</th>
<th>SiO\textsubscript{2}</th>
<th>CaO</th>
<th>MnO</th>
<th>FeO</th>
<th>K\textsubscript{2}O</th>
<th>Al\textsubscript{2}O\textsubscript{3}</th>
<th>SO\textsubscript{3}</th>
<th>TiO\textsubscript{2}</th>
<th>P\textsubscript{2}O\textsubscript{5}</th>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>0.72</td>
<td>0.86</td>
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</table>

Table 3. Major elemental data of cave sediments expressed as wt. %.
As a consequence, most of the fine sediment composition has, at its very beginning, an external origin entering to the system during flooding episodes favored by some openings of the cave. The observed mineralogy similar to the present-day soil composition (Fiol et al., 2006; Muhs et al., 2010) as in other Mediterranean caves (Iacovello & Martini, 2012) supports this fact. In this case the slackwater facies (Bosch & White, 2004) include muddy fine sands transported into the main galleries system as suspended load, which could settle out in secondary passages.

In any case, the slight reduction of the grain size from the base to the top indicates a decrease in the hydrodynamic energy conditions of the cave.

A carbonate crust covers the red muddy sediments (Fig. 4) thus indicating a change in the hydrologic regime that acted in this part of the cave, related to the fact that these passages became situated above the water table as a consequence of the sea level controlled fluctuations of the base level.

**Sediments in Galeria d’en Pau**

In this part of the cave a sparse detrital sedimentary accumulation can be observed (Fig. 5). Dusky red sands and silts form a thin deposit less than 5 cm thick in the floor of the passage and small accumulations less than 1 cm thick in holes and concavities of the walls can be observed. Sand fraction dominates and attaining values higher than 60% and LOI values between 3 and 6% (Table 2). The mean grain size corresponds to very fine sand, with a silt percentage of 34.60%, being the mean clay content of 3.35% (Table 5). The mineral content is quite variable. Phyllosilicates (mainly kaolinite) represent nearly 22% and carbonates around 9%. Quartz and feldspar are also represented with mean values around 10% as well as goethite. Mn-oxides and other Fe-oxides, as revealed by the elevated Fe-content of the samples (Table 3), may attain nearly 25% (Table 4).

In general the sediments present in this part of the cave show great similarities with those found in Sector dels Privilegiats.

**Consolidated sediments in Galeria d’en Pau**

In the northeastern end of Galeria d’en Pau, a superposition of two different phreatic passages shows a series of consolidated, well cemented, deposits that can be seen on the floor of the upper conduit. Neither reaching more than several decimeters (maximum observed thickness is 50 cm), they correspond to a diverse sequence of strata varying both in color and texture. Although they have not been studied in detail, black cemented silts, reddish yellow cemented silty sands or sands and, pale brown cemented sand, are the main facies present. Their sharp stratification stands out, showing the variability of the different layers and the strong planar millimeter scale clearly visible in the sand levels. The mineralogy of those deposits is clearly dominated by carbonates (mainly calcite), which

### Table 4. Mineralogy of cave sediments (%).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Montmorillonite</th>
<th>Palygorskite</th>
<th>Illite</th>
<th>Kaolinite</th>
<th>Goethite</th>
<th>Feldspar</th>
<th>Dolomite</th>
<th>Amorphous</th>
<th>Calcite</th>
<th>Mycetite</th>
<th>Hydration/serpentine</th>
<th>Anomalous</th>
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represent more than 90% (Table 4). The percentage of Fe-oxides is also significant (Table 3).

Although in this part of the cave these consolidated sediments are more clearly visible, they also exist in other passages (i.e., Galeria del Tragus; Fig. 6).

The consolidated deposits are probably related with an earlier phreatic phase in the cave evolution where the grains detached from the cave walls due to the contrasting corrosion of the bioclastic calcarenites, produced an abundant source of carbonate sand that was later accumulated thanks to the currents through the widened passages. This autochthonous sedimentation alternated sporadically with external flooding episodes.

**Sediments in Galeria del Tragus**

The sediments found in Galeria del Tragus represent the most important accumulation existing in all the galleries and chambers of the cave. In an irregular outcrop cut by several collapses (Fig. 7) and extending
along more than 200 m of passage, the deposits with a mean thickness of 2.5 m form a simple sedimentary sequence that displays small lateral variations and reveal four clearly differentiated levels (Fornós et al., 2010). It corresponds to a predominantly sand accumulation at the base and a clayey silt deposition becoming dominant at the top (Table 2). The entire sequence is partially covered by a thin flowstone. Mineralogical composition of sediments is characterized by the presence of carbonate minerals and of silicic materials (quartz and feldspars) together with minerals from the clay (Table 4).

From bottom to top (Fig. 8), the lower level (UNIT – A) composed by reddish-brown sandstone shows a thickness of 1-1.5 m having a high degree of cementation. The basal contact with the rock is not observable because it is below the water table. This level is quite homogeneous without showing any sedimentary structures and, apparently, without paleontological remains.

The next level (UNIT – B) is very similar, but with remarkable differences in the cementation degree along the stratigraphic column. This level is formed by carbonated brown fine sands and has a thickness of 25-30 cm without clear lamination. A slight stratification can be observed, mainly due to differences in the grain size (average at the base 179.6 µm and average at the top 139.80 µm), and showing a very good sorting (Table 5). Interspersed in the basal part of this level and related to layers with a coarser texture, a mixed facies characterized by a low degree of sorting can be observed. It is sandy silt with a high proportion of clay.

The sequence continues with a very small and discontinuous subaerial flowstone level (UNIT – C) which leads to a very clear sediment unit formed by a facies of brown silts and clays 1-2 cm in thickness, showing a clean contact at the base. The sequence that fills up the final part of the Galeria del Tragus ends with a coarser facies (UNIT – D). It consists of reddish sandy silt, with interspersed levels of a low sorting degree formed by silt (60%), clay (> 20%) and fine and very fine sand (near 20%), and other layers with a good sorting and formed mainly by silt (> 70%). This facies also contains sporadically heterometric and angular fragments of limestone, of gravel (or greater) size, from the gravitational collapse of the walls. This unit contains the main part of the vertebrate fossil remains found in all the sequence. The most superficial part displays a slight subaerial flowstone layer, which also covers part of the osteological remains found on the surface.

Texture and carbonate composition (bioclastic) characteristics of the sands (UNITS–A and B),
DISCUSSION: DIFFERENTIATING DEPOSITIONAL ENVIRONMENTS

Sediments in coastal karst represent an information source, nowadays poorly understood, of climate and past sea-levels. The environments within the coastal karst caves are continuously changing from vadose to phreatic conditions in response to repeatedly flooding and draining caused by oscillating past Quaternary sea levels. Different subenvironments that can be described by their sedimentary content are then changing continuously (van Hengstum et al., 2011).

In the case of Cova des Pas de Vallgornera, the interaction of three main speleogenetic pathways (meteoric recharge, coastal mixing, and hypogene deep-seated recharge; Ginés et al., 2014) that had accounted along the Quaternary sea level history, configures a really complex morpho-sedimentary setting.

Presence of fine detrital deposits representing the autochthonous sedimentation is very scarce in the whole cave system of Cova des Pas de Vallgornera, both in the air-filled and underwater passages. Only in the innermost galleries of the cave, patchy accumulations few centimeters in thickness can be observed, except in Galeria Navarrete and surrounding area where a considerable amount of muddy red deposits are present. In general, this detrital sedimentation is quite similar to other coastal caves of Mallorca (Fornós et al., 2009b) where muddy sediments derived from the infiltration of soil materials are deposited; in those cases the presence of carbonate rock particles detached from the walls is very scarce.

Other deposits

Apart from the detrital sediments described above, other kind of deposits occur in some of the cave chambers. Breakdown facies including unsorted boulders and cobbles (ranging in size from centimeters to several meters) with subangular textures are located as big accumulations on the floor of most of the greatest chambers. They show a chaotic disposition with no signs of any imbricated structure or transport. Their distribution is clearly related with the textural characteristics of the host rock (reef front facies, Ginés et al., 2014) and corresponds to the accumulation of debris from roof collapse favored by the preferential dissolution of aragonitic corals that build this part of the host rock cave. Together with their mean grain size and sorting, suggest an eolian origin of sediments being deposited through a nearby ancient entrance. The lack of tractive structures suggests a deposition promoted by low dynamic runoff processes. The presence in the basal levels of mixed facies seems to indicate that mobilization and mixing of eolian sands with muddy materials related to external detrital inputs by surface runoff from outside infiltration occurred. The UNIT–C is interpreted as the partial flooding of the cavity with subsequent decantation of the material transported in suspension. The red sandy silt facies (UNIT–D) can be interpreted as infiltration deposits provided by surface runoff during periods of heavy rainfall.
The periodical flooding of the cave by meteoric waters provoked the accumulation of very thin laminated fine sediments. In general, the observed sequence shows a slight diminution of the grain size from the base to the top indicating a faint decrease in the hydrodynamic energy conditions of the cave with time.

The preferential distribution of these reddish sediments occurs mainly in secondary passages like at Galeria Navarrete. Probably, main episodes of meteoric recharge derived from runoff related to some sinks from a major surface ravine (as that existing close to the northeastern end of the cave) drive water to the main drainage conduits. The higher flow that probably held in these master conduits prevented the sediments accumulation, and only when ponded waters occurred in their derivation to secondary conduits and minor lateral galleries, the waters became decelerated having time to settle out the carried suspended load. Presence of mud cracks on top of the sequence indicates the restoration of vadose conditions. Nevertheless we can’t discharge to consider these sediments as backswamp or quietwater facies (Bosch & White, 2004; Springer et al., 1997). Being deposited during one of the periodic episodes of permanent flooding of the cave during the Quaternary, they can suffer posterior washing (both siliciclastic thin sediments or detrital carbonates characteristics of the water mixing dissolution environments) in the main conduits due to a substantially higher flow in vadose conditions.

On the other hand, the already referred sedimentary sequence of Galeria del Tragus is completely different (Fornós et al., 2010). It is formed by sands (Fig. 9) and muddy silts that host highly interesting fossil osteological vertebrate (mainly mammals) remains linked to the existence of an ancient entrance to the cave system (Bover et al., 2014), thus permitting to consider the sediment sequence as allochthonous (entrance facies). The characteristics of these sediments seem to indicate the presence of a cave mouth through which these sand deposits first and then the sediments of surface runoff entered the cave until the likely closing of it after the collapse of this ancient entrance. The absence of a clear lamination and flow structures, in these sand deposits of clear eolian origin, suggests a ramp-type deposition favored by gravity. The whole stratigraphic set with a sub-horizontal location of the deposits suggests a low dynamic aquatic environment. The extension (some hundred meters) along the gallery, points toward episodes of surface recharge presumably linked to sinks from major outside creeks (Ginés et al., 2014). The presence of articulated skeletons of the bovid Myotragus agrees with the hypothesis of an original open entrance close to the deposit, and seems to indicate a limited horizontal transport of the bones inside the cave.

The sediments sequence at Galeria del Tragus points to the importance of the meteoric recharge in the evolution of the passages forming the inner sectors of the cave. An evident change in the external environmental conditions, from an arid and probably cold period (prevalence of sands with eolian origin) to a more humid and probably warm one, can be inferred from the stratigraphic sequence. During the humid period the increasing of rainfall would favor the entry of finer allochthonous material through surface runoff. In any case, the simplicity and homogeneity of the stratigraphic sequence indicate a deposition during a short period of time.

The presence of paleontological remains in these detrital sediments sheds light on the age of the deposits as well as to the reconstruction of the speleogenetic evolution of the cave (Ginés et al., 2014). They contain, among other remains of terrestrial mammals (Bover et al., 2014), articulated skeletons and skulls of a bovid (Myotragus) that arrived to the island during the Late Miocene and evolved isolated since then. The archaic intermediate forms placed between Myotragus antiquus and Myotragus kopperi, brings an Early Pleistocene age for this paleontological deposit (Bover et al., 2014).

The aforementioned siliciclastic fine sedimentation shares the spotlight with the accumulation of goethite-rich sediments and amorphous manganese oxides. Present patchily in several degrees through the entire cave passages and chambers (as Galería d’en Pau), but especially evident in the nowadays submerged...
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occurs at joint guided phreatic passages hosted in more calcisiltitic lagoon facies. The scarce sediment accumulation in the main passages would indicate periods of intense meteoric recharge that would have washed the accumulated sediments in the floor of passages being only deposited as odd accumulations on secondary passages or other restricted zones as hollows in walls, or blind conduits.

Remnants of carbonate consolidated sediments, which are eroded and fossilized by mainly siliciclastic unconsolidated sediments, show a clear difference in texture and composition. They correspond to different processes that characterize different events. Moreover, the link with entrance facies during periods of external aperture of the cave as well as the presence of carbonate crusts on top of most deposits also indicate the succession of periods of flooding with others of air-filled evolution.

As a whole, sediments in Cova des Pas de Vallgornera reflect the complexity of processes and sedimentary facies involved in this exceptional coastal cave (Fig. 10). The different morpho-sedimentary environments that can be distinguished within the cave can help to decode its evolutionary history (Ginés et al., 2014), mainly related to the sea-level fluctuations during the Plio-Quaternary times.

CONCLUSIONS

Although different kinds of sediments have been described with very similar characteristics to other coastal caves previously reported in Mallorca (Fornós et al., 2009b), at the present day sedimentary processes in Cova des Pas de Vallgornera are irrelevant. The most surprising fact and the main difference with other coastal caves in the island is the scarce presence of sediments in its chambers, and passages. Water chemistry influenced by the coastal mixing processes controls most of

Fig. 10. Illustrative sketch representing the main sedimentary environments and processes involved in Cova des Pas de Vallgornera. 1) Consolidated carbonate deposits from Galeria d’en Pau; 2) Allochthonous deposits in Galeria del Tragus with vertebrate fossil remains; 3) Si-rich muddy deposits from Galeria Navarrete; 4) Mixed muddy deposits rich in Mn and Fe. M - Miocene; PI + Q - Pliocene and Pleistocene calcarenites.
the autochthonous sedimentation related to the corrosion of walls; periodical meteoric flooding of the passages transported into the cave fine sediments from the external sources (mainly soil); depending on the characteristics of the ancient openings of the cave, allochthonous littoral sandy sediments, were accumulated at some spots as entrance facies. Along with these processes, the activity of the hypogenic episodes that acted at some moments during the cave evolution (Ginés et al., 2009a; Merino et al., 2011) masked part of the sediments present in the cave and added uncommon mineralogies (Merino et al., 2009; Onac et al., 2014).

In terms of the geochronological evolution, the osteological remains from Galeria del Tragus have been attributed to the Early Pleistocene (Fornós et al., 2010; Bover et al., 2014), so dating back the formation of the passages to the Pliocene. The observed consolidated sediments that are fossilized by these detrital paleontological deposits must have been accumulated probably along the Late Pliocene. This fact constrains the genesis of the main passages to mid-Pliocene times, where some high sea levels occurred (Dwyer & Chandler, 2009), or even earlier. The evolutionary history of the cave has experimented the successive periods of sea level changes during the Quaternary times, probably forming some additional cave horizons (Ginés et al., 2014) where different sedimentary processes can occur, probably redistributing part of the sediment but with no meaningful sedimentary addition due to the obstruction of the external apertures.

Trying to correlate speleogenetic pathways and sedimentary processes, several different situations can be identified, that could originate however transitional or mixed environments. The meteoric recharge is linked with the detrital sedimentation, including siliciclastic fines and coarse surface materials (basically eolian sands or other materials entered through ancient cave entrances). On the other hand, coastal mixing dissolution is responsible for the autochthonous sedimentation basically by means of the release of carbonate particles from the calcarenitic cave walls, though this situation can cause as well the dissolution of an important part of the particulate material. Finally, the hypogenic deep-seated recharge is probably responsible for the Fe- and Mn-rich waters that can be oxidized when approaching the water table. The long lasting episodes of low sea-level during the Quaternary, have allowed the formation of desiccation cracks and the deposition of flowstone layers, even in nowadays underwater passages. Unfortunately, the extremely fluctuating sea-controlled base level makes quite difficult the detailed chronological reconstruction of the cave morphogenesis.

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INTRODUCTION

The Balearic Islands are an archipelago located at the western area of the Mediterranean Sea (Fig. 1 A-B). It is composed of two different groups of islands. The Western set, or Pityusic Islands, consists of two main islands (Eivissa ["Ibiza"] and Formentera). On the other hand the Eastern set, or Gymnesic Islands, is more isolated than the Pityusics and constitutes of two main islands (Mallorca and Menorca). The current isolation of the Balearic Islands began at the end of the Messinian Salinity Crisis (MSC), 5.35 My ago (Gautier et al., 1994; Clauzon et al., 1996; Krijgsman et al., 1999).

The existence of abundant caves all around Mallorca is favoured by the geological characteristics of the island, mainly composed of limestones. More than 2,000 caves have been explored and surveyed in the island (Encinas, 2006). Exploration and paleontological excavation in some of these Balearic caves have allowed the discovery and subsequent study and analysis of the fossil fauna from these islands.

Different faunal assemblages have been identified in Mallorca, but the most relevant insular fauna has been recorded in post-Messinian deposits (e.g., Alcover et al., 1981). This faunal assemblage (called Myotragus-fauna) is mainly composed of an artiodactyl, Myotragus (Bovidae) (Bate, 1909), a rodent, Hypnomys (Gliridae) (Bate, 1918) and an insectivore, Nesiotites (Soricidae) (Bate, 1944). Although these three taxa survived during
all the Plio-Pleistocene, recent discoveries prove that other mammalian species colonized Mallorca during the Messinian, and that they became extinct during the Pliocene and Early Pleistocene (Bover et al., 2014, and references therein).

In 1968, a cave known since then as Cova des Pas de Vallgornera, and located on the southern coast of Mallorca, at the municipality of Llucmajor, was discovered in the course of a drilling carried out for the construction of a cesspit.

After the initial exploration of the cave (Collignon, 1982), a first detailed topographic survey published by Merino (1993) represents a cave with a total length of approximately 2 km. After the negotiation of two narrow passages in 1994 and 2004, the length of the cave has been remarkably increased reaching 6.5 km in 2000 (Merino, 2000), 23 km in 2006 (Merino et al., 2006), 40 km in 2007 (Merino et al., 2007), 56 km in 2008 (Merino et al., 2008), 62 km in 2009 (Gràcia et al., 2009; Merino et al., 2009) and 65 km in 2011 (Merino et al., 2011). Currently, more than 74 km have been already surveyed (Merino et al., 2014) and it is considered one of the 30 longest caves in the world (Fig. 1 C). Currently, this cave is only accessible through the artificial entrance excavated in 1968.

The Cova des Pas de Vallgornera (from now on CPV) is an extensive maze cave partially drowned by brackish phreatic waters and it lies in a tabular platform built up by an Upper Miocene reefal limestone sequence (Ginés et al., 2008; Fornós et al., 2010a, 2011, and references there in). It has emerged as a conspicuous coastal cave-system that allows to investigate complex speleogenetic mechanisms and speleothem formation processes, many of them controlled by Quaternary sea level changes (e.g., Ginés et al., 2009a, 2009b; Merino et al., 2009; Tuccimei et al., 2009; Dorale et al., 2010; Fornós et al., 2010a, 2011; Merino & Fornós, 2010).

In this paper we present the fossil faunal assemblage that has been recorded through a single excavation campaign carried out during May 2010 at CPV. The bones collected in the fossiliferous deposit provided relevant information on the collapse of the ancient natural entrance. Additionally, faunal remains also shed light on some other aspects on the geomorphological history of the cave and its chronology.

**METHODS**

The short time available for the excavation of the deposit and the complexity of the whole excavation in such a remote place of the cave precluded the use of grid squares to locate the bones in the deposit. Additionally, the main objective of the excavation was to remove the material from the surface, a rescue of material for its conservation and scientific study. Therefore, the collected material was reported on a detailed topographical survey of the passage based on landmarks of the topography and each collected item has been refered to its proximity to one of the 28 established sections (Fig. 1 D, T1-T28). The excavation was mainly collecting bones by hand, although the material partially covered by flowstone had to be
removed using mechanical techniques (Fig. 2.A). After labelling and packaging, the materials were placed in protected containers and carried outside the cave once every day by volunteers. All bones were initially cleaned with water without any kind of aggressive mechanical tool or chemical treatment. A professional conservator (Mr Bernat Font, St Llorenç, Mallorca) worked on a selection of bones that were embebed in hard sediment and/or flowstone, or fragmented. The cleaning of bones was done basically through a mechanical work, although when necessary it was done through a chemically controlled process (see Díaz et al., 2014).

The material from CPV and from other deposits used in this paper as comparison material is listed in Annex 1 (http://dx.doi.org/10.5038/1827-806X.43.2.6). See Díaz et al. (2014) for a complete list of the obtained bones from CPV during the excavation.

The nomenclature used for the teeth is as follows: lowercase letters (m' for molar, 'p' for premolar, and 'i' for incisor) for lower teeth, and uppercase letters ('M', 'P') for upper teeth. The number after the letter is the position that the tooth occupies in the mandible or maxilla.

Measurements of bones have been taken with a digital caliper (0.02 mm accuracy). Metric values for the Nesiotites bones were recorded using a stereomicroscope (Olympus MSZH, objective 64x) connected to a video camera. We followed Reumer (1984) for measurements, with some additions from Rabeder (1972). For the morphometric analysis we used the PAST v2.01 statistical programme (Hammer et al., 2001).

Measurements abbreviations are as follows: H: mandible height; HC: condyle height; Hi: height of i1; Hm1: height of mandibular ramus under m1, in medial view; Hm2: height of mandibular ramus under m2, in medial view; L: length of the jaw measured from P point to the mental foramen; Li: length of i1; Lm1: length of m1; Lm3: length of m1; Lm1-m3: m1-m3 length; Lp3: length of p3; Lp4: length of p4; Ltr: length of lower tooththrow; LLF: length of lower toothrow; LUF: length of the upper facet of the condyle; Lm1: width of m1 talonid; TRWm1: width of m1 trigonid; WC: condyle width; Wm3: width of m3; Wp4: width of p4.

In the case of the bovid Myotragus, as the teeth measurements can be influenced by the wear pattern, the measurements were taken at the base of the teeth, but also at 1 cm from the base to be compared with published data (see text and figure captions for further explanation).

Other used abbreviations: CPV: Cova des Pas de Vallgornera; IMEDEA: Institut Mediterrani d’Estudis Avançats (CSIC-UIB); FBE: Federació Balear d’Espeleologia (Balearic Federation of Speleology); ACAD: Australian Centre for Ancient DNA; MNIB-SHNB: Museu de la Naturalesa de les Illes Balears - Societat d’Història Natural de les Balears.

SITE DESCRIPTION

Geological background

The cave is located at the southern coast of Mallorca, a region called Migjorn. Upper Miocene tabular deposits outcrop all along the southern and eastern coast, shaping this flat karst region (Fornós & Gelabert, 2004). This region must be considered as a post-orogenic carbonate platform that discordantly onlaps the folded Mesozoic basement (Serres de Llevant and Serres Centrals). From a sedimentological point of view, the Upper Miocene deposits constitute a complex reef sequence related to the well-differentiated depositional environments characteristics of tropical carbonate platforms, with a wide textural variability as a function of the reef architecture related to the sea level oscillations and the resulting depositional environments (Pomar et al., 1996). This sedimentological complexity produces sharp lateral and vertical changes of rock facies, which have clear repercussions on the pattern and morphology of the cave. Three main units can be distinguished within the Upper Miocene deposits following Fornós et al. (2002): the basal one known as calcisiltites with Heterostegina unit (lower Tortonian in age), the reef complex whose age is Upper Tortonian-Lower Messinian and finally, the Santanyí limestones (also called Terminal Complex) corresponding to the Messinian. CPV is fully developed in the carbonate rocks appertaining to the reef complex (Fornós et al., 2002) being possible to observe, throughout the morphology of its chambers and galleries, the different facies that can be individualised within this unit (Gíñes et al., 2008, 2009b, 2014).

Deposit

CPV is an extensive maze cave whose development surpasses 74 km of passages and chambers disposed in two principal tiers regarding its elevation (Merino et al., 2011). The main fossiliferous deposit is located at the end of the northernmost passage called Galeria del Tragus with a length of nearly 300 m, mean width of 10 m and height of 10 m (see Fig. 1 D), which is situated in the Sector Descobriments 2004 (Merino et al., 2006). The rectilinear passage hosting the paleontological deposit runs in southwest-northeast direction and in its first 230 meters it is a wide and high gallery with blocks. At the beginning and end of this part of the gallery important and massive flowstone and speleothems deposits can be observed. A final chamber, the Sala del Col-lapse (Collapse Hall), accessed through a narrow passage, displays a huge collapse of blocks sealing the alleged former entrance from where the different fossil species recorded in the cave entered.

The presence of a flood paleolevel at +4-5 meters on the wall of the Galeria del Tragus suggests the presence of an ancient water-table drowning this part of the cave, which may have conditioned the emplacement of the fossiliferous deposit.

The fossil material was found mainly on surface and widely spread all over the Galeria del Tragus/Sala del Col-lapse (Fig. 2 B). Almost all the bones were in extremely good preservation state, but the bones located in parts of the cave close to walls and speleothems were partially covered by flowstone.

In the floor of Galeria del Tragus, some naturally produced pits reaching the current water-table...
Fourteen sediment samples were collected in three stratigraphic sections located at the end of the Galeria del Tragus (Fornós et al., 2010b). Sedimentological characteristics were analyzed and stratigraphical data were also recorded.

**Excavation remarks**

The fossiliferous deposit is reached after 4 hours of underground trip (including crawling and nearly 1 hour of swimming) from the sole current artificial entrance to the cave (a 6 m deep man-drilled well). At least two very narrow passages must be negotiated precluding the possibility to carry and use large or heavy equipment in the excavation.

The cave is currently under the protection of Government of the Balearic Islands, and was declared Site of Community Importance, within the Natura 2000 Network by the European Union (European Council Directive 92/43/CEE). The access to the cave is highly restricted and a permit for any research task in the cave must be requested. Moreover, some parts of the cave are specially protected for geological or speleological reasons. The transit across these particular spots is extremely restricted. For this reason, the way to reach the deposit was cautiously selected by the explorers from the FBE to avoid passing through these areas. One of these specially protected sectors, a narrow passage just prior to the Galeria del Tragus with fragile pool crystallizations, was unavoidable. Members of the FBE built a small bridge some weeks prior to excavation, to prevent damaging these formations.

The special protection of the cave and the tough efforts (both physical and in logistics) to reach the deposit forced the excavation team to realize all the work in a single campaign of three days spent inside the cave (28th-30th May 2010).

**Stratigraphy**

Fourteen sediment samples were collected in three stratigraphic sections located at the end of the Galeria del Tragus (Fornós et al., 2010b). Sedimentological characteristics were analyzed and stratigraphical data were also recorded.

Sediments sequence in Galeria del Tragus has a thickness of 2.5 m approximately, but it displays small lateral variations. A complete study of the cave sediments is presented in this volume (Fornós et al., 2014), but it is worth mentioning here that, in general, the sediment sequence observed at the Galeria del Tragus is formed by sands and mud-silts which can be considered allochthonous (entrance facies). This characteristic seems to corroborate the existence of an ancient cave entrance through which sand deposits first, and then sediments infiltrated by surface runoff, entered the cave until the likely closing of it after the collapse of this former entry. The absence of clear lamination and flow structures in the sand deposits of aeolian origin suggest a ramp-type deposition favored by gravity. Nevertheless, the sub-horizontal location of these deposits some hundreds of meters along the gallery seems to indicate a deposition of the whole stratigraphic set in a low dynamic aquatic environment.

The studied sediments sequence shows an evident change in environmental conditions from an arid and probably cold period (prevalence of sands with aeolian origin) to a more humid and probably warm one, during which the increasing of rainfall would have favoured the entry of allochthonus material through surface runoff (Fornós et al., 2010b). The simplicity of the sequence and the homogeneity of the units seem to indicate that their deposition was produced during a short period of time. This statement is in agreement with the lack of remarkable differences among the fossil remains obtained from the different stratigraphical units.

**Chronological remarks**

The chronology of the base of the Quaternary was updated and ratified in 2010 by the International Union of Geological Sciences changing its age from 1.8 My to 2.58 My (Gibbard et al., 2010). In this paper we use the proposed nomenclature according to this updated chronology, mainly for the chronological differentiation of “Late Pliocene” (Piacenzian) and “Early Pleistocene” (Gelasian-Calabrian) ranges.

**PALEOFAUNAL OVERVIEW**

As a complete analysis of the Pliocene and Pleistocene fauna from the Balearic Islands is beyond the main purpose of the present paper, we will focus on the paleofaunal overview of the island where CPV is located, Mallorca. Further information on the whole fossil faunal framework of the Balearic Islands can be found in Bover et al. (2014) and references therein. The fossil faunal assemblage of the last 5.35 My of the Balearic Islands is composed of the so-called *Myotragus*-fauna in Mallorca and the Menorcan Pleistocene and by the *Nuralagus*-fauna in the Menorcan Pleistocene (Bover et al., 2008, 2014). In Mallorca, three genera of mammals and a reptile of the original stock that arrived to the island during the Messinian Salinity Crisis (MSC) survived until the Holocene: *Myotragus* (Bovidae, Cetartiodactyla), *Hypnomys* (Gliridae, Rodentia), *Nesiotites* (Soricidae,
Eulipotyphla), and Podarcis (Lacertidae, Squamata), while a Vipera survived at least until the Late Pliocene. Other terrestrial vertebrates recorded so far in two Mallorcan Early Pliocene deposits, Caló den Rafelino and Na Burguesa-1, i.e., up to three mammals (a leporid, a cricetid, and a murid), up to eight reptiles (a viperid, a colubrid, a scindid, an anguid, a large lacertid, a gekkonid, a scolecodophilid, and a tortoise) (Bailon et al., 2010, 2014; Bover et al., 2007, 2010a, 2014; Quintana et al., 2010; Agustí et al., 2012), have not been recorded in fossil deposits with a post-Early Pliocene chronology of Mallorca.

The preliminary analysis of two Myotragus mandibles from CPV collected in 2009 allowed corroborating the importance of the deposit and establishing a Late Pliocene/Early Pleistocene chronology for the deposit. For this reason, the comparative analysis of the different taxa found in the cave will be focused on the species and fossil material already available from this epoch in Mallorca. Nevertheless, in this section, a general and short overview of the phylogenetic lineages or taxonomic groups present in the Pliocene, Pleistocene and Holocene Mallorcan deposits will be furnished.

**Myotragus**

Up to six chronospecies of Myotragus have been identified in Mallorca: *M. palomboi* from the earlier Early Pliocene (Bover et al., 2010a), *M. pepgonellae* from the Early-Late Pliocene (Moyà-Solà & Pons-Moyà, 1982), *M. antiquus* from the Late Pliocene (Pons-Moyà, 1977), *M. kopperi* from Early Pleistocene (Moyà-Solà & Pons-Moyà, 1981), *M. batei* from Early-Middle Pleistocene (Crusafont & Angel, 1966), and *M. balearicus* from the Late Pleistocene to Holocene (Bate, 1909).

Some evolutionary changes in the Myotragus lineage have been identified, such as a decrease in body size (through an increase of limb bone robustness and a decrease of bone length, especially in metapodials and stylododium elements), a progressive reduction of number and size of incisiform and premolar teeth, and the reduction of brain size and sense organs (e.g., Alcover et al., 1981; Köhler & Moyà-Solà, 2004; Bover & Tolosa, 2005). Changes in the longevity have been reported in the most recent species, *M. balearicus* (Köhler & Moyà-Solà, 2009; Jordana & Köhler, 2011).

**Hypnomy**s

Regarding Hypnomys, although remnants of this rodent have been obtained from deposits with Early Pliocene chronology (Alcover et al., 1981; Bover et al., 2014) the oldest formally described species is *H. waldreni*, from Late Pliocene deposits (Reumer, 1979). *H. onicensis*, initially described as *H. intermedius* (Reumer, 1981, 1994), from the Early Pleistocene, has been exclusively found in the Mallorcan deposit of Pedrera de s’Ònix (Manacor). The most recent species, *H. morpheus*, described by Bate (1918), has been recorded in the Middle Pleistocene to Holocene from Mallorca and Menorca.

The most remarkable evolutionary pattern of the lineage is the body size increase and differences among species are mainly related to this characteristic. Another evolutionary trend is the proportional increase of the zygopodium length (Alcover et al., 1981; Bover et al., 2010b).

**Nesiotes**

In Mallorca, the shrew genus Nesiotes is represented by three described species, *N. rafelinensis* (earliest Early Pliocene, Rosés et al., 2012, but see also Furió & Pons-Monjo, 2013 and Rosés et al., 2013), *N. ponsi* (Late Pliocene, Reumer, 1979) and *N. hidalgo* (Middle Pleistocene to Holocene; Bate, 1944). Additionally, Reumer (1981) described an intermediate form between the last two Mallorcan species, identifying it as *N. ex. interc ponsi-hidalgo* (or *N. aff. ponsi*, according to Alcover et al., 1981), in the Early Pleistocene deposit of Pedrera de s’Onix (Manacor). This intermediate form from Pedrera de s’Onix has been reported as indistinguishable from *N. meloussae* (Pons-Monjo et al., 2010, 2012), a species initially described from the Early Pleistocene of Menorca (Pons-Moyà & Moyà-Solà, 1980), although this identity remains unclear (e.g., it is not considered by Furió & Pons-Monjo, 2013).

Evolutionary trends of the genus include the size increase and the loss of the upper fourth unicuspid (in variable proportion of absence of this tooth in Late Pleistocene and Holocene populations; e.g., Reumer, 1980; Alcover et al., 1981; Pons-Monjo et al., 2012; Rosés et al., 2012).

**Herpetofauna**

As happens with the fossil mammals, although several endemic species of reptiles and amphibians have been recorded from the Mallorcan Early Pliocene (Bover et al., 2007, 2014; Bailon et al., 2010) belonging to the faunal stock that reached the island during the MSC, just one reptile, Podarcis lilfordi (Lacertidae, Squamata) and one amphibian, Alytes muletensis (Discoglossidae, Anura), survived until Late Pleistocene/Holocene. Both *P. lilfordi* and *A. muletensis* are still currently living in some Mallorcan localities. A Discoglossus (Discoglossidae, Anura) has been also recorded in the Early Pleistocene deposit of Pedrera de s’Onix, and a Vipera (Viperidae, Squamata) was present at the Late Pliocene.

**Birds**

The current knowledge of fossil bird fauna from the Early Pliocene of Mallorca comes from the site of Pedrera de s’Onix (Mourer-Chauviré et al., 1977, 1980; Alcover et al., 1981; Sondaar et al., 1995; Seguí, 2001). Twenty-seven taxa have been reported at this site, including Tyto balearica, Aegypius cf. monachus, Pica moureare, and Corvus pliocenus. A mixture of species linked to fresh-water masses and woodlands characterizes this fauna. The Late Pleistocene bird fauna from Mallorca known so far practically not includes species linked to fresh-water masses.

**SYSTEMATIC PALEONTOLOGY**

**Amphibians**

Three bones (fragmented urostyle, humerus and tibiofibula) belonging to Discoglossus sp.
(Discoglossidae, Anura) are the sole evidence for the presence of amphibians in the cave. Their morphology fits well with an undescribed species that previously was only known in Mallorca from Pedrera de s’Ònix, where it is relatively abundant (Alcover et al., 1981).

Reptiles

A small lizard has been also recorded in CPV through 12 bones (femora, humeri, jaws, and maxillae), representing at least 4 individuals, two adults and two juveniles. We attribute them to Podarcis aff. lilfordi (Lacertidae, Squamata). All bones are more gracile than in recent Podarcis lilfordi, and agree in size to the lizard present in Pedrera de s’Ònix (Kotsakis, 1981). A complete recovered jaw has 17 teeth, but alveoli for 5 more teeth can be observed.

Birds

Birds are slightly more abundant in CPV than amphibians and reptiles. Twenty-eight bones have been obtained, belonging to at least 14 species (see Table 1, Fig. 3). A fossil Little Owl has been described from this cave on the basis of two bones (Guerra et al., 2012), including a highly diagnostic tarsometatarsus: *Athene vallgornerensis*. It has the shortest tarsometatarsus among all the extant and extinct species from its genus in the Western Palearctic. Its shape resembles the *Athene angelis* tarsometatarsus, although it is markedly smaller. Currently *A. vallgornerensis* is only known from CPV.

Two bones of large sized vultures are present in the sample of CPV, a proximal fragment of a humerus and a distal fragment of a tibiotarsus (Fig. 3 A and B). The fragmentary condition of the material does not permit their accurate identification. We attributed the humerus to cf. *Gyps*, mainly on the basis of the morphology of the *crista deltoidea* and the morphology of the palmar surface, although the morphology of the pneumatic fossa disagrees with our comparison material of *Gyps*. The distal fragment of tibiotarsus belongs to *Aegypius* sp. The Black Vulture has been tentatively reported in Mallorca from Pedrera de s’Ònix (as *Aegypius* cf. *monachus*, see Mourer-Chauviré et al., 1977; Alcover et al., 1981). The large-sized Barn Owl Tyto baleara, a species also found in Pedrera de s’Ònix (Mourer-Chauviré et al., 1981), is recorded through a complete ulna (Fig. 3 G), and a kestrel-like Falcon Falco sp. is represented by two bones (Fig. 3 D-E). The Pleistocene corvid *Pica mourerae*, described from Pedrera de s’Ònix (Seguí, 2001), has also been identified in CPV (Fig. 3 N-P). Another corvid, *Corvus* sp., has been herein identified (Fig. 3 Q-S). Its size, as well as the *Corvus* remains found on other Balearic coeval sites, is smaller than the modern species *Corvus corax*, although it differs in size from *Corvus pliocanus*.

The avian assemblage obtained in the cave does not allow a global approach to the paleoecology from the Late Pliocene/Early Pleistocene of Mallorca, due to the small size of the sample. Nevertheless, the assemblage fits well with that obtained in Pedrera de s’Ònix, despite the latter being slightly more recent. Excepting *Athene vallgornerensis*, cf. *Gyps*, *Falco* sp., *Crex* sp. and *Columba palumbus*, all the taxa recovered in CPV are also present in Pedrera de s’Ònix. The whole fauna fits well with a rocky cliff’s avian community in an open shrub environment, with some close water sites.

Table 1. Bird species present in CPV. The taxa shared by CPV and Pedrera de s’Ònix (PO) are indicated. (*) 2 different Anatidae have been obtained from Pedrera de s’Ònix. (**) The species of *Corvus* found in the Pedrera de s’Ònix is *C. pliocanus*. Two of the obtained bird taxa, *Pica mourerae* and *Athene vallgornerensis*, have never been found outside Mallorca so far, and thus, they should be considered as endemic species to the island.
Fig. 3. Bird bones obtained from CPV. Top: Non-Passeriformes from Cova des Pas de Vallgornera (A-K), with comparison material (A’-K’). A: IMDEA 94691, cf Gyps, proximal end of a right humerus, caudal view; A’: IMDEA 60079, Gyps fulvus, proximal end of a right humerus, caudal view; B: IMDEA 91976, Aegypius sp., distal end of a left tibiotarsus, medial and cranial views; B’: IMDEA 60145, Aegypius monachus, distal end of a left tibiotarsus distal end medial and cranial views; C: IMDEA 91885, Accipiter nissus, proximal end of a right humerus, caudal view; C’: IMDEA 39403, Accipiter nissus, proximal end of a left humerus, reversed, caudal view; D: IMDEA 91955, Falco sp., fragmented left ulna, ventral view; D’: IMDEA 20772, Falco tinnunculus, left ulna, ventral view; E: IMDEA 91884, Falco sp., distal end of a right tibiotarsus, cranial view; E’: IMDEA 20772, Falco tinnunculus, right tibiotarsus, cranial view; F: IMDEA 91958, Athene vallgornerensis, right tarsometatarsus, cranial view; G: IMDEA 90468, Tyto balearica, right ulna, ventral view; G’: IMDEA 21884, Tyto alba, right ulna, ventral view; H: IMDEA 91889, Anatidae, undetermined genus and species, proximal part of a left ulna, ventral view; I: IMDEA 91887, Crex sp., fragmented left ulna, ventral view; I’: IMDEA 34882, Crex crex, left ulna, ventral view; J: IMDEA 91965, Scolopax rusticola, left humerus, cranial view; J’: IMDEA 60070, Scolopax rusticola, reversed right humerus, cranial view; K: IMDEA 91892, Columba palumbus, fragmented left scapula, medial view; K’: IMDEA 20898, Columba palumbus, left scapula, medial view. Bottom: Passeriformes from CPV (L-S), together with Pica mourerae comparison material (N’, P’). L: IMDEA 91969, Corvidae undetermined genus and species, distal fragment of left coracoid, dorsal view; M: IMDEA 91890, Corvidae undetermined genus and species, fragmented left tibiotarsus, cranial view; N: IMDEA 91883, Pica mourerae, right carpometacarpus, dorsal view; N’: IMDEA 2540, Pica mourerae, reversed left carpometacarpus, dorsal view; Pedrera de s’Onix, Mallorca; O: IMDEA 91968, Pica mourerae, distal part of a left tarsometatarsus, cranial view; P: IMDEA 91967, Pica mourerae, right tarsometatarsus, cranial view; P’: IMDEA 2568, Pica mourerae, right tarsometatarsus, cranial view, Pedrera de s’Onix, Mallorca; Q: IMDEA 90470, Corvus sp., right humerus, cranial view; R: IMDEA 91898, Corvus sp., distal end of right carpometacarpus, dorsal view; S: IMDEA 90471, Corvus sp., left tarsometatarsus, cranial view.
Mammals

Bones of the three taxa of terrestrial mammals present during all the Late Pliocene to Holocene in Mallorca have been recovered from CPV. Preliminary analysis of the morphological characteristics of these bones (e.g., following Alcover et al., 1981), allows the clear attribution of the obtained material as belonging to *Myotragus*, *Hypnomys* and *Nesiotites*. Thus, the objective of the analysis of the mammalian bones here presented is to identify them to species level. Specifically, the accurate taxonomic attribution of the bones of these three mammalian taxa can furnish an approximate chronological framework to the deposit as the fossil records of these three genera are remarkably complete, especially in the case of *Myotragus*. Additionally, some fossil remains of bats (Chiroptera) have been also obtained from the cave.

Eulipotyphla

Up to 30 bones of *Nesiotites* (Soricidae) have been recovered from CPV (Fig. 4 A). Although postcranial remains of this genus have been recovered, the identification of the different *Nesiotites* species using these bones is ambiguous. For this reason, in order to evaluate the taxonomical attribution of the species found in CPV a Principal Component Analysis (PCA) with tooth and linear measurements of six mandibles of *Nesiotites* from CPV (see Annex 1) and the other species from Mallorca has been performed (four mandibles of *N. ponsi*, six of *N. aff. ponsi* and nine of *N. hidalgo* as comparison material; see Rofes et al., 2012 for further information).

In Fig. 4 B, variables Lm1, TRWm1, TAWm1, Hm1, and Hm2 are included, whereas in Fig. 4 C the variables used are Li, Hi, Lm1, TRWm1, TAWm1, Hm1, Hm2, Lm1-m3, L, H, HC, WC, LUF, and LLF.

Both figures show that on PC1 (indicating the variance in size) the specimens are distributed in three main groups (from left to right): a) Farrutx (*Nesiotites ponsi*, Late Pliocene); b) CPV + Pedrera de s’Onix (*Nesiotites aff. ponsi*, Early Pleistocene; c) Cova de Llenaire + Cova Estreta + Cova de Canet (*Nesiotites hidalgo*, Late Pleistocene/Holocene). On PC2 (indicating mainly morphology), no clear-cut differentiation can be observed.

The distribution of CPV specimens mainly overlaps with the one of *N. aff ponsi* from Pedrera de s’Onix, especially in Fig. 4 C, in which a larger number of variables was obtained. This overlap suggests that the *Nesiotites* from CPV displays a greater affinity with *N. aff ponsi* than with *N. ponsi* or *N. hidalgo*. Nevertheless, the specimens from Pedrera de s’Onix are more robust than those from CPV and the coronoid process of the latter specimens lean slightly more lateralwards in posterior view (respect to the mandibular ramus) than those from Pedrera de s’Onix. Although an unequivocal attribution of the *Nesiotites* from CPV to *N. aff. ponsi* from Pedrera de s’Onix cannot be established, they share large number of affinities. We identify here the taxa from CPV as *N. aff. ponsi*, although further analyses and material will be necessary to evaluate its presumably close relationships with the Pedrera de s’Onix *Nesiotites*.

![Fig. 4. Analysis of the Nesiotites bones found in CPV. A: SEM photo of left mandible IMEDEA 95073, in lingual (top), occlusal (centre), and labial (bottom) views. Principal Component Analysis (PCA) with tooth and linear measurements of mandibles of several species of Nesiotites using variables Lm1, TRWm1, TAWm1, Hm1, and Hm2 in B, and variables Li, Hi, Lm1, TRWm1, TAWm1, Hm1, Hm2, Lm1-m3, L, H, HC, WC, LUF, and LLF in C. Abbreviations: Nr, *N. rafelinensis* from Caló den Rafelino. Np, *N. ponsi* from Crulls de Cap Farrutx. Nap, *N. aff. ponsi* from Pedrera de s’Onix. Nh LI, *N. hidalgo* from Cova de Llenaire, Nh Ca, *N. hidalgo* from Cova de Canet. Nh CEs, *N. hidalgo* from Cova Estreta. Vallg, Nesiotites aff. ponsi from CPV.](image-url)
Rodentia

Up to 483 bones of Hypnomys (Gliridae) have been recovered from the Galeria del Tragus/Sala del Col·lapse (Fig. 5 A-I). As in Nesiotites, the morphological differences of the postcranial skeleton among the Balearic Hypnomys species are small. Nevertheless, we analysed the size of the long limb bones, and teeth. Additionally to the material obtained in the Galeria del Tragus/Sala del Col·lapse, at least two articulated skeletons and an unarticulated skeleton of Hypnomys have been found in different parts of the cave, even in places located far from the former entrance of the cave (Fig. 6 B-D), in Llac de na Gemma, Sector Gregal, and Sector F (Fig. 6 B, C, D, and points 2, 3, 4 in Fig. 1 C, respectively).

No data of measurements of limb bones of the older species of Hypnomys have been published and complete specimens of these bones are scarce (personal observation). Mills (1976) published several measurements made on H. morpheus long bones. He used long bones lacking one of the epiphyses additionally to complete bones. Thus, the total length of limb bones of Hypnomys from CPV has been compared to those of the scarce complete available material of H. onicensis curated at IMDEA, and to the data published by Mills (1976) and Bover et al. (2010b). The measurements of long limb bones without one of the epiphyses and complete (when available) are furnished in Table 2. Data suggest that no clear distinction among the different species can be established with just postcranial length measurements as the range of measurements of each bone for every species widely overlaps among them.

For this reason, we compared the size of several teeth. As no upper cheek teeth have been obtained in CPV, just data of lower cheek teeth from this cave together with data from bibliography have been used (Reumer, 1979, 1981; Agustí, 1980).

According to Reumer (1981) the ratio width/length of p4 and m3 (Wp4/Lp4 and Wm3/Lm3) seems to discriminate among the different species of Hypnomys, and the scatter plot of this ratio also shows the differences in size of the different species. In Fig. 5 J-K, ratios Wp4/Lp4 and Wm3/Lm3 of Hypnomys from CPV are compared with the obtained for other Hypnomys species by Reumer (1981). Both ratios in
the figure indicate that the size and proportions of the studied teeth of CPV Hypnomys is included within the variability of H. onicensis from Pedrera de’sOnix, and thus, the rodent remains from CPV can be tentatively attributed to H. onicensis.

Agustí (1980) suggested that the presence of a long centrolophid in the m1 and m2 of H. waldreni is a primitive characteristic, which is not displayed by the more modern species of Hypnomys such as H. morpheus and H. eliomyoides. As in Pedrera de’sOnix (see Reumer, 1981), Hypnomys from CPV displays long centrolophids in m1 and m2 (Fig. 5A).

Chiroptera

Two species of fossil bats are present in CPV (Fig. 7). The most abundant is a horseshoe bat (Rhinolophus) of middle size, which used the cave as a refuge (Fig. 7 A-D). Currently, three species of middle-sized Rhinolophus inhabit the Mediterranean region: R. mehelyi, R. euryale (both in the named “euryale-group”) and R. blasii (in the “landeri-group”; Gábor, 2008). The morphology of the skull and humerus of CPV specimen fits well with the species of euryale group, and differs from the morphology of R. blasii, according to the criteria of Felten et al. (1973), Dodelin (2002), and Lindenau (2005). The shape of the distal epiphysis of the humerus, a highly diagnostic trait for the genus, resembles more to R. mehelyi than to R. euryale. Nevertheless, the bones measurements are slightly smaller than in recent populations of R. mehelyi, and are closer to R. euryale. Additionally, about 12 fossil species of Rhinolophus have been described in the Western Paleartic (for a summary, see Gunnell et al., 2011). We excluded most of them for comparison, as they are included in the hipposideros and ferrumequinum groups. Rhinolophus neglectus is the sole fossil species of the euryale group, and it should be considered as closely related to R. mehelyi (Woloszyn, 1987). This group also includes the fossil subspecies Rhinolophus euryale praeglacialis. R. neglectus and R. e. praeglacialis are both insufficiently defined (Popov, 2004). Waiting for a review of the group, CPV horseshoe bat is here attributed to R. aff. mehelyi. The second bat species present in the cave is a small Pipistrellus represented by two very incomplete specimens (see Fig. 7 E).

Cetartiodactyla

Around 970 bones of Myotragus (Bovidae) belonging to a minimum number of 38 individuals have been obtained from our excavation of CPV. They correspond to 894 individual bones, a near complete adult associated skeleton and two partial associate juvenile skeletons. The number of recovered femora is remarkably greater than the number of other limb bones, probably related to an unknown taphonomical reason.

Additionally to the scattered bones in the Galeria del Tragus, an almost complete skeleton of Myotragus was found the last day of the excavation in the Sala del Col-lapse at a depth of 10 cm. It was located in a corner of this chamber in anatomical position.

Associated partial skeletons of two Myotragus juvenile specimens were found at the beginning of the Galeria del Tragus (Fig. 1 and 2 C). The mandibles of these skeletons display a dp4 completely erupted and m1 near starting the eruption.

Another complete articulated skeleton of Myotragus was found far away from the Galeria del Tragus, in the passages of the Sector F (Fig. 6 A, and 1 in Fig. 1 C). This skeleton is covered by flowstone, so the risk of breaking the bones during extraction was extremely high, precluding its excavation. Other Myotragus isolated bones, covered with flowstone were found in the biggest chamber of the cave known as Sala Que No Té Nom (Unnamed Hall).

In order to determine the taxonomic identity of the Myotragus remains retrieved from the cave, two main characteristics have been observed, both related with teeth morphology in adult individuals: first, number and shape of incisors, and second, relative size of the lower and upper premolars (mainly p2-3, P2-3). Although some skulls of Myotragus from
The number of incisors is a rough indicative of the approximate evolutionary stage of the genus. In this sense, the most recent species, *M. balearicus*, displayed a single evergrowing incisor in each hemimandible (Bate, 1909), while the Early-Late Pliocene species, *M. pepgonellae* had four (Moyà-Solà & Pons-Moyà, 1982). No complete mandible with incisors is available for the oldest *Myotragus* species from the Early Pliocene, *M. palomboi* (Bover et al., 2010a). Between *M. pepgonellae* and *M. balearicus*, the other taxa of *Myotragus* display a progressive reduction of the number of incisors, i.e. three in *M. antiquus* (after Pons-Moyà, 1977) and *M. kopperi* (Moyà-Solà & Pons-Moyà, 1981) and two in *M. batei*. Although the holotype of this latter species displays 3 incisors (Crusafont & Angel, 1966), in our view, it represents an incompletely grown specimen and it has been considered that the third small incisor (probably the dI₃, third deciduous incisor) would be lost later. This same phenomenon has been recorded in some individuals of *M. balearicus* from Late Pleistocene deposits, in which a small distal incisor (or its alveolus) is displayed in juvenile stages, being posteriorly lost in adult ages (see Bover & Alcover, 1999, and references therein).

CPV are available, mandibles are more suitable for taxonomical identification and the analysis has been based on this bone.

Fig. 7. Bat bones from CPV. A-C: Specimens of *Rhinolophus* aff. *mehelyi* embebed in flowstone. A: IMDEA 94692, remains of an individual, with a rib of a juvenile *Myotragus*; B: IMDEA 94693, incomplete specimen, with two jaws, a clavicle and several vertebrae; C: IMDEA 94694, skull; D: Other specimens of *Rhinolophus* aff. *mehelyi*. 1: IMDEA 94695 and 2: IMDEA 94696, skulls, dorsal and ventral views; 3: IMDEA 94697, skull, dorsal view; 4: IMDEA 94698, left jaw, labial view; radius, left humerus, posterior view; 5: IMDEA 94700, 6: IMDEA 94704, and 7: IMDEA 94705, left humer, posterior view; 8: IMDEA 94699, 9: IMDEA 94701, 10: IMDEA 94706, and 11: IMDEA 94707, right humer, posterior view; E: Specimens of *Pipistrellus* sp. 12: IMDEA 94715, right jaw, labial view; 13: IMDEA 94717 and 14: IMDEA 94718, radii; 15: IMDEA 94716 and 16: IMDEA 94719, humer, posterior view.
Although the shape of the incisors in the different *Myotragus* species can depend on the wear stage of these teeth, the most mesial incisor of the most recent species, *M. batei* and *M. balearicus*, is generally a highly hypsodont evergrowing incisor (i.e., with open root) and very wide mesio-distally. The root of this tooth can be proximally located beyond the diastema, under the premolar series, and can produce a strong deformation of the lingual part of the mandibular body. *M. pepgonellae*, *M. antiquus* and *M. kopperi* display hypsodont incisors, but in a lesser degree than the most recent species, with closed roots and they are not as wide mesiodistally. The basis of the root of the incisors is never located beyond the diastema in the available material of these species.

In the case of the mandibles of *Myotragus* obtained from CPV, all of them display three alveoli for incisors, and the mandibles of the partial skeleton from the Sala des Col·lapse display three incisors each (Fig. 8). Their morphology, especially in the medial incisor, resembles the one of *M. antiquus* and *M. kopperi*, i.e., not extremely hypsodont, and not wide mesiodistally, none of the incisors of the mandibles from CPV extends beyond the diastema, their roots are closed, and the distal incisor (or its alveolus) is greater than the *M. batei* distal incisor (the one that is posteriorly lost in adult stages).

All these observations limit the analysis of the attribution of the CPV *Myotragus* to the species *M. antiquus* or *M. kopperi*. In order to establish a more accurate taxonomy of the mandibles and teeth was performed.

As mentioned above, in the evolution of the *Myotragus* lineage a progressive reduction of size and number of premolars have been identified (Alcover et al., 1981). *M. palomboi*, as other caprines, displayed a slightly reduced p2 (Bover et al., 2010a), and although no other lower premolars for this species are available, it is reasonable to assume that displayed a dentition similar to other mainland caprines (i.e., fully developed premolars). *M. pepgonellae* already displayed an important reduction of the p2, although present (Moyà-Solà & Pons-Moyà, 1982), whereas in *M. antiquus* and *M. kopperi* this teeth is already lost (Pons-Moyà, 1977; Moyà-Solà & Pons-Moyà, 1981). In these two latter species, the p3 is gradually reduced (Fig. 9 and 10 C). *M. batei* displays an extremely reduced p3 (Crusafont & Angel, 1966), and in the more recent species *M. balearicus*, this tooth has completely disappeared (Bate, 1909).

The scatter plots of the proportions of p3 (Lp3/Wp3, Fig. 10 A) and the relative length of this tooth (Ltr/Lp3, Fig. 10 B) suggest that the development of this premolar in the *Myotragus* from CPV falls in the range of variability of *M. kopperi*, especially in the case of Lp3/Wp3. In the case of Ltr/Lp3, the two mandibles measured from CPV show a slightly more developed p3 than *M. kopperi*, but as it happens in this latter species, some individuals display particularly long p3. This characteristic can be observed both in the specimen of *M. kopperi* from Pedrera de s’Onix IMDEEA 57665 (Fig. 10 C.2), and in the *Myotragus* mandible from CPV IMDEEA 90462 (Fig. 10 C.3), in which the size of p3 is slightly longer than other specimens from the same taxa collected in the same deposits. Nevertheless, these differences could be related to a greater wear of this tooth observed in older individuals, as the p3 is slightly wider and longer in the base of the tooth than in the tip. For all these reasons, the *Myotragus* from CPV is here attributed to *M. aff. kopperi*.

### ANCIENT DNA

One sample from CPV (IMDEEA 91480, second upper molar) was used to test for potential contaminating DNA introduced during ancient DNA (aDNA) extraction protocols at the ACAD. The obtained material from CPV was preserved inside the cave from at least 2 My (see below) until the excavation in 2010, free of contamination from other introduced species in Mallorca, and with a putative chronology far beyond the theoretical survival of DNA in ancient samples (e.g., Willerslev & Cooper, 2005). Thus, the sample used was considered to be an adequate negative control for aDNA extractions of *Myotragus balearicus* bones.

The ACAD has a dedicated laboratory on aDNA geographically separated by around 1.5 km from PCR and post-PCR laboratories. The extraction method and PCR (Polymerase Chain Reaction) set up parameters have been published elsewhere (e.g., Austin et al., 2013; Brotherton et al., 2013). Briefly, 0.26 g of tooth powder were incubated overnight under constant rotation at 55°C in a lysis buffer of 0.5M EDTA, pH 8.0; 10% SDS; and 20mg/ml proteinase K. DNA
was extracted using a silica-based suspension and
and in-house binding buffer method (Brotherton
et al., 2013). Universal primers for mammalian
mitochondrial DNA 12S gene (Mamm 12S E Forward:
5’ CTATAATCGATAAAACCCGATA 3’ and Mammal 12S
H Reverse: 5’ GCTACACCTTGACCTAAC 3’, amplifying
a fragment of 96 bp, and Mammal 12S N Forward
5’ CAGCAAAACCTAAAAAGG 3’ and Mammal 12S H
Reverse, see above, amplifying a fragment of 34 bp).
These primers were successful in the amplification
of Myotragus balearicus DNA from Holocene samples
as well as contaminating DNA from species as cow
(Bos taurus), pig (Sus scrofa), sheep (Ovis aries), goat
(Capra hircus) and dog (Canis familiaris) in other M.
balearicus samples (pers. obs.).

Two microlitres of extract were used to amplify,
together with an extraction control and negative PCR
control, in a 25 μl PCR containing: 1 × Platinum
Taq High Fidelity Buffer (Invitrogen), 2 mM MgSO₄,
0.4 μM each primer, 0.25 mM each dNTP, 0.5 U
Platinum Taq HiFi (Invitrogen), 1 mg/ml RSA (Sigma-
Aldrich) and sterile H₂O. PCR cycling conditions were:
initial denaturation at 94ºC for 2 min; 50 cycles of
denaturation at 94ºC for 20 s; primer annealing at
55ºC for 15 s; elongation at 68ºC for 30 s; a final
elongation step at 68ºC for 10 min. PCR products
were visualized under UV light on a 3.5% agarose gel
posteriorly stained with Gel-Red (Jomar Bioscience).

As expected, the PCRs of the CPV sample failed,
confirming that the extraction protocol used with
the Myotragus samples did not introduce detectable
amounts of contaminating DNA. The possible sources
of DNA contamination detected in some samples
should be then related to other agents in the deposits
(e.g., soil, or other species living in the same cave,
etc.) or even to PCR reagents.

**Fig. 10. Scatter plot and comparison of Myotragus teeth. A: Scatter plot of width (Wp3) versus length of p3 (Lp3) (measurements taken at 1 cm
from the base of the tooth. Data for M. batei, M. kopperi and M. antiquus from Moyà-Solà & Pons-Moyà, 1981. Data for M. pepgonellae obtained
from Moyà-Solà & Pons-Moyà, 1982. Used specimens from CPV are IMEDEA 90451, 90454 and 103003; B: Scatter plot of length of p3 (Lp3)
versus length of tooth row (Ltr) (measurements taken at the base of the tooth). Used specimens from CPV are IMEDEA 90451, 90452 and 90454;
C: Labial view of Myotragus mandibles to compare the size of the p3 in the different species. 1: M. antiquus IMEDEA 59245, left, reversed; 2: M.
kopperi IMEDEA 57665, right; 3: CPV IMEDEA 90462, left, reversed; 4: M. kopperi IMEDEA 57325, right; 5: CPV IMEDEA 90454, left, reversed;
6: CPV IMEDEA 90451, right; 7: M. kopperi Holotype IMEDEA 57320, left, reversed; 8: M. batei Holotype, curated at MNIB-SHNB, right. Arrows
indicate the p3 tooth.**
The similarity of the mammalian taxa from CPV to the species recorded in the Pedrera de s’Onix deposit sheds some light to the chronology of the deposit and the geomorphic processes involved in the development of the cave. As explained above, Myotragus from CPV has a morphotype similar to M. kopperi, Hypnomys to H. onicensis and Nesiotites to N. aff. ponsi from Pedrera de s’Onix. Regarding the birds, although there are some differences between these two deposits, up to 14 of the 18 bird taxa identified in CPV were also recorded in the Pedrera de s’Onix deposit. In Mallorca, the amphibian genus Discoglossus has been only found in CPV and in Pedrera de s’Onix, and the size of the lizard Podarcis from CPV agrees with the size of the Podarcis remains obtained from Pedrera de s’Onix. Thus, it seems appropriate to consider CPV as a paleontological deposit from the Early Pleistocene, with a close chronology to Pedrera de s’Onix.

Paleomagnetic analyses carried out in a Malloran cave with a remarkable stratigraphical record, Cova de Canet, furnished a date of 2.6 My for the stratigraphical levels (level J) containing M. antiquus and 2.4 My for the level (level E) containing Myotragus sp. according to Pons-Moyà et al. (1979), but it was later identified as a morphotype slightly more primitive than the type of M. kopperi, and consequently considered M. aff. kopperi (Alcover et al., 1981). The ratio Ltr/Lp3 (Fig. 10.B) indicates that the CPV Myotragus would be similar to this M. aff. kopperi from Cova de Canet. This paleomagnetic data allow us to narrow the deposition period of the fossil material at around 2.4 My ago. In this sense, the absence of more modern species of Myotragus in the deposit suggests that the collapse of the original and natural entrance to the cave was a quick event and caused the total sealing of the Galeria del Tragus/Sala del Collapse in a moment later than 2.4 My ago, trapping both the bone remains and the living animals that eventually were inside the cave at that moment. The presence of an adult Myotragus articulated skeleton (Sala del Collapse), and other two associated juvenile skeletons (Galeria del Tragus), agrees with the hypothesis of an original open entrance close to the deposit, and seems to indicate a limited horizontal transport of the bones inside the cave. This observation agrees with the scenario shown by the stratigraphical analysis of the sediments in Galeria des Tragus (Fornós et al., 2010b). In general, the sediment sequence observed at the Galeria del Tragus of CPV is formed by sands and mud-silts that can be considered allochthonous (entrance facies). This characteristic seems to corroborate the existence of an ancient cave entrance through which sand deposits first, and then sediments infiltrated by surface runoff, entered the cave until the likely closing of it after the collapse of this former entry. The absence of clear lamination and flow structures in the sand deposits of aeolian origin suggest a ramp-type deposition favored by gravity. Nevertheless, the sub-horizontal location of these deposits some hundreds of meters along the gallery seems to indicate a deposition of the whole stratigraphic set in a low dynamic aquatic environment.

The finding of some skeletons and other remains of terrestrial mammals in sites located far from the putative former entrance could provide information about other currently closed entrances or fissures. The case of the skeletons of Hypnomys in Llac de na Gemma, Sector F, and Sector de Gregal (Fig. 6 B-D) could be explained both by the existence of former entrances or, more probably, small fissures nearby that could be used by this small mammal to entry the cave. More intriguing is the presence of Myotragus bones in the Sala Que No Te Nom and specially the case of the articulated skeleton in the upper maze (Fig. 6 A). In several Malloran caves, Myotragus individuals have been found far away from the current entrance on the cave, indicating that the species was going relatively deep into caves (e.g., Cova des Penyal Blanc; Alcover et al., 1997, or Cova Genovesa; Gràcia et al., 2003). But the important distance from the former entrance, located at the Sala del Collapse, and the location of those Myotragus, together with the labyrinthine galleries beyond the Galeria del Tragus, seems to indicate the presence of other entrances currently collapsed.

Although an important number of Malloran caves containing Pliocene and Quaternary fossils has been already recorded (Bover & Alcover, 2005), the presence of paleontological remains of Myotragus is relatively frequent in coastal caves below the current water-table, as the Cova Genovesa (Gràcia et al., 2003) or in air-filled passages, as CPV. In the case of deposits older than Middle Pleistocene, they are mainly hard breccias in fossil caves, and the state of preservation of the bones is usually poor. For this reason, the finding of the fossil material in CPV, with a chronology around 2.4 My, or even older, and in this exceptional preservation state, is outstanding. The material obtained is being currently studied (e.g., Jordana et al., 2013) and it will surely improve our understanding, in a near future, of several aspects of the taxonomy, evolution and morphology of the species found in CPV.

The geochronological data supplied by the paleontologic deposit from Galeria del Tragus is quite determinant regarding the minimum age of speleogenesis that could be postulated for CPV (Ginés et al., 2014). In this respect, the main cave-formation phases must correspond at least to mid-Pliocene times, with a later sea-controlled complex evolution happened along the whole Quaternary.

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entitled the second and third days of the excavation campaign to carry the excavated material to outside the cave. Thanks are due to all of them. Enric Alcover (Palma) and Carl Mehling (New York) were part of the excavation team, and they highly contributed to the success of the campaign. Bernat Font (Sant Llorenç, Mallorca) restored an important part of the collected material.

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Pons-Moyà J. & Moyà-Solà S., 1980 - Nuevo representante del género Nesiotites Bate, 1944; Nesiotites meloussae nov. sp. (Soricidae, Soricidae) de los rellenos cársticos del Barranc de Binigaus (Es Mercadal, Menorca). Endins, 7: 53-56.


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Groundwater geochemistry observations in littoral caves of Mallorca (western Mediterranean): implications for deposition of phreatic overgrowths on speleothems

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Abstract: Phreatic overgrowths on speleothems (POS) precipitate at the air-water interface in the littoral caves of Mallorca, Spain. Mainly composed of calcite, aragonite POS are also observed in specific locations. To characterize the geochemical environment of the brackish upper water column, water samples and salinity values were collected from water profiles (0-2.9 m) in April 2012 and March 2013 near aragonite POS in Cova des Pas de Vallgornera and calcite POS in Coves del Drac (hereafter, Vallgornera and Drac). Degassing of CO₂ from the water was evidenced by the existence of lower dissolved inorganic carbon (DIC) concentration and enriched δ¹³C_DIC values in a thin surface layer (the uppermost 0.4 m), which was observed in both profiles from Drac. This process is facilitated by the efficient exchange of cave air with the atmosphere, creating a CO₂ partial pressure (pCO₂) disparity between the cave water and air, resulting in the precipitation of calcite POS as CO₂ degasses from the water. The degassed upper layer was not observed in either profile from Vallgornera, suggesting that less efficient cave ventilation restricts outgassing of CO₂, which also results in accumulation of CO₂ in the cave atmosphere. The presence of an existing uncorroded POS horizon, as well as higher concentrations and large amplitude fluctuations of cave air pCO₂, may indicate that aragonite POS deposition is currently episodic in Vallgornera. Ion concentration data from monthly water samples collected in each cave between October 2012 and March 2013 indicate higher Mg:Ca, Sr:Ca, Ba:Ca and Sr:Mg ratios in Vallgornera. Salinity alone does not appear to be a viable proxy for ions that may promote aragonite precipitation or inhibit calcite precipitation. Instead, these ions may be contributed by more intense bedrock weathering or deep groundwater flow.

Keywords: subaqueous calcite and aragonite; stable isotopes; CO₂ degassing; Mg:Ca ratio; littoral karst; Balearic Islands


INTRODUCTION

A variety of carbonate speleothems are deposited as CO₂ degasses from a solution containing calcium and dissolved inorganic carbon, thus triggering supersaturation and deposition of CaCO₃ (Fairchild et al., 2006). Since the beginning of phreatic overgrowths on speleothem (POS) investigations in Mallorca, CO₂ degassing from the cave water has been documented to cause POS precipitation (Pomar et al., 1976, 1979; Csoma et al., 2006). This is in accordance with the greater understanding of the development of floating cave rafts and shelfstones, which form at the surface of cave pools by CO₂ degassing to the cave air (Hill & Forti, 1997).

POS are widespread in the littoral caves of Mallorca, where the level of the Mediterranean Sea controls the water table. POS are precipitated at the air-water interface in brackish water onto preexisting supports, including previously deposited vadose speleothems or cave walls. POS are ideal proxies for sea level changes, as they can be precisely and accurately dated using the U/Th method, and constrain former high or low sea level stands with sub-meter precision (Ginés &
Calcite is the dominant mineral in the POS precipitated during the Holocene [Marine Isotope Stage (MIS) 1], while the CaCO$_3$ polymorph aragonite is less common. A notable exception is Cova des Pas de Vallgornera (Vallgornera), where POS preserved at the present water level are aragonite. However, both calcite and aragonite POS corresponding to previous high- and lowstands are also documented in this cave, suggesting that the recent geochemical environment is different compared to time periods when calcite precipitated. In Coves del Drac (Drac), current POS are calcite, but aragonite is also identified in older encrustations. For comparative purposes, data from Drac are presented in this paper to contextualize observations from Vallgornera.

Collecting geochemical data and samples from profiles of the upper groundwater column allows an evaluation of interactions that take place at the air-water interface, where POS precipitate. Profiles are commonly used to understand stratified bodies of water in karst features, where the freshwater lens, halocline, and marine groundwater can be delineated, such as in cenotes and blue holes (Pohlman, 2011; Martin et al., 2012). Although the deepest accessible water body was selected at each site, neither location was deep enough to sample through the halocline. In contrast to the typical Ghyben-Herzberg coastal aquifer model, a distinct freshwater lens is absent in these caves. Instead, a transition zone between the fresh- and seawater endmembers is present with brackish water found in the upper column. Conductivity, temperature, and depth data collected by divers with handheld sensors indicate that there are multiple layers of increasing salinity with depth before the sharp transition to marine groundwater, commonly regarded as the halocline (Gràcia et al., 2011a, b). This study investigated the upper 2 m or more of water columns in Vallgornera and Drac (Fig. 1).

The goal of this paper is to explain the mineralogical differences observed in Mallorca’s POS, assessing the following hypotheses using monthly air and water samples and water column profiles at each site:

1. In general, precipitation of carbonate POS is controlled by CO$_2$ degassing at the air/water interface. Without a sufficient difference between the partial pressure of CO$_2$ ($p$CO$_2$) of the water and air, precipitation will not occur. The rate of degassing is determined by the magnitude of the disparity between the $p$CO$_2$ of the cave water and cave atmosphere.
2. In Mallorca’s brackish cave waters, dense aragonite crystals making up the POS precipitate under low rates of CO₂ degassing, whereas porous and/or dendritic calcite POS are deposited when CO₂ outgases at faster rates as documented elsewhere by other studies (Frisia et al., 2000, 2002; Niedermayr et al., 2013).

3. Precipitation of aragonite is controlled by higher Sr:Ca, Mg:Ca, and/or Ba:Ca ratios, which inhibit calcite precipitation (Bernier, 1975; McMillan et al., 2005; De Choudens-Sánchez & González, 2009; Niedermayr et al., 2013). In the studied caves, these inhibitors may derive from seawater, bedrock, or deep groundwater flow.

4. Field observations suggest changes in salinity affect the kinetics of carbonate-solutions interactions, influencing the mineralogy of the carbonate phase (Folk, 1974; Zhong & Mucci, 1989). In the two investigated caves, salinity alone is not a suitable proxy for the mineralogy of carbonate encrustations or the rate of calcite and aragonite precipitation.

**STUDY AREA**

Located in the western Mediterranean Sea, Mallorca is the largest island of the Balearic Archipelago. The climate is typical of the western Mediterranean, with hot, dry summers, and mild winters. The average annual temperature is 16.6°C, and rainfall on Mallorca is highly variable, ranging from 300 to 1,400 mm (Gujarro, 1995). Most of its littoral caves are located along the south and east coasts in Upper Miocene reef limestones (Ginés et al., 2014). Here, at the mixing zone between fresh and marine groundwater, cave passages host water with a range of salinities.

Vallgornera is on Mallorca’s southern coast (Fig. 1), and is the longest known cave on the island with more than 74 km of mapped passage (Merino et al., 2014). The area above the cave includes a vacant hotel, residential buildings, and undeveloped land. The only known entrance to Vallgornera was opened in 1968 when excavation for the hotel septic system intersected a large chamber. As part of its Natura 2000 status, access to Vallgornera is only granted for scientific or exploration purposes. Since cavers traveling deeper into the cave avoid the study location, only minor effects of human visitation are expected.

Drac is located on the eastern coast (Fig. 1) near the village of Porto Cristo. Displaying typical mixing zone characteristics (Ginés & Ginés, 2007), the mapped vadose extent of Drac is 2,359 m, with an additional 600 m of submerged passages accessed by cave divers (Gràcia et al., 2007, 2011b). The cave was first opened for tourism around 1898 (Ginés & Ginés, 2011), and is currently the most visited cave in Europe (Robledo & Durán, 2010). The area above the cave is developed with cafés, shops, parking lots, and other infrastructure to support the local tourism industry. Tourists enter the cave through an artificial entrance, walking through well-decorated cave passages until they arrive at a large chamber where they sit for a 30-minute classical music concert performed from boats that navigate upon the underground Lake Martel. Tourists exit the cave through the natural collapse entrance. The tourist infrastructure has likely modified the cave environment in terms of ventilation, temperature, atmospheric gas concentration, and the introduction of non-native materials. However, the study area and the tourist route are on separate branches of the cave, so less touristic impacts are expected at the monitored site. The study area is located along a historic tour route that is at present exclusively accessed for scientific purposes. Calcite rafts are typically observed on the water surface at the study site. Active bat populations and guano deposits are present near the study area.

**METHODS**

Geochemical data and samples were collected from profiles in Vallgornera and Drac in April 2012 and March 2013 as scheduled fieldwork permitted. The deepest accessible body of water was selected in each cave, and the profiles were collected at the same location during the return visit. Profiles ranged to a maximum depth of 2.9 m; the extent of each profile was limited by the water level, which fluctuates within the tidal range of ±25 cm and is influenced by atmospheric pressure and wind stress (Gómez-Pujol et al., 2007). Salinity was assessed using a HI 9828 Multiparameter Meter (Hanna Instruments) and is presented in Practical Salinity Units (PSU; Millero et al., 2008) with manufacturer-specified accuracy of ±2% and precision of 0.01 PSU.

During the April 2012 site visits, water samples (analyses discussed below) were collected through disposable low-density polyethylene (LDPE) tubing attached to a hand pump. The March 2013 water samples were collected using a 1-liter capacity LaMotte Water Sampler that was simultaneously lowered with the HI 9828 probe. Samples were taken at 0.5 m intervals starting at the surface after the salinity reading was stabilized and recorded. In the April 2012 Drac profile the second sample was recovered at 0.4 m, and subsequent samples were obtained at 0.5 m intervals. Samples were refrigerated at 4°C until analysis.

Monthly cave air temperature and pCO₂ data is presented between October 2012 and March 2013. Values for both parameters were extracted from long-term monitoring records using CO2meter.com K33-ELG (accuracy ±0.4°C and ±30 ppm; precision ±0.1°C and ±20 ppm). Because relative humidity at each site approached 100% and the sensor operating range only extends to 95%, the instruments were placed upon Zorb-It desiccant packages within a plastic box with holes drilled in the sides. Non-dispersive infrared (NDIR) sensors measured CO₂ concentration and data were corrected using in-cave barometric pressure measurements to calculate pCO₂ according to Spötl et al. (2005). Cave barometric pressure was recorded using In-Situ Inc. BaroTROLL data loggers and is reported in hPa (accuracy ±1.5 hPa; precision ±0.075 hPa).
Monthly surface water physical parameters (pH, temperature, and salinity) were measured between October 2012 and March 2013 using the HI 9828 probe (accuracy ±0.02 pH, ±0.15°C, and ±2%; precision ±0.01 pH, ±0.01°C, and 0.01 PSU). A water sample was stored at 4°C and analyzed within 6 hours of collection for total alkalinity, sulfate, and total hardness. Total alkalinity was assessed using a Hach digital titrator (method 8230). Sulfate and total hardness were measured using an Orbeco-Hellige portable colorimeter (model 975MP). The saturation indices (SI) of calcite and aragonite and water $p$CO$_2$ were computed using CO2calc version 1.2 (Robbins et al., 2010) and input parameters of water salinity, temperature, total alkalinity, and air $p$CO$_2$.

Additionally, monthly water samples were collected into pre-cleaned 250 mL Nalgene containers with no headspace and stored at 4°C until analysis for Ca, Mg, Sr, and Ba concentrations. Analyses were completed at the University of South Florida School of Geosciences (USF-SG) Center for Geochemical Analysis using a Perkin-Elmer ELAN DRC II Quadrupole Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Percent error was determined based on replicate analysis of standard reference material NIST 1640a-1 throughout the run and varies by element. Ca and Mg are reported in ppm, whereas Sr and Ba are reported in ppb.

Stable isotope measurements are expressed in standard δ (delta)-notation:

\[
\delta \text{(ln)} = \left( \frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right) \times 1,000
\]

where $R_{\text{sample}}$ and $R_{\text{standard}}$ represent the measured $^{18}$O/$^{16}$O or $^{13}$C/$^{12}$C ratios in the sample and the standard, respectively. Isotopic and dissolved inorganic carbon (DIC) concentration analyses were conducted at the USF-SG Stable Isotope Lab using a Thermo Delta V 3 keV Isotope Ratio Mass Spectrometer (IRMS) equipped with a Thermo Gasbench II device and autosampler. Water samples for δ$^{18}$O measurements were collected in pre-cleaned 250 mL Nalgene containers with no headspace, whereas those for δ$^{13}$C$_{DIC}$ and [DIC] were collected according to the methods of Révész & Doctor (2014) using 5 mg copper sulfate as a bactericide. For each δ$^{18}$O analysis, 200 μL of sample was pipetted into a 12 mL vial. Samples were flushed with a mixture of 3% CO$_2$ in He and then stored at 20°C for 24 hours to promote complete $^{18}$O equilibration between CO$_2$ in the vial headspace and the sample water. Equilibrated CO$_2$$_{eq}$ was then analyzed on the IRMS; δ$^{18}$O values are reported with 0.1‰ precision relative to the V-SMOW scale.

To determine the δ$^{13}$C$_{DIC}$ of each sample, 1 mL of sample was injected into 12 mL vials that contained 1 mL of 85% phosphoric acid and were flushed with He$_{eq}$. The acidified sample was allowed to equilibrate at 25°C for 24 hours. The isotopic composition of CO$_2$ produced from the reaction of DIC and phosphoric acid was analyzed on the IRMS and δ$^{13}$C$_{DIC}$ values are reported with 0.1‰ precision relative to the V-PDB standard. Internal [DIC] standards were created using a range of weights of sodium bicarbonate (0.025 mg to 1 mg) in 12 mL vials, which were then flushed with He$_{eq}$. One mL of DIC-free water was then injected into each vial, followed by 1 mL of 85% phosphoric acid. The concentration standards were allowed to react at 25°C for 24 hours, and [DIC] of water was analyzed simultaneously with δ$^{13}$C$_{DIC}$. The April 2012 [DIC] results are reported in μmol/kg. The March 2013 [DIC] data are omitted as the samples were compromised.

### RESULTS

#### Salinity

Salinity increases with depth in both caves (Fig. 2, Table 1). Overall, salinity is higher in Drac than Vallgornera (Table 2). In both caves, the April 2012 profile displays higher salinity than the March 2013 profile at every comparable depth with the exception of the surface value. These trends are evident despite the more restricted salinity range of the Vallgornera March 2013 profile due to lower water level in the cave compared to the April 2012 sampling.

<table>
<thead>
<tr>
<th>Cave</th>
<th>Depth (m)</th>
<th>Salinity (PSU)</th>
<th>δ$^{18}$O (‰, V-SMOW)</th>
<th>δ$^{13}$C$_{DIC}$ (‰, VPDB)</th>
<th>[DIC] (μmol/kg)</th>
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<tr>
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<tr>
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</tr>
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</table>
Due to differences in the salinity gradient, the profiles in Vallgornera display a concave shape, with greater increases in salinity with depth (Fig. 2A). The shape of the Drac profiles opposes that of Vallgornera, with a convex shape created by the greatest increases in salinity at shallower depths (Fig. 2B).

### Oxygen isotopic composition

$\delta^{18}O$ values increased with depth in both caves, and were lower in Vallgornera samples than those from Drac at comparable depths (Fig. 3, Table 1). In both Vallgornera profiles, the $\delta^{18}O$-depth gradient is disrupted by a distinct shift toward lower values at 2 m (Fig. 3A). The March 2013 $\delta^{18}O$ profile from both caves is offset toward higher values; in Vallgornera, this offset ranges between 0.1 and 0.4‰, while it is larger in Drac (between 0.4 and 0.7‰).

### Carbon isotopic composition (DIC)

Though limited by the 2.5 m depth of the pool, it appears that there is a trend toward higher $\delta^{13}C_{\text{DIC}}$ values with depth in the April 2012 Vallgornera profile (Fig. 4A, Table 1). $\delta^{13}C_{\text{DIC}}$ values of the March 2013 profile increase with depth and display less variance than the April 2012 profile.

A distinct shape is observed in both Drac profiles, where surface $\delta^{13}C_{\text{DIC}}$ values are positively offset, with no evident trend observed between 0.5 m and the bottom of either profile (Fig. 4B). The surface offset (calculated by subtracting the surface value from the average of the deeper values) was 2.7 and 1.4‰ in the April 2012 and March 2013 profiles, respectively.

### DIC concentration

The April 2012 Vallgornera [DIC] generally decreased with depth, though variation is evident throughout the profile (Fig. 5, Table 1). Overall, [DIC] values vary by 3,180.7 μmol/kg in Drac, over three times the range observed in Vallgornera (940.9 μmol/kg). This is due largely to the 2,772.7 μmol/kg offset of the surface value from deeper values, which are higher in concentration.

The plot of $\delta^{13}C_{\text{DIC}}$ and [DIC] shows that the Vallgornera samples group distinctly with lower [DIC] and more positive $\delta^{13}C_{\text{DIC}}$ than Drac (Fig. 6). A notable exception is the surface value from Drac, the most positive value of the dataset, which does not group with the deeper water samples from that cave.

### $pCO_2$ in cave air and water

For each sample obtained, air $pCO_2$ is higher in Vallgornera (typically two times) than in Drac (Fig. 7A, Table 2). Over the short time period investigated, a distinct trend (part of a seasonal signal, as discussed in a forthcoming paper) is evident in both caves, with the highest values observed in October 2012 and decreasing throughout the monitoring period.

Water $pCO_2$ generally displays the same decreasing trend as air $pCO_2$ throughout the monitoring period (Table 2). Water $pCO_2$ is always greater than air $pCO_2$, which implies that a variable disparity between the water and the cave atmosphere is maintained over the monitoring period in both caves. The cave air $pCO_2$ was subtracted from the surface water $pCO_2$ for each corresponding month.
to obtain the $\text{CO}_2^-$ (aq-atm) difference (Fig. 7B). While there is no consistent trend over the monitoring period, samples for Drac display a higher $\text{CO}_2^-$ (aq-atm) disparity between the water and air, compared to Vallgornera, which is generally lower.

**Saturation state of cave water**

Water samples collected during monthly site visits suggest that groundwater in both caves is typically below saturation with respect to both calcite and aragonite (Table 2). Only one SI$_\text{Calcite}$ value from Vallgornera and two from Drac indicate that the water was supersaturated with respect to calcite (Fig. 8A). All samples for which SI$_\text{Aragonite}$ was calculated are undersaturated (Fig. 8B).

**Elemental ratios in cave water**

Concentrations of Mg, Sr, and Ba are higher in Drac than in Vallgornera for every monthly sample except for October 2012. Ca and Mg have percent errors of 1.4 and 2.6%, respectively, whereas Sr and Ba are much higher (5.7 and 5.3%, respectively; Table 3). However, when considering Mg:Ca, Sr:Ca, Ba:Ca, and Sr:Mg ratios, these are consistently higher in Vallgornera than Drac (Fig. 9A-D).

**DISCUSSION**

Percolating meteoric water mixes with the marine groundwater flooding the cave passages to create a brackish solution, which is confirmed by both salinity and $\delta^{18}$O values (Table 1). The salinity of infiltrating meteoric water is close to zero, and the amount-weighted annual average $\delta^{18}$O of precipitation in Palma de Mallorca is $-5.6\%$ (Araguas-Araguas & Diaz Teijeiro, 2005), while the salinity of Mediterranean seawater is approximately 37 PSU and its $\delta^{18}$O is 1.5-1.6% in samples along Mallorca’s coast. Indeed, the lowest salinity and most negative $\delta^{18}$O values were detected at the water surface in each cave, which documents the increasing influence of seawater with depth, despite the fact that the nature of the connection to the Mediterranean Sea (matrix or conduit flow) is not known at either site.

Though a traditional Ghyben-Herzberg freshwater lens and complete halocline are absent in the investigated upper water column in both caves, the surface layer in Vallgornera is homogenous due to continuous flushing of seawater that mixes with percolating meteoric water (Fig. 2a). Further, it seems that water level fluctuations prevent the development of the connection to the Mediterranean Sea (matrix or conduit flow) is not known at either site.

**Table 2. Monthly water and air sample geochemical parameters.** $p\text{CO}_2$, SI$_\text{Calcite}$, and SI$_\text{Aragonite}$ were calculated using $\text{CO}_2$calc.

<table>
<thead>
<tr>
<th>Date</th>
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<th>Temp (°C)</th>
<th>Salinity (PSU)</th>
<th>Total Alkalinity (mg/L)</th>
<th>Total Sulfate (mg/L)</th>
<th>Total Hardness (mg/L)</th>
<th>Cave Baro Pres (hPa)</th>
<th>$p\text{CO}_2$ Air (ppm)</th>
<th>$p\text{CO}_2$ Water (ppm)</th>
<th>SI$_\text{Calcite}$</th>
<th>SI$_\text{Aragonite}$</th>
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<tbody>
<tr>
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<td>19.92</td>
<td>6.1</td>
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<td>490</td>
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<td>-0.32</td>
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Groundwater geochemistry observations in littoral caves of Mallorca

cave atmosphere. The dataset presented in this study suggests that the cave water acts as a CO$_2$ source in both caves, as evidenced by a positive CO$_2$ (aq-atm) disparity (Fig. 7B). Isotopic fractionation occurs during degassing, thus enriching the surface of the water column in $^{13}$CO$_2$ (aq) (Vogel et al., 1970). The $\delta^{13}$C$_{DIC}$ data indicate that surface water with relatively high $\delta^{13}$C values (~8.5 and ~9.3‰) was less than 0.4 m thick in Drac (Fig. 4B). The [DIC] profile measured in April 2012 also shows that the uppermost layer in Drac was degassed, with a significantly lower [DIC] than deeper in the water column.

The $p$CO$_2$ data for both Vallgornera and Drac show large fluctuations that result from ventilation during the winter months (Fig. 7A). In samples collected from October 2012 through March 2013, the highest values were recorded in October 2012, likely reflecting the end of the growing season and the peak of soil microbe respiration. Cooler and denser external air replaced cave air during the following months, increasing the rate of ventilation, and likely causing decreases in cave atmosphere $p$CO$_2$ at both sites. The general value of cave air $p$CO$_2$ is controlled by the efficiency of ventilation: more efficient ventilation in Drac, due to its configuration and two entrances, causes lower overall values than those recorded in Vallgornera, a single, nearly sealed entrance cave.

Though believed to be unidirectional, the observed amount of CO$_2$ degassing is not strong enough to of a true freshwater lens at both sites as suggested by Mylroie and Vacher (1999) in other carbonate island caves, but do not preclude the stratification of brackish water in Vallgornera.

In both caves, samples in the March 2013 $\delta^{18}$O profile are overall more positive compared to those of April 2012, while still trending toward higher values with depth. Combined, the isotope and salinity gradients indicate a decrease of meteoric water influence with depth, suggesting that the offset (and its magnitude) between the two profiles (Figs. 2 and 3) may be controlled by temporal variations of different hydrologic regimes (matrix vs. fracture flow, precipitation/infiltration amount).

Water bodies present within caves may act as both sources and sinks for CO$_2$. The direction of CO$_2$ diffusion depends on the magnitude of the CO$_2$ (aq-atm) disparity and is site- and condition-specific. Baldini et al. (2006) report an example where cave water (a sump) acts as a CO$_2$ sink. Palmer (2007) also discusses examples where CO$_2$ is consumed by aqueous reactions during the dissolution of limestone. Conversely, CO$_2$ respired by microbial consumption of organic matter within the water column (Pohlman, 2011) or by inorganic precipitation of CaCO$_3$ at the air-water interface (Walvoord et al., 2005) may degas to the

Table 3. Monthly water sample elemental values. Percent error is reported for each element based on replicate analysis of standard reference material NIST 1640a-1.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mg (ppm)</th>
<th>Ca (ppm)</th>
<th>Sr (ppb)</th>
<th>Ba (ppb)</th>
</tr>
</thead>
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<td>Vallgornera</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/10/12</td>
<td>232</td>
<td>194</td>
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<td>196</td>
<td>169</td>
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<td>3/12/13</td>
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<td>1,590</td>
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<tr>
<td>Drac</td>
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<td>10/9/12</td>
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<td>278</td>
<td>2,123</td>
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</tr>
<tr>
<td>Error</td>
<td>1.4%</td>
<td>2.6%</td>
<td>5.7%</td>
<td>5.3%</td>
</tr>
</tbody>
</table>

Fig. 8. Calculated SI for calcite (A) and aragonite (B) using CO2calc.

Fig. 9. Element ratios for the monthly surface water samples collected between October 2012 and March 2013; Mg:Ca (A), Sr:Ca (B), Ba:Ca (C), and Sr:Mg (D) are consistently higher in Vallgornera than Drac.
cause extended periods of supersaturation with respect to carbonate minerals. Carbonate rafts, which precipitate as CO$_3^-$ degasses at the water/air interface, are ephemeral in Drac and are rarely observed in Vallgornera. Positive SI$_{calc}$, was only observed in one sample in Vallgornera and two in Drac, implying that over the observation period, the supersaturation state was not continuous.

Aragonite is believed to precipitate from supersaturated water under lower rates of CO$_2$ degassing, whereas porous calcite precipitates under faster conditions (Frisia et al., 2000; 2002; Niedermayer et al., 2013). These conditions match the relatively effective and more efficient ventilation patterns of Vallgornera and Drac, respectively. However, the limited occurrence of observed carbonate supersaturation in Drac and Vallgornera suggests that POS precipitation is presently inactive. For example, some studies suggest that a supersaturation threshold exists, below which nucleation of calcite crystals do not occur (Chafetz et al., 1991 and references therein). It may be possible that although supersaturation may have been occasionally reached in these sites, concentrations never exceeded the threshold required for nucleation.

U/Th dates of an aragonite POS from Vallgornera indicate that its deposition ceased about 600 years ago (Tuccimei et al., 2009, 2010), though this date may reflect a maximum age because the sample was not taken from the outermost layer of the POS. As evidenced by abundant encrustation at the current water level, both investigated sites contain POS precipitated some time during the present sea level stand. However, the geochemical data reported in this study documents conditions generally not conducive to POS precipitation. This is further confirmed by a lack of measurable, permanent carbonate encrustations over artificial supports that were installed in May 2011. Yet, the current POS horizon does not display signs of corrosion, which suggests that while POS precipitation may be episodic (currently halted), the surface water is certainly not sufficiently undersaturated with respect to CaCO$_3$ to corrode the existing POS.

While the data presented in this paper indicates that POS are not currently precipitating in either cave, the ion ratios observed in water samples align with established literature on the precipitation of aragonite instead of calcite. In vadose speleothems, the presence of the magnesium ion is the main control on the precipitation of aragonite (Thrailkill, 1971; Cabrol & Coudray, 1982; McMillan et al., 2005; Frisia & Borsato, 2010); this is commonly expressed as the ratio of Mg:Ca. Indeed, water samples from Vallgornera have an average Mg:Ca ratio of 1.17 while those from Drac averaged 1.02 (Fig. 9). Data aligns with experimental and field studies that reveal aragonite precipitation when Mg:Ca ratios are between 0.5 to over 4 (Fischbeck & Müller, 1971; Frisia et al., 2002; De Choudens-Sánchez & González, 2009; Niedermayr et al., 2013). While each study finds different Mg:Ca values within this range, it is likely that the precipitation of carbonate polymorphs depends not only on this ratio, but on a suite of other factors (acting alone or in combination) including trace elements, temperature, pCO$_2$, pH, salinity, Mg$^{2+}$ and Sr$^{2+}$ partition coefficients, mineralogy of the seed material, and activity of microorganisms (Ferrer et al., 1988; Zhong & Mucci, 1989; Hill & Forti, 1997 and references therein). To that end, the greater Sr:Ca, Ba:Ca, and Sr: Mg ratios observed in this study suggest that higher relative abundances of Sr$^{2+}$ and Ba$^{2+}$ may also encourage aragonite precipitation and/or inhibit calcite precipitation (Lippmann, 1973; Terakado & Taniguchi, 2006; Sunagawa et al., 2007).

Though seawater may contribute Mg, Sr, and Ba to the brackish water bodies in the two caves, the results of this indicate that salinity alone is not a suitable proxy for the presence of this suite of ions as suggested by Folk (1974). Consequently, interpreting the influence of salinity (only) on the mineralogy of carbonate encrustations is not straightforward. The occurrence of aragonite in Vallgornera, where lower salinity values were measured, may be triggered by the above-mentioned ions deriving from more intense bedrock weathering or a deep-water source that contains these ions. Alternatively, low salinity conditions caused by variations in the sulfate content may increase the Mg$^{2+}$ partition coefficient in calcite, enhancing aragonite precipitation (Mucci & Morse, 1983). However, because the solution is currently undersaturated, POS precipitation was not observed.

**CONCLUSION**

Unidirectional, though variable magnitude, CO$_2$ degassing from the water to cave atmospheres was observed in this study, with CO$_2$$_{aq-atm}$ disparities ranging from 525 to 3,397 ppm. These findings are consistent with the conclusions of previous petrographic investigations of POS and other speleothems that the major control on carbonate deposition is the ability of CO$_2$ to degas across the air-water interface (Pomar et al., 1976; Csoma et al., 2006).

The limited occurrences of aragonite POS in Mallorca indicate that specific conditions control its precipitation over calcite. In Vallgornera, aragonite POS are observed at the current sea level, whereas both calcite and aragonite are present in horizons precipitated at former lower or higher sea stands. Thus, although the micro-geochemical environment may be different in Vallgornera at present, allowing the precipitation of aragonite instead of calcite, results indicate that this process is currently episodic or halted. It is possible that slower/episodic CO$_2$ degassing because of less efficient cave ventilation allows precipitation of dense aragonite in Vallgornera as compared to other caves on Mallorca. Alternatively, in caves that have more efficient exchange of air with the atmosphere, CO$_2$ degassing is constant and faster, resulting in the growth of more porous calcite POS, like those observed in Drac (Ginés et al., 2012).

Several studies document that Mg, Sr, and Ba, contributed from seawater, inhibit precipitation of calcite or enhance precipitation of aragonite. Therefore, it may be appropriate to assume that salinity (via activity
coefficients) may be considered an adequate proxy for the relative abundance of these various ions. Furthermore, numerous field studies relating to beachrock cement and ooids suggest that salinity variations may control the mineralogy of the carbonate precipitates. The work of Zhong & Mucci (1989), however, refutes this hypothesis, concluding that the partition coefficient of Mg\(^{2+}\) in calcite increases with decreasing salinity of the parent solution. Increasing presence of Mg\(^{2+}\) is thought to poison calcite crystal growth, allowing aragonite to precipitate. This study of two caves in Mallorca aligns with the findings of Zhong & Mucci’s (1989) showing aragonite POS observed in a lower-salinity environment. The ions have higher relative abundances in Vallgornera than Drac, and may be contributed by higher/more intense bedrock weathering or deep groundwater flow; further work is required to shed light over the entire aragonite/calcite precipitation process within the particular Mallorcan cave environment.

ACKNOWLEDGEMENTS

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http://dx.doi.org/10.1029/2004WR003599

http://dx.doi.org/10.1016/0009-2541(89)90064-8
INTRODUCTION

The presence of carbonates in the deposits that make up the island of Mallorca, the largest of the Balearic Archipelago, have been subjected to long-term karstification processes that have generated a well-known variety of specific landforms and caves (Fornós et al., 2002; Gràcia et al., 2011). Apart from these, a wide range of intermingled karst and littoral processes were reported in the coastal karst areas of the island (Ginés & Ginés, 1986), an environment that is affected by changes in sea level and the subsequent shifts of the shoreline, introducing a chronological pattern that is directly controlled by the Pleistocene fluctuations of both climate and sea elevation (Tuccimei et al., 2006; Dorale et al, 2010; Ginés et al., 2012).

The deposition of speleothems is an active process happening in most karst regions around the world (Fairchild & Baker, 2012). In Mallorca, a great variety of speleothems are common occurrences within the different cave environments of the island, especially in the littoral caves. Although there is an abundant bibliography covering this topic (Merino et al., 2011a, 2011b, 2014a, 2014b) and considering the widely accepted issue that microorganisms, mainly bacteria, may contribute to the precipitation of carbonates and other minerals (Ehrlich, 2002; Melim et al., 2009; Jones, 2010), it is quite surprising that this topic is so little covered in the Mallorcan karst literature.

There are many interesting research topics related with geomicrobiological studies. One of them is the active role of microorganisms in carbonate precipitation in speleothems (Barton & Northup, 2007).
Sampling and analysis of the bacterial populations along the cave (Fig. 1), starting from the artificial entrance to the innermost part of the pools, allowed the assessment of the bacterial distribution. We analyzed by culture-dependent methods the diversity of bacterial species present in this habitat and we tested the ability of the isolated strains to form carbonate precipitates, and their mineralogical characteristics. Bacterial strains were isolated on R2A medium designed for oligotrophic bacteria and were identified by whole-cell protein profiles obtained by MALDI-TOF mass spectrometry and by molecular phylogenetic analysis of the 16S rRNA gene sequences.

A secondary purpose of the study was the description of the bacterial communities associated with the ferromanganese deposits (FMD) present in several parts of the cave showing uncommon mineral assemblages (Merino et al., 2009; Onac et al., 2014). These colorful deposits are likely related with ancient hypogenic episodes that have taken place during the cave speleogenesis (Fornós et al., 2011), and geochemical and microbiological studies suggest a biogenic origin as a result of redox reactions (Northup et al., 2001, 2003).

Study site: cave location and description

The Cova des Pas de Vallgornera lies in the Llucmajor municipality (located in southern Mallorca – Fig. 1) in the area known as “es Pas”, less than 500 m from the coastline, on a structural carbonate platform
Microbial communities in a Mallorcan coastal cave

In November 2011 a total of 3 water samples (Table 1) were obtained aseptically into a sterile tube at 0.2 m depth in 3 different brackish pools located more or less in an equidistant position from the entrance of the cave (Platja dels Fòssils) to the farthest area (between Galeria del Tragus and Galeria de les Columnes) in a north-east direction (Figs. 1 and 2). Water samples were labeled A1, A2, and A3. Two samples of the multicolored Fe-Mn rich deposits were also aseptically sampled by scraping the precipitate with a sterile scalpel into a sterile tube. Rock samples were labeled R1 and R2 (Table 1). Both types of samples were duplicated.

The samples of water and surface crust multicolored deposits (Fig. 3) were collected aseptically in sterile tubes and kept at 4°C, until microbiological analysis in less than 24 hours. The locations of the sampling sites are shown in Fig. 1.

Physical and chemical parameters of the water

Temperature, conductivity, pH, redox and dissolved oxygen saturation of the water in the ponds were determined at monthly intervals using a recently calibrated Hanna Instruments 9828 Multiparameter Meter that was slowly lowered through the water. Total organic carbon (TOC) was measured as described by Barrón & Durate (2009) with a TOC analyzer (Shimadzu TOC-5000A) in water samples taken at sampling point A1, assumed to be representative of the water body.

MATERIALS AND METHODS

Sampling

The sampling strategy was as follows: samples were collected from the water table starting near the artificial entrance up to the inner and less accessible part of the cave, trying to avoid external contaminations, and on the multicolored FMD related with the presence of hypogenic features.

The cave corresponds to a subterranean complex formed by a series of breakdown chambers which are interconnected with each other by a network of passages roughly situated at two different elevations, lying around 7 to 11 m above the present mean sea level, and close to the current water table level to underwater, and with a plan development more or less parallel among them (Merino et al., 2014a). Part of the cave shows a labyrinthine pattern, but a series of rectilinear main passages that are structurally controlled are clearly recognizable, running relatively parallel from SW to NE. The distribution of linear passages, breakdown chambers, and maze galleries is associated with the characteristic rock textures related with the reefal Miocene sub-environments (Ginés et al., 2009a; 2014).

The cave shows a wide variety of speleothems, the presence of deposits with uncommon mineralogies, as well as outstanding and unique solutional features which evidence a very complex speleogenetic setting (Ginés et al., 2009b; 2014). Several speleogenetic processes are involved in their sculpturing. Apart from the classical karst processes with a noticeable meteoric water recharge, the morphological frame of the cave illustrates the typical coastal karstification and a possible deep recharge of hypogenic character. Features consisting of upwards solutional channels are abundant, including a complete morphologic suite of rising flow supporting the involvement of hypogene speleogenetic processes (Ginés et al., 2009b; Merino et al., 2009; Fornós et al., 2011). Both processes take place in a coastal karst setting (Lace & Mylroie, 2013) where the mixing of marine and fresh waters leads to the presence of brackish water pools (Fig. 2), whose surfaces rise or fall with tidal (barometric) fluctuations of sea level. In this sense, the littoral mixing dissolution processes represent the most important speleogenetic mechanism to be considered in this eogenetic karst environment. The presence of copious cave rims and crusts developed along the floor, where vent features are clearly visible, shed light on the variety of minerals developed on these particular morphologies, apart from the ubiquitous carbonate minerals and the unexpected non carbonate minerals also identified (Merino et al., 2009; Onac et al., 2014).

Fig. 2. Gran Canyó passage where some of the water samples were collected (A2). The brackish water table clearly covers part of the gallery (Photo: Antoni Merino).
Table 1. Sampling sites location (Fig. 1) and characteristics.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location within the cave</th>
<th>Type</th>
<th>Location/depth</th>
<th>Distance from artificial entrance</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Platja dels Fossils</td>
<td>water</td>
<td>Pool surface</td>
<td>83 m</td>
</tr>
<tr>
<td>A2</td>
<td>Gran Canyó</td>
<td>water</td>
<td>Pool surface</td>
<td>875 m</td>
</tr>
<tr>
<td>A3</td>
<td>Between Galeria del Tragus and Galeria de les Columnues</td>
<td>water</td>
<td>Pool surface</td>
<td>1500 m</td>
</tr>
<tr>
<td>R1</td>
<td>Tragus survey station 840-841</td>
<td>Multicolored deposits</td>
<td>Rock wall (roof surface above vent)</td>
<td>1083 m</td>
</tr>
<tr>
<td>R2</td>
<td>Galeria de les Columnues</td>
<td>Multicolored deposits</td>
<td>Rock surface (Fig. 3)</td>
<td>1333 m</td>
</tr>
</tbody>
</table>

**Whole cell matrix-assisted linear desorption/ionization-time-of-flight mass spectrometry (WC-MALDI-TOF MS)**

WC-MALDI-TOF MS is a precise and rapid method used in microbial ecology for the analysis of a large set of colonies. The principle is the total cell protein profiling of the colonies and the groupings of the profiles in clusters of colonies of the same species. Details are given in Welker & Moore (2011). A small amount (5-10 mg) of material was taken from freshly grown colonies and transferred with a loop into a 1.5 ml Eppendorf tube. Three-hundred microliters of MilliQ sterilized water were added, mixed by pipetting and subsequently 900 µl of absolute ethanol was added and mixed. The Eppendorf tubes were centrifuged at 16,000 x g for 2 min and the supernatant removed. After this, 50 µl of formic acid (70%) was added and mixed by pipetting. Acetonitrile (50 µl) was added and mixed. The tubes were centrifuged at 16,000 x g for 2 min and the supernatant transferred to another tube. One microliter of the supernatant was placed on to a spot of a ground steel plate and air dried at room temperature. Each sample was overlaid with 1 µl of matrix solution (saturated solution of α-cyano-4-hydroxy-cinnamic acid in 50% acetonitrile-2.5% trifluoroacetic acid) and air dried at room temperature.

Spectra were obtained on an Autoflex III MALDI-TOF/TOF mass spectrometer (Bruker Daltonics, Leipzig, Germany) equipped with a 200-Hz Smartbeam laser. Spectra were recorded in the linear, positive mode at a laser frequency of 200 Hz within a mass range from 2,000 to 20,000 Da. The IS1 voltage was 20 kV, the IS2 voltage was maintained at 18.7 kV, the lens voltage was 6.50 kV, and the extraction delay time was 120 ns. Approximately 500 shots from different positions of the target spot were collected and analyzed for each spectrum. The spectra were calibrated externally using the Bruker Bacterial Test Standard (Escherichia coli extract including the additional proteins RNase A and myoglobin). Calibration masses were as follows: RL29 3637.8 Da; RS32, 5096.8 Da; RS34, 5381.4 Da; RL33meth, 6255.4 Da; RL29, 7274.5 Da; RS19, 10300.1 Da; RNase A, 13683.2 Da; myoglobin, 16952.3 Da).

The different spectra obtained for each isolate under study were analyzed with the Biotyper vs 1.0 software for presumptive identification and to determine the similarities among the spectra. A dendrogram was generated for clustering the strains with high similarity. Between 2 and 9 representatives of each cluster were selected for further molecular analysis.

**Microbial identification and phylogenetic analysis**

Representative strains of each WC-MALDI-TOF MS group (100 strains in total) were selected and their
**Diversity indices**

Diversity indices and rarefaction curves for statistical estimation of the bacterial diversity were calculated using the PAST software vs. 2.17. Shannon index was correlated with richness and relative species abundance. Abundance and dominance are indicated by the evenness index and by the Simpson’s index. Coverage index (C) was calculated as C = 1 - (n/N), n being the number of species appearing only once and N being the total number of colonies analyzed. The S_{chao} estimator (Kemp & Aller, 2004), as an estimate of the total number of species present, is calculated as S_{chao} = S_{obs} + F_{S}/2(F_{S}+1) - F_{S}/2(F_{S}+1)^{2}, where S_{obs} is the number of species observed in the bacterial strains collection, and F_{S} and F_{S} are the number of species occurring either one or two times. The same estimation was calculated for the genera detected.

**Calcite precipitation by bacteria**

To assess their possible influence on calcite precipitation or dissolution, all bacterial isolates (229) were cultured on 3 different media: B-4 agar (Boquet et al., 1973), B-4C agar (B-4 agar with an overlay of 1.5% agar with 2% calcium carbonate light powder (Panreac) as described by Banks et al. (2010) and R2AC agar (R2A agar with an overlay of 1.5% agar with 2% calcium carbonate light powder – Panreac). The plates were incubated aerobically at 18°C. Petri dishes were examined periodically by light microscopy for up to 25 days for the presence of crystals or clearing zone around the colonies. Controls consisted of non-inoculated culture medium incubated under the same conditions. Crystals from the positive plates were purified for further analysis as follows: all the agar of the Petri dish, 20 ml approximately, was transferred to a 50 ml Falcon tube and 30 ml of MilliQ sterile water was added. The sample was heated in a microwave oven until the agar was molten, and the crystals settled to the bottom of the tube without the need for centrifugation. The supernatant was removed and the sediment was air dried.

**X-ray diffraction analysis and SEM observation**

Crystals were observed under a binocular microscope before X-ray diffraction study. Their mineralogy was determined with a Siemens D-5000 X-ray diffractometer, with secondary graphite monochromator, fixed slit, CuKα radiation and on-line connection with a microcomputer. Data were collected for 5 seconds integration time at 0.05 2θ steps at 40 kV and 30 mA in a 2θ interval between 3 and 60°, using randomly oriented powders of the bulk sample. No pretreatment was made on them. Data processing was performed using EVA ver. 7.0 software program in order to obtain the mineral composition. When more than one phase was present, a semi-quantitative mineral analysis composition was obtained based on the peak areas. All samples were observed and photographed by scanning electron microscopy (Hitachi S-3400N Type II SEM microscope). Selected samples were analyzed by Energy-dispersive X-ray spectroscopy attached to SEM (EDX, Bruker X-Flash Detector 4020).

**RESULTS**

**Physical and chemical parameters of the brackish water**

Several physical and chemical parameters of the water at sampling point A1, as representative of the
whole water body, were determined from December 2011 until March 2013 at three hours interval. The average values were: temperature 19.5 (±0.1 °C), conductivity 10.26 (±1.1) µS/cm (equivalent to 0.6% salinity), pH 7.38 (±0.08), ORP 271.48 (±69.6) mV, dissolved oxygen 101.2 (±7.4) %. Total organic carbon (TOC) ranged from 0.69 to 0.92 mg/l (mean value 0.81 mg/l) characteristic of oligotrophic waters.

**DAPI and FISH bacterial cell counts**

Total cell counts by DAPI of the 3 water samples (A1, A2, and A3) ranged from 1.2x10³ to 4.5x10⁴ (Table 2). The results obtained for the FISH probes, EUB338 and GAMMA, showed that 15% of the total cell count can be considered as active Gammaproteobacteria and 31% as active bacteria in sample A1. In sample A2, 11% of the bacteria counted by DAPI stain can be considered as active gammaproteobacteria. FISH counts in sample A3 was below the detection limit of the method. Bacteria in the samples of the multicolored precipitate were detected associated with mineral particles and the EUB probe indicated that only 3.3% were active and none was detected with the gammaproteobacteria probe.

**Culturable bacterial cell counts**

Cell counts on plates of R2A medium for oligotrophic bacteria and CFC medium for *Pseudomonas* varied among the samples. Culturable bacteria in the cave entrance reached the highest value (sample A1) and decreased in sample A2 (5.5% of A1) and A3 (1% of A1). Cell counts obtained in CFC medium were lower, on the order of 6% in A1 and 0.5% in A2 of the values obtained in R2A medium and no colonies were detected in sample A3. In the multicolored deposit sample R1, 1,120 cfu/ml was detected, approximately 10 times the culturable bacteria detected in R2, which was 1-10% of the total cell count. In sample R1 two different colony morphologies were detected and only one in R2. In all samples, the FISH counts were 1-10% of the DAPI counts.

**Whole cell MALDI-TOF mass spectrometry**

Most of the isolates obtained in R2A medium (214 strains) and in CFC medium (34 strains) from the water and rock samples were analyzed by WC-MALDI-TOF MS. In total 248 isolates were analyzed, 263 colonies from A1, 50 from A2 and 10 from A3. The isolates of the multicolored deposits samples (R1 and R2) presented only two different colony morphologies in R2A agar and 25 isolates of both morphologies were selected for identification. As indicated in Supplementary Fig. S1 the clustering of the MALDI-TOF mass spectra based on a maximal 700 distance of 1,000, allowed the differentiation of 16 clusters of 3 or more strains, A to P. More than 50% of the strains clustered in 5 groups: group B with 32 strains, group C with 11 strains, group I with 55 strains, group O with 23 strains and group P with 16 strains. The groups A, F, G, H, I, J, M, N, and P included exclusively isolates of the cave entrance sample (A1) and the group K isolates of the intermediate sample (A2). Group C strains were isolated from the multicolored deposits samples (R). The groups B, D, and L contained isolates from the samples A1 and A2, and the group O is composed by isolates from the samples A1, A2, A3 and R. As visible in Supplementary Fig. S1 the Biotyper database allowed only the identification with confidence (values higher than 1.5 in the program) of 101 strains, 98 strains at the species, and 3 strains at the genus level.

**Strain identification by partial rRNA analysis**

A total of 100 representative strains, from 2 to 10 from each of the 16 MALDI-TOF clusters, comprising all the isolates that produced mineral precipitates (as explained later) were further analyzed by 16S rRNA gene sequence analysis. At least the first 700 nucleotides of the 16S rRNA gene were analyzed for the 100 isolates selected, with only 5 exceptions in which the length was shorter. Results are indicated in Supplementary Table S1 and Supplementary Figures S2 and S3. Most strains sequenced were Proteobacteria (72%) and Actinobacteria (19%). The predominant genera of the sample A1 were *Acinetobacter* and *Pseudomonas*, both members of the Gammaproteobacteria class. The most abundant genera in sample A2 were *Pseudomonas*, *Micrococcus*, and *Moraxella*. Sample A3 was dominated by *Psychrobacter* and *Pseudomonas*. The genera detected in sample R1 were *Nocardioides* and *Pseudomonas*, whereas only *Nocardioides* (Supplementary Fig. S3) was found in sample R2. Two genera of fungi were also identified by sequencing the 18S rRNA: *Aspergillus* and *Abortiporus* in samples A1 and A3.

**Combined identification**

Ninety-three percent of the isolates of the water samples were assigned to a known species or genus by combining the WC MALDI TOF groupings and the phylogenetic analysis of the representative strains. Thirty-four strains were only identified at the species level. Both methods assigned a strain to the same genus and species in most cases, but discrepancies were observed in 29 strains (the same phylogenetic species assignment of 2 strains but located in 2 MALDI-TOF groups, or 2 strains in the same MALDI-TOF group with different phylogenetic species assignation). The phylogenetic identification was considered as more reliable when discrepancies were observed. Table 3 indicates the species or genera identified in the 3 water samples. Strains isolated from samples R1 and R2 (multicolored precipitates) were ascribed to *Nocardioides luteus* and *Pseudomonas benzenivorans*. Sequences were deposited at the
Table 3. Identification of the strains isolated from the water samples in R2A agar.

**Sample A1**

<table>
<thead>
<tr>
<th>Genus assignation</th>
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<th>Species assignation</th>
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<th>Similarity to the type strain</th>
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<td></td>
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<td></td>
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<td></td>
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<tr>
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<td></td>
<td>Acinetobacter sp. D</td>
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EMBL database ([http://www.ebi.ac.uk/ena/](http://www.ebi.ac.uk/ena/)) under accession numbers HG738872-HG738971 and are given in Supplementary Table S1.

**Diversity indexes and rarefaction curves**

As indicated in Table 4, the number of genera and species detected on R2A in the water samples was: sample A1, 15 genera and 26 species (18 species were singletons); sample A2, 10 genera and 15 species (8 species were singletons); sample A3, 6 genera and 8 species (7 species were singletons). Due to the high number of singletons in the species analysis, the diversity indexes and rarefaction curves were only calculated for the genera detected. None of the rarefaction curves reached a saturation profile (Fig. 4) indicating that not all the diversity was detected. However, the coverage of genera was higher than 90% in samples A1 and A2. Table 3 also shows the indexes for bacteria isolated from the multicolored precipitate samples. Only 2 species were detected and the indexes demonstrate that species diversity was exhaustively analyzed.
**Mineral precipitates**

To assess whether microbial activity played a role in CaCO$_3$ deposition and dissolution, all bacteria isolated were plated onto B-4, B-4C and R2AC agar, which allow the discrimination of those bacterial strains with the ability to either precipitate or dissolve CaCO$_3$. Bacterial growth, crystal formation and crystal dissolution was checked at 18°C for 2–4 weeks. The strains able to precipitate CaCO$_3$ are indicated in Supplementary Table S1. None of the analyzed isolates dissolved CaCO$_3$. Forty-nine strains precipitated CaCO$_3$ and were classified in 30 species: Acinetobacter (10 strains, 3 species), Pseudomonas (8 strains, 5 species), Nocardiooides (4 strains, 2 species), Micrococcus (6 strains, 3 species), Psychrobacter (2 strains, 1 species), Shigella (2 strains, 2 species), Kocuria (2 strains, 1 species), Microbacterium (2 strains, 2 species), Sphingobium (2 strains, 1 species), Brevundimonas (2 strains, 2 species), Massilia (2 strains, 1 species) and Achromobacter, Hydrogenophaga, Moraxella, Stenotrophomonas, Streptomyces, Abiotiorpus, and Aspergillus (1 strain, 1 species each genus). Strains of the same species could differ in their capacity to precipitate crystals. In 9 species, strains were detected with the ability to form crystals and other strains in the same species were not. *P. xanthomarina* strain A1a-45 drew attention, because it was the only one of 25 strains isolated of this species that was able to precipitate CaCO$_3$ crystals.

Crystalline materials first detected by light microscopy were later observed by SEM and analyzed by X-ray diffraction. These observations were made in all the cases where mineral precipitates were present. In some of the samples the main phase present was calcite and verified by the EDX analysis that corroborated the presence of Ca, C, and O in atomic percent ratios related to CaCO$_3$.

In the case of calcite, variability in crystal growth and characteristics of external shape could be observed. The SEM results (Fig. 5) demonstrated the presence of calcium carbonate mineral polymorphs. The mineral precipitates show both spherical and rhombohedral morphological growth forms. Some of the aggregates resemble a cubic morphology. Larger scale morphologies are very variable showing twinning and intergrown crystalline aggregates. The anhedral spherical or globular forms (sometimes with a twin growth shape) dominated in most of the samples over the rhombohedra appearance. Those spherical aggregates are clearly made of rhombohedra crystals. The rhombohedral crystals show an idiomorphic tendency with the crystal size. The precipitates showed a white color or are slightly whitish to colorless. The mean grain size of calcite precipitates ranged between 50 and 70 µm in most of the samples, although some crystals are greater than 120 µm.

Apart from the differences in the external crystal shape and growth, some variations in mineralogy were observed. Struvite was only present in two samples. It showed a set of crystal aggregates ranging between 1 and 2 mm (Fig. 6) consisting of more or less idiomorphic pyramidal and bladed crystals (around 250 µm in length). This phase was present exclusively related with the fungal species *Aspergillus oryzae*. In the case of *P. xanthomarina* strain A1a-45 either calcite or struvite were observed.

In the case of isolates related with the FMD deposits (R1 and R2), only one species (*Nocardiooides luteus*) produced calcite precipitates. These crystals mostly showed a rhombohedral shape although some globular forms were also present (Fig. 6).

**DISCUSSION AND CONCLUSIONS**

The waters in Cova des Pas de Vallgornera originate from vertical infiltration from surface rainfall and the mixing with marine waters due to lateral infiltrations, resulting in brackish highly oligotrophic waters, which represent a singular habitat for microbial communities. To our knowledge, this is the first report of bacterial communities in cave anchialine waters of the Balearic Islands. It is a very stable habitat, with almost constant temperature all year and with low levels of organic matter. No photosynthetic activity has been detected in the cave and the contribution of organic matter by metazoan organisms is very limited (Gracia et al., 2009). Bacteria that have adapted their metabolic properties to this environment are only present in low numbers and are represented mainly by *Gamma- and Betaproteobacteria*, as well as *Actinobacteria*. Total cell counts diminished from the entrance of the cave to the most distal part. These results correlate with the distance to the sea water and with the frequency of visitors in the 3 parts of the...
Microbial communities in a Mallorcan coastal cave
genera diversity and Acinetobacter and Pseudomonas species dominated over the other species. Both genera are considered ubiquitous and metabolically versatile. The relevance of Pseudomonas populations was emphasized in recent culture independent analysis in karst aquifers (Gray et al., 2013).

Biologically induced mineralization of calcium carbonate can take place passively (metabolically driven changes in the chemistry around the living organisms) or actively (when the organism or its metabolic byproducts provide nucleation sites which allow the carbonate molecules to become particularly aligned in order to promote mineralization) (Northup & Lavoie, 2001; Jones, 2010). The bacterial surface (S-layers, specific proteins) has been suggested as possible nucleation sites that are probably just a side effect of their shape (Van Lith et al., 2003; Dupraz et al., 2004; Aloisi et al., 2006). These peculiarities can explain why some strains in a species are able to promote crystal formation and others not. Many of the isolates can contribute to the calcite deposition in the cave, and some of them seem to participate actively in the type of precipitate formed. Calcite is the mineral precipitated in all crystals detected and they present
cave studied. Visits are only allowed for exploration, survey, and research purposes. In the proximity of the entrance, only ~200 visitors are allowed each year, and the number decreases drastically towards the central part of the cave, whereas less than a few tens of visitors reach the distal parts. The detection in A1 of enterobacterial colonies (Shigella) can be related to levels of human exposure but the highest numbers of culturable bacteria detected at the entrance, and the different composition of the bacterial communities in each sampling point, can be explained by the infiltration of sea water providing nutrients for bacterial growth. The Gammaproteobacteria are present in all 3 samples, but were most abundant in the entrance. The Actinobacteria were most abundant in the distal part of the cave. The species or genera richness decreased with increasing distance to the entrance of the cave, the most visited part. With the culture methods used, only 2 species of fungi (Aspergillus sp. and Abortiporus sp.) were detected from sample A1.

The diversity of bacterial species was not exhaustively studied in the water samples, but the coverage index of the genera detected reached 95% of the estimated
genera diversity and Acinetobacter and Pseudomonas species dominated over the other species. Both genera are considered ubiquitous and metabolically versatile. The relevance of Pseudomonas populations was emphasized in recent culture independent analysis in karst aquifers (Gray et al., 2013).

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Fig. 5. SEM images of calcite precipitates showing differences in crystal morphology related with the bacterial species recovered in the water pools: a) Achromobacter spanius; b) Pseudomonas xanthomarina; c) Sphingobium rhizovicinum; d) Brevudimonas diminuta; e) Acinetobacter schindleri; f) Micrococcus terreus.

Fig. 6. SEM image of crystal precipitates. Struvite was found only with calcite in the precipitates of Pseudomonas xanthomarina isolates (a) or exclusively in the case of Aspergillus oryzae (b); c) SEM image of calcite precipitates from Nocardioides luteus isolates, sampled in the multicolored deposits.
high morphological differences in their external crystal growth shape, even when promoted by the same microbial strain. The most abundant bacterial species forming crystals described in the present study have been also detected by other authors (Cacchio et al., 2004; Schaberiet et al., 2004). Most precipitates were calcite crystals, but struvite was formed by 2 strains, 1 of Aspergillus and 1 of P. xanthomarina, which was the second most abundant species isolated in sample A1. No other strain of P. xanthomarina was able to form crystals, a strain-specific property that has to be studied in more detail.

The bacterial community detected in the multicolored precipitates was totally different. In one of the samples collected only Nocardioides strains were detected. In the second rock sample, P. benzenivorans was present and other strains of these species were scarcely detected in the water samples. These differences in the bacterial communities in the water and in the mineral crusts and scattered mineralizations that represent the multicolored deposits over the rock surface can be explained by the different nature of the habitat, related with the vent morphologies and composed by a substrate that is dominated by a Fe-Mn composition (Merino et al., 2009; Fornós et al., 2011). In contrast to these results, in the study of Northup et al. (2003) by a culture-independent method, the bacterial community on ferromanganese deposits at Lechuguilla cave was dominated by clones of mesophilic Archaea and lactobacilli.

To our knowledge, this is the first report on the identification at the species level of cultured bacterial strains isolated from anchialine waters. A limited number of studies have looked at culturable bacterial populations in cave environments (Ikner et al., 2007; Seymour et al., 2007; Gonzalez et al., 2011; Krstulović et al., 2013) and more recent investigations have been performed by a different approach, using culture-independent methods. Although the analysis of species in the bacterial community along the cave was not exhaustive, the bacterial populations present in these brackish waters are similar to those found in other karst environments. Ikner et al. (2007) detected by culture-based methods mainly Actinobacteria and Proteobacteria, but also Firmicutes, a species not detected in our samples. In the molecular survey performed by Pasic et al. (2010) members of the Gammaproteobacteria were most abundant in the clone libraries, followed in abundance by members of Actinobacteria. Proteobacteria predominated also in the study of Shabarova & Pernthaler (2010).

As this type of littoral karst cave of Mallorca represents a natural laboratory observation, we will use a long term project to highlight the microbial role in carbonate precipitation/dissolution of speleothems and carbonate rocks.

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Molecular analyses of microbial abundance and diversity in the water column of anchialine caves in Mallorca, Spain

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Abstract: Water column samples from the island of Mallorca, Spain were collected from one site in Cova des Pas de Vallgornera (Vallgornera) and three sites (Llac Martel, Llac Negre, and Llac de les Delícies) in Coves del Drac (Drac). Vallgornera is located on the southern coast of Mallorca approximately 57 km southwest of Coves del Drac. Drac is Europe’s most visited tourist cave, whereas Vallgornera is closed to the public. Water samples were analyzed for water chemistry using spectrophotometric methods, by quantitative PCR for estimated total abundance of microbial communities, and by length heterogeneity PCR for species richness and relative species abundance of Archaea, Bacteria, and microbial eukaryotes. Estimated total abundance was multiplied by relative species abundance to determine the absolute species abundance. All sites were compared to determine spatial distributions of the microbial communities and to determine water column physical and chemical gradients. Water quality and community structure data indicate that both Drac Delícies and Drac Negre have distinct biogeochemical gradients. These sites have communities that are similar to Vallgornera but distinct from Drac Martel, only a few hundred meters away. Drac Martel is accessible to the general public and had the most dissimilar microbial community of all the sites. Similarities among communities at sites in Drac and Vallgornera suggest that these two spatially separated systems are operating under similar ecological constraints.

Keywords: water quality; estimated total abundance; species richness; relative species abundance; microbial; community structure; anchialine; Mallorca

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INTRODUCTION

Biological communities, especially microbial communities, are important because they help shape the geochemistry within cave systems (Lovley & Chapelle, 1995; Léveillé et al., 2007; Por, 2007). These communities may contribute to speleothem formation as seen by Curry et al. (2009) who found calcitic deposits in Cataract Cave, Alaska, that were intertwined with microbial filaments they considered as biologically-influenced organominerals. These communities can also act as biological tracers in the same manner as stable isotopes to show hydrologic connections between systems (Ward & Palmer, 1994; Sanchez et al., 2002). Venarsky et al. (2009) found that the genetic structure of aquatic invertebrate populations within cave systems can be used to identify and prioritize geographic regions for conservation. Differences between microbial communities at different depths can be used to indicate the presence of geochemical gradients in the water column that help characterize the stability and potential mixing of waters within individual cave systems (Gili et al., 1986; Torres-Talamante et al., 2011).

Molecular techniques such as DNA sequencing, length heterogeneity PCR (LH-PCR), and quantitative PCR (q-PCR) (Suzuki et al., 1998; Ginzinger, 2002; Sogin et al., 2006; Ducklow et al., 2011) have provided the means to estimate biological species richness and abundance in cave systems (Garman et al., 2011; Garey & Menning, 2012). Length heterogeneity PCR uses fluorescently labeled primers targeted to conserved regions of the 16S rRNA gene. Different fragment lengths, as determined by gel electrophoresis, represent the 16S rRNA genes of different organisms. These data are used to estimate the relative abundance of species and species richness within a site and identify species that are present across sites. The method is fast, reproducible, and cost-effective,
but does not provide as precise identification as DNA sequence analysis allows. Quantitative PCR can be used to estimate the amount of DNA in a sample using primers targeted to conserved regions of rRNA genes. These data can be used to estimate increases and/or decreases in the absolute size of a community (Lloyd et al., 2013). Length heterogeneity PCR and q-PCR, when combined, can provide an estimate of absolute species abundance in a sample. These techniques can be used to determine similarities and differences between communities at different depths in the water column of each site, between sites within an individual cave, and between cave systems.

The purposes of this study are to: (1) describe the physical and chemical gradients that occur in the water columns of two cave systems on the Island of Mallorca; (2) determine if microbial communities within these caves vary with the physical and chemical water gradients; and (3) characterize the differences in microbial communities with different levels of spatial separation.

METHODS

Site description

Mallorca is the largest island in the Balearic Islands archipelago located off the eastern coast of Spain in the Mediterranean Sea. The coastal area of the island is approximately 45% karst limestone (Balaguer, 2005). Coves del Drac (Drac) is located on the eastern coast of the island under the town of Porto Cristo and contains three main galleries ending with brackish pools, Llac Martel, Llac Negre and Llac de les Delícies (hereafter Drac Martel, Drac Negre, and Drac Delícies). Cova des Pas de Vallgornera (Vallgornera) is located 57 km to the southwest of Drac on the southern coast under the town of Cala Pi (Fig. 1). Within Drac, the Llac Martel site is along a tourist route (Robledo & Duran, 2010), whereas the Llac Negre and Llac de les Delícies sites are not open to the public (Fig. 2). Vallgornera is not accessible to the general public. Both cave systems are anchialine, found in Upper Miocene rock, and are located in the subterranean mixing zone comprised of fresh groundwater and marine water from the Mediterranean Sea. These caves have submerged and dry passages (Ginés et al., 2012). Samples were collected from the brackish water bodies within each cave.

Sampling

Water column samples were collected from a single site in Vallgornera and from the three sites in Drac (Figs. 1 & 2) in March 2013. Four replicates of 500 ml were collected at each location from three depths (the surface, 1 m, and 2 m) using a 1077 Model JT-1 Water Sampler (LaMotte, USA). All samples were kept at 4°C until further processing. Concurrent with water column sampling, a HI 9828 Multiparameter Meter (Hanna Instruments, USA) was used to measure water temperature, dissolved oxygen, oxidation reduction potential (ORP), pH, salinity, and total dissolved solutes.

Sample processing

All water column samples were filtered through 47 mm diameter 0.2 µm pore size filters (Millipore, USA). The filtered water was used for subsequent chemical analyses. The 47 mm filters were stored at -20°C until further processing. Microorganisms were extracted from the filters by scraping the filter with a sterile DNA-free spatula in 1.5 ml of pH 7 phosphate buffered saline, followed by 30 seconds of vortexing in a 15 ml conical tube. The filters were washed twice in this manner. DNA extractions were performed using an Ultraclean Fecal DNA Kit (MoBIO, USA) following the manufacturer’s protocols except that following the bead beating step the supernatant was split into two 400 µl aliquots and processed in parallel. The aliquots were recombined during the first spin filter step. DNA concentrations were determined using a Thermo Scientific Nanodrop 2000 Spectrophotometer (Fisher Scientific, USA).

Water chemistry

Due to logistical constraints, only one water sample from each site and depth was analyzed for chemical parameters. Nitrate, ammonia, sulfate, hardness, and
Microbial diversity in caves of Mallorca, Spain

Quantitative PCR

Quantitative PCR was conducted on all samples to estimate the total abundance of Archaea, Bacteria (Oliver et al., 2014), and microbial eukaryotes (Eppendorf, USA). Fluorescent molecules are included in the PCR reaction mix to allow the quantification of amplified DNA fragments in real time. This allows the estimation of the quantity of DNA. The 16S (Giovannoni, 1991; Lane, 1991; Reysenbach & Pace, 1995; Baker et al., 2003) and 18S (Sogin & Gunderson, 1987) RNA gene primers used for each domain are listed in Table 1. Each reaction was performed in a 20 µL volume containing 2 µL of sample DNA, 0.5 µL of each primer (10 mM), 10 µL of SYBR Premix Ex Taq II (Takara, USA), and 7 µL of nanopure water. The q-PCR reaction conditions were: initial denaturation at 95°C for 30 seconds followed by 40 cycles of denaturing for 10 seconds at 95°C, annealing for 20 seconds (see Table 1 for temperature used for each primer set), and extension for 45 seconds at 70°C. A positive control (DNA from pure microbial culture, see Table 1) and a negative control (no DNA) were run to verify PCR efficiency. Log-linear standard curves were made using five 1:10 serial dilutions of DNA of known concentration from control organisms (see Table 1) and a negative control (no DNA) were run to verify PCR efficiency. Length heterogeneity PCR mixtures consisted of a 50 µL volume composed of 5 µL of 10X PCR Reaction Buffer (ID Labs, Canada), 1 µL of each primer solution (10 mM), 1 µL dNTP solution (10 mM), 0.25 µL Taq DNA Polymerase (1.25 U) (ID Labs, Canada), 10 ng of DNA (volume varies with sample), and nanopure water to 50 µL. A T3 Thermocycler (Biometra, Germany) was programed for an initial denaturation of 120 seconds at 95°C followed by 30 cycles of denaturation for 30 seconds at 95°C, annealing for 30 seconds (see Table 1 for temperature used for each primer set), and extension for 60 seconds at 72°C. A final extension was carried out for seven minutes at 72°C. PCR products (0.5 µL) were denatured in 9.0 µL Hi-Di formamide (Applied Biosystems, USA) with 0.5 µL GeneScan 600 LIZ internal size standard (Applied Biosystems, USA). Sample mixtures were heated for five minutes at 95°C, immediately placed in an ice bath for five minutes, and loaded on the genetic analyzer. Electropherograms were analyzed using Gene Mapper v4.0 (Applied Biosystems, USA). The expected amplicons contain two conserved flanking regions and two internal variable regions. Peaks from fragments of a size representing only the conserved flanking regions or less (250 bp for Archaea, 300 bp for Bacteria and microbial eukaryotes) were omitted from further analysis in order to only use fragments containing variable regions which represent unique species (Suzuki et al., 1998). Species richness was determined by counting the total number of peaks from each electropherogram. Relative species abundance of each peak was determined by dividing each individual peak area by the total area of all peaks in the sample used in the analysis to determine the proportion of each species in the sample.

Length heterogeneity PCR

Length heterogeneity PCR is a molecular technique used to compare biological communities by determining the lengths of fragments generated from each microbial species in the samples. PCR primers were selected that amplify variable regions of the target 16S and 18S rRNA genes. Each fragment size is assumed to represent a unique species, both within a sample and across samples. This allows a rapid estimation of the microbial communities and the comparison of communities across sites. LH-PCR does not identify particular species and tends to underestimate species richness and overestimate relative species abundance (Marzorati et al. 2008). LH-PCR was conducted using an ABI 3130 4-capillary Genetic Analyzer (Applied Biosystems, USA). Ten ng of DNA were used as the template for each reaction. The 16S and 18S rRNA gene primers used for each domain are listed in Table 1. The forward primer of each set was labeled with a 56-FAM fluorescent tag. A positive control (DNA from a pure microbial culture, see Table 1) and negative control (no DNA) were run to verify PCR efficiency. Length heterogeneity PCR mixtures consisted of a 50 µL volume composed of 5 µL of 10X PCR Reaction Buffer (ID Labs, Canada), 1 µL of each primer solution (10 mM), 1 µL dNTP solution (10 mM), 0.25 µL Idproof DNA Polymerase (1.25 U) (ID Labs, Canada), 10 ng of DNA (volume varies with sample), and nanopure water to 50 µL. A T3 Thermocycler (Biometra, Germany) was programed for an initial denaturation of 120 seconds at 95°C followed by 30 cycles of denaturation for 30 seconds at 95°C, annealing for 30 seconds (see Table 1 for temperature used for each primer set), and extension for 60 seconds at 72°C. A final extension was carried out for seven minutes at 72°C. PCR products (0.5 µL) were denatured in 9.0 µL Hi-Di formamide (Applied Biosystems, USA) with 0.5 µL GeneScan 600 LIZ internal size standard (Applied Biosystems, USA). Sample mixtures were heated for five minutes at 95°C, immediately placed in an ice bath for five minutes, and loaded on the genetic analyzer. Electropherograms were analyzed using Gene Mapper v4.0 (Applied Biosystems, USA). The expected amplicons contain two conserved flanking regions and two internal variable regions. Peaks from fragments of a size representing only the conserved flanking regions or less (250 bp for Archaea, 300 bp for Bacteria and microbial eukaryotes) were omitted from further analysis in order to only use fragments containing variable regions which represent unique species (Suzuki et al., 1998). Species richness was determined by counting the total number of peaks from each electropherogram. Relative species abundance of each peak was determined by dividing each individual peak area by the total area of all peaks in the sample used in the analysis to determine the proportion of each species in the sample.

Table 1. List of primers used for LH-PCR and q-PCR with associated data.

<table>
<thead>
<tr>
<th>Primer</th>
<th>Sequence (5'-3')</th>
<th>Regions Covered</th>
<th>Annealing temp. (°C)</th>
<th>Positive Control</th>
<th>Undiluted Concentration of Control Organism DNA</th>
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<tr>
<td><strong>Archea</strong></td>
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<tr>
<td>A109BF</td>
<td>CNGGCAACGGACGGAGCAC</td>
<td>7-8</td>
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<td>Sulflobus solfataricus</td>
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<td>UA1406R</td>
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<td>27F</td>
<td>AGAAGTTTCTAAGTCGCTAG</td>
<td>1-2</td>
<td>50</td>
<td>Escherichia coli</td>
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<td>2532R</td>
<td>CGGTGTAAAGGCCAGGG</td>
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</table>
Statistical analysis

Relative species abundance (LH-PCR) data was multiplied by estimated total abundance (q-PCR) data to calculate estimated absolute abundance. This dataset was analyzed by non-parametric multivariate analysis of multidimensional scaling (MDS) based on Bray-Curtis similarity using Primer v6 statistical software (Primer-E Ltd, UK). Least significant difference post-hoc tests were conducted on all estimated total abundance and species richness data to determine statistically significant differences (p<0.05) between samples at different depths at each site and between all sites using SPSS 20.0 (IBM, USA).

RESULTS AND DISCUSSION

Physical and chemical parameters sampled at all sites and depths are shown in Figure 3. Temperature, salinity, total dissolved solids, dissolved oxygen, hardness, ORP, and sulfate generally increase at all locations with increasing depth with a few exceptions. In contrast, two studies of anchialine water bodies in the caves of Mallorca (Carey et al., 2001; Sintes et al., 2004) found dissolved oxygen decreased with depth. Both of these studies also found that temperature and salinity increased with depth. The increases of salinity, dissolved oxygen, total dissolved solutes, sulfate, and temperature with depth observed in our study suggests that these caves have relatively warm oxygenated water entering the systems from below, presumably via salt water from the Mediterranean Sea.

Alkalinity, pH, and phosphate appeared to decrease at all locations with depth in our study. Zic et al. (2011) found similar patterns in anchialine caves in Croatia where phosphate and alkalinity decreased with depth, while pH decreased with depth to 4-6 m then increased. In our study, nitrate and ammonia did not appear to change with depth in a consistent pattern, similar to Zic et al. (2011) who found that nitrate did not change with depth in January 2010 but decreased with depth in January and July of 2009. They also found that ammonium did not change with depth in January 2010 but oscillated with depth in January and July of 2009.

The chemical gradients seen in the caves in this study can be explained by overlying fresh water mixing with deeper Mediterranean-derived salt water. Carey et al. (2001) found that in some of the water bodies of the caves of Mallorca, the amount of freshwater changes with the amount of rainfall entering the caves. They
did not find a clear halocline in Cala Varques ‘A’, which they attributed to brackish water entering the cave or possibly turbulent mixing of the overlying freshwater with the underlying saltwater but did find a halocline in Cova de na Barxa. They concluded that all the water bodies they studied showed similar chemical and physical profiles with increases of salinity and temperature and decreases of dissolved oxygen with depth. Some chemical constituents at the different sites in our study did not consistently follow the salt gradient as seen in Carey et al. (2001). Drac Negre had the lowest temperature compared to the other sites with a surface temperature 3-4°C below the other sites and 2°C lower at a depth of 2 m. It also appeared to be an outlier in terms of salinity, total dissolved solutes, dissolved oxygen, sulfate, ammonia, and ORP at one or more depths compared to the other sites (Fig. 3). This suggests that the water at Drac Negre has different inputs from that of the other sites. One possibility is that the Drac Negre site could be more strongly influenced by groundwater than the other sites which could explain the drop in dissolved oxygen content at the 1 m sample. The Drac Martel site appears to have the weakest salinity gradient from the surface to 2 m, suggesting that the water column is more mixed than the other sites. This could be due to the boat traffic transporting tourists across the water at Drac Martel (Fig. 2).

**Total abundance estimated by q-PCR**

Estimated total abundance of microbes as determined by q-PCR is shown in Table 2. Archaea appear to have the highest concentration of DNA per liter at all sites representing 94.4-97% of each sample followed by bacterial DNA (3.0-5.6%) and microbial eukaryote DNA (0.0-1.1%). These differences could be due to the different PCR primer sets used for each domain (e.g. Archaea, Bacteria, Eukaryota) and primer efficiency could vary with different primer sets specific for the different domains (Lloyd et al., 2013). In a study of a hypersaline lake in Turkey, Mutlu et al. (2008) found similar results where Archaea also appeared to be the most prevalent component of the microbial community. In this study, comparisons of estimated total abundance between all sites and depths show that microbial eukaryotes had the highest differences (235 fold). The absolute amounts of eukaryote DNA were so low that generally there were no significant differences among depths at each site. The eukaryote estimated total abundance was significantly higher in Drac Negre than the other three sites, including Vallgornera. Estimated total abundance of Bacteria varied 17 fold and Archaea eight fold. Vallgornera and Drac Negre showed an increase of estimated total prokaryote abundance with depth, whereas Drac Delícies showed a decrease with depth. In Drac Martel, estimated prokaryote abundance decreased from the surface to 1 m and then increased at a depth of 2 m. Archaea appear to be the most prevalent component of the water column community within the sampled caves.

Least significant difference post-hoc tests of estimated total abundance between all sites are shown in Table 3. These data indicate that all of the prokaryote communities are significantly different from each other with an exception found between Drac Martel and Vallgornera. Conversely, the only differences observed between prokaryote communities were seen between Drac Negre and the other 3 sites. This suggests that the different parts of the Drac system may have become distinct niches with potentially unique communities. Culver (1970) found that three gammarid amphipods inhabiting cave streams separated into niches based on habitat conditions such as stream flow and substrate. While amphipods were not examined in our study, Culver’s study shows that biological communities can separate into distinct ecological niches within the same cave system as we found with the microbial communities. The estimated total abundance of Drac Martel was not significantly different from Vallgornera indicating that both systems may be operating under similar ecological constraints. Microbial eukaryotes in Drac Negre appeared to be significantly higher in abundance than the three other sites indicating a separate niche environment within Drac Negre.

### Table 2. Estimated total abundance (average amount of DNA) as determined by q-PCR.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Vallgornera</th>
<th>Drac Martel</th>
<th>Drac Negre</th>
<th>Drac Delícies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Archaea</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Ave DNA (ng/L)</td>
<td>Std Dev</td>
<td>Ave DNA (ng/L)</td>
<td>Std Dev</td>
</tr>
<tr>
<td>-2</td>
<td>478.77</td>
<td>241.17</td>
<td>1753.42</td>
<td>712.63</td>
</tr>
<tr>
<td>-1</td>
<td>387.31</td>
<td>190.76</td>
<td>1769.48</td>
<td>1045.37</td>
</tr>
<tr>
<td>0</td>
<td>175.78</td>
<td>42.78</td>
<td>396.62</td>
<td>224.72</td>
</tr>
<tr>
<td><strong>Bacteria</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Ave DNA (ng/L)</td>
<td>Std Dev</td>
<td>Ave DNA (ng/L)</td>
<td>Std Dev</td>
</tr>
<tr>
<td>-2</td>
<td>19.15</td>
<td>10.91</td>
<td>103.28</td>
<td>38.10</td>
</tr>
<tr>
<td>-1</td>
<td>14.57</td>
<td>8.25</td>
<td>93.23</td>
<td>50.75</td>
</tr>
<tr>
<td>0</td>
<td>6.07</td>
<td>1.95</td>
<td>15.44</td>
<td>8.63</td>
</tr>
<tr>
<td><strong>Eukaryote</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Ave DNA (ng/L)</td>
<td>Std Dev</td>
<td>Ave DNA (ng/L)</td>
<td>Std Dev</td>
</tr>
<tr>
<td>-2</td>
<td>0.11</td>
<td>0.14</td>
<td>0.55</td>
<td>0.54</td>
</tr>
<tr>
<td>-1</td>
<td>0.05</td>
<td>0.03</td>
<td>2.98</td>
<td>5.22</td>
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<tr>
<td>0</td>
<td>0.17</td>
<td>0.16</td>
<td>4.70</td>
<td>3.21</td>
</tr>
</tbody>
</table>
Table 3. Least Significant Difference Post-Hoc showing statistically significant differences of estimated total abundance and species richness between sites.

<table>
<thead>
<tr>
<th>Dependent variable (cave)</th>
<th>Archaea</th>
<th>Bacteria</th>
<th>microbial eukaryotes</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vallgornera Drac Negre</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Vallgornera Drac Delícies</td>
<td>0.016</td>
<td>0.007</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vallgornera Drac Martel</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drac Martel Drac Negre</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Drac Martel Drac Delícies</td>
<td>0.026</td>
<td>0.008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drac Negre Drac Delícies</td>
<td>0.020</td>
<td>0.019</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>

Least significant difference post-hoc tests of estimated total abundance by depth at each site (Table 4) show that Drac Martel did not have any significant differences between depths in estimated total abundance for any domain whereas Drac Delícies showed statistically significant differences of Archaea and Bacteria abundances between all depths and statistically significant differences of microbial eukaryote abundance from the surface to 2 m. It appears from both salinity measurements and estimated total abundance that the water column in Drac Martel is well mixed, probably due to boat traffic while Drac Delícies is relatively undisturbed allowing biological gradients to form. Vallgornera and Drac Negre both showed statistically significant differences in Archaea and Bacteria abundance between the surface and 2 m but no differences between 1 m and 2 m. Drac Delícies was the only site that showed significant differences among depths for estimated total abundance of microbial eukaryotes. These data indicate that Drac Negre and Vallgornera have biological gradients that are less developed than Drac Delícies but more developed than Drac Martel. In a study of cavernicolous ciliates from anchialine water bodies in Mallorca, Carey et al. (2001) found that the populations were clearly stratified within them. Although ciliates were not specifically measured in our study, the universal eukaryotic primers we used for community structure analyses would include these organisms.

Species richness estimated by LH-PCR

Average species richness among all sites as estimated by LH-PCR is shown in Table 5. Archaea had the highest species richness across all sites with an average of 16 to 30.4 peaks per sample, followed by Bacteria (average of 1.0 to 25.2 peaks per sample), and microbial eukaryotes (average of 2.4 to 5.2 peaks per sample). Species richness either decreased or did not change with depth in Vallgornera, Drac Delícies, and Drac Martel, but increased with depth in Drac Negre. In a study of microbial communities inhabiting an anchialine sinkhole in Australia, Seymour et al. (2007) found that abundances of different groups of phytoplankton, Bacteria, and viruses varied with depth although concentrations were generally highest from the surface to 1 m. In our study, Drac Delícies was an exception where the number of bacterial peaks was much lower than the other sites although the number of archaeal and microbial eukaryote peaks were similar to those of the other sites. Considering that the amount of bacterial DNA from Drac Delícies samples was similar to other sites, but significantly lower in number of LH-PCR peaks, it appears that for some unknown reason, bacterial biodiversity at Drac Delícies is considerably less than the other sites.

Least significant post-hoc tests of species richness between sites (Table 3) indicate that Drac Negre had significantly different species richness of Archaea from that of the other three sites while Drac Delícies had significantly different species richness of Bacteria. The species richness of microbial eukaryotes was significantly different only between Drac Delícies and Drac Negre. Similar analyses of species richness by depth (Table 4) showed statistically significant differences of Archaea at Vallgornera and Drac Martel and of Bacteria at Drac Negre and Drac Delícies but no statistically significant differences were seen between microbial eukaryotes at any site. The unique archaeal communities in Drac Negre and the unique bacterial communities in Drac Delícies indicate a separation of biological communities into distinct niche habitats as was seen with gammarid amphipods in the study by Culver (1970).

Species richness and abundance

Estimated total abundance analyses suggest that the archaeal communities are similar (species richness) at different depths but different in amount (estimated total abundance) within Drac Negre and Drac Delícies. These analyses also indicate that the species richness of bacterial communities at Drac Negre and Drac Delícies vary with depth in the same manner. In Drac Negre, species richness increases with depth, while in Drac Delícies species richness remains constant. In Vallgornera, species richness is lower compared to the other sites and does not show any significant changes with depth.

Table 4. Least Significant Difference Post-Hoc showing statistically significant differences of estimated total abundance and species richness at each site between depths.

<table>
<thead>
<tr>
<th>Dependent variable (depth)</th>
<th>Archaea</th>
<th>Bacteria</th>
<th>microbial eukaryotes</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vallgornera Drac Negre</td>
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<td>0.000</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Vallgornera Drac Delícies</td>
<td>0.016</td>
<td>0.007</td>
<td></td>
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</tr>
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<td>Vallgornera Drac Martel</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drac Martel Drac Negre</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Drac Martel Drac Delícies</td>
<td>0.026</td>
<td>0.008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drac Negre Drac Delícies</td>
<td>0.020</td>
<td>0.019</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>

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Estimated total abundance analyses suggest that the archaeal communities are similar (species richness) at different depths but different in amount (estimated total abundance) within Drac Negre and Drac Delícies. These analyses also indicate that the species richness of bacterial communities at Drac Negre and Drac Delícies vary with depth in the same manner. In Drac Negre, species richness increases with depth, while in Drac Delícies species richness remains constant. In Vallgornera, species richness is lower compared to the other sites and does not show any significant changes with depth.
Table 5. Species richness (average number of peaks) as determined by LH-PCR.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Archaea</th>
<th>Vallgornera</th>
<th>Drac Negre</th>
<th>Drac Delícies</th>
<th>Drac Martel</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>Ave #</td>
<td>16.00</td>
<td>30.40</td>
<td>21.75</td>
<td>21.75</td>
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<tr>
<td></td>
<td>Dev</td>
<td>4.36</td>
<td>3.36</td>
<td>4.03</td>
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</tr>
<tr>
<td></td>
<td>Std</td>
<td>3.00</td>
<td>3.45</td>
<td>2.21</td>
<td>2.28</td>
</tr>
</tbody>
</table>

manner as estimated total abundance. Even though Drac Martel showed no statistically significant differences of estimated total abundance between any depths for all domains, there was a statistically significant difference of species richness of Archaea between the surface and 2 m. Vallgornera showed a statistically significant difference in estimated total abundance of Archaea and Bacteria between the surface and 2 m and a statistically significant difference of species richness of Archaea between the surface and 2 m. Seymour et al. (2007) found that microbial populations can be stratified within anchialine sinkholes and that some populations are only found in specific zones determined by water chemistry. For example, they found that phytoplankton abundance was greatest within a layer with high ammonia concentrations and that bacterial abundance was greatest near a layer of hydrogen sulfide. In our study, no statistically significant differences of species richness of microbial eukaryotes were seen with depth at any site and there was only a statistically significant difference of estimated total abundance of microbial eukaryotes between the surface and 2 m at Drac Delícies. No difference in estimated total abundance and species richness could be due to the low values for microbial eukaryotes at all sites suggesting that microbial eukaryotes may not contribute to the biodiversity of these systems as much as Archaea and Bacteria although they may still play an important ecological role.

Assessment of microbial communities

Estimated total abundance and species richness do not tell the entire story. For example, the results of least significant difference post-hoc tests presented in Table 3 show that there are no significant differences in estimated total abundance or species richness between Vallgornera and Drac Martel for any domain even though there are clear differences in salinity, sulfate, and other chemical gradients between the two sites. Estimated total abundance (q-PCR) only estimates the size of the community while species richness (LH-PCR) only estimates the total number of different species in the community. Relative species abundance is the proportion of each species (e.g. LH-PCR peaks) present in each sample. Multi-dimensional scaling (MDS) plots allow a closer look at the communities by comparing both estimated total abundance and relative species abundance among samples as estimated absolute abundance (see Methods).

The MDS plot displaying estimated absolute abundance data of the microbial communities at all sites and depths is shown in Figure 4. It can be seen that the communities clearly separate into four distinct groups. Drac Martel appears to have a unique microbial community that is different from the other three sites. The Drac Martel samples from different depths grouped together, with a few outliers, suggesting a well-mixed water column. Conversely, the MDS plot suggests that at Drac Delícies, there is a biological gradient with depth because the surface samples are to the left of the Drac Delícies cluster, the 1 m samples are in the middle and the 2 m samples to the right. The 1 m and 2 m samples from Drac Negre are tightly clustered with the 1 m samples to the left and the 2 m samples to the right but the surface samples are to the far right and not in the cluster. The Vallgornera samples are cluster tightly together, with the 1 m and 2 m samples mostly together and the surface samples farther to the right. The grouping of Vallgornera samples includes samples from the surface of Drac Negre and samples from 2 m of Drac Delícies. This could mean that similar communities are found within varying distances from each other, approximately 100 m between Drac Negre and Drac Delícies, and 57 km between Vallgornera and Coves del Drac. This finding suggests that these two spatially separated systems are operating under similar ecological constraints. In a study of cenotes and anchialine caves in the Yucatan Peninsula of Mexico, Sanchez et al. (2002) found similar results in that similar phytoplankton communities were found in systems approximately eight km apart. They suggest that the similarities seen between sites are due to a shared freshwater source. Future studies incorporating the complex hydrological framework underlying the island of Mallorca and microbial species information could possibly determine more conclusive microbial linkages between cave systems.

The Drac Martel samples appear distinct from samples of other sites within the Drac system (Fig. 4) and may be a result of exogenous biota or increased nutrients brought in by human activities due to the development of the site as a tourist attraction. Ikner et al. (2007) found that the development of a cave in Arizona, USA for tourism led to an increase of organic carbon inputs to the areas most traveled, but also found that the placement of lights along the tourist path led to algal growth near the lights. They determined that Proteobacteria were the most abundant microbe on the tourist path whereas Firmicutes were the most abundant microbes in areas.
less impacted by tourism. While our study did not examine species information, our MDS plot suggests differences in microbial communities between the tourist and non-tourist areas within the pools in Drac and similarities between non-tourist areas of different cave systems.

The MDS plots of microbial communities at each site by depth (Fig. 4) indicate varying degrees of biological gradation. Drac Delícies showed more biological gradation with depth than any of the other three sites whereas Drac Martel appeared to have no biological gradation. This most likely has to do with the amount of perturbation of the water column in Drac Martel due to tourist traffic. This analysis suggests that the drivers of microbial community gradation varied from site to site, and could be due to differences in the amount of mixing between fresh and salt water from different sources, freshwater inputs at Drac Negre, and/or water column mixing due to boat traffic at Drac Martel.

**CONCLUSIONS**

This study documented distinct biogeochemical differences between each site and depth in sampled water columns from two caves. Some of the chemical gradients observed within the sampled caves can be explained by simple mixing of surface fresh water with Mediterranean-derived salt water although data from Drac Negre indicates increased fresh groundwater input at that site. Not all chemical constituents followed a similar mixing pattern, indicating a complex hydrological model that needs further study. We found biological community differences with depth at all of the sites except for Drac Martel (Table 4). The biological gradients formed in Vallgornera, Drac Negre, and Drac Delícies are most likely due to the lack of water perturbation whereas the lack of biological gradients at Drac Martel is most likely due to mixing of the water by boat traffic.

Estimated total abundance data suggests that Archaea are the most prevalent component of the microbial communities in the sampled cave systems. Microbial eukaryotes represent an order of magnitude fewer microbial organisms than Archaea suggesting that nutrient limitations and/or other environmental factors may play a role in their low abundance. At Drac Negre, which was the only site with significant amounts of microbial eukaryote DNA, there appears to be an inverse relationship between the amount of microbial eukaryote DNA and prokaryote DNA with depth, suggesting predation of microbial prokaryotes by eukaryotes. Estimated total abundance data also suggests biological gradations at all sites with depth except for at Drac Martel. Within Drac, the different pools appear to support vastly different quantities of microbes. However, estimated total abundance data showed that there were no significant differences between Drac Martel and Vallgornera suggesting that these two sites may be operating under similar ecological constraints.

Relative species abundance data suggests that Archaea have the highest species richness within the sampled cave systems while microbial eukaryotes had the lowest species richness, similar to the estimated total abundance results. Drac Delícies showed far lower bacterial species richness than the other sites. The unique archaeal communities in Drac Negre and the unique bacterial communities in Drac Delícies

![Fig. 4. Multidimensional scaling plot showing community structure distribution of all sites and depths. Symbols with the same shape, color, and number represent replicate samples. Numbers within each sample symbol refer to the depth at which the sample was taken in meters. Lines around the data points indicate the percent similarity between samples contained within the line.](image-url)
suggest a separation of biological communities into distinct niche habitats within the same cave system.

The estimated absolute abundance data suggests that there are distinct communities inhabiting different ecological niches that may be dependent on chemical gradients within the water column. Distinct differences in both water chemistry (Fig. 3) and microbial communities (Table 3 and Fig. 4) are seen between all three sites within Drac despite their close proximity to each other. Drac Negre had the highest estimated total abundance of microbial eukaryotes of all the sites and was significantly different compared to the other three sites. The differences seen in the microbial communities of Drac may be due to freshwater inputs at Drac Negre and/or the introduction of exogenous biota and/or increased nutrients brought in by tourists in Drac Martel.

Our findings suggest that Drac Negre and Vallgonerma have biological gradients that are less developed than Drac Delícies, but more developed than Drac Martel, suggesting differences in hydrological patterns between the systems. The MDS plot of estimated absolute abundance data shows a high degree of similarity between Drac Delícies, Drac Negre, and Vallgonerma even though Vallgonerma is approximately 57 km to the southwest. This suggests there could be a biological connectivity between the spatially disconnected cave systems found on the island of Mallorca. Long-term studies incorporating more detailed species information and hydrological characteristics of the caves on the island of Mallorca are needed to determine the extent of connections between the spatially separated systems.

ACKNOWLEDGEMENTS

We thank the administration of Coves del Drac (Porto Cristo) who facilitated research in the cave. We also thank Antoni Merino, Emily Jackson, and Laura del Valle Villalonga for assisting with sample collection and field work.

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Fossil Vertebrate Database from Cova des Pas de Vallgornera (Llucmajor, Mallorca)

Anna Díaz1*, Pere Bover2, and Josep Antoni Alcover2*

1 Freelance biologist, Sineu, Mallorca, Spain
2 IMEDEA (UIB-CSIC), C/Miquel Marquès, 21, 07190, Esporles, Spain

Abstract: The data set presented in this paper includes the fossil fauna collected in the cave named Cova des Pas de Vallgornera (CPV), located on the southern coast of Mallorca (Balearic Islands, Spain). It holds 1481 catalogued items, 97.5% identified at species level. Mammalia, Aves, Reptilia, and Amphibia are represented in the Database. The fauna collected in the cave includes the three endemic mammals present on Mallorca during the Early Pleistocene (Myotragus aff. kopperi, Hypnomys onicensis, and Nesiotites aff. ponsi). There are also represented two taxa of Chiroptera (Rhinolophus aff. mehelyi and Pipistrellus sp.), 16 taxa of birds (6 of them identified at species level), one Reptilian taxon (Podarcis sp.), and one Amphibian taxon (Discoglossus sp.). Most fossils were collected during a single excavation campaign of 3 days (28-30th May, 2010). A few remains were obtained in two previous visits to the cave, in 2006 and 2009. All the specimens are curated and documented at the Vertebrate Collection of the IMEDEA [Institut Mediterrani d’Estudis Avançats (CSIC-UIB)]. The assemblage of CPV fossils is a part of the paleontological collection IMEDEA-PALEOVERT, included at the GBIF portal.

Keywords: fossil vertebrates; Cova des Pas de Vallgornera; Myotragus; Myotragus aff. kopperi; Nesiotites aff. ponsi; Hypnomys onicensis; Rhinolophus aff. mehelyi; Athene vallgornerensis; Discoglossus; podarcis

Received 15 October 2013; Revised 26 November 2013; Accepted 8 May 2014

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INTRODUCTION

The goal of this paper consists on a general description of the DataBase built on the vertebrate palaeontological material obtained from Cova des Pas de Vallgornera (Llucmajor, Mallorca). It includes information on the site, collecting methods, recorded specimens, taxonomic identification, and conservation procedures. The dataset can be consulted in the Spanish GBIF node IPT:
http://data.gbif.org/datasets/resource/13091

PROJECT DETAILS

Project title
Excavació i estudi dels materials procedents de la Cova des Pas de Vallgornera (Llucmajor, Mallorca). Primera fase.

Personnel
Pere Bover (leader of the Project), Josep Antoni Alcover, Alex Valenzuelu.

Funding
Consell Insular de Mallorca [infrastructure funding]; IMEDEA (UIB-CSIC) [expedition funding]; Research Project CGL2012-38087 [Dirección General de Investigación Científica y Técnica, Spanish Ministerio de Economía y Competitividad] [research funding].

TAXONOMIC COVERAGE

General taxonomic description coverage
Most of the taxa from CPV are Mammalia (97.1% of the catalogued items) followed by Aves (1.9%), Reptilia (0.8%) and Amphibia (0.2%). It is worth mentioning here that the data set contains the type material of an extinct species of little owl from the Early Pleistocene of Mallorca (Athene vallgornerensis Guerra et al., 2012).

The collection includes 23 taxa and 97.5% of the specimens are identified at a species level. Myotragus aff. kopperi is the most represented species in the database (897 catalogued items). The preservation of material is very good, allowing even detailed analyses on the teeth replacement and morphology using computerised tomography scan (Jordana et al., 2013).
**Taxonomic ranks**

Class
Mammalia, Aves, Reptilia, Amphibia.

Order
Cetartiodactyla, Rodentia, Eulipotyphla, Chiroptera, Anseriformes, Falconiformes, Gruiformes, Charadriiformes, Columbiformes, Strigiformes, Passeriformes, Squamata, Anura.

Family
Bovidae, Gliridae, Soricidae, Vespertilionidae, Rhinolophidae, Anatidae, Accipitridae, Falconidae, Rallidae, Scoplophacidae, Columbidae, Tytonidae, Strigidae, Corvidae, Fringillidae, Turdidae, Lacentidae, Discoglossidae.

Genus

Species
Myotragus aff. kopperi, Hypnomyx onicensis, Nesiotites aff. ponsi, Rhinolophus aff. melheyi, Athene vallgonerensis, Pica moureare, Columba palumbus, Accipiter nisus, Tyto balearica, Scolopax rusticola.

**Spatial and temporal coverage**

General spatial coverage
Cova des Pas de Vallgoneran is an extensive maze cave (more than 70 km) located on the south coast of Mallorca (Balearic Islands). Coordinates of the CPV entrance: 39°22′0″N, 2°52′25″E, Datum: WGS84. It is considered one of the 30 longest caves in the world. It was discovered in 1968 in the course of a drilling carried out for the construction of a cesspit. CPV is the longest karstic system of a cesspit. CPV is the longest karstic system in the Balearics. The fossiliferous deposit is located at the end of a passage known as Galeria del Tragus and Sala del Col-lapse. For a more extensive description see Merino et al. (2011, 2014) and Bover et al. (2014). The cave is under protection by the Balearic Conselleria de Medi Ambient, the Ministry of Environment of the Government of the Balearic Islands. It was declared Site of Community Importance within the Natura 2000 Network (European Council Directive 92/43/EEC, no. ES5310049).

Global Coordinates
39°8′24″N and 39°36′36″N Latitude; 2°31′12″E and 3°8′60″E Longitude

Temporal coverage
Early Pleistocene (see Bover et al., 2014)

Recovery dates
2006; 9th May 2009; 28th May 2010 – 30th May 2010

METHODS

After collection, the material was packed in protected containers that were carried outside the cave by a group of volunteers. The fossils have been identified by taxonomists of the IMEDEA (Pere Bover, Carmen Guerra and Josep Antoni Alcover), the University of the Basque Country - Euskal Herriko Unibertsitatea (Juan Rofes) and the Universidad de Zaragoza (Gloria Cuenca-Bescós).

The skeletal remains of Myotragus from CPV were generally in good preservation state. Most of bones are complete. From a conservation and restoration point of view, major issues are related to sediment presence. This sediment, which partially or fully covers some bones, can be present as: 1) a thin layer of calcium carbonate (less than 5 mm thick), or 2) as thick concretions, covering both the bone and the surrounding soft or hard clay. There is a number of cracked and broken bones. Some of these bones have been consolidated with acrylic resin (Paraloid B-67), and attached with nitrocellulose adhesive (Imedio). Some bones (like humeri and femora) have a more fragile consistency (with some powdering traces in both fracture plans and spongy tissue), while other bones, like jaws and metapodials, are very well preserved (they are very compact and without powdering traces).

The removal of the remains of sediment on the bones from CPV was mainly performed mechanically. Depending on the hardness and volume of sediment, vibroincisor, knife, punch and metal or wood poles were used. However, in many cases, the sediment was previously softened with distilled water and/or alcohol applied with brush or swab.

Only the parts of the bones with powder damage (especially in areas with cracks and fracture planes) were consolidated. In these cases an acrylic resin (Paraloid B-67) was used, diluted 5-10% in acetone, which was applied with a brush or by dripping. Both cellulose nitrate (Imedio) and acrylic resin (Paraloid B-67) were used to hold the fragments. When the fragments to be glued were small or lightweight only Paraloid B-67 was used. A professional conservator (B. Font) performed all the conservation work.

All the material was numbered to be included at the IMEDEA Vertebrate Collection, and it is currently preserved in plastic bags, plastic boxes and cardboard boxes.

All the material has been digitalized and included in the IMEDEA vertebrate Collection. To guarantee the quality of the database in the GBIF network, the CPV dataset has been standardized following the standard Darwin Core version 1.2 for information exchange of natural history collections, and it has been later analysed to correct any possible error with the Darwin Test (an application to test and check data in the Darwin Core format, developed and supported by the Coordination Unit of the Spanish GBIF national node [http://www.gbif.es/darwin_test/Darwin_Test.php](http://www.gbif.es/darwin_test/Darwin_Test.php); Ortega-Maqueda & Pando, 2008). Among the checks performed, errors of omission, typographic, convention and consistency were analysed.
STUDY AND SAMPLING DESCRIPTION

All the specimens were obtained in CPV. They were mainly obtained in Galeria del Tragus and the subsequent Sala del Col·lapse. The Galeria del Tragus is accessed through a 4h underground trip, including one hour of swimming and 3h walking, negotiating several narrow passages.

The Galeria del Tragus consists of a 270 m long, 10 m wide and 10 m high gallery, connected through a narrow passage to the Sala del Col·lapse, a hall c. 40 x 10 m sealed by a huge collapse of blocks and sediment, probably occurred shortly after the deposition of the bones. This gallery was in contact with the exterior during the Early Pleistocene, allowing the deposition of the bones at least partially through water transport.

The excavation campaign was carried out during 28-30th May 2010. All the obtained specimens were labelled and protected. The material was mainly collected by hand and situated in the topographical survey indicating the number of the closest established section. Material partially covered by flowstone was extracted from the deposit through mechanical methods. Associated skeletons have been individualized.

DATASETS

Parent collection identifier
IMEDEA-PALEOVERT

Collection name
IMEDEA

Collection identifier
7f591d18-f762-11e1-a439-00145eb45e9a

Specimen preservation method
Dried specimens, when necessary consolidated with acrylic resin (Paraloid B-67), and attached with nitrocellulose adhesive.

Curatorial unit
1481 (FossilSpecimen)

Object name of dataset
Darwin Core Archive Fossil Vertebrate Database from Cova des Pas de Vallgornera (Llucmajor, Mallorca)

Character encoding
UTF-8

Format name
Darwin Core Archive format

Format version
1.0

Distribution

ACKNOWLEDGEMENT

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Unidad de Coordinación de GBIF.ES, CSIC. Ministerio de Educación y Ciencia, España