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Mallorca: a Mediterranean Benchmark for Quaternary Studies

A. Ginés, J. Ginés, L. Gómez-Pujol
B.P. Onac & J.J. Fornós (eds.)



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A Mediterranean Benchmark for Quaternary Studies

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Edited by

A. Ginés, J. Ginés, L. Gómez-Pujol, B.P. Onac & J.J. Fornós



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*This book is an homage to Joan Cuerda, Gerd J. Hennig and Joan Pons-Moyà,
for their significant contributions to the Quaternary studies in Mallorca*


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Preface



This book is an homage to Joan Cuerda, Gerd J. Hennig and Joan Pons-Moyà, for their significant contributions to the Quaternary studies in Mallorca. It compiles and updates a number of key topics (i.e., beaches, eolianites, paleontology, phreatic overgrowths on speleothems, etc.) and is designed to reflect the current state of knowledge of the Quaternary geology and sea-level changes in Mallorca, integrating classical descriptions with the new more detailed perspectives developed over the past decades. Therefore, this book is also a tribute to all researchers that have contributed over the years with new and more detailed information from a wide range of localities in Mallorca, improving our understanding of the Quaternary of the Western Mediterranean.

At the same time, this publication is intended to be a useful "expanded" field trip guide addressed to the participants in the National Science Foundation-sponsored Workshop "*Sea level changes into MIS 5: from observations to predictions*", held at the Universitat de les Illes Balears in Palma de Mallorca between April 10 to 14, 2012. The workshop aims to foster communication between an interdisciplinary group of experts in the fields of paleoceanography, Quaternary geology, glaciology, geophysics, paleoclimatology, and karst geology. The proposed workshop emphasizes interactions among researchers at various stages of their careers. Junior researchers and students will have an unique opportunity to meet leading experts on the topic of sea level change and develop potential future advisor and/or collaborator relationships.

Given the present and projected future rates of global sea-level rise, it is important to identify the factors contributing to the observed sea level rise and the variability inherent in these factors. A deeper understanding of these factors will provide more accurate projections of long-term sea-level rise. Sea levels of MIS 5e, when eustatic sea levels were intermittently somewhere from 2 to 7 m higher the present, provide possible analogs for future scenarios of sea-level change. With about 200 million people living today within vulnerable coastal zones, an improved understanding of last interglacial sea level history may help in anticipating the future impacts of global sea level change.

The coastal caves of Mallorca with their unique speleothem encrustations provide a source of additional sea level data (apart from marine terraces, eolianites, paleontology, etc.), and can precisely document and potentially test the elevation and timing of various sea level stands in the Western Mediterranean region. The Western Mediterranean region is appealing because it appears to be tectonically stable over the last glacial/interglacial cycle, and the encrustation mechanism is unique in that it captures past sea level positions with sub-meter resolution.

The organizers of the "*Sea level changes into MIS 5: from observations to predictions*" workshop, acknowledge the owners, managers, and guides of Coves del Drac and

Coves d'Artà for their willingness in making accessible these famous show-caves for scientific research and, last but not least, in offering the participants the opportunity to visit them during the workshop field trips. During the workshop presentations and especially in the two-day field trip, you will all realize the significance of Mallorca's coastal caves in expanding and obtaining high-resolution Quaternary sea-level oscillation data. This is probably the most important contribution of this workshop to the future Quaternary studies on this topic. For this reason, we are indebted to the cavers of the Federació Balear d'Espeleologia who opened a promising field of research. Their dedication and continuous support is highly appreciated. We gratefully acknowledge the financial and logistic support received from NSF, PAGES, Universitat de les Illes Balears, University of South Florida, and the partnership with INQUA's Commission on Coastal and Marine Processes.

As editors of *"Mallorca: A Mediterranean benchmark for Quaternary studies"*, we acknowledge the kind collaboration of many colleagues, both in the publication of this book, but also in the organization tasks for the Workshop. We are especially grateful to Liana Boop, Jacqueline Diehl, and Jonathan G. Wynn who agreed to improve the English translation of our manuscripts and proof reading carefully the final texts. This publication is integrated within the research project CGL2010-18616 of the Spanish Government Ministerio de Economía y Competitividad/FEDER (previously MICINN) and National Science Foundation OISE #1032243 and AGS #1103108 projects.

The Editors,
Palma de Mallorca
March 2012



Mallorca:

A Mediterranean Benchmark for Quaternary Studies



An Introduction to the Quaternary of Mallorca

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1. Mallorca, an island in the Western Mediterranean

1.1. Geographic settings

Mallorca is the largest and the most central island of the Balearic Archipelago. The Balearic Islands are located in the middle of the Mediterranean basin, slightly displaced to the West. With a perimeter of approximately 560 km and a surface area of about 3,650 km², Mallorca is the seventh largest island in the Mediterranean and including Menorca they are the most remote with respect to any continental landmass. The island of Mallorca exhibits a rhomboidal shape (96 x 78 km), with its vertices oriented to the four cardinal points. The northern point is Cap de Formentor, located at 39° 58' N; to the East is Punta de Capdepera, located at 3° 29' E; to the South is Cap de ses Salines, located at 39° 16' N; and to the West is Sant Elm at 2° 21' E.

With the rest of the Balearic Islands, Mallorca is part of the emerged area of the so-called Balearic Promontory (Figure 1), a mostly submarine relief stretching from the Southeast of the Iberian Peninsula (Cap de la Nau) to the Northeast (Menorca Island). 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 East and Southeast and the Catalan-Balearic basin in the West and Northwest. This relief appears aligned from Southwest to Northeast and is the extension of the external and the northern internal Betic range towards the Northeast.

Regarding geomorphology and tectonics (Rosselló-Verger, 1977a; Grimalt *et al.*, 1991; Servera, 1995; Fornós & Gelabert, 1995), three geographical units are distinguished in Mallorca: Serra de Tramuntana, Es Pla and Serres de Llevant (Figure 2)



Figure 1. Location of Mallorca Island in the Western Mediterranean basin as a part of the so-called Balearic Promontory, a submerged prolongation of the Betic mountain chains stretching along the southern border of the Iberian Peninsula.

They are the result of a complex geological structure characterized as a set of horsts and grabens lengthened in a SW-NE direction. The horsts originate the main mountain ridges (Serra de Tramuntana and Serres de Llevant) as well as some of the central relief forms of the island. The grabens produce the central depressions, namely the flat areas of Mallorca that dominate in Es Pla, and several subsident basins at Palma, Sa Pobla and Campos. The Serra de Tramuntana constitutes the whole northwestern, straight and steepest, side of the island and is aligned in a NE-SW direction; along its approximate total length of 90 km and 15 km wide on average, where several main peaks, up to ten over 1,000 meters, are located (e.g., Puig Major 1,445 m). To the East, the Serres de Llevant Mountains run parallel to the southeastern coastline and show less rough topography even though the range attains a maximum height of 560 m, very close to the sea, at Talaia Freda, near Artà.

Serra de Tramuntana is the most prominent chain of mountains in Mallorca, which stretches from Andratx to Cap de Formentor. Its structure is characterized by a complex set of folds, faults and thrust sheets trending SW to NE. The most remarkable morphological aspect of Serra de Tramuntana is the distinct relief between the rugged and cliff-lined (NW-facing) coast and the gentler SE slopes. Such a distinction is conditioned by both the structural disposition of the materials, all dipping SE, as well as by the distinct maturity of the relief: while the coastal side presents juvenile relief, undergoing intense erosive processes and having an important gravitational instability which is revealed by frequent rockslides, the southeastern slope shows a much more rounded morphology, as the relief had already matured during the Upper Neogene.



Figure 2. Map of Mallorca Island showing the location of the main place-names referred throughout the text.

This northern range (from which Serra de Tramuntana gets its namesake) holds the highest elevations in Mallorca (Figure 3) and plays a significant role in conditioning Mallorca's diversified climate.

The central plain (or Es Pla) consists in an extensive area located between Serra de Tramuntana and Serres de Llevant. It comprises the smooth central relief around the

Figure 3. The Serra de Tramuntana mountain range is characterized by a rough landscape mainly shaped on alpine-folded and thrustured Jurassic limestones. The highest point in Mallorca corresponds to Puig Major (1,445 m ASL), which currently hosts a military installation over its summit. Some outcrops of marly materials support agricultural activities (e.g., L'Ofre Plain visible at the lower part of the picture). (Photo: J. Ginés).





Figure 4. Aerial photograph of Mondragó natural area, showing a remarkable assemblage of coves which are usually referred with the local geographical term of "cala". It is a typical landscape from the Miocene carbonate platform called Migjorn. (Photo: Ministerio Medio Ambiente).

villages of Sineu, Petra, Porreres and Lluçmajor, the subsident depressions of Palma, Inca-Sa Pobla and Campos and the Miocene carbonate platform called Migjorn (Figure 4). Large areas are completely flat and mainly covered with red soils, but elsewhere there is an undulating relief composed of low hills and occasional outstanding elevations like the mountains of Randa (540 m) and Bonany that rise prominently from the central plain. Nevertheless, it dominates the presence of flat-lying late Tertiary and Quaternary deposits and most of the plains correspond to old depressions, which underwent active subsidence during the Upper Neogene and the Quaternary.

Serres de Llevant is a complex mountain range that extends in a SW-NE direction through the entire eastern part of Mallorca and constitutes the second mountain chain of the island. It runs parallel to the southeastern coastline, showing roughly the same direction of Serra de Tramuntana, and spreads from Artà peninsula to the southern municipality of Santanyí. Its higher elevations are located almost in both extremes: in the northern half are the steep mountains of Artà (Figure 5), facing the Alcúdia Bay, including the summit of Talaia Freda de Son Morell at 560 m in height. The highest point in the southern half is Puig de Sant Salvador (509 m), located very close to Felanitx. This mountain range is composed of a series of folded deposits that include Jurassic, Cretaceous, Paleogene and Miocene materials. Its structure presents a thrusting complex system, with the appearance of orthogonal folds caused by the interaction between frontal ramps, aligned to NW, and lateral ramps.

1.2. The topography

The topography of Mallorca (Figure 6a) exhibits an almost unparalleled variety of forms within a relatively small territory: steep mountains, deep ravines and soaring cliffs, but also calm countryside, broad fertile plains, sandy bays and charming narrow coves (Rosselló-Verger, 1977a; Rose *et al.*, 1978; Parker, 1994). Mallorca is dominated by the results of complex tectonic movements that occurred in the late Tertiary, which formed and uplifted the gentle hills of the central plains as well as the rougher mountain chains of Serra de Tramuntana and Serres de Llevant. The rest of the island is characterized by subdued rolling terrains scattered in their major extensions on a nearly horizontally bedded Miocene platform (that in several areas is subjected to local subsidence), covered by Pliocene to Pleistocene sediments (Figure 6b). On the other

Figure 5. A view of the coastal fringe of Serres de Llevant mountains. The highest point in the middle of the picture is Sa Talaia Moreia (433 m ASL), built up of Mesozoic carbonate materials. (Photo: J. Ginés).



hand, regarding fluvial entrenchment, it is worth noting that no perennial watercourses are found in Mallorca. Rainfall is drained by a series of rushing streams that are intermittent and which only transport waters when great precipitational events occur; they are locally known under the term "torrent". In any case, the fluvial action of these temporary streams is not negligible, especially during heavy storms: for instance, exceptional peak discharges exceeding $1,000 \text{ m}^3\text{s}^{-1}$ were reported in the autumn of 1989 for catchments lesser than 20 km^2 in southern Mallorca (Grimalt *et al.*, 1991).

In the Serra de Tramuntana range, the repetitive structure of folds and overthrusting sheets, and the differential resistance to erosion of the beds, have produced a system of longitudinal ridges and valleys that drain out, transversely to the major tectonic directions, into spectacular narrow gorges cutting across the massive limestone beds. This chain lies on the Northwest border of the island and occupies a surface area of approximately $1,000 \text{ km}^2$. Owing to the geometry of the thrust system imbrications and the rise of the seaward side, the slopes are steeper towards the coast but, in general, a high energy relief is the common trend all over the Serra: nearly a third of the total area exhibits a 20% gradient or more. The most distinctive features of the landscape in Serra de Tramuntana are closely related to lithology. Relief features and vegetation show their dependence on rock substrates, remarkably emphasized in

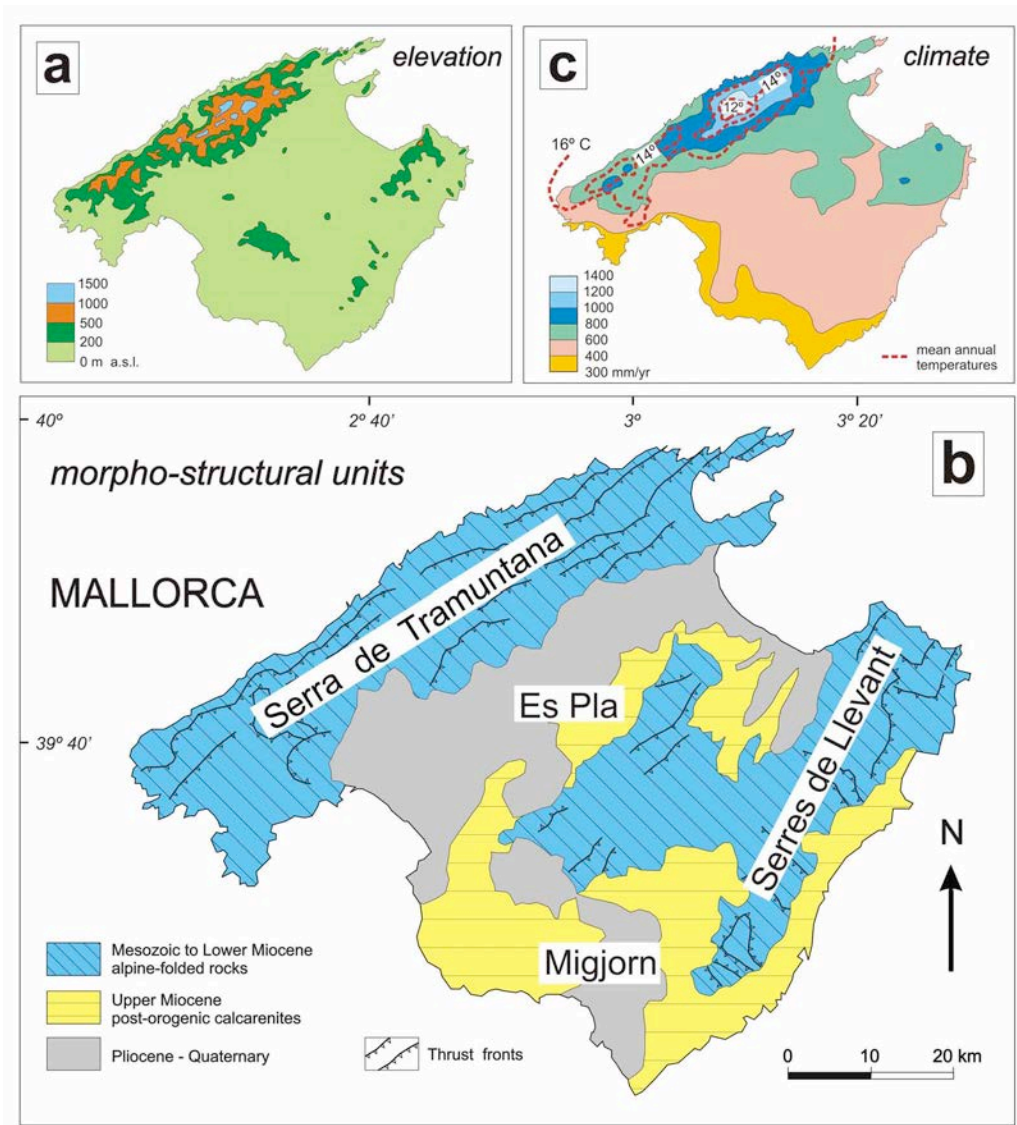


Figure 6. Basic geographical information on Mallorca Island: a. Simplified altimetry map; b. Main morphostructural units conditioned by the geological structure; c. Distribution of the average annual rainfall and temperature values.

the field by the tectonic patterns that caused the imbrication of different materials over long distances. Alternation of soft rocks (marls, clays, even volcanic materials) and hard competent limestones is essential in order to explain many of the landforms observed in the landscape. Because about 65% of the mountains are limestone outcrops, karst landforms are indisputably one of the most outstanding characteristics of the Serra de Tramuntana landscapes (Ginés, 1998). Polje-like depressions, dolines, large karrenfields and karstic gorges are widely distributed over the entire mountain range. The impressive gorge of Torrent de Pareis, with its 300 m deep walls, is a remarkable example of such a rugged terrain. Generally, the current landscape of the

Serra de Tramuntana is the result of a particular mixture of karstic wilderness and humanized features such as terraces, cultivated areas and farmhouses, whose economical upkeep is nowadays uncertain (Ginés, 1999).

Only two mountains of importance (Randa, 540 m and Puig de Bonany, 315 m), both placed not far from Porreres village, stand out almost in the middle of the central plains of Es Pla region. Their minor highlands partially delimit the catchment of several watercourses draining to the basins of Palma and Inca-Sa Pobla, in its West side, as well as constitute the watershed for the major incised valley of Torrent de na Borges, over the East, acting as topographic divide at the foot of Serres de Llevant. The limits between Serra de Tramuntana and the subsident basins of Palma and Inca-Sa Pobla are extensional faults active from post-Langhian times. To the North, Es Pla stretches toward the bays of Pollença and Alcúdia, including the significant salt marsh areas of S'Albufera. At the South of Randa, the Upper Miocene carbonate platform of Migjorn forms a large tabular surface, which spreads around southeastern Mallorca and appears furrowed by many narrow incised valleys. Their endings, invaded by the sea, produce in the coastline small bights and coves, locally called "calas" (Figure 4).

The landscape of Serres de Llevant range is composed of gentle hills aligned in a SSW-NNE direction, with slopes slanting towards the Southeast. It is built up by highly structured Mesozoic and Tertiary rocks. Several thrust sheets form a range of hills and peaks characterized by small cliffs of massive Jurassic limestones and hilly areas of crushed dolomites (early Jurassic in age) as well as thin bedded marls and limestones. In general, the relief of Serres de Llevant shows predominantly smooth slopes and rounded forms and is not so rugged than Serra de Tramuntana. The highest reliefs are made of Liassic limestones, while the valleys are preferentially developed on Mesozoic clays or marly limestones. Serres de Llevant appears as a gentle range of hills that stretch parallel to the eastern coast and, apart from in its northern end, is separated from the sea by a narrow coastal plain appertaining to the aforementioned Miocene carbonate platform.

1.3. The coasts

The coastal geomorphology of Mallorca is substantially varied in accordance with the effectiveness of coastal processes against resistant rock types and structural conditions of exposure and weakness, as well as the marked differences in wave energy regime. Three main types of coast can be distinguished around Mallorca: the steep rocky coasts of the northwestern side of Serra de Tramuntana and the northeastern end of Serres de Llevant; the low cliffed coasts of the southern platform of Migjorn; and the broad bays of Palma, Alcúdia, Pollença and the smaller ones of the Campos depression and Platja des Trenc. From a physiographic point of view, one can note that most of the 626 km of coastline are cliff coasts. In general, the coast is not especially rugged, although small coves and pocket beaches often disrupt the cliff-line. Thus, as much as 80% of Mallorca's coastline is rock coasts; beach and beach-barrier systems account for 10% of the Mallorcan littoral; and, finally, the human infrastructures that take up former coasts in the form of artificial dikes or other artificial facilities incorporate roughly 10% of the nowadays coastline (Balaguer, 2005).

Regarding the sea environment, the maximum wave height at deep waters rarely exceeds 8 m. The main storms are driven by heavy NW winds (up to 40 ms⁻¹) with a large associated fetch going from Liguria Sea to the Balearic Channel. The northwestern and central parts of the Balearic Sea are forced by northerly winds (Mistral) during the main part of the year, while the eastern part is generally modulated by a seasonal variability (Cañellas *et al.*, 2007). Forcing by tides is almost negligible in the Western Mediterranean with a spring tidal range of less than 0.25 m, although changes in atmospheric pressure and wind stress can account for a considerable portion of sea level fluctuations (Gómez-Pujol *et al.*, 2007b). The absence of significant tides restricts beach morphology changes to waves and coastal currents, and especially to the severe weather episodes when wave related processes are enhanced.

The large-scale coastal morphology of Mallorca, as explained in Gómez-Pujol *et al.* (2007a), is closely related to the main characteristics of the geological structure of the island, which is a set of horsts and grabens. Thus, the general picture for the horsts corresponding to the Serra de Tramuntana and Serres de Llevant ranges is one of plunging and composite cliffs with a large array of profiles developed on carbonate Mesozoic to Middle Miocene folded outcrops, in which the cliff face varies frequently from 3 to over 50 m in height, but locally larger than 100 m, and extends from 5 to 20 m below sea level. In these morpho-structural domains, shore platforms are patchily developed and appear closely related to lithological and structural control. For instance, in Liassic limestone it is quite difficult to find shore platform features because this coast is strongly affected by tectonics (Gómez-Pujol *et al.*, 2006) and is represented by structural plunging cliffs. Nevertheless, softer rock outcrops such as Neogene turbidites or Rhaetian dolostones allow the development of composite cliffs and narrow shore platforms. Rock falls, rock debris and wave quarrying at the cliff toe are the dominant processes in shaping the rock coasts associated to both mountain ranges (Swantesson *et al.*, 2006).

Bounding the Serres de Llevant range is a limestone plateau built up by post-orogenic Upper Miocene reefal limestones. The coastlines associated with the outcrops of these Upper Miocene calcarenites present composite cliffs with step-like forms closely related to former Pleistocene sea levels (Butzer, 1962). These steps are enhanced by the geometry of the Upper Miocene tabular strata as well as by differences in the geo-mechanical properties between depositional facies. Cliffs cut in Upper Miocene rocks range from 3 to 20 m in height (Figure 7). Fornós *et al.* (2005) suggest a tectonic origin for most of these cliffs, relating to extensional faulting that took place between the Middle and the Upper Pleistocene. Shore platforms, although patchily distributed, are more continuous within this morpho-structural unit than along the stretches of coasts where folded rocks outcrop. Cliff face granular disintegration related to salt weathering, wave quarrying and rock falls are the main mechanisms responsible for the overall morphology of cliffs from this post-orogenic Upper Miocene plateau (Balaguer *et al.*, 2007). Secondary features including basin pools, notches, organic rims and other coastal karren features are conspicuous features superposed to the basic cliff profile (Gómez-Pujol & Fornós, 2009).



Figure 7. The cliffed littoral of south-eastern Mallorca present abundant paleokarst features, developed on the Upper Miocene carbonates, which create an irregular and multi-colored coast-line showing abundant marine-erosion caves and arches. This picture corresponds to Caló de Solimina, within the Mondragó natural area. (Photo: J. Ginés).

Finally beach-barrier sandy or cobble coasts are characteristic from graben units that are adjacent to the sea. Major Holocene beach-ridge coasts preceding lagoons and fields of littoral dunes –mainly parabolic dunes– appear at Palma Bay, Campos basin and Alcúdia and Pollença Bays (Servera *et al.*, 2009). Mallorcan sandy beaches include intermediate beaches with crescentic bars, although sheltered beaches are characterized by reflective configurations (Gómez-Pujol *et al.*, 2007b). Except a few beaches located in the northern coast, the rest of the sandy beaches are constituted by biogenic carbonate sands (ca 70%). It is relevant to notice that streams are ephemeral and only supply fine to very fine sediments to the coastal sediment budget.

1.4. Geologic settings

The stratigraphical history of Mallorca includes deposits ranging from Carboniferous to Quaternary, with an important gap at the base of the Tertiary. The sedimentology of the extant materials is fairly complex and shows great variation regarding different sedimentary environments, which include lacustrine, littoral, platform, slope and pelagic facies, according to the various stages of structural setting and tectonic events (Colom, 1975; Pomar, 1979; Rose *et al.*, 1978; Adams, 1988; Jenkyns *et al.*, 1990; Rodríguez-Perea & Gelabert, 1998; Gibbons & Moreno, 2002; Fornós & Gelabert, 1995, 2004, 2011). The approximate thickness of the stratigraphic sequence is 3,000 meters, in which carbonate rocks constitute the majority, with scarce siliciclastic materials.

The oldest materials, found in Mallorca in very small outcrops localized at the northwestern foot of Serra de Tramuntana, are Carboniferous grey pelites interlayered with quartz sands. They show weak metamorphism, and the effects of the Hercinian orogeny appear in the form of intense cleavage folding.

The Mesozoic sequence deposits in Mallorca are over 1,500 meters thick. Triassic, Jurassic and (in a lesser extent) Cretaceous rocks constitute the vast majority of the outcrops in both mountain ranges, Serra de Tramuntana and Serres de Llevant, as well as in some of the small hills at the central Es Pla area. Triassic materials include the mainly continental Buntsandstein mudstones and red sandstones, the shallow marine limestones and dolomites of the Muschelkalk and the Keuper, which represent a regressive and continental facies characterized by pelitic sediments, red and yellowish marls, evaporites and volcanic rocks. Evolving gradually upwards to the Jurassic, the Rhaetian dolomites point out the beginning of marine sedimentation that continues, with a progressive deepening, through the rest of the Mesozoic. The Lower Jurassic rocks (Lias) are mainly constituted by massive micritic limestones, with a thickness up to 400 meters, corresponding to the depositional environment of a shallow carbonate platform; it is important to emphasize that these limestones form the bulk of the main summits at Serra de Tramuntana ridge and are intensely karstified. The variegated rocks of Middle Jurassic (Dogger) and Upper Jurassic (Malm) are related to the progressive transition toward more hemipelagic and pelagic environments. The pelagic sedimentation, begun during the Upper Jurassic, increases its depth during the Lower Cretaceous with the deposition of marls and white marly limestones, which evidence a deep sea pelagic sedimentation. The Cretaceous is hardly represented in Mallorca, although it can reach a thickness of 150 meters in some places: its lower levels mostly outcrop on the southeastern slopes of Serra de Tramuntana and Serres de Llevant, even if its upper levels are scarcely present.

Cenozoic rocks are widely represented in Mallorca, generally exceeding 1,500 meters in thickness. On the other hand, over the entire Balearic area, the Paleocene and the Lower Eocene are absent, as a consequence of both the emersion of the area, which is at present occupied by the Valencian Trough and the Balearics, and the former erosional processes, which also affected those Upper Cretaceous deposits. The older Paleogene materials outcrop over a few tens of meters in Serres de Llevant and are of Middle and Upper Eocene age; they are formed chiefly by calcarenites and marls rich in nummulites, but there are some other rocks of this age in Serra de Tramuntana. More abundant are the Oligocene rocks: a continental detritic unit that consists of massive sandstones, silts and reddish clays in Serres de Llevant, and polygenic conglomerates, siltstones and limestones with algal concretions at the Serra de Tramuntana outcrops. Sediments accumulated along Lower-Middle Miocene times were affected by the Alpine orogeny, being involved in complex folding and thrusting. The synorogenic sequences found in Mallorca comprise lacustrine and pyroclastic rocks from the earliest Miocene, turbiditic sedimentation during Burdigalian-Langhian tectonic pulsations and resedimentation, as well as lacustrine and alluvial fan deposits in fault-bounded basins, corresponding to the emergence and erosion of uplifted areas related to the final Serravallian compressional episodes.

The post-orogenic Upper Miocene rocks form a tabular area (called Migjorn) which surrounds the mountain ranges, previously structured in Langhian times, and delimit

today the coastal cliffs at the South and East of the island. It consists, at the base, of alternating calcarenite and calcisiltites evolving upwards to massive reefal limestones and calcarenites, ending with oolite limestones, stromatolites and calcarenites (the so called "Terminal Complex" that finishes this Tortonian-Messinian reef sequence). The Pliocene hardly outcrops in Mallorca, despite its important thickness of over 200 meters; it corresponds to the filling-up of depressed areas placed at the foot of the mountain ridges, where its denudation materials became accumulated in some typical bay, littoral and deltaic environments. The Plio-Quaternary is basically constituted by beach-dune calcarenites. Finally, Pleistocene sediments consist of patches of marine deposits around the coastline and the margins of the central plain, as well as extensive alluvial fans along the foothills of the mountain ridges.

Mallorca is the most extended emerged sector of the Balearic Promontory and consequently is part of the folded and thrust belt resulting from the continental collision between the African and Iberian plates. Such a collision took place from the Upper Cretaceous (approx. 84 Ma) to the Middle Miocene (15 Ma) and affected the Betics and the Balearics owing to the anticlockwise rotation of Africa and Arabia caused by the opening of the South Atlantic Ocean. The main deformation structures were produced during the Alpine orogeny and consist of thrust sheets imbricated in a NW transport direction (Sàbat, 1986; Gelibert, 1998; Fornós *et al.*, 2002). The glide planes between each sheet are preferentially located along incompetent materials; for this reason the Triassic rocks of Keuper facies act in most of the cases as detachment horizons. Each thrust sheet comprises a series of complex structures. The general orientation of the thrust and folds produced by the alpine compression is approximately ENE-WSW and the associated shortening is around 44%. Post-Langhian extensional deformation, causing a series of horst and graben structures, is evidenced by the uplift of Pleistocene shorelines and the development of the subsident basins of Palma, Inca-Sa Pobla and Campos.

In short, the present geological architecture of Mallorca (Figure 6b) could be explained as the result of a three-fold complex evolution, involving sediment accumulation (mainly through Mesozoic times), compressive tectonics during the continental collision and extensional processes from the Upper Neogene to Quaternary, that finally generate the aforementioned geomorphological and structural units, namely Serra de Tramuntana, Es Pla and Serres de Llevant (Fornós & Gelibert, 1995).

1.5. The climate

Mallorca is situated in medium latitudes, in the center of the Western Mediterranean and has a typical Mediterranean climate, characterized by hot dry summers and mild winters. The present climate of Mallorca is that of a typical summer-dry mesothermal climate (Csa in the Köppen classification). Owing to the latitude of the island, the alternated influence of two features of the general circulation of the atmosphere must to be considered: 1) during the winter, the Balearic Islands are situated in the southern part of the belt of general western winds and, from time to time, they receive the frontal systems associated to it; 2) in summer, however, the western wind belt rises to a higher latitude, remaining under the influence of the

subtropical belt of high pressures, causing the dominance of dry and sunny weather as well as the convective character of some scarce rainfalls (Guijarro, 1995).

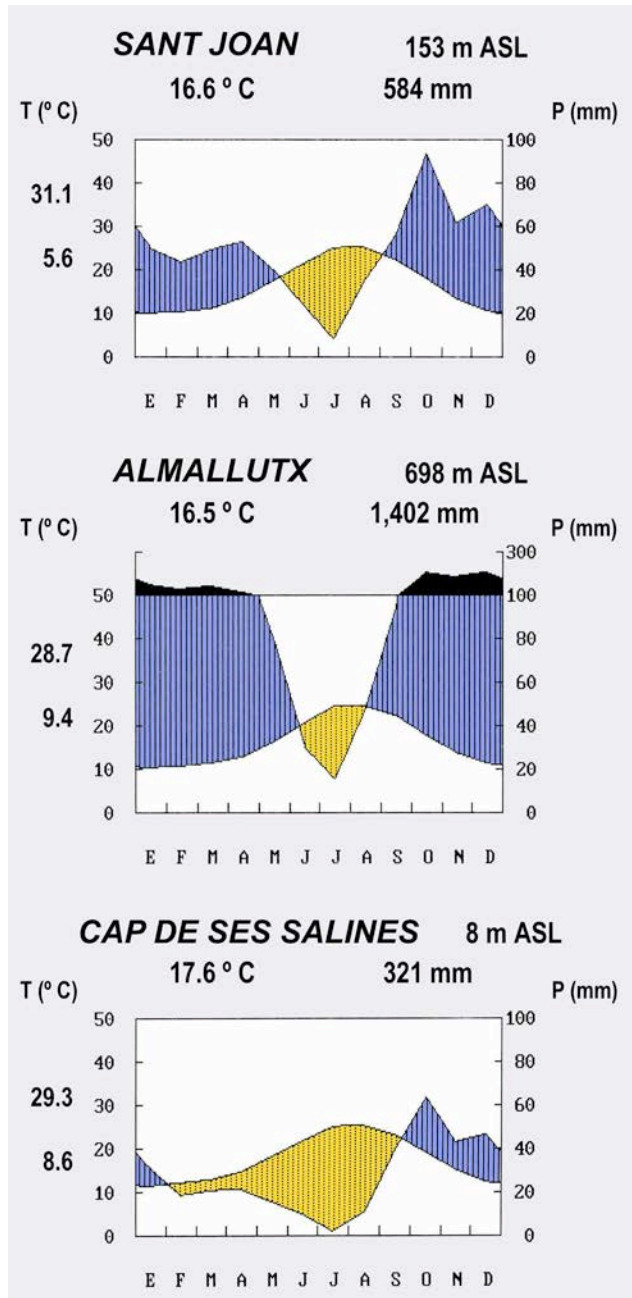
The orography around the Mediterranean impose other substantial conditionings upon the climate: the mountains of the Atlas in the South, the Betic and the Iberian ranges in the West, and the Pyrenees and the Alps in the North, act like barriers which notably alter the circulation of air that reaches the Mediterranean, producing great contrasts between the air masses. This particular trend often generates depressions and, in this manner, causes the western part of the Mediterranean to be one of the areas which has the greatest cyclogenetic activity in the world (Guijarro, 1995).

The consequence of these factors is a very irregular climate, with spectacular variations in the amount of precipitation from one year to another. The Mediterranean itself constitutes a very important climatic factor. The heat accumulative capacity of sea water acts like a moderating element of the temperature variations, both in the daily cycle and among the seasons of the year. This is why the winters are relatively mild, with few frosts, and the summers, although hot, do not attain the maximum temperatures typical of more continental areas. Furthermore, the accumulated heat through the action of the sea during summer has another effect: in the autumn, it destabilizes the atmosphere, creating severe storms when cold air from the middle and upper layers of the troposphere interact with the warmer sea. These storms deliver the greatest amounts of annual precipitation, and at these times floods are very common due to the bursting of the mountain streams or of whatever large flat areas affected by such intense rains (over 200 lm^{-2} per day).

In order to illustrate the main features characterizing the climate of Mallorca, the pluvio-thermic diagram of Sant Joan village (Figure 8), a locality situated near the center of the island and far enough from climatic extremes, could be useful. Placed at an elevation of 153 m, it has an annual average precipitation of 584 mm, with a monthly maximum of 93.8 mm in October and a minimum of 8.7 mm in July. Practically all this amount falls in the form of rain: snowfall on the central plain of Mallorca (Es Pla) is infrequent; hailstones can fall during some of the average 15 annual stormy days, but again with an insignificant contribution to the total amount of precipitation. On average, there are 60 days with precipitation equal to or over 1 mm. In 18 of these rainfall events, rainfall values of 10 mm can be attained or surpassed. On the other hand, with regard to temperatures, the annual average is of 16.6 °C, with 31.1 °C as the average of daily maximums of the hottest month (August), and 5.6 °C as the average of daily minimums of the coldest month (January). Occasionally, there may be some frosts (the days with a minimum temperature of 0 °C or less) from December to March.

Although the pluvio-thermic diagram of Sant Joan shows the general trends of the climate in Mallorca (Guijarro, 1986, 1995), it is important to outline here the great extent to which the orography of the island introduces variations from one place to another, owing particularly to the remarkable heights of its mountain chains; those of Serra de Tramuntana facing the Northwest and in a lesser degree those of Serres de Llevant. As could be expected, the most important differences appear as rainfall variations (Figure 6c), which oscillate between 1,400 mm in the heart of Serra de

Figure 8. Pluvio-thermic diagrams of three representative localities from Mallorca (after Guijarro, 1995). Sant Joan is located in the center part of the island, whereas Almallutx (at Serra de Tramuntana, close to Puig Major) and Cap de ses Salines (the southernmost coastal site) represent the humid and arid extremes of Mallorcan climate, respectively.



Tramuntana up to a little over 300 mm in the southern points of the island (Cap de ses Salines). Apart from these extreme conditions, most part of Serra de Tramuntana receives average annual precipitation exceeding 800 mm, and the heights around Artà, in the Northeast, receive from 700 to 800 mm annually. In the rest of central and northern Mallorca, annual precipitation averages exceed 500 mm, whereas the southern part is the driest area with less than 500 mm annually.

With regard to variations in average temperatures, the most important factor is the elevation (Figure 6c), and it happens that the coldest recorded temperatures are observed in the heart of the mountains and the hottest on the coastal plains. The thermometric oscillation throughout the day is, however, greater on the plains or extensive valleys than in the orographic heights, because radiative interchanges are more intense, and furthermore the cold air accumulates during the night, due to its greater density, moving down from the higher areas. It is frequent to record, in the abundant calm and cloudless nights, some thermic inversions which cause, for example, the minimum temperature of Palma's airport, practically at sea level, to be even lesser than Serra d'Alfàbia's, at about 1,100 m height.

Figure 8 include also the data and pluviothermic diagrams from two Mallorcan localities with extreme average precipitations (Guijarro, 1995). In Almallutx, placed in the higher part of Serra de Tramuntana, on the southern bank of the Gorg Blau reservoir, monthly average precipitations over 100 mm are observed from almost September to April, with a total amount of 1,402 mm per year. The dry season is reduced to a little more than two months, from approximately 10 June to about 20 August. However, at the extreme South of Mallorca (Cap de ses Salines) precipitation is considerably lower, with 321 mm of estimated annual average, and the "dry season" extends about eight months (from February to September). These strong climatic gradients show additional complex patterns, at a microclimatic level, because the orientation of slopes has a remarkable importance as a result of the great differences of solar irradiation that exist between the slopes that overlook the North or the South.

Another characteristic of the Mediterranean climate lies in its temporal variability, which becomes evident when compared the great differences, especially with regard to precipitation, between one year to another, not only in the total amount, but also regarding its distribution throughout the year. A good example to illustrate these variations from year to year is the series of average precipitation and temperature from Palma's observatory, the oldest of the Balearic Islands, with records since 1862 (Guijarro, 1995). In Palma, the annual precipitations can oscillate between 200 and 700 mm, with a minimum of 164.6 mm in 1945 and a maximum of 777.4 mm in 1898. Those of the annual average temperature are not so significant as throughout 132 years the minimum was 15.7 °C in 1925 and 1941, whereas the maximum was 18.8 °C just in 1989.

1.6. The soils

The soils of Mallorca were studied and described by Klinge & Mella (1958) using the soil classification postulated by Kubiěna (1953). Unfortunately, pedological research has not been updated in the last years in the Balearic Islands, and for this reason the current state of knowledge is rather unsatisfactory.

There is a variety of different types of soils in Mallorca, including types such as rendzinas, xero-rendzinas and humid rendzinas and terra fusca in the mountains; in the plains terra rossa soils are the quite dominant whereas solonchak saline soils are documented in S'Albufera and around the Campos depression (Klinge & Mella, 1958; Crabtree, 1978; Jenkyns *et al.*, 1990). The terra rossa sediments are considered to be relicts because their derivative materials frequently appear reworked and transported

as components of alluvial and colluvial deposits accumulated along the piedmont of Serra de Tramuntana (Mensching, 1955; Butzer, 1964, 1975) and eastern Mallorca (De la Cruz et al., 2001); furthermore, several episodes of terra rossa pedogenesis are evidenced as interbedded paleosols between sequences of Pleistocene eolianites (Butzer, 1975).

The Holocene climax soil on calcareous bedrock seem to be rendzina soils (Butzer, 1964), but some authors suggest that terra fusca could be probably the soil climax under the present climate of Mallorca (Klinge & Mella, 1958; Crabtree, 1978). Terra fusca is described by Kubiěna (1953) as "usually humus-deficient loamy soils with ochre yellow, brown to reddish-brown color on limestone rocks which contain ferric hydroxide in the form of limonite". After Crabtree (1978): "A shallow (2-10 cm) humus-deficient grey-brown A horizon overlies a moderately deep B horizon (15-50 cm). In the typical terra fusca this horizon is dense, impermeable, sticky and difficult to work. It also has strong, intense coloring. In the earthy terra fusca, the darker colors predominate and the B horizon is more porous and friable, with a tendency to form crumbs. This is a widespread soil under the maquis vegetation in Mallorca". (Note that maquis is the French word for "garriga" shrublands).

Most of the soils in Mallorca have suffered considerable erosion, and according to the former ideas of Mensching (1955) and Butzer (1964), Crabtree (1978) state that "many of the present profiles are developed on truncated profiles of older soils, or upon redeposited materials from older soils". In uneroded conditions, relict soils of terra rossa are deep red in color and should have a reddish brown A horizon and a reddish brown to red textural B horizon showing strong blocky structure. Terra rossa soils are found on carbonate terrains along the continental shores of Southern Europe and the islands of the Mediterranean basin, which is the classical region in which they have been studied. On the other hand, terra rossa formation requires a long time under a climate which provides abundance of moisture causing intense clay migration by leaching, but also sufficient seasonal drying to promote the dehydration of iron oxides which produce the characteristic reddening; however, it is probable that ageing alone may enhance this particular feature (Crabtree, 1978). In whatever case, all the authors agree on the fact that either the climatic regime or the time elapsed has not been enough for their formation during the Holocene times in Mallorca. As pointed out by Muhs *et al.* (2010), the origin of Red Mediterranean soils and its relation to dust inputs, as reported by Fiol *et al.* (2005), are controversial topics, but today the contribution of Saharan dust to the formation of many terra rossa soils on relatively pure carbonate rocks around much of the Mediterranean region seems clear.

1.7. The vegetation

Following a general trend, most small islands have lower biodiversity values than that of similar regions of the continent. Nevertheless, around 1,500 plant species have been described for the Balearic Islands, of which 3 to 4% are endemic species, with a density of 13.5 per 1,000 km² (Mayol & Machado, 1992). Only a few tree species are able to form extensive woodlands: namely, the holm-oak *Quercus ilex* and the Mediterranean pine tree *Pinus halepensis*. After thousands of years of human occupation, most of Mallorca has been transformed in rural agricultural and urban

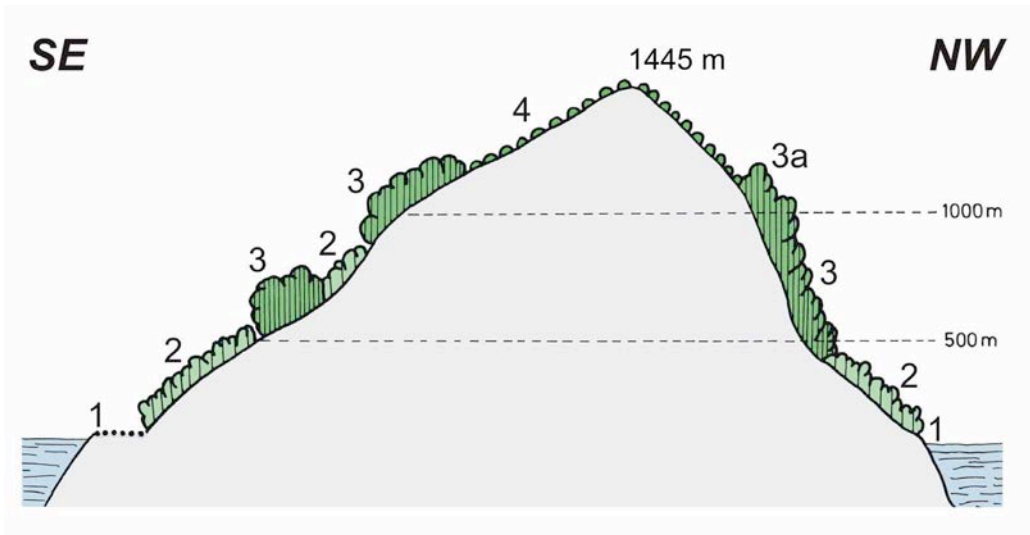


Figure 9. Idealized profile of the main vegetation zones across Mallorca Island (based on Bolòs & Molinier, 1958). 1: Littoral communities; 2: "garriga" shrublands and pine woods; 3: evergreen *Quercus ilex* forest; 3a: remnants of deciduous forest; 4: hedge-hog low shrubs at the summits of the mountains (known as the "Balearic zone").

areas, with the natural vegetation only remaining in the areas, such as hills, mountains and coastal plains, which soils are of low agronomic value.

The most comprehensive studies about the vegetation of Mallorca (Knoche, 1921-1923; Bolòs & Molinier, 1958, 1969; Bolòs, 1996) differentiate three main vegetation zones largely related to altitude and precipitation: a dense "garriga" or shrubland dominated by *Olea europaea* var. *oleaster* ("ullastre") and *Pistacia lentiscus*, from sea level to over 400 meters ASL; an evergreen *Quercus ilex* forest, until an elevation of 800 meters ASL; and, above this, a so called "Balearic zone", placed at the summits of the mountain ridges and containing many endemic species as well as typical cushion-like thorny plants (Figure 9).

A dense "garriga" shrubland (called *Oleo-Ceratonion* after the classification from the SIGMA school of Braun-Blanquet), 1 to 3 meters high, and dominated by shrubs of *Pistacia lentiscus*, wild olive "ullastre" and the carob tree *Ceratonia siliqua*, is the characteristic plant community spreading over the lower rainfall areas. In the southernmost part of Mallorca, in semi-arid conditions, bushes of rockroses *Cistus albidus* and *Cistus monspeliensis* are dominant, but many other typical species are also present in the northern lowland terrains, as the dwarf fan palm *Chamaerops humilis*, *Cneorum tricoccon* or the very common *Rosmarinus officinalis*. At higher elevations some species of the "Balearic zone" come in together with the grass clumps of *Ampelodesmos mauritanica*, called "càrritx".

Widespread holm-oak evergreen woodlands (the *Cyclamini-Quercetum ilicis* after the SIGMA school classification) are present in the Serra de Tramuntana mountain ridge and also appear scattered across the central part of the island. These evergreen woodlands are considered to be the climax community rank, both in southern France

and eastern Spain, corresponding to a relatively humid Mediterranean climate and being characterized by sclerophyllous forests dominated by the species *Quercus ilex*. Although it was in former times spread over larger extensions, it is now best developed on the North and West facing slopes of the mountains where the rainfall exceeds 600 mm (Figure 10). Associated shrub and smaller plants include some characteristic species and many which are spread across different plant communities, as the strawberry tree *Arbutus unedo*, *Rhamnus* spp., *Cyclamen balearicum*, *Smilax aspera* var. *balearica*, *Asparagus acutifolius* and *Ruscus aculeatus*.

The "Balearic zone" is classed as the *Teucrietum subspinosi* association (once again, after the nomenclature from the SIGMA school) and dominates exclusively above 1,100 meters ASL on the highest mountains of Serra de Tramuntana (Figure 10), but also at very much lower elevations on the exposed rocks of Cap de Formentor and Serres de Llevant. It is a zone composed of low shrubs, plenty of endemic species, with bare ground, usually limestone, in between. Besides several spiny hedge-hog plants (namely *Teucrium marum* ssp. *subspinosum* and *Astragalus balearicus*), the endemic St Johnswort *Hypericum balearicum*, *Rosmarinus officinalis* var. *palaui*, *Smilax aspera* var. *balearica*, *Pastinaca lucida*, *Teucrium asiaticum* and *Paeonia cambessedesii* are among the most significant species characterizing this plant community (the most typical



Figure 10. The climax vegetation in Serra de Tramuntana is represented by extensive forests of holm-oak (*Quercus ilex*). Above 800 m ASL these forests are substituted by an arbustive, cushion-like thorny plant community, rather rich in endemic species, collectively known as the "Balearic zone". In the center of the picture, Puig de Massanella (1,365 m ASL) is Mallorca's second highest summit. (Photo: J. Ginés).



Figure 11. Deforested slopes of mesozoic limestones near Sa Calobra gulf, on the northwestern coast of the Serra de Tramuntana. Karren features and scattered *Ampelodesmos mauritanica* grasslands are widespread over these karstified terrains. (Photo: A. Ginés).

"association" clustered in the so called *Hypericion balearici* "alliance"), which is well adapted to the harsh and especially windy conditions of the mountain summits.

Many areas of the coast and lower slopes of the mountains are covered in woods of *Pinus halepensis*. The Mediterranean pine tree is a heliophilous invader species, taking advantage of natural or man-induced disturbances, as wild fires, felling, eroded soils and forest degradation. Mixed oak and pine woodlands are common everywhere, but *Pinus halepensis* is also found in the most termophilous and arid "garriga" communities. In the very dry southern terrains, where rainfall is less than 400 mm, an open pine forest exists, including species like *Anthyllis cytisoides*, *Lavandula dentata*, *Erica multiflora* and *Globularia alypum*. From the point of view of SIGMA school, it is assumed that *Pinus halepensis* woodlands do not belong to a single recognizable plant community.

Another frequent vegetation type is the monotonous grassland of "càrritx", *Ampelodesmos mauritanica*. In many deforested slopes, when periodic fire-raising accelerates the degradation of the plant community and inhibits forest recovery, the growth of this pyrophytic, North African grass, tolerant to arid conditions and able to spread on very poor soils, is strongly favored (Morey & Ruiz-Pérez, 2008). The repetitive burning of herbaceous brushwoods of "càrritx" for the renewal of cattle pasturing produces further degradation of scrub formations and soil removal, leading

to a gradual increase of the bedrock exposed after erosion (Ginés, 1999). This trend is particularly clear in the mountains, especially over karstified limestones (Figure 11).

1.8. The landscapes

As in most of the Mediterranean Islands, the landscape diversity in Mallorca is much higher than the mean value for the continental areas around (Morey & Ruiz-Pérez, 2008). High landscape diversity is a product of the differences in geology, relief, coastal variation, climate and vegetation (Figure 12). This amount of variety is reinforced by distinct cultural traits, which in turn, can be attributed to the history of human intervention on the formerly natural ecosystems, but also to the geological, biological and cultural isolation. The present scenery is a mix of natural and ancient cultural landscapes, with modern urban-tourist landscapes mainly in the coastal areas. In general terms, Mallorca appears as a mountainous island, which Serra de Tramuntana range in the Northwest side protects the rest of the island from the cold winter winds, and provides the lowlands with a mild and comfortable climate. Because of this wind protection, traditional dry extensive agriculture consists of annual cereal crops with scattered almond and carob trees and post-cereal-harvest cattle grazing, producing a typical "dehesa"-like humanized landscape (a sort of artificial savanna) especially in the central plains of Es Pla as well as on the foot of the mountain ridges (Morey & Ruiz-Pérez, 2008).



Figure 12. The littoral of eastern Mallorca is mainly shaped by small cliffs (max. 20 m high) cutting the Upper Miocene post-orogenic calcarenites that build up the so-called Migjorn region. The coastlines are very pronounced owing to the presence of inlets or coves –locally designed with the term "cala"– corresponding to the end part of short, temporary streams. In the background of the picture, the mountains of Serres de Llevant are visible (So na Moixa, 333 m ASL); the cove in the left side is Cala Virgili and that of the right side is named Cala Magraner. (Photo: J. Ginés).

The whole landscapes in Mallorca have been strongly influenced by the impacts of the different peoples who have inhabited the island: namely, from the prehistoric inhabitants to the current mass tourism development in Southern Europe, through Phoenician, Roman, Arabic and Catalan colonizations (the latest after the conquest in 1229 by the king James I of Aragon). Human settlement in Mallorca, a little more than 5,000 years ago (Alcover *et al.*, 2001), necessarily brought about changes both in the plant cover and in the predominant erosion mechanisms. The main impact of the first inhabitants, from the arrival of man during the 3rd millennia BC, was caused by the use of fire, increasing the frequency of fire-raising beyond the rate of natural occurrence and triggering deforestation and soil removal processes. It is likely that during the first millennia human activity had few ecological consequences.

But the men of different cultures who subsequently inhabited the island introduced important cattle-raising and farming changes, so causing the regression of the steady-state forests of *Quercus ilex* and also of the more thermophilous ones of *Pinus halepensis*. The Roman colonization commenced in 123 BC, but it seems that the greatest agricultural changes in Mallorca took place during the Muslim epoch, between the 9th and the 13th centuries. In this way, cultural landscapes related to traditional agriculture and farming practices were developed over the centuries (Morey & Ruiz-Pérez, 2008). These interesting cultural landscapes include, for instance, the extensive terraced fields of olives intercropped with other cultivated plants in the steep mountains of Serra de Tramuntana (Ginés, 1999). They were abandoned at the beginning of tourism development and are at present threatened landscapes (Morey & Ruiz-Pérez, 2008).

Until the arrival of mass tourism the main impacts on the natural environment induced by humans were due to overexploitation and hunting, without extreme damaging of the traditional rural landscapes. Long afterward, tourism exploitation leads to the abandonment of traditional activities and uses, such as agriculture, forestry, hunting and fishing. Today, after more than 50 years of tourism growth, substantial impacts affected chiefly the coastal landscapes, especially those of the sandy coast: beaches, sand dunes, littoral systems, and marsh areas that became partially or totally occupied by hotels and other tourism infrastructures (Mayol & Machado, 1992). Unfortunately, some marine Quaternary faunal deposits and several interesting Pleistocene shoreline sites are threatened and unprotected against expanding tourism.

2. The Quaternary of Mallorca

2.1. Remnants of the Upper Pliocene times

At the end of the Pliocene, Mallorca reached a general morphology similar to that of the present. However, during the Plio/Quaternary transition, the detailed morphology of its coastal areas has been further controlled by sea level. Changing location of the shoreline is crucial in defining the base level for most geomorphic processes. Specifically, knowing the position of the sea level throughout the Late Pliocene can be very useful to place chronological constraints on processes that acted during the Quaternary period such as topographical leveling caused by marine

abrasion, accumulation of eolianites, or development, infilling and collapse of caves. Thus many of the features we observe in the Mallorcan Quaternary record are inherited from, and overprinted on features of the Pliocene. Examples of this include some of the major speleogenetic phases and the different chronospecies of fossil endemic fauna subjected to restricted environments for several millions of years.

Butzer (1962) opened a discussion on the origin of the pre-Tyrrhenian platforms of the Upland Plain, developed on the Upper Miocene around the Campos Basin, as well as on the Lowland Plains occupied by the Palma, Alcúdia, and Campos depressions. Based on his interpretation, four "marine abrasional platforms...are preserved as shallow, level hollows, or flat plains bounded by low step-like echelons running roughly parallel to the coasts". These are all pre-Mindel shorelines, located at 48-50 m, 60-62 m, 70-72 m, and about 110 m ASL, and are considered of Lower Pleistocene age. Furthermore, in explaining the genesis of the "calas", he argues for "a fluvial dissection of the edge of the Upland Plain during one or more phases of low sea level during the Tertiary and the Basal or Lower Pleistocene". Later studies at the southern foot of the hills located between the villages of Llucmajor and Porreres (Colom *et al.*, 1968; Cuerda *et al.*, 1969) have demonstrated the presence of an old shoreline, localized at an elevation of 150-160 m ASL and characterized by the presence of *Strombus coronatus*. These marine deposits are of Astian (Upper Pliocene) age and stretch several kilometers at the foot of Randa Mountain, appearing in Cova Vella de Son Lluís as an impressive coquina that constitutes the ceiling of the cave.

Aside for the Upper Pliocene shoreline, the evolutionary framework of the endemic vertebrate fauna present in Mallorca during the Pleistocene is pinpointed by two significant cave sedimentary sequences that goes back to the Upper Pliocene times: Cova de Canet and Cova des Fum. These old caves, completely disconnected from the current karst drainage, provided fundamental data on the intermediate forms of the genus *Myotragus* –an insular bovid resembling the goat– just before the onset of the Pleistocene. The stratigraphy of sediment deposits in Cova de Canet (Figure 13) was described by Pons-Moyà *et al.* (1979) who present a sequence of more than 3 meters of sediments showing different layers of clays, silts, and flowstones dated by means of paleomagnetic techniques. The presence of *Myotragus kopperi* in the level E, underneath 1.5 meters of silts, just at the transition between the Gauss epoch (normal paleomagnetic polarity, during Upper Pliocene) to Matuyama epoch (reversed paleomagnetic) places this chronospecies at about 2.4 Ma, whereas an underlying bone breccia containing fragments attributed to *Myotragus antiquus* was dated to ~2.6 Ma.

The complex stratigraphy of Cova des Fum (Figure 14) includes thick basal speleothems underlying a bone breccia rich in *Myotragus antiquus* that appears sealed upward by bioclastic marine calcarenites and flowstone. In spite of the lack of precise datings, the elevation of the cave (about 80 m ASL), the stratigraphic context of the paleontological site (Ginés & Fiol, 1981), and the morphology and morphometry of teeth (Moyà-Solà *et al.*, 2007) suggest a Late Pliocene age for this locality, from where a fossil dormouse of the endemic genus *Hypnomys* was also reported.

2.2. Cold climate evidence

Given the location of Mallorca Island (i.e., latitude) and its topography (landscape

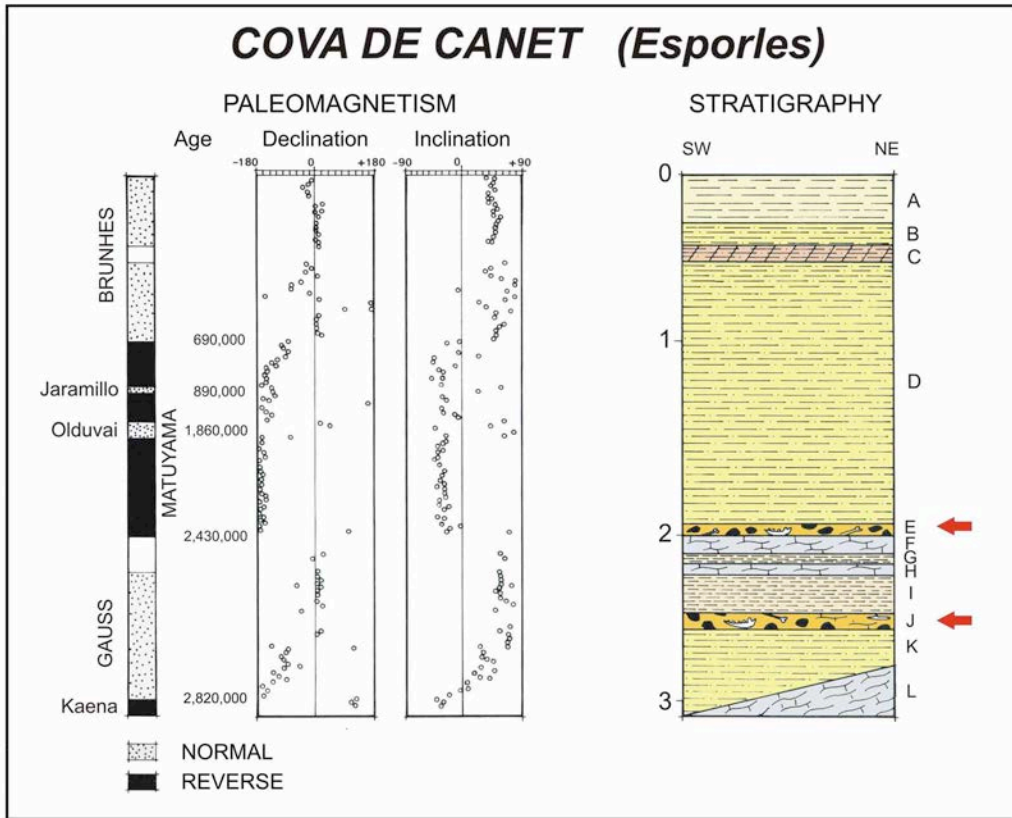


Figure 13. Stratigraphy and paleomagnetic information corresponding to the Plio-Quaternary sedimentary sequence of a cave in the southern slopes of Serra de Tramuntana. Red arrows indicate the layers containing bones of *Myotragus kopperi* (E) and *Myotragus antiquus* (J); After Pons-Moyà *et al.* (1979).

spanning from sea-level to 1,445 m ASL), a complex interplay of periglacial and pluvial phenomena likely repeated several times along the Quaternary glacial periods, at least in the higher mountainous areas (Butzer, 1964). The present climate of Mallorca is characterized by mild winter temperatures (even in the mountains) and high rainfall values (over 1,000 mm of precipitation/year) in the central parts of Serra de Tramuntana. Although snowfalls are uncommon in the lowlands, during cold winters snow usually persists for 1-2 weeks each year at above 1,000 m ASL. This suggests that assuming the temperatures are lower by about 5°C, only the higher mountains would be significantly affected by cold-climate processes over the recurrent glaciation episodes. Unfortunately, research on Mallorca’s cold climate phenomena is scarce and therefore, the current state of knowledge is somewhat unsatisfactory.

After Butzer (1964), the only typical periglacial phenomena visible in Mallorca are located on the southern side of the Puig Major massif, near the saddle point of Coll de ses Vinyes, a mountain pass between Son Torrella and Cals Reis farmhouses. They comprise: 1) a massive solifluction lobe of crudely stratified coarser and finer subangular detritus, forming a small terrace 50 m long and 35 m wide at an elevation of 900 m ASL, 2) several block streams, with surface slopes of 12-18%, extending down

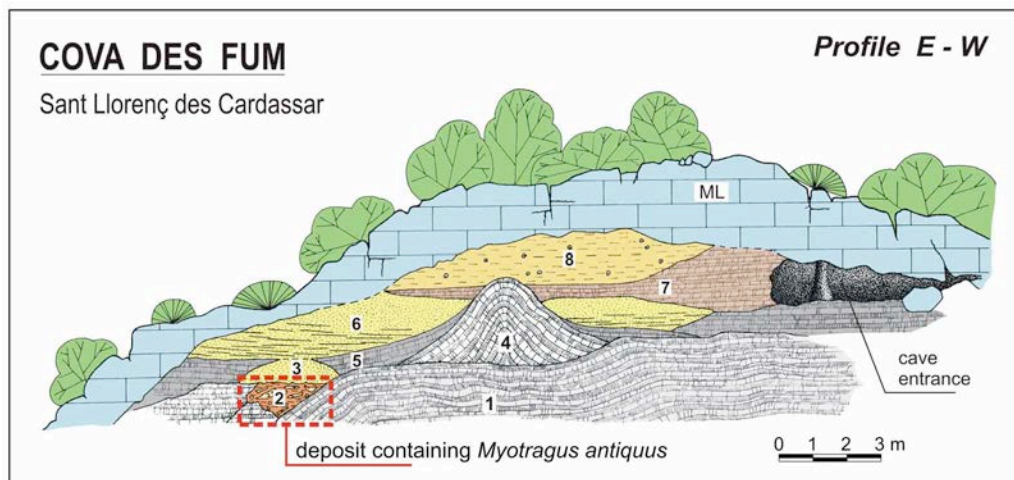


Figure 14. Stratigraphic sequence from a cave in eastern Mallorca (modified from Ginés & Fiol, 1981). 1: basal flowstone. 2: bone breccia including remains of *Myotragus antiquus*, whose age presumably corresponds to the Pliocene/Quaternary transition. 3 & 6: eolian calcarenites. 4, 5, & 7: multi-generations of flowstone. 8: silty deposits with terrestrial gastropods.

to about 850 m ASL, 3) a dissected-terrace exposure of well stratified, semi-cemented silts and fine to medium deposits corresponding to periglacial stream alluviation, 4) some moderately developed *éboulis ordonnés* deposits, denoting active frost-weathering, and 5) a cryoplanation terrace (called Sa Plana), cut into an anticlinal fold of soft Burdigalian marls and limestones planed off to a sub-horizontal surface by protracted gelifraction at approximately 900 m ASL.

More controversial is the attribution to periglacial processes, postulated by Mensching (1955) and Solé-Sabarís (1962), of some cryoclastic formations and *brèches litées*, as well as many outcrops of detrital mantles composed of angular materials affected by solifluction, found at lower altitudes on the steep slopes of the Serra de Tramuntana range. In both cases, that only in a qualified sense can be assumed as cold climate features (but not real periglacial ones at all), colluviation, slope breccia and scree formation, and the presence of solifluctional contorted patterns on the sediments or weathered residual products are involved. The correlation of intense colluviation with solifluctoidal phenomena suggests that moisture and freeze-thaw oscillations are significant factors that controlled the distribution of these features that occur as low as 250 to 650 m ASL in the Serra de Tramuntana mountains. The most suitable evolution pathway of the cold-climate colluvia is: first generation of crude rubble by frost-wedging processes and then a pluvial saturation, which along with gravity induced instability that enabled mass-sliding either by washing or sheet-flooding. Presumably, the major role in generating colluvia was water, whereas frost action only had a secondary role.

Neither traces of solifluction features nor colluvial breccias have been reported from the central plains and Serres de Llevant range. Only minor indicators of periodically colder climate and cryoclastic deposits may be found in the lowlands of the island. No evidence for glacial features was noticed in the summits of Serra de

Tramuntana. The cirque-like landform that constitutes the headwall of the steep-sided valley of Coma des Ribell (Figure 15), on the northern face of the Puig Major massif, over 1,100 m ASL, is considered to be "the result of fluvial erosion along structural lines, very probably aided by gelivation" (Butzer, 1964).

With respect to periglacial evidence, the southerly and southwesterly exposure of the aforementioned Puig Major locations, all at elevations above 750 m ASL (Butzer, 1964; Rosselló-Verger, 1977b; Grimalt & Rodríguez-Perea, 1994), suggests that frequent freeze-thaw cycles were, at least in this case, more important than severe cold periods. Complementary observations on the outcrop of the semi-cemented deposits laying above Cals Reis farmhouse leave no doubt those are pre-Upper Pleistocene, possibly even Lower Pleistocene (Butzer, 1964). According to this author, "... the Upper Pleistocene was the least effective of the Pleistocene morphodynamic phases of Mallorca. Maximum cold (January temperature depressions of 10°C) is recorded during one or more Lower Pleistocene glacials, which suggests that a fair part of the solifluctoidal features of Serra de Tramuntana may be older than the Middle Pleistocene". Therefore, it is assumed that the severe cold climate was established only during the Lower Pleistocene times. Furthermore, moderate effects of frost on Pleistocene soil down to elevations of 250-650 m ASL are documented by cryoclastic and freeze-thaw processes affecting both alluvial and colluvial deposits in the



Figure 15. Coma des Ribell cirque, situated in the northern side of Puig Major massif (1,445 m ASL), exhibits cold-climate related features as are scree-formations related to frost-weathering processes. To the bottom of the image, Puig Roig massif reaches an elevation of 1,003 m ASL. (Photo: J. Ginés).

piedmont and the foothills of Serra de Tramuntana. More recently, based on oxygen isotope signatures from soil cements at the Caloscamps locality (alluvial fans located in the eastern side of Alcúdia Bay), Rose *et al.* (1999) estimated that the mean annual temperatures during MIS 4 was between 8.2 and 4.9° C.

2.3. Shoreline changes and Quaternary coastal deposits

In the Mediterranean Basin, research on the Pleistocene marine shorelines began as early as the beginning of the 20th century, and for decades focused on molluscan faunas and altimetric correlations of raised beaches. During the 1950s, the Mediterranean shoreline studies shifted their emphasis to the interdigitation of marine and continental deposits, as colluvial silts and eolian sands (Butzer, 1983). After the innovative work of Cuerda (1957) and Muntaner-Darder (1957), Palma Bay proved to be particularly suitable for such mixed lithostratigraphy studies due to its low-energy conditions and slow uplift rates. In his "appraisal to the global sea stratigraphy", Butzer (1983) explains the pioneer contributions of Cuerda and Muntaner-Darder, particularly underlining the following four aspects: 1) identification of full faunal assemblages demonstrating that were many locally extinct Senegalese species in several Tyrrhenian beaches of Mallorca and these species varied in frequency during their specific time frame; 2) the faunal assemblages also varied with distinct facies and they formed part of sedimentary sequences usually comprising beach sands, conglomerates, terrestrial silts, and dune sands; 3) not all beaches located at similar elevations are of same age, fact supported by differences in faunal assemblages, beach facies, and under/overlying continental deposits; and 4) the complexity of the Mallorcan sites and their unique resolution with respect to the Tyrrhenian substages (Butzer & Cuerda, 1962a, 1962b), subsequently became included in the international literature (see Flint, 1966).

Most of the interest in examining marine and continental interdigitations was to distinguish between transgressive and regressive deposits and, as a consequence, to reconstruct the geomorphic processes that dominate each Pleistocene event. According to Butzer (1975, 1983) "the typical sedimentation cycle ..., in the calcareous environments of the Mediterranean Basin, southwestern Iberia and Morocco,... shifts from a transgressive beach, possibly with an interbeach argillic paleosol, to a colluvial silt, incorporating reworked red soil derivatives and possibly interfingered with alluvium, to a regressive, upward-fining eolianite of bioclastic debris, interrupted or followed by pedocal or caliche formation". The evidences from Mallorca point to at least six marine and six terrestrial hemicycles dated by means of marine biostratigraphy, enclosing multiple sea-levels oscillations during each of them (see Fig. 3 in Butzer, 1975).

A very useful overview on the debate concerning the Mediterranean Pleistocene shorelines, their regional significance, and the unsatisfactory terminology addressing these topics is provided by Rose *et al.* (1978). This includes a summary account on the Pleistocene beach deposits that followed. The Lower Pleistocene beaches have experienced some uplift and furthermore they are not so well represented in number of outcrops as the Middle and Upper Pleistocene ones. For the older Pleistocene beaches, prior to the so-called Tyrrhenian II (Eutyrrhenian, see Figure 16), the species *Patella ferruginea* may be taken as the characteristic fossil and is associated with a

common fauna assemblage. The typical *Strombus bubonius* beaches form the best documented marine deposits on Mallorca and they contain the widest range of Senegalese thermophilous species; these represent the classic Tyrrhenian II or Eutyrrhenian beaches (corresponding to MIS 5e). The post *Strombus* beaches of the Tyrrhenian III or Neotyrrhenian (Figure 16), which was originally considered by Cuerda as an interstadial sea level high stand between the Würm I and Würm II of Central Europe (today is attributed to MIS 5a), is distinctive in that much of the Senegalese element vanished. In later publications, Cuerda (1975, 1987) gives detailed information on the species, sub-species, and varieties of the molluscs fauna which are of stratigraphic or ecological interest for the Pleistocene of Mallorca. Some Pleistocene fossils are extinct or rare today in the Mediterranean, but many other species are considered ordinary fauna, indicating that in most of the transgressive phases (e.g., Tyrrhenian beaches) surface water temperatures were at least as high as those of today and during some periods, probably higher. A good example for this is, for instance, the occurrence of fully developed Senegalese fauna, including *Strombus bubonius*.

Identification of sea-level oscillations below the present day one is based on deductions from the regression series of eolian sediments and soils. Butzer (1975) states that: each basal unit of silts marks the transition from a terminal transgressive oscillation to a major regression with eolianite development; each subsequent silt unit document a shift from pedogenesis to accelerated erosion and deposition during a renewed, major regression; each eolianite seems to record a major regressive oscillation of sea level; and each pedocal marks dry morphostatic conditions. Rose *et al.* (1978) argue that "eolianites are considered to have formed during periods of sparse vegetation cover and abundant sediment availability from the adjacent sea-bed. Thus a period of relative coldness is inferred and from this a relatively low eustatic sea-level is deduced. Relatively high sea-levels are related to the colluvial deposits and the paleosol formation, which are considered to represent a relative reduction in the sediment supply and more effective pedogenesis. Also the colluvial deposits are considered to reflect a warm, moist climate with accelerated geomorphic activity".

Both marine and eolianite deposits, from which shoreline positions in Mallorca over the Pleistocene time were reconstructed, are largely discussed in other chapters of this book. Since the study of Stearns & Thurber (1965) who first provided U/Th age data, recent application of dating techniques (Hearty, 1987; Hillaire-Marcel *et al.*, 1996; Goy *et al.*, 1997; Rose *et al.*, 1999; Clemmensen *et al.*, 2001; González-Hernández *et al.*, 2001; Zazo *et al.*, 2003; Nielsen *et al.*, 2004; Fornós *et al.*, 2009; Bardají *et al.*, 2009) have improved our current knowledge on Pleistocene shoreline history on Mallorca in a substantial way.

2.4. Paleosols

The lack of a coherent system of river terraces around the mountain ranges leaves soils stratigraphy the only available method to correlate coastal and inland deposits. For this reason, special attention has been paid to paleosols as stratigraphic markers (Figure 17) ever since the pioneer studies undertaken by Mensching (1955) and Butzer (1964). As reported by Osmaston (1978), the main types of paleosols in Mallorca are: 1) relict terra rossa and yellow clay soils developed on hard montane limestone, 2) red clay soils developed on old eolianites, 3) calcareous silt containing *Chondrula gymnesica*

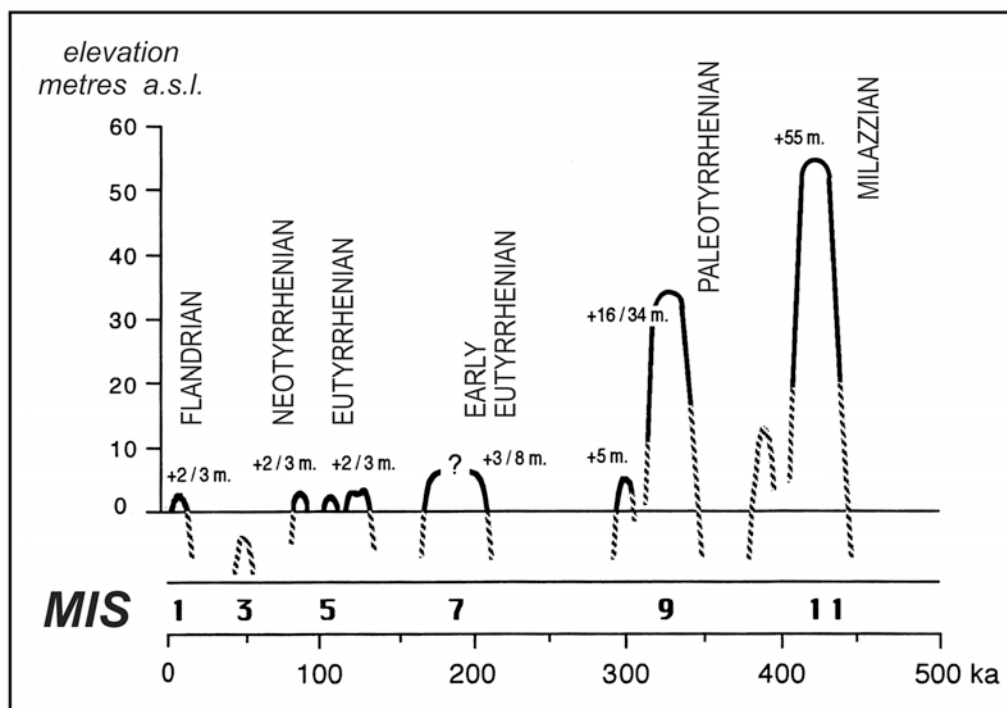


Figure 16. Sea level changes curve resulting from the studies of malacological fauna contained in fossil beach rocks of Mallorca (based on Butzer & Cuerda, 1962a; Butzer, 1975; Cuerda, 1975).⁴

land snails, also developed on eolianites and, 4) calcareous crusts, either buried or exposed at the surface, most of them found as fossil calcretes in both alluvial piedmont fans and eolianite accumulations.

The problem of terra rossa soil (relict and/or transported) and its relationship with karst processes and colluviation in Serra de Tramuntana was addressed by Mensching (1955), who stated that some terra rossa deposits were probably formed before the Tyrrhenian II (namely, before the Last Interglacial). However, the same author afterward argued that some periods during the Last Glaciation were moist enough to produce terra rossa formation. Butzer (1964) disagrees with this statement and concludes that "... the last minor phase of terra rossa or terra fusca development took place between the Tyrrhenian II (MIS 5e) and Tyrrhenian III (MIS 5a) transgressions. The last major phase of terra rossa soil development is even older ... antedating the penultimate major regressional complex of the Mediterranean Sea". A more specific placement of terra rossa paleosols into the relatively cool periods that occurred within the interglacials was later postulated by Butzer (1975). Recently, Muhs *et al.* (2010) consider that "because eolianites were likely deposited primarily during glacial periods, these paleosols probably represent interglacial or interstadial periods".

In the drier lowlands, especially in the southern part of Mallorca, evaporation exceeds rainfall, and most of the dissolved carbonate is redeposited at the surface or in a lower soil horizon, in the form of calcareous crusts or caliche. In humid areas deposi-



Figure 17. Late Pleistocene paleosol developed over MIS 4 dunes and covered with alluvial deposits, at the Pollença Bay in northern Mallorca. (Photo: J.J. Fornós).

tion occurs within the soil profile. In places it is difficult to separate relict and contemporary calcareous horizons (Crabtree, 1978). Throughout the southeastern end of the island large surfaces are covered with a calcareous crust of which thickness vary from a few millimeters to a few meters. It may be crumbly or massive and almost porcellanous. It is either covered by thin topsoil or exposed as a hard pavement, bare of soil and vegetation (Osmaston, 1978). Calcareous crusts are often associated with colluvial material.

2.5. Alluvial fans on subsident basins

From a structural point of view, Mallorca consists of a series of horst and grabens, corresponding to the ranges and plains of the island, respectively. The plains are often limited by Tertiary fractures, but occasionally their limits are angular discordances, situation when Tertiary deposits cover older structures. The most depressed zones lies at the foot of the mountain ranges (Palma and Inca-Sa Pobla basins) and accumulated sediments continuously since the uppermost Miocene and Pliocene, and until today. The sediments represent materials resulted from the intense denudation of the mountains. Along the southeastern slope of Serra de Tramuntana, the fluvial activity of the streams draining the mountain ridge produced a succession of piedmont alluvial fans. As a consequence, a large expanse of braided-river conglomerates, gravels, and fluvial sands and silts stretches today over the central lowlands of Es Pla region.

Unfortunately, the research on Mallorca's alluvial deposits has been rather scarce and, therefore, the current state of knowledge is inadequate. Muntaner-Darder (1954) and Verd (1972) describe the main characteristics of the alluvial plain around the Bay of Palma and provide data on the thickness of the Pleistocene alluvia that fill-up the Palma Basin (i.e., from 60 m to more than 150 m). Verd (1972) also investigated the morphometry and geometrical placing of the pebbles, in relation to the topography of this subsiding basin and the direction of the paleocurrents involved. Butzer (1964) touched briefly on the alluvial beds located ~240-250 m ASL at the foot of the mountains that surrounds the Plain of Palma, and also on some terraces located along the major valleys at Esporles, Puigpunyent (Sa Riera), Bunyola, and Alaró (Torrent de Solleric). Some of these are laterally changing into colluvial slope deposits. More recently, Rodríguez-Perea (1998), Rose & Meng (1999) and Rose *et al.* (1999) investigated the coalescent alluvial-fan complexes from the eastern side of the Alcúdia Bay, located at the foot of Serres de Llevant.

The chronological data available are limited; Muntaner-Darder (1954), suggests a pre-Tyrrhenian age for most of the alluvial deposits outcropping around the Bay of Palma, based on correlation with marine beaches containing *Strombus*. Butzer (1964) reports that "fluvial beds with pebbles, mechanically fractured during or after transport, are particularly common in the piedmont alluvial deposits at the foot of Serra de Tramuntana"; also claims that "the formation of the great piedmont alluvial plains adjacent to the Serra de Tramuntana range was completed during the Middle Pleistocene"; and finally states that "genuine stream gravels of Post-Paleotyrrenian date show little cryoclasticism anywhere on the island". Verd (1972) ascribes several alluvium sites around Palma to the Riss-Würm interglacial. Rose *et al.* (1999), by means of biostratigraphy, amino-acid racemization (AAR) and OSL techniques, demonstrate that the stacked sequences of fluvial, beach, paleosols, and eolian sediments of Caloscamps site (in the Alcúdia Bay) provide evidence for fluvial activity over a period spanning the last 140 ka.

2.6. Karst phenomena and cave sediments

Islands like Mallorca, mainly constituted of limestone and dolomite rocks, are subjected to long-term karstification processes that generate a variety of specific landforms and caves (including cave-sediment infillings). Apart from these, a wide range of intermingled karst and littoral processes were reported in the coastal karst areas of the island (Ginés & Ginés, 1986), an environment that is affected by the changes in sea level and the subsequent shifts of the shoreline, introducing in this way a chronological pattern that is directly controlled by the Pleistocene fluctuations of both climate and sea elevation.

The cave environments are especially suitable for the preservation of fossil remains (i.e., endemic vertebrates in the case of many islands as Mallorca) and at the same time are usually characterized by widespread speleothem deposition (particularly in the Mediterranean bioclimatic region). These biological and chemical deposits are not only great archives for paleoenvironmental and paleoclimate information, but also, useful in generating chronological data (Ginés & Ginés, 1995, Ginés *et al.*, 2011).

The fluctuation of the Pleistocene sea-level left marks both in the littoral caves and along the cliffy coasts. It is common to observe the presence of features produced by marine abrasion or boring organisms in the entrances of a great number of coastal caves at elevations that, in some cases, can be correlated with Tyrrhenian paleo-sea levels (Gràcia & Vicens, 1998; Vicens *et al.*, 2011). Patches of marine fossiliferous sands and conglomerates can be found, especially in marine-abrasion caves (see, for example, Cova de sa Plana in Butzer & Cuerda, 1962a), but they are also frequent in formerly solutional-karst caves subsequently intersected/opened by sea erosion. Interesting examples of eolian sand cones have been documented inside several caves (Figure 18), not far from the current coastline: namely, the Riss dune sands accumulated at the bottom of Cova de sa Font in the islet of Dragonera (Egozcue, 1971), and the inner sand cone of presumably Würmian age found in the lower passages of Cova de sa Bassa Blanca (Ginés & Ginés, 1974).

The deposition of speleothems is an active process happening in most of the karst regions around the world. In Mallorca, flowstones and stalagmites are common occurrences within vadose and littoral caves. These speleothems are associated or intermingled with different kind of autochthonous and allochthonous sediments of distinct origins resulting in complex sedimentary sequences. Both stalagmites and flowstones are datable by means of U-series dating methods, thus providing reliable chronologies. For many years, U/Th datings of speleothems in Mallorca (Ginés *et al.*, 1999) only focused on the phreatic overgrowths on speleothems (POS), which occur in coastal caves partially drowned by brackish waters (Ginés & Ginés, 1974; Tuccimei *et al.*, 2010); this topic is covered in detailed in other chapters of this book. Apart from dating POS, some research was carried out recently by Hodge (2004) on common Mallorcan stalagmites in order to reconstruct the Upper Pleistocene paleoclimate. One outstanding result of his studies is that some of the speleothems document very fast growth rates, similar to those calculated for relict speleothems from southeastern Australia and Oman. As both these regions are currently in semi-arid conditions, it has to be assumed that they have experienced pluvial conditions during the times of speleothem growth. Furthermore, during the process for sample screening, almost half of the sampled stalagmites were found to be older than 200 ka. Hodge *et al.* (2008) present a high-resolution paleoclimate record from one stalagmite (25 cm in height) recovered from Cova de Cala Falcó, which grew between 112 and 48 ka (MIS 4 to 3). Based on 10 MC-ICP MS U-series datings and a total of 579 oxygen and carbon stable isotopes measurements, the authors suggest that arid episodes in Mallorca appear to correlate with extremely cold periods in northern Europe. It also demonstrated that climate changes in western Mediterranean, from relatively humid to arid, occurred in less than 200 years during rapid, episodic stalagmite growth periods, at 75 ka.

Overall, the vast majority of Mallorca's caves underwent limited morphological evolution during the Middle and Upper Pleistocene. Our statement is supported by: 1) presence of speleothems older than 300 ka in cave sections that have not changed since their deposition (e.g., Cova Tancada, Cova de sa Bassa Blanca, Cova del Dimoni, and Cova des Pas de Vallgornera) and 2) complementary geomorphological and paleontological evidences. The caves have experienced very few changes since the Last

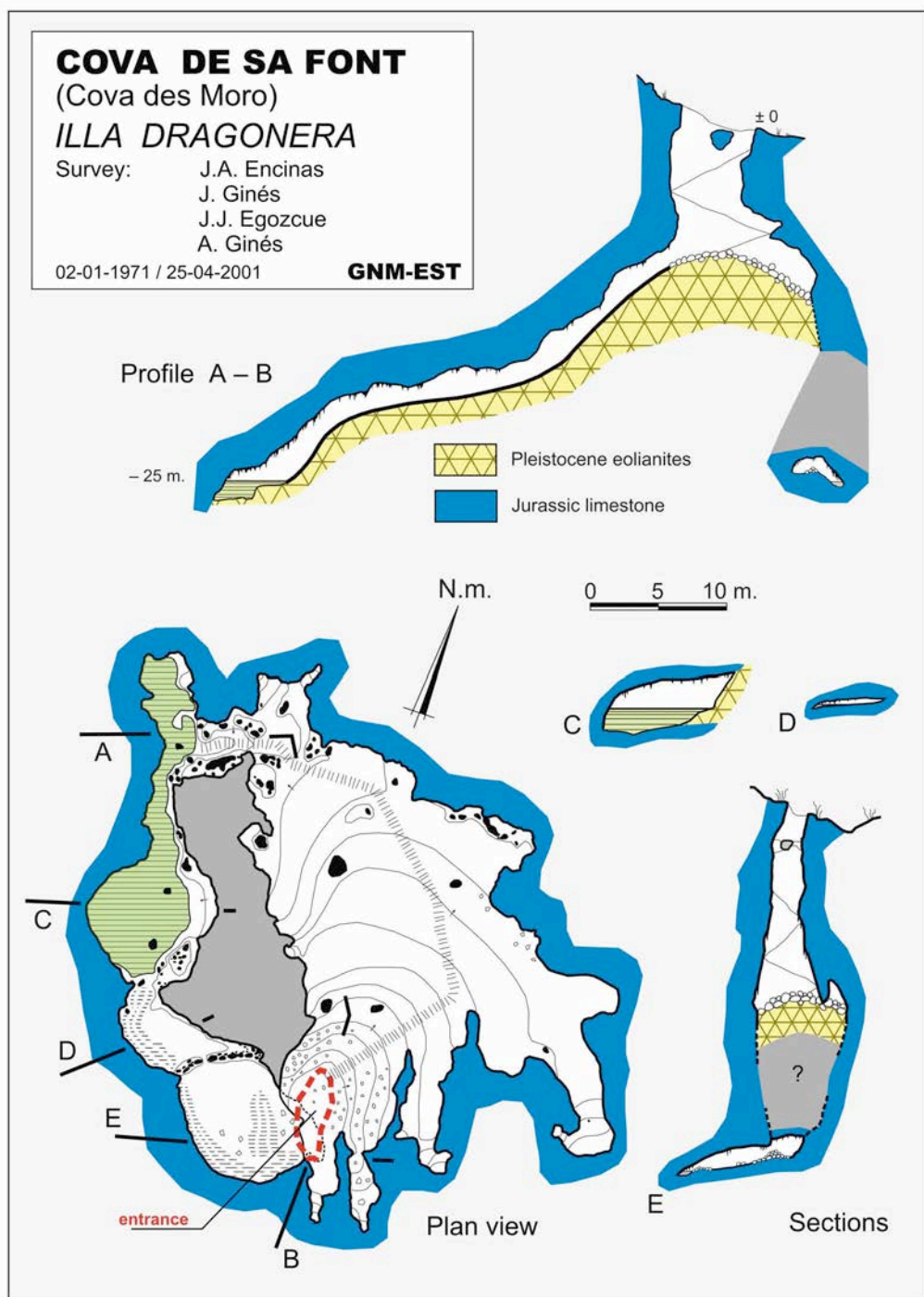


Figure 18. Topographical surveys of a littoral cave located in Sa Dragonera (small island on the western tip of Mallorca). The gravity emplaced Riss eolianites inside the cave, formed a conspicuous cone-shaped deposit covered by a thin flowstone layer.

Interglacial until the Holocene as demonstrated by the excellent conservation of old POS within many of the coastal caves. In general, the late evolution of most of the Mallorcan caves seem to be limited to the widespread and locally intense growth of speleothems along with the accumulation of some detrital infillings (bone remains, gravels, sand, collapse debris, etc.), many of them being related to the Pleistocene oscillations of sea level (Figure 19).

2.7. Insular evolution of endemic vertebrates

Insular evolution has been widely studied by paleontologists around the world. A special attention has received the changes happened in vertebrate communities and individuals due to the effect of long time isolation. Taxonomical "poverty", important differences in body size in vertebrates when compared with mainland related species, lack of ecological components (as predators), and a high number of endemic species are among the most remarkable characteristics of insular vertebrate communities. The island of Mallorca is not an exception. The vertebrate faunal assemblage that lived on this island during the Quaternary, comprise remaining taxa that arrived in Mallorca during the Messinian Salinity Crisis. This was a major desiccation event in the Mediterranean Sea that occurred 5.6 to 5.32 Ma ago (e.g., Clauzon *et al.*, 1996; Krijgsman *et al.*, 1999) and provided land bridges between the Balearic Islands and the surrounding mainland. After these land connections were re-flooded, the Balearic Islands remained physically isolated and all species evolved during more than 5 million of years without any further major colonization (except of flying vertebrates).

Although the most ancient record of this post-Messinian fauna is known from only one Mallorcan deposit (with documented Early Pliocene chronology), we can state that from the initial 5 mammalian and up to 7 reptilian taxa, just 3 mammals and 1 reptile survived until the arrival of the first humans in the Balearic Islands around 5,000 years ago. A reptile (genus *Podarcis*) and an amphibian (genus *Alytes*), which appeared in the fossil record at the beginning of the Quaternary, are the sole living fossil vertebrates that are currently seen on the island of Mallorca and its surrounding islets (Figure 20).

During 5 million years of evolution under special ecological conditions (isolated and predator-free environment), some of the species acquired remarkable morphological and physiological adaptations (Bover *et al.*, 2008). This is especially true for the spectacular adaptations displayed by three Mallorcan endemic mammals and their indisputably most peculiar species, the small bovid of the genus *Myotragus*. Certainly, the last species of the phylogenetic lineage, *M. balearicus*, is one of the most bizarre mammals that lived on the Earth (Figure 21). It was a dwarf species with a shoulder height not greater than 50 cm, with very short and robust limb bones and important changes in skull morphology, namely the frontalization of eye orbits and the reduction of brain size (Köhler & Moyà-Solà, 2004). It also displayed a reduced number of cheek teeth and a single ever-growing incisor in each mandible (not four as observed in recent bovids). Current research has demonstrated that physiological patterns and changes in sense organs can be studied on the basis of *Myotragus* bones. Several authors stated that the species had a reduction in vision and olfactory ability (Köhler & Moyà-Solà, 2004; Bover & Tolosa, 2005) and it ceased growth periodically (Köhler & Moyà-Solà, 2009).

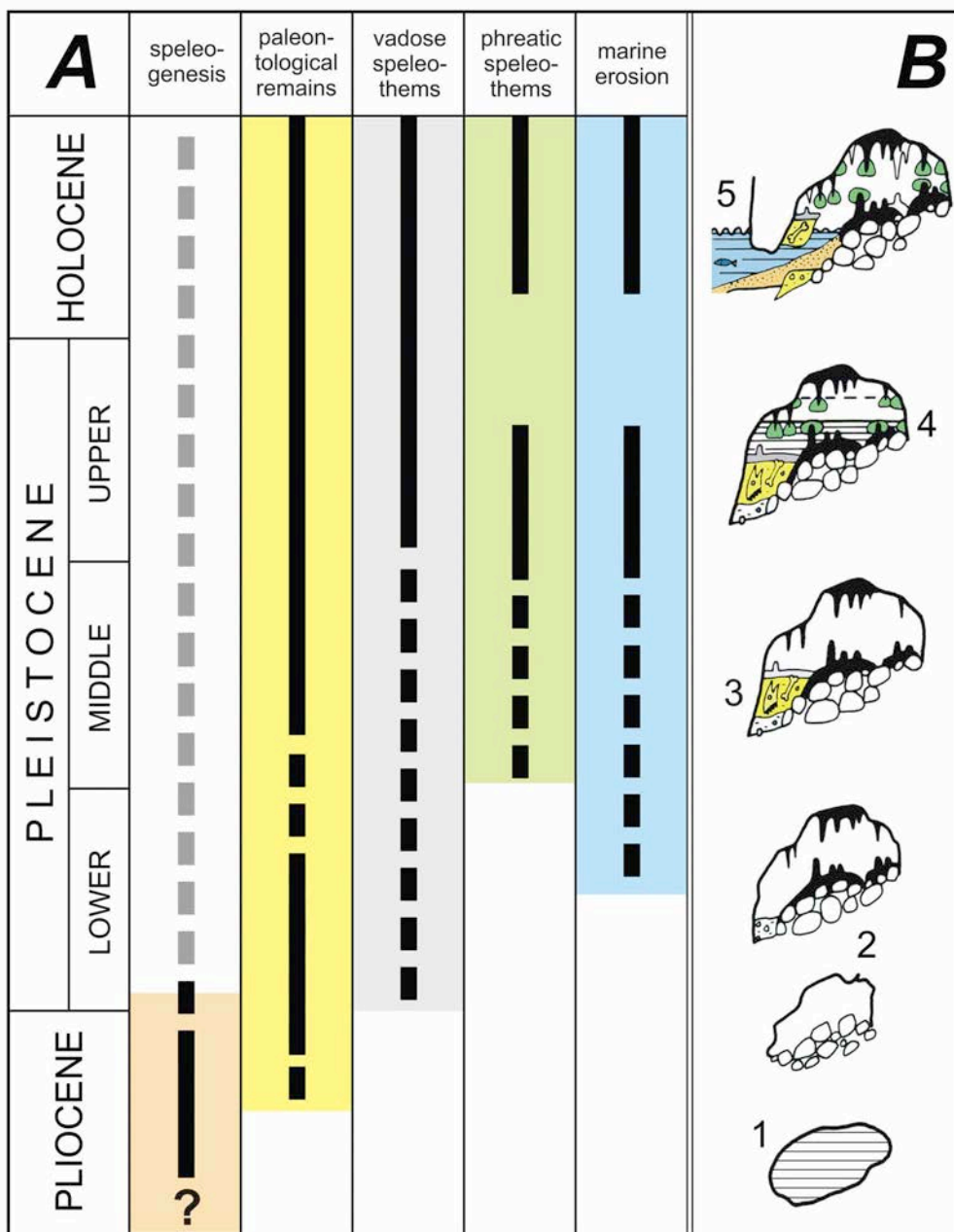


Figure 19. Idealized geochronological synthesis of the morphological and sedimentary evolution in the littoral endokarst of Mallorca. **A:** temporal reconstruction of the main morphogenetic processes and the associated cave infillings. **B:** general morphological appearance of the caves at different times during their evolution. **1:** excavation of an initial network of phreatic voids; **2:** breakdown processes alternate with phases of vadose speleothem deposition; **3:** paleontological remains of endemic vertebrates accumulate within caves; **4:** episodes of phreatic speleothems deposition corresponding to paleo-sea level high stand in the western Mediterranean basin; **5:** recent erosional and sedimentary processes, marine in origin, affect caves that are closer to the coastline.

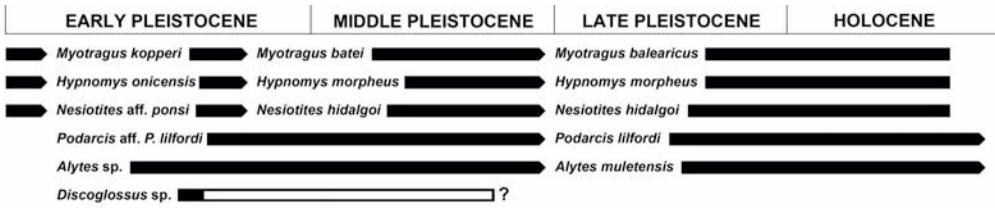


Figure 20. Schematic summary of the faunal assemblages (terrestrial vertebrates) from Mallorca during the Pleistocene.

In addition to *Myotragus balearicus*, Quaternary mammals also included *Hypnomys*, a glirid rodent and *Nesiotites*, a sorcid shrew. Although these two mammals are not as well-known as *Myotragus*, some morphological characteristics in skeleton show, at least in *Hypnomys*, remarkable changes in size and locomotion when compared with current mainland related species. Thus, *Hypnomys morpheus* (the most modern species of the genus) displayed a greater size and a more terrestrial locomotion than its current related species, the dormouse *Eliomys quercinus* (Bover *et al.*, 2010). With respect to *Nesiotites hidalgoi*, the terminal species of the genus was also a great-sized shrew; analysis of locomotion are currently being carried out.

A schematic chronological framework that covers the several vertebrate lineages living in Mallorca during Pleistocene times is presented in Figure 20. Osteological remains of *Myotragus* and *Hypnomys* are frequently found in many caves of Mallorca (Moyà-Solà & Pons-Moyà, 1979; Alcover & Bover, 2005). However, the availability of precise datings is rather scarce. Most of the cave deposits containing endemic mammals are presumably of Upper Pleistocene to Holocene age and only a very few paleontological sites has been dated as older than Middle Pleistocene based on stratigraphical criteria or using radiometric techniques. One femur of *Myotragus* sp. found in alluvial sediments from the central plains of the island is considered to be Lower Pleistocene in age (Muntaner-Darder, 1956; Moyà-Solà & Pons-Moyà, 1979). But the only numerical dating constraining the age limit for *Myotragus balearicus* is provided by Andrews *et al.* (1989) in their study of Cova de na Barxa stratigraphy, just where Dorothea Bate found its type-specimens (Bate, 1909). Uranium series analysis of several flowstone layers, both underlying and sealing the bone-bearing sediments, demonstrated that two separate bone deposits are present in the cave: the first is older than 195 ka BP, whereas the second one is aged between 119 and 7.5 ka BP.

2.8. The Holocene times and the impact of human arrival

The earliest palynological studies investigated the sediment sequences from the marshland areas of Palma Nova (Menéndez-Amor & Florschütz, 1961) and S'Albufera d'Alcúdia (Burjachs *et al.*, 1994). More recently, Pérez-Obiol *et al.* (2003), based on pollen analysis of some isolated samples recovered in S'Albufera from a depth of 19.5 m, document an interstadial period characterized by a remarkable expansion of deciduous trees and thermophilous species at the end of the Last Glaciation, about 31 ka BP (^{14}C dating). Subsequently, they also provided a general explanation of the evolution of plant communities throughout the entire Holocene. In a preliminary report presented by Waldren (1982) on the sediments of Cova de Moleta containing *Myotragus balearicus*, the end of Würmian glaciation, around 14 ka, appears associated



Figure 21. Skull and mandibles of *Myotragus balearicus* from Cova des Tancats. (Photo: IMEDEA).

to a pollen dominance of Asteraceae and Poaceae (gramineae) and an impoverished presence of tree species. According to Pérez-Obiol *et al.* (2000, 2003), during the lower part of the Holocene, the pollen diagrams indicate that Mallorca had an arboreal cover represented by *Corylus*, *Buxus*, *Juniperus*, *Betula*, and *Acer*. This vegetal association suggests a wetter climate with less marked seasonality than nowadays. The presence of deciduous forests of *Quercus* and *Fagus* in Serra de Tramuntana is also reported during the same time period (Pérez-Obiol & Yll, 2003). Around 6,000 years BP, a major change in the composition and structure of the vegetation occurred, fact that led to the dominance of sclerophyllous taxa. This event was coincident in time with a significant increase of aridity in the Western Mediterranean region and with the first human colonization of the Balearic Islands. At about 2,500 BP, a progressive decrease in arboreal species is observed, being replaced by *Pistacia* and *Ericaceae*. The Late Holocene is represented in Mallorca by a typical sclerophyllous plant community with a great importance of *Olea*.

Archeological research advocates that the first human settlement occurred in Mallorca approximately during the 3rd millenium BC. The archeological and paleontological studies performed particularly in Cova de Moleta, Balma de Son Matge, Cova Estreta, and Cova des Moro have been complemented with a substantial number of radiocarbon datings (Fernández-Miranda & Waldren, 1979; Waldren, 1992; Castro *et al.*, 1997; Guerrero, 2000). These numerical ages allowed a detailed analysis of

the extinction patterns of the mammalian endemic species of Mallorca and Menorca through the Middle Holocene (Bover & Alcover, 2003, 2008). The wide overlap between the 2σ intervals of the ^{14}C ages on the arrival of humans on the island and the oldest dated remains of *Myotragus balearicus*, suggests that human colonization promoted the extinction of those species.

Finally, concerning the postglacial changes that affected Mediterranean sea level position, some chronological constraints are now available thanks to the studies of Tuccimei et al. (2009, 2010, 2011) on the POS. As a consequence of these new data, it appears that the previous assumptions about Flandrian sea level high stands reported by Butzer (1962) and Cuerda (1975) have to be revisited, mainly because the U/Th and ^{14}C datings of POS document a stable sea level at its current elevation since 2.8 to at least 0.6 ka BP. The POS data are in good agreement with the estimated age of a prehistoric stone pathway, submerged at a depth of 1 m below the current watertable in the nearby Cova Genovesa (Gràcia et al., 2003). Combining archeological data and isotope chronology of POS, Tuccimei et al. (2009) recognize a relative sea level low stand at about -1 m ASL, around 3,700 – 3,000 years BP, followed by a rise of sea level, with a successive stabilization at present elevation, from ~2,800 years BP until today.

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Quaternary beach deposits in Mallorca: paleontological and geomorphological data

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1. Research on Quaternary shorelines from Mallorca. Historical background

Many researchers have worked on the Quaternary deposits scattered along the littoral zones of Mallorca Island. As a consequence, there are a significant number of publications on this topic, being almost impossible to assemble a comprehensive review in a general chapter like this one. Therefore, the present paper exclusively provides a historical background on the knowledge of Mallorcan Quaternary shorelines, along with their paleontological remains and chronology.

La Marmora (1834) was the first geologist writing about Quaternary deposits on Mallorca Island. This author reports the presence of sandstones (with modest fossil content) in the southern flat areas of the island and conglomerates with marine shells, resembling those of present-day beaches, in just a few places.

Haime (1855) dedicates only a paragraph in his study on the Quaternary paleontology, citing 12 species. Hermite (1879) distinguishes two levels within the marine raised beaches existing to the east of Palma Bay. The lower level is composed of some conglomerates previously mentioned by Haime, containing *Acanthocardia tuberculata*, along with other species currently living in the Mediterranean Basin, except for the thermophilous species *Strombus bubonius*. The upper level, abundant on fragments of small-sized marine shells and foraminifera, is correlated with the deposits cited by La Marmora.

Hermite (1879), Hoernes (1905), and Collet (1909) described some calcareous deposits containing *Helix*. However, it was Gignoux (1913), who indicated the real origin of these formations, i.e., they are ancient hardened dune materials. This author also establishes the synchronism of the Mallorcan deposits containing *Strombus bubonius* with those from other sites in the Western Mediterranean Basin, but he

considers quite difficult to resolve the precise elevation of the sea level at the time when the sedimentation of these materials took place.

When referring to the Quaternary of Mallorca, Fallot (1922) focuses his attention on the alluvial sediments but when discussing the marine formations, he simply reproduces the previous observations of Hermite.

Beginning with 1950, Andreu Muntaner and Joan Cuerda started to publish some notes on the Quaternary from Palma Bay, in the *Bolletí de la Societat d'Història Natural de les Balears*. As a result of these investigations, in 1952, two levels situated at +4 and +2 m ASL, respectively, were distinguished within the Eutyrrhenian (or Tyrrhenian II). In addition, their studies are citing a total of 110 marine species (Cuerda & Muntaner, 1952). The researches continued over the next years, culminating with two major papers: one by Joan Cuerda on the paleontology of marine Tyrrhenian deposits in the Bay of Palma (Cuerda, 1957), and the other by Andreu Muntaner devoted to the Tyrrhenian stratigraphy in the same area (Muntaner, 1957). The scientific expertise of the two authors, as well as their abundant publication record and the paleontological collections assembled by them, prompted the Organizing Committee of the *V International Quaternary Congress (INQUA)* to develop a fieldtrip in Mallorca in September 1957 (Figure 1).



Figure 1. A visit to Es Carnatge site (known in most of the papers as "Campo de Tiro") in September 1957, during the 5th INQUA Congress fieldtrip to Mallorca. Joan Cuerda (a) and Andreu Muntaner (b), two remarkable local Quaternary researchers, were part of the committee organizing the Mallorca fieldtrip (Photographic archive of Andreu Muntaner).

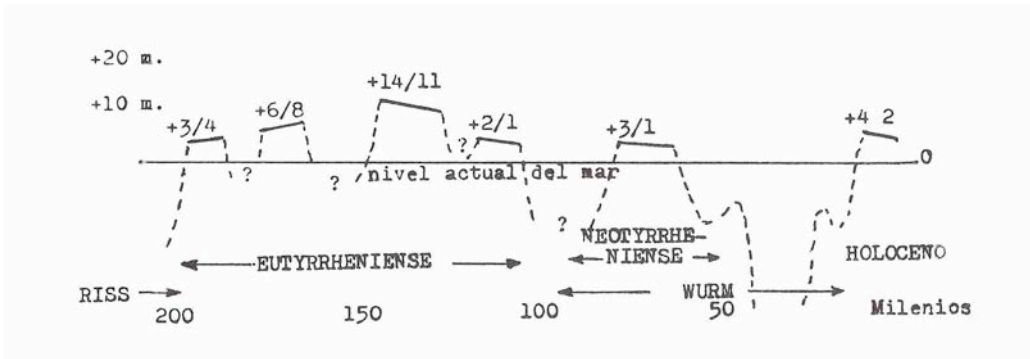


Figure 2. Eustatic sea-level curve proposed by Cuerda (1975) based on the elevation of Mallorcan marine deposits and the U/Th datings of shells published by Stearns & Thurber (1965).

Between 1950 and 1962, Karl W. Butzer and Joan Cuerda conducted three research campaigns in the Balearic Islands revealing a large number of Middle and Upper Pleistocene shorelines and marine deposits. Their investigations on marine erosion platforms and the paleontological remains in the littoral deposits, pointed out to a multitude of ancient sea levels recorded along the Mallorcan coasts (Butzer & Cuerda, 1960, 1962a, b).

Also, the paper by Solé-Sabaris (1962) is remarkable in that it reviewed the marine Quaternary deposits in the Balearics and attempted to elucidate their relationships with the shorelines of the Iberian Peninsula. Furthermore, of special significance was the first U/Th age determinations conducted by Stearns & Thurber (1965) on molluscs from Mallorcan marine deposits, belonging to the Upper Pleistocene. These age-data allowed Cuerda (1975) and Butzer (1975) to generate tentative eustatic sea-level curves (Figure 2), exclusively based on the elevation and chronology of the studied sites.

Certainly, the year 1975 represents a milestone for the Quaternary studies in the Balearic Islands due to the publication of the monograph compiled by Joan Cuerda. In this outstanding work (Cuerda, 1975), apart from some general concepts about the Quaternary, the author focuses his attention on the marine deposits of the Balearics both from the stratigraphic and paleontological points of view. Another publication synthesizing the information that became available for the Quaternary in Mallorca was elaborated by Pomar & Cuerda (1979).

A few years later, a stimulating book edited by Rose (1978) is published on the Quaternary of Mallorca. A large part of the information provided is based on the earlier works of Cuerda, but new data supplied by researchers from the United Kingdom were also included. Richards (1985) made some contributions to the topic using previous publications and his own personal data; the author suggested that the highest raised beaches of the Eutyrrhenian were affected by tectonic movements. Stearns (1985) presented some criticisms on their own pioneer U/Th dating work.

In 1987, another important monograph resulting from Cuerda's continuous dedication was published. The work contains a complete catalogue of marine and

brackish water molluscs collected from Pleistocene littoral deposits of the Balearic Islands (Cuerda, 1987). The very same year, Hearty (1987) published a paper that presents the dating of 15 Mallorcan sites using amino acid racemization technique; the obtained data are presented in the context of aminostratigraphic studies carried out around the world.

Cuerda & Sacarés (1992) published a book that compiles all their investigations on the Quaternary deposits from Lluçmajor municipality. Also in the 90s, two more relevant studies which provide new absolute ages for the Pleistocene littoral deposits from Mallorca were published by Hillaire-Marcel *et al.* (1996) and Rose *et al.* (1999).

In an extensive investigation of the phreatic overgrowths on speleothems (POS) in the coastal caves of Mallorca, Ginés (2000) critically reviewed the sea-level and the chronological data emerging from the stratigraphic study of raised beaches. Using the POS record, Ginés's PhD dissertation suggests some preliminary eustatic sea-level curves rather different to those of Cuerda (1975) and Butzer (1975). More detailed and updated contributions to sea level history in Mallorca have been recently published by Tuccimei *et al.* (2006) and Dorale *et al.* (2010), both based on the investigation of phreatic speleothems.

Several papers –some relatively recent– deal specifically with stratigraphic, paleontological, or chronologic aspects of the Pleistocene sites from Mallorca; the following are worth to mention: Cornu *et al.* (1993), Goy *et al.* (1997), González-Hernández *et al.* (2000), Vicens *et al.* (2001), Zazo *et al.* (2005), Vicens & Pons (2007), and Muhs *et al.* (2010). All these papers include extensive reference lists that give readers access to more information on those specific topics. Significant to the Western Mediterranean domain are also the publications of Hearty *et al.* (1986), Zazo *et al.* (2003, 2004), and Bardají *et al.* (2009). Even the paper of Meco (2008) on Canary Islands is of great interest from a paleontological point of view, because during MIS 5e the Mediterranean Sea shared species of thermophilous fauna with this Atlantic archipelago.

2. The Pleistocene littoral fossil assemblages

There are a series of taxa that are extremely useful with respect to the chronology of marine deposits in the Balearic Islands. In particular, those species corresponding to the Upper Pleistocene are the best known due to the abundance of sites allowing the study of their paleontological records. The Lower- and Middle Pleistocene-related taxa are really scarce and not well-documented up to now.

The taxonomic nomenclature used in this paper are not updated, but suggested instead those habitually used in the marine Quaternary of Mallorca reference. However, the correspondence between the used taxonomy and the alternative equivalence of Appeltans *et al.* (2011) is listed in Table I.

Currently, the institution in the Balearic Islands that hosts the most extensive collection of Pleistocene littoral fossils is the *Societat d'Història Natural de les Balears*. This collection was assembled thanks to a number of donations from different local

researchers, among which the late Joan Cuerda. The majority of the available collections (Figure 3) are partially catalogued; nowadays the paleontological register includes nearly 8,000 entries and the number of specimens exceeds 28,000 fossils (Table II).

2.1. Marine fossils from the Lower and Middle Pleistocene

There are few known marine fossil taxa reported from the Lower and Middle Pleistocene of Mallorca (Cuerda, 1987). Among the most representative, *Saccostrea virleti* and *Purpura gallica* (nowadays extinct molluscs) are attributed to the Plio-Quaternary limit.

Two species from the Lower Pleistocene are cited: *Saccostrea cucullata* and *Purpura pleissi*. The first one lives today along the Red Sea and African inter-tropical coasts, whereas the second one is an extinct taxon.

Table I. Marine and brackish-water species having stratigraphic significance after Cuerda (1987), and their correspondence with the nomenclature by Appeltans *et al.* (2011). (♦): correspondence proposed by the authors of this paper. (●): doubtful correspondence that needs further in-depth revision. (♥): the type-species is banal, but a variety (var. *nodulosa*) and a subspecies (ssp. *consul*) have stratigraphic significance. (---): the correspondence has not been established, perhaps because there are mainly brackish-water species and no strictly marine ones. (♠): Cited by Cuerda (1975).

Class	Cuerda (1987)	Appeltans <i>et al.</i> (2011)
Bivalvia	<i>Barbatia plicata</i> (Chemnitz, 1870)	<i>Barbatia plicata</i> (Dillwyn, 1817)
	<i>Anadara geissei</i> (Dunker, 1891)	<i>Mosambicarca hians</i> (Reeve, 1844)
	<i>Brachidontes senegalensis</i> (Lamarck, 1819)	<i>Brachidontes puniceus</i> (Gmelin, 1791) ♦
	<i>Hyotissa hyotis</i> (Linné, 1758)	<i>Hyotissa hyotis</i> (Linnaeus, 1758) ●
	<i>Ungulina rubra</i> Roisy, 1802	<i>Ungulina cuneata</i> (Spengler, 1798) ♦
	<i>Cardita senegalensis</i> Reeve, 1843	<i>Cardita senegalensis</i> Reeve, 1843
	<i>Eastonia rugosa</i> (Chemnitz, 1782)	<i>Eastonia rugosa</i> (Helbling, 1779)
Gastropoda	<i>Patella ferruginea</i> Gmelin, 1790	<i>Patella ferruginea</i> Gmelin, 1791
	<i>Monodonta lineata</i> (da Costa, 1778)	<i>Osilinus lineatus</i> (da Costa, 1778)
	<i>Mathilda granosa</i> (Borson, 1821)	-----
	<i>Melania tuberculata</i> (Müller, 1773)	-----
	<i>Pirenella conica</i> (Blainville, 1826)	<i>Potamides conicus</i> (Blainville, 1829)
	<i>Theridium minutum</i> (De Serres, 1822)	-----
	<i>Strombus bubonius</i> Lamarck, 1822	<i>Persististrombus latus</i> (Gmelin, 1791)
	<i>Polinices lacteus</i> (Guilding, 1831)	<i>Polinices lacteus</i> (Guilding, 1834)
	<i>Naticarius turtoni</i> (E.A. Smith, 1890)	<i>Natica turtoni</i> E.A. Smith, 1890
	<i>Cymatium costatum</i> (Born, 1780)	<i>Monoplex parthenopeus</i> (Salis-Marschlin, 1793) ♦
	<i>Bursa scrobilator</i> (Linné, 1758)	<i>Bursa scrobilator</i> (Linnaeus, 1758)
	<i>Thais haemastoma</i> (Linné, 1767)	<i>Stramonita haemastoma</i> (Linnaeus, 1767) ♥
	<i>Cantharus viverratus</i> (Kiener, 1834)	<i>Gemophos viverratus</i> (Kiener, 1834)
	<i>Arcularia gibbosula</i> (Linné, 1767)	<i>Nassarius gibbosulus</i> (Linnaeus, 1758)
	<i>Mitra fusca</i> Swainson, 1833	<i>Scabricola fusca</i> (Swainson, 1824)
	<i>Conus testudinarius</i> Martini, 1773	<i>Conus ermineus</i> Born, 1778
Crustacea	<i>Ocypoda cursor</i> (Linné) ♠	<i>Ocypode cursor</i> (Linnaeus, 1758)

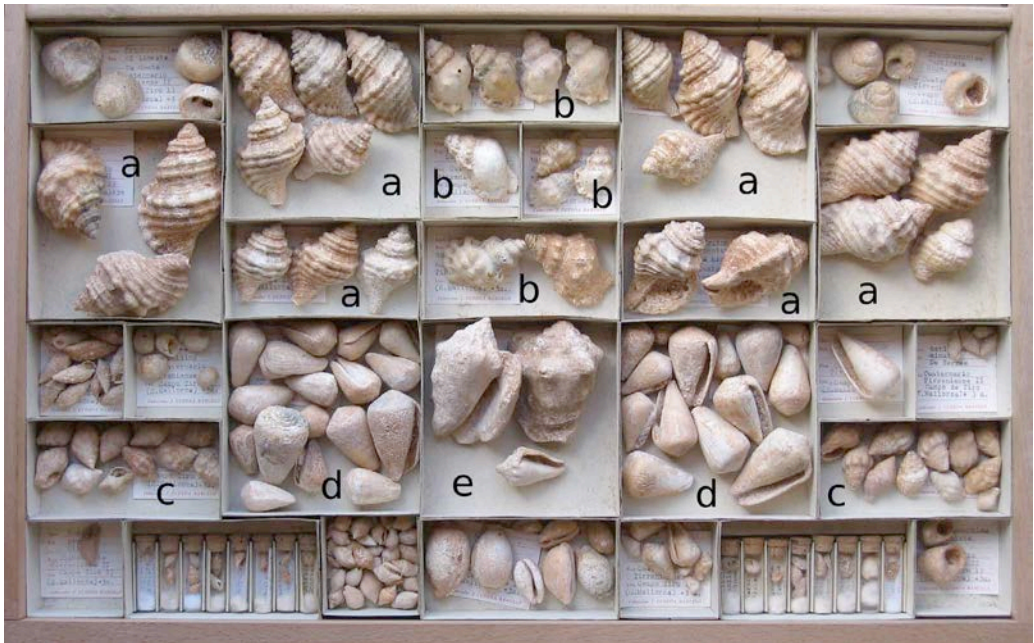


Figure 3. Fossils from the Palma Bay (collection Joan Cuerda-SHNB) shown as they were stored at the original collection (Archive SHNB). a- *Cymatium costatum*. b- *Bursa scrobiculator*. c- *Cantharus viverratus*. d- *Conus testudinarius*. e- *Strombus bubonius*.

Patella longicosta and *Patella* cf. *ambrogii* can be found –though with some taxonomic doubts– in Plio-Quaternary and Lower Pleistocene deposits. They are currently extinct species in the Mediterranean Basin, living only in South Africa.

Patella ferruginea, according to Cuerda (1975, 1987), is a characteristic taxon in the Paleotyrrenian of Mallorca (Middle Pleistocene) and fairly abundant in deposits belonging to this stage.

2.2. Marine fossils from the Upper Pleistocene

Among the taxa found in the Upper Pleistocene deposits of the island, there are species living today in the Western Mediterranean waters, which are referred in the

Table II. An estimate of the number of paleontological registers (RP) and the amount of specimens (NS) within the collections of *Societat d'Història Natural de les Balears*, coming from Upper Pleistocene marine deposits at the Balearic archipelago. About 99% of the specimens are from Mallorca Island.

SHNB collections	Marine fossils		Terrestrial fossils	
	RP	NS	RP	NS
Col. Joan Cuerda	3,700	16,000	350	1,600
Col. Andreu Muntaner	850	1,800	50	100
Col. Damià Vicens	2,000	7,000	500	1,000
Col. F. Gràcia- D. Vicens	350	1,600	3	10
Col. Gabriel Fornés	61	277	-	-
TOTAL	6,961	25,077	903	2,710

literature as "banal fauna" due to their lack of stratigraphic interest. Besides, other taxa do not live today in the Balearics although they were common during some Quaternary stages (Figure 4). Within this second group of species –that have stratigraphic interest– one can distinguish two categories based on whether they are nowadays present or not, in different regions of the Mediterranean Basin.

2.2.1. Taxa that are extinct in the Balearics, but living in Southern Mediterranean waters or neighboring Atlantic areas

Fossils corresponding to this category have been reported from the Last Interglacial marine deposits. According to Cuerda (1987), the most representative taxa are:

Bivalvia: *Ungulina oblonga* and *Eastonia rugosa*.

Gastropoda: *Patella ferruginea*, *Monodonta lineata*, *Theridium minutum*, *Bursa scrobiculata*, *Arcularia gibbosula*, and *Mitra fusca*.

Exceptionally, some of these species can be found alive in the Western Mediterranean, as is the case of *Bursa scrobiculata*, whose presence may be considered accidental since it is a typical Atlantic species (Verdejo, 2001). Cuerda (1987) gave stratigraphic value to *Eastonia rugosa*, a slightly thermophilous taxon, which currently is missing from the Balearic waters. Recently, La Valle *et al.* (2007) and López *et al.* (2010) found this taxon living in the littoral regions of Catalonia (Spain) and Rome (Italy), where apparently was introduced not long ago.

A fossil crab currently extinct in the Balearics, *Ocypoda cursor*, was reported living in the Eastern Mediterranean and the Atlantic inter-tropical coasts of Africa (Via, 1966).

2.2.2. Taxa that are currently extinct in the Mediterranean

Among the fossil marine molluscs there is a group of taxa traditionally referred as "Senegalese" species, which are nowadays extinct in the Balearics but today they are living along the coasts of Senegal and other neighbor African countries. Favored by a warm climate, they invaded the Mediterranean during the Eutyrrhenian (MIS 5e), but became extinct over the Last Glacial period (Cuerda, 1987). The "Senegalese" species are the following:

Bivalvia: *Anadara geissei*, *Brachidontes senegalensis*, *Hytissa hyotis*, and *Cardita senegalensis*.

Gastropoda: *Strombus bubonius*, *Polinices lacteus*, *Naticarius turtoni*, *Cantharus viverratus*, and *Conus testudinarius*.

In the Balearic Islands, this molluscs assemblage is characteristic for the marine stage known as Eutyrrhenian. Normally, two additional taxa, also from the Atlantic coasts of Africa (*Cymatium costatum* and *Bursa scrobiculata*) accompany the "Senegalese" species. Because of the warm climate that characterized the Eutyrrhenian, these species flourished along the Mallorcan coasts (Cuerda, 1987), but are completely extinct nowadays from the Balearic Islands.

The most characteristic and emblematic species is *Strombus bubonius*. Comprehensive and interesting information on this taxon are available in Meco *et al.* (1977) and Torres *et al.* (2006). Based on chronological criteria –established from Es Carnatge site by Hillaire-Marcel *et al.* (1996)– Bardají *et al.* (2009) suggest that *Strombus bubonius* vanished from Mallorca at the end of MIS 5e. However, this species populated the Iberian Peninsula coasts throughout the entire MIS 5. We think this topic deserves further attention.

Barbatia plicata is another taxon, currently extinct in the Mediterranean Sea, which does not belong to the "Senegalese" species and is found at the Balearics in deposits corresponding to the Last Interglacial. Today is living in the Red Sea region.

Within the Neotyrrenian (MIS 5a) deposits from the Balearics, not all the characteristic species of the "Senegalese" group are present. Among them, only *Brachidontes senegalensis*, *Cantharus viverratus*, and *Conus testudinarius* are found. Furthermore, *Barbatia plicata*, a thermophilous taxon (not belonging to the "Senegalese" group) is also present. In this respect, the Neotyrrenian deposits as a whole are characterized by an "impoverished thermophilous fauna" (Cuerda, 1987).

Moreover, is worth mentioning *Thais haemastoma* var. *nodulosa*, a variety of gastropod that is no longer living in the Balearic Islands. This taxon is present within the Eutyrrhenian raised beaches from Mallorca, but was not reported from the Neotyrrenian deposits (Cuerda, 1987). There are no valid information on this variety, likely because authors could not distinguish it from the type-species (Vicens, 2010). Within this taxon, there is another sub-species –*T. haemastoma* ssp. *consul*– never found in the taphocoenosis of present-day beaches, although it has been collected alive in the Palma Bay from depths between 20 and 40 m; this sub-species is present in the Eutyrrhenian deposits from Mallorca, but it is rather rare in the Neotyrrenian sediments (Cuerda, 1987).

2.2.3. Additional paleontological data

When speaking on the percentages of specimens found in the marine Upper Pleistocene sites, molluscs (*Bivalvia*, *Scaphopoda*, and *Gastropoda*) are the most common ones. Statistical analyses are useful to gain a general view over this issue, although not all of them refer to the entire island of Mallorca. On one hand, Cuerda *et al.* (1989-1990) described 1,003 specimens from a Neotyrrenian site named by the authors "Sa Tanca de sa Torre II". These specimens belong to the following 9 classes: *Rhodophyceae*, *Anthozoa*, *Bryozoa*, *Echinoidea*, *Bivalvia*, *Scaphopoda*, *Gastropoda*, *Malacostraca*, and *Acinopterygii*; molluscs, with 952 individuals, represent 94.9% of all specimens found at this site.

On the other hand, 153 marine taxa belonging to the Upper Pleistocene and Holocene (the latter being very scarce) have been identified from fossil remains collected over a large area of Mallorca (Vicens 2010). Molluscs from *Bivalvia*, *Scaphopoda*, and *Gastropoda* classes, with 46, 2, and 87 taxa determined respectively, represent as a whole the 88.23% of taxa located in the selected area, comprising Pollença, and Alcúdia bays. The rest of classes, like *Rhodophyceae*, *Anthozoa*, *Malacostraca*, *Chondrichthyes*, *Actinopterygii*, and *Mammalia* have fewer taxa identi-

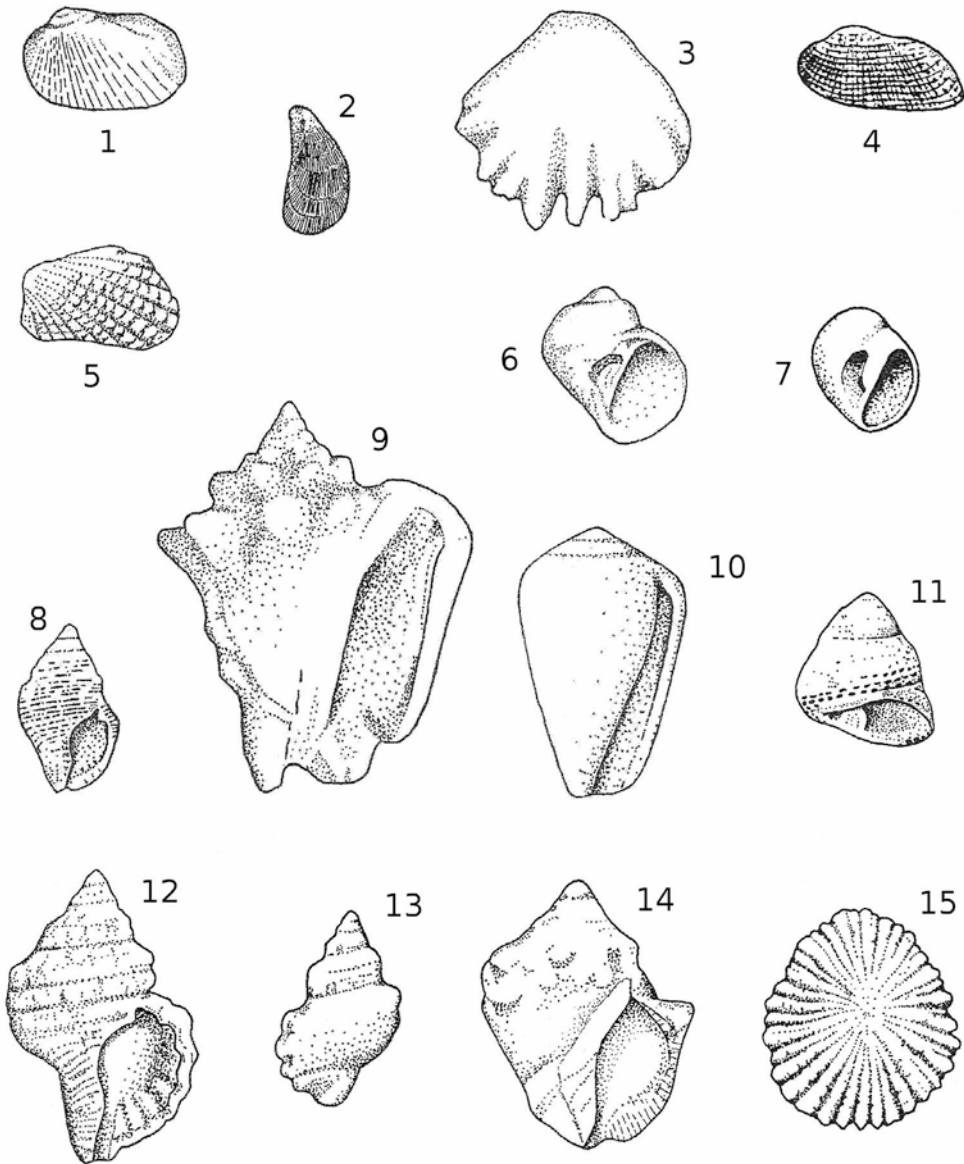


Figure 4. Marine fossils with stratigraphic significance from Mallorca, corresponding to MIS 5. Within brackets, the major axis length of each specimen is indicated. 1- *Anadara geissei* (28 mm). 2- *Brachidontes senegalensis* (23 mm). 3- *Hyotissa hyotis* (55 mm). 4- *Barbatia plicata* (20 mm). 5- *Cardita senegalensis* (28 mm). 6- *Naticarius turtoni* (22 mm). 7- *Polinices lacteus* (19 mm). 8- *Cantharus viverratus* (32 mm). 9- *Strombus bubonius* (70 mm). 10- *Conus testudinarius* (55 mm). 11- *Monodonta lineata* (33 mm). 12- *Cymatium costatum* (80 mm). 13- *Bursa scrobiculata* (55 mm). 14- *Thais haemastoma* ssp *consul* (57 mm). 15- *Patella ferruginea* (70 mm).

identified in the paleontological record of the area. If instead of using the taxa above, an inventory is compiled based on the specimens present in the *Societat d'Història Natural de les Balears* collections (col. Joan Cuerda, col. Andreu Muntaner, and col. Damià Vicens), the percentages will vary considerably. This is mainly because the poorest classes, such as Chondrichthyes, Actinopterygii, and Mammalia, are each represented by just one specimen.

The total number of specimens from the above-mentioned collections is of 1,269 individuals, and the percentage of molluscs (Bivalvia, Scaphopoda, and Gastropoda) is 94.3%. The marine vertebrate fossils are unusual in the Quaternary littoral deposits, being most of them fish teeth (Vicens & Gràcia, 1999; Vicens 2010).

2.3. Continental fossils

The Quaternary littoral-continental deposits basically consist of eolianites, reddish silts, and paleosols that mainly yield molluscs fossils (Figure 5). In particular, faunal differences can be found in each of the islands, but is the greatest between those from Gimmèsies (Mallorca, Menorca, and Cabrera) and Pitiüses islands (Eivissa and Formentera) (Gasull, 1966; Cuerda, 1975). It seems that extinctions have occurred in both groups of islands, probably during or before the Last Glacial period. The present malacological fauna of native molluscs would be the survivors of that stage (Pons & Palmer, 1996).

The nomenclature and the systematic position of continental molluscs remain controversial. In this light, the work of Beckmann (2007) is very useful as provides synonymies and descriptions of all current Balearic molluscs along with excellent photographs.

Among molluscs with significance for warm periods, *Rumina decollata* has been found in the Lower Pleistocene levels of the Balearics (Cuerda, 1975). Vicens & Pons (2011) questioned its presence because only one specimen was found at Cala Pudent within a Eutyrrhenian beach. Recently, another specimen was discovered in the Eutyrrhenian beach from Cala Murada. This fact signifies that *Rumina decollata* likely lived during the Last Interglacial period in Mallorca. In spite of intensive search conducted by Vicens & Pons (2007), this species has not been found in the most recent Upper Pleistocene deposits from Mallorca. Currently, it dwells in Mallorca as a consequence of its Holocene introduction by humans.

Chondrula gymnesica (Figure 5), known until recently as *Mastus pupa*, was part of the endemic malacological fauna of Mallorca and Menorca, but vanished during the Würm glaciation (Quintana, 2006). It has always been considered a warm climate species (see Cuerda, 1975), although it likely survived the Riss glaciation; otherwise it would be difficult to justify its presence in the Eutyrrhenian silts, unless it was a newcomer. This mollusc is mentioned by Vicens & Pons (2007) at Caloscamps at a level dated by Rose *et al.* (1999) as 62.8 ± 8.5 ka BP.

Oestophora cuerdaei is another extinct taxon that is only found as a fossil in the Upper Pleistocene of Mallorca (Quintana *et al.*, 2006).

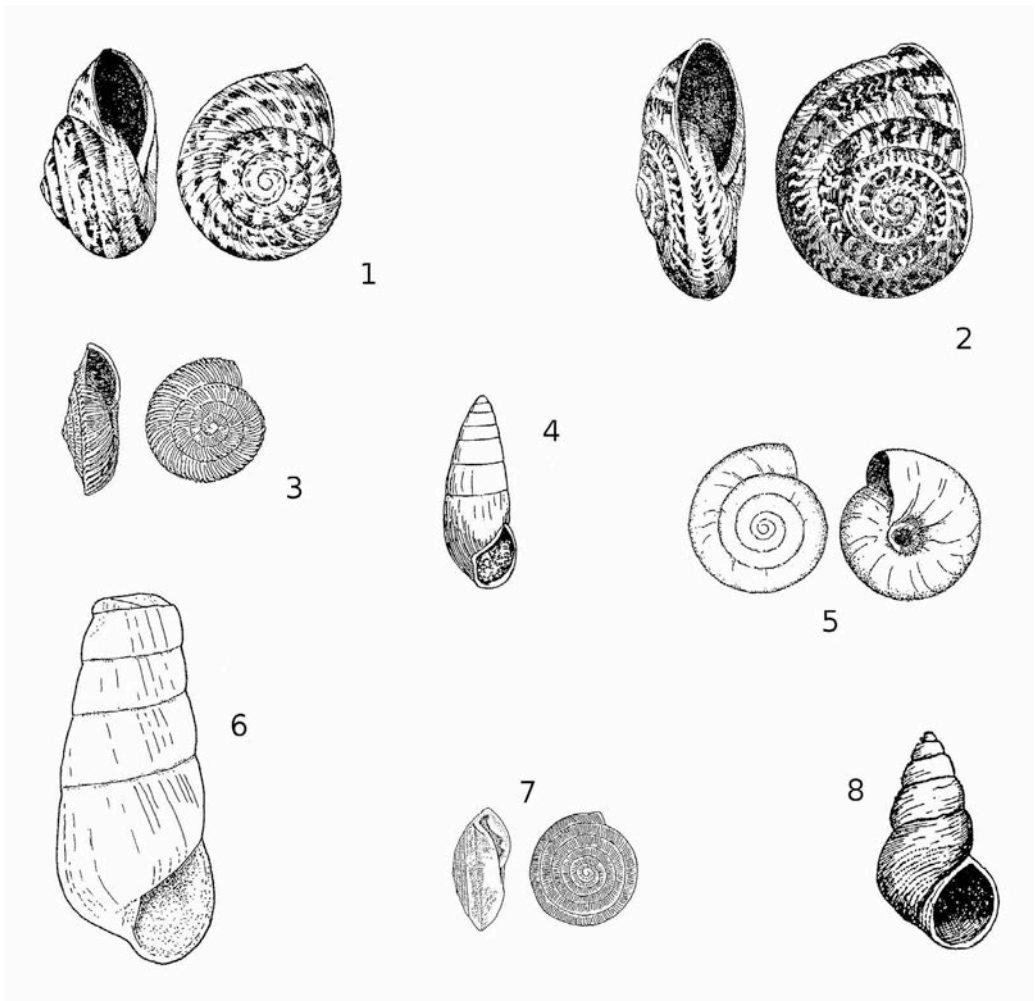


Figure 5. Continental molluscs from the Upper Pleistocene of Mallorca. Within brackets, the major axis length of each specimen is indicated. 1- *Iberellus companyonii* (20 mm). 2- *Iberellus balearicus* (25 mm). 3- *Xerocrassa frater* (11 mm). 4- *Chondrula gymnesica* (extinct) (16 mm). 5- *Oxychilus lentiformis* (11 mm). 6- *Rumina decollata* (35 mm). 7- *Oestophora cuerdae* (extinct) (9 mm). 8- *Tudorella ferruginea* (19 mm). Drawings 1, 2, 3, and 5 after Colom (1957), 4 and 8 after Colom (1987), and 6 and 7 by D. Vicens.

Apart from the former mentioned molluscs, in the Upper Pleistocene sediments of Mallorca *Iberellus* sp., *Tudorella ferruginea*, *Oxychilus lentiformis*, and *Xerocrassa frater* are commonly found; all of them are part of the current native fauna of Mallorca.

Throughout the Quaternary, in Mallorca and Menorca, an assemblage of vertebrates genus, such as *Myotragus*, *Hypnomys*, *Nesiotites* and *Podarcis*, yielded different endemic species (Alcover *et al.*, 1981). Most of the fossils belonging to these taxa are found in sedimentary traps, like some littoral caves (Soondar *et al.*, 1995; Bover, 2011). *Myotragus* tracks discovered on littoral eolianites are rather common (Fornós *et al.*, 2002). Remains of fossil birds like *Puffinus mauretanicus*, *Columba* sp. (Vicens *et al.*, 1998), and *Phalacrocorax aristotelis* (McMinn & Vicens, 2007) have also

been found in Upper Pleistocene littoral deposits. The former is an endemic marine bird from the Balearics, whereas the last one is a bird with large distribution range. The vertebrate sites different to those in caves are particularly scarce in the Balearics (Alcover & Bover, 2002).

Coprolites are highly interesting trace fossils found both outside and in caves (Alcover & Bover, 2002). Excluding the sites of karstic origin, Cuerda *et al.* (1969) and Servera *et al.* (2001) described them from subaerial outcrops but, however, it is highly possible they are not coprolites but nests of some sort of insects. The deposits between Cala Figuera and el Toro (Calvià) and the ones from Es Bancals and Vallgornera, formed by weathering of eolianites and red silts of assumed Pliocene or Lower Pleistocene age, contain a great deal of these nests (Vicens, 2010). They have also been identified in some Upper Pleistocene deposits from southern Mallorca (personal obs.).

To conclude this section, it should be said that deposits of pedo-diagenetic carbonate surrounding plant roots (rizhocretions) are abundant in the littoral eolianites; the taxa that generated them is unknown.

3. The Quaternary raised-beaches

Pomar & Cuerda (1979) counted 70 Pleistocene marine sites in the littoral of Mallorca, but a few years later Cuerda (1987) mentioned 75. This figure has constantly increased year after year as new sites were discovered and studied. Presently, based on our own data we estimate that in Mallorca are about 130 such locations. The vast majority of sites are from the Upper Pleistocene and only a few of them belong to the Middle or Lower Pleistocene. The coast of Serra de Tramuntana is very poor in Pleistocene marine deposits, probably owing to active uplift and intense erosion. Not all sites are exactly ancient beaches; many of them are fissure infillings, occasional accumulations of beach sands caused by storm events, lagoon deposits, etc.

3.1. Lower Pleistocene

Lower Pleistocene deposits have been found in southern Mallorca, at sites located on littoral cliffs. Cuerda & Sacarés (1970) studied an outcrop discovered at Vallgornera (+12 m ASL) and claimed it represents the Lower Pleistocene, possibly the Pliocene-Pleistocene boundary. Other younger locations compared to the previous one was discovered at Es Pas des Verro at +70 m, and at Can Xarpa at +50 m ASL, respectively (Butzer & Cuerda, 1962b).

3.2. Middle Pleistocene

References to the Middle Pleistocene fossil deposits are scarce in the island, and like the older horizons, the deposits are found in southern Mallorca. Marine erosion platforms and notches have been located at Punta de Sa Plana area, between +16 and +34 m ASL, with no marine fossils. Butzer & Cuerda (1962a) assigned the level located at +5 m ASL at Sa Torre de s'Estelella and another deposit at Es Bancals (+16 m ASL), where *Patella ferruginea* is abundant, to the Middle Pleistocene (Tyrrhenian I = Paleotyrrhenian). Besides, at the latter site, a level scarce in fossils exists at +22 m ASL (Cuerda & Sacarés, 1966).

3.3. Upper Pleistocene

In the Mediterranean region, the following terms have been used to refer to the Upper Pleistocene stages: Tyrrhenian II (Eutyrrhenian), Tyrrhenian III (Neotyrrhenian), and the Würm glaciation. The Neotyrrhenian was chronologically placed at the end of the Last Interglacial *sensu lato* (MIS 5) and just before the onset of the Würm glaciation (Cuerda, 1975, Pomar & Cuerda, 1979). This nomenclature has been in use in Mallorca until very recently (mainly the terms Eutyrrhenian and Neotyrrhenian). The relative chronology derived from these terms is somewhat useful because allows to distinguish between the sites containing the so-called "Senegalese" fauna (Eutyrrhenian) and those with impoverished thermophilous fauna (Neotyrrhenian). When correlating these periods with those defined as marine isotope stages, a consensus seems was reached for the Neotyrrhenian, which would correspond to the MIS 5a. The Eutyrrhenian period is much more controversial. For example, Cuerda (1975) located the early Eutyrrhenian within today's MIS 7 –based on Stearns & Thurber (1965) absolute datings– but overall, he considered the Eutyrrhenian positioned within the Upper Pleistocene. According to Ginés (2000) the Eutyrrhenian, as defined by Cuerda (1975), encompasses the MIS 7 and MIS 5e deposits.

The Eutyrrhenian sites are usually found between +2 and +5 m above the current sea level and yield, among other fossils, species that imply a warmer than present climate; these thermophilous species are not currently living in the Mediterranean Sea, but live today in the inter-tropical region of the Atlantic African coasts and nearby islands. The Neotyrrhenian localities are found at lower elevations, generally less than +3 m ASL, and show impoverished thermophilous fauna, lacking the majority of the so-called "Senegalese" species (Pomar & Cuerda, 1979).

Most of the sites are formed by cemented beach sands with pebbles and marine fossils. In many outcrops, a mixture of sands and silts of continental origin is present, fact that causes the matrix to be reddish in color (Cuerda, 1975). The sand of the fossil beaches is mainly bioclastic, similar to the present one in the Mallorcan beaches (Jaume & Fornós, 1992). Mallorca has about 120 Upper Pleistocene sites with marine fauna (personal obs.). Many of the deposits are found over paleosols or eolianites. The raised-beaches can be covered with paleosols, eolianites, other beach deposits, or sometimes with none.

Cuerda (1975) and Pomar & Cuerda (1979) pointed out the existence of early Eutyrrhenian fossil beaches at ~ +3 m ASL in the Palma Bay (Cala Pudent, Es Carnatge, etc.); more recent deposits are found at +7.5 m (S'Illot), +11 m (Torre de S'Estelella; see detailed discussion in the next section 4.2), and +13 m (Es Bancals), with ages of about 130 ka BP (the last two) according to former datings from Stearns & Thurber (1965), later questioned in Stearns (1985). The data provided by Cuerda, could indicate the existence of a transgressive maximum at +13 m ASL, about 130 ka BP (MIS 5e). This interpretation does not agree with the study of Hillaire-Marcel *et al.* (1996), which pointed out that the Eutyrrhenian deposits existing at Es Carnatge (located at +3 and +2 m ASL) have ages between 135 and 117 ka (MIS 5e) and 100 ka BP (MIS 5c), respectively. It seems likely that the elevations assumed by Cuerda (1975) for some Eutyrrhenian beaches of Mallorcan coasts, situated between +6 m and +13 m ASL, are

not confident (Ginés, 2000), perhaps owing to inconsistency of the absolute datings available on these deposits; moreover, they could have been affected by recent tectonic deformations.

The Neotyrrenian is present in Mallorca by means of deposits situated at elevations close to +2 m ASL. One of the most paradigmatic site is Es Carnatge, which can be correlated to the MIS 5a.

Around mid-Holocene the sea level reached a maximum, with some fossil beaches belonging to the Flandrian located up to +2 m ASL.

According to Morey & Cabanellas (2007-2008), approximately 33% of the Upper Pleistocene sites have disappeared as a consequence of anthropic impacts. In another paper, Morey (2008) states that half of the known sites are in bad preservation conditions or have already disappeared. Unfortunately, these percentages reflect a number of fundamental mistakes that were made when the conservation of the sites was checked. In our view, the estimated percentage of disappeared sites is much lower than the one established by these authors. Morey (2008) in his paper, evaluated the Upper Pleistocene Mallorcan deposits, based on different aspects (status of the investigations, conservation of the deposits, etc.). On the other hand, his inventory list includes sites that have never been studied from a paleontological point of view; this fact, along with other mistakes existing in his table of checked sites, make us question its reliability.

4. Main Quaternary marine sites from Mallorca

Throughout this section, few of the most relevant raised-beaches in Mallorca Island (Figure 6) will be described, emphasizing on their stratigraphy, paleontological records, as well as the chronology of each deposit.

4.1. Cala Pudent - Es Carnatge

Without a doubt, internationally, the most well-known sites on the island are those from Cala Pudent and Es Carnatge –both located in Palma Bay– also referred as "Campo de Tiro" in many of the previous papers. This last toponym, introduced by Joan Cuerda and Andreu Muntaner, relates to a military area dedicated to gunshot training. The first author to publish a stratigraphy of these marine sites was Muntaner (1957) whereas the paleontological study was conducted by Cuerda (1957).

The Cala Pudent site shows two superposed Eutyrrhenian (MIS 5e) raised-beaches with thermophilous "Senegalese" fauna, observable exclusively at the western part of the small bay (Figure 7C); at its eastern part, only one Eutyrrhenian fossil beach is recognized (Cuerda, 1979). At its base, the deposit starts with Riss eolianites (MIS 6) showing a marine erosion platform developed on it. The eolianite are covered by reddish to yellowish paleosols with terrestrial mollusca, including the extinct species *Chondrula gymnesica*. Cuerda (1979) presents a faunal list corresponding to the raised-beach from the eastern part of the bight, which is correlated to the more ancient beach occurring in its western part. There is a large number of fossils cited from this site,

among which the most characteristic are: *Barbatia plicata*, *Hyotissa hyotis*, *Cardita senegalensis*, *Patella ferruginea*, *Monodonta lineata*, *Strombus bubonius*, *Polinices lacteus*, *Cymatium costatum*, *Bursa scrobiculata*, *Cantharus viverratus*, and *Conus testudinarius*. Stearns & Thurber (1965) reported U/Th ages of ~200 ka BP for these deposits; but in a later paper (Stearns, 1985) these ages were questioned. The exact location (which of the two beaches) where the authors collected their samples is furthermore unknown.

The site of Es Carnatge (Figure 7A) is located 170 m to the SSE from Cala Pudent. Cuerda (1975) describes four different levels with marine fauna. According to Zazo *et al.* (2003), the four marine units are separated by reddish continental deposits or by erosive surfaces, extending between the present-day sea level and +3 m. The lower two levels (units 1 and 2) contain the oldest fossils and were correlated with the Eutyrrhenian levels from Cala Pudent. They consist of beach-rock deposits with thermophilous fauna including the characteristic *Strombus bubonius*. The unit 3, composed of rock blocks from the lower units (mean diameter between 0.5 and 1 m) along with rounded clasts embedded within a clayey-silty matrix of a red coloration, overlies an erosion surface that cut across units 1 and 2. According to Cuerda (1975), *Cantharus viverratus* and *Conus testudinarius* were recovered from unit 3. The most recent marine deposit, the unit 4, is represented by beach-rock conglomerates and covers an erosion surface affecting unit 3 (Zazo *et al.*, 2003). From unit 4, Cuerda (1975)

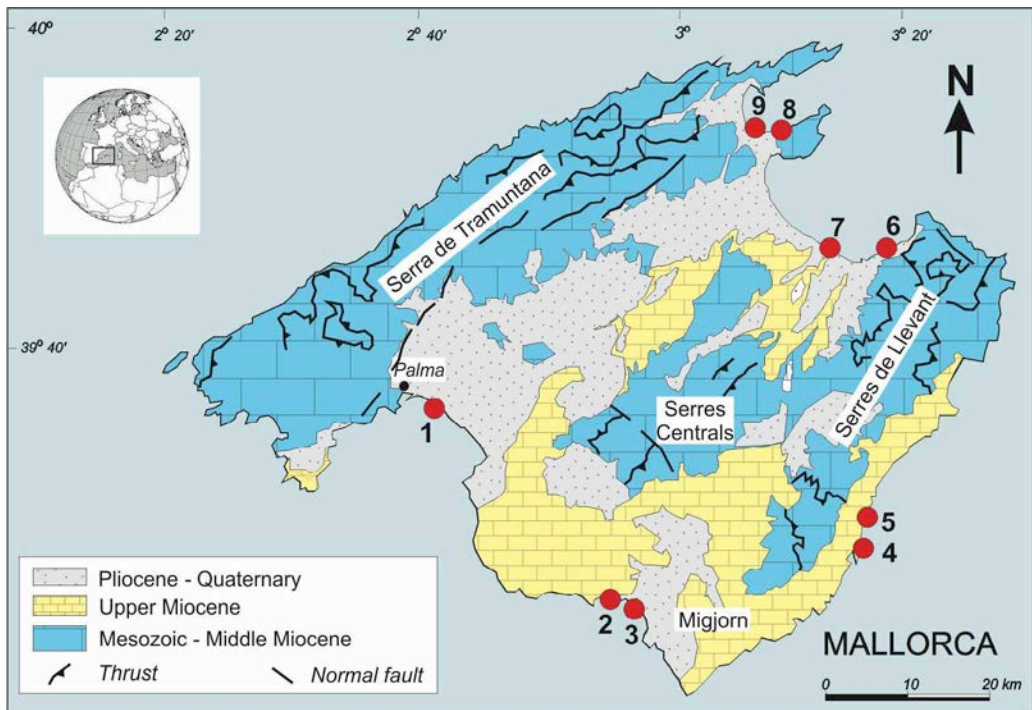


Figure 6. Locations referred throughout the text. 1- Cala Pudent-Es Carnatge (also known as "Campo de Tiro" in most publications). 2- S'Estelella. 3- Rentador de ses Egos. 4- Sa Tanca de sa Torre II. 5- Cala Murada. 6- Caloscamps. 7- Torrent de Son Real. 8- Platja de la Font de Sant Joan. 9- Sa Marina.

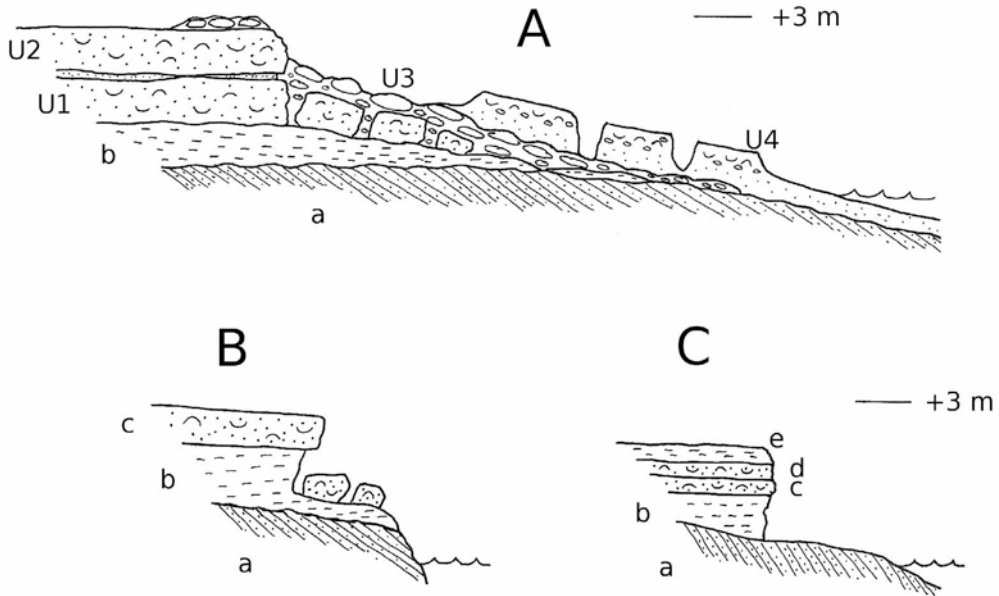


Figure 7. A- Es Carnatge: a- Riss dune (MIS 6). b- Reddish-yellow silts with *Chondrula gymnesica*. U1- Beach with Senegalese species (MIS 5e). U2- Beach with Senegalese species (MIS 5e). U3- Displaced blocks of lower levels cemented altogether (MIS 5a?). U4- Fine beach sands which pass upwards into coarse sands and gravels (MIS 5a?). B- Cala Pudent (East) according to Cuerda (1979): a- Riss dune (MIS 6). b- Reddish-yellow silts with *Chondrula gymnesica*. c- Beach with Senegalese species (MIS 5e). C- Cala Pudent (West) according to Cuerda (1979): a- Riss dune (MIS 6). b- Reddish-yellow silts with *Chondrula gymnesica*. c- Beach with Senegalese species (MIS 5e). d- Beach with Senegalese species (MIS 5e). e- Reddish-yellow silts.

reports the presence of *Barbatia plicata*, *Cantharus viverratus* (only fragments), and *Conus testudinarius*. The author emphasizes important differences concerning the paleontological content of units 3 and 4 when compared with units 1 and 2. The abundant thermophilous fauna characterizing units 1 and 2, is not fully represented in the upper 3 and 4 units. These differences apply to some sedimentological aspects of the discussed levels as well.

Stearns & Thurber (1965) obtained U/Th ages of 75 ka BP for samples collected within unit 3. Hearty (1987) attributes the deposits of Es Carnatge to the amino-zone E, corresponding to MIS 5e, and suggests that probably the deposits from unit 3 are younger (MIS 5c or 5a). This author identifies only three marine units, which correspond to units 1, 2, and 3 after Zazo *et al.* (2003). Based on Hearty's drawings, in our opinion, these levels are related, however, to units 1, 2, and 4 of Zazo *et al.* (2003).

Hillaire-Marcel *et al.* (1996) performed U/Th TIMS datings on molluscs shells from all four units. The data suggest an age of 135 ka BP in the case of unit 1; units 2 and 3 yielded ages of 117 ka BP; for unit 4 ages cluster around 100 ka BP. These chronological data point towards an interpretation that correlates the oldest three units with two sea-

level high-stands occurred during MIS 5e; however, the stratigraphic, sedimentological, and faunistic data suggest the existence of even a third high sea stand within the MIS 5e. The unit 4 represents a well-defined high-stand that reasonably correlates with MIS 5a (Zazo *et al.*, 2003). Bardají *et al.* (2009) also discuss this location so important for the Western Mediterranean region.

Although the ages reported for units 2 and 3 are the same (117 ka BP), in our opinion is very probable that unit 3 contains reworked fossils coming from the lower two units, since unit 3 erosionally cuts these older levels. This could be a possible explanation for the MIS 5e age obtained for the third unit.

Within the current state of the knowledge on this site, and considering valid the eustatic curve of Tuccimei *et al.* (2006), it seems the most feasible interpretation to consider the units 1 and 2 as corresponding to MIS 5e and units 3 and 4 belonging to MIS 5a.

4.2. S'Estelella

Butzer & Cuerda (1960) are the first authors to report at S'Estelella, in southern Mallorca, an Upper Pleistocene marine level at +10.5 m ASL, based on its paleontological content. According to their study, over the Riss eolian complex, 30 cm of consolidated fine sands are observed up to a maximum elevation of +10.5 m ASL, along with red silts, sharp clasts and fossils. They proposed a chronology that corresponds to the early Eutyrrhenian (Tyrrhenian II). Butzer & Cuerda (1962a) revised their study and added a much more accurate stratigraphic profile compared to their initial description of the site (Figure 8B). The following species described by Cuerda (1975) from this level have stratigraphic significance: *Barbatia plicata*, *Brachidontes senegalensis*, *Hyotissa hyotis*, *Strombus bubonius*, *Cymatium costatum*, *Cantharus viverratus*, *Mitra fusca*, and *Conus testudinarius*. Stearns & Thurber (1965) dated this level, by means of the U/Th method, using samples collected by Cuerda; the obtained age was 135 ka \pm 10 ka BP.

Zazo *et al.* (2003) suggest that the unusual high elevation of this deposit might have been affected by recent tectonic movements. These authors believe that units 1, 2, and 3 from Es Carnatge (referred in the original paper as "Campo de Tiro") located at elevations of +3, +1.5, and +1 m ASL, respectively, are represented at S'Estelella at higher altitudes. Hearty (1987) considers that the presence of marine specimens at this high elevation could be explained by strong storm events with high waves. If the sedimentological characteristics of the deposit at +10.5 m ASL are taken into account, one can observe marine sands mixed with continental silts, hence, these deposits cannot be considered genuine beach formations. Although tectonics cannot be completely ruled out, Hearty's suggestion seems more feasible. In this respect, 2.3 km to the west of this location, an Upper Pleistocene marine deposit has been found –at an elevation of +2 m ASL– at the base of a 20 m high coastal cliff (personal obs.); this finding argues for a tectonic stability of the area, at least since the Upper Pleistocene.

(Butzer & Cuerda (1962b) described another Eutyrrhenian deposit at +4.5 m ASL. The marine materials represented by beach sands, are overlying reddish-yellowish sandy-silty deposits (Figure 8C). The thermophilous fauna described by Ginard *et al.*

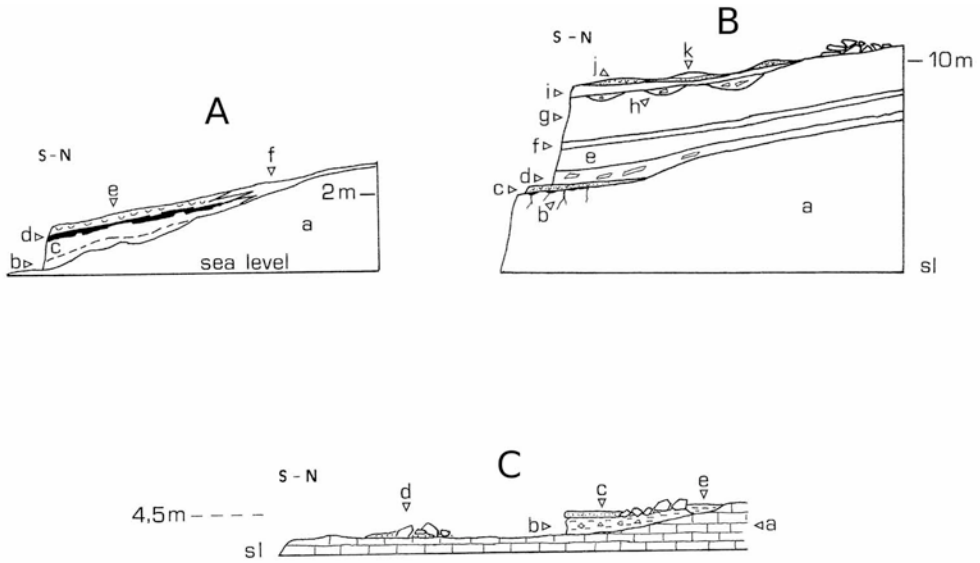


Figure 8. Stratigraphy of selected Upper Pleistocene marine deposits. A- Rentador de ses Egos (in the original paper cited as "Punta de Son Bieló") according to Butzer & Cuerda (1962a): a- Miocene limestones. b- Colluvial silts. c- Colluvial silts. d- Beach rock. e- Fossiliferous marine sand. f- Terrestrial silts. B- Torre de s'Estelella, level +10.5m ASL (Butzer & Cuerda, 1962a): a- Miocene calcarenite. b- Terra rossa soil in situ. c- Tyrrhenian I beach. d- Silt and colluvium. e- Eolianite. f- Silt and colluvium. g- Eolianite. h- Silt and colluvium. i- Eolianite. j- Eutyrrhenian (Tyrrhenian II) beach containing *Strombus bubonius*. k- Terrestrial silts. C- Torre de s'Estelella, level +3m/+4.5m ASL (Cuerda, 1975): a- Miocene calcarenite. b- Breccia with silts. c- Late Eutyrrhenian marine sediments. d- Cemented blocks with sandy silts and marine fossils. e- Würmian silts.

(2008) from this marine layer consist of: *Barbatia plicata*, *Hyotissa hyotis*, *Strombus bubonius*, *Bursa scrobiculator*, *Cantharus viverratus*, and *Conus testudinarius*.

Later on, Cuerda (1975) reported yet another Quaternary deposit located between the coastline and the one situated at +4.5 m ASL. In this case, sandy and silty materials are cementing a set of rocks disposed parallel to the coast, at an elevation of +3 m ASL (Figure 8C). *Patella ferruginea* was the only fossil bioindicator found in this deposit. Taking into account its elevation and the scarce presence of thermophilous species, the deposit was assigned to the end of Eutyrrhenian stage, thus, younger than the two other higher levels. More recently, Cuerda & Sacarés (1992) proposed a Neotyrrhenian age for this deposit. Also assigned to Neotyrrhenian is the presence of *P. ferruginea* in this site (Cuerda, 1987). However, in the very same study, when referring to *Conus mediterraneus* var. *vayssieri* (within the same deposit) the authors proposed an Eutyrrhenian age. It is evident from the above discussion that there is much confusion concerning the chronology of the lowest deposit.

Obviously, the very few bioindicator taxa had a crucial impact in separating this level from the one at +4.5 m ASL, which abounds in thermophilous taxa. Reviewing

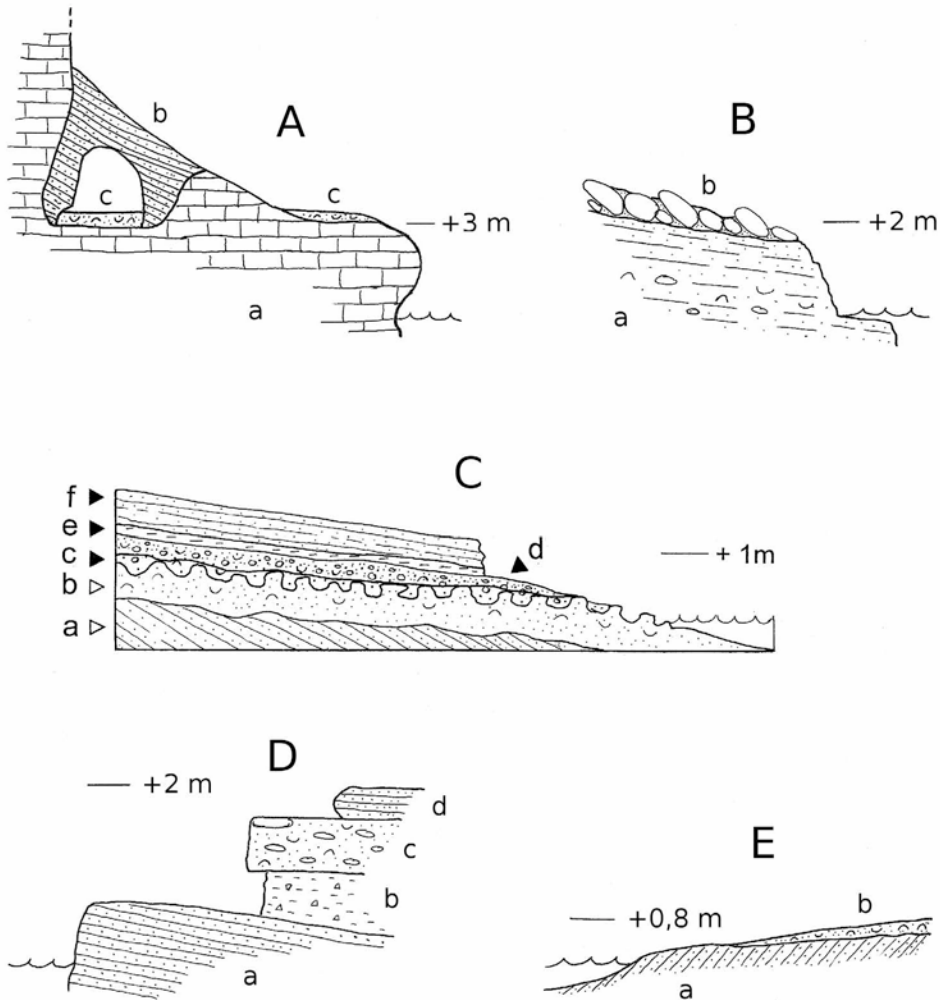


Figure 9. Upper Pleistocene marine sites from Mallorca. A- Sa Tanca de sa Torre II (Cuerda *et al.*, 1989-90): a- Miocene calcarenite. b- Eolianite. c- Beach with marine species (MIS 5a). B- Cala Murada: a- Beach with Senegalese species (MIS 5e). b- Cemented blocks with silts and terrestrial fossils. C- Torrent de Son Real (Vicens, 2010): a- Riss dune (MIS 6). b- Beach with Senegalese species (MIS 5e). c- Sandy silts with Senegalese species (MIS 5e). d- Beach with marine species (MIS 5a). e- Terrestrial silts. f- Eolianite. D- Platja de la Font de Sant Joan (Vicens, 2008): a- Riss dune (MIS 6). b- Reddish silts. c- Beach with Senegalese species (MIS 5e). d- Eolianite. E- Sa Marina according to Vicens (2008): a- Riss dune (MIS 6). b- Beach with marine species (MIS 5a).

the Vicens-SHNB collection, two additional bioindicator species have been found: *Cantharus viverratus* and *Bursa scrobiculator*. According to Cuerda (1987), the latter species has been reported in the Balearics exclusively from Eutyrrhenian deposits. Thus, the +3 m level hosts four bioindicator taxa. Taking into consideration its geomorphological context and its faunal content, we propose an Eutyrrhenian age (MIS 5e) for this lower deposit (personal obs.).

4.3. Rentador de ses Egos

Rentador de ses Egos, also referred as Punta de Son Bieló by Butzer & Cuerda (1960, 1962a), is a site located at a maximum elevation of +2 m ASL in southern Mallorca (Figure 8A). It comprises a unique, thin, marine level with abundant fossils. Although 38 different taxa from this location were cited by Butzer & Cuerda (1960) and Ginard *et al.* (2008), none of them reported the presence of any thermophilous species or even fragments. For this reason, and also considering the stratigraphic and geomorphological context, Butzer & Cuerda (1960) attributed this site to Neotyrrenian (Tyrrenian III), a chronology that is fully supported by Ginard *et al.* (2008) and Vicens *et al.* (2011) studies.

4.4. Sa Tanca de sa Torre II

This location was described and studied by Cuerda *et al.* (1989-1990), showing a unique marine deposit, located over a littoral erosion platform that develops at +3 m ASL (Figure 9A) in the eastern coast of the island. A total amount of 1,003 specimens were determined, including 3 valves of *Barbatia plicata* and 2 fragments of *Cantharus viverratus*. According to the fauna present in this site, the authors placed the deposit within the Neotyrrenian (MIS 5a).

4.5. Cala Murada

Cala Murada is a site that contains a Quaternary deposit, first mentioned by Pomar & Cuerda (1979) but not yet described. Morey & Cabanelles (2007-2008) and Morey (2008) mistakenly stated that this locality is today totally destroyed.

In this location there is only a marine level characterized by the presence of a raised-beach deposit (Figure 9B) containing the "Senegalese" species *Strombus bubonius*. Within this outcrop, the terrestrial gastropod *Rumina decollata* has been collected. It is a thermophilous mollusc never documented in more recent sediments from the Upper Pleistocene of Mallorca. Based on its faunal content, the deposit belongs to Eutyrrhenian. Above the marine sediments there are reddish silts, from which the terrestrial gastropod *Chondrula gymnesica* has been recovered. The contact between these sediments and the lower marine layer is erosional. It is difficult to propose a chronology for this upper level, but according to its stratigraphic position may correspond to the Neotyrrenian (MIS 5a)

4.6. Caloscamps

Located in the eastern part of the Alcúdia Bay, Caloscamps site is without a doubt the most studied locality in that area, being first investigated by Cuerda & Galiana (1976). There are two marine units. The oldest level lies over the Riss eolianites, and is represented by a wide marine erosional platform located +0.5/+1 m ASL (Figures 10 and 11). This horizon consists of well-cemented clasts, sands, and silts, including thermophilous fauna such as *Barbatia plicata*, *Brachidontes senegalensis*, *Cardita senegalensis*, *Cantharus viverratus*, and *Conus testudinarius*. Chronologically, this layer corresponds to the Eutyrrhenian. The upper level, a mixture of sands, reddish silts, and abundant marine fauna, appears to be an erosional deposition of materials over

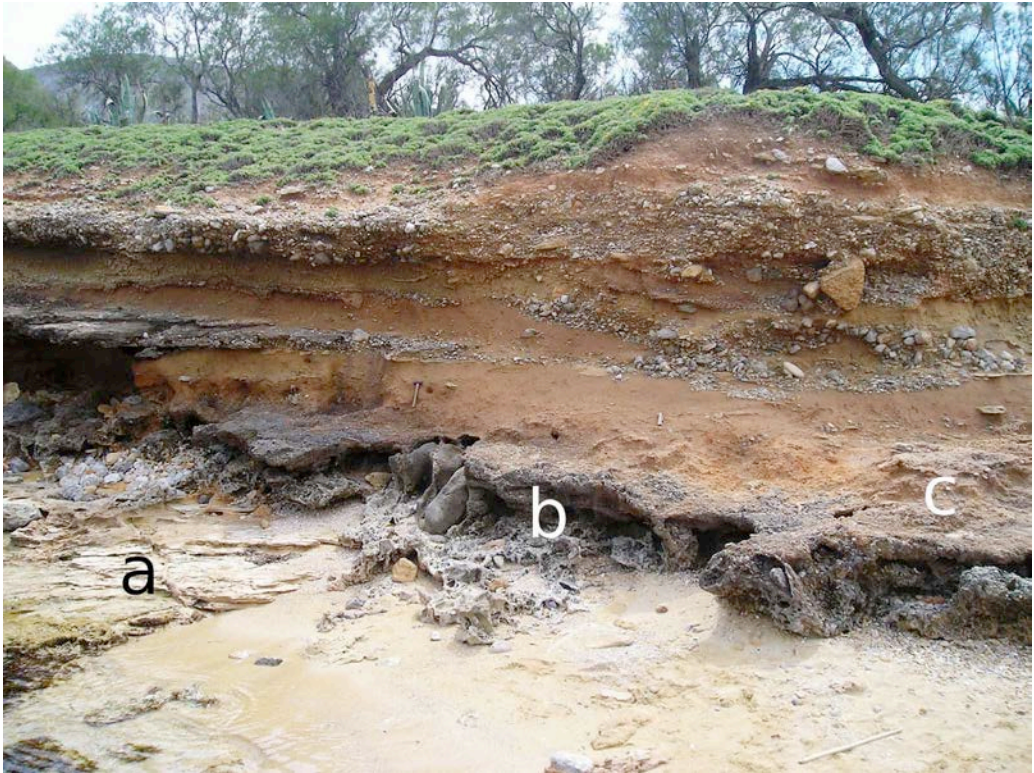


Figure 10. Caloscamps: a- Calcarenites (MIS 6). b- Beach with Senegalese species (MIS 5e) c- Sandy silts with marine species (MIS 5a).

the lower unit. No thermophilous fauna has been recovered from this level; therefore, Cuerda & Galiana (1976) placed the upper level to the end of the Eutyrrhenian stage.

The horizons existing over the marine units have significant lateral variation, which lead to different stratigraphic profiles even in very close locations; this fact is shown in Figure 10.

Rose *et al.* (1999) studied and dated three stratigraphic columns from this location. In the light of their age data, the lower eolianite unit corresponds to MIS 6. Above it, the ages cover the time interval from MIS 5e to MIS 1. Using the data from Rose *et al.* (1999) and taking into account the lack of thermophilous species, Vicens *et al.* (2001) consider that the upper marine unit (level "c" from Cuerda & Galiana, 1976) was deposited during MIS 5a.

Unlike Cala Pudent site, the silty level existing between the Riss eolianite and the Eutyrrhenian unit is not visible at this locality.

4.7. Torrent de Son Real

Torrent de Son Real was initially investigated by Cuerda *et al.* (1991), who supplied the first stratigraphic interpretation, later modified by Vicens (2010). It is located at the mouth of an important torrential stream ending in the Alcúdia Bay. Three superposed

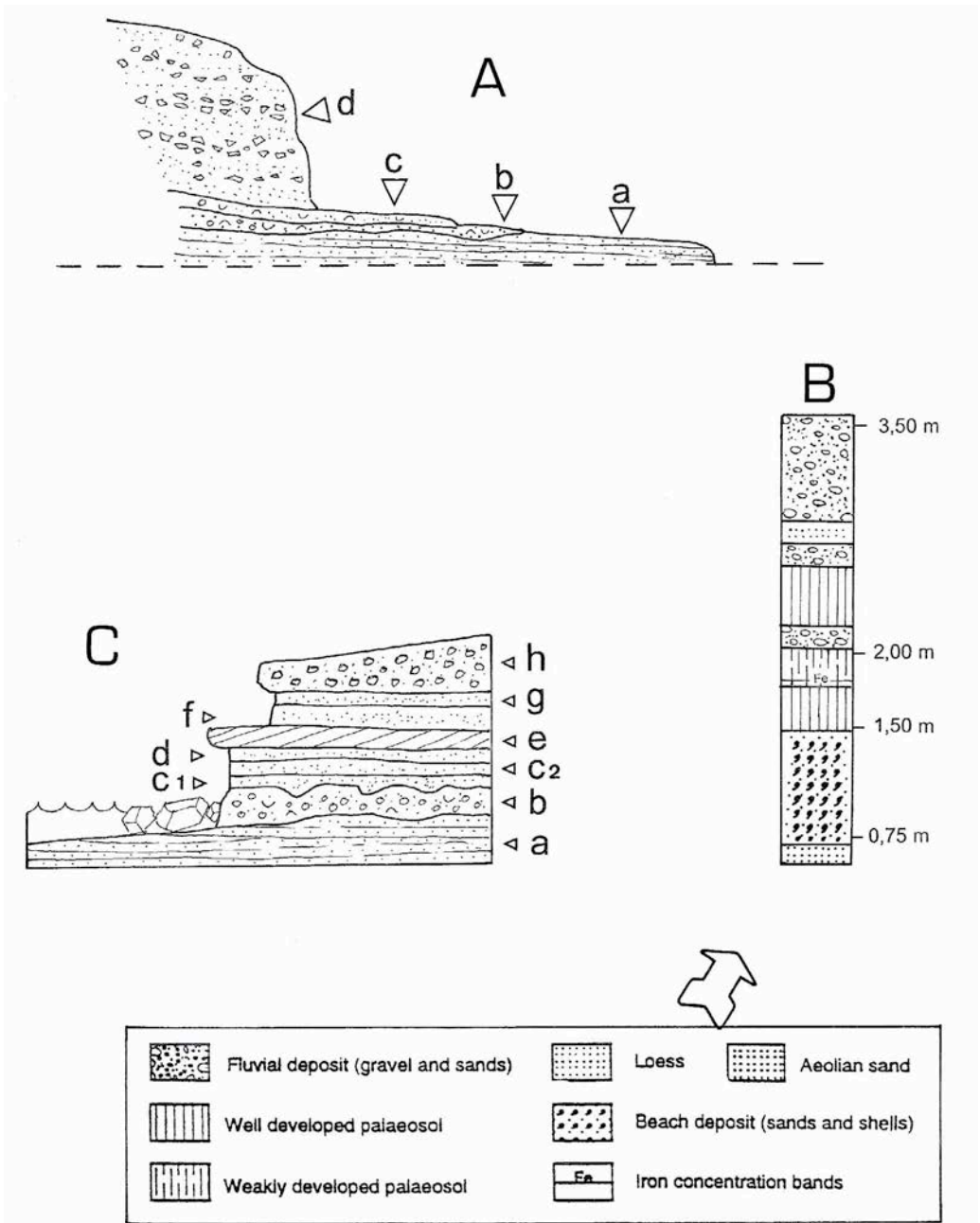


Figure 11. Some stratigraphic profiles of Caloscamps site. A- According to Cuerda & Galiana (1976): a- Basal Quaternary dune. b- Beach rock with Eutyrrhenian marine fauna. c- Sandy silts with marine fauna. d- Alluvial sediments composed by detritic elements together with silty layers containing *Chondrula gymnesica*. B- Profile B, according to Rose *et al.* (1999); the legend is in the lower part of the figure. C- Profile N-S, according to Vicens & Pons (2007): a- Eolianite (MIS 6). b- Beach deposit with marine fossils (MIS 5e). c1- Reddish silts with marine fossils (MIS 5a). c2- Reddish silts. d- Reddish silts. e- Eolianite. f- Reddish silts. g- Green-olive silts (MIS 3). h- Breccia.

marine levels can be distinguished in this outcrop (Figures 9C and 12). The oldest marine level consists of well-cemented marine sands, erosionally emplaced over a presumed Riss eolianite unit. The marine unit contains thermophilous fauna, such as *Cantharus viverratus* and *Conus testudinarius*. Above the lower level, there is another unit formed by sandy-silty deposits with marine fossils and some centimetric size pebbles; the marine fauna include thermophilous species like: *Barbatia plicata*, *Cardita senegalensis*, *Strombus bubonius*, *Cantharus viverratus*, *Conus testudinarius*, *Cymatium costatum*, and *Bursa scrobiculator*. The contact with the first level is clearly erosional. These two units are interpreted to belong to the Eutyrrhenian according to their stratigraphic, geomorphological context, and faunal content. The upper level consists of coarse marine sands, with reddish silts and centimeter-size pebbles. All taxa present in the upper unit are currently living in the Mediterranean Sea, with the only exception of a fragment of *Strombus bubonius* that Vicens (2010) interpreted as a reworked fossil coming from some of the lower levels; for this reason, the upper unit is considered Neotyrrhenian (MIS 5a).

4.8. Platja de la Font de Sant Joan

This Pleistocene site –located at Pollença Bay – is comparable to that of Cala Pudent, or even more to the Ses Covetes site described by González *et al.* (2001). The differences between Platja de la Font de Sant Joan and the two others are as follows: 1) a marine erosion platform over the Riss eolianite is not clearly visible, 2) there are no



Figure 12. Torrent de Son Real. Beach rock with marine species (MIS 5a).

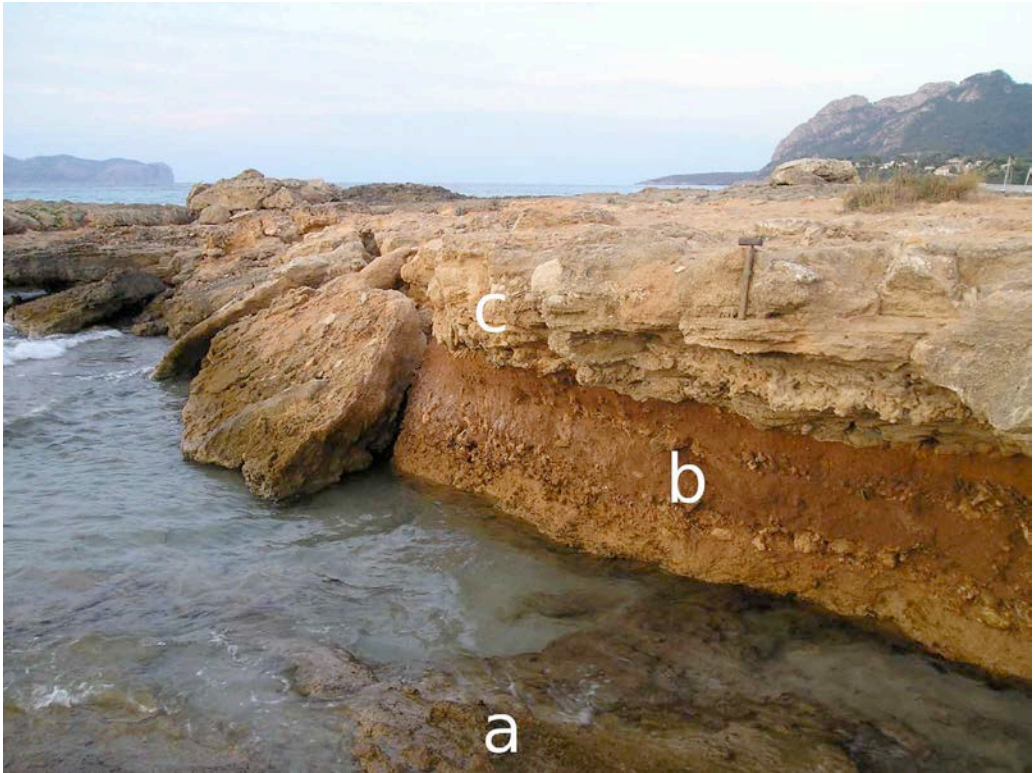


Figure 13. Platja de la Font de Sant Joan: a- Riss dune (MIS 6). b- Reddish silts. c- Beach with Senegalese species (MIS 5e).

terrestrial molluscs in the reddish silts existing below the raised-beach deposit, and finally, 3) over the Eutyrrhenian beach there are eolianite deposits instead of yellowish-reddish silts. Among the fossils collected, Cuerda *et al.* (1983) mentioned: *Barbatia plicata*, *Cardita senegalensis*, *Strombus bubonius*, and *Cymatium costatum*. The presence of *Cardita senegalensis* and *Strombus bubonius* (typical "Senegalese" fauna), denote that these deposits are from the Eutyrrhenian (MIS 5e). Moreover, *Barbatia plicata* and *Cymatium costatum* also have a clear chrono-stratigraphic significance. The same authors consider that above this beach there is another one of Neotyrrhenian age (MIS 5a). Contrary to this hypothesis, Vicens (2010) considers highly possible that in fact only one beach deposit exists (Figures 9D and 13).

Curiously, in the Canary Islands a reddish paleosol is also present beneath the beach deposits with *Strombus* corresponding to the Last Interglacial (Meco *et al.*, 2007).

4.9. Sa Marina

Sa Marina is located in the Pollença Bay and is mentioned in Vicens (2008, 2010) studies as Sa Marina-1 site. At the end of the 80s, some remnants of continental reddish silts with fossil molluscs still existed between the coastline and the first line of houses. Today, this site completely disappeared. At this location it used to be a single marine level, of modest thickness (Figure 9E), made of indurated silts with marine fossils emplaced over an eolianite unit, presumably of Riss age.

The recovered fauna includes 38 taxa, none of them being thermophilous species. Based on the malacological data, Vicens (2008, 2010) placed it in MIS 5a, which could be stratigraphically correlated with some nearby outcrops at Corral d'en Bennàssar and Sa Marina-2.

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Pleistocene eolianites and low sea levels

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1. Introduction

Eolianites are lithified eolian deposits most commonly preserved in the form of eolian limestones; they formed on the coastal and lowland areas of islands around the world between 55°N and 45°S, where relatively constant winds and warm weather occur. They are usually related to subtropical marine platforms or tropical (Tucker & Wright, 1990) or temperate (James & Clarke, 1997) areas with abundant carbonate production. Notable outcrops occur in the Mediterranean, South Africa, southern Australia, and Caribbean areas (Brooke, 2001).

Eolianites form at low latitudes in both hemispheres and are a distinctive feature of the Pleistocene sedimentary record (Abegg, *et al.*, 2001; Brooke, 2001; Fornós *et al.*, 2002a; Nielsen *et al.*, 2004; Radies *et al.*, 2004; Sivan & Porat, 2004; Munyikwa, 2005; Andreucci *et al.*, 2006; Andreucci *et al.*, 2010a). The record preserved in eolian deposits can be accurately dated (Price *et al.*, 2001; Frenchen *et al.*, 2004) and can be used to evaluate the complex relationships with other deposits including marine terraces, alluvial and colluvial deposits and/or paleosols to obtain important paleoclimatic information, including sea level oscillations and landscape evolution (Kindler *et al.*, 1997; Carew & Mylroie, 2001; Kindler & Mazzolini, 2001; Rose *et al.*, 1999; Preusser *et al.*, 2002; Coltari *et al.*, 2010; Elmejdoub *et al.*, 2011).

In the western Mediterranean the Pliocene-Pleistocene successions including eolianites are widespread in many coastal areas (Andreucci *et al.*, 2010b; Gutiérrez-Elorza *et al.*, 2002; Nielsen *et al.*, 2004; Fornós *et al.*, 2009; El-Asmar, 1994). Middle to Late Pleistocene coastal carbonate successions where marine beach deposits alternate with eolianites and paleosols and/or colluvial deposits are also widely distributed in the Mediterranean area (Hearty, 1987; El-Asmar, 1994). The quick lithification of these carbonate eolianites upon subaerial exposure preserves a high-resolution stratigraphic record. In this sense, eolianite successions that outcrop extensively all around the

island of Sardinia, which have been recently dated by modern techniques (Andreucci *et al.*, 2006, 2009, 2010b; Thiel *et al.*, 2010), are especially important.

The island of Mallorca (Balearic archipelago) located in the middle of the western Mediterranean (Figure 1) represents a classic area for the study of the Pleistocene deposits (including eolianites as well as marine terraces) and their relationship with climate and sea level change history (Butzer & Cuerda, 1962; Butzer, 1975; Cuerda, 1975; Hillaire-Marcel *et al.*, 1996, Hearty, 1987; Clemmensen *et al.*, 1997; Rose *et al.*, 1999; Clemmensen *et al.*, 2001; Fornós *et al.*, 2009). The Middle and Late Pleistocene Camp de Tir deposits contain the most extensive marine record (Bardají *et al.*, 2009) and host the type locality for Tyrrhenian marine deposits (i.e. *Strombus bubonius*-bearing) in the Balearics (Hearty *et al.*, 1986; Cuerda, 1989; Goy *et al.*, 1997; Zazo *et al.*, 2003). Most of these deposits rest on Miocene limestones (Pomar *et al.*, 1985) and, although they appear all around the coasts of Mallorca, they are particularly well-exposed in the southern part of the island.

This paper is a review and deal with the Pleistocene sedimentary record of Mallorca in the context of the geological setting of the island. We will describe the characteristics of the sedimentary facies, mainly the eolianites, their petrology, vertebrate tracks, trackways, and rhizocretions. We will focus on the description of the Late Pleistocene eolian sequences, their architecture and characteristics. Finally, the paleoclimatic and sea-level oscillation implications during the Middle and the late Pleistocene are discussed.

2. Geological and environmental setting

Mallorca, the largest island of the Balearic archipelago, is located in the temperate climate area of the middle of western Mediterranean Sea. This archipelago corresponds to the eastern emergent part of the so-called Balearic Promontory, a mostly submarine

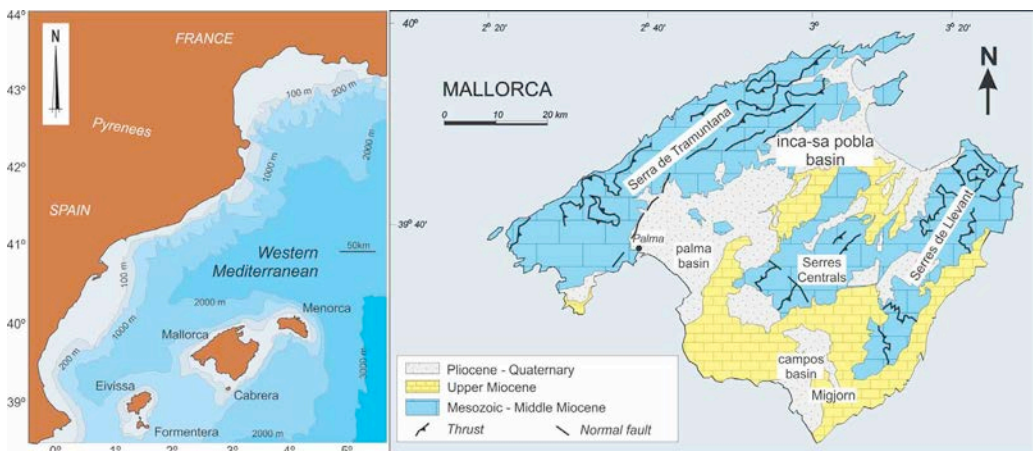


Figure 1. Location of Mallorca in the Western Mediterranean and geological sketch map showing main structural and stratigraphical elements.

relief extending from the Iberian Peninsula to Menorca, the north-eastern most island of the archipelago. It represents the thickened continental crustal unit forming the NE continuation of the Alpine Betic thrust and fold belt build during the Middle Miocene (Gelabert *et al.*, 1992), that resulted from the continental collision between the African and the Iberian plates. The normal faulting that affected Mallorca during the Middle Miocene-Pleistocene times gave way to a set of horsts (ranges) and grabens (plains) that characterized the present-day physiographic appearance of the island.

The stratigraphic record ranges from the Carboniferous to the Quaternary, with the common feature being carbonate deposits. Mainly Mesozoic to Paleogene deformed deposits crop out in the resultant structured relief of the ranges (Serra de Tramuntana and Serres de Llevant), while post-orogenic sediments cover the Neogene basins (Fornós & Gelabert, 1995). These depressed areas are filled with a thick sequence of Plio-Pleistocene deposits (Figure 1).

These Plio-Pleistocene deposits range from continental sediments (conglomerates, sands and red silts) related to erosional processes of the highest mountain ranges of the island, to calcareous and fossiliferous sands that correspond to beach and dune deposits of coastal environments that reflect the Pleistocene sea-level oscillations.

The most important Quaternary deposits in Mallorca are located in the northern bays of Alcúdia and Pollença on the north-eastern coast, the Palma bay in the south-western coast, and Campos bay in the south. Modern deposits are characterized by a beach-dune-lagoon system extending a variable distance along the coastline, flanked by folded Jurassic and Cretaceous limestones (Figure 2). Pleistocene marine, colluvial, fluvial and eolian deposits of variable thickness cover most of these outcrops. Holocene and recent coastal dunes in the lowlands have been stabilized by shrub vegetation. The presence of notches and littoral platforms, understood as marks corresponding to the high-stand sea levels, are conspicuous features in the southern and eastern parts of Mallorca, shaping rock coasts developed on Upper Miocene calcarenite deposits.

The climate of the island is typical of the Mediterranean, with very hot, dry summers and mild, wet winters. The mean temperature is roughly 17°C, with mean winter and summer values of 10 and 25°C, respectively. The mean annual precipitation is about 500 mm and is mostly concentrated in autumn (Guijarro, 1986).

The wind regime in the northern bays is characterized by westerly and northerly winds (annual frequencies of winds over 4 m/s are 27% and 17% respectively) (Servera, 1997). The island's location is very favorable to the development of sea breezes (Ramis *et al.*, 1990); these are very often present from April to November, and occur almost every day during the summer. Wind velocities associated with sea breezes are generally approximately 3 m/s, but velocities as high as 10 m/s are not uncommon (Ramis, 1998).

Two clear Mediterranean community types form the characteristic vegetation: holm oaks, *Cyclamini-Quercetum ilicis*, with boreal characteristics abundant at the mid-altitudes and macchia and garrigue bushes *Oleo-Ceratonion*, *Hypericion balearici*, *Rosmarino-Ericion* mainly in the dry lowlands (Bolòs, 1996).

3. The Pleistocene sedimentary record of Mallorca

The work of Butzer and Cuerda (1962) started the comprehensive scientific study of Pleistocene deposits in Mallorca. Pleistocene sedimentary deposits, outcropping patchily along the majority of Mallorca's coastline, provide an unsurpassed record of glacial and interglacial climate, atmospheric circulation patterns and eustatic sea levels. Since then, this Pleistocene record has been thoroughly described and discussed in the literature, establishing Mallorca as one of the classic localities in the study of the marine Pleistocene in the western Mediterranean basin (Bardají *et al.*, 2009).

The existing literature began with the works of Butzer (1962) and Butzer and Cuerda (1962) in the second half of the twentieth century and reached its maximum expression in the comprehensive books of Cuerda (1975, 1987, 1989). These books provide a complete and excellent record of the paleo-sea levels based on fossil beaches, and additionally incorporate extensive paleoclimatic information based on the paleontological content (Cuerda, 1987, Gómez-Pujol *et al.*, 2007).

Although composed mainly of eolian and littoral marine facies, the Mallorcan deposits also comprise a wide spectra of colluvial, fluvial, and alluvial fan facies. The interfingering of the various facies give the deposits a complex sedimentary architecture (Rose *et al.*, 1999; Fornós *et al.*, 2009; Clemmensen *et al.*, 2001).

As the Balearic Islands represent a relatively stable area with negligible or very minor tectonic activity (Hearty, 1987; Fornós *et al.*, 2002a; Giménez, 2003; Silva *et al.*, 2005), results from Pleistocene studies are relatively easy to interpret because there are no tectonic effects to be adjusted for from the effects of the sea-level change. This fact gives to these studies a special relevance and more meaningful results. For this reason, Mallorca is one of the areas of major interest for much recent research concerning the register and evidences of sea-level changes forced by large Pleistocene climatic oscillations.

Sea-level oscillations have been deduced by the analysis of marine terraces and accompanying geomorphologic imprints (Cuerda, 1989; Goy *et al.*, 1997; Zazo *et al.*, 2003), the analysis of eolian sequences (Clemmensen *et al.*, 1997) and their correlated soils (Rose *et al.*, 1999; González-Hernández, *et al.*, 2001; Nielsen *et al.*, 2004; Muhs *et al.*, 2010), as well as from the stratigraphy of eolian, colluvial and alluvial fan deposits (Clemmensen *et al.*, 2001; Fornós *et al.*, 2004, 2009).

The first accurate chronological data by means of modern technologies on Mallorcan deposits took place at the second half of the last century, which included U/Th (AAR) methods on marine shells (Stearns & Thurber, 1965; Hearty *et al.*, 1986; Hearty, 1987; Hillaire-Marcel *et al.*, 1996; Goy *et al.*, 1997; Zazo *et al.*, 2003), and paleomagnetic analyses (Nielsen *et al.*, 2004). From the former references it is possible to identify at least four highstands: three during MIS 5e, at 135 kyr and 117 kyr (two events); and the fourth, at ca. 100 kyr (MIS 5c or 5a). Additionally, there are more recent and precise data based on U-series geochronology, on sea level history based on phreatic overgrowths in speleothems obtained in littoral caves in eastern and southern Mallorca (Ginés & Ginés, 1972; Vesica *et al.*, 2000; Tuccimei *et al.*, 2006; Onac *et al.*, 2006; Tuccimei *et al.*, 2012). Conflicts arise between the two-generation of proxies due to

discrepancies between ages of events. In these caves, three highstands have been recognized (Tuccimei *et al.*, 2006) corresponding to MIS 5e (138-128 and 122-116 kyr) and one more in MIS 5a (82-80 kyr) (Dorale *et al.*, 2011; Tuccimei *et al.*, 2012).

4. Petrology of eolianites (the sediment)

4.1 Some terminological aspects of eolianites

Eolianites are windblown deposits (dunes and less commonly eolian sand sheets) of carbonate composition (some authors also use eolianites for deposits poor in carbonate!) that are usually associated with coastal environments that have undergone rapid carbonate deposition. Initially described by Sayles (1931), the terminology has changed over time with variable differences in characterization (including emplacement and composition): from backshore lithified carbonate sands (Davis, 1983) to eolian limestone (or carbonate eolianite) with more than 50% of carbonate constituents (Abegg *et al.*, 2001). The current use of the term 'eolianite' in a broad sense refers to a coastal calcarenite that corresponds to the accumulation of dune deposits that consist of reworked carbonate marine (mainly bioclastic) sands (Brooke, 2001) that have undergone carbonate cementation, and which have been deposited in a



Figure 2. The Late Pleistocene colluvial, fluvial and eolian deposits in the northern bay of Alcúdia flanked by folded Jurassic and Cretaceous limestones. Height cliff *ca.* 10 m.

coastal carbonate environment (Fairbridge & Johnson, 1978) during the Quaternary (Gardner, 1983).

4.2 Sedimentary characteristics of the Mallorcan eolianites

Bioclastic sand is the principal constituent of the Mallorcan eolianites (Figure 3). The main components include red algae (constituting more than 50%), followed by fragments of molluscs (mostly bivalves and gastropods), echinoids, benthic foraminifera, bryozoans and other marine unidentified bioclastic grains. Peloidal grains are present and a small proportion of calcareous lithoclasts (mainly dolomite) can also be observed at specific geological settings. Ooids are scarce and are only present in Early Pleistocene deposits (Calvet, 1979).

The bioclastic composition of the eolian sand reveals that the nearest shallow marine environments are the source of the sediment. This ancient platform had an ecosystem similar to the present Balearic carbonate platform (Fornós & Ahr, 1997, 2006), where biotic and textural characteristics vary with depth. Sea grasses (mainly *Posidonia oceanica* meadows) extend across the inner and the middle ramp, sheltering and protecting a variety of calcareous organisms. Most of the modern beach and dune sediments consists of bioclasts derived from the communities that thrive in the seagrass meadows, but the greatest volume of skeletal carbonates is produced as bryozoan, rhodalgal and molluscan gravels that occur as patchy blankets, primarily on the middle ramp (Canals & Ballesteros, 1997). The accumulation and fragmentation of this skeletal material produces bioclastic sands that, once deposited on the beach by waves and marine currents, are wind-transported inland mainly by the dominant winds and by the constant and regular sea-breezes normal to the coasts.

In general terms, the eolian dune sediments are composed of fine to medium-grained bioclastic sands that were lithified by fresh-water cementation (Calvet *et al.*, 1980). The deposits are well sorted and typically composed of 2-5 mm thick laminae of medium to coarse sand alternating with very thin laminae of fine sand. This lamination, which we interpret as a type of pin-stripe lamination formed by migrating wind ripples (cf., Fryberger & Schenk, 1988), is overprinted by a crude rhythmic

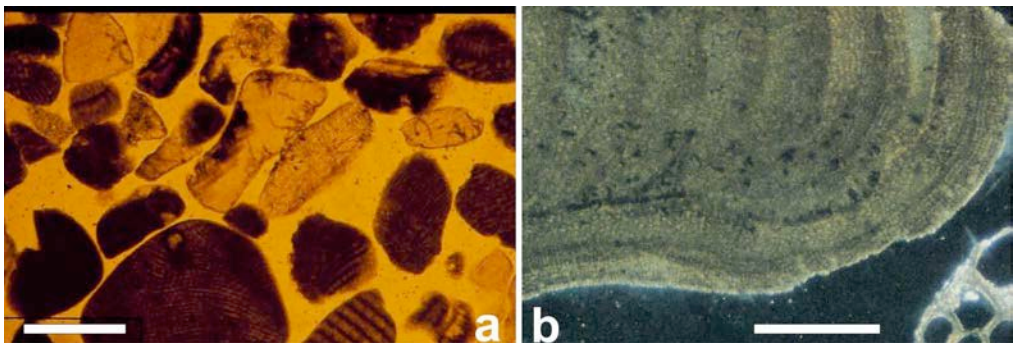


Figure 3. Thin sections showing that bioclastic sand is the principal constituent of the Mallorcan eolianites (a) Dune sediment viewed in plane polarized light, showing its bioclastic composition and the low degree of vadose cementation; (b) detail showing red algae as the main constituent. Scale bar 0.5 mm.

Inferred MIS	Marine cycle	Apparent sea level (in meters)	Faunal characteristics	Radiometric age
MIS 1	Z3	2	Banal	Post-Roman
	Z2	2	Banal	
	Z1	3	Banal	
MIS 2 to 4	Three eolianite generations		HEMICYCLE B	
MIS 5a	Y3	0.5 – 3	Probably banal	80,000 ± 5,000 BP
MIS 5e	Y2	1.5 – 2	Partial <i>Strombus</i> fauna	110,000 ± 5,000 BP
MIS 5e	Y1	9 – 15	Partial <i>Strombus</i> fauna	125,000 ± 5,000 BP
MIS 6	Two eolianite generations		HEMICYCLE C	
	X2	6.5 – 8.5	Impoversihed Senegalese fauna	190,000 ± 10,000 BP
MIS 7?	X1	2 – 4.5	Full <i>Strombus</i> fauna	210,000 ± 10,000 BP
MIS 8?	Two eolianite generations		HEMICYLCE D	
	W4	4 – 8	Banal	> 250,000 BP
MIS 9?	W3	15 – 18	<i>Patella ferruginea</i>	?
	W2	22 – 24	<i>Patella ferruginea</i>	
	W1	30 – 35	?	
MIS 10?	Three eolianite generations		HEMICYCLE E	
MIS 11?	V (22)	ca. 15	Banal	
	V (21)	45 – 50	Banal	
??	Two eolianite generations		HEMICYCLE F	
??	U	30 (?)	<i>Patella ferruginea</i>	
	?	60 – 65	?	
	?	75 – 80	?, <i>Purpura pleissi</i> , <i>Ostrea cucullata</i>	
	?	100 – 105		

Figure 4. The six continental hemicycles (F, E, D, C, B, A) from Butzer (1975). The eolianites, Early to Late Pleistocene in age, were arranged according to several criteria including the altitude (higher altitude means older age), the fauna content (differentiating cold and warm faunas) and some radiometric data.

Lamination (2-5 cm) and related to differential cementation of the laminae. The variation in the degree of cementation is tentatively ascribed to typical Mediterranean seasonal alternations of humid and dry periods (Fornós et al., 2002b). More rarely other eolianites contain laminae that can be interpreted as grain flow and grain fall deposits. The eolianites have cross-bedding of different types ranging from classical large-scale trough-formed and/or tabular cross-bedding to spectacular critical to supercritical dune cross-stratification formed by large climbing dunes (Clemmensen *et al.*, 1997, Clemmensen *et al.*, 2001)

4.3 Dating the eolianites

The first attempt to isotopically date Quaternary deposits from the Balearics was by Stearns & Thurber (1965) on marine molluscan shells from the Middle and Upper Pleistocene, which established the basis for correlation of later research, especially those from Cuerda (1975). This author made a detailed study of the Quaternary sediments by means of their faunal content, differentiating warm and cold faunas in the beach and dune sediments, thereby recognizing the main stages of the Pleistocene. Based on Cuerda's former work, Butzer (1975) arranged the eolianites into six

continental hemicycles (F, E, D, C, B, A), Early to Late Pleistocene in age (Figure 4), according to several criteria including the altitude (higher altitude means older age), the fauna content (differentiating cold and warm faunas) and some radiometric data obtained by earlier techniques. Butzer (1975) separated the units into the last marine isotope stage (MIS 1; post-Roman), and three different eolianite generations (Hemicycle B, probably of MIS 4 to 2). After the identification of three marine highstands representing MIS 5 (80 ± 5 kyr for MIS 5a; 110 ± 5 kyr for MIS 5c?; 125 ± 5 kyr for MIS 5e), he separated two other eolianite generations (Hemicycle C, probably MIS 6). MIS 7 is represented by two marine highstands (190 ± 10 kyr and 210 ± 10 kyr), which lie below two more eolian generations of the Hemicycle D (probably MIS 8). MIS 9 is defined by four possible highstands at different altitudes with an age older than 250 kyr, covered with three new eolianite generations (Hemicycle E, that must correspond to the MIS 10). The highstands of MIS 11 and older (perhaps MIS 13) are separated by two more eolianite generations (Hemicycle F).

Aminostratigraphy has been used extensively in the Mediterranean (Hearty, 1986; Hearty *et al.*, 1986; Miller *et al.*, 1986), especially in Mallorca by Hearty *et al.*, (1986, 1987) and Rose *et al.* (1999) to date the individual lithostratigraphic units. The mollusc shells corresponding to marine deposits were used to make the allo/iso-leucine as well as U/Th (by alpha technique) measurements. The lack of precision of both methods and the presence of reworked shells did not allow unequivocal assignment of each marine unit with a precise highstand. Hearty's work documented the chronology of Camp de Tir section, which was deposited during MIS 5.

Hillaire-Marcel *et al.* (1996) developed a pioneering work on the marine deposits of the Camp de Tir section, near Palma, using precise U-series dating by means of thermal ionization mass spectrometry (TIMS). This approach permitted precise location of the chronostratigraphic events reflected in the Tyrrhenian deposits resulting in the definition of two highstands during the Last Interglacial as well as dating of the faunal changes concurrent with it. As the Holocene to Upper Pleistocene eolian sequences are interbedded (Bardají *et al.*, 2009) with marine deposits in southern Mallorca (Camp de Tir in Palma and Campos bay), these eolian deposits have been correlated from different outcrops by means of the U/Th radiometric dating of the marine terraces bearing *Strombus bubonius* that characterize the MIS 5e highstand (González-Hernández *et al.*, 2001; Bardají *et al.*, 2009).

Nielsen *et al.* (2004) described the geochronologic framework of the Middle Pleistocene carbonate eolian sequences by means of magnetostratigraphy and susceptibility stratigraphic analysis supplemented by luminescence dating. The Els Bancals sequence in southern Mallorca consists of alternating colluvial and eolian deposits resting on an eroded marine platform, probably corresponding to the sea-level highstand of MIS 11 (427-364 kyr) as indicated by the presence of beach deposits. Nielsen *et al.*, (2004) recognize several eolian periods in the eolian-colluvial sequence deposited during the interval 333 ± 70 kyr (eolianites at the base of the sequence) to 275 ± 23 kyr (eolianites at the top of the sequence). The presence of three reversal excursions that can be correlated with the Levantine (400-360 kyr), the CR1 (325-315 kyr), and the CR0/BiwaIII excursions (280-260 kyr) suggests that the cyclic terrestrial succession at Els Bancals was deposited during insolation peaks 38-24 (Laskar *et al.*, 1993), which correlates with MIS 11-8 (410 to 260 kyr).

Paleomagnetic surveys have also been used by González-Hernández *et al.* (2000) to date eolianite deposits appertaining to the Lower Pleistocene (Matuyama epoch) for the Badia Blava (eastern part of Palma bay) eolianites and the even older Upper Pliocene eolian deposits at Banc d'Eivissa, which crop out respectively in east and west sides of Palma Bay.

Recent contributions offer a detailed Upper Pleistocene sea-level curve obtained by means of U-series analysis (TIMS) on phreatic overgrowths in speleothems (Vesica *et al.*, 2000; Fornós *et al.*, 2002a; Tuccimei *et al.*, 2006; Dorale *et al.*, 2010). This sea-level curve shows at least three highstands during the Last Interglacial (80-82 kyr MIS 5a, 116-122 kyr and 128-138 kyr both from MIS 5e), matching the highstands identified by study of the marine terraces (Hillaire-Marcel *et al.*, 1996; Goy *et al.*, 1997; Zazo *et al.*, 2003; Bardají *et al.*, 2009). This scenario permits the assignation of at least two cemented eolian units, which occur interbedded with paleosols, to the pre-isotopic substage 5e and another two to the Last Interglacial (MIS 5). Additionally, three other eolian units have been identified in the Last Glacial (MIS 4 to 2), which present a variable cementation and are separated by erosional surfaces or weak soil formation. At least three non-cemented eolian units, which belong to the Present Interglacial (MIS 1), have been identified and appear interbedded with blackish soils with high organic matter content. The ^{14}C dating of gastropod shells from the top of the lower eolian unit yielded an age of 4.370 ± 40 ^{14}C a BP.

Modern Optically Stimulated Luminescence (OSL) techniques where used to establish the chronological framework of the Upper Pleistocene deposits from north-eastern Mallorca (Fornós *et al.*, 2009). OSL datings (Figure 5) were made through the scarce quartz grains present in the eolianites that are thought to be deposited during dust rains related to aerosol components from the desert areas in North Africa (Fiol *et al.*, 2005).

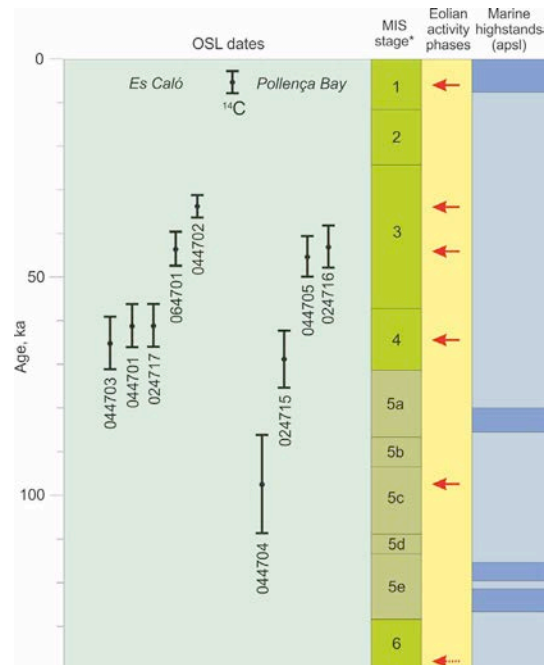


Figure 5. Main eolian activity phases since the Last Interglacial (modified from Fornós *et al.*, 2009; [*] Source: Martrat *et al.* 2004)

OSL ages from eolian deposits separated by alluvial and fluvial deposits at the Bay of Pollença and in Es Caló study sites give ages of 97 ± 12 kyr, suggesting eolian deposition during MIS 5c or 5b. The 69 ± 7 to 61 ± 6 kyr ages advocate for a renewed eolian deposition during the MIS 4 and parts of the MIS 3 (45 ± 5 kyr to 43 ± 5 kyr). An additional period of eolian deposition, belonging to the end of MIS 3 appears at the uppermost eolian unit that overlaps a fluvial entity yielding age values of 33 ± 0.5 kyr. All these datings are similar to those reported by Rose *et al.* (1999) in Caloscamps location and also in the north-eastern Mallorca.

5. Dune systems

5.1. Cliff-top Middle Pleistocene eolianites

At most localities on Mallorca, the Middle Pleistocene eolianites and associated paleosols form impressive cliff-top deposits with individual layers that have extensive lateral continuity (Nielsen *et al.*, 2004). Upper Pleistocene eolianites located in the depressed areas also show similar characteristics and the most prominent eolianites appear in the Pliocene to Middle Pleistocene sedimentary sequences, which cover most of the depressed areas of Mallorca and exhibit the typical large-scale cross bedding. Eolian deposits are composed of sets of trough-shaped and sometimes even tabular, 1 to 2 m thickness, although occasionally they can reach more than five meters with foresets dipping up to 30° . In some places the presence of rhizocretions is abundant and they can obliterate all of the sedimentary structures. Most deposits have a sheet-like geometry, suggesting an intense deflation after their deposition. Nevertheless, in some cases, the eolian dune facies shows a low-relief lens-shaped geometry suggesting the preservation of the original morphology. Occurring within the aforementioned eolian deposits, another type of deposit (i.e., corresponding to eolian sand-sheets) can be recognized. They form sheet-like layers with thickness ranging from 1 to 3 m.

Usually, they appear structureless although rare horizontal or very low-angle dipping strata can be observed. The lack of physical sedimentary structures in this kind of deposit can be explained by the common presence of rhizocretions. A classical location corresponding to the Middle Pleistocene is the Els Bancals succession (Figure 6) in the southern part of Mallorca (Nielsen *et al.*, 2004).

5.2 Cliff-front Upper Pleistocene eolianites

Topographically controlled eolian accumulations (cliff-front) comprise echo dunes, climbing dunes and sand ramps (Livingston & Warren, 1996; Lancaster & Tchakerian, 1996). Along the eastern coast of Mallorca, spectacular eolian accumulations appear in front of a cliffy coast that ranges 20 to 30 m in height (Figure 7). When this continuing cliff is disrupted by an embayment, the eolian accumulations are especially well developed. Sea cliffs shaped in Upper Miocene calcarenites and limestones show several wave-cut platforms at 3 and 10 m a.m.s.l related to sea-level highstands (Clemmensen *et al.*, 2001). Those limestone cliffs experienced a noticeable retreat since the Middle Pleistocene (Fornós *et al.*, 2005) and probably reached their present position and morphology a short time before the deposition of the eolian accumulation during the Last Interglacial.



Figure 6. The Pleistocene succession at Els Bancals section formed by eolian units (A1, A3, A5) alternating with red colluvial deposits. Arrow indicates a wave-cut platform (modified from Nielsen *et al.*, 2005).



Figure 7. Field appearance of the Late Pleistocene cliff-front accumulations near Pedreres des Bauç. Height of cliff in the distance approximately 35 m.

The cliff-front sediments can be divided in two sedimentary cycles; each is initiated by colluvial deposits and overlain by dune deposits. The dune deposits in the lowermost cycle are climbing, echo dune deposits, while those in the uppermost cycle are ascending dune deposits. The colluvial deposits that separate the two dune deposits contain eolian sand ramp deposits (Clemmensen *et al.*, 2001).

The echo dune deposits of the lowermost cycle shows a large-scale, critical to supercritical climbing dune cross-stratification (Clemmensen *et al.*, 1997) with well-developed seaward facing stoss-side deposits with surfaces dipping normally between 15 and 25° (rarely more than 30°) and cliffward facing lee-side deposits with its surfaces between 20 and 26° dip (rarely reaching dips larger than 32°). In cross section the dune brink line varies from sharp-crested to rounded, the latter form being associated with reactivation surfaces. Very often the strikes of the eolian dune deposits follow the coastal morphology alignment.

Marine carbonate sand was deposited as dunes in front of steep cliffs separated from the sea by a coastal plain larger than 2 km in width assuming a sea level 50 m lower than today (Bradley, 1999). Dating suggest that deposition took place around 40 kyr (Clemmensen *et al.*, 1997; 2001). The exposed dune heights in eastern Mallorca can reach more than 30 m, although they should be higher due to the fact that dune bodies continue beneath the present sea level. Sand transport inferred from sedimentary structures shows a trend perpendicular to the coast morphology, similar to the current eolian sediment transport in the island dune systems (Servera & Rodríguez-Perea, 1999).

The eolian deposits that appear in the basal part of the second sedimentary cycle formed in a classical sand-ramp configuration (Lancaster & Tchakerian, 1996). They appear as 3 m thick packages of eolian sand, dipping away from the cliff between 20 and 30°; the eolian deposits are closely associated with colluvial (talus) deposits. The sand ramp takes on the present height of the cliff in many locations.

The colluvial deposits form discrete layers that never reach more than 2 m thick and that appear interbedded with the eolian sediments. They are composed of breccias with scattered, very poorly classified angular limestone clasts, floating in a red (silty) matrix. The sharp and mostly erosional contact with the underlying echo dune deposits contrasts with the gradual transition to the overlying eolian deposits. The colluvial deposits represent debris flow avalanches going down over the slope of the eolian sand accumulation in front of the cliff.

The ascending dune deposits of the uppermost cycle show large-scale, landward dipping cross-bedding, with typical set heights between 1 and 2 m. Part of the dune cross-bedding has been disrupted by root casts, stem imprints and animal tracks. The dunes formed on top of the ramp and especially in areas where the ramp was lower than the cliff. Dune formation was related to a new input of marine carbonate sand from the coastal area.

The alternation of colluvial and eolian deposits records the transition from relatively humid (colluvial) into arid (dunes) climatic intervals. This scenario can tentatively be related with two Dansgaard-Oeschger cycles (interstadial and stadials)

during MIS 3 (Clemmensen *et al.*, 2001) that coincide in the Mediterranean area with a special dry climate period (Rossignol-Strick & Planchais, 1989).

5.3 Eolian - fluvial Upper Pleistocene successions at slopes or low cliffs toe

The second group of eolian deposits comprises systems deposited over a gentle slope or low cliffs. The coastal outcrops of Upper Pleistocene deposits in northeastern Mallorca (Alcúdia and Pollença bays) record such a system with a complex interaction between eolian, colluvial, and alluvial fan deposition (Fornós *et al.*, 2009). This interaction results in a variable stratigraphical architecture of the alluvial fan - dunefield system that overlies the Eemian (MIS 5e) beach deposits (Rose *et al.*, 1999).

The facies architecture of the systems varies considerably and reflects the pre-existing morphology as well as the complex interaction between eolian, colluvial and alluvial fan deposition. The existing relief controls both the eolian and the slope-alluvial processes that contribute to build up the deposits.

At Alcúdia Bay, the Upper Pleistocene facies are located at the piedmont of the Serres de Llevant (Figure 8). Alluvial fan deposits appear here and exhibit a large variability of facies and, in some parts of the alluvial fan systems, the eolian facies are



Figure 8. Eolian sand bodies, water-reworked eolian deposits and water-laid alluvial fan deposits cause the complex stratigraphy of the system at Es Caló (Alcúdia Bay), where the Upper Pleistocene facies are located at the piedmont of the Serres de Llevant.

dominant (Gelabert *et al.*, 2003). The sediment bodies and facies have a great lateral variation along the coast with a local architecture that reflects the relative position with respect to the axis of the alluvial fan and to the influx of eolian sand from the coast. The proportion between eolian sand bodies, water-reworked eolian deposits and water-laid alluvial fan deposits cause the complex stratigraphy of the system. In the coastal sequence, three main eolian units can be distinguished (Figure 8): the eolian deposits are interbedded with alluvial deposits (sheet-flood, fluvial channel and especially, water-reworked eolian deposits), as well as with some paleosols. The two lowermost eolianites correspond to migrating crescent dunes that were not obstructed by inland cliffs. They are large-scale with cross-stratification and 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 flow from the alluvial fan. The uppermost eolianites are located at the top of the cliff exposure in near contact with alluvial fan deposits.

At Pollença Bay, the basement morphology consists of crenulated cliffs shaped in Jurassic rocks that control the overall architecture of the Upper Pleistocene deposits formed by cliff-front dune, sand ramp, rock fall, alluvial fan and colluvial deposits as well as by some paleosols (Figure 9). The thickest eolian deposits are located in front of the steep cliffs whereas alluvial fan deposits are best developed in the intervening low-relief areas. The eolian deposits form three overlapping units. The lowermost eolian deposit is a cliff-front dune unit that overlies coastal cliff-toe breccias and cobble beach deposits (MIS 5e?). The eolian deposits are characterized by the typical cross-stratification composed of well-developed topsets and foresets indicating an asymmetric dune moving inland. The second eolian deposit corresponds to an ascending dune or sand ramp that develops over a thick paleosol, which can be followed laterally along wide sectors of the cliff outcrops. Finally, the third eolian unit is new ascending dune deposit that shows wind-ripple lamination and sand flow stratification; this unit, which onlaps alluvial fan sediments, is overlain by younger colluvial deposits (Fornós *et al.*, 2009).



Figure 9. At Pollença Bay, the basement morphology of crenulated cliffs shaped in Jurassic rocks control the overall architecture of the Upper Pleistocene deposits formed by cliff-front dune, sand ramp, rock fall, alluvial fan and colluvial deposits as well as by some paleosols. Height of the cliff (left side) *ca.* 18 m.

The interbedded non-eolian deposits vary locally, in some parts consisting exclusively of alluvial fan facies (sheet-flood, channel deposits) whereas in other parts they include water-reworked eolian deposits. This latter facies evidences the contemporary eolian sand transport and alluvial fan activity.

There are differences in the stratigraphic setting of the eolian deposits at Alcúdia (es Caló) and Pollença Bays, but these can readily be explained in terms of differences in local topography and according to the distance from watersheds to the sea. Cliff-front dunes and related ascending dunes, as well as sand ramp deposits appear seaward of steep inland cliffs (Pollença), while ordinary migrating dune deposits relate with distal alluvial fan areas (Alcúdia). Both sequences record four phases of eolian activity between MIS 5c and MIS 3 (Fornós *et al.*, 2009) as described above.

6. Implications for landscape and sea level evolution

6.1. Paleoclimatic and paleoenvironmental implications during the Middle Pleistocene

Regional studies of Mediterranean soils formed during the Pleistocene interglacial periods highlights that they are usually reddish and have high magnetic susceptibility and negative $\delta^{18}\text{O}$ values (El-Asmar, 1994; Rose *et al.*, 1999). These attributes suggest that the climate was warm and moist during soil formation. Studies by Gunster & Skowronek (2001) indicate that Pleistocene soil formation occurred under warm and moist (interglacial or interstadial) conditions with dense vegetation cover and a stabilized landscape. In contrast, the eolianites are thought to record arid glacial or stadial periods and therefore they were formed during sea-level lowstands (cf. Butzer, 1975).

The Els Bancals sequence constitutes the reference location for the Middle Pleistocene at Mallorca. According to Nielsen *et al.* (2004), the colluvial soils that appear interbedded with eolianites at Els Bancals record warm and moist conditions. The relatively thick and dark red colluvial soil complexes containing prominent magnetic susceptibility values likely record prolonged periods of warm and relative humid climate, and was thus probably formed during interglacial periods.

In this way, eolian deposits from Mallorca would differ from other common Pleistocene eolianites, which formed during sea-level highstands (Brooke, 2001). Thus the terrestrial part of the Middle Pleistocene succession at Els Bancals seems to record from the base to the top: interglacial climate and colluviation, glacial climate and episodic dunefield formation, a second period of interglacial climate, and finally glacial climate and episodic dunefield formation. In the glacial periods, interstadial and stadial conditions alternated with eolian activity during the stadials and colluvial soil formation during the interstadials.

6.2. Paleoclimatic and paleoenvironmental implications during the Late Pleistocene

The Late Pleistocene composite sequences of eolian, colluvial, and fluvial facies present in the coastal areas of north-eastern, south and south-eastern Mallorca, along

with new stratigraphic and OSL chronologic data, indicate that deposition of eolian sediments took place during the colder, probably more arid, and windier periods, when the sea-level was lower than present. Probably a decrease in vegetation cover would allow sand transport inland from exposed shelf areas. This interpretation is supported by the presence of semi-arid vegetation in southern Mediterranean associated with a drastic reduction of temperatures and precipitation during cold climatic intervals (Bout-Roumazeilles *et al.*, 2007). The eolian and fluvial deposition were linked to cold climatic intervals between 95 and 35 kyr. These were also the periods of lower sea level and maximum exposure of carbonate shelf and shoreline deposits. If winds were strong enough, during these stages this material would have been transported inland in the form of migrating dunes.

Four main periods of eolian activity with formation of dune deposits can be identified and related with different isotopic stages. The first one, ordered from base to top, occurred during MIS 5c or 5b at about 97 kyr. This was a period of intermediate sea level (-10 to -20 m in Mallorca; Tuccimei *et al.*, 2006; 2012). During this time, annual mean sea surface temperatures were falling from around 20°C at about 100 kyr to around 15°C at about 90 kyr (Martrat *et al.*, 2004). Mean annual land temperatures were 17.9-13.6 °C in MIS 5c, but only 10.8-7.6 °C in MIS 5b (Rose *et al.*, 1999). Modern day mean annual temperature is 17.3°C. A second period of eolian activity, MIS 4 at about 65 kyr, was a period of low sea level (Siddall *et al.*, 2003; Rabineau, *et al.*, 2006); annual mean sea surface temperatures were as low as 12°C (Martrat *et al.*, 2004), and mean annual land temperatures were likewise low, with estimated values between 8.2 and 4.9°C (Rose *et al.*, 1999). A third period of eolian activity and dune formation accounts in the middle part of MIS 3 at about 45 kyr. Sea level remained low (Siddall *et al.*, 2003; Rabineau, *et al.*, 2006); annual mean sea surface temperatures were around 15°C (Martrat *et al.*, 2004), while mean annual land temperatures were between 14.6 and 9.9 °C (Rose *et al.*, 1999). The final period of limited eolian activity corresponds to the end of MIS 3 at about 34 kyr. This was a period of low sea level (Siddall *et al.*, 2003; Rabineau, *et al.*, 2006); annual mean sea surface temperatures were around 12°C (Martrat *et al.*, 2004).

From the data obtained, it seems clear that episodes of eolian activity and dune formation can be linked to periods of low sea level, when extensive parts of the shore and platform carbonates would have been exposed to wind transport. Also, the vegetation cover would have been limited and rivers must have been an effective erosive agent inland (Rose *et al.*, 1999) during these cold climatic intervals. Winds were probably stronger, and coastal dunes would have been able to move inland until they were trapped in front of inland cliffs or in the distal part of the coastal alluvial fans. Similar weather conditions as today probably were responsible for the inland transport of eolian material during cold climate intervals in MIS 5c/b, 4 and 3. Inland wind transport of marine carbonate sand currently takes place primarily during the winter. Strong westerly and northerly winds are common, with mean velocities higher than 8 m/s blowing more than 10% of the time (Servera, 1997; Jordi *et al.*, 2006).

The dominant fluvial deposition that took place just after 65-70 kyr in MIS 4 eroded the underlying eolian sediments; preservation was controlled by early lithification and also made possible by a rising base level at about 65 kyr causing only limited fluvial incision. A second and more extensive phase of fluvial deposition took place just after

45 kyr in MIS 3, which resulted in alluvial fan formation at both sites (Pollença and Alcúdia Bays). Rose *et al.* (1999) also suggest that MIS 2 was a period of significant landscape change and extensive fluvial and eolian activity.

OSL ages of eolianites from Sardinia indicate that the northwestern coast of this island was covered by dunefields in MIS 4 (Pascucci *et al.*, 2008). Similarly, in Mallorca, intense inland transport of eolian sand occurred during MIS 4. Great dunefields covered large parts of the coastal areas along the bays of the north-eastern part of the island. These results suggest enhanced storminess in large parts of the western Mediterranean during this cold period. This interpretation is supported by climate simulations indicating a decrease in winter storm days during the warm MIS 5e (ca. 125 kyr) and an opposite, but weaker change in storm activity during the beginning of the relatively cold MIS 5d (115 kyr; Kaspar *et al.*, 2007). Data from the Alboran Sea also suggests an intensification of northwesterly winds in the western Mediterranean Sea during cold climatic intervals (Moreno *et al.*, 2002).

Recent palaeoclimatic data inferred from vadose spellothems isotopic composition from Mallorca (Hodge *et al.*, 2008) show environmental changes during the Last Interglacial period. In MIS 5e (130 to 120 ka) an evolution from pluvial to more arid conditions is seen. Additionally during MIS 5a (85 a 80 ka) there was marked climate variability with abrupt changes in temperature and precipitation in periods shorter than 200 years. Otherwise MIS 4 and MIS 3 relate to dry and cold episodes.

7. Other aspects

7.1 Rhizcretions

In the dune deposits, and especially beneath the colluvial and paleosol horizons, extensive root structures are developed in many sizes and styles (Calvet *et al.*, 1975; Esteban & Klappa, 1983). Smaller plants colonizing dunes commonly develop root networks parallel with lamination and their structures are easily overlooked (Loope, 1986). Conspicuous root structures are common in most of the dune deposits, except in the echo dunes where there is little evidence of the presence of such structures indicating a scarce colonization by the vegetation.

The rhizcretions are a characteristic diagenetic structure of eolianites present in Mallorca. These carbonate concretions are formed by preferential cementation around the roots of the vegetation on the dunes. They are characterized by a vertical orientation (Figure 10) and locally they present branching forms with sections ranging from millimeters to several centimeters in diameter and in some cases of metric order in vertical dimension (Calvet *et al.*, 1975; Ward, 1975). The presence of laminated concretions (crusts) and caliche related paleosols (Klappa, 1978) are also very common, highlighting the presence of a spherical microstructure formed by radial calcite prisms and produced by the calcification of *microrizae* associations called *Microcodium* (Esteban & Klappa, 1983). The massive presence of all these structures can obliterate the entire lamination of the dune system (the "*dikaka*" of Glennie & Evamy, 1968).



Figure 10. The rhizocretions are a characteristic diagenetic structure of eolianites present in Mallorca. Width of rhizocretions *ca.* 2 cm.

7.2 Ichnology: Tracks and trackways of *Myotragus balearicus*

Tracks and trackways of the ruminant goat, *Myotragus balearicus* (Bate, 1909) are a common feature in the Pleistocene eolianites of coastal areas of Mallorca (Fornós *et al.*, 2002b). First described by Fornós and Pons-Moyà (1982) in a small quarry in the southeastern part of the island, they are ubiquitous in all Pleistocene littoral eolianites, and disappearing around 5000-4000 yr BP when the extermination of *Myotragus* occurred with the *Homo* arrival (Alcover, 2004).

The tracks can be observed in all the eolian units (Figure 11) being especially abundant in the cliff-front related deposits that correspond to the MIS 3 (Fornós *et al.*, 2002b), where tracks are abundant in the crestal zone deposits, common in the stoss-side deposits and rare in the lee-side deposits of the dunes. There are thousands of laminae in the lithified eolianites that have been tracked by this ruminant goat endemic to the Balearics. The extensive sections provided by the quarry exploration of the calcarenites for building purposes, parallel and perpendicular to the bedding, allow seeing the track in vertical as well as in horizontal sections. Plastic deformation and microtectonic rupture in the form of microfaults and microthrusts are involved in the sediment disturbance caused by the trace maker.

Almost all exposed bedding surfaces show horizontal sections, both epirelief and hyporelief, of tracks at various levels beneath the tracking surface. When observed

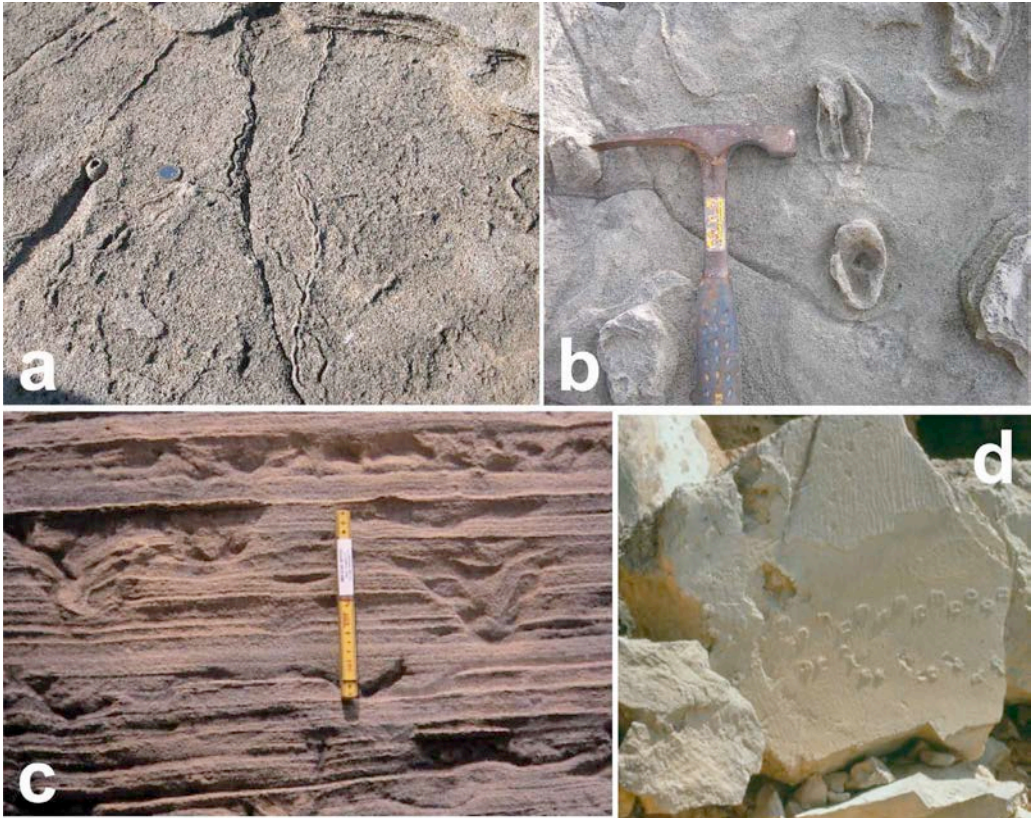


Figure 11. Ichnology in the Upper Pleistocene eolianites: (a) Insect trace fossils; (b) bifid foot impressions of *Myotragus* seen in distal transverse sections; (c) Perpendicular sections of tracks showing the disturbed dune lamination; and (d) two trackways of *Myotragus* at the dune crest.

from a section concave-up, deformation structures are common corresponding to the downward fading deformation of the subjacent laminae within the substrate.

The tracks formed in the dune deposits and all of the preserved trackways indicate impression into moist sand. Special features of the tracks include the structure produced by the withdrawal of the foot, and an adjacent disturbance zone of plastic deformation. On dune crests, the disturbance zone surrounds the axis more or less symmetrically. However, in addition, a “pressure pad” of dislocated, slightly rotated sediment bound by curved microfaults, is commonly produced posterior to the axis by propulsive pressure of the foot. On steep windward and lee slopes, the pressure pad becomes oriented in a downslope position as a result of gravitational slip of the walking animal.

Combination of disturbance of the sediment in this way by *manus* followed by overprinting of similar disturbance by *pes* produces highly complicated track structure. This structure may be characteristic of artiodactylous mammals in soft sand, particularly eolian deposits.

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❧

Phreatic Overgrowths on Speleothems (POS) from Mallorca, Spain: Updating forty years of research

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1. Introduction

Mallorca Island is internationally renowned as one of the classical sites for marine Pleistocene studies in Western Mediterranean basin (Hey, 1978; Pirazzoli, 1987; Zazo, 1999; Zazo *et al.*, 2003). Owing to a series of remarkable papers, started in the second half of the 20th century, an excellent record of high sea-stands is now available in the literature (Butzer & Cuerda, 1962; Butzer, 1975; Cuerda, 1975; Pomar & Cuerda, 1979). Besides the mentioned publications, additional investigations have recently been performed on Pleistocene beach deposits from Mallorca, using various geochronological techniques such as amino acid racemization, optical stimulated luminescence, and U-series radiometric dating of fossil mollusca (Hearty *et al.*, 1986; Hearty, 1987; Hillaire-Marcel *et al.*, 1996; Rose *et al.*, 1999).

On the other hand, an outstanding aspect of the Mallorcan's endokarst is the presence of sea level controlled phreatic crystallizations. This kind of deposits is commonly found in the subterranean pools of littoral caves, at current sea level (Pomar *et al.*, 1979; Tuccimei *et al.*, 2009). The main interest in these carbonate precipitates is that they record ancient higher and/or lower sea-stands, by means of horizontal alignments of water-table crystalline overgrowths in coastal caves of the island.

During the last decades, a new approach to the Mediterranean sea-level history has arisen from the interdisciplinary study of such Phreatic Overgrowths on Speleothems (POS) in the littoral caves of Mallorca (Figure 1). A comprehensive bibliographic revision on this topic is provided by Ginés (2000), whereas recent updated data sets are available in Tuccimei *et al.* (2006, 2010) and Dorale *et al.* (2010). The geomorphological approach to these karst deposits has been fully supported by chronological information obtained from U-series datings of the POS samples. The data gathered altogether represent a very precise archive of glacioeustatic fluctuations during the

Quaternary in the studied area. The eustatic curve for the time span between 150 and 60 ka BP is especially detailed.

Here we present the state-of-the-art on POS studies from littoral caves in Mallorca, with emphasis on their morphological, mineralogical, and crystallographic aspects as well as their significance in investigating sea-level history.

2. Investigations of Mallorcan POS: a four decades story

Examination of phreatic speleothems in littoral caves of Mallorca Island started in 1972, when striking bands of subaqueous crystallizations were observed in Cova de sa Bassa Blanca (Alcúdia) being tentatively credited to represent past Pleistocene sea stands (Ginés & Ginés, 1972). In fact, this kind of speleothem had been previously mentioned in earlier papers on Coves del Drac (Manacor), predicting their formation during some drowning events related to past elevations of the water table (Rodés, 1925; Joly, 1929; Colom *et al.*, 1957).

The first work on Mallorcan POS focused on correlating their elevation with the fossil beach sequences, abundant along the coasts of the island (Cuerda, 1975; Pomar &

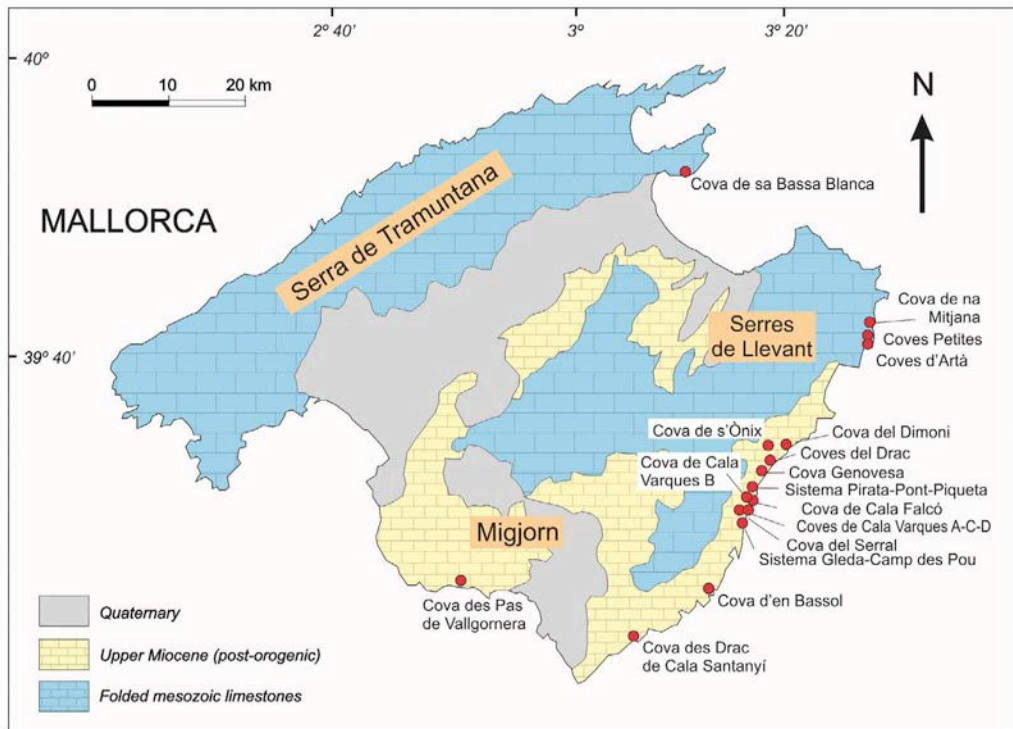


Figure 1. Location map of the most significant caves containing sea level controlled Phreatic Overgrowths on Speleothems (POS) along the coasts of Mallorca.

Cuerda, 1979). Using this approach, the phreatic speleothems bands, distributed from the current sea level (0 ASL) to +46 m ASL, were correlated to ancient coastlines encompassing the time span from the Last Interglacial to the Middle Pleistocene for the highest observed POS (Ginés, 1973; Ginés & Ginés, 1974; Ginés *et al.*, 1975). Meanwhile, the precipitation of carbonates at present-day sea level was described in the form of floating calcite rafts (Pomar *et al.*, 1975) and bulky calcite overgrowths. Both of these speleothems develop within the current tidal range of the coastal cave pools (Pomar *et al.*, 1979). Early mineralogical and crystallographical studies on POS identified the presence of aragonite deposits, pointing out their potential paleoclimatic significance (Pomar *et al.*, 1976). All these aspects were internationally disseminated during the 8th *International Congress of Speleology* held in Bowling Green (USA), in two papers dealing with the morphology and mineralogy of POS and, especially, to their potential as records of past sea levels (Ginés *et al.*, 1981a, b). These investigations, that started from the Mallorcan speleological scene owing to the already cited works by A. Ginés and J. Ginés, very early were developed as a collaborative project within the *Universitat de les Illes Balears* (UIB), particularly with L. Pomar and subsequently with J.J. Fornós.

During the 1980s, a programme of U-series datings was commenced due to the interest and dedication of the late G.J. Hennig. Up to 16 U/Th ages on POS were performed at the *Niedersächsisches Landesamt für Bodenforschung* (Köln, Germany) by means of alpha-spectrometry techniques. The ages range from Holocene to older than 350 ka BP, including samples that clearly corresponded to the Last Interglacial (Hennig *et al.*, 1981; Ginés & Ginés, 1989, 1993a, b, 1995). During these years, electron spin resonance (ESR) measurements were also conducted in order to obtain additional geochronological data on Mallorcan POS. This dating method was applied to a core drilled in the thick phreatic coatings covering the walls of Cova de sa Bassa Blanca (Maroto & Font, 1981; HADES, 1985). This publication also supplied 4 new U/Th ages of the core, and suggests that the complex sequence –including both phreatic and vadose crystallizations– was deposited over a long time span, ranging from 700 to 200 ka BP (Grün, 1985, 1986). More recently, stable isotope data were published in a paleoclimatic study of the same drilled core from Cova de sa Bassa Blanca (Csoma *et al.*, 2006).

Between 1995 and 2000, a second U-series dating programme was conducted in collaborative research with the *Università Roma Tre* (Rome, Italy), under the leadership of Paola Tuccimei. More than 30 U/Th ages were published during this period, corresponding to POS paleolevels situated both above and below the current sea level (Tuccimei *et al.*, 1997, 1998, 2000; Ginés *et al.*, 1999, 2001a, b, 2002, 2004). The tasks of sampling the submerged phreatic speleothems were accomplished during important underwater exploration carried out by an extremely active and dedicated team of Mallorcan speleo-divers (Gràcia *et al.*, 2007). Most of the U-series analyses resulting from this dating campaign were performed by means of alpha-counting techniques, with only a few obtained by thermal ionisation mass spectrometry (TIMS). The ages range between 67 ka and >350 ka BP, with over 16 dates corresponding to different substages of MIS 5. These allowed our team to reconstruct, for the first time, a detailed eustatic curve for western Mediterranean basin between 150 and 60 ka BP (Tuccimei *et al.*, 2000; Ginés *et al.*, 2003). The geochronological investigations carried out along this period were complemented with a few stable isotopes data on POS, meant to provide some preliminary paleoclimate information (Vesica *et al.*, 2000). Furthermore, research

on Mallorca's recent tectonics was evaluated in a paper that highlights the potential use of POS in structural geology studies (Fornós *et al.*, 2002). A detailed revision on the knowledge about POS of Mallorca was included in the PhD dissertation of Ginés (2000). His work deals with the geomorphological aspects of Mallorca's littoral endokarst, emphasizing chronological aspects related to coastal caves. Some efforts were also directed towards the mineralogical, crystallographic, and textural description of different types of phreatic speleothems, generating a paper on this topic a few years later (Ginés *et al.*, 2005). Finally, it is worth mentioning that the POS investigations were extended to Sardinia (Italy) in order to elucidate the tectonic situation of both islands in the frame of the Western Mediterranean basin (Tuccimei *et al.*, 2003, 2007).

During the most recent decade, a third programme of radiometric investigation commenced on POS with a two-fold purpose: first, to obtain accurate U/Th ages by means of multi-collector inductively coupled plasma mass-spectrometry technique (MC-ICPMS) and second, to study in detail the Holocene POS. Over 47 mass-spectrometry datings were performed mainly at the laboratory of the Institute of Geology from the *University of Bern* (Switzerland) -owing to the collaboration of Jan Kramers and Igor M. Villa- as well as 12 additional dates completed by Bogdan P. Onac (*University of South Florida*) and Jeffrey A. Dorale (*University of Iowa*) who in the last years joined this research project. The recent research on subactual POS have two

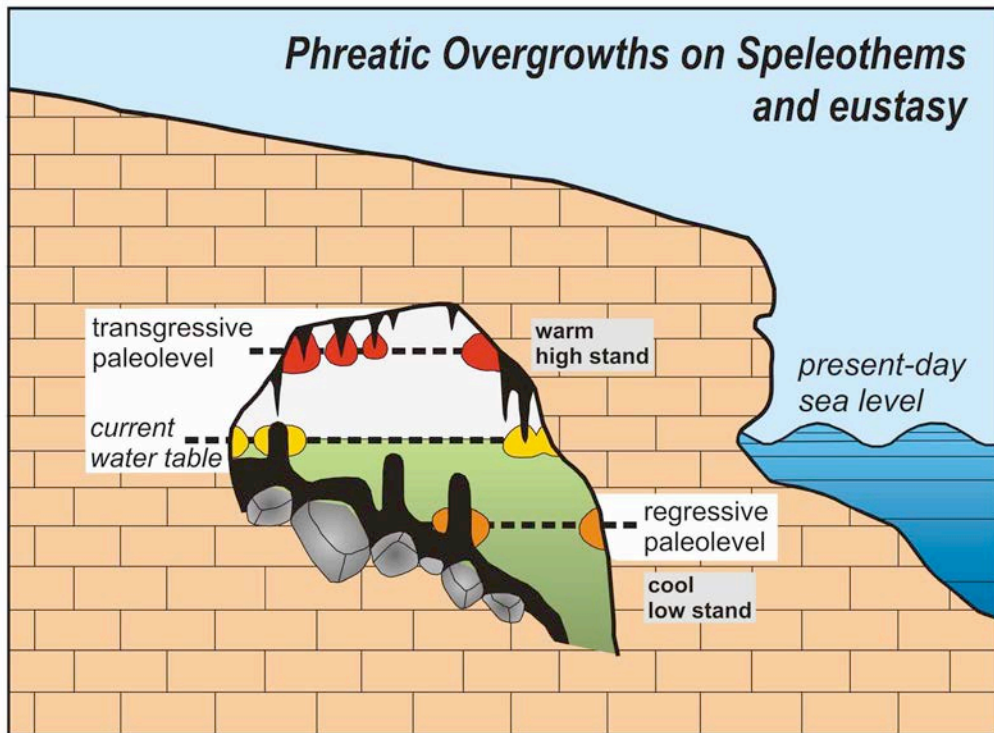


Figure 2. Sketch of a karstic littoral cave of Mallorca hosting present-day as well as ancient POS deposits. Broken lines represent the mean elevation attained by the ground water table during each recorded sea stand.

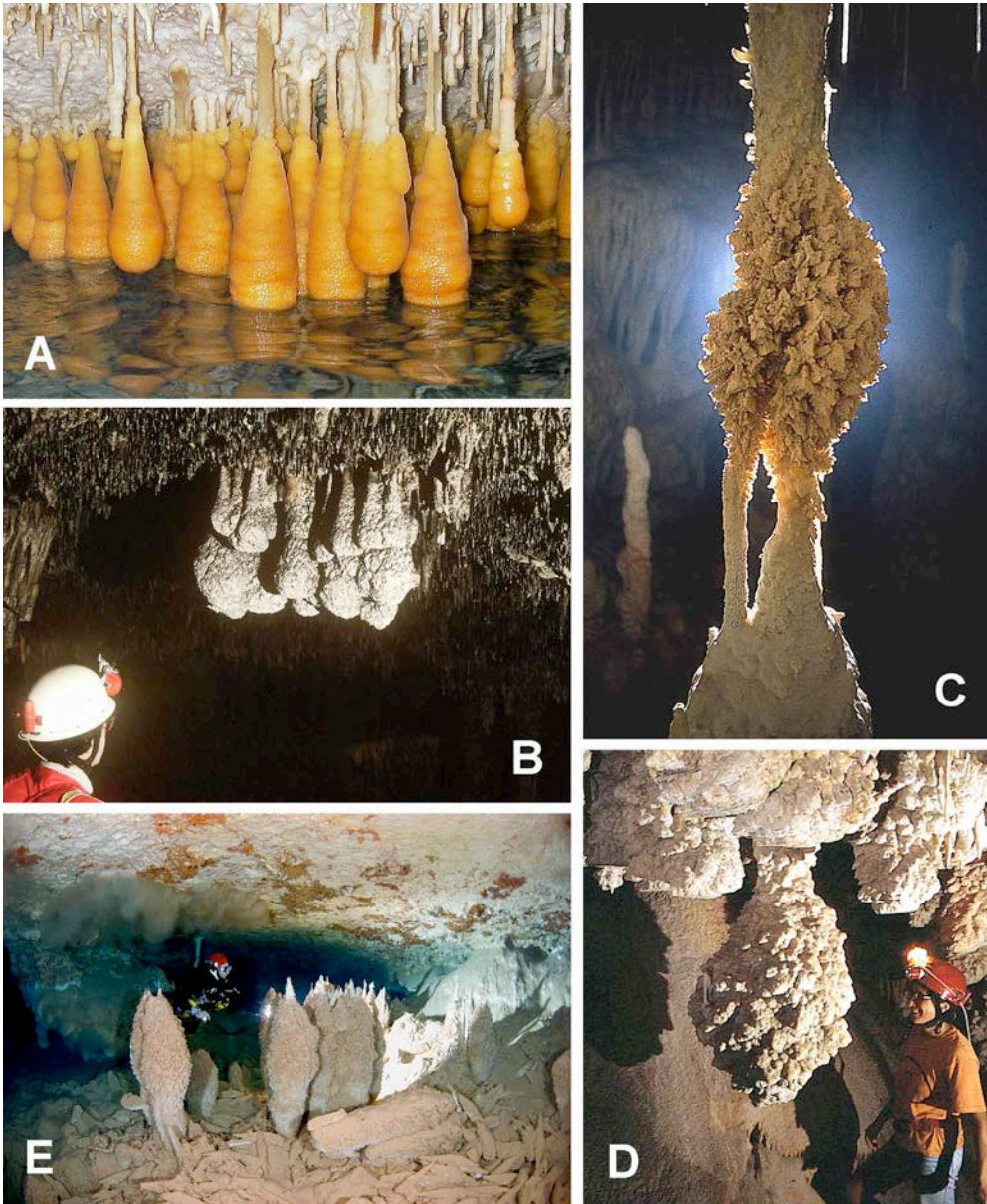


Figure 3. Photos of Phreatic Overgrowths on Speleothems (POS) from several Mallorcan caves. A: nice aragonite encrustations growing at the current water table in Cova des Pas de Vallgornera, Lluçmajor. (Photo: A. Merino). B: group of POS crystallizations that record an ancient sea stand in Coves del Drac (Manacor), at an elevation of +4 m above the present-day sea level. (Photo: J. Ginés). C: spectacular calcite overgrowth corresponding to MIS 5e in Cova des Pas de Vallgornera (Lluçmajor), located at an elevation of +2.6 m ASL (Photo: A. Merino). D: bulky macrocrystalline POS deposits from Cova de na Mitjana (Capdepera), recording a Middle Pleistocene high sea stand at +6 m ASL (Photo: J. Ginés). E: band of POS deposits corresponding to a regressive event, submerged in Cova de sa Gleda (Manacor) at a depth of -15 m ASL. (Photo: A. Cirer).

clear objectives: firstly, to confirm the presumed postglacial age of these deposits, as well as to supply new data on Holocene sea level in Mallorca (Tuccimei *et al.*, 2009, 2010); and second, additional ^{14}C analyses were conducted on these postglacial precipitates (Tuccimei *et al.*, 2011). Undoubtedly, the main achievement of this third dating programme is the generation of an accurate eustatic curve (for the Last Interglacial to Holocene times) based on all available U-series data on POS. The new dates, especially those falling between 150 and 60 ka BP, provide reliable information about sea level history during MIS 5 in Mallorca (Tuccimei *et al.*, 2006), novel data on the MIS 5a high sea stand (Onac *et al.*, 2006; Dorale *et al.*, 2010), and on the glacial isostatic adjustments in the Western Mediterranean area (Tuccimei *et al.*, 2012).

3. Phreatic Overgrowths on Speleothems (POS) from Mallorca Island

Karst caves are abundant along the southern and eastern coasts of Mallorca, particularly in the Upper Miocene post-orogenic carbonate rocks (Ginés, 1995; Ginés & Ginés, 2009). One of the most distinctive features of the coastal endokarst on Mallorca Island is the presence of extensive subterranean brackish pools. These ponds are currently flooding the lower parts of the caves, in elevational and hydrodynamic correspondence with present-day Mediterranean sea-level (Ginés & Ginés, 2007). The sea-level control over the littoral cave pools is evident since their surface undergoes daily fluctuations, related to minor tidal and/or barometric sea-level oscillations.

In this particular microenvironment, geochemically characterized by relatively elevated contents of chloride, sulfate, magnesium, and calcium, it is possible to observe freshly precipitated carbonates (crystalline overgrowths forming horizontal bands, floating calcite rafts, etc.) linked to the surface of these subterranean ponds (Pomar *et al.*, 1976, 1979; Tuccimei *et al.*, 2010). Just as the POS record the current sea-level position, ancient crystallizations of the same type –situated both above and below the present-day ± 0 elevation datum– prove to be an excellent register of past sea-level (Figure 2), a fact documented in a number of papers (Ginés, 2000; Vesica *et al.*, 2000; Fornós *et al.*, 2002; Tuccimei *et al.*, 2006; Dorale *et al.*, 2010).

Generally speaking, the POS from Mallorcan littoral caves are crystalline coatings that define strictly horizontal bands. These carbonate encrustation develop along the cave walls, or over any suitable support (for example, common vadose speleothems) penetrating below the surface of the subterranean pools (Figure 3). The morphology of these coatings is bulky and its maximum thickness corresponds to the mean position of the water-table. As a rule, the thickest part of the overgrowth is located in the middle of the crystallizations belt, gradually decreasing upward and downward.

The belt-like form of POS deposits has a rather simple statistical explanation that relates to the position of the water table, where the maximum thickness occurs at the mean sea level during its growth period (Pomar *et al.*, 1979). The aforementioned morphology develops when the POS inner support is always and continuously in contact with the fluctuating water table (i.e. columns, tall stalagmites and stalactites, or cave walls; case 1 in Figure 4). However, the overgrowth shape can be substantially different when POS develops on small stalactites –formed during sea-lowering events–

whose tips do not penetrate deep enough below the pool surface. In this situation, the precipitation is abruptly truncated and flat-bottomed bulky overgrowths form (case 2, in Figure 4). The resulting appearance is simply due to the lack of the lowest part of the overgrowth.

The morphological variety of phreatic speleothems is enormous (Ginés & Ginés, 1974; Ginés *et al.*, 2005). Very abundant and conspicuous are those globular forms described above. At the same time, some other forms are represented, but to a lesser extent, as for example the deposits of floating calcite and/or aragonite rafts, as well as cave cones produced by the accumulation of sunken floating rafts (Pomar *et al.*, 1976; Ginés *et al.*, 2005). These variegated phreatic crystallizations constrain (in a very noticeable manner) fully horizontal belts of encrustations, whose elevation correspondence with contemporaneous sea-level is the central to the present investigations, as earlier postulated by Ginés & Ginés (1974), Ginés *et al.* (1981a), and Pomar *et al.* (1987).

Currently up to 30 paleolevels of POS (ranging from +46 m ASL to -23 m below the current ± 0 datum) have been recognized in Mallorcan caves (Ginés, 2000). Overall, the POS alignments that are localized at positive elevations record transgressive high-stands associated with interglacial or interstadial periods, whereas the speleothem bands or overgrowths situated below the current sea-level may correspond to regressive pulsations linked to glacial or stadial conditions. Referring briefly to the

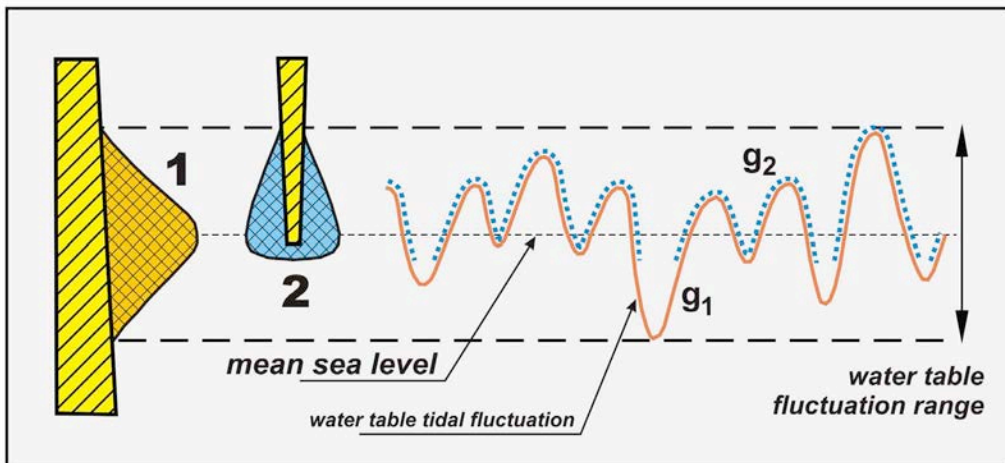


Figure 4. Schematic cross-view of phreatic carbonate encrustations (POS) developed over two different supports (after Tuccimei *et al.*, 2010). In case 1, POS develops on a support that is continuously in contact with the fluctuating water table (a stalagmitic column, for instance), originating a symmetric overgrowth with the maximum thickness corresponding to the more frequent position of the water table. In case 2 the crystallization develops over a stalactite, whose tip does not penetrate deep enough below the pool surface, producing an asymmetric flat-bottomed overgrowth. The solid (g1) and the dotted (g2) line are the growth histories of speleothems in case 1 and 2, respectively; note that g1 is coincident with the full sea level fluctuation range, whereas g2 only records the upper part of that range.

mineralogy of POS, it is possible to assess how calcite and (in a lesser extent) aragonite are predominant in these deposits. Aragonite crystallizations occur particularly in some paleolevels located above the current sea-level, as well as Holocene POS in the Cova des Pas de Vallgornera. The aragonitic mineralogy likely has paleoclimatic significance (Pomar *et al.*, 1976; Ginés *et al.*, 1981b; Vesica *et al.*, 2000), being present in samples belonging to warmer substages of MIS 5. Aragonite encrustations originate characteristic smooth coatings, whereas calcite POS show macrocrystalline textures with rough surfaces. All these mineralogical and crystallographic aspects will be discussed in a further section.

4. Methodology

The first step in the present research was the identification of phreatic speleothem bands, which are clear recorders of sea-level. Investigations were formerly centered in eastern and southern coasts of Mallorca, areas with abundant coastal endokarstic phenomena. The alignments of POS recognized inside the caves were extensively sampled with selective criteria (in particular those forms developed on stalactites, that are of easier collection without drilling equipment), being at the same time topographically determined their elevation with respect to the current ± 0 ASL datum. Exploration of caves has required the use of conventional speleological and the more specialized scuba-diving techniques in the cave pools for sampling the lower sea-level stands.

The collected samples have been radiometrically dated by means of the U-series method. The first programmes of U/Th datings were carried out by alpha-counting, at the laboratories of *Niedersächsisches Landesamt für Bodenforschung* (Köln, Germany) and *Università Roma Tre* (Rome, Italy). Nevertheless the major bulk of datings were performed in the last decade by mass-spectrometry techniques (TIMS and MC-ICPMS), mainly at the *University of Bern* laboratory (Bern, Switzerland). Average errors of the obtained ages are respectively about 3% (1s) for alpha-counting and 1.5% (2s) for TIMS and MC-ICPMS analyses (see additional technical details in Vesica *et al.*, 2000 and Tuccimei *et al.*, 2006). The availability of reliable chronological data concerning the sampled POS should potentially contribute to the reconstruction of Mediterranean sea-level history during the last 500 ka, age that constitutes the applicability limit of the U-series radiometric techniques. Additional geochronological tasks have included ^{14}C dating of Holocene samples (Tuccimei *et al.*, 2011), as well as ESR measurements of some ancient POS paleolevels (Grün, 1986).

Mineralogical and crystallographic investigation of the samples involved XRD analyses as well as optical and scanning electron microscopy observations. The aim of such studies was to evaluate the paleoclimatic information archived within these speleothems. Particular attention would be focused on the environmental controls of aragonite precipitation in the littoral phreatic zone. Finally, C and O stable isotope analyses were performed on the growing layers of some samples, in order to gather additional paleoclimatic data at the time these carbonate deposits were precipitated (Vesica *et al.*, 2000; Csoma *et al.*, 2006).

5. Results of U/Th dating and proposed eustatic curve

The core of these researches is represented by the results generated over several dating programmes (U/Th method), starting in the eighties of the last century (Hennig *et al.*, 1981; Ginés & Ginés, 1989, 1993a) and until the present (Tuccimei *et al.*, 2000, 2006, 2010; Dorale *et al.*, 2010). From a total of 97 U-series ages ranging from 0.6 ka to >350 ka BP (44 based on alpha-counting techniques and 53 obtained by means of mass-spectrometry measurements), up to 55 dates cluster between 60 and 150 ka BP. The obtained data provide accurate elevations of sea level high- and low-stands both during the Holocene and over the MIS 5 and 4; these data are discussed below. The acquisition of absolute ages based on the investigated POS paleo sea-levels, coupled with the precise determination of their elevation, have allowed us to tentatively reconstructing an eustatic curve for the Western Mediterranean basin covering the time period between the Middle Pleistocene until present.

5.1. Dating of Holocene POS

The investigations on POS deposits (Figure 5) that are presently located around the current sea level were directed towards two different goals: first, it was necessary to check the postglacial age of these deposits, in order to confirm the potentiality of POS as recorders of the subactual sea level; second, the obtained results must provide precise data on Holocene sea level in the Western Mediterranean basin.

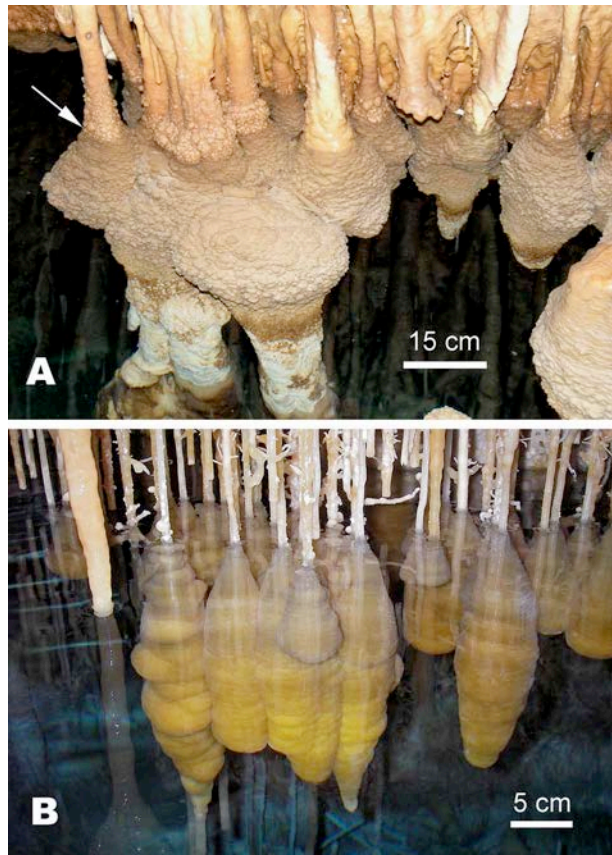


Figure 5.

Carbonate crystallizations occurring at the surface of brackish pools in Mallorcan caves.

A: Calcite belt of phreatic overgrowths on speleothems (POS) in Cova de Cala Varques A (Manacor); white arrow emphasize water table position when the picture was taken, which was higher than mean sea level. (Photo: B.P. Onac).

B: Aragonite belt of POS from Cova des Pas de Vallgornera (Llucmajor); the thickest part of the overgrowth band corresponds to the mean sea level. (Photo: A. Merino).

Two caves in Eastern Mallorca were chosen for this purpose. Cova de Cala Varques A (Manacor municipality) is an outstanding site located only a few metres away from the coastline, and is characterized by the presence of bulky calcite POS encrustations developed all along the margins of extensive brackish pools (Figure 5a). On the other hand, Cova des Pas de Vallgornera (Llucmajor) is a vast littoral cave system with more than 67 km of passages, showing prominent aragonite POS located at the surface of the underground brackish pools (Figure 5b); the artificial cave entrance is about one hundred metres from the sea cliff.

Fourteen samples were drilled from speleothem VA-D1 (Cova de Cala Varques A), two of them from the inner vadose stalagmite and twelve from the phreatic overgrowth. From VL-D3 speleothem (Cova des Pas de Vallgornera), five samples were obtained from the aragonite phreatic encrustation. The samples were drilled along transects transverse or parallel to the POS growth axis (Figure 6). The VA-D1 overgrowth consists of high-Mg calcite, crystallized as mm-size rhombohedral crystals that are growing in a parallel or dendritic pattern, whereas VL-D3 sample is composed of 20 μm wide and 1 mm long acicular aragonite crystals, arranged in 0.3-1 mm thick growth layers.

The age data (Table I) show that POS from the two caves grew approximately the same time, although there is a slight shift at the beginning and interruption of deposition. In particular, calcite precipitation at Cova de Cala Varques A took place from about 2.8 to 1.1 ka BP, whereas the aragonite deposition in Cova des Pas de Vallgornera occurred from about 2.0 to 0.6 ka BP (Tuccimei *et al.*, 2009, 2010). Subaerial calcite deposition in vadose conditions was active between 18.3 and 7.7 ka BP, in agreement with the younger phreatic overgrowth. In both cases, the ages of phreatic

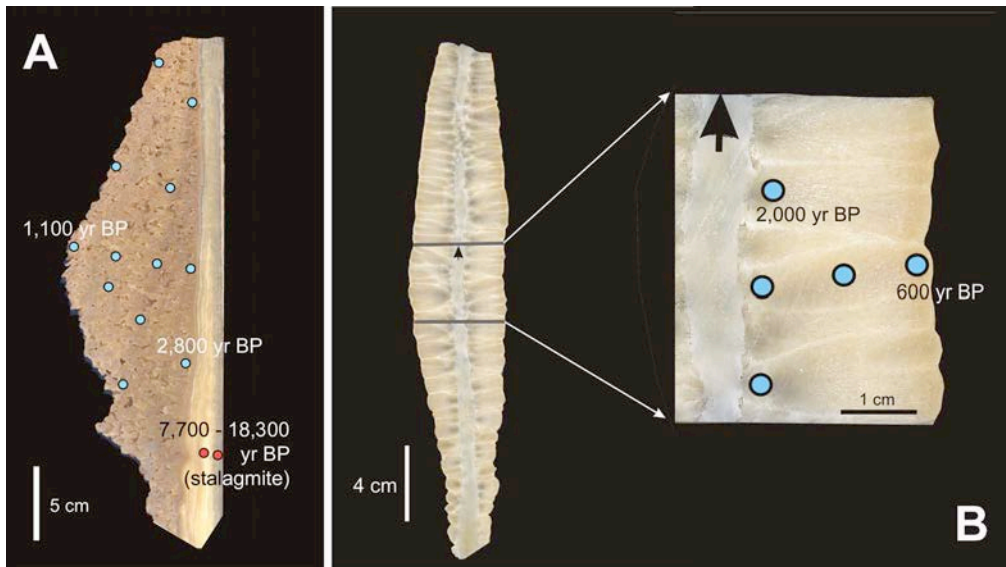


Figure 6. A: Location of samples drilled on speleothem VA-D1 (Cova de Cala Varques A). B: General cross-view of speleothem VL-D3 (Cova des Pas de Vallgornera) and location of the drilled samples. In both cases, the most illustrative U/Th ages are labeled over the pictures.

Table I. U/Th datings of Holocene POS samples, collected at the present-day sea level in two Mallorcan coastal caves.

Cave	Sample	U (ppb)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	$^{230}\text{Th}/^{238}\text{U}$	$(^{230}\text{Th} / ^{238}\text{U})_{\text{corr}}^*$	Age-C * (ka ± 2σ)	Age-I ** (ka ± 2σ)
Cova de Cala Varques A	VA-D1-1	406	1.632 ± 0.001	2.52 ± 0.04	0.0460 ± 0.0003	0.0310 ± 0.0065	2.08 ± 0.44	2.80 ± 0.04
	VA-D1-9	473	1.710 ± 0.001	6.90 ± 0.05	0.0450 ± 0.0003	0.0397 ± 0.0023	2.55 ± 0.15	
	VA-D1-2	306	1.457 ± 0.001	4.71 ± 0.06	0.0309 ± 0.0003	0.0255 ± 0.0023	1.92 ± 0.18	2.30 ± 1.40
	VA-D1-5	304	1.462 ± 0.001	2.93 ± 0.04	0.0341 ± 0.0004	0.0244 ± 0.0042	1.83 ± 0.31	
	VA-D1-6	316	1.494 ± 0.001	6.06 ± 0.04	0.0312 ± 0.0002	0.0270 ± 0.0018	1.98 ± 0.14	
	VA-D1-7	281	1.442 ± 0.001	5.33 ± 0.08	0.0287 ± 0.0004	0.0242 ± 0.0020	1.85 ± 0.15	
	VA-D1-8	279	1.425 ± 0.001	2.84 ± 0.03	0.0295 ± 0.0003	0.0209 ± 0.0037	1.60 ± 0.29	
	VA-D1-3	294	1.416 ± 0.001	7.12 ± 0.08	0.0212 ± 0.0003	0.0188 ± 0.0011	1.45 ± 0.09	1.50 ± 0.07
	VA-D1-10	294	1.424 ± 0.001	4.93 ± 0.04	0.0224 ± 0.0001	0.0186 ± 0.0016	1.43 ± 0.13	
	VA-D1-4	310	1.415 ± 0.001	0.471 ± 0.006	0.0580 ± 0.0006	-0.0521	negative age	1.10 ± 0.50
	VA-D1-11	336	1.384 ± 0.002	0.362 ± 0.005	0.1221 ± 0.0015	-0.2307	negative age	
	VA-D1-12	322	1.435 ± 0.001	0.757 ± 0.010	0.0254 ± 0.0003	-0.0032	negative age	
	VA-D1-13 +	270	1.170 ± 0.001	7.00 ± 0.06	0.2022 ± 0.0015	0.1821 ± 0.0089	18.30 ± 1.0	
	VA-D1-14 +	106	1.160 ± 0.001	17.4 ± 0.2	0.0829 ± 0.0001	0.0792 ± 0.0016	7.70 ± 0.20	
Cova des Pas de Vallgornera	VL-D3-1	8829	1.480 ± 0.002	271 ± 2	0.0262 ± 0.0002	0.0261 ± 0.0002	1.94 ± 0.01	
	VL-D3-2	7396	1.478 ± 0.002	69.3 ± 0.4	0.0250 ± 0.0002	0.0247 ± 0.0002	1.84 ± 0.02	
	VL-D3-3	8139	1.475 ± 0.001	510 ± 3	0.0264 ± 0.0002	0.0271 ± 0.0001	2.02 ± 0.01	
	VL-D3-4	8217	1.487 ± 0.001	457 ± 3	0.0183 ± 0.0001	0.0183 ± 0.0001	1.35 ± 0.01	
	VL-D3-5	8015	1.503 ± 0.002	145 ± 1	0.0084 ± 0.0002	0.0084 ± 0.0002	0.61 ± 0.01	

† Cross indicates subsamples from the inner vadose support
 * $(^{230}\text{Th}/^{238}\text{U})_{\text{corr}}$ and Age-C have been corrected for an initial $^{230}\text{Th}/^{232}\text{Th}$ ratio of 0.85 ± 0.36
 ** Age-I is calculated from the intercept of $^{232}\text{Th}/^{238}\text{U}$ vs $^{230}\text{Th}/^{238}\text{U}$ isochron diagrams for VA-D1 samples (see details in Tuccimei et al., 2010)

encrustations are stratigraphically consistent, suggesting the chemical system probably remained closed since deposition and no leaching or preferential dissolution occurred. The time shift and mineralogical differences could be explained by changes in the local chemical conditions of the pool waters (Pazzelli, 1999), which could be related to the fact that the two caves sit at different distances from the coastline. It is worth noting that the extent 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. The fine-scale spatial distribution of ages among VA-D1 subsamples also suggests a possible slight rise of sea level (~5-10 cm) during its precipitation.

Detailed information regarding the methodology and the results of MC-ICPMS dates performed on these samples is available in Tuccimei *et al.* (2010). Special attention is given to detrital Th corrections applied for each speleothem, according to their different mineralogy, U contents, and isotopic activity ratios. Stable isotope analyses provided in that paper document relatively high $\delta^{18}\text{O}$ (from -4.2 to -3.4‰ VPDB) and $\delta^{13}\text{C}$ (from -3.2 to -2.2‰ VPDB) values if compared with those of the vadose stalactite ($\delta^{18}\text{O}$ from -5.6 to -4.9‰ VPDB; $\delta^{13}\text{C}$ from -7.9 to -5.9‰ VPDB). This is likely due to different proportions in which sea water and groundwaters mix and also depends on the distance between the cave pools and the coastline.

The coherent ages obtained demonstrate that POS are excellent recorders of postglacial sea level, being readily datable by U-series methods. This fact allows to

foresee POS as useful indicators of past sea stands, especially when these precipitates are found in coastal caves at different elevations above or below the present sea level, as is the case in Mallorca's littoral caves.

Regarding the Holocene sea level history, it is worth mentioning some complementary archeological evidence from a cave in the studied area. In the entrance chamber of Cova Genovesa (a cave located only a few kilometres away from Cova de Cala Varques A), a drowned prehistoric construction 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 first chamber pool 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. The occurrence of a past sea level at a depth of ~ -1 m is also strengthened by the presence of a horizontal coloration mark, observable at both sides of the construction, as well as along the submerged cave walls. Scarce pottery findings date back to 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 archeological data and U/Th chronology of POS (Tuccimei *et al.*, 2009, 2010), it is possible to recognize a relative low stand at about -1 m, around 3.7-3.0 ka BP, followed by a rise of sea level, with a successive stabilization at the present elevation since ca. 2.8 ka BP.

5.2. Dating of Pleistocene POS

The early U/Th dating programmes conducted by means of alpha-spectrometry on phreatic speleothems from Mallorca –collected both above and below the current sea level– yielded ages from about 63 ka to >350 ka BP (Hennig *et al.*, 1981; Ginés & Ginés, 1989, 1993a; Tuccimei *et al.*, 1998, 2000; Ginés *et al.*, 2003). Apart from a few POS samples presumably corresponding to MIS 7 or even earlier (MIS 9 or 11), the vast majority of ages were in the range 150-60 ka BP providing valuable information on sea level history during MIS 5. Additional research taking advantage of recent mass-spectrometry techniques have allowed lately constraining a more detailed and accurate Upper Pleistocene eustatic curve for the Western Mediterranean basin (Tuccimei *et al.*, 2006; Dorale *et al.*, 2010), which will be conveniently discussed in the next sections. In total, more than 50 phreatic speleothems collected in 17 littoral caves of Mallorca (Figure 1) were investigated over the last four decades.

5.2.1. High and low sea level stands around MIS 5 documented by dating POS

The ages of phreatic overgrowths, dated by means of TIMS and MC-ICPMS techniques, range from 143.6 to 77.8 ka BP, covering the entire Last Interglacial interval (Table II). The following three high stand episodes (i.e., past sea levels located at elevations higher than present-day) have been detected. The height, age, and duration of these high stands are listed below from the oldest to the youngest:

- a first stand (MIS 5e₂) at +1.5/+3 m ASL, with possible initiation as early as 140.8, but not later than 135.2 ka BP. The termination of this episode can be set somewhere between 131 and 126 ka BP, resulting in a possible duration of 4.2 to 14.8 ka.

Table II. U/Th ages of Upper Pleistocene POS samples from caves along the eastern and southern Mallorcan coasts.

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	Age (ka ± 2σ)
Cova del Dimoni	DI-D1-1 # a	+2.5	2531 ± 7	1.273 ± 0.002	1.372 ± 0.003	236 ± 2	0.654 ± 0.004	109.9 ± 1.1
	DI-D1-2 # a	+2.5	1254 ± 5	1.087 ± 0.001	1.122 ± 0.014	5231 ± 62	0.670 ± 0.003	118.4 ± 0.9
	DI-D3 # a	+2.5	2050 ± 6	1.192 ± 0.001	1.265 ± 0.001	2834 ± 55	0.664 ± 0.003	114.2 ± 0.9
	CDD-1 * b	+1.5	1191 ± 19	1.178 ± 0.003	1.223 ± 0.038	18814	0.530 ± 0.004	80.4 ± 0.6
	CDD-2 * b	+1.5	1186 ± 18	1.177 ± 0.027	1.222 ± 0.034	17160	0.530 ± 0.003	80.7 ± 0.5
Coves del Pirata	PI-D1 # a	+2.1	300 ± 1	1.649 ± 0.006	1.945 ± 0.010	1681 ± 20	0.751 ± 0.006	133.0 ± 1.9
Cova de Cala Falcó	FA-D3-4 # a	+1.9	3976 ± 11	1.589 ± 0.001	1.743 ± 0.002	4236 ± 81	0.551 ± 0.004	82.3 ± 0.8
	CCF-1 * b	+1.6	208 ± 23	2.113 ± 0.009	2.397 ± 0.011	2410	0.551 ± 0.002	80.4 ± 0.5
	CCF-2 * b	+1.6	202 ± 21	2.137 ± 0.012	2.431 ± 0.015	990	0.556 ± 0.002	81.1 ± 0.5
Cova de Cala Varques A	CCVA-1 * b	+1.3	110 ± 22	1.377 ± 0.069	1.476 ± 0.086	9077	0.545 ± 0.002	82.0 ± 0.6
	CCVA-2 * b	+1.3	121 ± 18	1.379 ± 0.055	1.478 ± 0.069	5599	0.544 ± 0.002	81.7 ± 0.5
Cova de Cala Varques B	VB-D2 # a	+1.4	445 ± 1	1.476 ± 0.003	1.643 ± 0.005	133 ± 1	0.557 ± 0.004	84.2 ± 1.0
	VB-D3 * a	-14.0	680 ± 2	1.881 ± 0.020	2.256 ± 0.028	320 ± 14	0.735 ± 0.007	125.0 ± 2.0
	VB-D5 # a	-16.5	786 ± 2	1.822 ± 0.003	2.169 ± 0.005	891 ± 11	0.730 ± 0.003	124.7 ± 0.9
	CCVB * b	+1.3	101 ± 21	1.376 ± 0.017	1.473 ± 0.021	418	0.541 ± 0.005	80.8 ± 1.0
Cova des Serral	SE-D2 # a	+1.5	198 ± 1	1.521 ± 0.009	1.752 ± 0.013	591 ± 5	0.736 ± 0.005	130.2 ± 1.6
Cova de sa Gleda	GL-D1 # a	-15.0	412 ± 1	1.949 ± 0.004	2.185 ± 0.005	201 ± 2	0.540 ± 0.004	78.6 ± 0.8
	GL-D2 # a	-14.0	505 ± 1	1.968 ± 0.004	2.450 ± 0.009	242 ± 2	0.796 ± 0.005	143.4 ± 1.6
	GL-D3 # a	-17.5	454 ± 1	1.931 ± 0.007	2.210 ± 0.009	336 ± 3	0.606 ± 0.004	92.7 ± 0.9
	GL-D5 * a	-16.0	385 ± 1	2.094 ± 0.026	2.364 ± 0.032	230 ± 11	0.539 ± 0.004	77.8 ± 0.8
	GL-D6 # a	-17.0	614 ± 2	1.931 ± 0.005	2.227 ± 0.008	671 ± 6	0.628 ± 0.005	97.7 ± 1.1
	GL-D7 # a	-13.5	272 ± 2	1.667 ± 0.003	1.903 ± 0.008	42 ± 1	0.661 ± 0.022	107.4 ± 2.8
	GL-D8 # a	-20.5	375 ± 1	1.840 ± 0.003	2.069 ± 0.005	43 ± 0.4	0.571 ± 0.011	85.4 ± 0.9
Cova d'en Bassol	PS-D2 * a	-10.5	212 ± 1	1.611 ± 0.016	1.810 ± 0.020	45 ± 2	0.630 ± 0.005	100.0 ± 1.0
	PS-D5 # a	-18.0	152 ± 1	1.858 ± 0.017	2.114 ± 0.022	157 ± 1	0.604 ± 0.008	92.6 ± 1.8
Cova des Pont	PO-D2 # a	+2.1	347 ± 1	1.381 ± 0.003	1.539 ± 0.005	529 ± 9	0.704 ± 0.006	122.7 ± 1.9
Cv. Drac Cala Santanyi	CS-D3 # a	-17.0	325 ± 1	1.365 ± 0.003	1.466 ± 0.004	25 ± 0.2	0.563 ± 0.004	86.3 ± 0.9
Cova Genovesa	GE-D1 # a	+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 # a	-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 # a	-19.5	349 ± 1	1.731 ± 0.003	1.965 ± 0.006	72 ± 0.9	0.571 ± 0.004	85.9 ± 1.0
Cova de s'Ònix	OX-D1 # a	+3.0	254 ± 1	1.443 ± 0.002	1.637 ± 0.005	37 ± 0.5	0.727 ± 0.008	128.5 ± 2.5
Cova des Pas de Vallgornera	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
#	MC-ICPMS		*	TIMS				
a	data from Tuccimei et al. (2006)		b	data from Dorale et al. (2010)				

- a second stand (MIS 5e₁), apparently longer than the first, at +2.5 m ASL, begun between 124.6 and 120.8 ka BP and ended sometimes between 111 and 108.8 ka BP, hence lasting 9.8 to 15.8 ka.
- a third short-lived stand (MIS 5a) was documented at +1.3 to +1.9 m ASL; the starting dates cluster between 85.2 and 82.5 ka BP. The demise of this high stand event was anywhere between 81.5 and 79.5 ka BP, resulting in its possible duration of 1 to 5.7 ka.

At least six low stand episodes (i.e., past sea levels found at elevations lower than the current sea level) have been documented, two of which at the MIS 6/MIS 5e and MIS 5a/MIS 4 transitions. The other four low stands fall within MIS 5. All six episodes are listed below from the oldest to the youngest:

- a first low stand is $\sim -14/-13$ m ASL and coincides with the MIS 6/MIS 5e transition, at ~ 143.5 ka BP.
- a second stand with a maximum depth of -16.5 m ASL was documented within MIS 5e, around 125 ka BP.
- a third stand at -13.5 m ASL (~ 107.4 ka BP) was tentatively correlated with MIS 5d.
- a fourth sea level stabilisation at -10.5 m ASL occurred around 100 ka BP (MIS 5c?) between the proposed MIS 5d paleolevel and the next recorded low sea stand at about -17 m ASL.
- a fifth low stand consisting of two main events: a first sea level stabilisation at $-18/-17$ m ASL from about 97.7 to 92.6 ka BP, and a second low stand at $-20.5/-19.5$ m ASL around 85.9 to 85.4 ka BP. The POS record for this interval, roughly corresponding to MIS 5b, remains open for different interpretations.
- a sixth low stand at the MIS 5a/MIS 4 transition was identified at $-16/-15$ m ASL and around 78.6 to 77.8 ka BP.

This detailed succession of Upper Pleistocene high and low sea stands, documented by the Mallorcan POS record, allows the construction of an eustatic curve for the Western Mediterranean encompassing the chronological and elevation data supplied by these crystallizations.

5.2.2. Comparison between mass-spectrometry and alpha-counting U/Th dating

High precision MC-ICPMS and TIMS data presented in the paragraphs above can be compared with previous alpha-counting derived ages (Table III) as discussed in Tuccimei *et al.* (2006). It is worth noting that the average errors associated to alpha-counting, and quoted as 2σ , ranged from 5 to 15%, while those obtained from mass-spectrometry measurements are generally around 1% or better. This implies that the time interval associated to ages of 100 ka for example is reduced from 10 ka (alpha-counting) to 1 ka (mass-spectrometry). This is crucial in the process of generating a detailed sea level changes curve.

By comparing the age results obtained by means of MC-ICPMS and TIMS (Tuccimei *et al.*, 2006) with those produced by alpha-counting (Tuccimei *et al.*, 1998, 2000; Ginés *et al.*, 2003), one can observe that both data always agree within the error range (quoted as 2σ), supporting the accuracy of the U/Th ages used for the construction of the proposed eustatic curve. Only in a single case (sample DI-D3), the mass-spectrometry age has led to a different interpretation of the POS record, suggesting the absence of carbonate deposits that could document a MIS 5c high stand.

the MIS 6 to MIS 5 transition, much earlier than the insolation maximum in the northern hemisphere centered ~128 ka ago (Winograd *et al.*, 1996). Shopov *et al.* (1998) report an increase in solar insolation occurred $\sim 139 \pm 5$ ka BP and attribute it to a cycle of solar luminosity, with duration of 11.5 ka, superposed on the orbital variations curve. In addition, it is worth noting that the average duration estimated for the MIS 5e₂ high stand is 9.5 ka, in agreement with the estimated length of the referred solar activity cycle. This suggests that the solar luminosity contribution to the global insolation curve may be underestimated.

During MIS 5e (i.e., 138 to 110 ka BP), two high sea stands separated by a brief low stand episode have been identified (Figure 7). The same marine regression within the Last Interglacial was recognized in Mallorca Island (Hillaire-Marcel *et al.*, 1996) and other geographical areas: peninsular Spain (Zazo, 1999; Zazo *et al.*, 1997, 2003), Central Italy (Riccio *et al.*, 1999), Tunisia (Jedoui *et al.*, 2003), Bermuda and Bahamas Islands (Chen *et al.*, 1991; Neumann & Hearty, 1996; Hearty, 1998), Western Australia (Zhu *et al.*, 1993), and the Seychelles Islands (Israelson & Wohlfarth, 1999). Evidence of a sudden and short-lived chill during MIS 5e (at about 122 ka BP) has also been reported by Maslin & Tzedakis (1996). From the POS data it seems that MIS 5e₁ high sea stand have occurred at an elevation slightly higher than the MIS 5e₂ (Table II, Figure 7), as also indicated by Hillaire-Marcel *et al.* (1996). It is important to note that, to date, the low stand within MIS 5e is only documented by means of two samples from the same cave; thus, additional data are required in order to fully document the presence of this low stand in the POS record.

A low stand episode correlated to MIS 5d has been recognized in Mallorca at -13.5 m ASL around 107.4 ka BP. Another stand at a lesser depth (-10.5 m) follows at about 100 ka BP. This can tentatively be attributed to MIS 5c, which in Eleuthera Island (Bahamas) was also correlated to deposits located at about -15 m ASL (Hearty, 1998). At the same time, Zazo (1999) reports deposits in the Barbados and Bermuda credited to be MIS 5c that are now located below present sea level. It is essential to remark that in Vesica *et al.* (2000) the sample DI-D3 -now dated at 114.2 ± 0.9 ka BP- was not unequivocally assigned to the late MIS 5e, being then attributed to MIS 5c on the basis of an alpha-counting age of 107.9 ± 5.7 ka BP.

The low stand referred here to MIS 5b appears to be the longest of MIS 5 and also at the greatest depth (at least -20.5 m ASL). During the substage MIS 5b, Rose *et al.* (1999) reported mean annual temperatures in Mallorca in the order of 10.8-6.7°C, generally lower than those estimated during the low stand episode recognized within MIS 5e that is up to 11.3°C. The probable mean duration of this episode could be around 12.3 ka, from about 97.7 to 85.4 ka BP. The interpretation of sea level changes over this time period is not unequivocal, but it appears that sea level never rose above -17 m ASL.

During MIS 5a strong evidence points toward a relatively short-lived high stand at +1.3/+1.9 m ASL. Ages calculated in Tuccimei *et al.* (2006) are in the range 84.2 to 82.3 ka BP, but recent dates published by Dorale *et al.* (2010) cluster around 81 ka BP. Finally, the sea level recorded at the MIS 5a/MIS 4 boundary is situated -16 m ASL and chronologically corresponds to 78 ka BP.

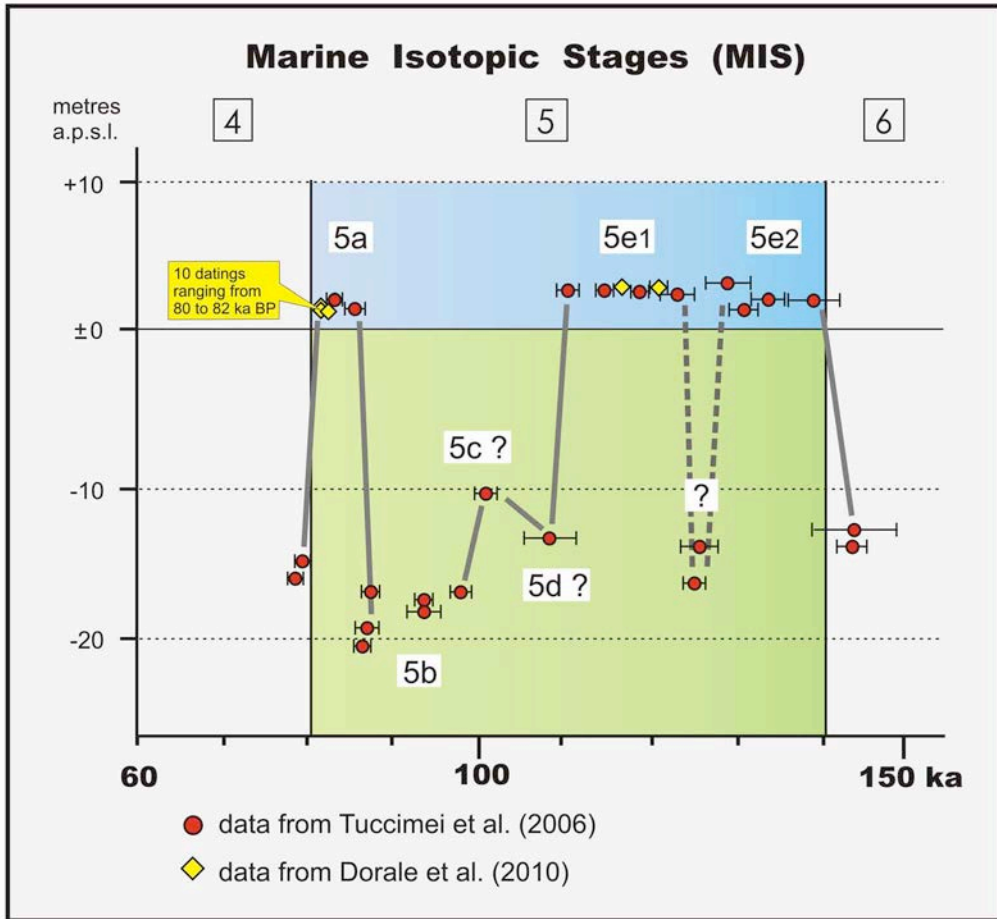


Figure 7. Eustatic curve during MIS 5 deduced on the basis of U/Th ages of Phreatic Overgrowths on Speleothems (POS) from Mallorca Island. Errors are quoted as 2σ .

Some of the results from POS dating, in particular those concerning the sea level drop near 125 ka BP and the high sea stand during stage MIS 5a, contrast with most of those derived from oxygen isotopic composition of oceanic benthic foraminifera (Imbrie *et al.*, 1984; Martinson *et al.*, 1987). Benthic curves do not typically match sea level estimates due to global causes like variations in deep water temperature or salinity (Chappel & Shackleton, 1986; Shackleton, 1987; Rohling & Bigg, 1998) or in the composition of melted ice (Clarke *et al.*, 2002). Moreover, the oscillations of relative sea level recorded in the Spanish Mediterranean coasts depend on regional influences (Goy *et al.*, 2003), acting superimposed to the global factors, like changes in the influx of Atlantic superficial waters, fluctuations of the North Atlantic Oscillation (NAO), variations of solar activity, as well as different crustal responses to isostatic adjustments. Therefore, estimates of sea level based on benthic foraminifera are somehow problematic in the Western Mediterranean basin, being more straightforward using the direct record of past sea levels supported by local stratigraphic, geomorphological, and paleontological evidence.

The particularities of our proposed eustatic curve must be discussed in comparison with other curves published for Mallorca Island (Butzer & Cuerda, 1962; Butzer, 1975; Cuerda, 1975; Pomar & Cuerda, 1979; Hearty *et al.*, 1986; Hearty, 1987). With respect to the Neothyrrenian (MIS 5a) transgressive peak, no relevant discrepancies occur. However, for the Euthyrrenian (MIS 5e), major differences can be noted. In particular, Cuerda (1975) and Butzer (1975) report Euthyrrenian marine levels up to +11/+14 m ASL, but no evidences of sea levels higher than +2.5/+3 m ASL during MIS 5 have been found in the course of our investigations. This can only be explained if the duration ascribed to the Euthyrrenian by Cuerda (1975) and Butzer (1975) is taken into account. These authors consider that the Euthyrrenian period lasted from 230 to 100 ka BP, so including MIS 7. Over this time period (namely, the penultimate interglacial), only one high stand has been recorded in POS at +5/+6 m ASL, about 232 ka BP (Ginés, 2000; Vesica *et al.*, 2000).

5.2.4. Additional considerations on MIS 5a high stand

Recently, new insights on the ~81 ka BP high stand (MIS 5a) recorded in Mallorca have been provided by Dorale *et al.* (2010). These authors study POS encrustations collected from +1.3 to +1.6 m ASL in five different caves of southern and eastern coasts of the island, obtaining TIMS U/Th ages ranging from 82.0 to 80.1 ka BP. These geochronological data undoubtedly confirm the existence of a sea-level stand higher than the current one during MIS 5a, as was previously recognized by Tuccimei *et al.* (2006). 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.

If interpreted solely as a change in ice-equivalent sea level, the presence of MIS 5a POS at an elevation >1 m ASL conflicts with reconstructions based on raised coral reefs from uplifting coasts as Barbados or New Guinea (Gallup *et al.*, 1994; Lambeck & Chappell, 2001). However, the relative sea level changes at a given site reflect not only changes in global ice volume but also the response of Earth to changes in surface loading in the form of surface deformation and geoid changes (Lambeck & Chappell, 2001; Mitrovica & Milne, 2002), as well as local Global Isostatic Adjustment (GIA). The Mediterranean Sea is an intermediate-field basin, moderately distant from former major glaciation centers. Thus, the +1.5 m high stand at 81 ka BP in Mallorca may plausibly contain a significant effect of GIA, associated to Northern Hemisphere ice sheet history. But, in this respect, Dorale *et al.* (2010) propose that the GIA effects have been overestimated for this region, suggesting the possibility that Mallorca occupies a narrow transition zone between regions of emergence and submergence in the Mediterranean Basin, where sea level nearly follows the eustatic curve. This point of view was recently substantiated by Tuccimei *et al.* (2012).

From the data on Mallorcan POS supplied by Tuccimei *et al.* (2006), Onac *et al.* (2006), Hodge *et al.* (2008), and Dorale *et al.* (2010), it seems well-constrained that MIS 5a sea level high stand involved a very rapid ice melting leading up to this event, which had an estimated duration of maximum 4 ka, from 84 to 80 ka BP. The rates of sea level change were very fast, being comparable to the meltwater pulses of the last major deglaciation (Edwards *et al.*, 1993).

The simple interpretation of these data implies that an eustatic high stand during MIS 5a occurred at 1.3-1.6 m above present sea level. This notion implies less ice on Earth 81 ka ago than today. Furthermore, the suggestion that MIS 5a sea level was slightly higher than present, and only slightly lower than the MIS 5e sea level, implies that most of the ice built up during MIS 5b would have melted during the onset of MIS 5a. The 84 to 80 ka timing of this high stand closely match the June 60°N insolation peak at 84 ka BP, a pattern consistent with the Milankovitch model. The data from Mallorca –and from other sites around the world– gives solid support to the existence of a high stand at ~81 ka BP; if this is true, the 100 ka cycle so universally accepted as the main rhythm of the Middle and Late Quaternary glaciations, in fact, applies rather poorly to ice growth and decay, but much better to carbon dioxide, methane, and temperatures recorded by polar ice (Toggweiler, 2008).

5.2.5. Patterns of sea level changes in Mallorca during MIS 5

The availability of samples of submerged POS provides new data regarding low sea stands during the Upper Pleistocene, a poorly documented aspect of the sea level history in the Western Mediterranean. It is also feasible to determine some new information on the pattern and rates of sea level change, based on U-series ages performed on the POS alignments supporting the eustatic curve discussed in this paper.

Sea level fluctuations during the Last Interglacial seem to occur in the following pattern: periods of sea stands (long enough to allow the formation of POS at a given elevation) alternate with rapid sea level changes (positive and negative), greater than 18 m in amplitude, occurring within intervals shorter than 5 ka. An approximation of the duration of sea stand episodes can be deduced from the above referred dates of Holocene POS (Tuccimei *et al.*, 2010), now growing at the present sea level in numerous littoral caves of the island; these U-series age determinations suggest that at least more than 1 ka of sea level stabilization may be necessary for the formation of a significant POS encrustation. It is worth reminding the reader that the duration of the high stands 5e₂ and 5e₁ has been estimated on the order of 10 ka, on the basis of several high precision dates (Tuccimei *et al.*, 2006). This is consistent with an extended time of climatic stability during MIS 5e (136 to 124 ka BP), as also shown in the Devils Hole record by Winograd *et al.* (1997) in southwestern North America, partly overlapping with the episode here attributed to MIS 5e₂.

The rates of sea level changes that can be deduced from our data range from a minimum of 2.9 mm/year to a maximum of 20 mm/year, with average figures of 5.9 mm/year (Tuccimei *et al.*, 2006; Dorale *et al.*, 2010). These values have been inferred by taking into account the age calculated for each sample, without considering the quoted errors of the datings. The sea level drop that occurred during MIS 5e was presumably very fast; especially rapid was the rising trend associated with the onset of MIS 5e₁. In the same manner, the rise from MIS 5b to MIS 5a happened at the highest rate (>8 mm/year) throughout MIS 5. Such tendencies agree with quicker sea level shifts during transgressions as discussed by Harmon (1980). In general terms, the obtained rates are similar to those calculated by Harmon (1985) in Bermuda Islands, 3.5-6.0 mm/year.

5.2.6. Incidence of local tectonics

The eastern littoral area of Mallorca has proven to be suitable for sea-level change studies because it is considered tectonically stable, although affected by some recent minor tectonic activity. U-series dating of emerged POS demonstrated a maximum of 1 m vertical displacement among encrustations formed during MIS 5e and 5a in several caves (Fornós *et al.*, 2002). These authors have discussed the slightly different elevations of coeval POS samples, in light of other regional geomorphological, structural, and stratigraphical evidence. This approach has outlined a general tectonic tilting of the eastern part of Mallorca, with a maximum displacement of 1.5 m, which results in progressive lowering of the southern end of the island. The proposed tilting has occurred, at least partially, after MIS 5a, because the deposits of that age also seem to be affected. The rate of tectonic lowering was evaluated at 0.02 mm/year (Fornós *et al.*, 2002).

These small tectonic disturbances can be considered negligible with respect to the fluctuation amplitudes existing between the high and low stands recorded in the studied caves; therefore, the Mallorcan POS arise as valuable and accurate proxies of sea level in the Western Mediterranean basin, at least during Holocene and Upper Pleistocene times. Within this context, and taking into account the fact that MIS 5e POS deposits are located at a mean height of +2 m ASL –hence, not substantially uplifted by tectonic movements–, the presence of MIS 5a encrustations between +1.3 and +1.9 m ASL, clearly indicate a sea stand higher than the current one that is not, by any means, the result of tectonic uplifting of deposits precipitated at lower elevations. In other words, it is implausible that MIS 5a deposits could have been significantly elevated by tectonics while MIS 5e deposits were not.

6. Additional chronological approaches

Recently, additional studies were directed towards the ^{14}C dating of Holocene POS. The aim of these investigations was to compare the ^{14}C and U/Th ages previously obtained and determine whether incorporation of dead carbon inherited from the dissolution of ^{14}C -free limestone poses any problems. Generally speaking, the ^{14}C ages are consistent with those generated by U/Th dating (Tuccimei *et al.*, 2011), although some of the results prove to be site dependent and linked to the local residence time of waters. In the case of Cova de Cala Varques samples, ^{14}C and U/Th ages are coincident within the error range (2.8 to 1.1 ka and 2.8 to 0.3 ka BP, respectively). In Cova des Pas de Vallgornera, ^{14}C ages are steadily 2.3-2.4 ka older than the U/Th data (4.1 to 3.0 ka vs. 1.8 to 0.6 ka BP) a fact that was linked to higher values (~25%) of dead carbon estimated for these samples. Nevertheless, the constant differences between the two data sets and the fairly constant $\delta^{13}\text{C}$ values of the speleothem (around -5‰ VPDB) suggest that the system was stable over the entire growth period of the phreatic encrustation. It seems that the use of radiocarbon dating in POS geochronological studies is promising, but in some situations might be problematic due to the so-called reservoir effect. Obviously, its use is restricted to the investigation of Last Glaciation and post-glacial samples.

During the 1980s, attempts were made to apply ESR dating techniques to the study of Pleistocene POS from Mallorca. These investigations were focused on the very complex record existing in Cova de sa Bassa Blanca (Alcúdia), where an extensive sampling campaign was completed in 1981 including the extraction of 25 horizontal drill-cores from the walls of the cave (Maroto & Font, 1981; HADES, 1985). The ESR measurements were conducted by Grün (1985, 1986) on the 190 cm long core SBB/S21, collected 8 m above present-day sea level. This author proposed that the analyzed sequence of carbonate precipitates –mostly phreatic in origin, but also showing alternate layers of vadose flowstone– covers a time span ranging from 700 to 200 ka BP, hence going back from the earlier times of the Middle Pleistocene to the MIS 7. Some U/Th ages were also obtained in order to constrain the chronology of the core; these investigations concluded that the deposition of the outer part of the sequence took place during the penultimate interglaciation.

In this collaborative research carried out in the 80s with G.J. Hennig, eight different samples were measured (Ginés, 2000) ranging from the Holocene encrustations of Cova de Cala Varques A to some Middle Pleistocene POS from caves in the northeastern coasts of Mallorca. The results were inconsistent in general, except for the postglacial sample from Cova de Cala Varques A (accumulated dose <1 krad). Most of the measured samples yielded accumulated doses in the range of 10 to 27 krad, pointing to a Middle Pleistocene chronology (MIS 7 to 11, presumably), which is not contradictory with the scarce and inaccurate U/Th data available on the same samples (Hennig *et al.*, 1981; Ginés & Ginés, 1989, 1993a). Particularly inconsistent are the ESR measurements of two samples from Coves Petites, collected at elevations of +30 and +40 m ASL, but with very low accumulated doses of 6 and 7 krad respectively; it seems that intense recrystallization processes are responsible for the rejuvenation of these POS, otherwise clearly Middle Pleistocene in age. After an initial enthusiasm in using this geochronological method, scientists are aware about its serious limitations, particularly when computing the annual dose of radiation received by speleothems (Gillieson, 1996; Ford & Williams, 2007).

7. Additional paleoclimatic data

Significant paleoclimatic information is recovered from the rates of sea-level rise and fall discussed previously. A mean rate on the order of 6 m/ka was calculated for sea-level oscillations in Mallorca, linked to the climatic changes documented in our cave records. The obtained values imply that fluctuations of the Mediterranean Sea as high as 20 metres might occur in time spans shorter than 5 ka (Tuccimei *et al.*, 2006; Dorale *et al.*, 2010). In spite of the high rate shown by the fluctuating pattern deduced from our data, the formation of phreatic speleothem paleolevels requires that sea-level is stable long enough to allow the deposition of noticeable crystalline overgrowths. The length of these sea-stands may at least span a few thousands of years, as suggested by Tuccimei *et al.* (2006). The postulated fluctuation-stabilization pattern is further supported by the relatively stable sea-level at least since 2.8 ka BP (Tuccimei *et al.*, 2010, 2011); this steady state sea-level is recorded by a spectacular decimeter-size thick POS. Therefore, the deposition of similar bulky crystallization paleolevels (both at higher or/and lower elevations) requires the existence of some stable sea-stands,

related to relatively even climatic conditions that were stepping the fluctuating trend exposed in Figure 7.

The data on MIS 5 and 4 recovered from Mallorca's POS clearly show a complex series of dramatic paleoenvironmental changes, related to extreme climate shifts happened during the time interval 150 to 60 ka BP. The magnitude of thermal variations over this time period (Muller & MacDonald, 2000) is undoubtedly large enough to explain, in a satisfactory manner, sea-level decreases of at least 20 metres like those documented in the littoral caves of the island. In this sense, Rose *et al.* (1999) presented differences as high as 11°C between the mean temperatures calculated for the thermal maxima and minima across the entire MIS 5 in Mallorca. Furthermore, one cannot exclude the possibility that during some of the cold events documented in our record –particularly, MIS 5b and 4– regressive pulses could have been even greater than the ones predicted through our studies.

A limited number of oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) stable isotope analyses were performed on phreatic speleothems corresponding to transgressive peaks (Figure 8). The values obtained from the growing bands of some samples belonging to MIS 5, show an isotopic evolution towards heavier compositions through the warm substages 5a and 5e. Vesica *et al.* (2000) explain this trend as a result of excessive marine water intrusion in the geochemical system of the cave ponds, linked to increasing aridity.

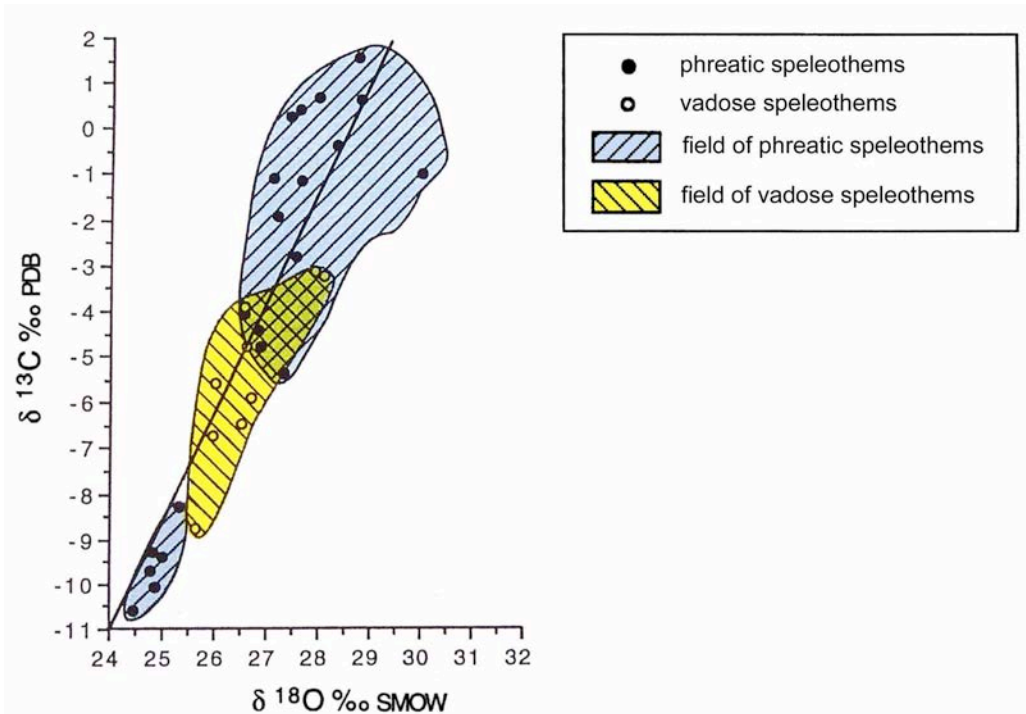


Figure 8. Some data on stable isotopes: $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ of different kinds of speleothems and their relative fields (from Vesica *et al.*, 2000). The correlation coefficient of the regression line is 0.89.

Similarly, Durán & López (1999) also found climatic evidence of notable aridity during MIS 5, whereas in the next cold stage (MIS 4) there are reliable evidences of a significant hydrological activity (increase of precipitation) over the endokarstic systems from southern Spain. These paleoclimatic interpretations may surface some controversy on the usual assumption that –in this geographical area– the interglacial periods correlate with events of high rainfall rates (Cuerda, 1975; Rose *et al.*, 1999). The fact we have not been able, until today, to perform stable isotope analyses on POS samples collected below the current sea-level, hinders the possibility of attaining additional information on the environmental depositional conditions that prevailed during the Upper Pleistocene cold events.

Finally, it must be mentioned the study of Csoma *et al.* (2006) on a 122 cm long core (SBB/S24) drilled out from the walls of Cova de sa Bassa Blanca, 8 m above the current sea level. The complex sequence hosted by this cave includes episodes of phreatic aragonite precipitation alternating with phases of vadose flowstone deposition. Stable isotope analyses conducted on vadose speleothems show a slight increase of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ towards higher values, which indicate their deposition during cold climate events when seawater $\delta^{18}\text{O}$ became more positive. Concerning the phreatic precipitates, it appears that local geochemical conditions (CO_2 degassing, depth below the water table, etc.) are the main controls on their stable isotope values, rather than the linear mixing between meteoric and marine end-members. Csoma *et al.* (2006) attributed the presence of aragonite in the phreatic deposits to episodes characterized by a reduced meteoric recharge during different interglacial stages.

8. Mineralogical and crystallographic aspects

The petrology, mineralogy, and crystallography of POS are topics still not investigated in depth. Nevertheless, some pioneering contributions more or less extensive and detailed were published a few decades ago (Pomar *et al.*, 1976, 1979; Ginés *et al.*, 1981b; HADES, 1985). Furthermore, some recent studies have been published on the Middle Pleistocene deposits from Cova de Sa Bassa Blanca (Csoma *et al.*, 2006) as well as on Upper Pleistocene crystallizations from different caves of eastern Mallorca (Ginés, 2000; Ginés *et al.*, 2005). The mineralogical, textural, and crystallographical aspects of POS, based on samples used for our geochronological investigations are presented in the paragraphs below.

8.1. Mineralogy

The mineralogy of different growth layers corresponding to 13 phreatic speleothems was determined by XRD semiquantitative techniques (Ginés *et al.*, 2005). From each POS specimen, two to five sub-samples were recovered, depending on the complexity of the speleothem and the thickness of the phreatic overgrowth; all analyzed samples were collected from the phreatic encrustation, whereas the vadose support of these crystallizations were not sampled.

The mineralogical data are assembled in Table IV, along with the U/Th ages of the samples and the geological setting from each cave. Calcite is the dominant phase, in

particular high-Mg calcite (HMC) whose magnesium content is comprised between 4 and 11%. Only a few samples are composed of low-Mg calcite (LMC) or by HMC calcite with Mg values higher than 11%. The second more frequent mineral is aragonite (a CaCO_3 polymorph) that exceeds 70% in several samples.

Dolomite $-\text{CaMg}(\text{CO}_3)_2-$ is always irrelevant from a quantitative point of view (<5%), although in two samples, it reaches values higher than 10%. Its presence could be related, in all cases, to the dolomitic character of the cave hosting rocks. Quartz has been detected (<5%) exclusively in the outer layer of one speleothem, therefore linked probably to an exogene source.

Considering the POS ages, one can note that the aragonite crystallizations were formed only in different MIS 5 high sea stands. This fact could support the paleoclimatic significance of aragonitic mineralogy, which would be linked to warmer periods (Pomar *et al.*, 1976; Ginés *et al.*, 1981; HADES, 1985; Ginés, 2000; Vesica *et al.*, 2000).

Although the mineralogical variability in the marine carbonates as a consequence of different water temperatures is well documented (Mitsuguchi *et al.*, 1996; Marshall & McCulloch, 2002), the real situation in the littoral cave environments appears to be much more complex (Ginés, 2000). It is therefore, necessary to take into account that among the investigated speleothems corresponding to MIS 5 there are abundant deposits of calcite, a fact that does not support the existence of an unambiguous causal relationship between aragonite precipitation and interglacial thermal maximum. Within this context, Rao (1996) and Hill & Forti (1997) highlighted the participation of many different factors –in addition to high temperatures– which control the deposition of aragonite in the subterranean environment: Mg and Sr content of waters, saturation of the solutions, evaporation processes, pCO_2 , salinity, concentration of Ca, etc. Following this argument, it is feasible to consider the effect of other variables, potentially related to climate, which control the kinetics of aragonite deposition; for example, low Mg/Ca ratios in the solutions favor the precipitation of calcite, whereas Mg/Ca ratios higher than 4.4 cause the deposition of aragonite (Folk, 1974; Hill & Forti, 1997). Consequently, the presence of this mineral could identify important information on sea water intrusion (high ratio Mg/Ca) that could be related to periods of marked aridity. In conclusion, the precipitation of aragonite during MIS 5 should be perceived as a potential paleoclimatic indicator, regardless the mechanism controlling its deposition (i.e., relatively high mean temperature or significant saltwater intrusion associated with low rainfall; Vesica *et al.*, 2000).

8.2. Crystallography

The description of the samples included in Table IV was undertaken in order to propose a classification (Figure 9) that attempts to relate the crystallographical aspects the mineralogy and morphology of the phreatic speleothems. As a general observation we note that the crystals size making up the POS tend to be equant and they appear relatively homogeneous in successive depositional bands. In certain cases, inequicrystalline aggregates are observed, often involving superimposed micrometric-size calcite crystals on fibro-radial acicular aragonite crystals whose size is millimetric to centimetric (Figure 10a).

Table IV. Mineralogical semi-quantitative data corresponding to POS samples collected in littoral caves of Mallorca (data from Ginés *et al.*, 2005). VB: Cova de Cala Varques B; FA: Cova de Cala Falcó; DI: Cova del Dimoni; SE: Cova des Serral; PI: Coves del Pirata; PO: Cova des Pont; all of them in Manacor municipality. BA: Cova de na Barxa; MI: Cova de na Mitjana; both in Capdepera municipality. a: outer subsample; b - e: subsamples obtained sequentially towards the inner part of the speleothem.

Sample	Calcite			Aragonite	Dolomite	Quartz	MIS	Geological setting
	LMC < 4% Mg	HMC 4-11% Mg	HMC >11% Mg					
VB-SA	a	—	100.00	—	—	—		
	b	—	100.00	—	—	—	1	m
	c	—	100.00	—	—	—		
VB-D2	a	—	100.00	—	—	—		
	b	—	100.00	—	—	—		
	c	—	100.00	—	—	—	5a	m
	d	—	100.00	—	—	—		
	e	—	100.00	—	—	—		
FA-D3-4	a	—	23.85	60.18	2.62	13.35		
	b	—	11.73	—	85.64	2.63	5a	m
	c	—	12.68	—	82.32	5.00		
DI-D3	a	—	—	—	98.00	2.00		
	b	—	53.59	—	45.61	0.80	5e	m
	c	—	1.88	—	94.77	3.35		
	d	—	25.95	—	74.05	—		
DI-D1-1	a	—	28.03	—	68.71	3.26		
DI-D1-1	b	—	44.48	—	54.12	1.40	5e	m
	c	—	74.74	—	25.26	—		
	SE-D2	a	—	100.00	—	—	—	
SE-D2	b	—	100.00	—	—	—	5e	m
	c	—	100.00	—	—	—		
	PI-D1	a	—	100.00	—	—	—	5e
PI-D1	b	—	100.00	—	—	—		
	PO-D2	a	—	100.00	—	—	—	5e
PO-D2	b	100.00	—	—	—	—		
	BA-D3	a	63,44	—	—	34.92	1.64	
BA-D3	b	—	—	90.76	1.30	7.94	5e	Mz
	c #	—	95.50	—	—	4.50		
	d	—	—	81.60	—	18.40		
	MI-D1	a	—	100.00	—	—		
MI-D1	b	—	100.00	—	—	—	7 ?	Mz
	c	—	100.00	—	—	—		
	d	—	100.00	—	—	—		
	MI-D2	a	—	100.00	—	—		
MI-D2	b	—	100.00	—	—	—	7 ?	Mz
	c	—	100.00	—	—	—		
	MI-D3	a	—	100.00	—	—	—	
MI-D3	b	—	100.00	—	—	—	9 ?	Mz
	c	—	100.00	—	—	—		
	DI-D4	a	—	41.02	52.62	1.02	0.46	4.88
DI-D4	b	—	100.00	—	—	—	without dating	m
	c	—	100.00	—	—	—		

traces of clay minerals
m Upper Miocene calcarenites **Mz** Mesozoic limestones

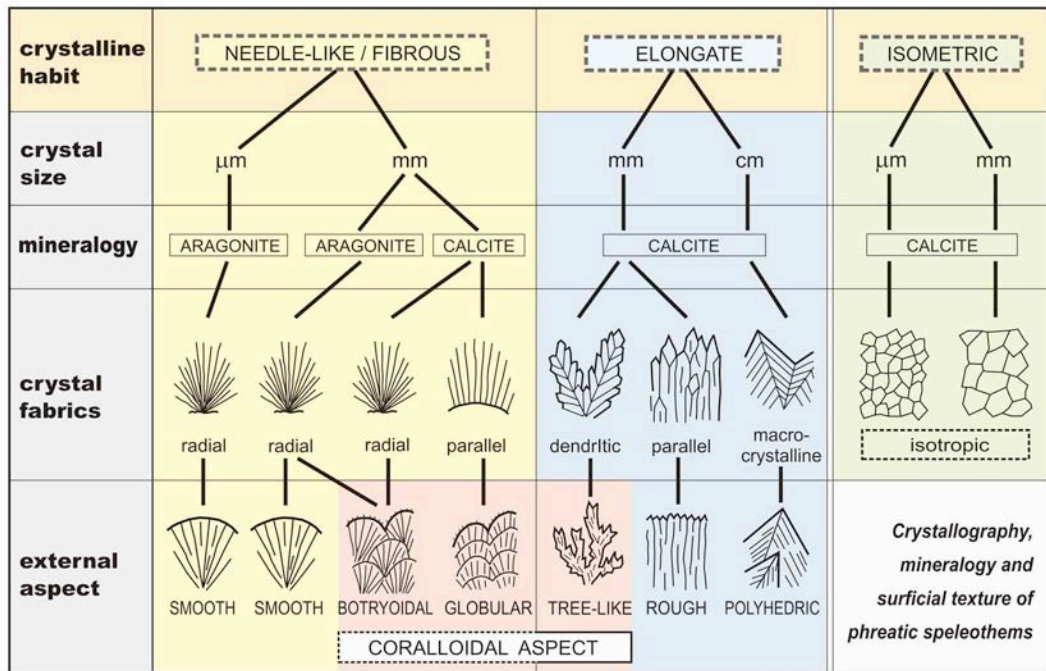
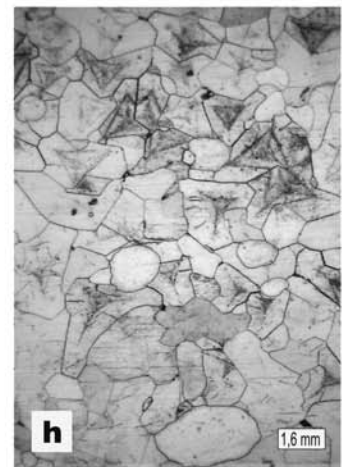
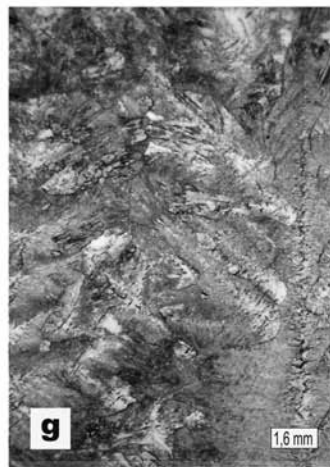
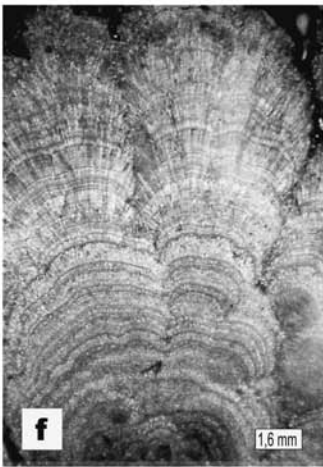
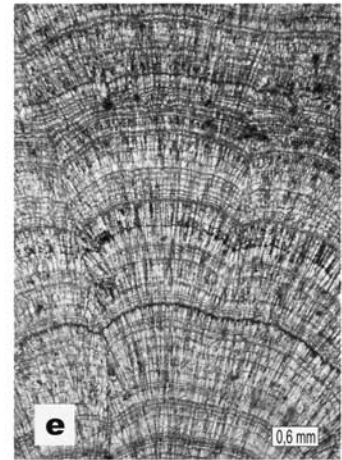
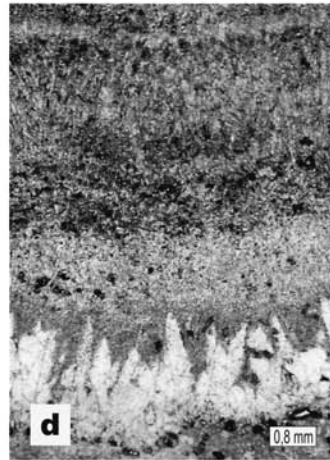
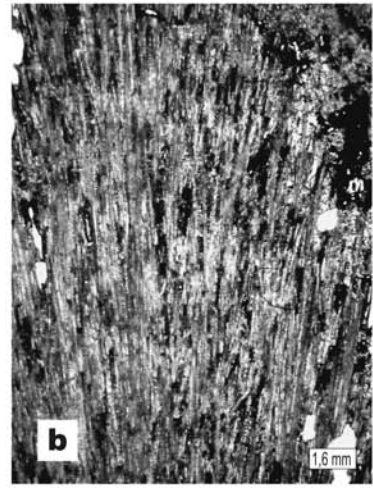
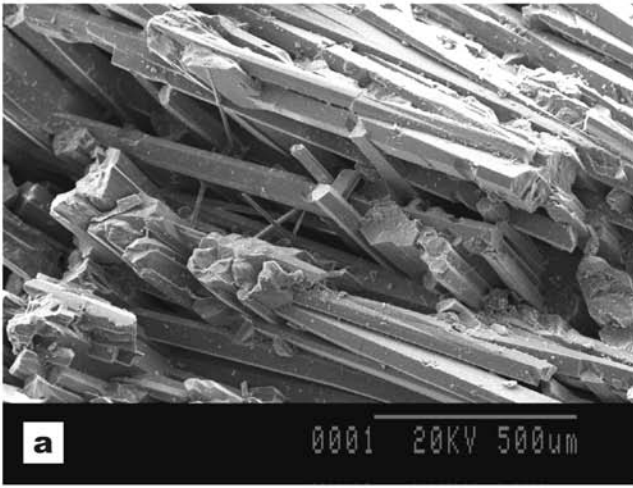


Figure 9. Synthesis of the results obtained from some textural researches about phreatic crystallizations of Mallorcan caves (according to Ginés *et al.*, 2005).

Both with naked eyes and under the microscope, it is always possible to observe the radial-fibrous/acicular fabric of aragonite speleothems (Figure 10b). This fabric is the result of the aragonite crystals arrangement around the inner vadose support (upper part of Figures 10c and 10d). The resulting external morphologies of aragonite POS are rounded and smooth, yielding in some cases encrustations that are rather botryoidal, due to the fibro-radial aggregates of millimetric crystals that often constitute hemispheric bumps. On the other hand, crystallizations made up of calcite fall roughly into three main habits: fibrous, elongated, and isometric (Figure 9). The first two habits produce fabrics related to the competitive growth of crystals, which takes place whenever the growth vector is perpendicular to the substrate (Chafetz *et al.*, 1985, González *et al.*, 1992).

Figure 10. (next page) Microphotographs of some POS samples (after Ginés *et al.*, 2005). a: SEM image of an aragonitic sample from Cova des Pas de Vallgornera (Llucmajor); b, c: radial aggregates of needle-like aragonite crystals (sample DI-D4; Cova del Dimoni, Manacor); d: micrometric calcite crystals covered with successive layers of aragonite needles (sample FA-D3-4; Cova de Cala Falcó, Manacor); e, f: fibrous calcite crystals forming aggregates of parallel fabrics and globular morphology (sample VB-SA; Cova de Cala Varques B, Manacor); g: elongate calcite macrocrystals that build up speleothems with a polyhedral surface (sample MI-D2; Cova de na Mitjana, Capdepera); h: millimetric crystals of isotropic calcite, corresponding to the inner layers of a phreatic overgrowth (sample PO-D2; Cova des Pont, Manacor).



The fibrous calcites, with small crystals of millimetric size, produce two kinds of fabrics: radial and parallel. The radial fabrics are entirely similar to those observed in the crystallizations of aragonite, consisting of bundles of fibrous crystals growing divergent from specific points of nucleation. The parallel fabrics (Figure 10e) show a growth pattern perpendicular to the support or substrate, pattern that in the outer layer of the speleothem can generate structures morphologically similar to radial aggregates (Figure 10f). The external appearance of the two fabrics often converges, resulting in rounded protuberances of globular or botryoidal aspect whose sizes are centimetric.

The calcite deposits arranged in aggregates of large elongated crystals, with sizes millimetric to centimetric (see Figure 9), creates three basic types of fabrics: dendritic, parallel, and macrocrystalline. On the one hand, large rhombohedral euhedral crystals are organized in fabrics that build up speleothems of branching structure and dendritic appearance. This class of deposits resembles the coralloid speleothems described by Hill & Forti (1997) in a broad sense, although the globular and botryoidal morphologies, related to fibrous crystalline habits, can also resemble coralloids in the most extreme cases of their development. Secondly, there are parallel calcite fabrics which result in rounded and bulky speleothems, but with an uneven surface due to the small faceted crystals macroscopically observable on its outside part. Finally, it is worth mentioning the spectacular overgrowths whose external morphology display striking polyhedral facets due to the calcite macrocrystals on millimetric to centimetric scales (Figure 10g).

The isometric calcite crystallizations seem to be limited to equicrystalline aggregates (Figure 10h). They only occur in the early growth bands of the phreatic speleothems and are associated with abundant nucleation points.

The broad crystallographic variability observed (Figures 5 and 10) involves a complex web of physical and chemical parameters –temperature, $p\text{CO}_2$, saturation index, Mg^{2+} content, water movement, etc– that control the mineralogy and size of precipitated crystals, as well as their growth rates (Folk, 1974; Giménez & Taberner, 1997; Schneidermann & Harris, 1985). Therefore, much more studies need to be carried out in order to shed light on this aspect of POS.

9. Conclusions: state-of-the-art and future perspectives

The time span elapsed since the beginning of our studies on POS of Mallorcan caves –about 40 years– allowed us to gain a proper perspective on the geochronological relevance and possible limitations concerning this particular record of the sea level history. Based on a remarkable set of geomorphological and U/Th data produced since 1972, today is possible to emphasize the reliability of this special proxy for Quaternary sea-level reconstruction. The radiometric dating programmes confirmed the Holocene age for the POS deposited around the current sea level (Tuccimei *et al.*, 2010, 2011), as well as the general stratigraphic consistency of the U/Th dates on all the other samples covering the Upper Pleistocene (Tuccimei *et al.*, 2006).

The analytical results also pointed out the possibility that neomorphic processes affecting the POS might be responsible for some of the inconsistent ages obtained by means of U/Th dating method. In this respect, the recrystallization processes that affect certain speleothems are relatively more frequent among the samples that are older; especially those of Middle Pleistocene age (Ginés, 2000).

To the above-mentioned problems, post-depositional diagenesis of the isotopic content of some POS samples also need to be considered. These processes seem to be relatively common for most of the speleothems collected below the present sea level (i.e., corresponding to regressive events). It seems reasonable to predict that the prolonged and repeated immersion of these POS in the coastal mixing zone caused, in some cases, the partial dissolution of these deposits (i.e., open geochemical system), triggering all the dating problems that this process entails. To minimize such problems, several age determinations were conducted on each speleothem. Doing so, the lack of samples out of stratigraphic order confirmed that the geochemical system remained closed.

Regarding the paleoclimatic data that POS can provide, it is necessary to recognize some important limitations related to the fragmentary nature of this record. This is because both in time and space, each marine sea-stand is only documented by the period of stabilization of the coastal water table at a given elevation. Obviously, this means that there is not a continuous record of POS over the last 500 ka. Therefore, stable isotope data obtained are scarce and poorly illustrative. However, this does not diminish the possibility of obtaining detailed paleoclimatic data, particularly in what concerns specific geochronological events such as the Holocene sea level or the high sea stands related to the Last Interglacial, for instance.

So far, the geomorphological and chronological data set accumulated during the last four decades, has allowed the reconstruction of a fairly detailed eustatic curve in the Western Mediterranean basin for the time span between 150 and 60 ka BP (Tuccimei *et al.*, 2006). This curve highlights the existence of a high sea level stand ~81 ka ago, during MIS 5a (Dorale *et al.*, 2010), a finding that is criticized by some scientists, because GIA was not used to reconcile this high stand.

In the current state of knowledge, it becomes increasingly clear that the study of coastal phreatic speleothems (POS) constitutes a new tool with established validity for the study of sea level history in limestone coastal areas. This particular kind of speleothem encrustations favorably complements the conventional littoral records (beaches, ancient shorelines, coastal fossil deposits, etc.), providing even more accurate data on the elevation of the coastlines and the magnitude of tidal fluctuation. In addition, the geographic setting (karst caves) of this type of phreatic crystallizations protects them against dynamics that marine erosion imposes to the evolution of the coastline. Undoubtedly, the data supplied by the POS deposits existing in coastal caves from other parts of the world could contribute important data to the global sea level history, effectively complementing other proxy records. With over one third of the world's population living within coastline regions, understanding the history and future impacts of global sea-level change ranks as a top priority in the Earth Sciences.

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Late Quaternary Sea-level History: a Speleothem Perspective

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1. Background

Among the many impacts associated with impending climate change, those related to rapid sea-level rise are of immediate concern to society (Alley *et al.*, 2005). Today, over one third of the world's population lives along low-lying coastal areas, and for these areas, future sea-level rise (even small amounts) will generate substantial societal and economic impacts (Milne *et al.*, 2009). How quickly sea level rises is among the more pressing concerns, and for the coming centuries, this prediction basically remains an unresolved issue.

In the broadest sense, global sea level is an important integrative measure of the climate state of the Earth. Sea level variations involve the transfer of water between ice sheets and oceans (Figure 1, inset). The history of sea-level change contains valuable information on the possible magnitudes and rates of this transfer. Thus one approach for assessing future vulnerability to rapid sea level rise is to improve our understanding of the forcing mechanisms and responses of past events.

Sea-level history also indicates considerable spatio-temporal variations that contain information not only about climate but a number of solid-Earth processes. This is because relative sea-level change at a given site reflects not only changes in ice volume variations (eustatic variations), but also the response of the Earth to changes in surface loading in the form of surface deformation and geoid changes, or "glacial isostatic adjustment" (GIA) (Lambeck & Chappell, 2001; Mitrovica & Milne, 2002). Eustatic sea-level reconstructions require accurate models of GIA, which in turn require prescriptions of ice sheet history (including distribution, volume, and duration of former ice loads) and Earth's rheological properties (e.g., lithospheric and mantle heterogeneities, viscosity). Recent studies have pointed out that even when all of the available relative sea level data for the last 6000 years are

incorporated in two distinct global surface load models, it is impossible to discern between homogeneous and heterogeneous GIA models (Spada *et al.*, 2006). Therefore, Milne (2009) concluded that most models are affected by errors that depend on the accuracy of each model prediction for a given site.

Because uncertainties of some type are inherent not just to models but to all of the methodologies and settings of past sea level reconstructions, there is a continued need for additional, independent sources of sea-level data that might provide unique insight and cross-checks to the existing framework of past eustatic changes in sea level. When we consider the pressing concern posed by rising sea levels to our coastal communities, there is a particular urgency for improving our understanding of past, present, and future sea-level variations.

2. Sea level reconstruction: methods and limitations

Evidence of past sea levels comes in many forms, each with certain strengths and weaknesses (Siddall *et al.*, 2007). The method that allows for a *continuous* sea-level reconstruction is based on the interpretation of $\delta^{18}\text{O}$ variations recorded by

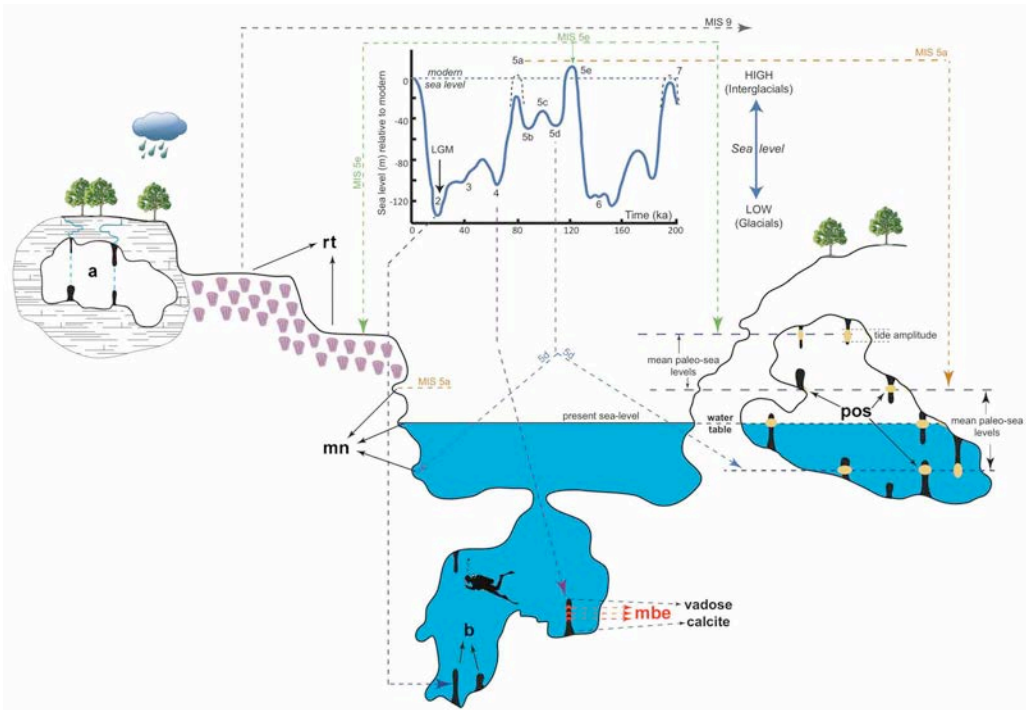


Figure 1. Composite diagram showing how speleothems form in vadose caves (a) along with various proxies used to reconstruct past sea-level stands: submerged speleothems (b); submerged speleothems with marine biogenic encrustations (mbe); phreatic overgrowths on speleothems (pos); marine notches (mn); reef terraces (rt). The glacial/interglacial sea level history (adapted from Shackleton & Opdyke, 1973 and Imbrie *et al.*, 1984) is shown in inset.

calcareous foraminifera in deep marine sediments (Shackleton, 2000; Lea *et al.*, 2002). The lighter ^{16}O isotope is preferentially evaporated from oceans and accumulates in ice sheets. As ice volume increases, seawater is progressively enriched in ^{18}O (Dansgaard *et al.*, 1984). In addition to the ocean isotopic composition, ocean water temperature is also a determining factor in the $\delta^{18}\text{O}$ value of foraminiferal calcite. These two unknown variables (ice volume and temperature) cannot be resolved explicitly without making assumptions about ice $\delta^{18}\text{O}$ and the ocean temperature structure (Shackleton, 1987), and therefore some error associated with these assumptions is inherent to this particular method of sea-level reconstruction. Furthermore, while the continuous character of deep sea $\delta^{18}\text{O}$ variations is a clear strength, the dating is not absolute, and relies on assumptions of the Milankovitch Theory of Earth's orbital forcing on global ice volume changes (Milankovitch, 1941; Shackleton & Opdyke, 1973; Hays *et al.*, 1976).

The $\delta^{18}\text{O}$ values of deep sea sediment foraminifera carbonates is an *indirect* measure of past sea level (Shackleton & Opdyke, 1973; Imbrie *et al.*, 1984; Figure 1 inset). A fundamentally different approach focuses on *direct* sea level estimates provided by markers that document the former position of sea level via either erosion (e.g., wave cut notches) or deposition (e.g., sand barriers, coral reefs, and speleothems; Figure 1). Unfortunately, most direct sea level techniques provide *discontinuous* records of sea level change.

To date, the primary evidence of a close linkage between insolation forcing, ice sheet growth, ice sheet melting, and sea level change comes from the combined application of deep-sea $\delta^{18}\text{O}$, U/Th dated fossil coral reefs, marine terraces, archaeological observations, and U/Th dated submerged speleothems (Figure 1; Broecker & van Donk, 1970; Richards *et al.*, 1994; Hays *et al.* 1976; Hearty, 1998; Shackleton, 2000; Gallup *et al.*, 2002; Edwards *et al.*, 2003; Zazo *et al.*, 2003; Antonioli *et al.*, 2004; Alley *et al.*, 2005; Thompson & Goldstein, 2005; Dutton *et al.*, 2009a; Siddall *et al.*, 2009; Anzidei *et al.*, 2011; Muhs *et al.*, 2011; Thompson *et al.*, 2011). Thus, it seems clear that a combined approach utilizing the strengths and weaknesses of the various techniques is probably the best overall approach to accurately reconstructing past sea level.

Remarkable efforts were put into U/Th dating of fossil coral reefs, which capture the position of sea level directly and with absolute dating (Figure 1 rt). These are significant strengths, and along with the widespread nature of reefs throughout the warm regions of the world, explain why reefs have played a dominant role in Quaternary eustatic sea-level reconstructions. Yet a number of factors commonly hinder ultra-precise determination of both the height and the age of the sea level stand using fossil reefs (and reef records are highly discontinuous). Some of these factors include: 1) uncertainties of water depth above the reef (each coral species grows within a range of water depths of several meters to tens of meters; Ludwig *et al.*, 1996), 2) questions concerning the provenance of corals (i.e., in-situ or reworked; Kench *et al.*, 2009), 3) complications arising from the reef type, i.e., keep-up, catch-up, give-up (Neumann & MacIntyre, 1985), 4) lags between the timing of sea level change and the timing of reef growth (shown to be on the order of thousands of years in some cases; Hearty *et al.*, 2007), and 5) uncertainties on age estimates due to coral diagenesis (Henderson *et al.*, 1993; Edwards *et al.*, 2003). In addition to these,

reef reconstructions from tectonically active areas also contain significant uncertainties related to the rates and consistency of tectonic movements.

3. Cave deposits

3.1. Speleothem: Definition and Growth

The term *speleothem* (*cave deposit* in Greek) was first coined by Moore (1952) to define secondary minerals precipitated from chemical solutions or by solidification of a fluid **after** the cave formed. The word speleothem refers to the mode of occurrence (i.e., stalactite, stalagmite, flowstone, cave raft, etc.) of a mineral and not to its composition (Hill & Forti, 1997).

In most karst regions, carbonic acid is responsible for limestone dissolution (with very few exceptions; Palmer, 2007), and results from mixing of meteoric water with atmospheric and especially soil carbon dioxide. The acidified waters trickle down along fractures, fissures, or bedding planes and dissolve limestone bedrock. Speleothems are precipitated from such bicarbonate-rich percolating waters when these waters become supersaturated with respect to calcite or aragonite upon entering a cave passage. The driving force behind speleothem growth is degassing of CO₂ in the cave atmosphere, a process that is triggered by the difference between the partial pressure of CO₂ in the cave (10^{-2.5}-10^{-3.5} atm.) and soil (10^{-1.5} atm.). This implies that speleothems like stalagmites and flowstone can only form when caves are air-filled. However, even if caves remain air-filled, certain climate and hydrologic conditions (prolong drought, permafrost/ice cover, percolation of unsaturated water, river flooding, etc.) may prevent speleothem deposition. During such periods, hiatuses (periods of no speleothem deposition) are inferred from the petrography of the speleothems by the occurrence of corrosion surfaces and/or very sharp changes in color due to the presence of thin (mm to sub-mm) brownish detrital-rich laminae.

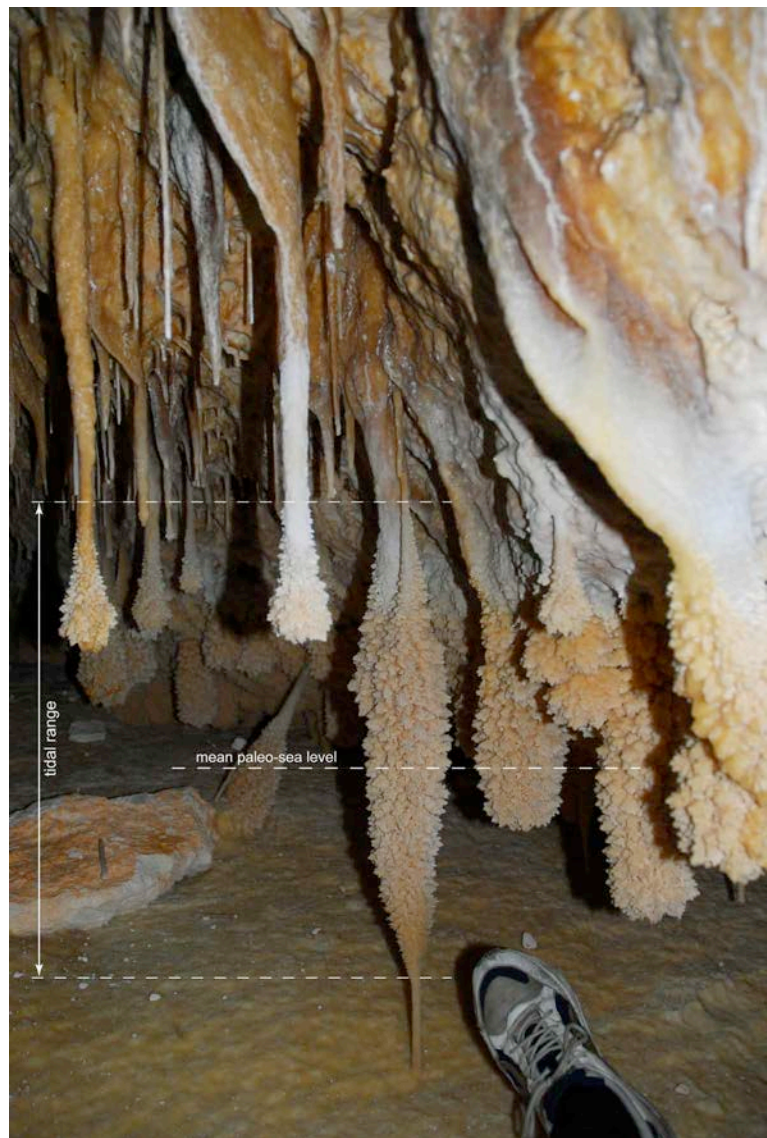
Because deposition of speleothems is closely link to the Earth's hydrosphere, biosphere, and atmosphere, they prove to be ideal paleoclimate and paleoenvironmental archives (Richards & Dorale, 2003; Lachniet, 2009; Fairchild & Baker, 2012). To date, a large and growing speleothem science literature exists, with a strong bias toward various qualitative and quantitative Quaternary climate change reconstructions. Studies utilizing speleothems to document earthquake activity, landscape evolution, biomineralization, or *sea-level changes* are comparably fewer. Here we focus on the application of speleothems to sea level change.

Proxies for cave-based sea-level reconstructions include biological, mineralogical, and sometimes, archeological records. While biological and archeological archives rarely provide a direct and precise measure of past sea-level elevation and timing, they can provide indirect qualitative constraints on these indices. Speleothems used for sea-level reconstruction are of three types: 1) ordinary stalagmites and flowstones that form sub-aerially (Figure 1a) and become drowned by rising sea level (Figure 1b and 2) submerged speleothems coated by biogenic encrustations (Figure 1 mbe), and

3) phreatic overgrowths on speleothems (Figure 1 pos; Ginés *et al.*, 1981), presented in detail in the previous chapter of this book.

The following discussion is intended to clarify some confusion regarding those vadose speleothems that contain carbonate overgrowths. There is a clear distinction between marine biogenic encrustations (see subchapter 3.2.2 below) and phreatic overgrowths on speleothems (see chapter 3 in this volume and subchapter 3.3 below). Keeping both terms under a general heading of “*marine overgrowths on speleothems*” (Ford & Williams, 2007) is misleading because biogenic encrustations are indeed marine in origin, whereas the POS are only forming in brackish water at and a few centimeters below present or a former sea level being exposed to minor tidal oscillations that are reflected in a particular morphology (Figure 2).

Figure 2.
POS in Cova des Pas de Vallgornera. The thickest part of the encrustation corresponds to the mean sea level, whereas the gradually decreasing up-ward and downward overgrowth reflects the tidal fluctuation.



Furthermore, POS should not be misidentified with the shelfstone, which is common in vadose caves as flat deposits attached to cave walls or speleothems in confined passages where the percolation water forms pools (Hill & Forti, 1997). These speleothems do record the past or present pool level via a number of distinct shelfstone horizons (mm to cm one below each other) but morphologically are very different from the POS (Figure 3a and 3b). We therefore suggest that when discussing these unique speleothem-based proxies for reconstructing sea levels to make a clear difference between the *marine biogenic encrustations* (Figure 4) and the *phreatic overgrowths on speleothems*.

3.2. Submerged speleothems

In an air-filled cave formed on a carbonate island, a variety of speleothems would commonly being precipitated as discussed above (Figure 1a). If sea-level rises and completely floods the cave, the growth of speleothem ceases. While submerged, speleothems may be preserved intact, or, a number of chemical and biological processes may affect the external and internal structure of the submerged speleothems, providing great visual templates for detecting growth hiatuses, which in turn help in deciphering sea-level changes. These features (sometimes very complex in nature at both macro- and microscopic scale) are highlighted by the 1) presence of corroded layers caused by dissolution at the halocline (Li *et al.*, 1989; Surić *et al.*, 2009), 2) existence of biogenic encrustations (Antonioli *et al.*, 2001; Figure 4), or 3) deposition of seawater precipitated minerals (e.g., halite, gypsum; Surić *et al.*, 2009).

The timing of initiation and cessation of speleothems growth is relatively easy to resolve applying U/Th measurements on carbonate material extracted from the



Figure 3. A (left): Multiple shelfstone levels in Lechuguilla Cave (Photo: A. Palmer). B (right): Present-day phreatic overgrowths on speleothems in Cova des Pas de Vallgornera, Mallorca.

Figure 4.
Submerged speleothem showing
marine biogenic encrustations
(Argentarola Cave, Italy; Photo: F.
Antonioli).



bottom and top of a speleothem. The obtained ages will roughly indicate when the cave was air-filled and then invaded by seawater (Li *et al.*, 1989; Richards *et al.*, 1994). Nevertheless, the precise elevation of the sea level stand will remain unknown unless additional information (e.g., marine organisms that colonizes very narrow habitats below sea surface) becomes available. After a preliminary study published by Spalding & Mathews (1972) on a submerged stalagmite from Ben's Hole (Grand Bahama Island), the idea of using such speleothems in reconstructing Quaternary sea-levels made headlines in journals such as *Science* and *Nature* (Gascoyne *et al.*, 1979; Harmon *et al.*, 1981; Li *et al.*, 1989; Richards *et al.*, 1994).

3.2.1. Submerged speleothems with or without growth hiatuses

The development of thermal ionization mass-spectrometry in measuring U-series isotopes (Edwards *et al.*, 1987) constituted a huge step forward from the α -spectrometric methods of the day. Employing this new technique and using samples of at least one order of magnitude smaller, Li *et al.* (1989) and Richards *et al.* (1994)

deciphered the changes in sea level over 280 ka and pinpointed the maximum sea level for the Last Glacial period in the Bahamas, respectively.

If corroded hiatuses exist along a given speleothem, their ages need to be constrained by U/Th technique, below and above them (Li *et al.*, 1989; Lundberg & Ford, 1994; Hodge *et al.*, 2008; Surić *et al.*, 2009). However, we have to keep in mind that even in a coastal cave setting, this particular type of hiatus (if not accompanied by burrows, biogenic encrustations, seawater precipitated minerals, etc.) is not always caused by sea-level fluctuation. Changes in hydrology and hydrochemistry above the cave may also result in either a temporary or permanent cessation of speleothems deposition. If one can safely document the hiatus is sea-level related, the carbonate layer underneath the hiatus indicates the minimum age for the timing of the rise in sea level that caused cessation of speleothem deposition by drowning. The growth of speleothems may resume at any time after the sea-level falls. Therefore, dating the newest carbonate layer immediately above each of these hiatuses provides a first-order estimation of when the cave became air-filled again, however it may take decades or millennia before specific climatic, land surface, and cave hydrology conditions allow the speleothems to commence their growth. Thus, such carbonate accumulations provide a relatively imprecise age constraint on the initiation of growth after sea level regression. In summary, while U/Th dating works very well to constrain the ages of these hiatuses, the method, really only documents the “moment” when a particular elevation within the cave became flooded or air-filled, not precisely when and where the water level was actually located throughout the bulk of the rise-fall cycle (Lundberg & Ford, 1994; Richards *et al.*, 1994; Surić *et al.*, 2009). Particularly in the case of sea level drop, the “moment” may be significantly compromised by unknown lags between the timing of sub-aerial exposure and the initiation of speleothem deposition. Therefore, caution is needed in interpreting the relationship between speleothem growth and sea-level history (Smart *et al.*, 1998; Dutton *et al.*, 2009a).

3.2.2. Submerged speleothems coated by/containing biogenic encrustations (\pm burrows)

Submerged speleothems that contain biogenic overgrowth crusts (e.g., serpulid worm secreted calcite) and/or preserve fragments of various boring organism shells refine the basic submerged speleothem technique. The first workers to explore this field was a team led by Gascoyne who documented a MIS 6 sea level low stand (at least 42 m below present level) between 160 and 139 ka based on five stalagmites recovered from a blue hole just east of Andros Island (Gascoyne *et al.*, 1979). Later, Alessio *et al.* (1992, 1996), generated a sea-level curve over the past 40 ka by radiocarbon dating marine biogenic carbonates precipitated on submerged speleothems from the central Tyrrhenian region of Italy. Antonioli & Oliverio (1996) recovered a stalagmite from a depth of -48 m in the Scaletta-Punta Iacco cave system (Capo Palinuro, Italy) that not only was bored by the date shell *Lithophaga lithophaga*, but at several locations the shells were actually sealed-in by the subsequently formed calcite. Considered an early colonizer of bare limestone (mainly in the low tide zone, but never below -20 m), this species indicates the time of marine transgression and hence inundation and submergence of the cave. Precise radiocarbon or U-series dating on such shells may provide supplementary data to help reconstruct local sea-level changes.

Figure 5.
Speleothem ASI from Argentarola
Cave (Italy). For details see the text
(Photo: F. Antonioli).



To date, the most detailed studies on stalagmites that show sequences of sub-aerial precipitated calcite (i.e., times of low sea-level stands) and marine biogenic overgrowths (serpulid colonies; corresponding to periods of highstands) were carried out by Bard *et al.* (2002) and Antonioli *et al.* (2004). Their work is based on a number of speleothems recovered from Argentarola Cave (Italy) from depths between -3.5 and -21.7 m below present sea-level. Particularly important was stalagmite ASI (Figure 5), which displayed five marine and four terrestrial calcite layers that allowed the authors to generate the history of sea-level changes over the past 215-ka. From the very same cave, using two additional submerged speleothems, Dutton *et al.* (2009a) documented three sea-level highstands between 245 and 190 ka (MIS 7).

Similar studies (some combining submerged speleothems with archeological markers) have been undertaken on the western Mediterranean (Ginés *et al.*, 1975), Tyrrhenian Sea (Antonioli *et al.*, 2001), Ionian Sea (Scicchitano *et al.*, 2008; Dutton *et al.*, 2009a, b), and on the eastern seaboard of the Adriatic Sea (Surić *et al.*, 2005, 2009).

Apart from their implications in reconstructing sea-level oscillations over various parts of the Quaternary, the submerged speleothems also provided tectonic uplift rates for many regions within the Mediterranean basin. Last but not least, the compilation of a large submerged speleothem-based sea-level dataset helps inform the glacio-hydro-isostatic models.

One advantage of using submerged stalagmites is that they allow estimation of past low sea level stands (lower than today) in both interglacial and glacial periods. Such information is critical especially in tectonically stable regions (Bahamas, part of the Mediterranean Basin) where evidence (marine and/or reef terraces) is not exposed above sea level the way it is in uplifting coastline regions (e.g., Huon, Barbados, Haiti).

3.3. Phreatic Overgrowths on Speleothems (POS)

Because this topic is abundantly discussed in the previous chapter of this book, only a brief presentation is given here. The coastal caves of Mallorca provide an extraordinary setting for capturing past sea-level changes. Along its eastern and southern coast, the interaction between freshwater and seawater produces a geochemical environment that allows caves and speleothems to develop in a unique manner (Myroie & Carew, 1990; Ginés, 1995) when compared to caves formed in more common inland settings (Palmer, 2007). Most of these caves are highly decorated with vadose speleothems that formed in early Quaternary time when the caves were air-filled chambers. Throughout the Middle and Late Pleistocene, the caves were repeatedly flooded by glacio-eustatic sea level oscillations. The water level of each flooding event left a clear mark as a distinct encrustation of calcite or aragonite over existing speleothems and along cave walls (Figure 1 pos). Experienced cave divers also noticed the presence of unusual bulky speleothems at different depths within most of the flooded caves along Mallorca's coastlines. Thus far, several well-defined carbonate overgrowth horizons above and below the present-day sea level (corresponding to older sea-level high and low stands) have been recognized (Figure 1). These ancient encrusted speleothems are considered ideal sea-level indicators in terms of both age and elevation.

Similar encrustations form at present in a low-amplitude, tide-controlled microenvironment, at or a few centimeters below and above the water table where CO₂ escapes the brackish water causing precipitation of calcite and/or aragonite (Figure 5; Tuccimei *et al.*, 2010). All caves hosting these encrusted speleothems are within a short horizontal distance of the coast; thus, the water table of the caves is, and was in the past, coincident with sea level. The very narrow environment in which the encrustations form coincides with the "*mineral sea-level*". Hence the vertical accuracy achieved is better than 10 cm and their respective time of formation can be determined by U/Th dating, with unprecedented resolution and time control, over the past two glacial/interglacial cycles.

Speleothems that possess these types of carbonate overgrowths (or similar) are widespread, with most of the investigated sites being located in Mallorca (Ginés & Ginés, 1995; Vesica *et al.*, 2000; Fornós *et al.*, 2002; Dorale *et al.*, 2010; Tuccimei *et al.*, 2006, 2010, 2011) and to a lesser extent in Sardinia (Tuccimei *et al.*, 2007), Bermuda

(Harmon *et al.*, 1978), Nansei islands, Japan (Pacific Ocean; Urushibara-Yoshino, 2003), and Christmas Island, Australia (Indian Ocean; Grimes, 2001).

Particular types of POS are those that on either one occasion or repeatedly were exposed to the meteoric-marine mixing zone; these are excellent indicators of paleoclimate and sea-level changes (Harmon *et al.*, 1978; Csoma *et al.*, 2006). Geochemical and petrographical studies on such carbonates have shown that the alternation of vadose and phreatic precipitates mirrors changes from meteoric-vadose to meteoric-marine mixing zone environments. Specifically, during glacial stages when sea-level was below the present one, vadose conditions prevailed. The most common carbonate mineral precipitated during this phase was calcite (columnar, prismatic, or bladed). Throughout interglacial stages when caves were partly flooded, new carbonate material coated the vadose support at the water-air interface. Both calcite and aragonite (acicular, bladed, and prismatic) were deposited from the brackish water pooling in the cave. Isotopic and fluid inclusion salinity analyses allowed Csoma *et al.* (2006) to suggest that although both minerals are associated with sea-level high stands, calcite precipitated during periods of more meteoric recharge, whereas aragonite formed under conditions of lower rainfall. Therefore, studying the mineralogy and geochemistry of vadose and phreatic speleothems could provide local climatic insight tied to past sea-level stands. A better understanding of calcite and aragonite precipitation in the freshwater/seawater mixing zone (i.e., controlling factors such as CO₂ degassing, salinity, CO₃²⁻ supply, saturation index, etc.) is crucial if these speleothems are to be used in either paleoclimate or sea-level reconstructions.

The advantages of using POS for reconstructing sea level are straightforward and powerful: within a single cavity one can document several sea level stands and provide a test of the tectonic stability of the area by comparing their elevation against well-known markers, such as MIS 5e. Furthermore, the past sea level high stands are well preserved in POS as the cave environment protects them from processes that disrupt or remove other terrestrial archives.

4. Conclusions

Compared to any of the methods discussed above, the phreatic overgrowth mechanism arguably provides a more precise and less ambiguous indicator of the timing and the absolute elevation of the sea level position, as illustrated in the previous chapter of this book by Ginés *et al.* (2012).

Presently, most of the sea-level fluctuations encoded in cave-based records are from the northern hemisphere and cover MIS 7 through 1. Littoral caves at low- and mid-latitudes offer a means of addressing the temporal and spatial sea-level data gaps in other proxies. Investigations in the North Atlantic and Mediterranean Basin show that cave-based proxy records provide an opportunity to independently date sea-level changes without using the deep sea isotope record and associated orbital tuning techniques. These studies are important tools in the documentation of rapid sea-level events that may have occurred in response to large hemispheric temperature

variations, and to better quantify the rate of sea-level change at various Terminations and within interglacial or glacial stages.

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❧

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 km². 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.

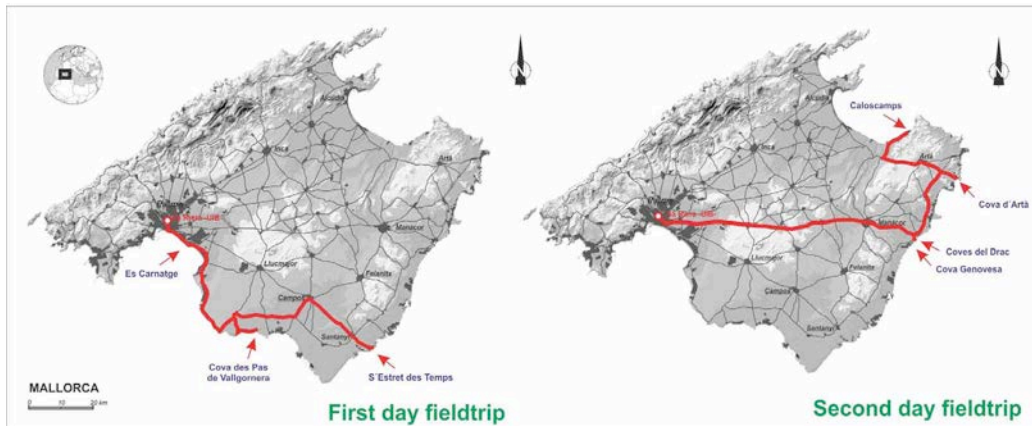


Figure 1. Location map showing the two-day field trip that will be dedicated to the observation of the littoral landscapes of Mallorca Island where Pleistocene deposits and karst features are exposed.

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 Islands from Africa and Iberia, 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 thrust belt resulting from the continental collision between the African and the Iberian 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 thrust 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 thrust 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.

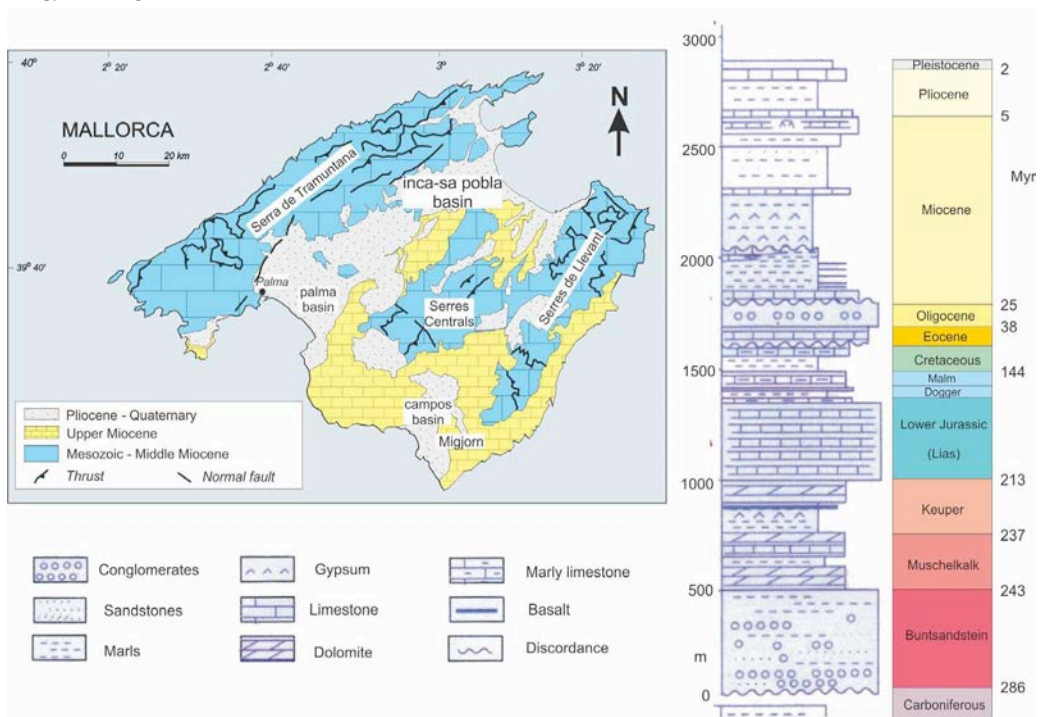


Figure 2. Simplified geological map of Mallorca and synthetic lithostratigraphical column (modified from Rodríguez-Perea, 1992).

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

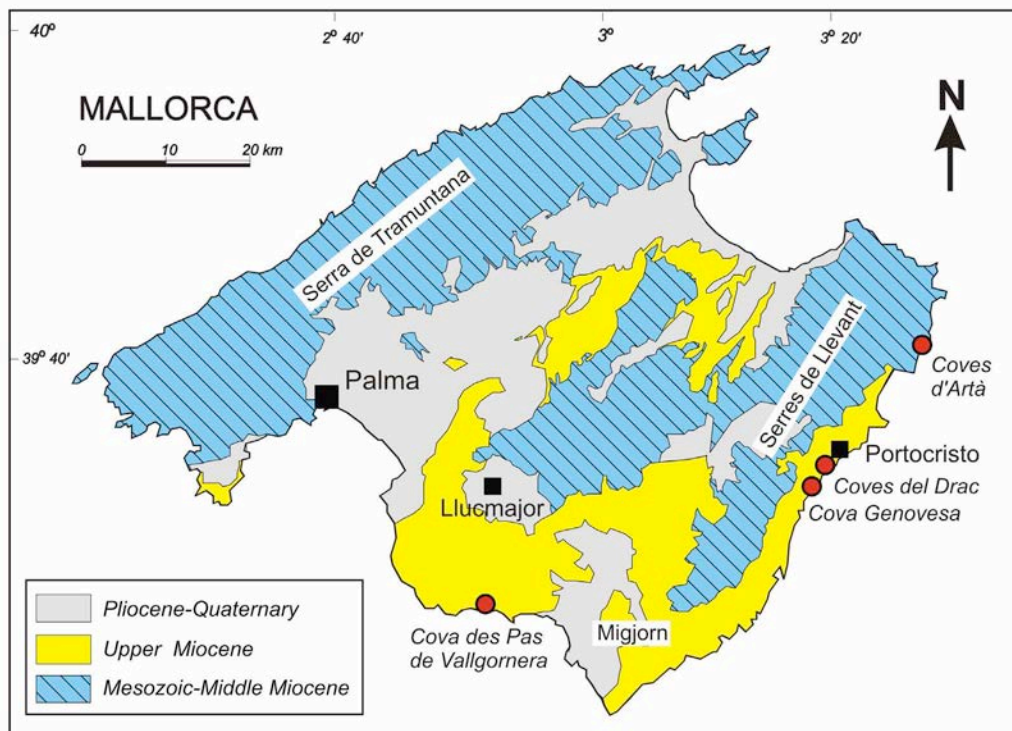


Figure 3. The main karst regions in Mallorca and location of the caves visited during the fieldtrip.

temperature oscillates around a mean of *ca.* 17°C, with mean winter and summer values of *ca.* 10 and 25°C, 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 Lluçmajor 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 Lluçmajor 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

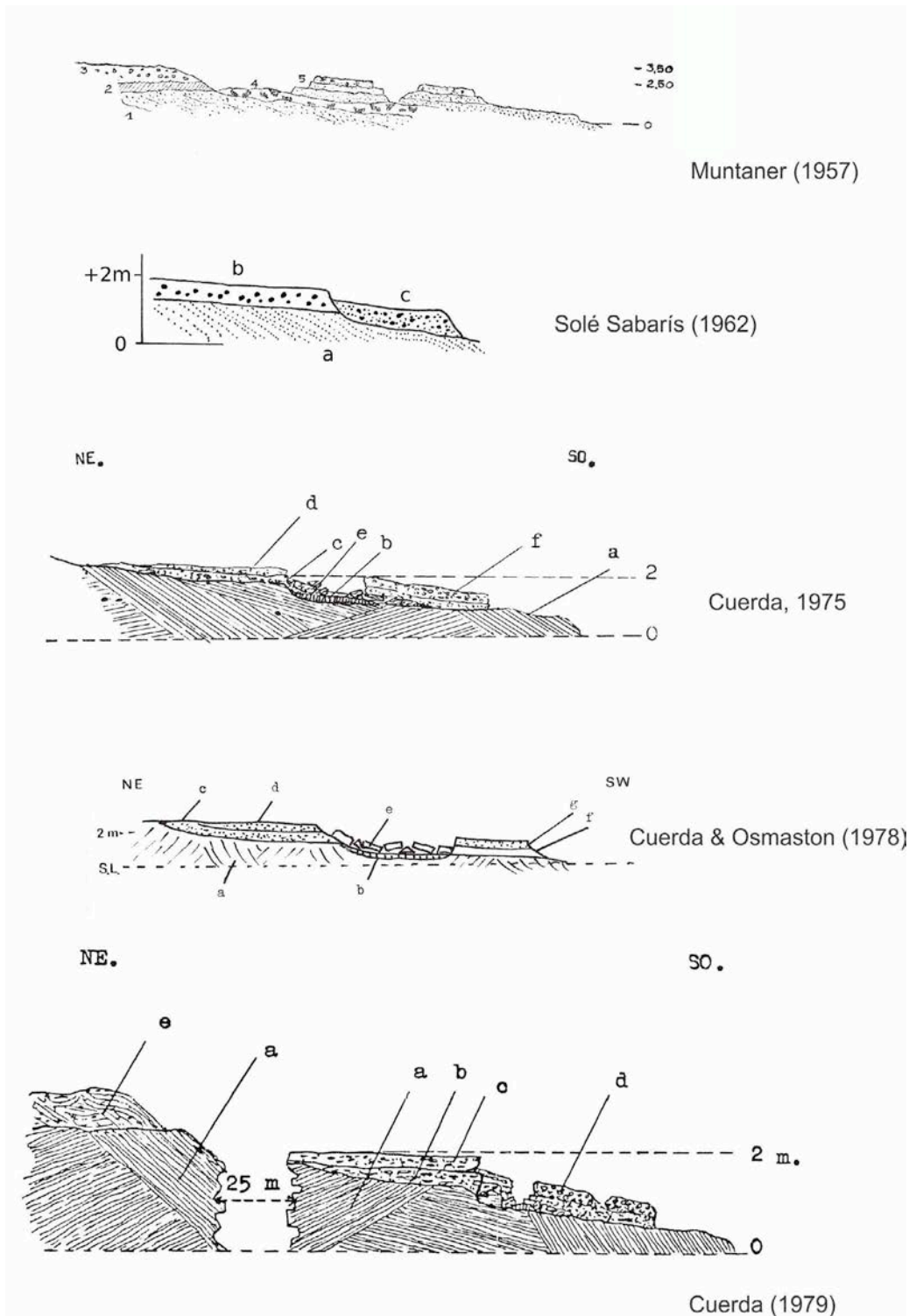


Figure 4a. Cross-sections historical evolution of the Es Carnat Pleistocene deposits.

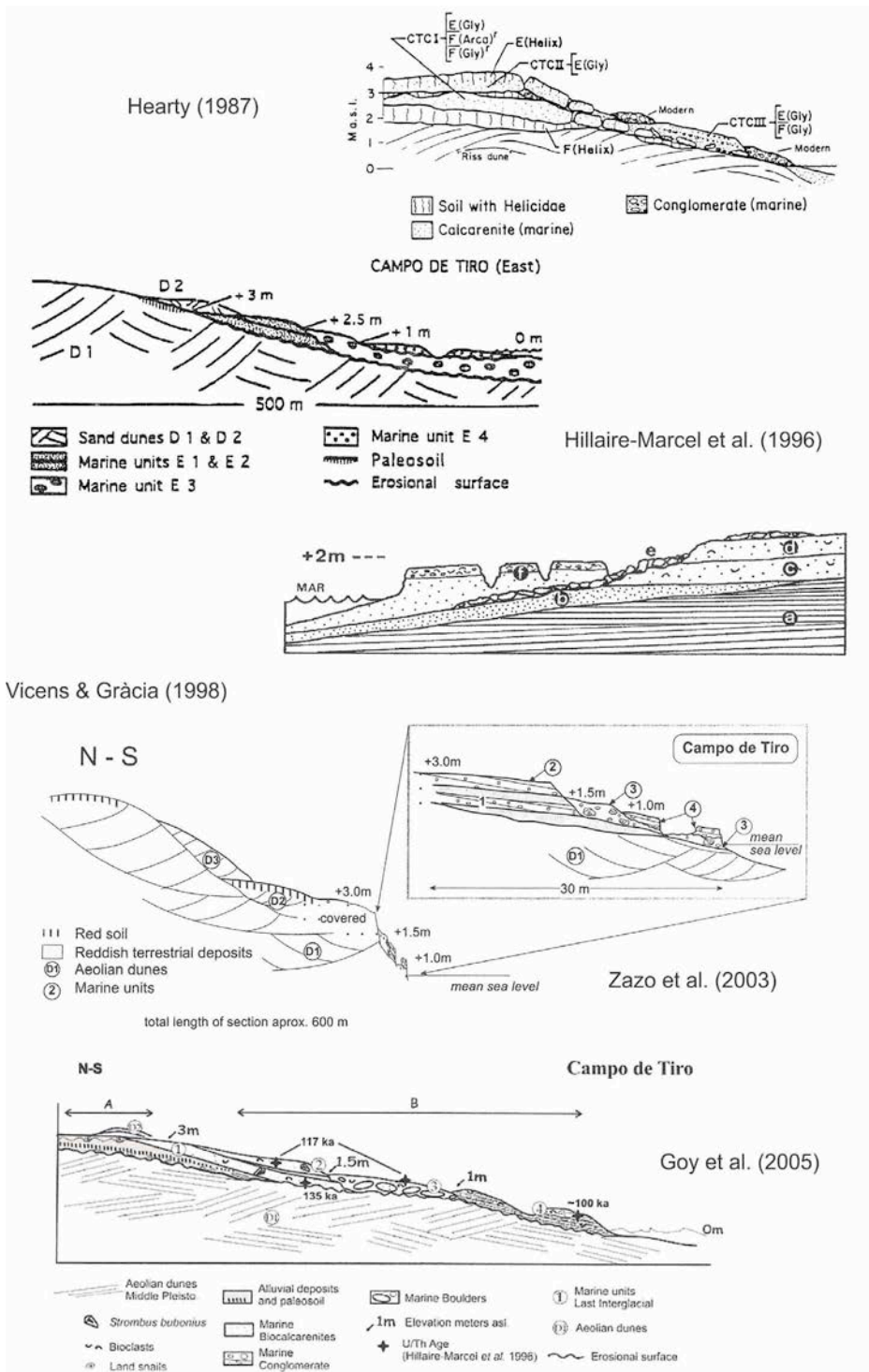


Figure 4b. Cross-sections historical evolution of the Es Carnatge Pleistocene deposits.

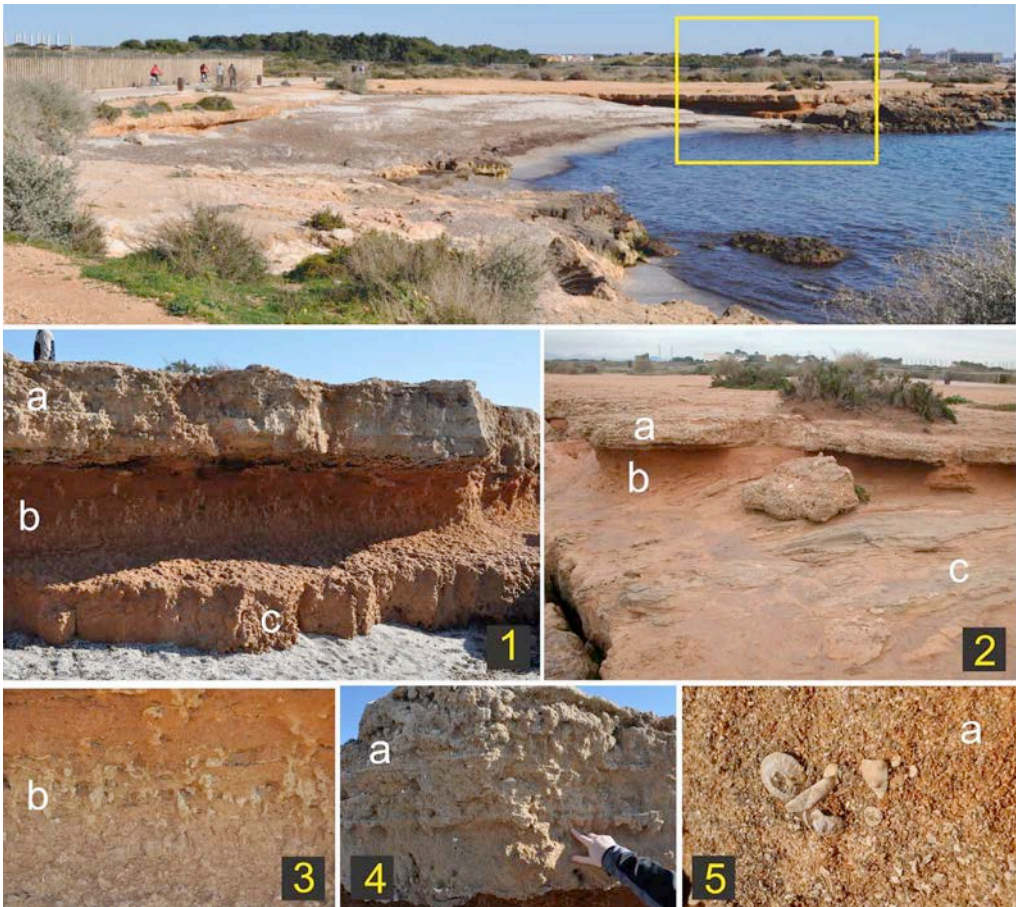


Figure 5. Panoramic view of the Late Pleistocene sequence at the east side of Cala Pudent (1, 2). From top to base (a) the marine levels (4, 5) corresponding to MIS 5e; (b) the paleosol (3); and (c) the MIS 6 eolianite (1, 2).

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 Eutirrhenean (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 gymmesica*. 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 scrobiculata*, *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 Euthyrranian.

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

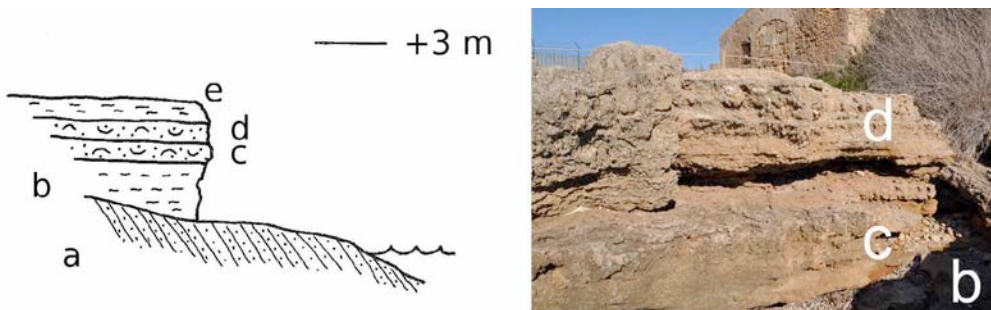


Figure 6. Two marine levels (c, d) separated by a thin silty level over a reddish paleosol (b) can be observed at the cliff near the Es Carnatge houses. The section was dated by Hillaire-Marcel *et al.* (1996) to 135 ka (lower unit) and 117 ka (upper unit), respectively.

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*, *Hytotissa 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/iso-leucine 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

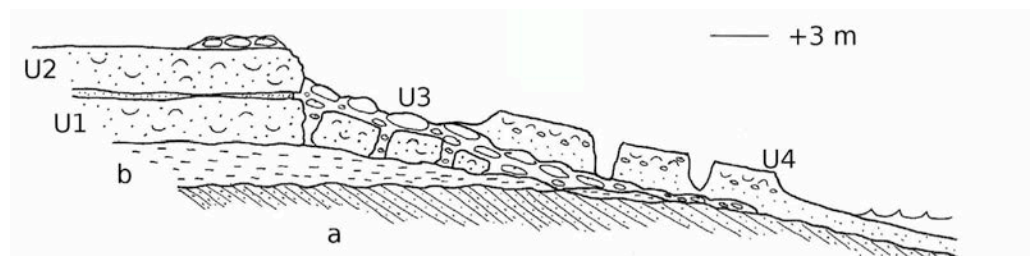


Figure 7. Sketch of the Late Pleistocene units at Es Carnatge; a) basal eolianite (MIS 6); b) paleosol; U1 and U2) marine units corresponding to MIS 5e; U3) Marine reworked unit, MIS 5c or 5a?; and U4) beach sands and conglomerates corresponding to MIS 5a.



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).

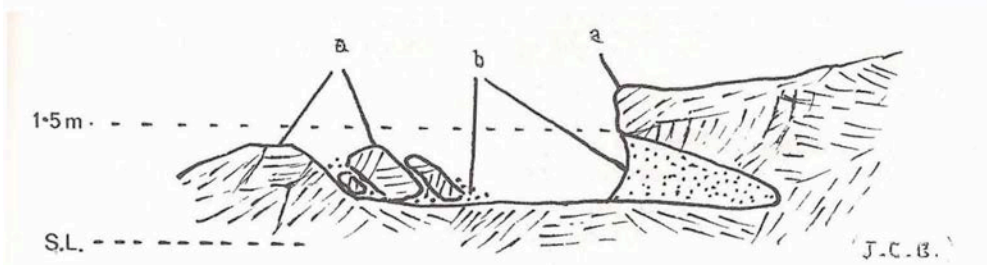


Figure 10. General view and sketch section from Cuerda & Osmaston (1978) showing the infilling with sandstones (MIS 5a) of the notch and associated marine erosion cave cut into the basal MIS 6 eolianites.

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 paleoclipf (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 since 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 30°. Ripples at the surface of the lamina are also visible, as well as rzhocretions disturbing the lamina. In some places the presence of rzhocretions 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

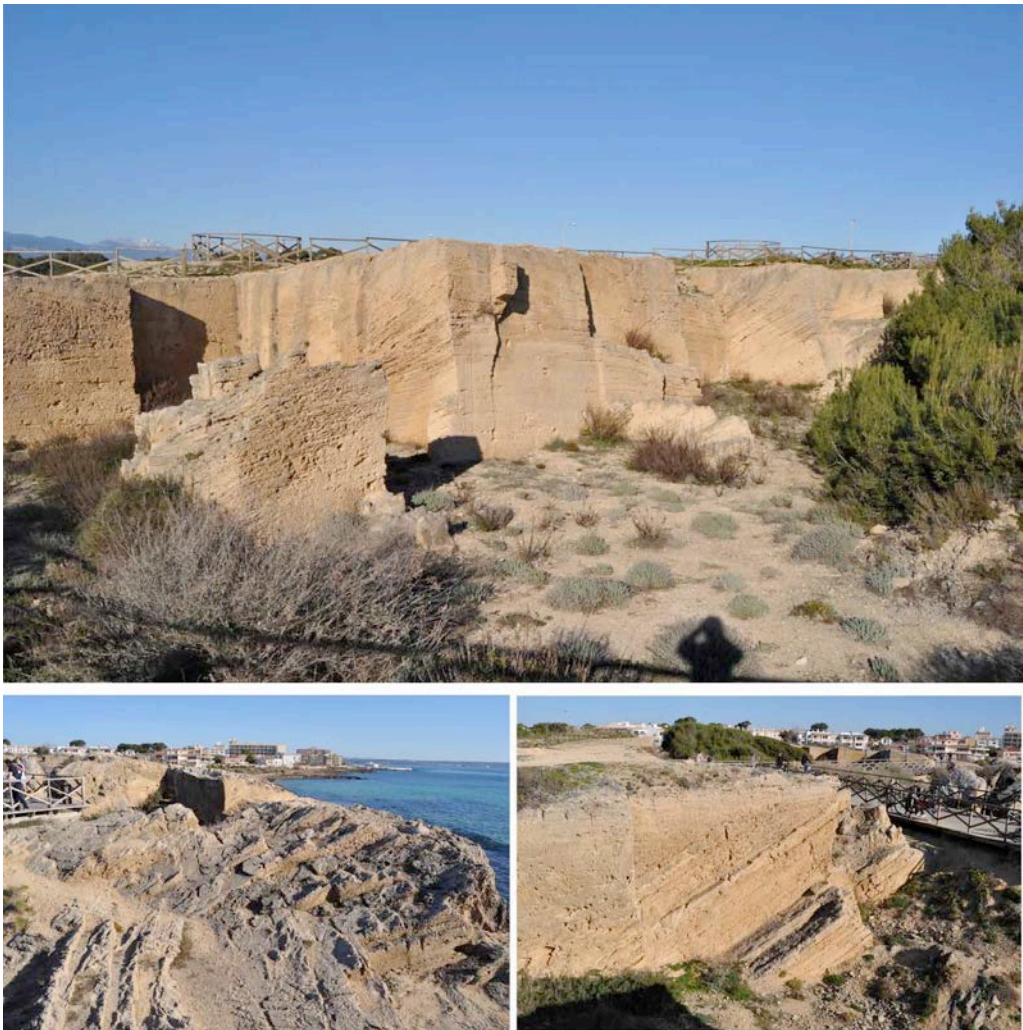


Figure 12. Son Mosson Quarry where the MIS 6 eolianite are exposed.

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

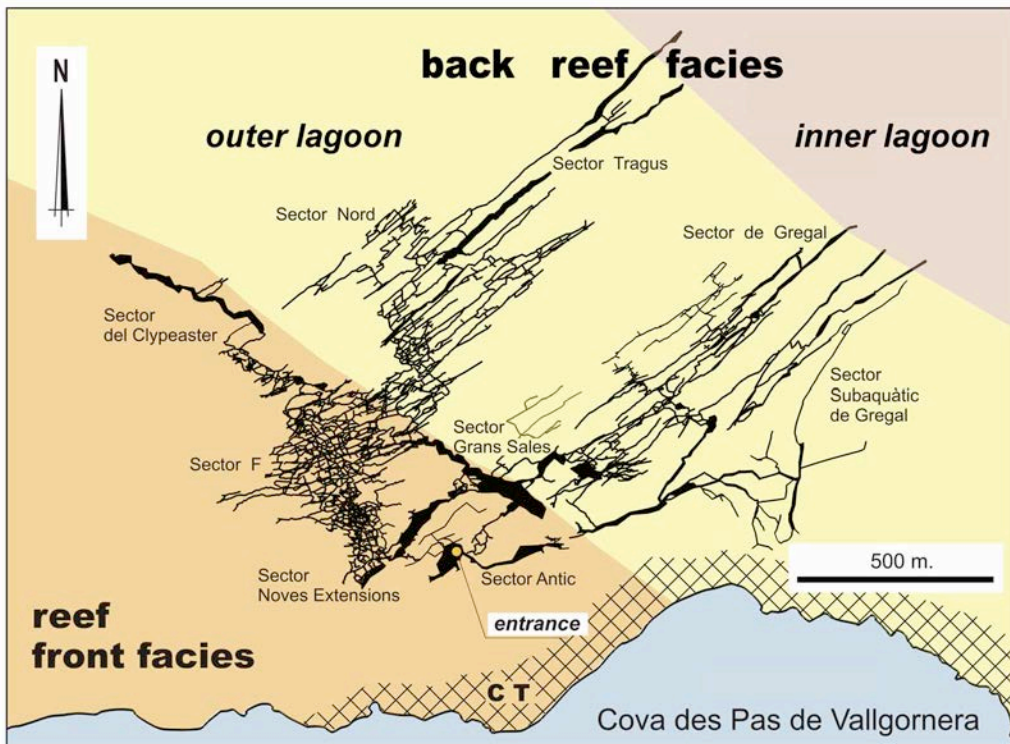


Figure 13. The survey of Cova des Pas de Vallgornera (Llucmajor) with indication of the lithological variability within the Upper Miocene (Tortonian) carbonates (after Ginés *et al.*, 2009). CT: Messinian terminal complex.



Figure 14. Picture of a collapse chamber in Cova des Pas de Vallgornera showing the extensive brackish pool that flooded 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 calcisiltitic 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

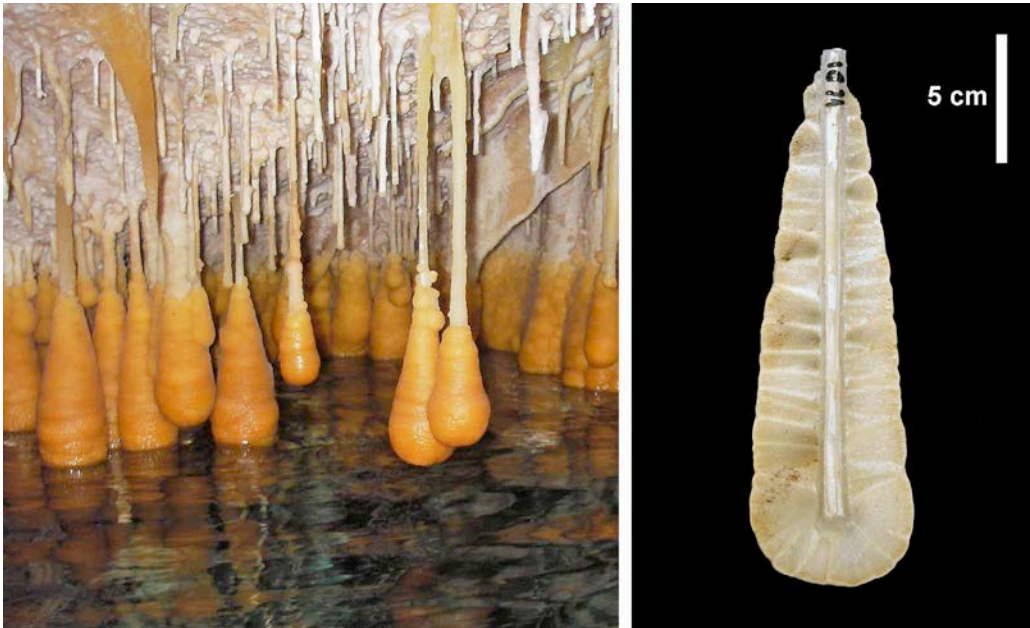


Figure 15. Aragonite POS belt developed at the current fluctuation range of the coastal water table in pools from Cova des Pas de Vallgornera (Photo: Antoni Merino). A longitudinal section of these deposits are shown in the left side of the figure.

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)	$^{234}\text{U} / ^{238}\text{U}$	$(^{234}\text{U}/^{238}\text{U})_0$	$^{230}\text{Th}/^{232}\text{Th}$	$^{230}\text{Th} / ^{234}\text{U}$	$^{230}\text{Th} / ^{238}\text{U}$	Age (ka $\pm 2\sigma$)
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.

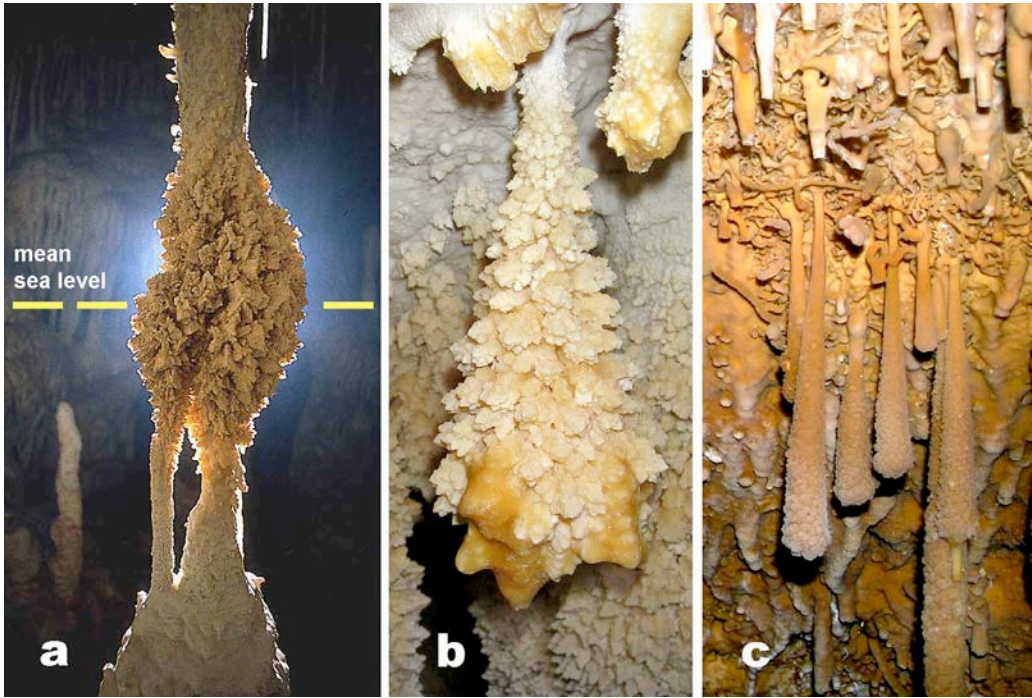


Figure 16. Upper Pleistocene POS deposits from Cova des Pas de Vallgornera located at an elevation of +2.6 m ASL and corresponding to MIS 5e high stand. **a)** Phreatic macrocrystalline calcite encrustation in the Noves Extensions sector. **b)** Detail of the same MIS 5e paleo-level at the entrance to 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 a 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 aeolianites 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 (rhizcretions).

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 50°. Windward surfaces normally dip 15-25° but may reach up to 31° in the steepest cases. Lee-side surfaces typically have dips between 20 and 26° with a few dips reaching 30-32°. 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 12-25°; the strata flatten towards the crest. The lee-side deposits dip 20-26°. 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 20-26° and leeward side deposits dip at 22-26°. 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 25° and the leeward-side deposits dip up to 30°. The dune profile is weakly asymmetric and the angle of climb is supercritical (may reach 50°). 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 from 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.

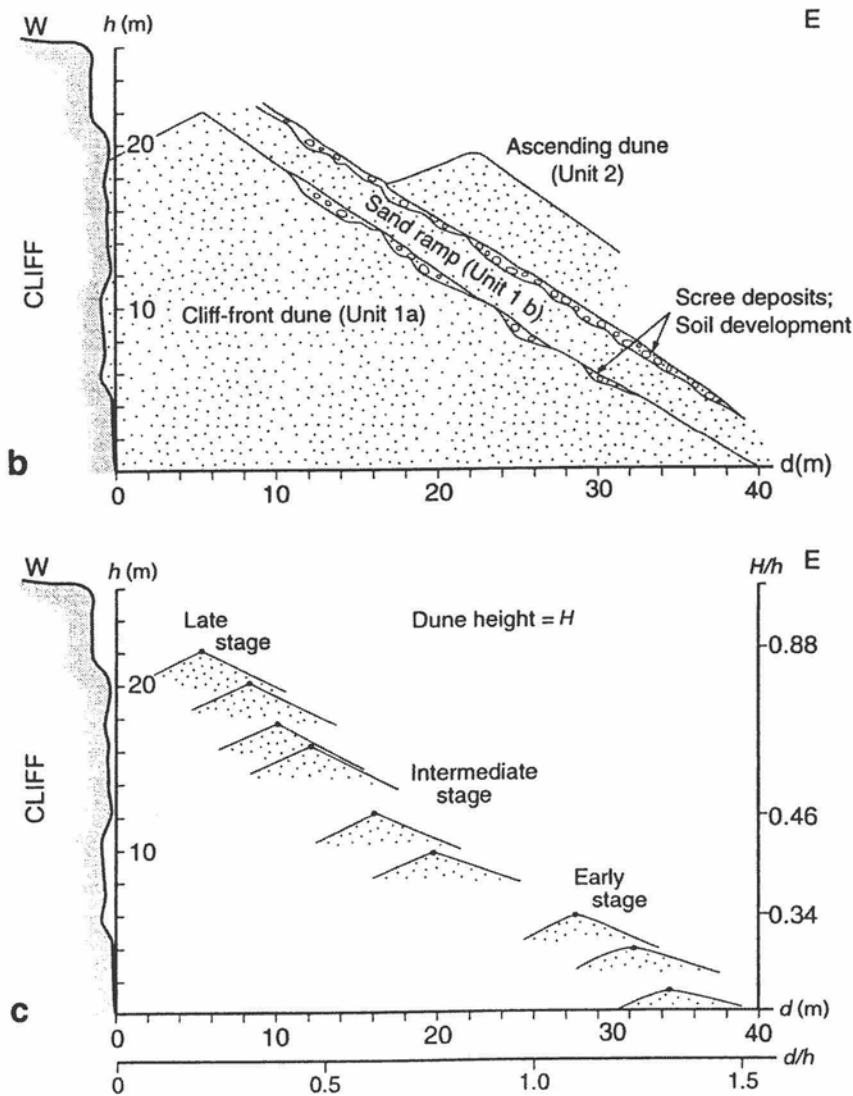


Figure 19. Idealized stratigraphy and growth stages of the cliff-front dune (modified of Clemmensen *et al.*, 1997).



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 30°. 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.

They represent 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 crestral 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

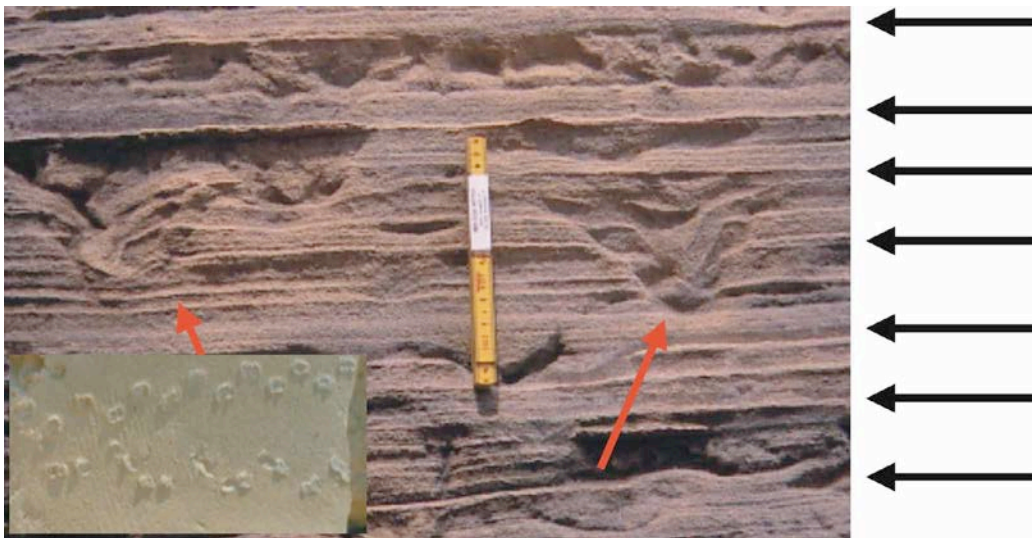


Figure 22. Perpendicular sections of tracks and trackway of *Myotragus balearicus* at s'Estret des Temps.

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 simple 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 or 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 invariably 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

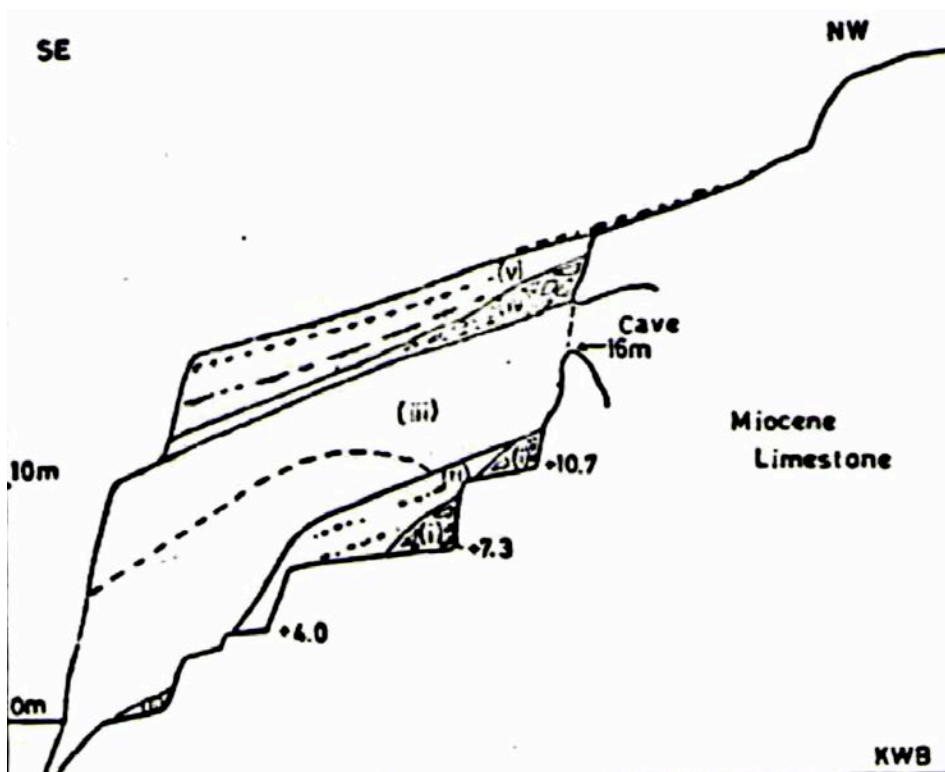


Figure 23. Composite section of the last regressional deposits at s'Estret des Temps showing marine terraces at different heights after Butzer & Cuerda (1962).

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 Lluçmajor 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

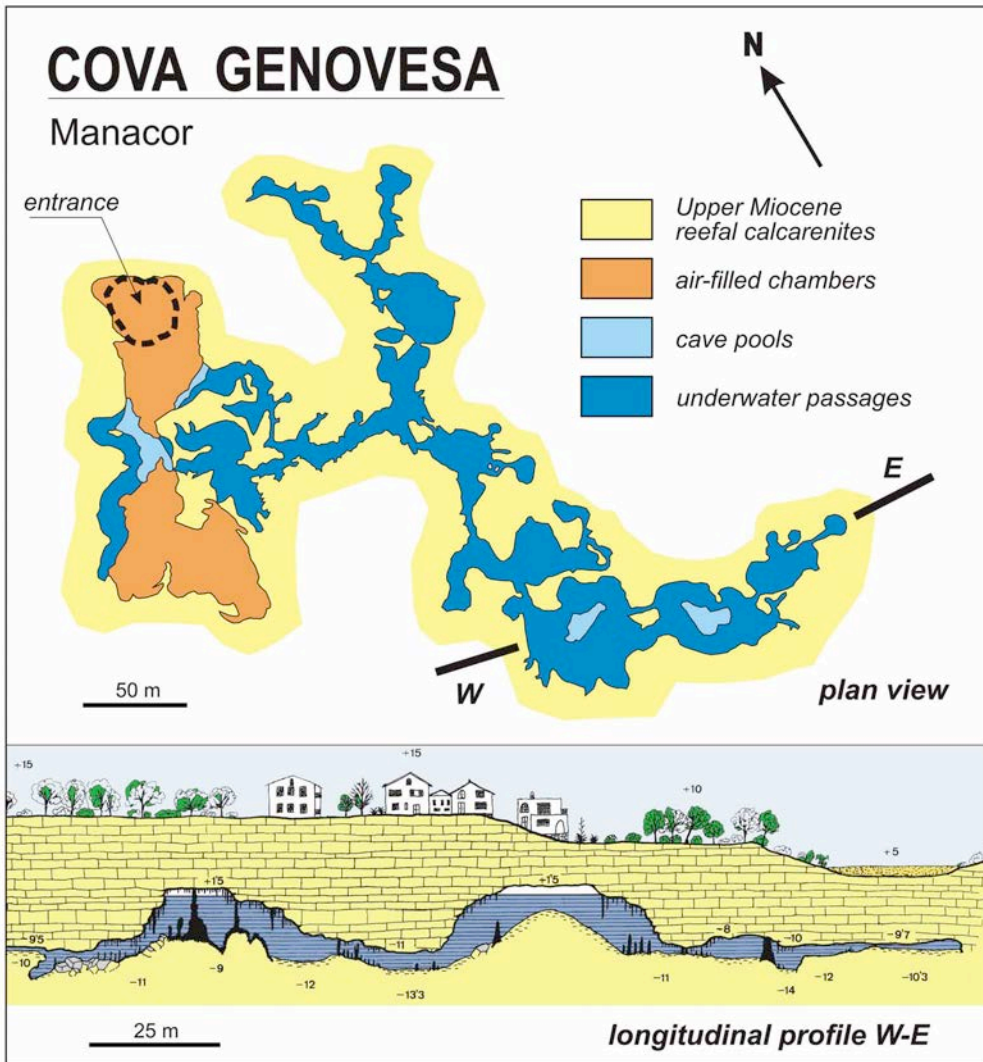


Figure 24. The map of Cova Genovesa (Manacor). A longitudinal profile of the submerged passages is included (after Gràcia *et al.*, 2003).

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 stands (-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).

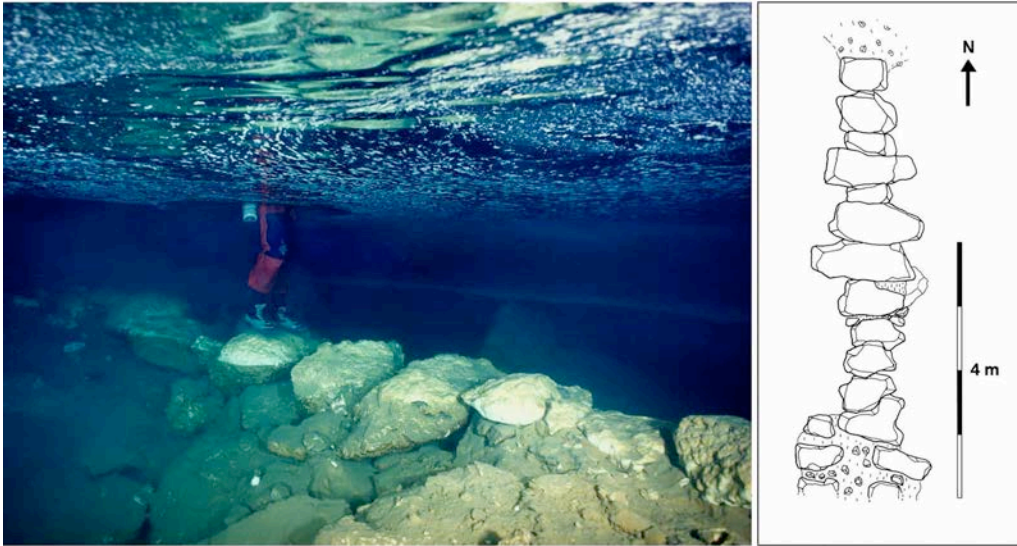


Figure 26. Underwater picture and schematic map of the stone-built walkway existing in Cova Genovesa (Photo: Robert Landreth). It allowed to cross in dry conditions the pool existing at the bottom of the entrance chamber, though currently it is submerged at a depth of -1 m ASL. The ritual use of the 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

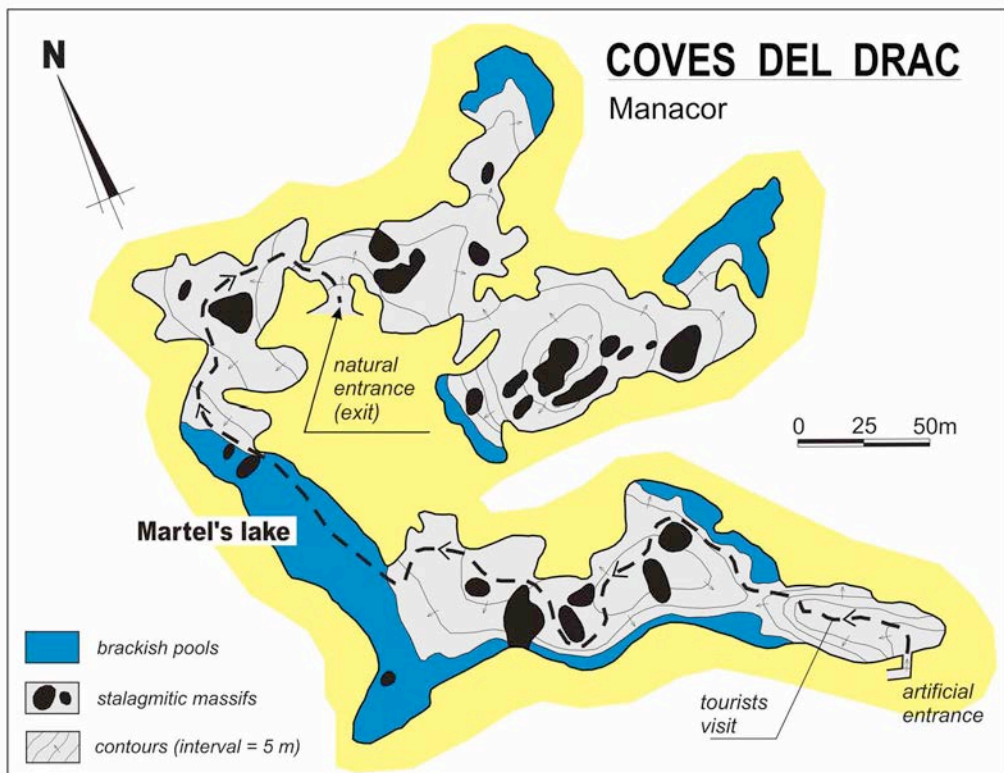


Figure 28. Survey of Coves del Drac (Manacor), with indication of the course of touristic visits (after Ginés & Ginés, 2007).

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. Racoviță 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. Racoviță had for the subterranean ecosystem (Racoviță, 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 m² (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 ¹⁴C 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

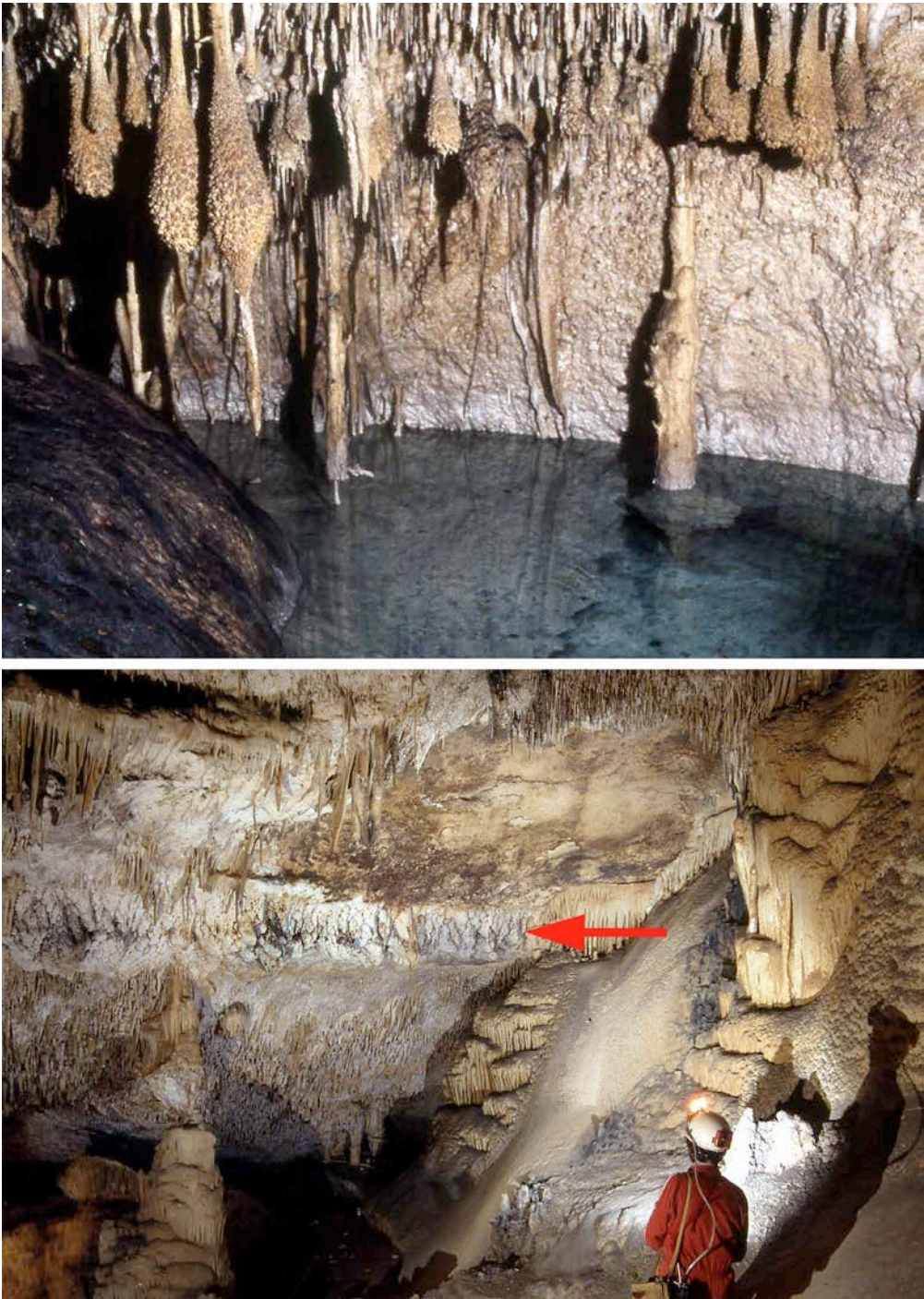


Figure 31. POS deposits in Coves del Drac. In the upper image, a paleo-level (at +1.2 m ASL) of phreatic speleothems is clearly defined by several stalactites coated by a rounded calcite encrustation. In the lower picture, a POS belt of crystallizations (see arrow) marks the paleo-level at +7.5 m ASL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

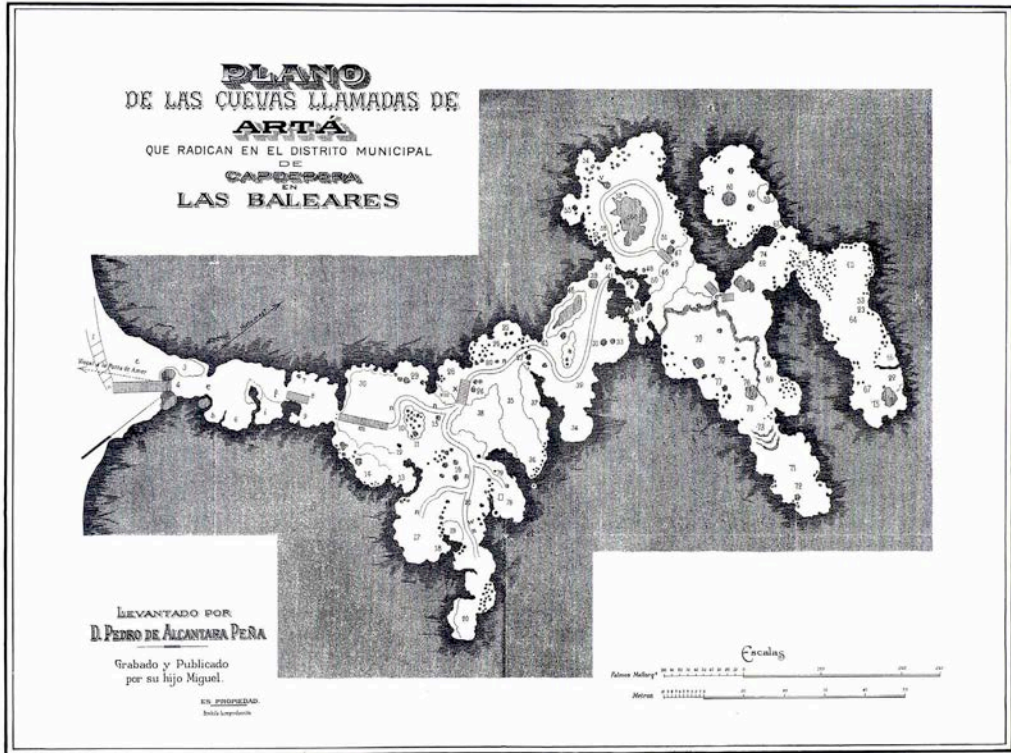


Figure 33. The survey of Coves d'Artà (Capdepera) performed in 1862 by the Mallorcan scholar Pere d'Alcàntara Peña.

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).

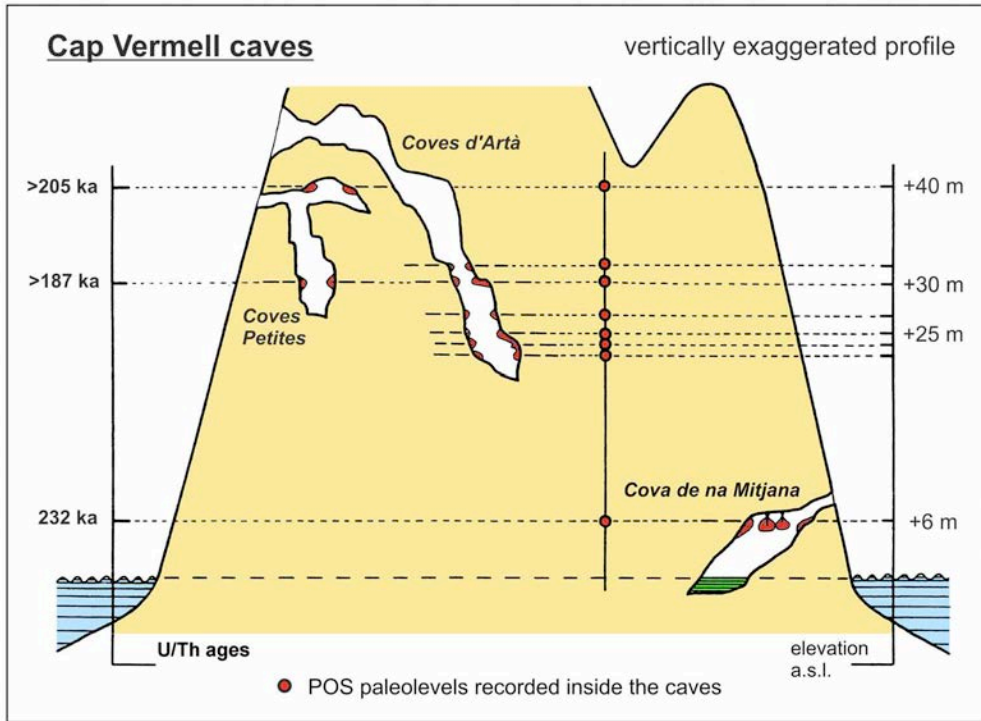


Figure 36. Schematic cross-section of Cap Vermell coastal promontory, showing the POS deposits observed in the caves and the limited U/Th data available.

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, fluvial, 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 fluvial 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 km²). 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, fluvial, 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

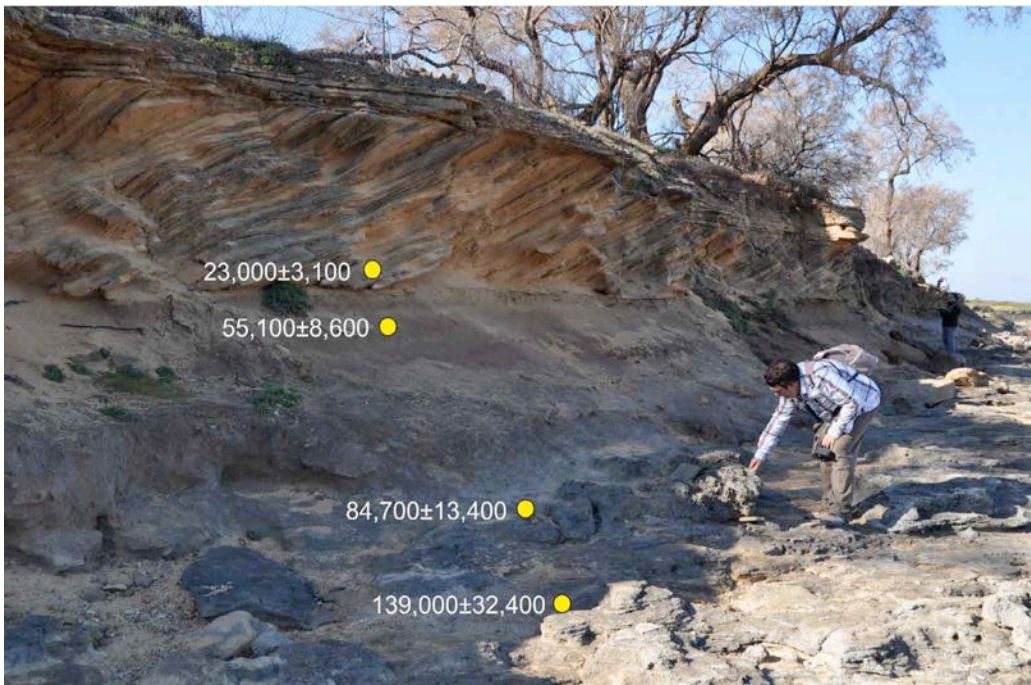


Figure 38. Datings from Rose *et al.* (1999) at the main section at Caloscamps cliff outcrops.

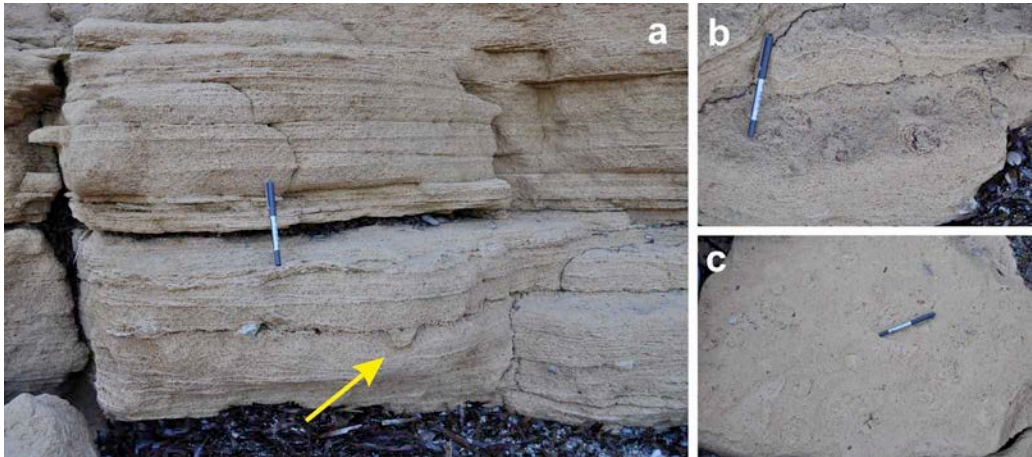


Figure 39. Tracks and trackways of *Myotragus* at the base level fluvial reworked eolian sands.

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 fluvial 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-fluvial 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 fluvial 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

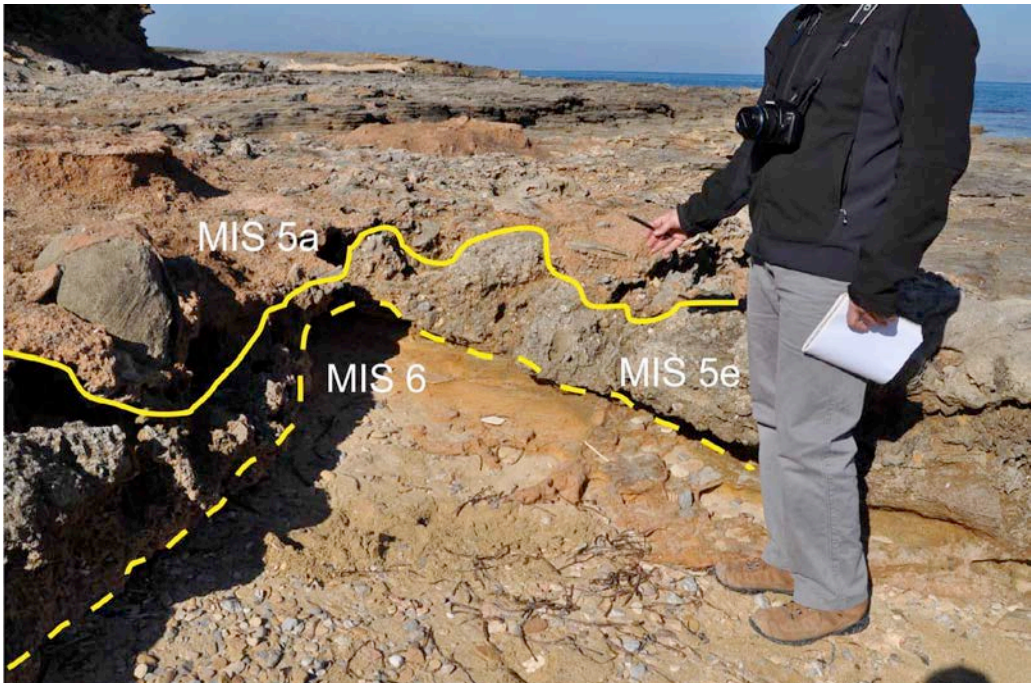


Figure 40. Detail of the two marine levels corresponding to MIS 5e and 5a that overly the sands attributed to MIS 6.

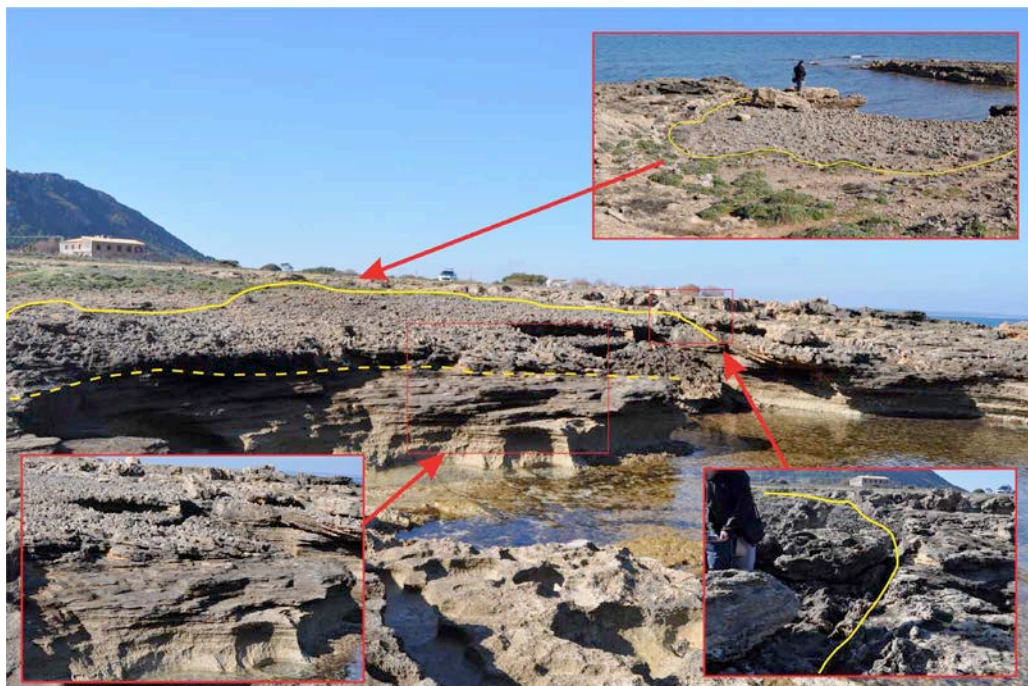


Figure 41. Detail of sa Cugusa site (100 m westwards from Caloscamps), where beach sands from MIS 5a overlies dune and fluvial deposits formed during MIS 6.



Figure 42. General view of the soil showing iron concentration bands (and eolian and fluvial 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 fluvatile 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 interbedded by fluvatile 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 fluvatile 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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