Upper Pleistocene deposits and karst features in the littoral landscape of Mallorca Island (Western Mediterranean): a field trip

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1. Introduction

The two-day fieldtrip –Figure 1– will visit the littoral landscapes of Mallorca Island with its prominent Pleistocene deposits and karst features. The presence of the MIS 5 marine terrace sequences, represented by eolianites, paleosoils, and beach deposits will be examined at the following two locations: Palma Bay (***Es Carnatge***) and NE Alcúdia Bay (***Es Caló-Caloscamps***). The Upper Pleistocene aeolianite cliffs shape most of the present-day littoral landscapes. Their complex depositional architecture along with the imprints of the extinct ruminant goat *Myotragus*, will also be observed (***Estret des Temps***). The tour of the most remarkable Pleistocene outcrops will be complemented with visits of several cave sites in the Migjorn area (***Cova des Pas de Vallgornera***) and along the eastern coast of the island (***Portocristo*** caves and ***Coves d'Artà***). At these locations, the Pleistocene sea level oscillations are recorded inside the littoral caves in the form of phreatic overgrowths on speleothems. The topic of low- and high-sea stand will be discussed in the light of the present knowledge of paleoclimate and Pleistocene sea level oscillations in the Western Mediterranean basin.

1.1 Geology and geomorphology of Mallorca Island: an introduction

The island of Mallorca, located in the western Mediterranean Sea, is the largest of the Balearic Archipelago covering an area of 3,640 km^2. These islands are the eastern emergent part of the Balearic Promontory, which is a mostly submarine relief extending from Cap de la Nau (Alacant) in the Iberian Peninsula, to NE of Menorca.

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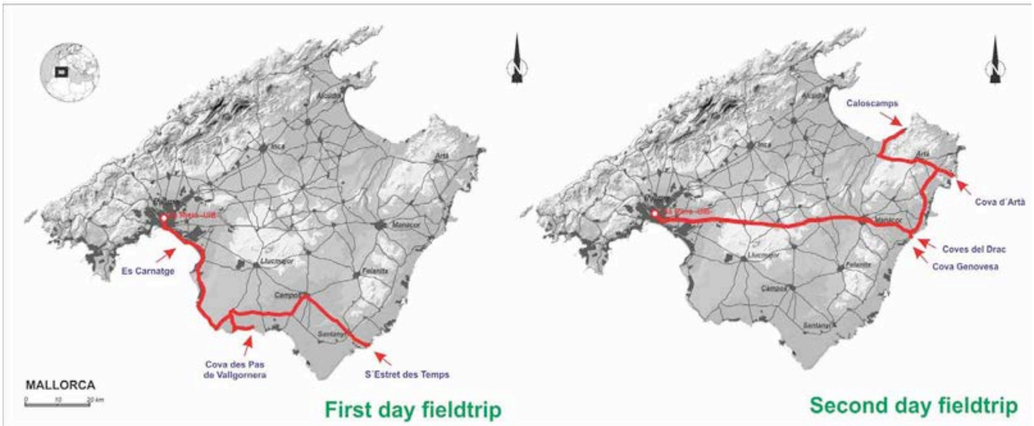

Figure 1. Location map showing the two-day field trip that will be dedicated to the observation of the littoral landscapes of Mallorca Island where Pleistocene deposits and karst features are exposed.

The Balearic Promontory is 440 km long and is limited by steep slopes which clearly separate it from the adjacent deep seas: the Algerian basin in the E and SE and the Catalan-Balearic basin in the W and NW, which in turn isolate the Balearic lslands from Africa and lberia, respectively. It corresponds to a thickened continental crustal unit forming the NE continuation of the Alpine Betic thrust and fold belt generated during the Middle Miocene (Fallot, 1922; Gelabert *et al*., 1992). The structure of the Island of Mallorca trends NE-SW, and represents the north-eastern extension of alignments of the Subbetic Cordillera of southern Spain (Fontboté *et al*., 1990) along with a series of tectonic thrusts from the southeast. Mallorca is part of the folded and thrusted belt resulting from the continental collision between the African and the lberian plates. The collision took place between Upper Cretaceous (approx. 84 Ma) and Middle Miocene (15 Ma), and had an effect on the Betics and the Balearics. It was caused by the anticlockwise rotation of Africa and Arabia as a response to the South Atlantic opening (e.g., Olivet et al., 1984). Within this Alpine realm, post-orogenic deposits rest discordantly over the Mesozoic to Miocene rocks that were thrusted and folded during the Alpine orogeny.

The geological structure as well as the lithological distribution shape the overall morphology of the island (Fornós & Gelabert, 1995), in which three major physiographic and structural units can be differentiated: Serra de Tramuntana, El Pla, and Serres de Llevant (Figure 2). Mallorca's present day topography can be explained mainly as the result of normal movements along a series of NE-SW faults (between Middle Miocene and Quaternary), which created a set of horsts and grabens corresponding to the ranges and plains (depressions), respectively.

The highest mountain range, known as Serra de Tramuntana, consists of folded and thrusted deposits, mainly of Mesozoic age aligned in a NE-SW direction. It is on the northwestern side of the island where the main peaks stand (e.g., Puig Major 1,445 m). The Serres de Llevant mountains in the east, show more gentle relief despite the fact that they are also composed of Mesozoic deposits (more dolomitic) and underwent the same alpine tectonic influence. Lastly, nested in the central part of the island, El Pla area is formed by broad and flat Neogene post-orogenic deposits.

The stratigraphic history of Mallorca (Gibbons & Moreno, 2002; Vera, 2004) extends from Carboniferous to Quaternary, with an important gap at the beginning of Tertiary (Figure 2). The sedimentology of the existing deposits is highly complex reflecting different depositional environments, such as lake, littoral, platform, slope, and pelagic. The most remarkable common feature to almost all deposits is their carbonate composition; siliciclastic materials are scarce. This reflects, not only the potential representation of the stratigraphic series, but also the presence of outcrops which can be mapped on the surface. Sitting discordantly over a small outcrop of Carboniferous pelites, the Mesozoic sequence is over 1,500 m thick, with the upper 1,000 m consisting mostly of limestones. The Mesozoic deposits extensively outcrop in Serra de Tramuntana, Serres de Llevant, and in the small hills of El Pla. The steepest topography of these ranges is composed of Jurassic limestones and dolomites, thus hosting the most spectacular karst features, especially exokarst. The Cenozoic is widely represented on the island, having a total thickness of over 1,500 m (Ramos-Guerrero *et al*., 1989). Two main units can be distinguished: a pre-, and syntectonic unit (Middle Eocene to Lower Miocene; Langhian) and a post-tectonic one (Middle Miocene to present). The first unit outcrops in Serra de Tramuntana, Serres de Llevant, and irregularly, in the central part of the island. The second unit, occupies most of the depressed areas in the Pla de Mallorca, as well as those known as "*Marines*" in the Migjorn region.

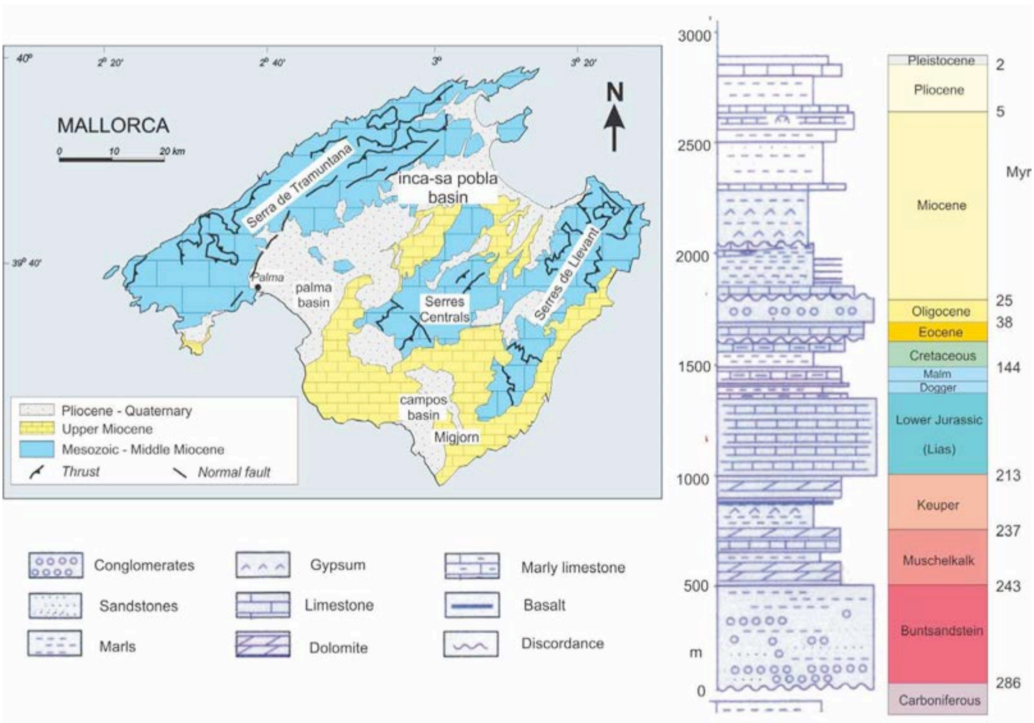

Figure 2. Simplified geological map of Mallorca and synthetic lithostratigrapical column (modified from Rodríguez-Perea, 1992).

Plio-Pleistocene deposits are abundant in Mallorca. They range from continental sediments (conglomerates, sands, and red silts) related to erosional processes of the highest mountain ranges on the island, to calcareous and fossiliferous sands corresponding to beach and dune deposits accumulated in coastal environments. The latter type reflects the sea-level oscillations over the Pleistocene time.

The presence of Quaternary deposits is especially important in the depressed areas (Neogene basins): the northern bays of Alcúdia and Pollença (north-eastern coast), the Bay of Palma (south-west), or the Campos Bay in the south of Mallorca. These are characterized by beach-dune-lagoon systems extending some km along the coastline, and are flanked by folded Jurassic and Cretaceous limestones (Figure 2). Quaternary marine, colluvial, fluvial, and aeolian deposits of variable thickness cover most of these outcrops. The Holocene deposits and all recent coastal dunes in these lowlands have been stabilized by shrub vegetation. Notches and littoral platforms, interpreted as marks corresponding to sea level high-stand, are conspicuous features in the southern and eastern parts of the island shaping the rocky coasts developed on Upper Miocene deposits.

1.2 Climate and biogeography

The climatic and biogeographical characteristics of the island are typical for the Mediterranean climate with very hot, dry summers and mild, wet winters. The annual

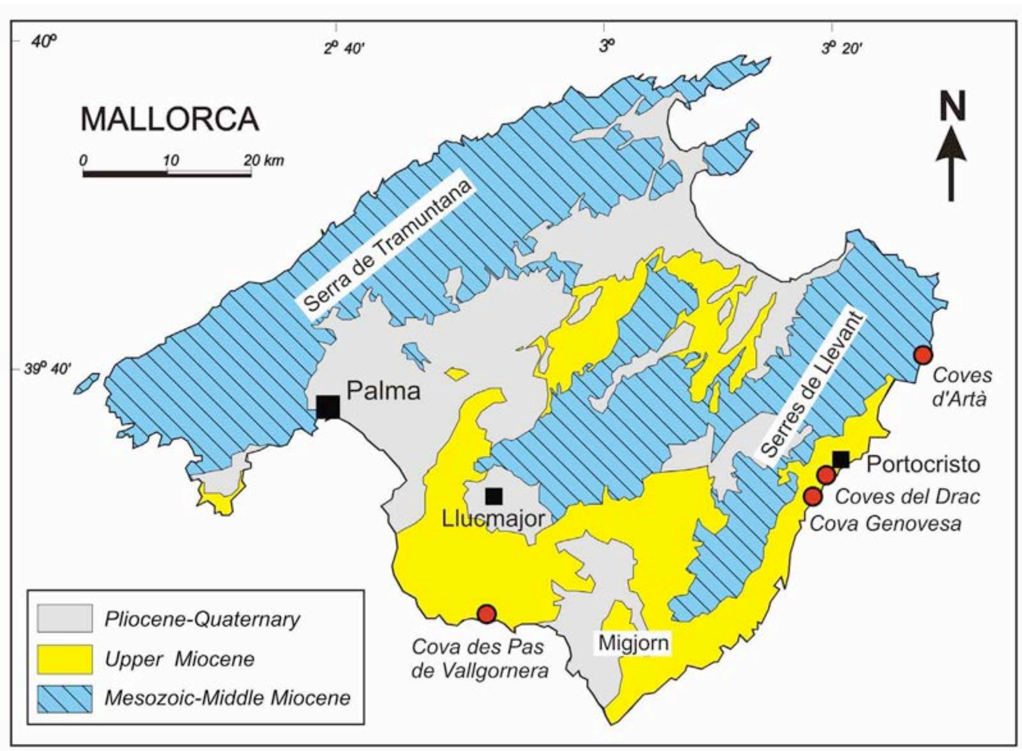

Figure 3. The main karst regions in Mallorca and location of the caves visited during the fieldtrip.

temperature oscillates around a mean of *ca*. 17ºC, with mean winter and summer values of *ca*. 10 and 25ºC, respectively. Average annual precipitation is ~500 mm with most of the rainfall in autumn (Guijarro, 1986). The northern bays are characterized by westerly and northerly winds (27% and 17% of the windy days of the year, respectively) blowing at speeds over 4 m/s (Servera, 1997). Plentiful sunshine and cooler seawaters favor well-development sea breeze fronts (Ramis *et al.,* 1990). These are very common from April to November, and occur almost every day during the summer. Wind speeds associated with sea breezes are generally at ~3 m/s, but values as high as 10 m/s are not uncommon (Ramis, 1998). From a biogeographically point of view, two clear Mediterranean vegetation communities are known on the island: *Quercus ilex*, *Cyclamini-Quercetum ilicis*, with boreal characteristics and abundant at mid-altitudes, and macchia and garrigue bushes, with *Oleo-Ceratonion, Hypericion balearici, Rosmarino-Ericion* mainly in the dry lowlands (Bolòs, 1996).

1.3 The karst regions of Mallorca

Some of the sites visited during this fieldtrip are littoral caves located along the southern and eastern coast of Mallorca, which are representative of the different karst regions of the island. These caves clearly illustrate geomorphological and hydrological connections existing between karst processes and littoral dynamics, and archive valuable records of the Pleistocene sea level history in the Western Mediterranean basin.

Based on the complex geological structure of the island (Fornós *et al*. 2002), three main karst regions can be distinguished in Mallorca: the Mesozoic limestone units of Serra de Tramuntana and Serres de Llevant and the Miocene unit of Migjorn (Figure 3). The presence of two parallel mountain ranges (Serra de Tramuntana and Serres de Llevant) is related to the Mid-Miocene alpine compression that mainly affected Mesozoic carbonate rocks, forming a complex system of folds and overthrusts. The show cave named Coves d'Artà –which will be visited during the second day fieldtrip– is located in the Jurassic limestones of Serres de Llevant and is a nice example of littoral cave developed in the tectonically complex settings of Mallorca mountains.

An extensive coastal platform of Upper Miocene (Tortonian-Messinian) reefal carbonates (referred too as the Migjorn region) develops along the southern and eastern coasts of the island (Figure 3). This unit constitutes the most important karst region with respect to cave development; some minor outcrops of Upper Miocene rocks are also present in the central part of the island. Besides the lithological homogeneity of the entire Migjorn region, important differences arise between the eastern coastal area (where a lot of caves develop near Portocristo village) and the extensive southern platform around Llucmajor where Cova des Pas de Vallgornera is located. The differences between both subregions are related to their hydrogeology (Ginés *et al*., 2009a), including in the case of the Llucmajor platform a more significant surficial extension along with the presence of some geothermal phenomena. Finally, some graben-related depressions parallel the mountain chains and are filled with Plio-Quaternary deposits.

2.1 Es Carnatge (Cala Pudent, "Camp de Tir" – Palma) Upper Pleistocene marine deposits
(J.J. Fornós, L. Gómez-Pujol & D. Vicens)

A continuous succession of Pleistocene deposits is exposed in the central part of the Palma coastal zone (Western Mallorca) (Figure 1), just at the head of the airport runway. From Sant Joan de Déu hospital to Can Pastilla low rock cliffs show piled beds of beach, eolian, and alluvial deposits with paleosols. The area, known in most of the papers as Camp de Tir, hosts two of the most international cited outcrops for the Pleistocene of the Mediterranean area: Cala Pudent and Es Carnatge.

The fieldtrip description starts at the Sant Joan de Déu Hospital and follows the path that runs parallel to the coast as far as the neighborhood of Can Pastilla village. Several stops along the path allow observing the Last Interglacial marine deposits at Cala Pudent and Es Carnatge that overlie a thick eolianite formation well exposed in the Son Mosson Quarry.

2.1.1 Introduction

The present basin of Palma was configured at the beginning of Quaternary times as an independent basin along a NE-SW trending through (Del Olmo & Alvaro, 1984; Benedicto *et al.*, 1993) resulting from the major distension faults that transformed the large-scale geological compressive structure of the island into a system of horsts and grabens. Two main fault systems limit the basin: the Palma fault (NNE-SSW) and the Sineu-Algaida and Enderrocat faults (NE-SW). Both systems acted since the Late Miocene and were active until at least Middle Quaternary times.

The Pleistocene outcrops of this area in the Palma Basin are under investigations since their first description by Muntaner (1957) and Cuerda (1957) (Figure 4a, b). Further exhaustive studies (Butzer & Cuerda, 1962, Cuerda, 1975; Cuerda, 1979) were carried out on this type-section for the Tyrrhenian marine levels that bear the classical thermophile senegalese fauna headed by the gastropod *Strombus bubonius*.

Apart from the Mediterranean Pleistocene chronology generated on the basis of the paleontological contents of Mallorca’s sedimentary deposits (op.cit., Tyrrhenian, Eutyrrhenian, etc.), many papers are devoted to improving the chronology of these deposits using U-series dating (Stearns & Thurber, 1965, 1967; Hillaire-Marcel *et al.*, 1996) and amino acid racemization –AAR– (Hearty *et al.*, 1986). Stratigraphic studies and synthesis concerning the sea-level high stands, coastal uplift, and hemispheric climate changes have been recently published by Zazo *et al*. (2003) and Bardají, *et al*. (2009), among others.

Following the field description of Silva *et al*. (2005), the Pleistocene sequence at Camp de Tir consists of four Last Interglacial marine units (MIS 5), separated either by reddish terrestrial deposits or erosional surfaces that overlie older terrestrial Pleistocene deposits mostly eolianites belonging to the penultimate glaciation (Riss), probably MIS 6 (Cuerda, 1989). Above the eolian deposits reddish clayey-silty sediments that include clasts of the underlying eolian units evolve to a well-developed red-clay paleosol. Finally, over an erosional surface, there are alluvial deposits composed of medium-size grains of silty sand with abundant bioclasts, continental

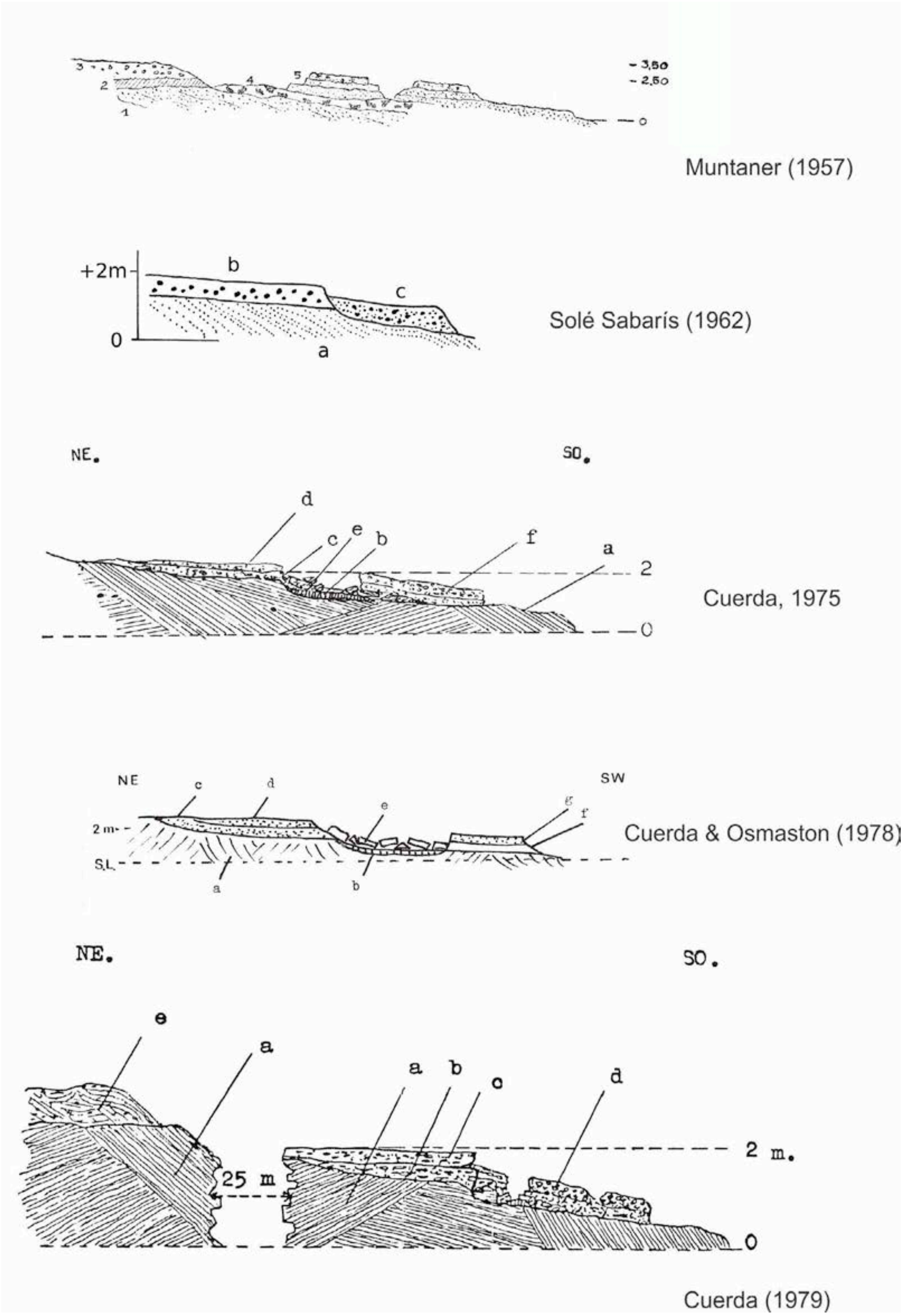

Figure 4a. Cross-sections historical evolution of the Es Carnatge Pleistocene deposits.

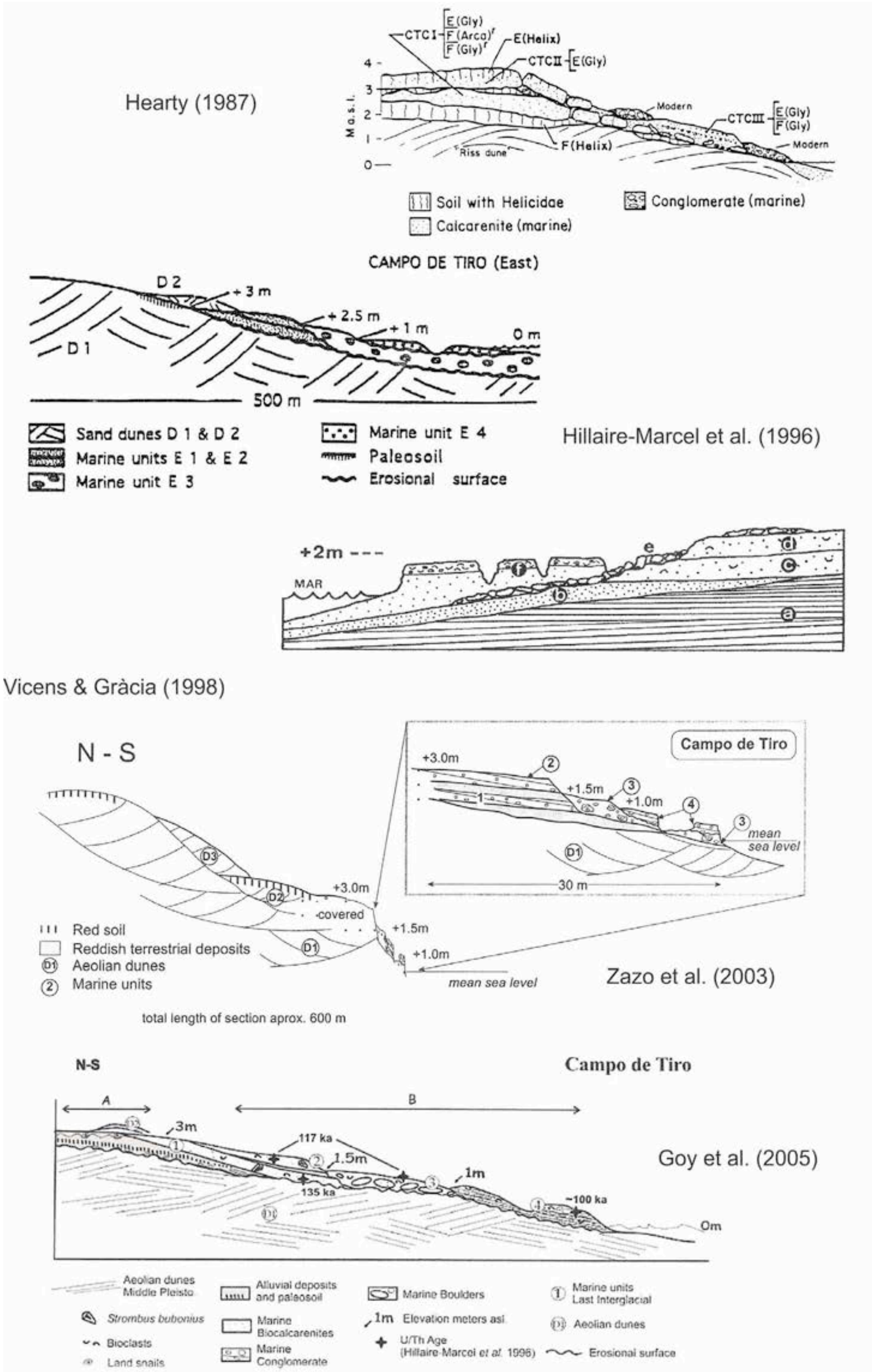

Figure 4b. Cross-sections historical evolution of the Es Carnatge Pleistocene deposits.

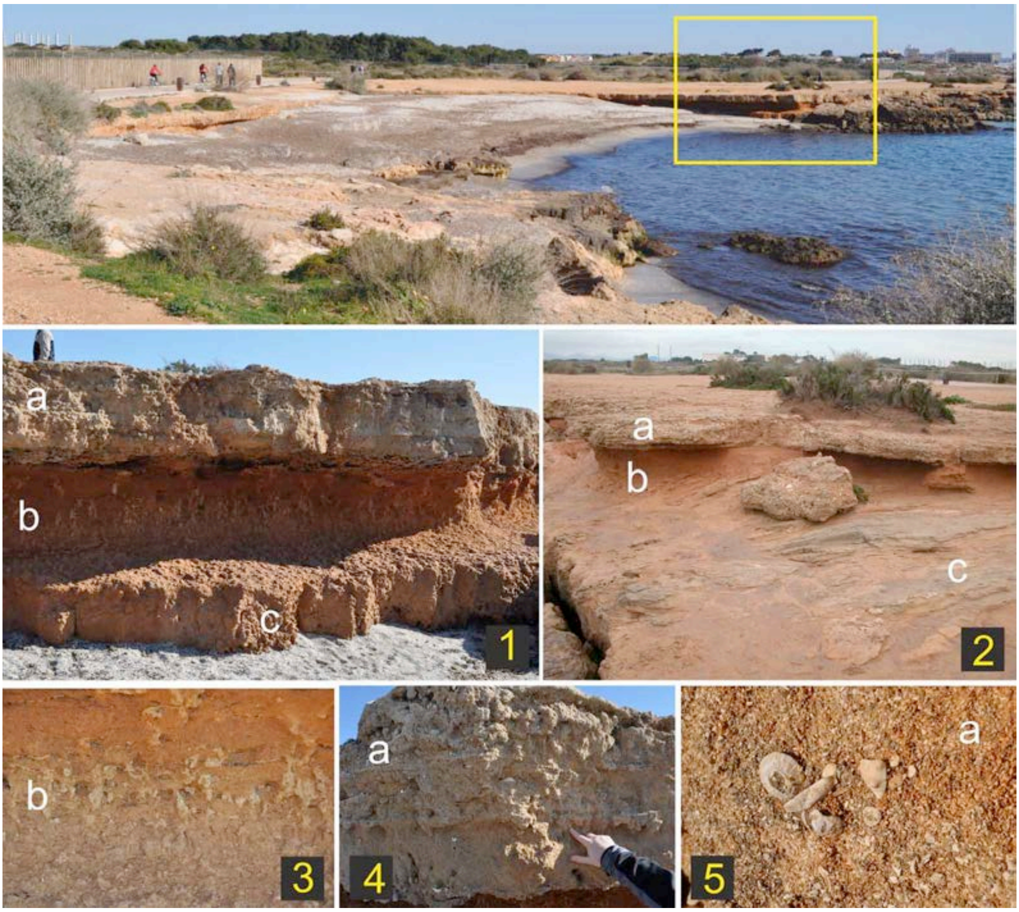

Figure 5. Panoramic view of the Late Pleistocene sequence at the east side of Cala Pudent (1, 2). From top to base (a) the marine levels (4, 5) corresponding to MIS 5e; (b) the paleosol (3); and (c) the MIS 6 eolianite (1, 2).

gastropods, and micrite cement. On top of the former entities, in an offlapping disposition the older Last Interglacial units develop, reaching to an elevation of +3 m above present mean sea level. They consist of a complex architecture formed by cemented biocalcarenites with cross bedding structure, which contains the classical warm climate "*senegalese*" fauna.

2.1.2 Cala Pudent

In a small cove (*cala*) east of Coll d'en Rebassa village and near the Sant Joan de Déu Power Station, two marine high stands represented by beach deposits can be observed over a palaeosol that lies unconformably over an eolianite unit (Figure 5).

First described by Muntaner (1957) and Cuerda (1957) who made the paleontological description, two different beaches containing *senegalese* thermophile fauna of Eutirrhenian (MIS 5e) age were differentiated in the west side of the cove. Nowadays, these two levels are no longer visible being destroyed at the time when the littoral walkway and the connection pipes that bring the gas to the electrical power plant were built.

In the east side of the cove only one of these beach levels is visible (Cuerda, 1979). The sequence at this location (Figure 5) starts with a deposit composed of well-sorted medium to coarse sand interpreted as eolianites. Following the coast, a low cliff allows the observation of a prominent lamination that shows the typical eolian large-scale cross bedding. On top of this level or over irregular erosion surfaces, a sandy yellowish red paleosol develops. It contains abundant molluscan terrestrial fauna that includes the extinct *Chondrula gymnesica*. Abundant carbonate rhizocretions can also be observed.

At +3 m above present sea level, a calcarenite unit nearly 1 m in thickness is overlying the paleosol. It corresponds to a coarse to very coarse sandstone that is rich in bioclastic fragments. It mainly contains fragments of molluscs, although the presence of whole shells, both gastropods and bivalvia can be clearly observed (Figure 5). Cuerda (1979) describes for this level the characteristic *senegalensis* fauna. The most important are: *Barbatia plicata*, *Hyotissa hyotis*, *Cardita senegalensis*, *Patella ferruginea*, *Monodonta lineata*, *Strombus bubonius*, *Polinices lacteus, Cymatium costatum*, *Bursa scrobiculator*, *Cantharus viverratus*, and *Conus testudinarius*.

From a sedimentological point of view, this marine level progresses inland from a foreshore to a continental deposit. It includes reddish clayey silts, the grain size texture becomes to middle or fine sand, marine fauna gradually disappear and is substituted by terrestrial fauna, mainly dominated by the genera *Helicella*.

Although this unit was dated by means of U/Th to 200 ka (Stearns & Thurber, 1965) (the exact location of the sampled site is unknown), the present fauna and the lateral correlation with the units at Es Carnatge (see next paragraph) warrants the attribution of this level to the Euthyrrenian.

2.1.3 Es Carnatge

Walking eastwards along the coast, the Last Interglacial marine units can be tracked for another 300 m, being especially interesting the sequence that crop out at the base of

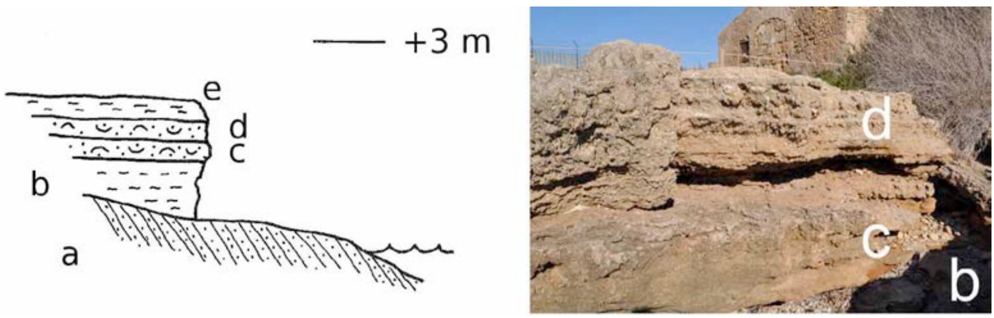

Figure 6. Two marine levels (c, d) separated by a thin silty level over a reddish paleosol (b) can be observed at the cliff near the Es Carnatge houses. The section was dated by Hillaire-Marcel *et al*. (1996) to 135 ka (lower unit) and 117 ka (upper unit), respectively.

the old building (now in ruins) of Es Carnatge (slaughterhouse). Two marine units (units 1 and 2 of Silva *et al*., 2005) located at +3 m asl are visible over the reddish silty paleosol. They consist of two beds, 1-m thick each, separated by a discontinuous thin layer of red silt with angular clasts (Figure 6). The two units were interpreted as foreshore deposits and are composed of pebble-rich fossiliferous calcarenites, well cemented by sparite having a vadose fabric. The fossil content show abundant warm *senegalese* fauna. Apart from the typical *Strombus bubonius* there are other species such as *Brachidontes senegalensis, Hyotissa hyotis, Cardita senegalensis, Polinices lacteus, Naticarius turtoni, Cantharus viverratus,* and *Conus testudinarius* (Cuerda, 1989).

Based on the chronological analyses carried out by Hearty *et al.* (1986) and Hearty (1987) using allo/isoleucine and U/Th measurements (alpha spectrometry), these units were assigned to aminozone E. From the very same two units, Hillaire-Marcel *et al.* (

1996) reported 34 additional U-series TIMS measurements. The ages for the lower unit cluster around 135 ka, whereas for the upper unit they were around 117 ka, thus both units belong to the Last Interglacial.

These two MIS 5e units are cut by a clear erosion surface giving way to a new scattered and complex unit that is located at +2.5 m amsl (Figure 7). It varies laterally from a well-cemented marine breccia to conglomerate that shows large sub-rounded to sub-angular blocks and pebbles clearly reworked from the other units (Figure 8). The matrix content is a reddish clayey-silt with micrite cement and abundant faunal content. The fossils analysis shows an abrupt change marked by the disappearance of *Strombus bubonius* and part of the *Senegalese* faunal assemblage. Zazo *et al*. (2003) interpreted the deposit as a beach setting (foreshore to shoreface).

The chronological attribution of this unit is somewhat problematic. The U/Th age measurement reported initially by Stearns and Thurber (1965) indicated an age of ca. 75 ka, whereas Hillaire Marcel *et al.* (1996) who used TIMS technique assigned it within unit 2 (117 ka, end of MIS 5e). After these studies, additional investigations focusing on lithological aspects of the unit and its faunal content were carried out by Zazo *et al.* (2003), Silva *et al*. (2005), and Bardají *et al*. (2009). Their findings suggest an intensification of storm events and a change in the sea surface temperature (probably cooler) by the end of MIS 5e. The occurrence of two different high stands (unit 2 and

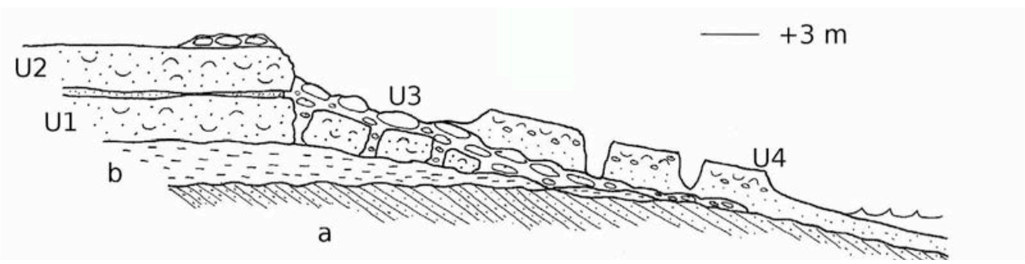

Figure 7. Sketch of the Late Pleistocene units at Es Carnatge; a) basal eoliante (MIS 6); b) paleosol; U1 and U2) marine units corresponding to MIS 5e; U3) Marine reworked unit, MIS 5c or 5a?; and U4) beach sands and conglomerates corresponding to MIS 5a.

Figure 8. The sedimentary architecture and characteristics of the marine unit U3 (see text for explanation).

Figure 9. Panoramic view at Es Carnatge showing the relationships between the basal eolianite (a) and the uppermost Pleistocene marine units (U3 and U4). Below, details of the alternating sequence of conglomerates and sandstones of U4 (MIS 5a).

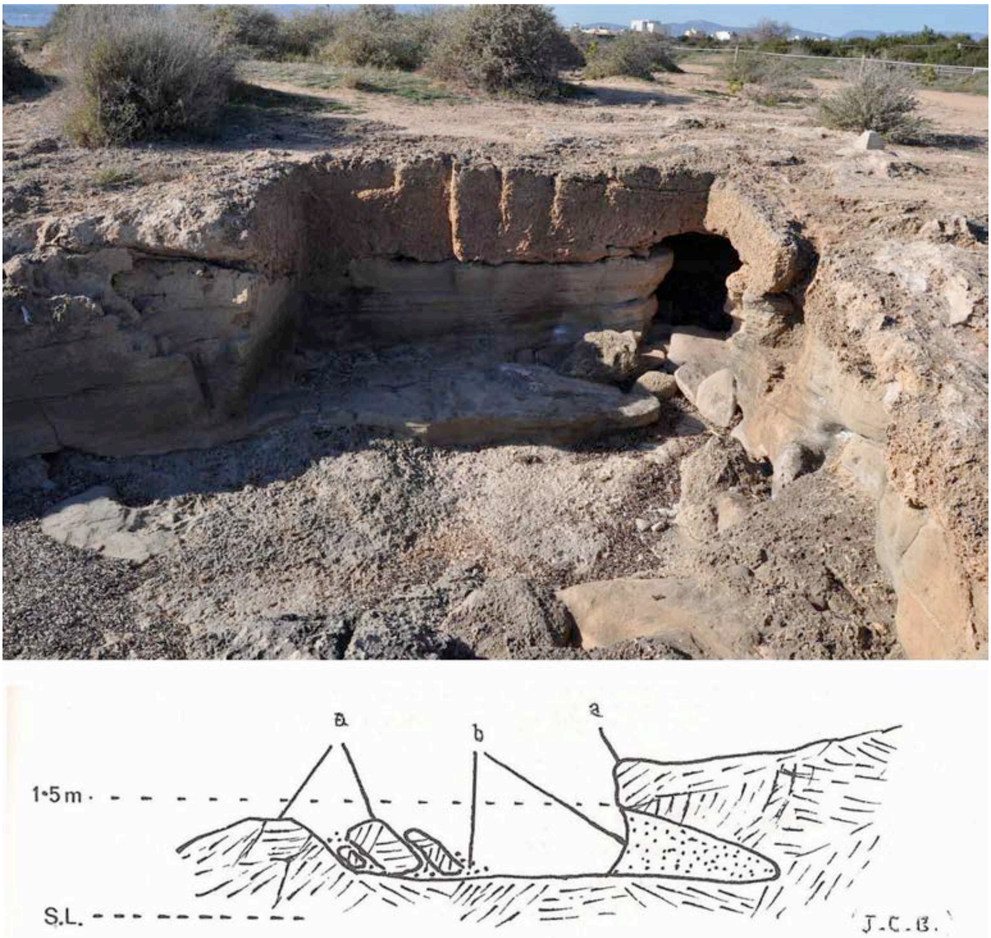

Figure 10. General view and sketch section from Cuerda & Osmaston (1978) showing the infilling with sandstones (MIS 5a) of the notch and associated marine erosion cave cut into the basal MIS 6 eolianites.

unit 3) with the same age (117 ka) also points to rapid sea-level change and instability at the end of this isotopic substage. Hearty (1987) placed this unit into the aminozone E, suggesting however, the possibility that it might be younger (MIS 5c or even 5a). The clear presence of material reworked from the previous units explains the confusion regarding the age of this level.

A younger marine deposit (MIS 5a) covers all these units and reposes over an erosional surface (Figure 9). It consists of finely laminated bioclastic sandstones at the base that changes in the upper part to beach conglomerates. Faunal contents do not show the typical warm assemblage (*Strombus bubonius* is missing), being similar to the present day fauna. The only exception is the abundant occurrence of *Acar plicata*, a species that was not described in the Late Holocene deposits of Mallorca (Cuerda, 1989; Goy *et al.*, 1997). Cuerda (1975) also revealed the presence of *Cantharus viverratus* and *Conus testudinarius.* The U/Th age data published by Hillaire Marcel *et al.* (1996)

scatters around 100 ka, but the elevation of this horizon (~ 1 m amsl better fits the sea level position during MIS 5a proposed by Dorale *et al*. (2010) for Mallorca.

An erosion surface with a very well developed notch (Cuerda & Osmaston, 1978) is associated with a sea cave (Figure 10) that can be observed near the Son Mosson quarries (see next paragraph). Located around 1.5 m amsl, the erosive cavity is filled in its western side with the laminated bioclastic sandstones attributed to MIS 5a. In the eastern side, attached to the small paleocliff (2 m in height), an accumulation large of boulders detached from the eolian basal unit are embedded in the same bioclastic sandstone unit. The marine fossils present at this site do not show the typical warm *senegalese* fauna.

2.1.4 Son Mosson Quarry (Cova des Bufador, Vista Alegre)

Once the head of the airport runway is passed, in the vicinity of the Can Pastilla village there are several great exposures of eolian Pleistocene deposits showing complex sedimentological architecture (Figure 11). The occurrence of few small abandoned quarries enables to observe in 3D the evolution of the dunes (Clemmensen *et al*., 1997, 2001). These Pleistocene eolian calcarenites (known as *marès* by local people) can be found all along Mallorca's coastlines. They were exploited as raw material for building ssince the Roman times until the second half of the last century. Cuerda (1989) considers that the eolianites formed during the penultimate glacial period (Riss; probably MIS 6).

Figure 11. Panoramic view near Son Mosson Quarry showing the arrangement of all the Late Pleistocene units: a) Basal eolianite (MIS 6); b) paleosol; U2) MIS 5e; U3) marine reworked unit; U4) marine sandstone from MIS 5a; and d) the uppermost eolian unit.

Eolianites are composed of medium to coarse sand and show a very good degree of sorting. Well-defined lamination that display the typical large-scale cross bedding are visible in the walls of several quarries (Figure 12). They normally include trough-shaped and even tabular sets, 1 to 4 m in thickness. Occasionally, they can reach more than five meters with foresets dipping as much as 30º. Ripples at the surface of the lamina are also visible, as well as rizhocretions disturbing the lamina. In some places the presence of rizhocretions is so abundant that they obliterate the entire sedimentary structures. Track ways of invertebrate fauna are common, but not as frequent as the tracks and track ways of the vertebrate *Myotragus balearicus* found in other Upper Pleistocene eolian deposits of the island (e.g., s'Estret des Temps; Fornós *et al*., 2002).

Myotragus is an endemic fossil goat that is present on the islands of Menorca, Mallorca, and Cabrera. It lived in the Balearics from Mid-Pleistocene up to the Holocene and it is presumed that its ancestors colonized the islands during the Upper

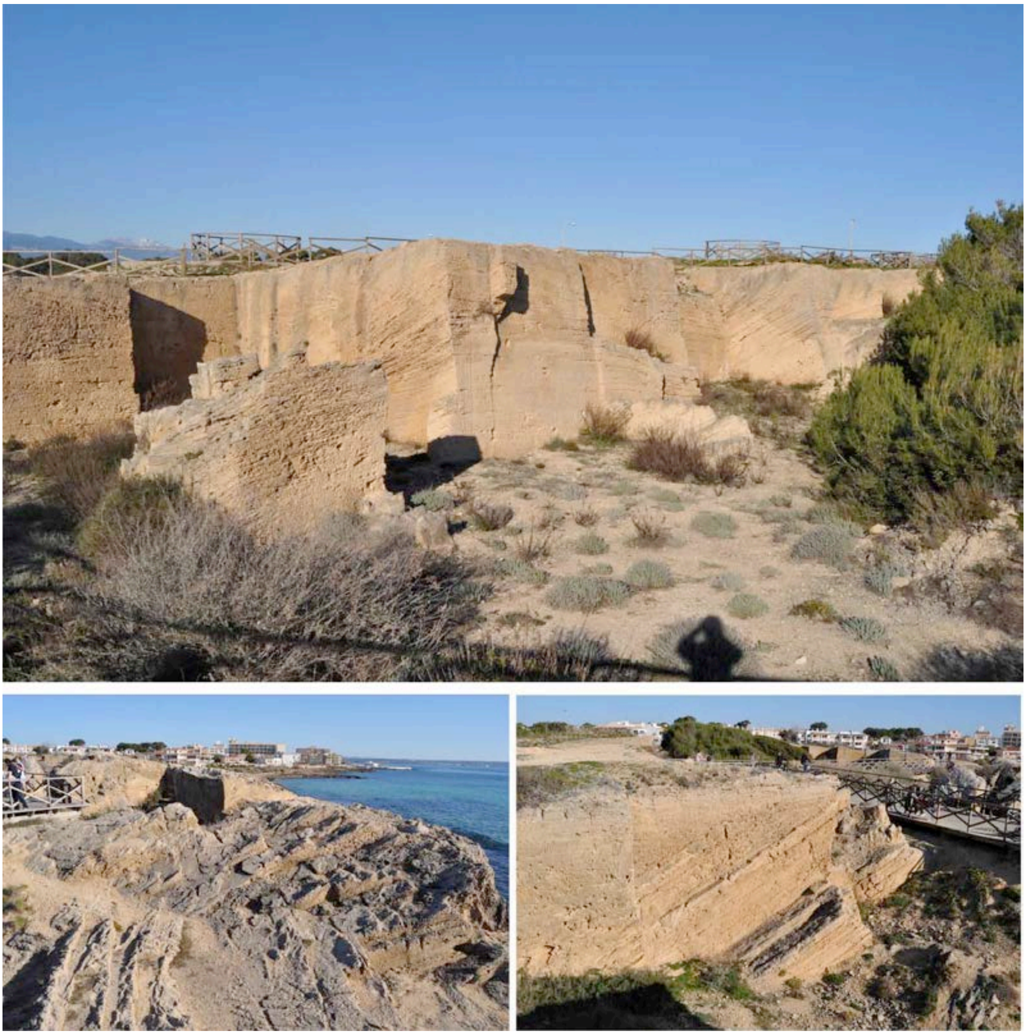

Figure 12. Son Mosson Quarry where the MIS 6 eolianite are exposed.

Miocene (Messinian Salinity Crises) when these were connected to the continent. *Myotragus* evolved rapidly in the absence of predators until the arrival of the first humans around 5000-4000 yr BP (Alcover, 2004).

2.1.5 Summary

At es Carnatge site, the architecture of littoral marine and alluvial and eolian continental deposits with paleosols reflects the complexity of the Last Interglacial. Alternating marine high and low stand phases separated in between by terrestrial deposits or erosional surfaces are present. Accurate sedimentological and faunal analysis corroborated with the chronological data allowed defining a precise stratigraphy that confirms the existence of at least three high sea level stands during MIS 5. Two of them with very similar elevation (~3 m amsl) correspond to the MIS 5e; in a clearly distinct position follows another high stand characterized by the disappearance of the warm "*Senegalese fauna*", event corresponding to the MIS 5a and which is prior to the Holocene as evidenced by the presence of *Acar plicata*, (~1 m amsl).

Between the two well-defined elevations, an additional, yet questionable high stand exists. This one cuts across laterally older units attributed by some authors to either MIS 5e or MIS 5a. It represents an important change in the littoral dynamics, marks the extinction of most "*Senegalese fauna*" (particularly *Strombus bubonius*), and evident higher energy conditions related to stronger wave action.

2.2 Cova des Pas de Vallgornera (Llucmajor)
(*J. Ginés, A. Ginés, A. Merino, B.P. Onac & P. Tuccimei*)

This cave is located in the urbanized area of Cala Pi, near the southern cliffs of the Llucmajor platform (Figure 3) and is the most important karst cave in Mallorca with a development exceeding 67,000 m of passages and chambers (Figure 13). The cave has no natural entrances currently and it was accidentally discovered in 1968 when drilling a sewage cesspit during the construction of a hotel (presently abandoned). The artificial cave entrance is about four hundred meters from the sea cliffs.

2.2.1 Description and morphology of the cave

The cave begins with a series of breakdown chambers that all stretch to the phreatic level (the so-called Sector Antic, including the entrance chamber) and then connect with a spectacular sequence of partly flooded galleries abundantly decorated with speleothems (Sector Noves Extensions). A tight passage at the furthest end of that sector gives access to important cave extensions discovered in 2004 that begin with several big chambers along a NW-SE trend; among them, the Sala Que No Té Nom (200 by 80 m) is an outstanding example. Apart from this section of the cave, known as Sector Grans Sales, six additional sectors are distinguished (Figure 13), all located roughly on two different levels. The lower level develops near the current water table (or below it) and includes Sector de Gregal and Sector Subaquàtic de Gregal, while the higher level is located 11 m (or more) above the brackish phreatic waters, embracing Sector Tragus, Sector Nord, and Sector F. Finally, the Sector del Clypeaster is mainly developed near the water table but it ascends progressively towards its NW end. The inner parts of Cova des Pas de Vallgornera show an irregular maze pattern in which up to seven main galleries could be clearly differentiated. Each of these galleries exceed one kilometer in length and develop on a SW-NE direction. Underwater exploration has revealed the presence of extensive passages situated below the current water table. Detailed descriptions of this site are available in: Ginés *et al*. (2009a), Merino *et al.* (2009), and Gràcia *et al*. (2009).

The morphological features within Cova des Pas de Vallgornera are really variegated, fact that is expected in large cave systems that hosts several well-differentiated underground environments (e.g., vadose chambers, phreatic brackish pools...). Breakdown processes are ubiquitous within the cave (Figure 14), particularly in some specific sections such as Sector Antic and Sector Grans Sales. These zones are connected between them by extensive phreatic brackish pools (Sector Noves Extensions) where solutional spongework features are omnipresent along with rich speleothem decorations; some of the maze areas also developed near the current water table. In the seaward part of the cave system, strongly corroded coral structures are rather frequent, producing solutional voids of irregular forms and sizes. The pattern and morphology of the cave change in a fundamental way from Sector Grans Sales towards inland to form a set of joint-guided galleries. Starting from the network maze

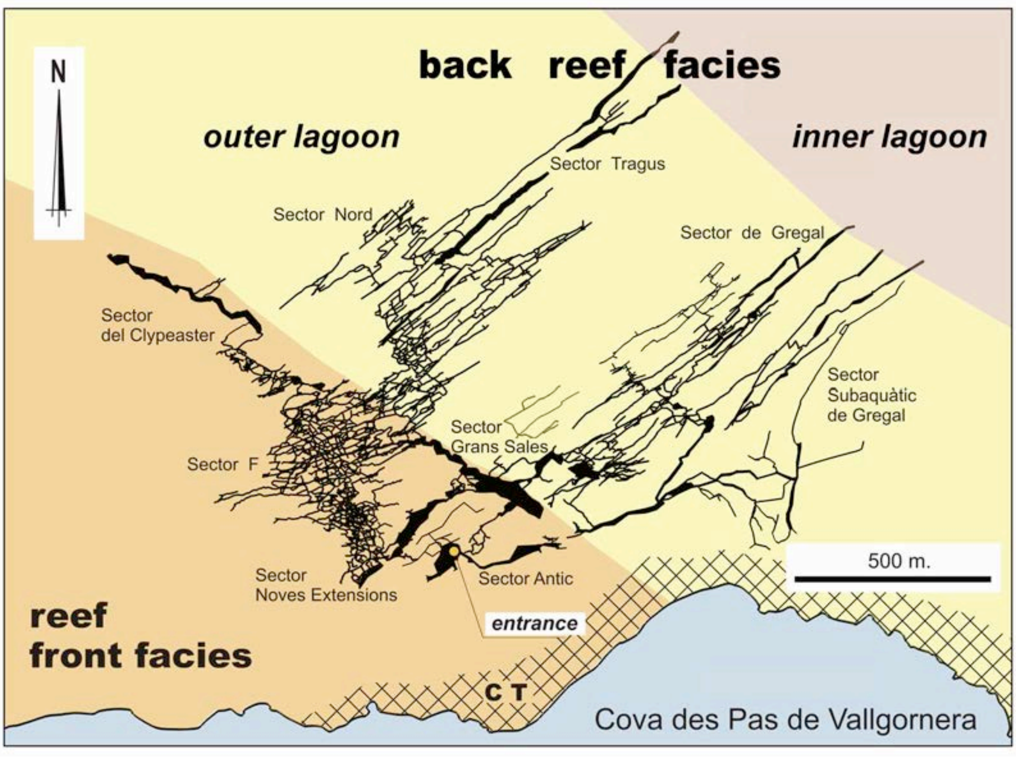

Figure 13. The survey of Cova des Pas de Vallgornera (Llucmajor) with indication of the lithological variability within the Upper Miocene (Tortonian) carbonates (after Ginés *et al*., 2009). CT: Messinian terminal complex.

Figure 14. Picture of a collapse chamber in Cova des Pas de Vallgornera showing the extensive brackish pool that flood the lower part of the cave (Photo: Bogdan P. Onac).

of Sector F, an array of parallel galleries, which are strictly controlled by prominent joints or fractures, individualize towards the NE (Figure 13). Phreatic solutional features shape the walls of these passages with dissolution pockets of various size and morphology dominating; no true scallops are present. Horizontal solution notches, whose lower parts form dip bevels or facets showing smooth dissolution channels incised on their slopes, are also well represented. In the inner part of the cave, ascending solutional channels were documented and interpreted to have hypogenic origin (Klimchouk, 2007). The entire cave is highly decorated with speleothems whose richness and morphologies are unique to Mallorca.

2.2.2 The lithological control over the pattern of the cave

The different depositional environments known within the Upper Miocene (Tortonian) reef complex, control the existence of well-individualized sets of morphologies, which mirrors the lithological and hydrogeological characteristics of these young carbonate rocks (Ginés *et al*., 2009b). Contrasting passage morphologies were noticed between parts of the cave excavated in the reef front facies and the galleries developed in the back reef facies (Figure 13). The cave zones characterized by significant breakdown processes occur in the highly porous reef front facies, where coral structures are affected by intense differential dissolution phenomena. A paradigmatic example of speleogenetic processes fully controlled by the reef barrier topography is found at the NW end of Sector del Clypeaster (Figure 13). In this section, a wide gallery develops for more than 500 m as a consequence of solutional excavation of the coral barrier; this passage lacks any structural guidance, showing a rather wandering pathway conditioned by the reef front architecture.

In the outer lagoon facies of the Tortonian reef complex (Pomar *et al.*, 1996), an extensive network of galleries develops inland towards the NE. These carbonate materials are rather massive and less permeable (less porous and more calcisiltitic) than the reef front facies, being affected by fractures dominantly along the SW-NE direction (Figure 13). The passages that are characteristic of the outer lagoon facies consist of joint-guided galleries whose walls appear completely sculptured by a variety of solutional features. These long passages also exhibit some collapse morphologies where patchy coral structures are present within the outer lagoon deposits; in such areas, the rectilinear galleries show sudden widening as a result of substantial dissolution processes affecting these isolated coral buildings.

The NE end of the long galleries integrating Sector Tragus and Sector de Gregal seem to be coincident with another lithological change, particularly with the presence of deposits attributed to the inner lagoon facies of the reef complex. In the terminal parts of these sectors the rock becomes less massive, showing alternating layers of calcisilitic and marly materials ranging in thickness from decimeters to meters. The major system of galleries, trending SW-NE in the inner sectors of the cave, ends abruptly at a rather constant distance with respect to the inferred position of the Tortonian reef barrier (Figure 13).

2.2.3 Speleogenetic mechanisms

Aside from the contribution of coastal mixing processes in the genesis of Cova des Pas de Vallgornera, its inner sectors show somewhat different morphological features consisting of long conduits integrated in an irregular network maze. These galleries appear to be the result of speleogenetic processes that occurred in shallow phreatic conditions within a littoral aquifer effectively drained along remarkable joints and fractures. Although the current rate of rainfall is low (approx. 400 mm/yr), the meteoric recharge of the littoral aquifer should be taken into account, as it is evidenced by several episodes of fine detritic sedimentation observed in the passages of Sector Tragus and Sector de Gregal.

Furthermore, the presence of solutional ascending flutes resembles the uprising flow morphologies described by Klimchouk (2007). They consist of channels of various sizes (from millimeters to decimeters in width and up to more than one meter long), etched in the overhanging walls of the inner cave passages (Fornós *et al*., 2011). These features, along with other morphological and mineralogical evidence (short galleries ending in cul-de-sac, floor feeders, Mn- and Fe-rich crusts, presence of celestine and barite) point to an hypogenic basal recharge. This process is likely related to the geothermal phenomena associated with the extensional faults causing subsidence of the Campos Basin. According to this point of view, Cova des Pas de Vallgornera is a polygenetic cave complex (Ginés *et al*., 2009a) due to the combination of three different speleogenetic vectors: coastal mixing zone phreatic dissolution, epigenic karstification, and an hypogenic basal recharge.

2.2.4 The Holocene Phreatic Overgrowths on Speleothems (POS)

Among the carbonate precipitates found in the cave, abundant aragonite deposits form at the surface of the brackish subterranean pools. These pools are presently flooding the lower parts of the cave (Figure 14), in altimetric and hydrodynamic correspondence with present-day Mediterranean datum. The sea-level control over these phreatic cave pools is evident since their surface undergoes daily fluctuations, related to minor tidal and/or barometric sea oscillations.

In this particular microenvironment, geochemically characterized by relatively elevated contents of chloride, sulfate, magnesium, and calcium, one can observe newly precipitated POS deposits (mainly crystalline overgrowths forming horizontal bands) linked to the surface of these subterranean ponds (Tuccimei *et al.*, 2010). These eye-catching phreatic crystallizations include abundant delicate stalactites with their tips coated by smooth yellowish aragonite overgrowths (Figure 15).

The investigations on these POS deposits that are presently located around the current sea level were directed towards two different goals: 1) to check the postglacial age of these deposits, in order to confirm that POS record the subactual to present sea level, and 2) to provide precise data on Holocene sea level changes in the Western Mediterranean basin.

Some POS specimens were collected at the current sea-level (Figure 15) in the entrance section of Cova des Pas de Vallgornera, and dated by means of U/Th and ^{14}C. Five samples were drilled-out from VL-D3 aragonite phreatic encrustation along two

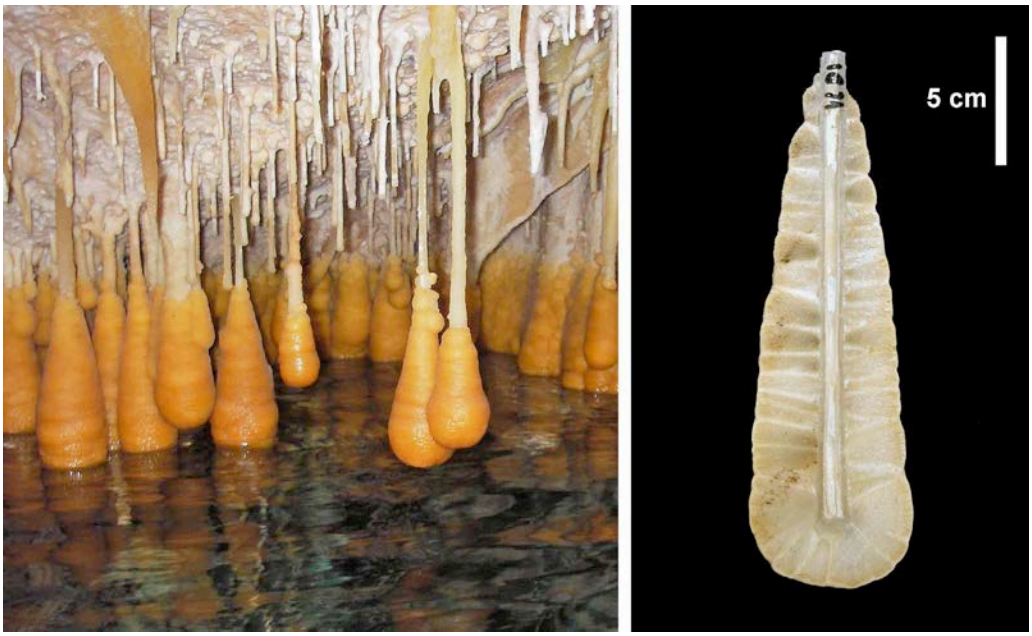

Figure 15. Aragonite POS belt developed at the current fluctuation range of the coastal water table in pools from Cova des Pas de Vallgornera (Photo: Antoni Merino). A longitudinal section of these deposits are shown in the left side of the figure.

Table I. U/Th datings of POS samples from Cova des Pas de Vallgornera (Llucmajor) and Cova Genovesa (Manacor).

Cave	*Sample*	*Height a.s.l. (m)*	U (ppb)	$^{234}U / ^{238}U$	$(^{234}U/^{238}U)_0$	$^{230}Th/^{232}Th$	$^{230}Th / ^{234}U$	$^{230}Th / ^{238}U$	*Age* (***ka*** **± 2σ**)
Cova des Pas de Vallgornera	VL-D3-1 # ***a***	±0	8829	1.480 ± 0.002		271 ± 2		0.0262 ± 0.0002	**1.9 ± 0.01**
	VL-D3-2 # ***a***	±0	7396	1.478 ± 0.002		69.3 ± 0.4		0.0250 ± 0.0002	**1.8 ± 0.02**
	VL-D3-3 # ***a***	±0	8139	1.475 ± 0.001		510 ± 3		0.0264 ± 0.0002	**2.0 ± 0.01**
	VL-D3-4 # ***a***	±0	8217	1.487 ± 0.001		457 ± 3		0.0183 ± 0.0001	**1.4 ± 0.01**
	VL-D3-5 # ***a***	±0	8015	1.503 ± 0.002		145 ± 1		0.0084 ± 0.0002	**0.6 ± 0.01**
	CPV-1 * ***b***	+1.6	156 ± 30	1.325 ± 0.019	1.408 ± 0.024	31537	0.535 ± 0.003		**80.1 ± 0.5**
	CPV-2 * ***b***	+1.6	144 ± 28	1.329 ± 0.021	1.413 ± 0.026	34757	0.536 ± 0.002		**80.1 ± 0.5**
	CPV-B8 * ***b***	+1.6	119 ± 18	1.391 ± 0.016	1.492 ± 0.020	1812	0.541 ± 0.002		**81.0 ± 0.5**
	CPV-B6 * ***b***	+2.6	108 ± 20	1.141 ± 0.013	1.198 ± 0.018	1892	0.683 ± 0.003		**120.6 ± 0.9**
	CPV-B9 * ***b***	+2.6	122 ± 14	1.173 ± 0.012	1.240 ± 0.017	1151	0.671 ± 0.002		**116.2 ± 0.6**
Cova Genovesa	GE-D1 # ***c***	+2.0	179 ± 1	1.102 ± 0.003	1.151 ± 0.004	59 ± 0.9	0.729 ± 0.007		**138.0 ± 2.8**
	GE-D2 # ***c***	-13.0	244 ± 1	1.233 ± 0.005	1.349 ± 0.009	38 ± 0.4	0.756 ± 0.012		**143.6 ± 4.6**
	GE-D3 # ***c***	-19.5	349 ± 1	1.731 ± 0.003	1.965 ± 0.006	72 ± 0.9	0.571 ± 0.004		**85.9 ± 1.0**

\# MC-ICPMS   * TIMS
a data from Tuccimei et al. (2010)   ***b*** data from Dorale et al. (2010)   ***c*** data from Tuccimei et al. (2006)

transects, one transversal and the other one parallel to the POS growth axis. From acrystallographical point of view, the sample is composed of acicular aragonite crystals (20 µm wide and 1 mm long), arranged in 0.3 to 1 mm thick growth layers.

The age data (Table I) show that these POS deposits grew approximately from about 2.0 to 0.6 ka BP (Tuccimei *et al.*, 2009). It is worth noting that the duration of POS deposition represents a minimum time interval for sea stand at the current elevation, since the chemical properties of phreatic waters can change during a given sea stand, causing the POS growth to cease. Detailed information regarding the methodology and the results of MC-ICP MS dates performed on these samples is available in Tuccimei *et al*. (2010), whereas the ^{14}C data are presented by Tuccimei *et al*. (2011). The coherent ages obtained in this case, as well as in other caves of eastern Mallorca, demonstrate that POS are excellent recorders of postglacial sea level, being readily datable by U-series methods. This fact allows foreseeing POS as useful indicators of past sea stands, especially when these precipitates are found in coastal caves of an island at different elevations above or below the present sea level.

2.2.5 The Upper Pleistocene POS deposits

In the same way that subactual POS record the current sea-level position, ancient crystallizations of the same type –both above and below the present-day ±0 elevation datum– prove to document past sea-level elevation, a fact documented by a number of papers (Ginés, 2000; Vesica *et al.*, 2000; Fornós *et al.*, 2002b; Tuccimei *et al.*, 2006; Dorale *et al.*, 2010). The Pleistocene POS from Mallorcan littoral caves are crystalline coatings that rigorously define horizontal bands along cave walls, or over whatever suitable support (e.g., common vadose speleothems) penetrating below the surface of the subterranean pools. Commonly, the morphology of these coatings is bulky and its maximum thickness corresponds to the mean position of the groundwater table (Figure 16a). As a rule, the thickest part of the overgrowth is located in the middle of the crystallization belt, gradually decreasing upward or/and downward.

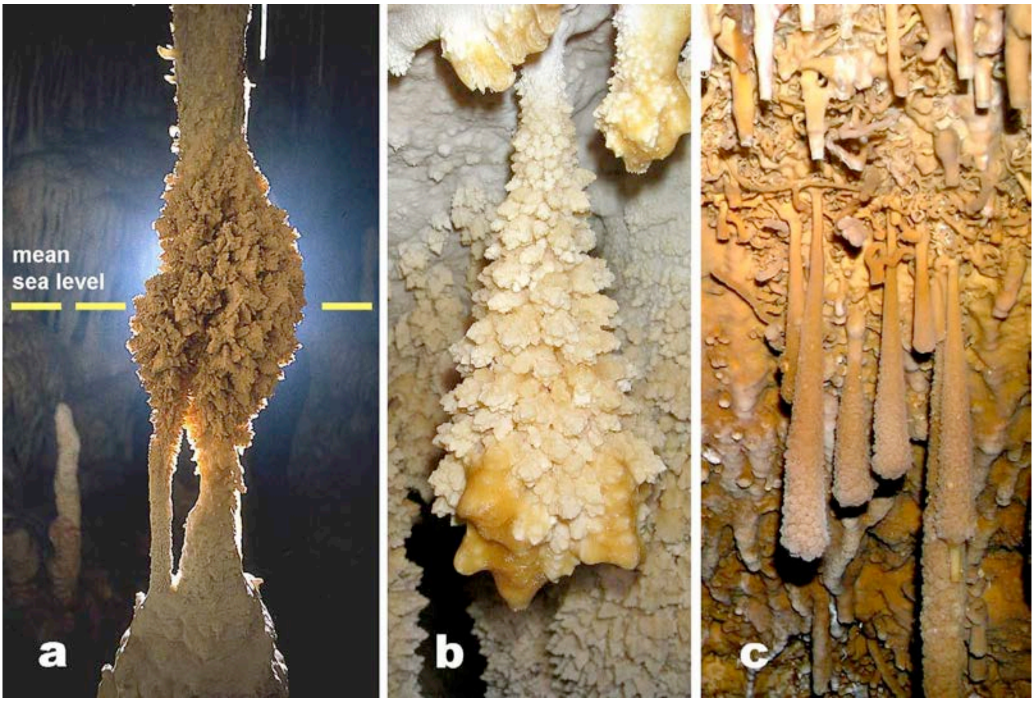

Figure 16. Upper Pleistocene POS deposits from Cova des Pas de Vallgornera located at an elevation of +2.6 m ASL and corresponding to MIS 5e high stand. **a**) Phreatic macrocrystalline calcite encrustation in the Noves Extensions sector. **b**) Detail of the same MIS 5e paleo-level at the entrance to Sala Que No Té Nom chamber (Photos: Antoni Merino). **c**) Microcrystalline calcite overgrowth observable in the Entrance chamber, at the spot named S'Amfiteatre (Photo: Bogdan P. Onac).

In Cova des Pas de Vallgornera, several POS paleo-levels occur at different elevations above the current sea level, particularly in the Sector Antic and Noves Extensions passages. The most striking of them develop at a height of +2.6 m ASL, and mainly consists of bulky overgrowths made up of calcite macrocrystals (Figures 16a and b). Another POS paleo-level is recognized at a lower elevation (+1.6 m ASL) in the form of a thinner microcrystalline calcite encrustation.

The U/Th ages obtained for the above-mentioned POS paleo-levels (Table I) correlate well with two distinct sea level high-stands belonging to MIS 5 (Dorale et al., 2010). Specifically, the overgrowth at +2.6 m ASL yielded ages between 120.6 and 116.2ka BP (MIS 5e), whereas the paleo-level situated at +1.6 m ASL occurred at ~80-81 ka BP, thus corresponding to MIS 5a. The latter data set represents strong evidence for a relatively short-lived high stand during MIS 5a, at an elevation higher than present-day sea level. The obtained ages are in agreement with those published by Tuccimei *et al.* (2006) documenting POS deposits from MIS 5a in the age range of 84.2 to 82.3 ka BP, located at heights of +1.3/+1.9 m ASL. Therefore, Dorale *et al.* (2010) have elaborated on an alternative view that argues that this substage was as ice-free as the present, challenging the conventional view of MIS 5 sea level history and certain facets of ice-age theory.

2.3 s'Estret des Temps (Santanyí): Upper Pleistocene cliff-front eolianites

(*J.J. Fornós, L.B. Clemmensen* & *L. Gómez-Pujol*)

Mondragó Natural Park is a few kilometres south of Santanyí village (Figure 1). At this southernmost entrance following the coast and very near to the touristic place of Cala Santanyí, the coast forms an small but broad shallow embayment called s'Estret des Temps, where an impressive sequence of Late Pleistocene cliff-front aeolian deposits can be observed in 3D (Figure 17). The Pleistocene aeolinites show sections in all directions thanks to quarrying that exploited the aeolian calcarenites for a very common and appreciated building stone on the island called "*marès*". Part of this fieldtrip guide has been previously published in Silva *et al.* (2005).

2.3.1. Introduction

The Late Pleistocene cliff-front aeolian deposits constitute wind-borne marine carbonate sand trapped in front of a prominent cliff that runs along the southeast coast of Mallorca near the village of Santanyí. These deposits form part of the Pleistocene succession that is well represented in southern Mallorca (Butzer, 1975), occurring on top of the Upper Miocene Reefal Unit and/or the Santanyí Limestone Formation (Pomar *et al.*, 1985). The succession is composed of sedimentary cycles related to Pleistocene glacial-eustatic sea-level variations, each composed of marine (beach) and continental deposits (carbonate aeolianites and colluvial deposits; Butzer, 1975). The

Figure 17. General overview of the Miocene paleocliffs at s'Estret des Temps showing the cliff-front related eolianites.

aeolianites were assumed to have formed during glacial periods characterized by low sea level and strong winds.

The aeolian deposits at s'Estret des Temps (Cala Figuera) corresponds to an impressive example of a topographically controlled aeolian accumulation. Owing to the occurrence of small abandoned quarries (Figures 17, 18), the 3D architecture of the sediments can be studied in detail (Clemmensen *et al*., 1997, 2001).

Topographically controlled aeolian accumulations are common features in coastal areas (Pye & Tsoar, 1990; Livingstone and Warren, 1996). Aeolian accumulation related to the cliff (cliff-front aeolian accumulations) comprises echo and climbing dunes and sand ramps (Livingstone & Warren, 1996; Lancaster & Tchakerian, 1996). The information preserved in the sedimentary structures or internal structure at s'Estret deposits allows interpretation of the genesis of echo and related climbing dunes.

2.3.2. Stratigraphy and sedimentology

At s'Estret des Temps, the Pleistocene succession lies above a number of wave-cut terraces formed during the last interglacial cycle and the beginning of the last glacial period (Butzer, 1975; Butzer & Cuerda, 1962).

The cliff-front aeolian accumulation comprises the four sedimentary facies (colluvial and aeolian) separated by bounding surfaces of event-stratigraphic significance. Contacts between colluvial and aeolian deposits are sharp and relatively

Figure 18. Sedimentary architecture of the Late Pleistocene cliff-front dune at s'Estret des Temps.

planar, marking the sudden onset of aeolian activity. Contacts between aeolian and overlying colluvial deposits show much variation. They are typically erosional and display a meter-scale relief with large slabs of reworked aeolianites and variations along-slope in sedimentary characteristics. From base to top (Figure 18) the sedimentary facies include the following sequence (Clemmensen *et al.*, 2001).

Cliff-front dune deposits

An accumulation up to 30 m height of thin laminated fine to coarse grained carbonate sand (mainly marine bioclasts), with a little terrigenous material cemented by calcite, that corresponds to dune deposits which record the trapping of wind-transported marine carbonate sand in front of a steep cliff. This accumulation overlies basal colluvial deposits. It presents low-relief wind ripple lamination and numerous tracks and trackways of the extinct goat-like animal *Myotragus balearicus* (see below) as well as invertebrate trace fossils and root structures (rhizocretions).

The dune strata are arranged in large-scale, critical to supercritical climbing dune cross-stratification with well-developed seaward facing stoss-side deposits and cliffward facing lee-side deposits. Climbing angles typically increase towards the cliff and may reach 50º. Windward surfaces normally dip 15-25º but may reach up to 31º in the steepest cases. Lee-side surfaces typically have dips between 20 and 26º with a few dips reaching 30-32º. The dune profile is slightly asymmetric and the brink-line varies from sharp-crested to rounded, the last one typically assisted with reactivation surfaces.

Morphology and sedimentary architecture

The dune evolution can be divided into three growth stages (early, intermediate and late) each having a characteristic morphology and sedimentary architecture (Clemmensen *et al.*, 1997, 2001). The *early stage* (Figure 19) comprises sediments lying between 1.5 and 0.9 d/h (d = distance from the cliff; h = cliff height) with H/h-values (H = dune height) of 0.34. The dune profile is typically rounded and the brinkline is not too well defined but becomes sharply defined towards the cliff. The windward-side deposits increase in the slope angle towards the cliff dipping 12-25º; the strata flatten towards the crest. The lee-side deposits dip 20-26º. The *intermediate-stage* of the dune comprises sediments lying between 0.9 and 0.6 d/h with H/h values of 0.46. Dunes deposits on the windward-side dip at 20-26º and leeward side deposits dip at 22-26º. The dune profile is typically slightly asymmetric. In cross section the dune brinkline varies from sharp-crested to rounded, and at some intervals the associated internal structures of the crest resemble the zig-zag structures of Rubin (1987). The *late-stage* of dune accumulation presents H/h-values up to 0.88 and the accumulation lies between 0.6 d/h and the cliff. The dune windward-side dip around 25º and the leeward-side deposits dip up to 30º. The dune profile is weakly asymmetric and the angle of climb is supercritical (may reach 50º). The dune brinkline is most commonly sharp-crested and the related brinkline deposits show little architectural complexity.

From the observation of sedimentary structures, and the experiments for Tsoar (1983) on echo-dune formation in front of a vertical cliff, one can consider that in time the dunes evolved from classical echo dunes (initial sand accumulation between 0.3

and 2.0 d/h; steady state between 0.5 and 0.6 d/h and with a H/h-value of 0.3-0.4, where there is a balance between primary air flow and the reversed air flow) to climbing dunes. As the cliffline shows a curved trend, that affects the response of the growth dune architecture with a substantial sand transport form dune flanks toward the dune head. In fact, only in the intermediate stage was there near balance between the primary airflow and the reversed airflow as indicated by the common occurrence of reactivation surfaces.

In agreement with Clemmensen *et al*. (1997) all these genetically related dune sediments are termed "cliff-front dune deposits" to stress the importance of topography in controlling the aeolian accumulations.

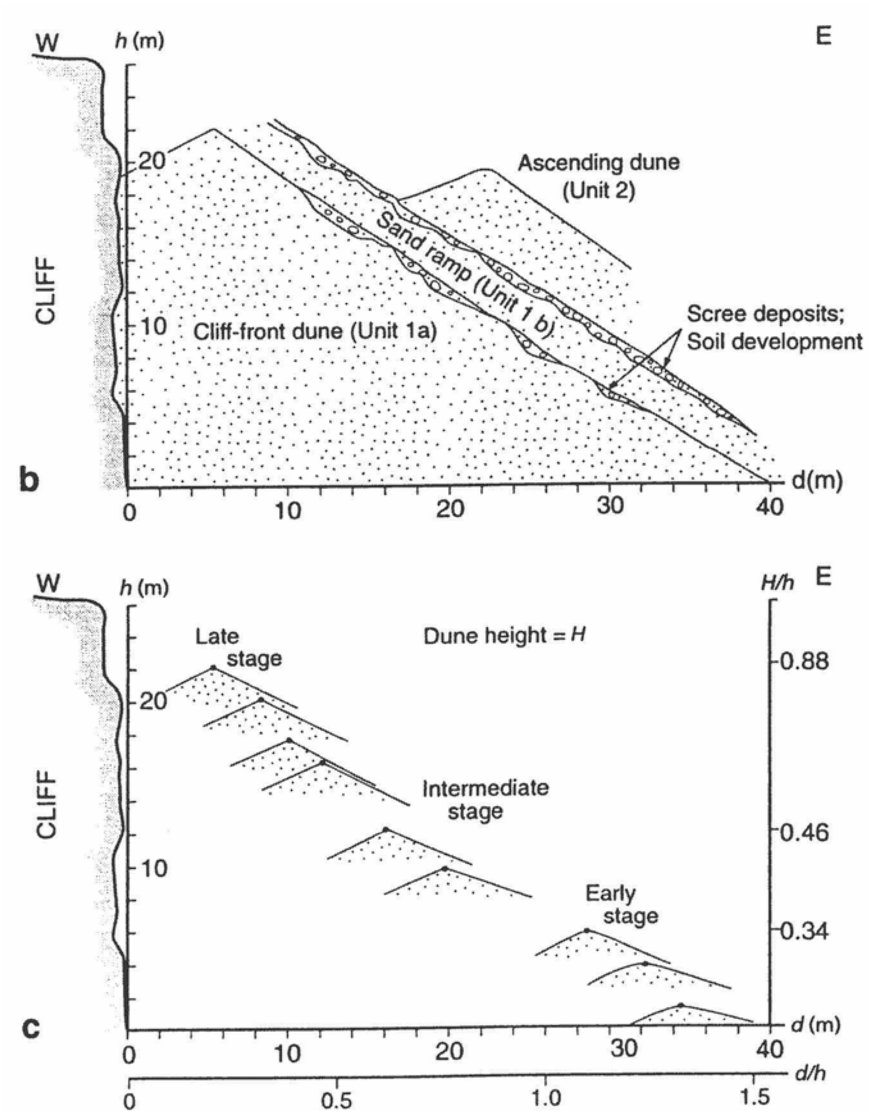

Figure 19. Idealized stratigraphy and growth stages of the cliff-front dune (modified of Clemmensen *et al*., 1997).

Figure 20. Red matrix-supported breccias, matrix consisting of silt-rich carbonate sand with some terrigenous material, that form the colluvial-ramp deposits at s'Estret des Temps.

Colluvial-ramp deposits

This deposits consists of red matrix-supported breccias, matrix consisting of silt-rich carbonate sand with some terrigenous material (Figure 20). Clasts correspond to Miocene calcarenites or lithified aeolian sediment. Depositional packages slope away from the cliff and typically thicken downslope. They lie at the foot of the fossil sea cliff or drape underlying aeolian deposits and slope away from the cliff. They have a sharp and mostly erosional contact with underlying aeolian deposits, and a gradational to sharp contact with overlying aeolian deposits. Root casts are common at the upper contacts. They correspond to intense periods of rainfall with the reworking of aeolian sand, soil products and rock-fall material on ramp during debris flow events.

Sand-ramp deposits

These deposits form 1-3 m thick sheet-like packages of aeolian sand that overlie stratified cliff-front dune and colluvial deposits. *Climbing* sand ramp deposits at s'Estret des Temps develop as a sand sheet that slopes away from the fossil sea-cliff with angles between 20 and 30º. They are composed of fine to coarse-grained carbonate sand with some terrigenous material. They present wind-ripple lamination, *Myotragus* tracks and root casts and, seaward-sloping, even, parallel lamination.

Theyrepresent the trapping of the carbonate sand on a ramp developed in front of the cliff of the material transported by the southeasterly winds.

Ascending-dune deposits

These deposits correspond to the uppermost part of the cliff-front accumulations. They are formed by fine to coarse-grained carbonate sand, showing wind-ripple and sandflow lamination. They present thick (1-2 m) sets of large-scale landward-dipping cross-stratification. The deposits of this unit record two closely related events of ascending-dune formation on the colluvial ramp. They primarily developed at places where the colluvial ramp was significantly lower than the cliff. The dunes were relatively small and present sinuous-crested bedforms due to the influence of the vegetation.

2.3.3. Related biogenic structures

Tracks and tackways of Myotragus balearicus, Bate 1909

Described originally from Late Pleistocene cliff-front dune and sand ramp deposits in a small quarry in the southeastern part of Mallorca (Fornós & Pons-Moyà, 1982), *Myotragus* tracks are a common feature in all Late Pleistocene littoral aeolianites in Mallorca, especially those that correspond to the OIS 3 (Fornós *et al,* 2002). They have been identified in the greater part of the Pleistocene and Early Holocene

Figure 21. Skeleton of *Myotragus balearicus* (Museu Balear de Ciències Naturals, Sóller).

aeolianites, increasing their presence through time until 5000-4000 BP when the extermination of *Myotragus* occurred with the arrival of *Homo* (Alcover, 2004).

Myotragus balearicus (Figure 21) is a fossil ruminant goat endemic through a process of insular evolution (Alcover *et al*., 1981) of the Middle Pleistocene to Holocene of the Gymnesic islands (Mallorca, Menorca and Cabrera). Their ancestors presumably colonized the Balearic islands during the Uppermost Miocene, and then evolved rapidly during insular conditions and in absence of mammalian predators. Adult specimens reached approximately 45 cm at the shoulder and their estimated weight varies between 20 kg for the smallest individuals to 50 for the largest specimens (Alcover *et al.,* 1999).

In s'Estret des Temps quarry, the tracks can be observed in all the aeolian units. Their distribution is more frequent in the basal cliff-front dune deposits, where tracks are abundant in the crestal zone deposits, common in the windward-side deposits and rare in the lee-side deposits.

There are thousands of laminae in the lithified aeolianites that have been tracked by *Myotragus balearicus*. The extensive sections, parallel and perpendicular to the bedding, provided by the quarry allows seeing them in vertical as well as in horizontal sections.

The sediment disturbances caused by the trace maker involve both plastic deformation and microtectonic rupture in the form of microfaults and microthrusts.

The large majority of perpendicular sections are external, and consists of concave-upward laminae that diminish downward, and at some horizons these structures are so abundant that they completely overprint the wind-generated lamination and impart an ichnofabric to the rock (Figure 22). These deformation structures are either tangential sections of pressure pads or aspects of down warping structures and

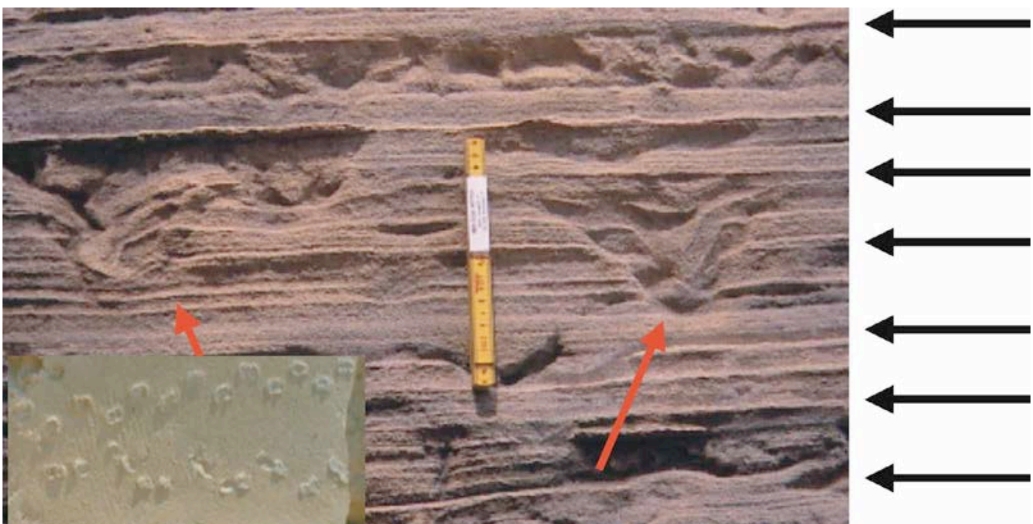

Figure 22. Perpendicular sections of tracks and trackway of *Myotragus balearicus* at s'Estret des Temps.

undertracks. In this perpendicular section, the fault describing the dislocated pressure pad of sediment is seen to follow a circular course leading from the axis in the most simples cases, but usually are multiples, comprising several dislocated pressure pads stacked more or less concentrically within each other.

In horizontal or near-horizontal surfaces, tracks can be more o less symmetrical and circular, or strongly asymmetrical elongate structures in the longitudinal plane. Bedding-parallel sections show, in the most symmetrical cases a disturbance zone around the axis which outer limit is sharp indicating a microfault. When the disturbance zone is developed asymmetrically to one side of the axis, it is invariable delimited by a sharp, microtectonic boundary. This disturbed sediment has been dislocated and slightly rotated out of its original position along the fault representing the pressure pad.

Associated trace fossils

Associated with these goat tracks, trace fossils attributable to insects (Fornós *et al.*, 2002) are present in sparse horizons. They correspond to horizontal galleries and branched networks that usually develop empty tubes having a well-cemented margin. Extensive root structures are present beneath the colluvial paleosol horizons (Calvet & Pomar, 1975). In the margins of the dune deposits these root structures are

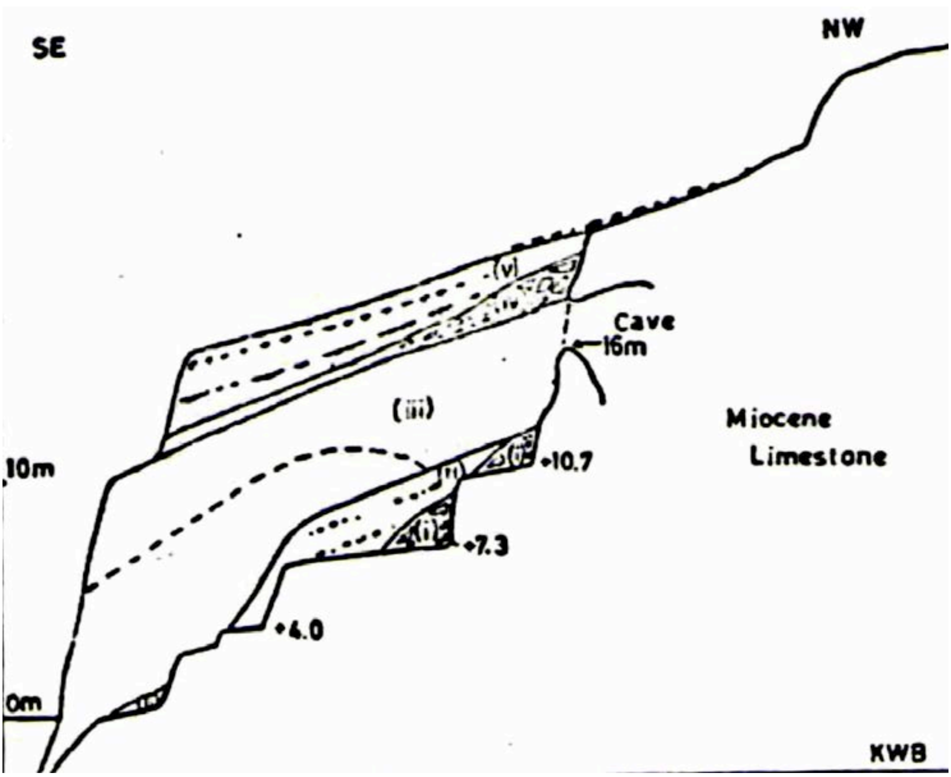

Figure 23. Composite section of the last regressional deposits at s'Estret des Temps showing marine terraces at different heights after Butzer & Cuerda (1962).

also seen. Elsewhere, the dune sands, show no such structures and there is no evidence that the cliff-front dunes were extensively colonized by vegetation, only very locally and with a limited extent. The dunes were not an environment that could support a resident community of herbivores.

2.3.4. Marine terraces

The s'Estret des Temps Late Pleistocene outcrop that was first described by Butzer & Cuerda (1962) is a composite section of the last regression during the Würm period. Following these authors "the sequence was composed by two dunes that represent the last regression from its initiation to the maximum lowering of the sea level. The oscillation present toward the end of the sequence may represent one of the major higher latitude interstadials. Local contemporary sea level was below that of the present". Butzer & Cuerda (1962) cite in their paper that the aeolian sequence lies over a series of abrasion platforms cut in the Miocene limestone that presently forms the main cliff wall (Figure 23). The marine terraces that are located at the altitudes of 3.3 m, 4.0 m, 7.3 m and 10.7 m above the present sea level may probably represent the Tyrrhenian II and Tyrrhenian III transgressions (Zazo & Goy, 1989), the MIS 5e highstands.

3. Second day fieldtrip

3.1 The cave area near Portocristo (Manacor)

(*J. Ginés & A. Ginés*)

The Upper Miocene rocks that build up the flat-lying coastal area of Migjorn region embrace the southern part of Mallorca (including the previously referred Llucmajor platform) and surround the heights of Serres de Llevant, forming a great part of the eastern coast of the island (Figure 3). These post-orogenic carbonates host a well-developed eogenetic karst (Ginés & Ginés, 2007), in which the area near Portocristo village outstands owing to the abundance and dimensions of its littoral caves. The most important endokarst feature in the area is the Gleda-Camp des Pou cave system that exceeds 13,500 m of passages and chambers, mainly developed underwater (Gràcia *et al.*, 2010).

Morphogenetic features of caves in Portocristo are related to phreatic dissolution in the mixing zone between fresh water and marine water, although extensive collapse processes add to the volumetric enlargement of these cavities (Ginés & Ginés, 2007). At present, the caves of this region are partially drowned by brackish waters, forming large subterranean pools. Speleothems are abundant in the caves above and below the current littoral water table. In addition to conventional speleothems such as stalagmites, stalactites, or flowstones, POS are also common in these caves. Among the many caves in the area, two sites near Portocristo village will be visited: Coves del Drac –an internationally renowned show cave explored by the French researcher E.A. Martel in 1896– and Cova Genovesa, a wild cave with important underwater extensions as well as interesting prehistoric vestiges. From the geomorphological point of view, both caves are very representative for the endokarst developed in the eastern coast of Mallorca.

Regarding the hydrogeology of the Migjorn region, the Upper Miocene reefal carbonates have a high porosity and permeability, supporting a continuous phreatic zone with very low hydraulic gradients (lower than 0.1%). In this coastal karst, the water table is fully controlled by sea level, and is affected by minor daily oscillations caused by tides or barometric changes. From a hydrochemical point of view, the phreatic zone is represented by a body of brackish waters (with salinity ranging from 3 to 30‰). This is separated from the underlying sea water by a major halocline horizon located at depths between −2 and −15 m below sea level, depending on the distance from the coast and the extent of recharge in the wetter seasons. Usually, these phreatic waters show characteristic profiles in which salinity increases with depth in a stepped way, producing several minor haloclines that separate water bodies with different density, salinity, and temperature (Gràcia *et al.*, 2007; Jaume *et al.*, 2008); a decrease of dissolved oxygen concentration with depth is also recorded.

3.2 Cova Genovesa (Manacor)

(*J. Ginés, A. Ginés, F. Gràcia & P. Tuccimei*)

Cova Genovesa (also known as Cova d'en Bessó) opens a few kilometers south of Portocristo village, near the small-urbanized cove of Cala Anguila. This cave shows the typical morphological features of the endokarst in the eastern part of Migjorn region. The total cave extension (mostly underwater) exceeds 2,447 m (Gràcia *et al*., 2003).

3.2.1 Description and morphology of the cave

The cave entrance consists of a wide collapse doline that gives access to two large chambers, separated by a brackish pool that in fact is the littoral water table. From this pool, a succession of drowned passages and chambers totaling more than 1,800 m (Figure 24) has been explored. The morphology of the cave is characterized by extensive breakdown processes, which are dominant at the entrance chambers and even in the underwater parts of the cave (see a longitudinal profile in Figure 24). This morphological configuration is rather usual in the eogenetic endokarst developed in the Upper Miocene carbonates of the eastern coast of Mallorca (Ginés & Ginés, 2007). However, remnants of small phreatic passages, unaffected by collapse processes were observed in the deepest parts of the subaqueous extensions. The speleothems in general are abundant all along the submerged chambers, obviously deposited when the cave was air-filled during Pleistocene regressions linked to cold events.

3.2.2 The POS deposits and their chronology

In Cova Genovesa, as in most of the littoral caves in this area, the POS are abundant at elevations corresponding to present-day or past sea levels. The POS encrustation that develops in the fluctuation zone of today's water table, consist of millimeter-size crystals of calcite forming a bulky belt that is visible in the inner part of the pool separating the two main chambers. Similar deposits in a cave in the vicinity were assigned to Holocene based on U/Th ages ranging from 2.8 to 1.1 ka BP (Tuccimei *et al*., 2010).

Furthermore, a clear paleo-horizon of POS was identified at an elevation of +2 m ASL. The U/Th age of 138 ka BP (Table I) suggests its deposition corresponds with the

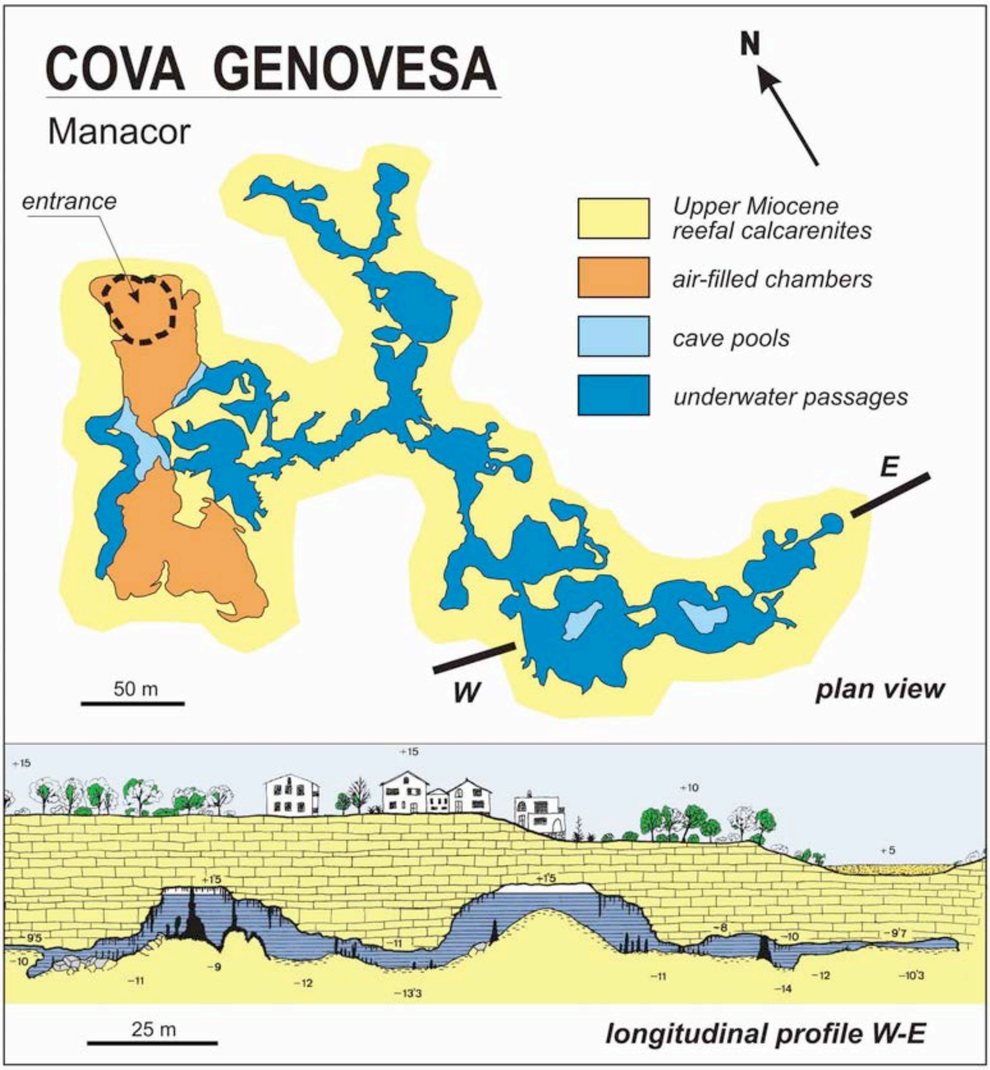

Figure 24. The map of Cova Genovesa (Manacor). A longitudinal profile of the submerged passages is included (after Gràcia *et al.*, 2003).

onset of the MIS 5e high stand (Tuccimei *et al.*, 2006). POS deposits have also been sampled from the underwater passages (depths between −13 and −20 m below the present-day sea level). The U/Th dating of these samples document a low sea stans (−13 m ASL) at 143.6 ka BP, thus corresponding to Termination II (MIS 6 to MIS 5 transition) and a second low stand (−19.5 m ASL) at 85.9 ka BP, likely recording the sea level fall that occurred during MIS 5b.

3.2.3 Paleontological and archeological data

The archeological evidence from Cova Genovesa are outstanding from the point of view of Holocene sea level history in Mallorca. In the entrance chamber, some prehistoric constructions belonging to the Bronze Age are present. Among other vestiges, a stone-paved pathway (Figure 25) leads down to the pool occupying the lower parts of this chamber. A special interest arises from the presence of a drowned prehistoric bridge that lies 1 m below the present-day water table (Gràcia *et al*., 2003).

This archeological vestige consists of a stone-built passage that, at the time of its construction, enabled users to cross the pool in the first chamber without getting wet; it is a 7 m long stepping stones path, composed of at least 14 deliberately aligned rock blocks, some of them with the major axis greater than 1 m (Figure 26). The occurrence of a past sea level at a depth of ~ −1 m ASL is reinforced by the presence of a horizontal coloration mark, visible at both sides of the construction, as well as along the submerged cave walls (Figure 26). Scarce pottery findings date to the Bronze Age (Gràcia *et al*., 2003) and chronologically constrain the use of the cave to the final stage of the Navetiform culture (3.7 to 3.0 ka BP). Combining these archeological data and the U/Th chronology of POS from other caves in the area (Tuccimei *et al*., 2009, 2010), we argue for a relative low sea stand (~ −1 m ASL), around 3.7-3.0 ka BP, followed by a rise of sea level, with a successive stabilization at the present level since ca. 2.8 ka BP.

Figure 25. View of the entrance chamber in Cova Genovesa. Note the prehistoric stone-paved path that goes down to the phreatic pool occupying the lower parts of this chamber (Photo: R. Landreth).

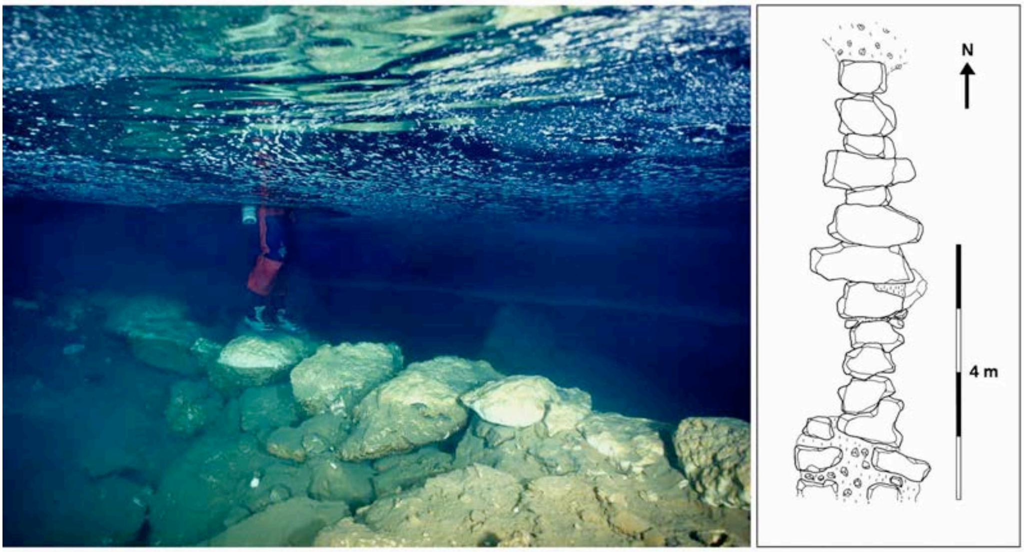

Figure 26. Underwater picture and schematic map of the stone-built walkway existing in Cova Genovesa (Photo: Robert Landreth). It allowed to cross in dry conditions the pool existing at the bottom of the entrance chamber, though currently it is submerged at a depth of –1 m ASL. The ritual use of the cave corresponds presumably to the final stage of Navetiform culture (~ 3,700/3,000 years BP).

Abundant *Myotragus balearicus* (Figure 27) bone fragments were recovered from submerged passages of Cova Genovesa (−11/−13 m below the current sea level; Gràcia *et al*., 2003), making the cave an important paleontological site. Most bones of the extinct Pleistocene goat of Mallorca and Menorca were found in articulation. This clearly indicates that the animals entered the cave when air-filled, during cold periods (probably the Last Glaciation) when sea level was lower than today.

3.3 Coves del Drac (Manacor)
(*J. Ginés, A. Gimés & P. Tuccimei*)

The Coves del Drac is a classical and fully representative cave for the eastern coast of the Migjorn karst region. It is the most important show-cave on Mallorca and, unquestionably, one of the principal touristic attractions in the Island; with over 1,000.000 tourists per year, it is among the most visited caves in the world (Ginés & Ginés, 2011). The location of the cave in the outskirts of Portocristo, along with another show-cave (Coves dels Hams) existing in the vicinity, greatly impacted the economic growth of this coastal village. The spectacular subterranean sceneries, along with the morphological features related to the coastal endokarst evolution, make Coves del Drac a required stop for any fieldtrips.

3.3.1 Some historical data

The cave was entered since prehistoric times (Bronze Age) and presents near its entrance an interesting underground cyclopean construction. It belongs to the Navetiform culture (~3-4 ka BP) and is related to an unknown ritual use of the site

Figure 27. A skull of *Myotragus balearicus* photographed in a submerged passage of Cova Genovesa, at a depth of –12 m below the present-day sea level (Photo: Pedro Gracia). The recovered remains of this Pleistocene extinct bovid denote that the animals enter the cave when being air-filled, probably during the Last Glaciation.

(Ramis & Santandreu, 2011). During the second half of the 19th century, several travellers, and naturalists (mostly foreign) visited it. The first survey of the cave was completed in 1880 by the German scientist Friedrich Will (Mader, 2005).

The knowledge and exploration of Coves del Drac were tightly linked to the Archduke Ludwig Salvator Habsburg-Lothringen, a member of the Austrian Imperial family, who spent long periods of time in Mallorca between 1867 and 1913. This remarkable personage, stirred by the mystery that surrounded some of the pools

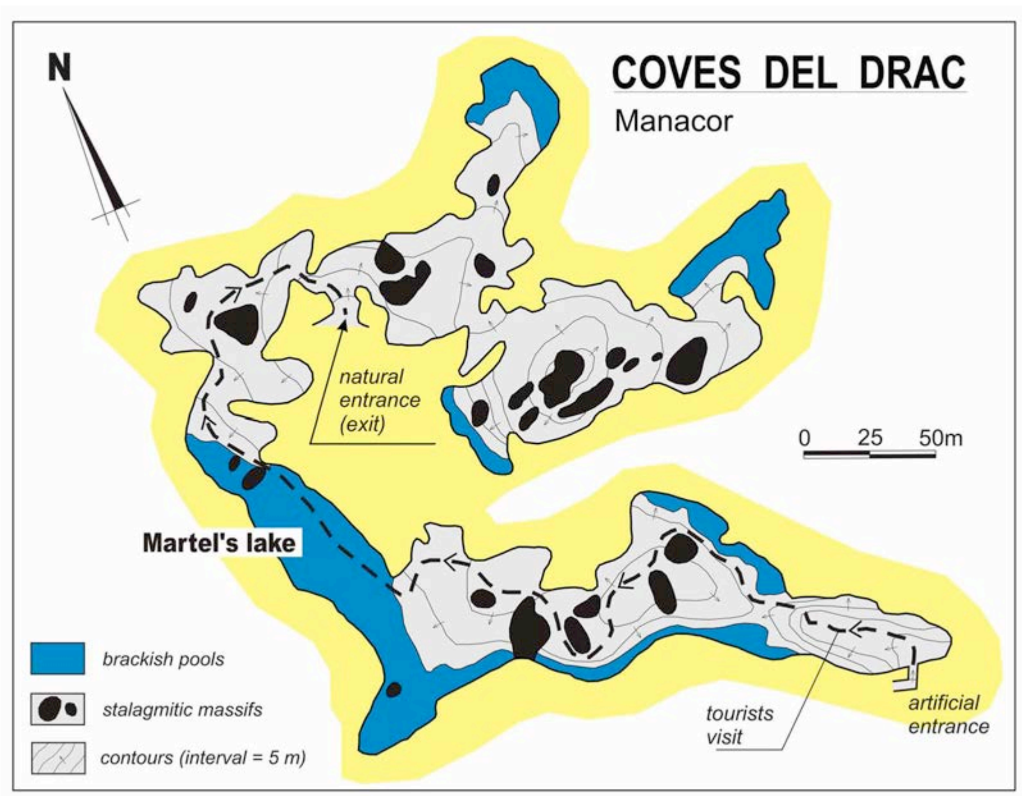

Figure 28. Survey of Coves del Drac (Manacor), with indication of the course of touristic visits (after Ginés & Ginés, 2007).

existing inside the cave, sponsored the visit to the island of the famous French explorer Édouard-Alfred Martel. As a result, important discoveries were made in 1896 after a large brackish pool (being the end of the known cavern at that time) was crossed. Based on surveys undertaken during these explorations, Martel drew a nice and detailed cave map and published a paper (Martel, 1896). In this study, however, he mistakenly considers Coves del Drac as an unusual example of marine erosion cave (Ginés, 1999).

In 1904, during an oceanographic campaign in Mallorca, the Romanian biologist Emil G. Racoviţă visited the cave and collected some crustaceans from its brackish pools. These findings allowed the study of a new troglobiontic species of isopoda, described a year later as *Typhlocirolana moraguesi*. The description of this Mallorcan taxon is internationally considered as a milestone that signifies the birth of modern *biospeleology*. The origins of this new branch of science that deals with the study of cave organisms, come from the growing interest Emil G. Racoviţă had for the subterranean ecosystem (Racoviţă, 2005).

During the first decades of the 20th century the cave was prepared for tourism, and it opened in 1922 to an increasing amount of visitors. The electric illumination of the cave dates back to 1934, time when the artificial entrance used currently as starting-point of the guided trips was also excavated (Figure 28). With the boom of massive tourism in Mallorca, from the 1950-60 decades till present times, this cave arises as the most important show-cave both in Mallorca and in Spain. For a comprehensive account on the history of Coves del Drac readers are directed to the paper of Ginés & Ginés (1992).

3.3.2 Description and morphology

The cave is carved in the Upper Miocene reef carbonates and consists of a complex system of chambers and passages totalizing over 2,300 m in length. Presently, it has two entrances: the first one is artificial and leads directly to the southern end of the rooms discovered during the explorations of Martel; the other one, is the natural entrance now used as exit point for the visiting tours (Figure 28). To the East of the natural entrance there are several chambers that are not included in the touristic trip, mainly corresponding to the anciently known parts of the cave.

The cavern hosts a number of large chambers, heavily affected by breakdown processes. The collapse blocks (Figure 29) are opulently decorated by stalagmitic deposits of various shape, size, and color. Numerous and picturesque brackish pools (i.e., the coastal water table which coincides with present day sea level) occupy the lower sections of the chambers. Some of the pools have remarkable dimensions, e.g., Martel's Lake (also known as Llac Miramar) measures 125 m in length and covers an area of more than 2,000 m^2 (Figure 30). The submerged passages, totaling more than 600 m of development, are currently under exploration throughout different parts of the cave.

From a morphological point of view, Coves del Drac represents a classical example of cave developed within the coastal mixing zone of eastern Mallorca’s eogenetic karst (Ginés & Ginés, 2007). The overall cave pattern shows not structural control but instead

Figure 29. View of a chamber in the touristic section of Coves del Drac. Large breakdown blocks surface from the brackish pools corresponding to the coastal water table. A light-colored calcite encrustation is visible within the current fluctuation range of the phreatic waters, roughly in the center of the picture (Photo: B.P. Onac).

Figure 30. View of the Martel's Lake (also known as Llac Miramar) in Coves del Drac (Photo: Gabriel Santandreu).

instead a rather rambling plan emphasizing the role of the primary porosity in the reefal carbonates. The cave pattern mirrors a series of wide range (in terms of volume and size) collapse halls (Figure 28), connected between them in a relatively irregular and casual way. Some phreatic passages, less affected by breakdown were documented along the underwater sections.

Summarizing the underground landscape of this cave, three facets define its present morphology: the extensiveness of breakdown phenomena, the presence of brackish pools, and its beauty and richness of speleothems. Referring to this last aspect, dripping and flowing water speleothems are the most represented typologies; when these deposits form over collapse blocks, frequent mechanical adjustments occur causing stalagmites, columns, or flowstones to tilting or even fracture. Finally, we note the existence of wide areas where the ceiling is almost fully covered by well-packed fine stalactites. This feature reflects the high primary porosity of the carbonate bedrock that minimizes the role of joints in the emplacement of dripwater speleothems.

3.3.3 The POS deposits

Among the outstanding crystallizations that justify the reputation of Coves del Drac as a natural touristic attraction, POS deposits are also abundant along all the brackish pools. These encrustations, made up of calcite crystals, formed within the fluctuation range of the present-day water table; its bulky appearance is controlled by the small tidal variations of the water surface. Based on U/Th and ^{14}C measurements, these deposits are all Holocene in age (Tuccimei *et al*., 2010, 2011).

Additionally, up to five paleo-levels of phreatic speleothems have been recognized (Figure 31) at the following elevations: +1.2, +2.4, +3.3, +4.5, and +7.5 m ASL (Ginés, 2000). Although there are no chronological data on these deposits, the lowest two could be tentatively assigned to MIS 5a and 5e, respectively. Preliminary U/Th datings of the higher paleo-levels yielded inconsistent isotopic data (i.e., geochemical open system), thus preventing reliable age determinations.

3.4 Coves d'Artà (Capdepera)
(*J. Ginés, A. Ginés & P. Tuccimei*)

Indubitably, Coves d’Artà was Mallorca’s most famous natural cave before the discoveries of Martel in Coves del Drac. Its spectacular subterranean sceneries, consisting in giant chambers extraordinary decorated by large speleothems, made the cave an internationally attraction during the 19th century. It is located in the southern sea-cliffs of Cap Vermell, a coastal promontory developed on Jurassic limestones in the north-eastern part of the island (Figure 32).

3.4.1 Historical data

In early times the cave was also known as Cova de s'Ermita. Although the first references about Coves d’Artà date back to the 17th and 18th centuries, the earliest detailed exploration presumably happened in 1806 and its first thorough description was published by Cabrer (1840). In 1862 the Mallorcan writer and scholar Pere

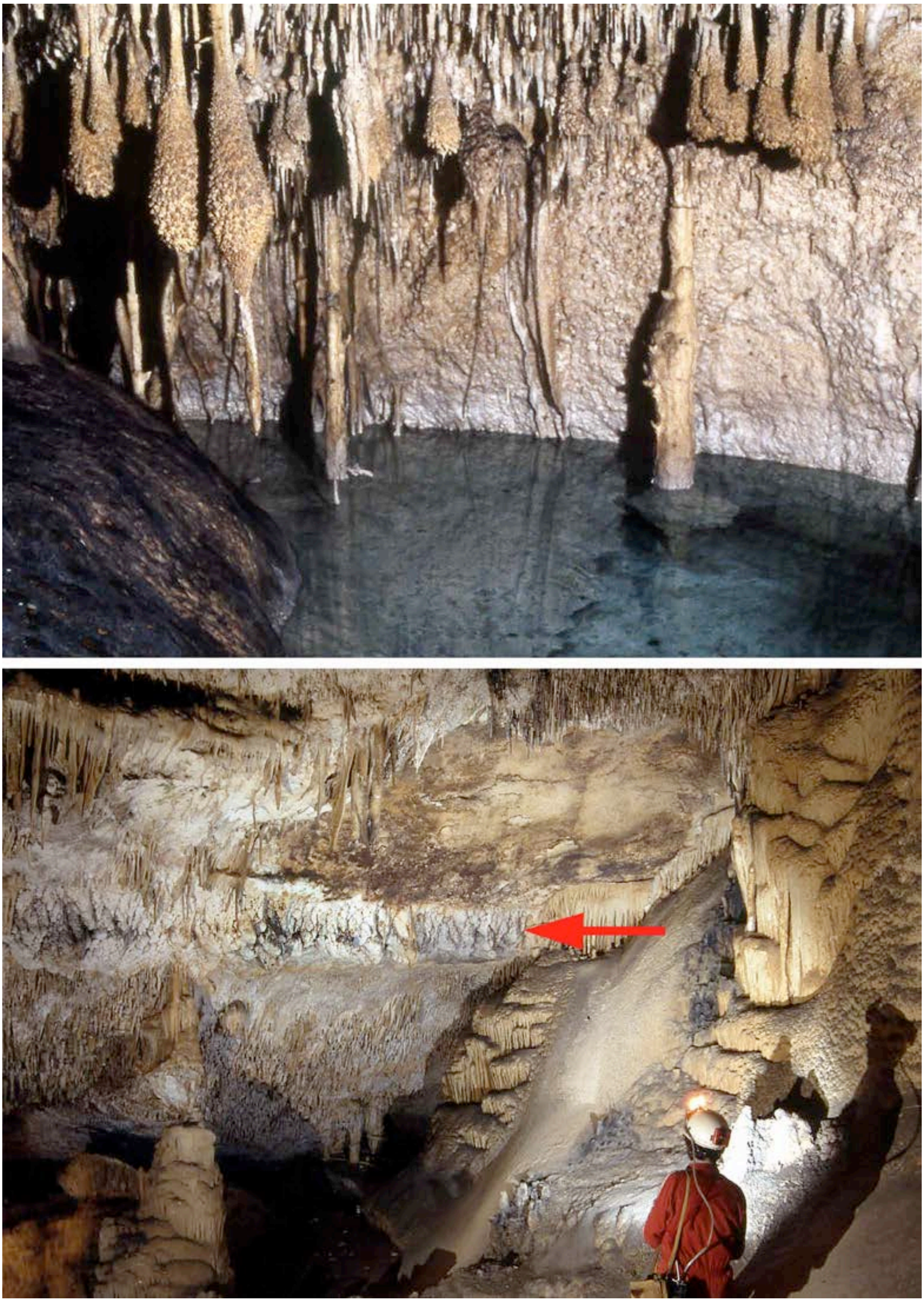

Figure 31. POS deposits in Coves del Drac. In the upper image, a paleo-level (at +1.2 m ASL) of phreatic speleothems is clearly defined by several stalactites coated by a rounded calcite encrustation. In the lower picture, a POS belt of crystallizations (see arrow) marks the paleo-level at +7.5 m ASL (Photos: J. Ginés).

Figure 32. The entrance to Coves d'Artà in the sea-cliffs of Cap Vermell. The monumental stairway access to the cave is visible in the middle part of the spectacular entrance shelter.

d'Alcàntara Peña, laid out the first topographic survey of the cavern (Figure 33). Among the numerous European travellers who visited the cave during the second half of the 19th century, we find the German naturalist H.A. Pagenstecher who travelled to Mallorca in 1865 accompanied by his compatriot and famous chemist R.W. Bunsen. Further information on historical aspects of Coves d'Artà is available in Ginés (1993).

Beginning with the 19th the cave was gradually fitted for tourism. Remarkable is the construction of the access stairway, which was built in 1860 in preparation for the Spanish Queen Isabel II visit to Mallorca. The simple fact that a *Guest Book* exists at this site since 1869 suggests the reputation the cave acquired and the frequent visits carried out to it.

The beginning of significant visits to the cave is linked to the outburst of tourism in Mallorca, a phenomenon of economic relevance that occurred at the beginning of 20th century. In this context, the first guide-map of the cave was published in 1912. The touristic exploitation goes on up to present times, having this Mallorcan cave the largest tradition in what concerns its recreational uses. Since the 20's, Coves d'Artà was somehow downgraded to a second position as a result of the increasing celebrity gained by the show-caves in Portocristo area (Ginés & Ginés, 2011).

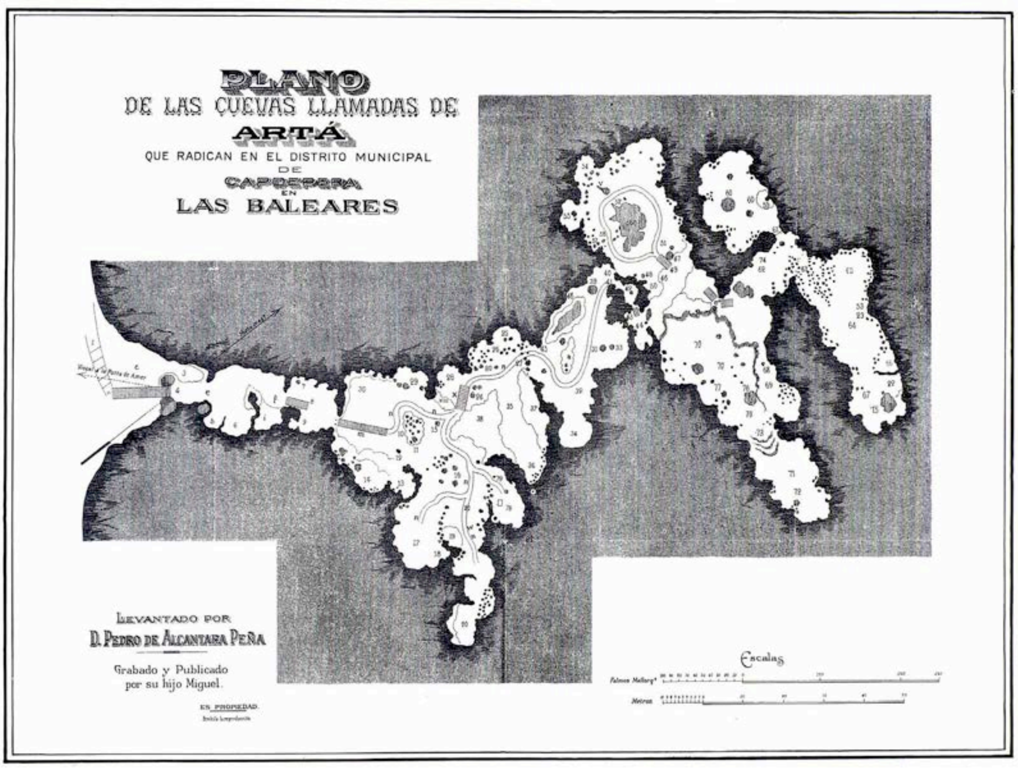

Figure 33. The survey of Coves d'Artà (Capdepera) performed in 1862 by the Mallorcan scholar Pere d'Alcàntara Peña.

3.4.2 Description and morphology

This giant cave consists of a succession of large underground chambers (some of them more than 20 m high), developed within the folded Jurassic limestones corresponding to the karst region of Serres de Llevant (Figure 3). Coves d'Artà opens at an elevation of 45 m and totals 650 m of halls and passages. It stretches to a maximum depth of approximately 30 m, so without reaching the current coastal water table.

The underground scenery is overwhelming given the dimensions of both chambers and speleothems decorating them (Figure 34). The size of columns and stalagmites is remarkable, including some examples that are more than 20 m tall. Among the large variety of speleothems, the cave shields and POS paleolevels are abundant and spectacular. The latter are bulbous in appearance and unusually voluminous (Figure 35).

The morphology of the cave is related to the evolution, under vadose conditions of an ancient network of phreatic conduits developed along some important fractures. There is no clear evidence to link the cave genesis with solutional processes acting in the coastal mixing zone. However, its overall morphology, location in the sea-cliffs, and the occurrence of ancient POS deposits at various elevations, clearly suggest that Coves d'Artà is a littoral cave regarding its morphogenetic story.

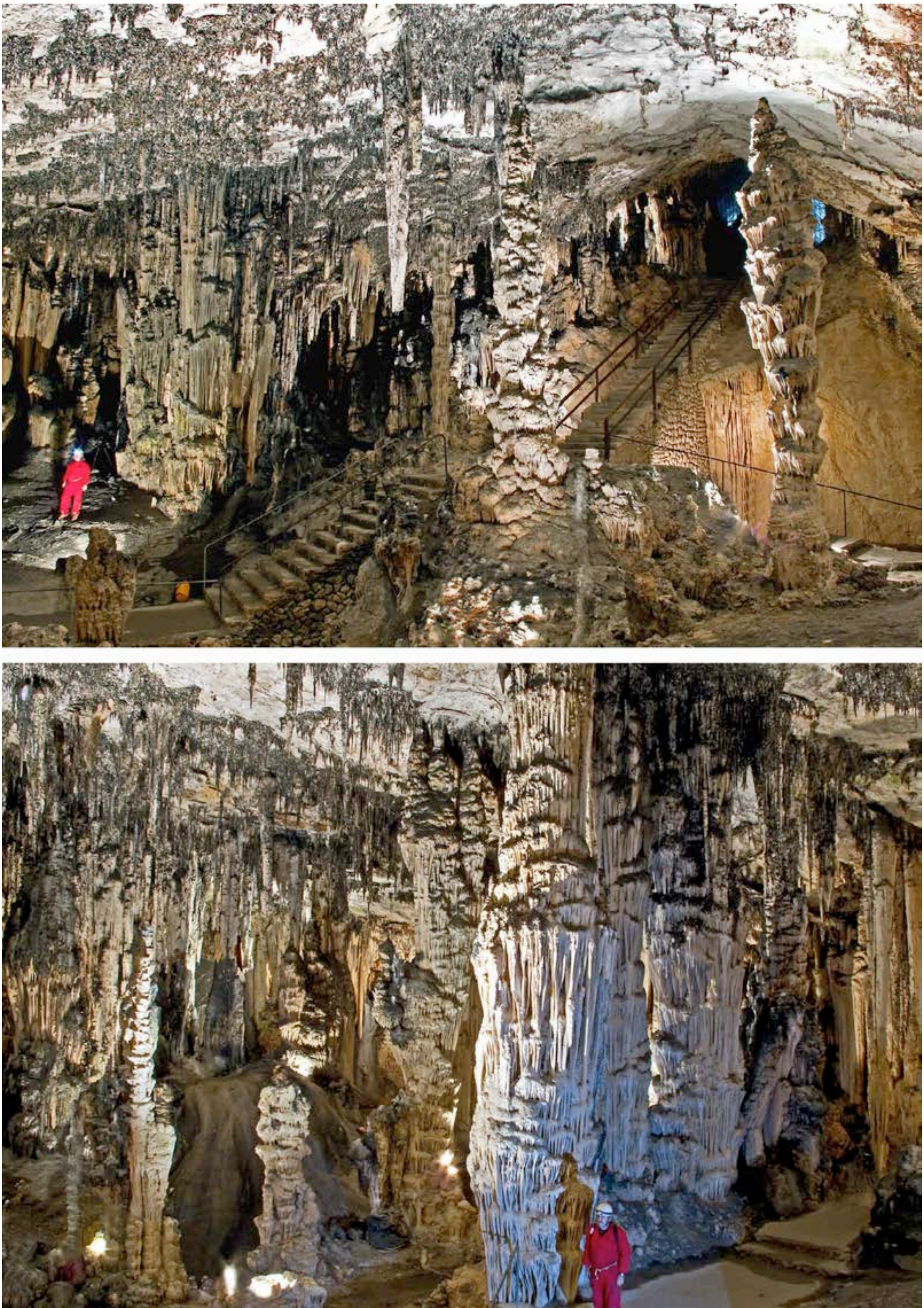

Figure 34. Two images of the highly-decorated chambers in Coves d'Artà. (Photos: F. Alabart).

3.4.3 The Middle Pleistocene POS deposits in Cap Vermell caves

In the inner chambers of Coves d'Artà –particularly in the Infern, Baptisteri, and Teatre halls– is easy to recognize several very evident POS paleo-levels, consisting of bulky horizontal belts that gives place to striking bulbous and large speleothems (Figure 35). The external surface of the encrustations is rather smooth, fact that points towards an aragonitic composition of these crystallizations; however, no mineralogical investigations have been conducted at this site. In total, up to six POS paleo-levels have been identified at elevations ranging between +23 and +32 m ASL (Ginés, 2000). The most outstanding are the prominent horizontal belts contouring the chamber known as Infern. No U/Th dates have been performed on samples from this cave so far.

The Cap Vermell area hosts another two caves containing POS deposits (Figure 36). One is Coves Petites, located in the vicinity of Coves d'Artà, and contains several paleo-levels from +30 to +46 m ASL. The other one, Cova de na Mitjana, opens in the northern slopes of Cap Vermell, showing an impressive macrocrystalline POS paleo-level at an elevation of approximately +6 m ASL. Some preliminary U/Th work has been conducted on samples from both these caves, but the results are somehow questionable due to recrystallization processes affecting these POS deposits. As such, one of the samples from Cova de na Mitjana yielded an age of 232 ka BP that points to a MIS 7 sea level high stand. In the case of Coves Petites, the analysis of samples from the +30 and +40 m ASL paleo-levels gives isotopic ratios very close to the unit, which allowed only the calculation of minimum ages of >187 and >205 ka BP respectively (Ginés & Ginés, 1993). Although not conclusive, the U/Th data from Coves Petites supports a tentative adscription of the POS paleolevels from Coves d'Artà to some Middle Pleistocene interglacial older than MIS 9.

Figure 35. Spectacular POS deposits existing in Coves d'Artà. Chronologically, these deposits were likely precipitated during the Middle Pleistocene (Photos: B.P. Onac).

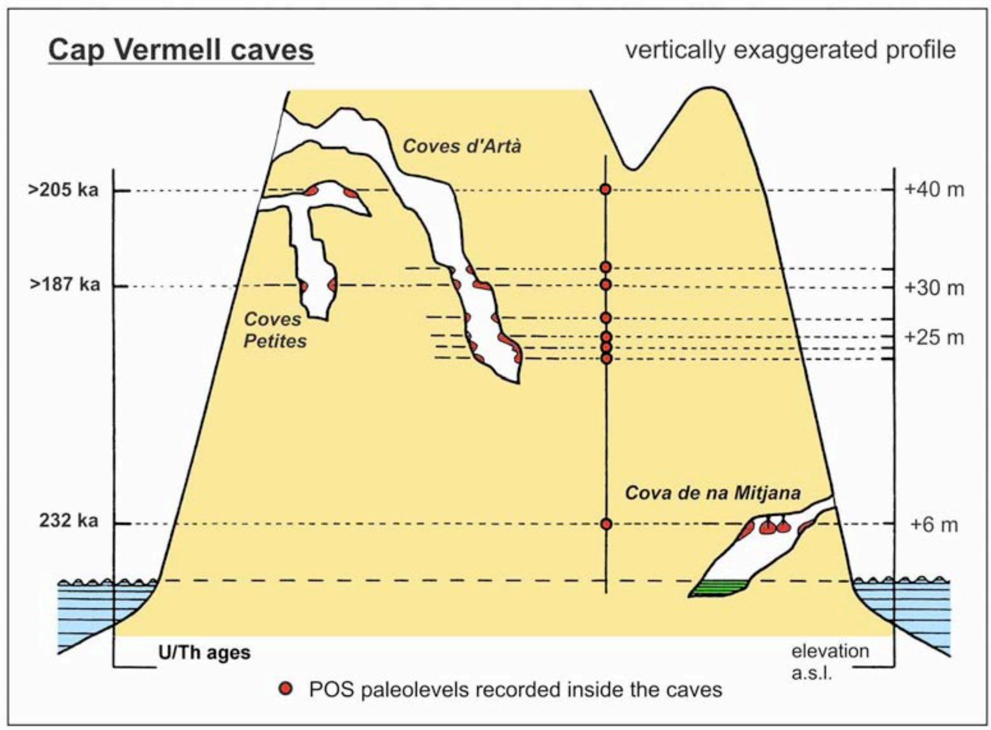

Figure 36. Schematic cross-section of Cap Vermell coastal promontory, showing the POS deposits observed in the caves and the limited U/Th data available.

3.5 Caloscamps - Es Caló (Colònia de Sant Pere): Eolian - fluvial Upper Pleistocene succession

(J.J. Fornós, L. Gómez-Pujol & D. Vicens)

3.5.1 Introduction

The eastern flank of the Alcúdia Bay hosts the coastal boundary of the deformed Mesozoic geological units of the Llevant Ranges (Figure 2). Along this ~7 km coastal band, from north of the town of Colònia Sant Pere to Cap Ferrutx, a piedmont zone made up of eolian-alluvial fan depositional systems precedes structural cliffs and abrupt reliefs (Figure 37). This landscape results in a rugged coastline with low, narrow shore platforms at the toe of 1 to 5 m in height cliffs. Cliff retreat and fluvial trenches expose stacked sequences of marine, fluviatile, colluvial, and eolian deposits that are interspersed with paleosols. Rodríguez-Perea (1998), Rose & Meng (1999) and Rose *et al*. (1999) described different southward sections, whereas Gómez-Pujol (1999), Gelabert *et al*. (2003), and Fornós *et al*. (2009) northward. All of them attribute the majority of these formations to the Upper Pleistocene. Additionally, age-equivalent outcrops and sedimentary systems have been described at the neighbor Bay of Pollença (Fornós *et al*., 2009).

The Upper Pleistocene deposits in northeastern Mallorca record a complex interaction between eolian, colluvial, and alluvial fan deposition, resulting in a complex stratigraphical architecture of alluvial fans and dunefield systems that overlie the Eemian beach deposit (Rose *et al*., 1999). The type and geometry of dunes, the composition of sands and fluviatile sediments vary considerably and reflect the pre-existing landscape morphology and its control on both, the eolian and the fluvial processes. Locally, eolian bodies participate significantly in the composition of alluvial fans that exhibit larger geometries with respect to the catchment-feeding basin (Gómez-Pujol *et al*., 2008). On some other occasions, however, the eolian sediments are reworked and incorporated into the alluvial fan bodies and sediments (Fornós *et al*., 2009). The contribution of the fan and dune deposits to the local architecture reflects both the relative position with respect to the alluvial fan axis and the seaward influx of eolian sand.

In all the coastal sequence, four main eolian units interbedded with alluvial deposits (sheet-flood, fluvial channel, and especially, reworked eolian deposits) and some paleosols can be distinguished. The sequence records four phases of eolian activity between MIS 5c and MIS 3 (Fornós *et al*., 2009). The three lowermost eolianite units consist of migrating crescent dunes that were not obstructed by inland cliffs and correspond to ordinary dune deposits in distal alluvial fan areas. They display large-scale through cross-stratification with wind ripple lamination and sand-flow stratifications. Their inland migration was apparently only controlled, apart from the dominant westerly wind, by the amount of water runoff from the alluvial fan. The uppermost eolianite is located at the top of the cliff exposure in near contact with alluvial fan deposits. The interbedded non-eolian deposits are composed, in some parts, exclusively by alluvial fan facies (sheet-flood, channel deposits) whereas in other parts include water-reworked eolian deposits, evidencing the contemporary eolian

Figure 37. General overview of the eastern flank of Alcúdia Bay and location of sections and the study cited in text.

sand transport and alluvial fan processes. Therefore, marine sands were blown inland and integrated with typical continental deposits.

3.5.2 Caloscamps section

The Caloscamps is a small cove located 1.7 km north of the town of Colònia de Sant Pere. The site is a coastal plain located at the base of a small river catchment (3.14 km^2). The present river channel –torrent des Cocó– is narrow and incised to the valley bottom and occasionally produces storm-related flood events capable of transporting gravels with very large individual clasts. The waterfront is characterized by a continuous horizontal shore platform at 1-1.5 m amsl A 3 m in height sedimentary cliff rests on the shore platform exhibiting paleosols, eolian, fluviatile, and marine sediments. A boulder beach rests at the torrent des Cocó river mouth.

Cuerda & Galiana (1975) presented the first description of Caloscamps outcrop and differentiated two marine levels according to their fauna assemblages. The older one rests at 1 m above present sea level over a marine erosion surface that shapes the supposed rissean eolianites. Breccia and conglomerates with a sandy matrix that contain abundant termophile fauna as *Barbatia plicata*, *Brachidontes senegalensis*, *Cardita senegalensis*, *Cantharus viverratus*, and *Conus testudinarius* compose this level. This faunal assemblage belongs to the Eutyrrhenian (Cuerda, 1979). Otherwise, the younger level, which according to the location lies on both the erosive contact over the rissean eolianites and/or over the former marine breccias, is composed of medium to coarse silty sands with marine non-termophile fauna. Vicens *et al.* (2001), who revisited this outcrop, consider this second marine level to be MIS 5a. Paleosols, alluvial

Figure 38. Datings from Rose el al. (1999) at the main section at Caloscamps cliff outcrops.

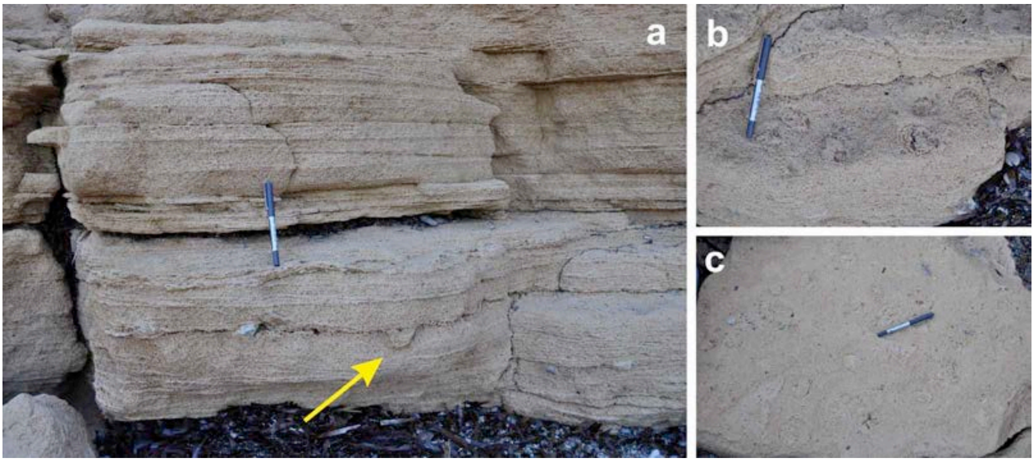

Figure 39. Tracks and trackways of *Myotragus* at the base level fluvial reworked eolian sands.

and eolian sediments ranging from MIS 5e to MIS 1 cover the marine levels (Rose *et al*., 1999).

The waterfront section around Caloscamps is rather inconsistent because of the influence of river mouth and eolian processes. That scenario results in a major or minor contribution of eolianites or fluviatile deposits in the section as observer approaches or moves away from the fluvial trench. Nevertheless, in general terms, the Late Pleistocene section at Caloscamps presents the following sequence (Figure 38) that is equivalent to section C of Rose *et al*. (1999):

At the base: calcarenite (1 to 2 m thick) that corresponds to a lithified, well-sorted medium sand rich in silt. It is primarily composed of rounded bioclasts, mainly molluscs fragments, and has a bright brown color. It is a horizontally bedded sandstone cemented by calcite with bed thicknesses between 0.1 to 1 m. Additionally, tracks and trackways of *Myotragus* can be observed in this unit (Figure 39). Locally, this deposit shows erosive bases and many interbedded gravelly layers. Some of these beds are cut by fluvial channel and lag deposits composed of clast-supported, pebbly to cobbly gravel beds, crudely stratified with an erosive lower boundary.

Channel size is normally around 1-2 m width. Rose *et al.* (1999) interpreted this unit as beach sands and related it to MIS 6. Fornós *et al*. (2009) offer a different view by relating these levels to waterlaid-fluviatile reworked eolian deposits. This conclusion is based on detailed observations described above and after investigating other outcrops in Alcúdia and Pollença bays, Despite sand particles are composed primarily of wind-transported marine sediment, These deposits are fairly rich in Jurassic limestone gravels and lamination departs largely from typical eolian stratification. The laminated sandstone facies resemble flashy ephemeral sheet flow or waterlaid alluvial deposits. All of these suggest that this facies was formed by fluvial reworking of pre-existing sand-ramp deposits, probably in relation to heavy rains.

Covering an erosive contact, the sequence continues with a bed of 0.5 to 1 m of breccia and conglomerates having sandy matrix that contain abundant termophile fauna as *Barbatia plicata*, *Brachidontes senegalensis*, *Cardita senegalensis*, *Cantharus* *viverratus*, and *Conus testudinarius* (Figure 40). This unit is interpreted as a beach deposit and by means of regional paleontological criteria is attributed to MIS 5e (Vicens *et al*., 2001). It appears isolated and changes across an erosive contact to a new laterally continuous beach deposit composed of medium to coarse sand with a very pale brown color. Bioclasts, molluscs fragments, and shells, are the main constituents. In contrast to the former beach deposit, the second one misses the termophile fauna and is assigned to MIS 5a (Vicens *et al*., 2001). At sa Cugusa site (100 m west of Caloscamps), the MIS 5a beach overlies directly (by an erosive contact) the lower calcarenite unit. It is interesting to notice that at this site, some authentic dune deposits, overlapping fluviatile reworked eolianites can be recognized (Figure 41).

A well-developed and laterally continuous paleosol reposes on the younger beach deposit (Figure 42). It reaches in some places almost 2 m in thickness and clearly shows two different levels distinguished by their color. The lower one, yellowish red (showing iron concentration bands), is mainly composed of coarse silt with a large share of clay. The presence of sand is especially abundant at the base, probably due to the reworking of the lower levels. Rose *et al*. (1999) interpret the iron band as an indication of a moist period with a high biomass cover that could fit with the environmental conditions occurred during the fall of sea-level in MIS 5d. The well-developed paleosol changes into a yellowish brown softly paleosol that also show some iron concentrations bands. It is mainly composed of silt with small amounts of clay and sand. Silica and calcite dominate the mineralogical composition, although feldspars and micas are present. Rose *et al*. (1999) interpret this uppermost bed as a

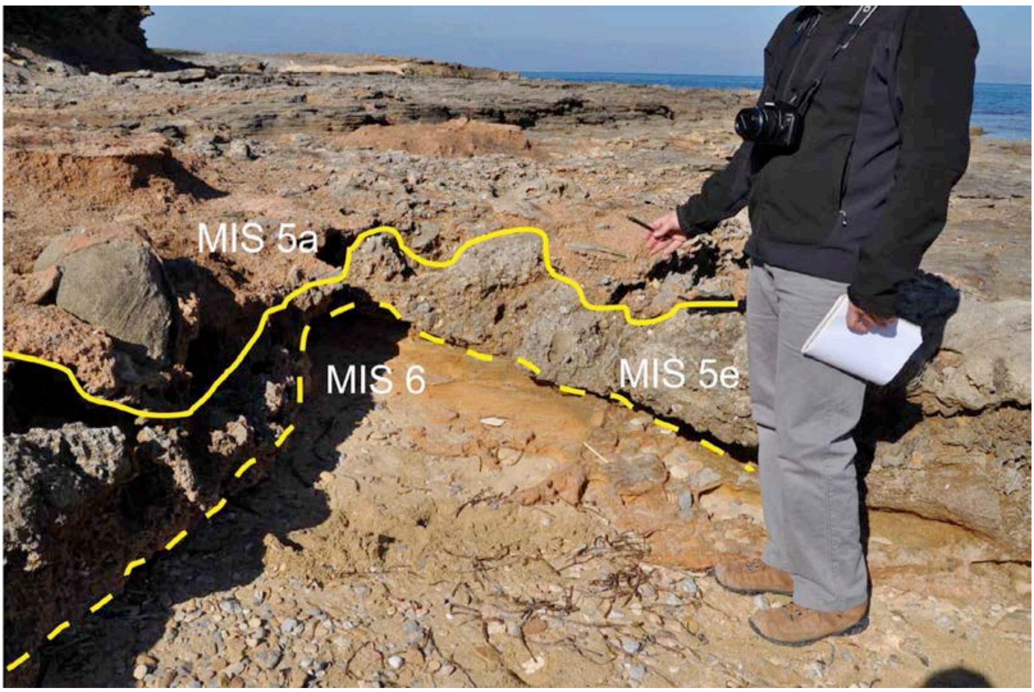

Figure 40. Detail of the two marine levels corresponding to MIS 5e and 5a that overly the sands attributed to MIS 6.

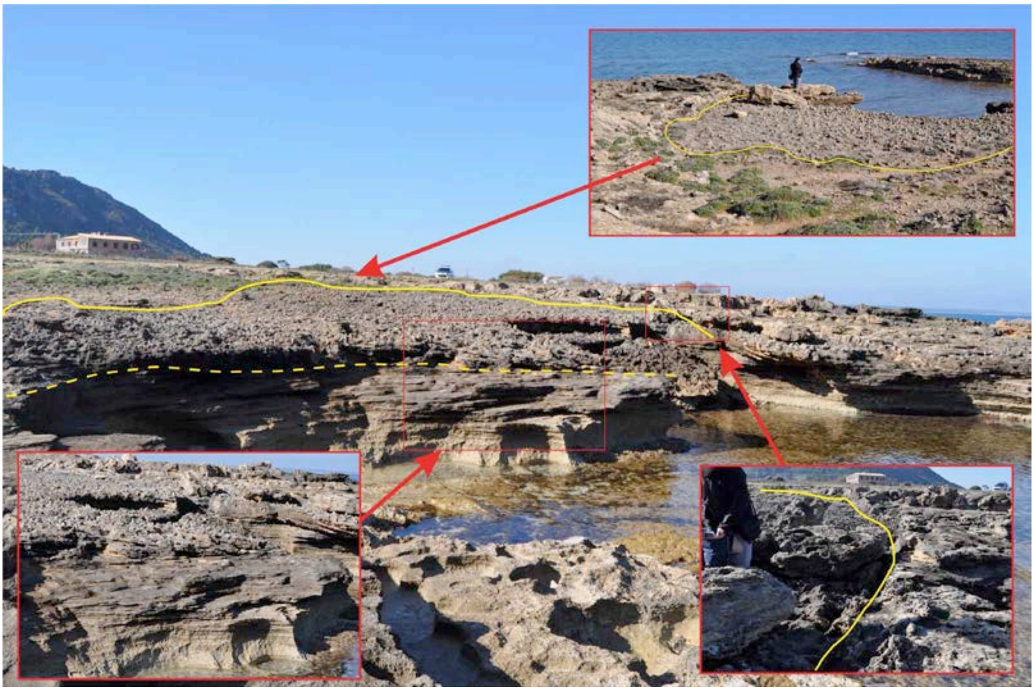

Figure 41. Detail of sa Cugusa site (100 m westwards from Caloscamps), where beach sands from MIS 5a overlies dune and fluvial deposits formed during MIS 6.

Figure 42. General view of the soil showing iron concentration bands (and eolian and fluviatile deposits) that cover the MIS 5e beach deposit.

loess deposit derived from a broad region as rainout from dust-charged atmosphere, and assign it to MIS 4. The paleosol and loess deposits thinners eastwards interfingering with fluviatile deposits.

A pink to very pale brown eolian sand deposit develops over the paleosol. It forms dunes of almost 2 m in thickness composed of fine- to coarse-grained very well-sorted sand that is mixed with marine bioclasts, a negligible amount of reworked Jurassic particles, as well as few quartz grains. It shows large-scale trough cross-stratification partially disrupted in some places by root casts. This deposit records the inland migration of relatively large crescentic dunes. Wind-transported sediment was near shore carbonate sands and sediment derived from local marine sources (Fornós *et al.*, 2009). Rose *et al*. (1999) frames the dune deposition within the MIS 3.

Laterally, the eolian deposit is disrupted and interbeded by fluviatile bodies of sands and gravels (Figure 43). Both sub-angular to sub-rounded pebbles, cobbles, and gravels come from the Lower and Middle Jurassic limestone and dolomite rocks, present in the catchment area. This suggests that ephemeral rivers once draining the nearby small catchments were the source for the detrital sands and gravels. These small catchment rivers build up alluvial fan at the toe of Serres de Llevant abrupt topography. Eolian deposition occurred beyond the influence of such ephemeral streams and alluvial fan deposition. Were both processes (eolian and fluvial) interact

Figure 43. Disposition of fluviatile and reworked dunes units above the marine deposits in the middle section of Caloscamps sequence.

Figure 44. Interference of alluvial, dune, and paleosol deposit in the upper member of Calocamps

mixed facies is recognizable. The conglomerates form a stacked sequence with three different sedimentary facies. The plane-stratified to cross-bedded conglomerates that are composed of well-sorted massive to crudely-bedded gravel beds, and show limited internal structures or grading, sometimes cross bedding with a sheet-like geometry that thickens laterally. They are interpreted as sheet-flood deposits and record rapid deposition during sheet flooding following episodes of intense rainfall. The channel-shaped conglomerates are composed of clast-supported, pebbly to cobbly gravel beds interlayered with poorly sorted and stratified sand beds rich in silts. These are loosely stratified and show normal grading, whereas larger clasts show imbrication. Locally matrix-supported gravel beds occur on carbonate sand as that described by the eolianite levels. They have a restricted lateral continuity with erosive lower boundaries (Figure 43). Interpreted as fluvial channel deposits, they record the deposition from confined water flow in incised channels over the alluvial fan architecture (Fornós *et al.*, 2009).

Finally, both matrix- or clast-supported conglomerates, showing a great variability with clast-size ranging from gravel to granules in a well sorted medium-grained carbonate sand matrix form the graded to plane-stratified gravel-sand couplets. These deposits are well laminated with parallel bedding, crude imbrication of clasts and incipient parallel lamination in the sand matrix. They resulted from the mixing of eolian and alluvial deposits and record the mixing of eolian carbonate sand (usually forming the matrix of the conglomerates) and alluvial clasts during turbulent flows under flooding conditions. Locally, eolian sand sheets develop showing incipient paleosol formation with abundant root casts (Figure 44). Rose *et al*. (1999) date this deposits as deposited during MIS (3)-2 stages under cold and arid conditions with limited vegetation cover. Finally, on top of the sequence, a thin horizontally laminated sand deposit is visible; it is partially covered by humic sandy loam.

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References

Alcover, J.A. (2004): Disentangling the Balearic first settlement issues. *Endins*, 26: 143-156.

Alcover, J.A., Moyà-Solà, S. & Pons, J. (1981): *Les quimeres del passat. Els vertebrats fòssils del Plio-Quaternari de les Balears i Pitiüses*. Ciutat de Mallorca. Mon. Científica. Editorial Moll, 1: 1-260.

Alcover, J.A., Pérez-Obiol, R., Yll, E.I. & Bover, P. (1999): The diet of *Myotragus balearicus* Bate 1909 (Artiodactyla, : Caprinae), an extinct bovid from the Balearic Islands : evidence from coprolites. *Biological Jornal of the Linnnean Society*, 66: 57-74.

Bardají, T.; Goy, J.L.; Zazo, C.; Hillaire-Marcel, C.; Dabrio, C.J.; Cabero, A.; Ghaleb, B.; Silva, P.G. & Lario, J. (2009): Sea level and climate changes during OIS 5e in the Western Mediterranean. *Geomorphology*, 104: 22-37.

Benedicto, A.; Ramos, E.; Casas, A.; Sàbat, F. & Barón, A. (1993): Evolución tectonosedimentaria de la cubeta neógena de Inca (Mallorca). *Rev. Soc. Geol. Esp.*, 6: 167-176.

Bolòs, O. (1996): *La vegetació de les Illes Balears. Comunitats de plantes*. Institut d'Estudis Catalans. Arxius de la Secció de Ciències. CXIV Secció de Ciències Biològiques, 267 pp.

Butzer, K.W. (1975): Pleistocene littoral-sedimentary cycles of the Mediterranean Basin: A Mallorquin view. In: *After the Austrolopithecines* (K.W. Butzer and G. Isaac eds.) Mouton Press. The Hague.

Butzer, K.W. & Cuerda, J. (1962): Coastal stratigraphy of southern Mallorca and its implications for the Pleistocene chronology of the Mediterranean Sea. *The Journal of Geology*, 70(4): 398-416.

Cabrer, A. (1840): *Viaje a la famosa gruta llamada Cueva de la Ermita en el distrito de la villa de Artá de la isla de Mallorca*. Imprenta de Pedro José Gelabert, 87 pp, Palma de Mallorca.

Calvet, F. & Pomar, L. (1975): Las rizocreciones del Pleistoceno de Mallorca. *Univ. Barcelona. Inst. Invest. Geol.*, 30: 35-60.

Clemmensen, L.B., Fornós, J.J. & Rodríguez-Perea, A. (1997): Morphology and architecture of a late Pleistocene cliff-front dune, Mallorca, Western Mediterranean. *Terra Nova*, 9: 251-254.

Clemmensen, L.B., Lisborg, T., Fornós J.J. & Bromley, R.G. (2001): Cliff-front aeolian and colluvial deposits, Mallorca, Western Mediterranean : a record of climatic and environmental change during the last glacial period. *Bulletin of the Geological Society of Denmark*, 48: 217-232.

Cuerda, J. & Galiana, R. (1975): Nuevo yacimiento del Pleistoceno superior marino en la costa norte de Mallorca. *Boll. Soc. Hist. Nat. Balears*, 21: 115-124.

Cuerda, J. (1957): Fauna marina del Tirreniense de la Bahía de Palma (Mallorca). *Boll. Soc. Hist. Nat. Balears*, 3: 3-76.

Cuerda, J. (1975): *Los tiempos Cuaternarios en Baleares*. Inst. Est. Bal. Palma. 304 pp.

Cuerda, J. (1979): Formaciones cuaternarias de la Bahía de Palma. *Guía a la excursión nº 4 del VI Coloquio de Geografía*. 22 pp. Palma.

Cuerda, J. (1989): *Los tiempos Cuaternarios en* Baleares. Dir. Gral. Cultura, Conselleria de Cultura, Educació i Esports. Govern Balear, Mallorca. 305 pp.

Cuerda, J. & Osmaston H.A. (1978): Quaternary deposits in the central part of the Bay of Palma. A: Rose, J. (ed.). *The Quaternary of Mallorca.* Quaternary Research Association-Field Meeting Guide: 61-71.

Del Olmo, P & Alvaro, M. (1984): Control estructural de la sedimentación Neógena y Cuternaria de Mallorca. *I Congreso Español de Geología, Segovia*, 1: 219-228.

Dorale, J.A.; Onac, B.P.; Fornós, J.J.; Ginés, J.; Ginés, A.; Tuccimei, P. & Peate, D.W. (2010): Sea-level highstand 81,000 years ago in Mallorca. *Science*, 327: 860-863.

Fallot, P. (1922): *Étude géologique de la Sierra de Majorque*. PhD Thesis. Lib. Polyt. Ch. Béranger ed. Paris, 420 p.

Fontboté, J.M.; Guimerà, J.; Roca, E.; Sàbat, F.; Santanach, P. & Fernández-Ortigosa, F. (1990): The enozoic evolution of Valencia trough (Western Mediterranean). *Revista de la Sociedad Geológica de España*, 3: 249-259.

Fornós, J.J. & Gelabert, B. (1995): Lithology and tectonics of the majorcan karst. *Endins*, 20: 27-43.

Fornós, J.J., Bromley, R.G., Clemmensen, L.B. & Rodríguez-Perea, A. (2002): Tracks and trackways of Myotragus balearicus Bate (Artiodactyla, Caprinae) in Pleistocene aeolianites from Mallorca (Balearic Islands, Western Mediterranean). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 180: 277-313.

Fornós, J.J.; Clemmensen, L.B.; Gómez-Pujol, L. & Murray, A.S. (2009). Late Pleistocene carbonate aeolianites on Mallorca, Western Mediterranean: a luminescence chronology. *Quaternary Science Reviews*, 28 (25-26): 2697-2709.

Fornós, J.J.; Gelabert, B.; Ginés, A.; Ginés, J.; Tuccimei, P. & Vesica, P.L. (2002b): Phreatic overgrowths on speleothems: a useful tool in structural geology in littoral karstic landscapes. The example of eastern Mallorca (Balearic islands). *Geodinamica Acta*, 15: 113-125.

Fornós, J.J.; Merino, A.; Ginés, J.; Ginés, A. & Gràcia, F. (2011): Solutional features and cave deposits related to hypogene speleogenetic processes in a littoral cave of Mallorca Island (western Mediterranean). *Carbonates and Evaporites*, 26 (1): 69-81.

Fornós, J.J.; Pomar, L. & Ramos-Guerrero, E. (2002a): Balearic Islands. In: Gibbons, W. & Moreno, T. (eds.) *The Geology of Spain*, The Geological Society, 327-334. London.

Gelabert, B.; Fornós, J.J. & Gómez-Pujol, L. (2003): Geomorphological characteristics and slope processes associated with different basins: Mallorca (Western Mediterranean). *Geomorphology*, 52: 253–267.

Gelabert, B.; Sàbat, F. & Rodríguez-Perea, A. (1992): A structural outline of the Serra de Tramuntana of Mallorca (Balearic Islands). Tectonophysics. 203 :167-183.

Gibbons, W. & Moreno, T. (2002): *The Geology of Spain*. The Geological Society, London, pp. 649.

Ginés, A. (1993): Apuntes históricos sobre las Coves d'Artà (Capdepera, Mallorca). *Boletín del Museo Andaluz de la Espeleología*, 7: 21-27. Granada.

Ginés, A. (1999): Edouard-Alfred Martel et la spéléologie à Majorque. In: André, D. & Duthu, H. (eds.) *L'homme qui voyageait pour les gouffres.* Archives Départamentales de la Lozère. 291-300. Mende.

Ginés, A. & Ginés, J. (1992): Las Coves del Drac (Manacor, Mallorca). Apuntes históricos y espeleogenéticos. *Endins*, 17-18: 5-20.

Ginés, A. & Ginés, J. (2007): Eogenetic karst, glacioeustatic cave pools and anchialine environments on Mallorca Island: a discussion of coastal speleogenesis. *International Journal of Speleology*, 36 (2): 57-67.

Ginés, J. (2000): *El karst litoral en el levante de Mallorca: una aproximación al conocimiento de su morfogénesis y cronología*. PhD Thesis. Universitat de les Illes Balears, 595 pp. Palma de Mallorca.

Ginés, J. & Ginés, A. (1993): Speleochronological approach to some coastal caves from Cap Vermell area in Mallorca island (Spain). *Proc. 11th Int. Congress Speleol.* 56-59. Beijing.

Ginés, J. & Ginés, A. (2011): Les coves turístiques de les Illes Balears: antecedents i estat de la qüestió. In: Gràcia, F.; Ginés, J.; Pons, G.X.; Ginard, A. & Vicens, D. (eds.) *El carst: patrimoni natural de les Illes Balears*. Endins, 35 / Mon. Soc. Hist. Nat. Balears, 17: 333-344.

Ginés, J.; Ginés, A.; Fornós, J.J.; Merino, A. & Gràcia, F. (2009a): On the role of hypogene speleogenesis in shaping the coastal endokarst of southern Mallorca (Western Mediterranean). In: Klimchouk, A.B. & Ford, D.C. (eds.) *Hypogene speleogenesis and karst hydrogeology of artesian basins*. Ukrainian Institute of Speleology and Karstology, Special Paper 1: 91-99. Simferopol, Ukraine.

Ginés, J.; Ginés, A.; Fornós, J.J.; Merino, A. & Gràcia, F. (2009b): About the genesis of an exceptional coastal cave from Mallorca Island (Western Mediterranean). The lithological control over the pattern and morphology of Cova des Pas de Vallgornera. In: White, W.B. (ed.) *Proc. 15th Int. Congress Speleol.*, 1: 481-487. Kerrville, U.S.A.

Gómez-Pujol, L. (1999): Sedimentologia i evolució geomorfológica quaternària del ventall al·luvial des Caló (Betlem, Artà, Mallorca). *Boll. Soc. Hist. Nat. Balears*, 42: 1017-1124.

Gómez-Pujol, L.; Fornós, J.J.; Pope, R.J. & Clemmensen, L. (2008): Los abanicos aluviales litorales del NE de Mallorca: morfometría y arquitectura de facies. In Benavente, J., Gracia, F.J. (eds). *Trabajos de Geomorfología en España, 2006-2008*: 331-334. Sociedad Española de Geomorfología, Cádiz.

Goy, J.L.; Zazo, C. & Cuerda, J. (1997): Evolución de las áreas margino-litorales de la Costa de Mallorca (I. Baleares) durante el Último y Presente Interglacial. Nivel del mar, Holoceno y clima. *Bol. Geol. y Minero*, 108: 127-135.

Goy, J.L.; Zazo, C.; Hillaire-Marcel, C.; Cabero, A.; Bardají, T.; Bassam, G.; Silva, P.G. & González-Hernández, F.M., (2005): Stop 1. In: Silva, P.G., Goy, J.L., Zazo, C., Jiménez, J., Fornós, J.J., Cabero, A., Bardají, T., Mateos, R., González-Hernández, F.M., Hillaire-Marcel, C., Bassam, G., "*Mallorca Island: Geomorphological Evolution and Neotectonics*". In: Desir, G., Gutiérrez, F. & Gutiérrez, M. (eds.), Field Trip Guide Book, Sixth International Conference on Geomorphology, Zaragoza, Spain, p. 6–8.

Gràcia, F.; Clamor, B.; Gamundí, P. & Fornós, J.J. (2010): El sistema de cavitats Gleda - Camp des Pou (Manacor, Mallorca). *Endins*, 34: 35-68.

Gràcia, F.; Fornós, J.J.; Clamor, B.; Febrer, M. & Gamundí, P. (2007): La Cova de sa Gleda I. Sector Clàssic, Sector de Ponent i Sector Cinc-Cents (Manacor, Mallorca): geomorfologia, espeleogènesi, sedimentologia i hidrologia. *Endins*, 31: 43-96.

Gràcia, F.; Fornós, J.J.; Gamundí, P.; Clamor, B.; Pocoví, J. & Perelló, M.A. (2009): Les descobertes subaquàtiques a la Cova des Pas de Vallgornera (Llucmajor, Mallorca): història i descripció dels descobriments, hidrologia, espeleotemes, sediments, paleontologia i fauna. *Endins*, 33: 35-72.

Gràcia, F.; Jaume, D.; Ramis, D.; Fornós, J.J.; Bover, P.; Clamor, B.; Gual, M.A. & Vadell, M. (2003): Les coves de Cala Anguila (Manacor, Mallorca). II: La Cova Genovesa o Cova d'en Bessó. Espeleogènesi, geomorfologia, hidrologia, sedimentologia, fauna, paleontologia, arqueologia i conservació. *Endins*, 25: 43-86.

Guijarro, A. (1986): Contribución a la Bioclimatología de Baleares. PhD Thesis, Departament de Biologia, Universitat de les Illes Balears. Palma.

Hearty, P.J. (1987): New Data on the Pleistocene of Mallorca. *Quaternary Sciencs Reviews*, 6: 245-257.

Hearty, P.J.; Miller, G.H.; Stearns, Ch.E & Szabo, B.J. (1986): Aminostratigraphy of Quaternary shorelines in the Mediterranean Basin. *Geol. Soc. Am Bull.*, 97: 850-858.

Hillaire-Marcel, C., Gariepy, C., Ghaleb, B., Goy, J. L., Zazo, C. & Cuerda, J. (1996): U-Series measurements in tyrrhenian deposits from Mallorca - Further evidence for two last-interglacial high sea levels in the Balearic Islands. *Quaternary Science Reviews*, 15: 53-62.

Jaume, D.; Boxshall, G.A. & Gràcia, F. (2008) Stephos (Copepoda: Calanoida: Stephidae) from Balearic caves (W Mediterranean). *Systematics and Biodiversity*, 6 (4): 503-520.

Klimchouk, A.B. (2007) *Hypogene speleogenesis: hydrogeological and morphogenetic perspective*. National Cave and Karst Research Institute, Special Paper 1, 106 pp. Carlsbad, U.S.A.

Lancaster, N. & Tchakerian, V.P. (1996): Geomorpholog and sediments of sand ramps in the Mojave desert. *Geomorphology*, 17: 151-165.

Livingstone, I. & Warren, A. (1996): *Aeolian geomorphology. An Introduction.* Addison Wesley Longman, Essex.

Mader, B. (2005): Reiseskizzen von den Balearen. Der Entomologe Friedrich Will und Erzherzog Ludwig Salvator. *Endins*, 28: 61-70.

Martel, E.A. (1896): Sous Terre. Cueva del Drach, a Majorque. *Ann. Club Alpin Franc.*, 23: 1-32.

Merino, A.; Mulet, A.; Mulet, G.; Croix, A. & Gràcia, F. (2009): Cova des Pas de Vallgornera: an exceptional littoral cave from Mallorca Island (Spain). In: White, W.B. (ed.) *Proc. 15th Int. Congress Speleol.*, 1: 522-527. Kerrville, U.S.A.

Muntaner, A. (1957): Las formaciones cuaternarias de la Bahia de Palma. *Boll. Soc. Hist. Nat. Balears*, 3: 77-126.

Olivet, J.L.; Bonnin, J.; Beuzart, P. & Auzende, J.M. (1984): *Cinématique de I'Atlantique nord et central*. In: Rapports scientifiques. CNEX, O. 108 pp. Paris.

Pomar, L., Fornós, J.J. & Rodríguez-Perea, A. (1985): Reef and shallow carbonate facies of the Upper Miocene of Mallorca. IAS 6th European Regional Meeting, Excursion Guidebook, 494-518.

Pomar, L.; Ward, W.C. & Green D.G. (1996): Upper Miocene reef complex of the Llucmajor area, Mallorca, Spain. In: Franseen, E.; Esteban, M.; Ward, W.C. & Rouchy J.M. (eds.) *Models for carbonate stratigraphy from Miocene reef complexes of the Mediterranean regions*, SEPM Concepts in Sedimentology and Paleontology 5, 191-225.

Pye, K. & Tsoar,H. (1990): *Aeolian Sand and Sand Dunes*. Unwin Hyman, London.

Racoviţă, G. (2005): La découverte de *Typhlocirolana*. Moment crucial dans la marche de la Biospéologie. *Endins*, 28: 11-18.

Ramis, C. (1998): L'embat a l'illa de Mallorca. *Territoris*, 1: 253-274.

Ramis, C.; Jansà, A. & Alonso, S. (1990): Sea breeze in Mallorca. A numerical study. *Meteorology and Atmospheric Physics*, 42: 249-258.

Ramis, D. & Santandreu, G. (2011): Arqueologia de les cavernes de les Illes Balears. In: Gràcia, F.; Ginés, J.; Pons, G.X.; Ginard, A. & Vicens, D. (eds.) *El carst: patrimoni natural de les Illes Balears*. Endins, 35 / Mon. Soc. Hist. Nat. Balears, 17: 317-332.

Ramos-Guerrero, E.; Rodríguez-Perea, A; Sàbat, F. & Serra-Kiel, J. (1989): Cenozoic tectosedimentary evolution of Mallorca island. *Geodinamica Acta*, 3 (1): 53-72.

Rodríguez-Perea, A. (1992): Geologia de Mallorca. *Gran Enciclopèdia de Mallorca*, 8: 225-238.

Rose, J.; Meng, X. & Watson, C. (1999): Paleoclimate and paleoenvironmental responses in the western Mediterranean over the last 140 kyr: evidence from Mallorca, Spain. *Journal of the Geological Society London*, 150: 435-448.

Rubin, D. (1987). *Cross-bedding, Bedforms and Paleocurrents.* SEPM Concepts in Sedimentology and Paleontology. SEPM, Tulsa, OK.

Servera, J. (1997): Els sistemes dunars litorals de les Illes Balears. PhD Thesis. Universitat de les Illes Balears. Mallorca.

Silva, P.G., Goy, J.L., Zazo, C., Jiménez, J., Fornós, J.J., Cabrero, A., Bardají, T., Mateos, R.M., González-Hernández, F.M., Hillaire-Marcel, Cl. & Bassam, G. (2005): Mallorca Island: Geomorphological evolution and neotectonics. In: Desir, G.; Gutiérrez, F; and Gutiérrez, M. (eds). *Field Trip Guides. Sixth International Conference on Geomorphology. The International Association of Geomorphologists*, Zaragoza, Spain, pp. 433–472.

Solé Sabaris, L. (1962): Le Quaternaire marin des Baleares et ses rapports avec les côtes meditérranéenes de la Peninsule Ibérique. *Quaternaria*, 6: 309-342.

Stearns, C.H. & Thurber, D. (1965): ^{230}Th/^{234}U dates on Late Pleistocene marine fossils from the Mediterrnean and Moroccan littorals. *Quaternaria*, 7: 29-41.

Stearns, C.H. & Thurber, D. (1967): ^{230}Th/^{234}U dates on Late Pleistocene marine fossils from the Mediterrenean and Moroccan littorals. *Prog. Oceanography*, 4: 293-305.

Tsoar, H. (1983): Wind tunnel modelling of echo and climbing dunes. In: Eolian *Sediments and Processes* (M.E Brookfiels and T.S. Ahlbrandt, eds.), pp. 247-259. Elsevier, Amsterdam.

Tuccimei, P.; Ginés, J.; Delitala, C.; Ginés, A.; Gràcia, F.; Fornós, J.J. & Taddeucci, A. (2006): Last interglacial sea level changes in Mallorca island (Western Mediterranean). High precision U-series data from phreatic overgrowths on speleothems. *Zeitschrift für Geomorphologie*, 50 (1): 1-21.

Tuccimei, P.; Soligo, M.; Fornós, J.J.; Ginés, A.; Ginés, J.; Onac, B.P. & Villa, I.M. (2009): Precipitation of phreatic overgrowths at the water table of meteoric-marine mixing zones in coastal cave systems: a useful tool in sea level change reconstruction. In: White, W.B. (ed.) *Proc. 15th Int. Congress Speleol.*, 1: 554-560. Kerrville, U.S.A.

Tuccimei, P.; Soligo, M.; Ginés, J.; Ginés, A.; Fornós, J.J.; Kramers, J. & Villa, I.M. (2010): Constraining Holocene sea levels using U-Th ages of phreatic overgrowths on speleothems from coastal caves in Mallorca (Western Mediterranean). *Earth Surface Processes and Landforms*, 35 (7): 782-790.

Tuccimei, P.; Van Strydonck, M.; Ginés, A.; Ginés, J.; Soligo, M.; Villa, I.M. & Fornós, J.J. (2011): Comparison of ^{14}C and U-Th ages of two Holocene phreatic overgrowths on speleothems from Mallorca (Western Mediterranean): Environmental implications. *International Journal of Speleology*, 40 (1): 1-8.

Vera, J.A. (ed.) (2004): *Geología de España*. Sociedad Geológica de España, Instituto Geológico y Minero de España, pp. 884.

Vesica, P.L.; Tuccimei, P.; Turi, B.; Fornós, J.J.; Ginés, A. & Ginés, J. (2000): Late Pleistocene paleoclimates and sea-level change in the Mediterranean as inferred from stable isotope and U-series studies of overgrowths on speleothems, Mallorca, Spain. *Quaternary Science Reviews*, 19: 865-879.

Vicens, D. & Gràcia, F. (1998): Aspectes paleontològics i estratigràfics del Plistocè superior de Mallorca. In: Fornós J.J. (ed.) *Aspectes geològics de les Balears*: 191-220. UIB. Palma.

Vicens, D.; Pons, G.X.; Bover, P. & Gràcia, F. (2001): Els tàxons amb valor bioeogràfic i cronoestratigràfic: bioindicadors climàtics del Quaternari de les Illes Balears. In Pons, G.X. & Guijarro, J.A. (eds). *El Canvi Climàtic: Passat, Present i Futur*. Mon. Soc. Hist. Nat. Balears, 9: 121-142.

Zazo, C. & Goy, (1989): Sea level changes in the Iberian Peninsula during the last 200.000 years. In: Scott, D., Pirazzoli, P. & Honing, G. (Eds.), *Late Quaternary correlations and applications*. Kluwer Academic, Dordrecht, 256, pp. 27-39.

Zazo, C.; Goy, J.L.; Dabrio, C.J.; Bardají, T.; Hillaire-Marcel, C.; Ghaleb, B.; Gonzalez-Delgado J.A. & Soler, V. (2003): Pleistocene raised marine terraces of the Spanish Mediterranean and Atlantic coasts: records of coastal uplift, sea-level highstands and climate changes. *Marine Geology*, 194: 103-133.