An Introduction to the Quaternary of Mallorca

Angel Ginés[1,2], Joaquín Ginés[1,2], Joan J. Fornós[2], Pere Bover[3], Lluís Gómez-Pujol[2,4], Francesc Gràcia[1,2], Antoni Merino[1] & Damià Vicens[5]

[1]*Federació Balear d'Espeleologia, Palma, Spain.*
[2]*Karst and Littoral Geomorphology Research Group, Universitat de les Illes Balears, Palma, Spain.*
[3] *IMEDEA (CSIC-UIB), Institut Mediterrani d'Estudis Avançats, Esporles, Spain.*
[4] *SOCIB, Balearic Islands Coastal Observing and Forecasting System, Palma, Spain.*
[5] *Societat d'Història Natural de les Balears, Palma, Spain.*

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 km^2, 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 39º 58' N; to the East is Punta de Capdepera, located at 3º 29' E; to the South is Cap de ses Salines, located at 39º 16' N; and to the West is Sant Elm at 2º 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)

Ginés, A., Ginés, J., Gómez-Pujol, L., Onac, B.P. & Fornós, J.J. (eds.). 2012. Mallorca: A Mediterranean Benchmark for Quaternary Studies. Mon. Soc. Hist. Nat. Balears, 18: 13-53. ISBN 978-84-615-7918-1.

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.

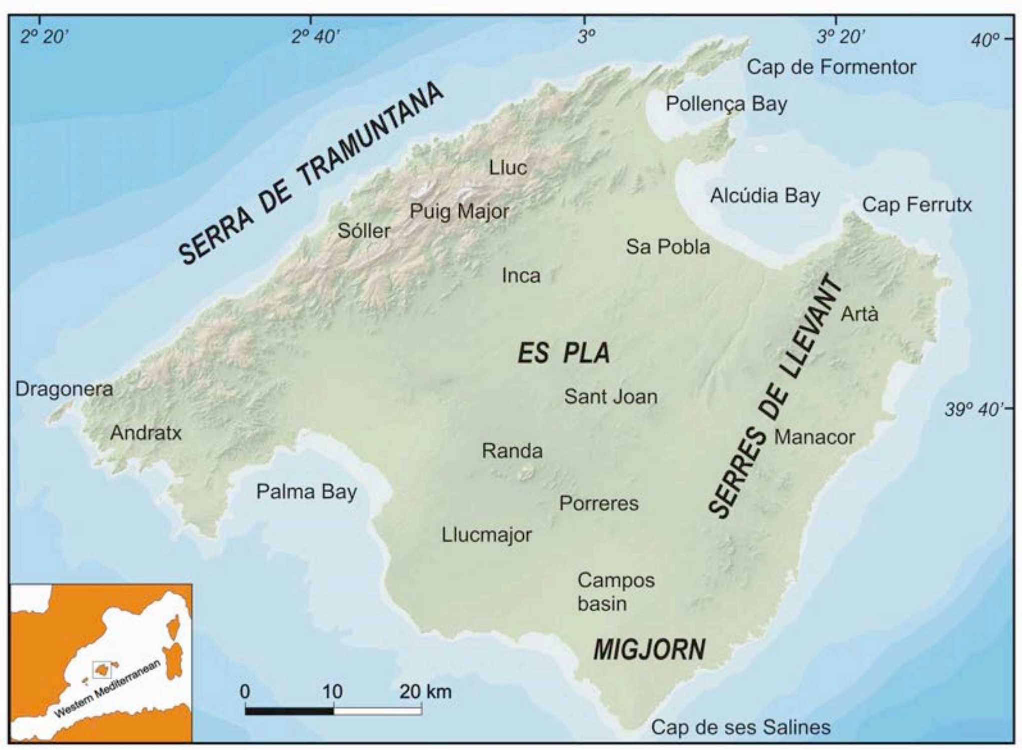

Figure 2. Map of Mallorca Island showing the location of the main place-names referred throughout the text.

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 thrusted 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 Llucmajor, 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 m^3s^{-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 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

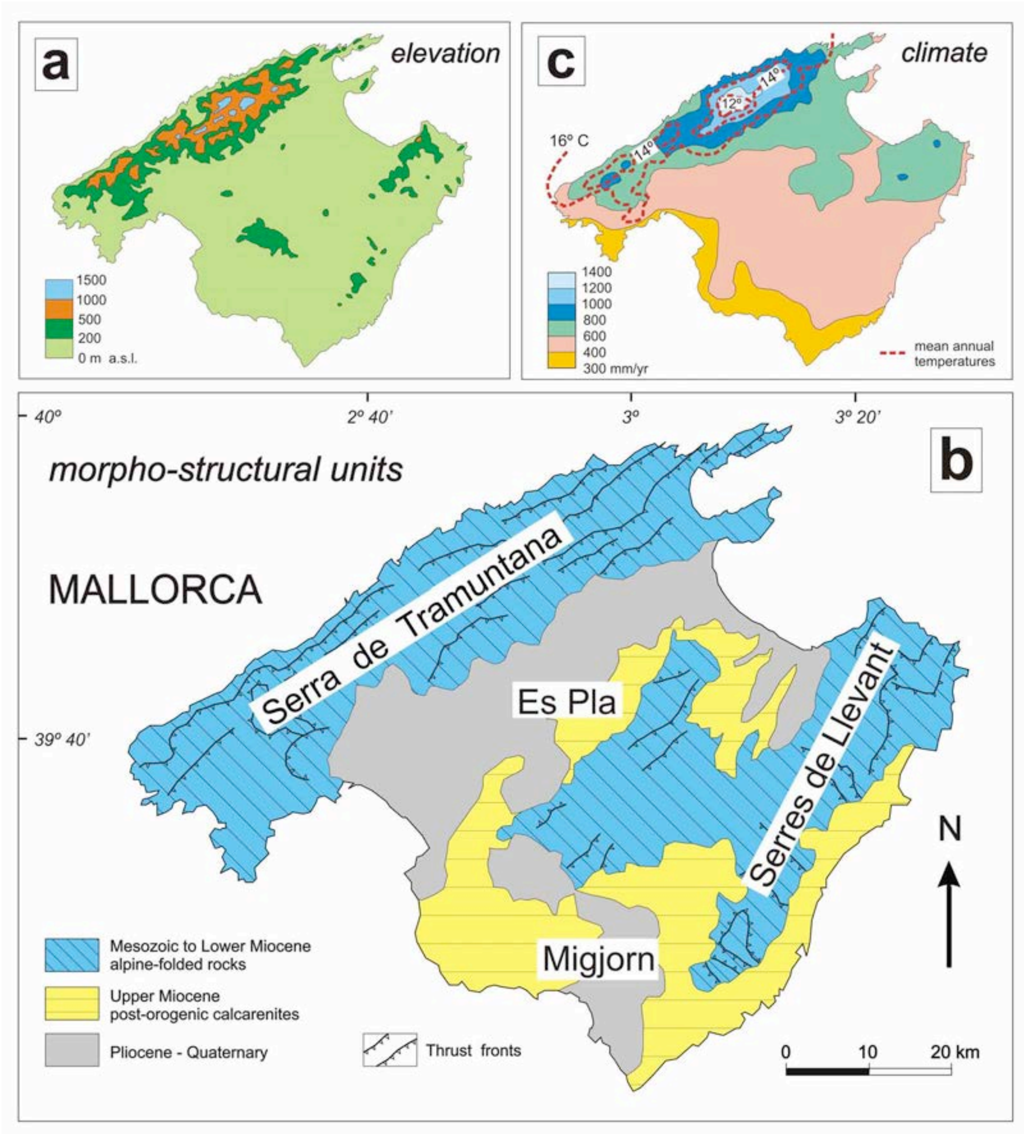

Figure 6. Basic geographical information on Mallorca Island: a. Simplified altimetry map; b. Main morphostructural units conditioned by the geological structure; c. Distribution of the average annual rainfall and temperature values.

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 thrusted 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; Gelabert, 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 & Gelabert, 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 ºC, with 31.1 ºC as the average of daily maximums of the hottest month (August), and 5.6 ºC 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 ºC 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

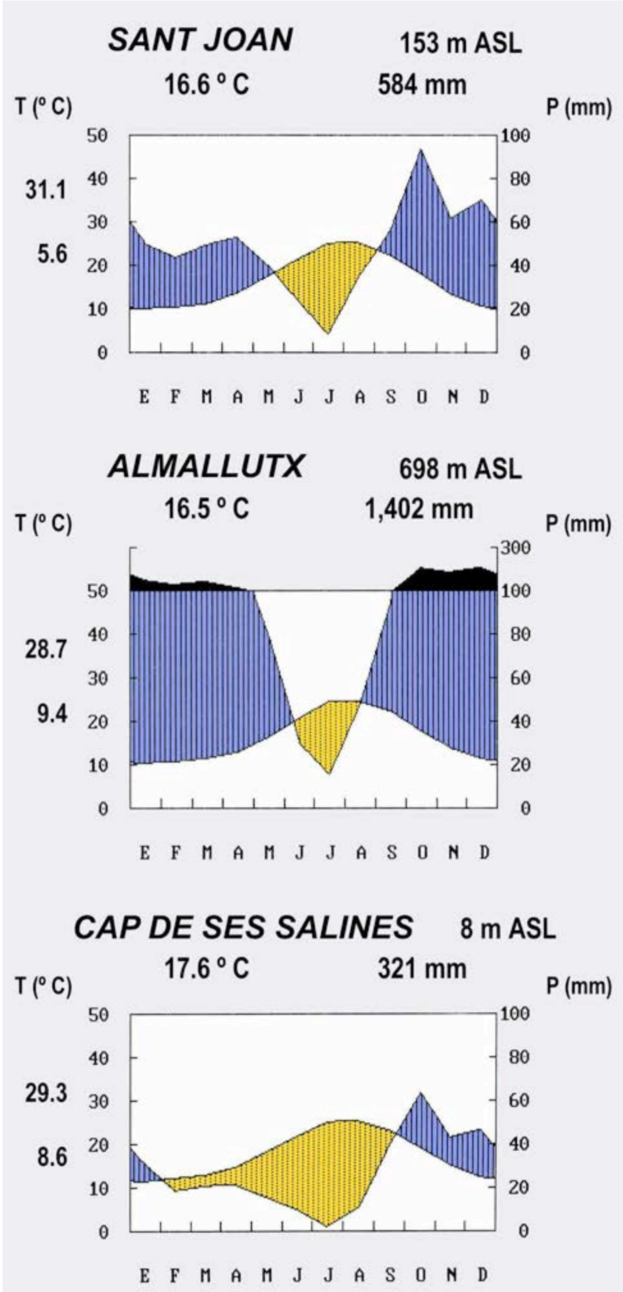

Figure 8. Pluvio-thermic diagrams of three representative localities from Mallorca (after Guijarro, 1995). Sant Joan is located in the center part of the island, whereas Almallutx (at Serra de Tramuntana, close to Puig Major) and Cap de ses Salines (the southernmost coastal site) represent the humid 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'Alfabia'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 ºC in 1925 and 1941, whereas the maximum was 18.8 ºC 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 Kubiëna (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 Kubiëna (1953) as "usually humus-defficient 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-defficient 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 km^2 (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

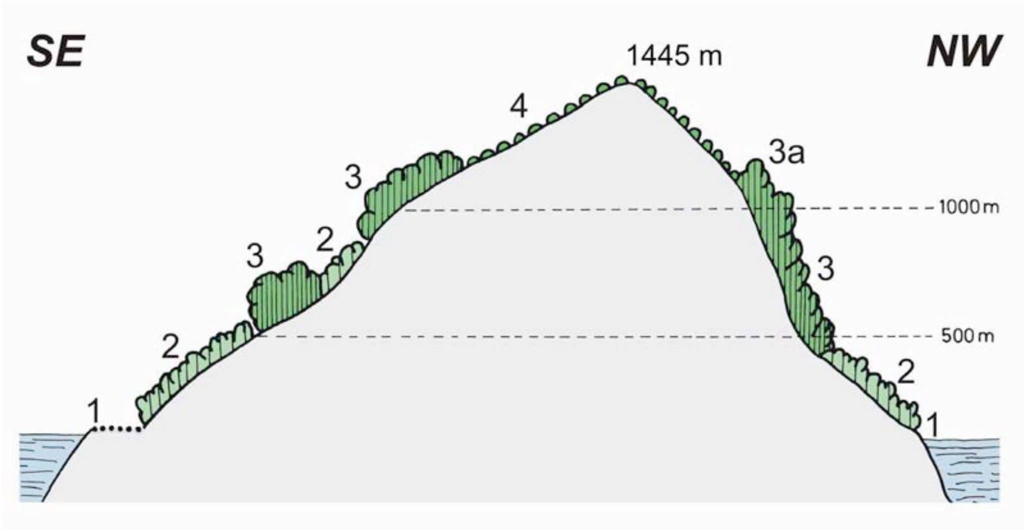

Figure 9. Idealized profile of the main vegetation zones across Mallorca Island (based on Bolòs & Molinier, 1958). **1**: Littoral communities; **2**: "garriga" shrublands and pine woods; **3**: evergreen *Quercus ilex* forest; **3a**: remnants of deciduous forest; **4**: hedge-hog low shrubs at the 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-raisings accelerate the degradation of the plant community and inhibit 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-raisings 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 steplike 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 fluviatile 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

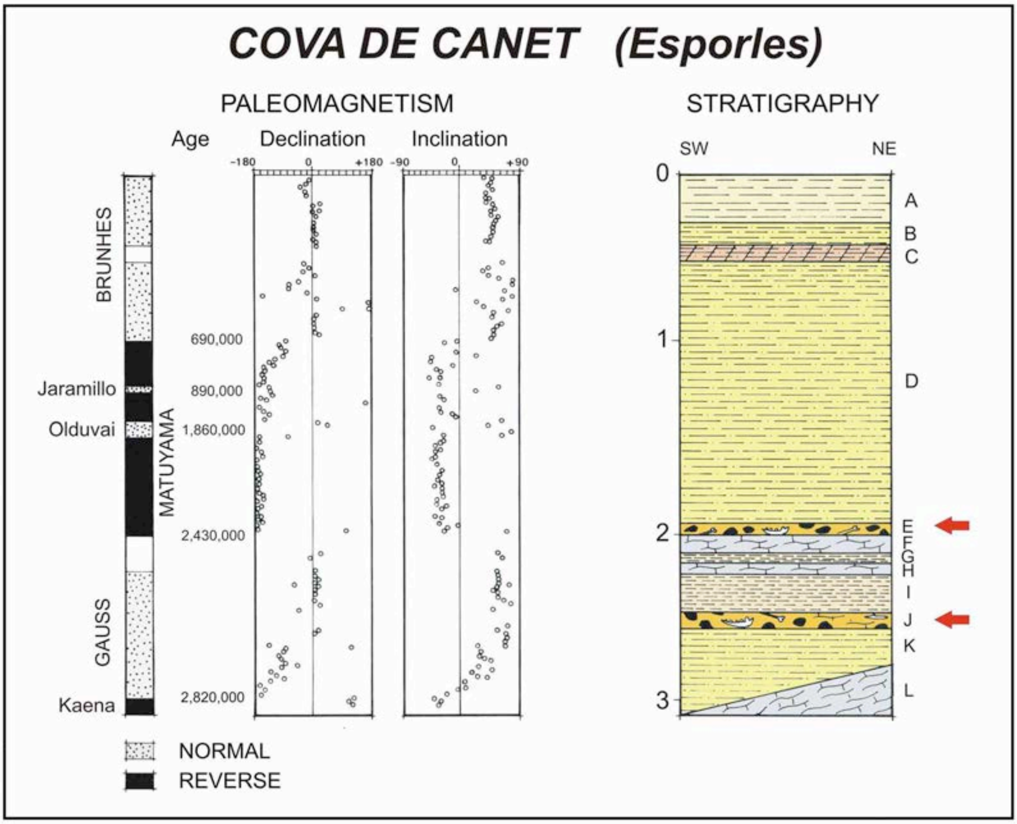

Figure 13. Stratigraphy and paleomagnetic information corresponding to the Plio-Quaternary sedimentary sequence of a cave in the southern slopes of Serra de Tramuntana. Red arrows indicate the layers containing bones of *Myotragus kopperi* (E) and *Myotragus antiquus* (J); After Pons-Moyà *et al*. (1979).

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 5ºC, 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

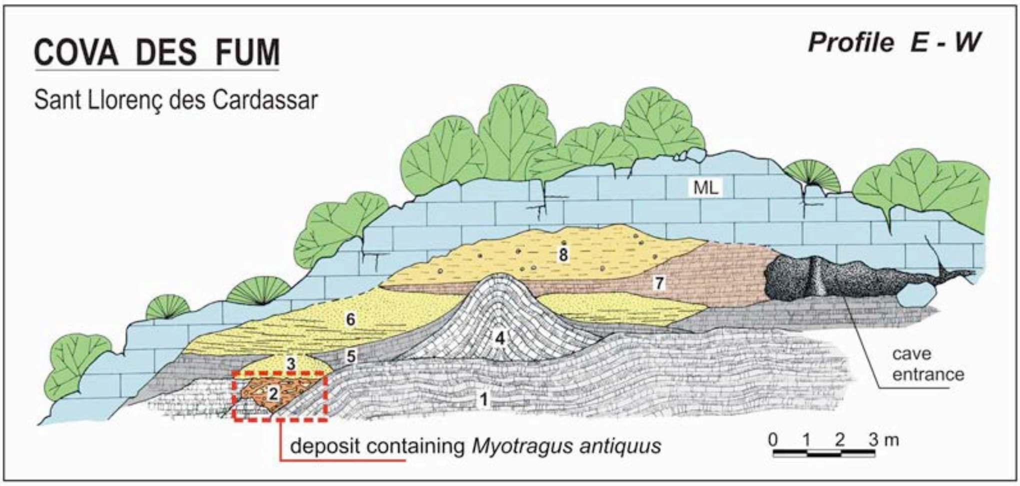

Figure 14. Stratigraphic sequence from a cave in eastern Mallorca (modified from Ginés & Fiol, 1981). **1**: basal flowstone. **2**: bone breccia including remains of *Myotragus antiquus*, whose age presumably corresponds to the Pliocene/Quaternary transition. **3** & **6**: eolian calcarenites. **4**, **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 10ºC) 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 4.9º 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*

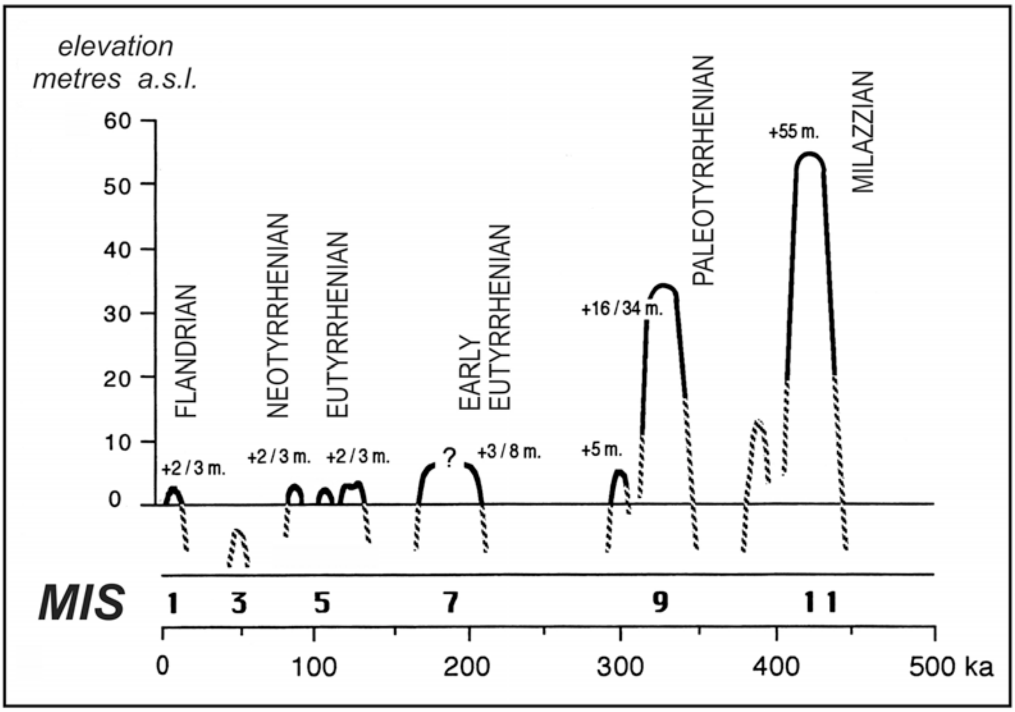

Figure 16. Sea level changes curve resulting from the studies of malacological fauna contained in fossil beach rocks of Mallorca (based on Butzer & Cuerda, 1962a; Butzer, 1975; Cuerda, 1975).4

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-Paleotyrrhenian 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

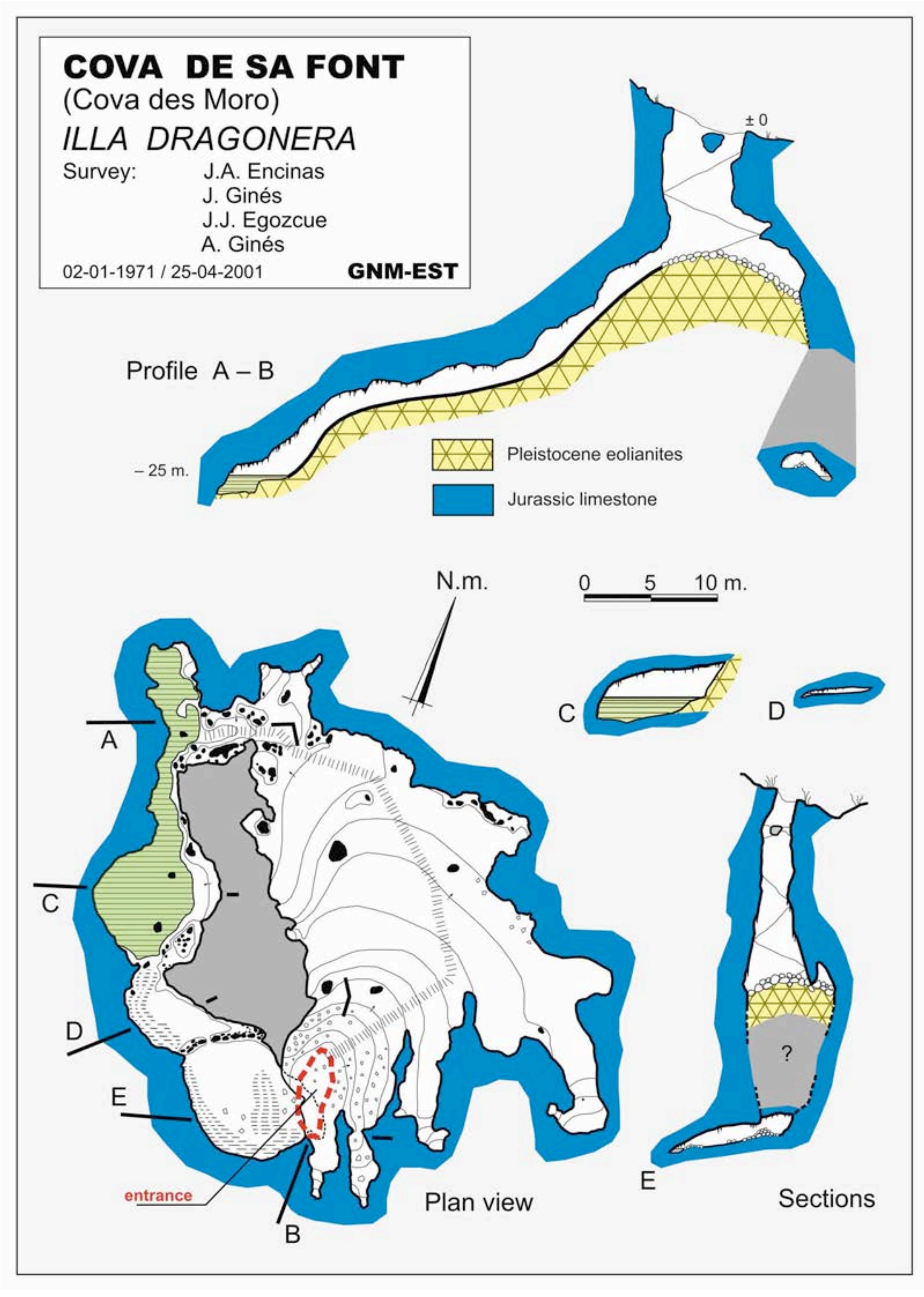

Figure 18. Topographical surveys of a littoral cave located in Sa Dragonera (small island on the western tip of Mallorca). The gravity emplaced Riss eolianites inside the cave, formed a conspicuous cone-shaped deposit covered by a thin flowstone layer.

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 adaptions 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).

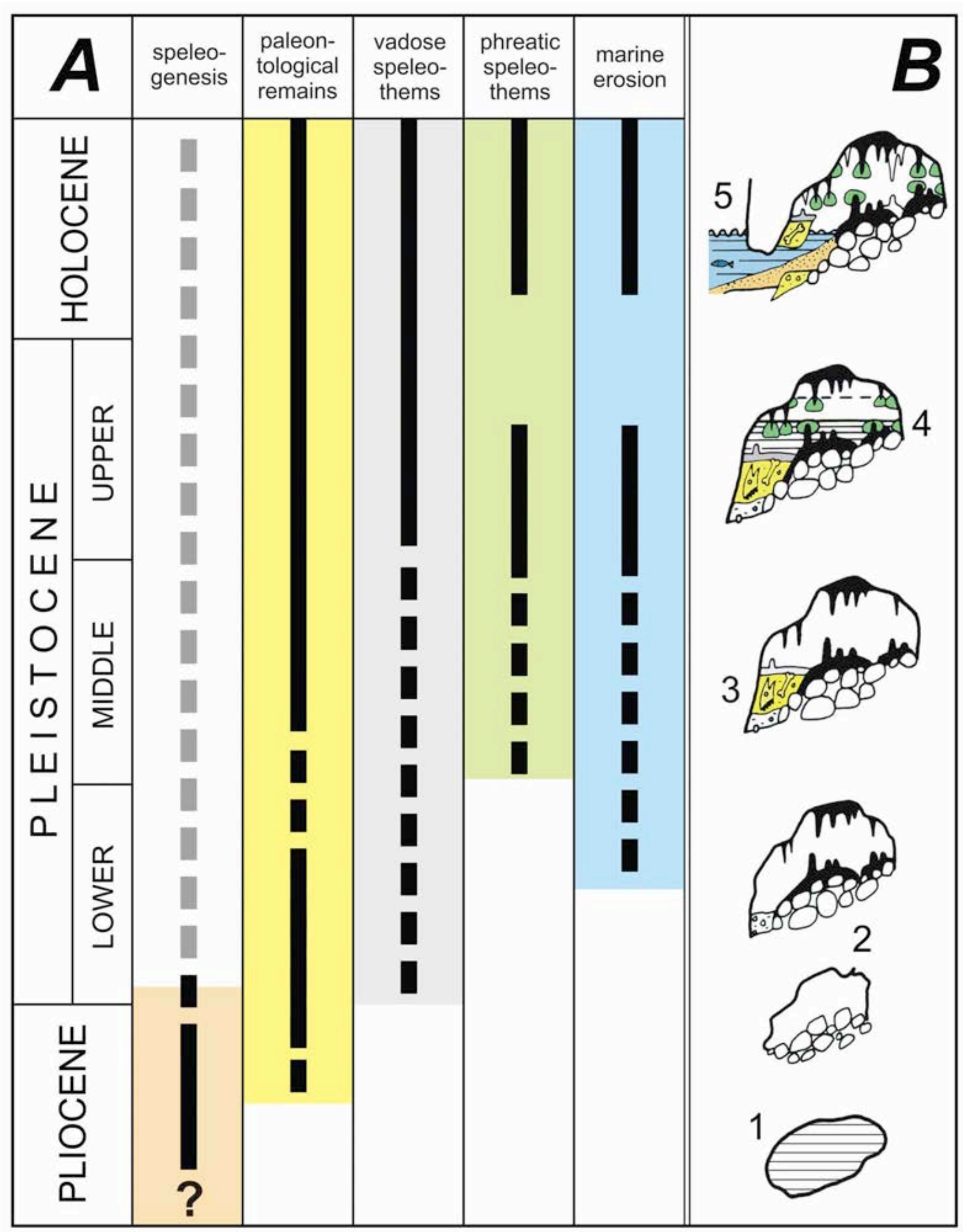

Figure 19. Idealized geochronological synthesis of the morphological and sedimentary evolution in the littoral endokarst of Mallorca. **A**: temporal reconstruction of the main morphogenetic processes and the associated cave infillings. **B**: general morphological appearance of the caves at different 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.

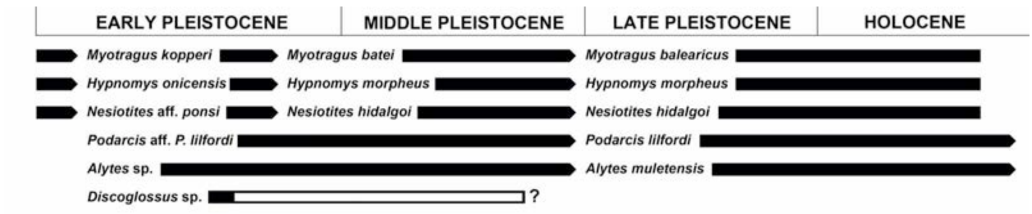

Figure 20. Schematic summary of the faunal assemblages (terrestrial vertebrates) from Mallorca during the Pleistocene.

In addition to *Myotragus balearicus*, Quaternary mammals also included *Hypnomys*, a glirid rodent and *Nesiotites*, a soricid 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 hidalgo*, 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.

Acknowledgements

We are especially thankful to Liana Boop, Jonathan G. Wynn and Bogdan P. Onac for their assistance in the English translation of the text and for their valuable suggestions that substantially improved this contribution. These investigations are integrated within the research project CGL2010-18616 of the Spanish Government Ministerio de Economía y Competitividad/FEDER (previously MICINN).

References

Adams, A.E. (1988): *Mallorcan Geology*. Department of Extra Mural Studies, University College. 61 pp. Cardiff, U.K.

Alcover, J.A. & Bover, P. (2005): Catàleg dels jaciments de *Myotragus* a les Illes Balears. In: Alcover, J.A. & Bover, P. (eds.) *Proceedings of the International Symposium "Insular Vertebrate Evolution: the Palaeontological Approach"*. Monografies de la Soc. d'Història Natural de les Balears, 12: 51-58. Palma de Mallorca.

Alcover, J.A.; Ramis, D.; Coll, J. & Trias, M. (2001): Bases per al coneixement del contacte entre els primers colonitzadors humans i la naturalesa de les Balears. *Endins*, 24: 5-57.

Andrews, J.N.; Ginés, A.; Pons-Moyà, J.; Smart, P.L. & Trias, M. (1989): Noves dades sobre el jaciment paleontològic de la Cova de na Barxa (Capdepera, Mallorca). *Endins*, 14-15: 17-25. Palma de Mallorca.

Balaguer, P. (2005): *Tipus i evolució de les costes rocoses de Mallorca*. Tesi Doctoral. Departament de Ciències de la Terra, Universitat de les Illes Balears. 373 pp. Unpublished. Palma de Mallorca.

Balaguer, P.; Fornós, J.J.; Pons, G.X. & Gómez-Pujol, L. (2007): Movimientos de masas, disgregación granular y bioerosión en la costa rocosa meridional y oriental de Mallorca. In: Fornós, J.J.; Ginés, J. & Gómez-Pujol, L. (eds). *Geomorfología litoral: Migjorn y Llevant de Mallorca*. Mon. Soc. Hist. Nat., 15: 137-152. Palma de Mallorca.

Bardají, T.; Goy J.L.; Zazo C.; Hillaire-Marcel C.; Dabrio, C.J.; Cabero, A.; Ghaleb, B.; Silva, P.G. & Lario, J. (2009): Sea-level and climate changes during OIS 5e in Western Mediterranean (Spain). *Geomorphology*, 104: 22–36.

Bate, D.M. (1909): Preliminary note on a new Artiodactyle from Majorca. *Myotragus balearicus*, gen. et sp. nov. *Geological Magazine*, NS 5,6: 385-388.

Bolòs, O. de (1996): *La vegetació de les Illes Balears. Comunitats de plantes*. Institut d'Estudis Catalans. 267 pp. Barcelona.

Bolòs, O. de & Molinier, R. (1958): Recherches phytosociologiques dans l'île de Majorque. *Collectanea Botanica*, 5(3-4): 699-865.

Bolòs, O. de & Molinier, R. (1969): Vue d'ensemble de la végetation des îles Baléares. *Vegetatio*, 17: 251-270.

Bover, P. & Alcover, J.A. (2003): Understanding Late Quaternary extinctions: the case of *Myotragus balearicus* Bate 1909. *Journal of Biogeography*, 30: 771-781.

Bover, P. & Alcover, J.A. (2008): Extinction of the autochthonous small mammals from Mallorca (Gymnesic Islands, Western Mediterranean Sea) and its ecological consequences. *Journal of Biogeography*, 35: 1112-1122.

Bover, P. & Tolosa, F. (2005): The olfactory ability of *Myotragus balearicus*: preliminary notes. In: Alcover, J.A. & Bover, P. (eds.) *Proceedings of the International Symposium "Insular Vertebrate Evolution: the Palaeontological Approach"*. Monografies de la Soc. d'Història Natural de les Balears, 12: 85-94.

Bover, P.; Quintana, J. & Alcover, J.A. (2008): Three islands, three worlds: paleogeography and evolution of the vertebrate fauna from the Balearic Islands. *Quaternary International*, 182: 135-144.

Bover, P.; Alcover, J.A.; Michaux, J.J.; Hautier, L. & Hutterer, R. (2010): Body shape and life style of the extinct Balearic dormouse *Hypnomys* (Rodentia, Gliridae): new evidence from the study of associated skeletons. *PLoS ONE*, 5(12): e15817. doi: 10.1371/journal.pone.0015817.

Burjachs, F.; Pérez-Obiol, R.; Roure, J.M.; Julià, R. (1994): Dinámica de la vegetación durante el Holoceno en la isla de Mallorca. In: Mateu, I.; Dupré, M.; Güemes, J. & Burgaz, M.E. (eds.) *Trabajos de Palinología básica y aplicada*. Universitat de València: 199-210. València.

Butzer, K.W. (1962): Coastal Geomorphology of Majorca. *Annals of the Association of American Geographers*, 52: 191-212.

Butzer, K.W. (1964): Pleistocene cold-climate phenomena of the island of Mallorca. *Zeitschrift für Geomorphologie*, 8 (1): 7-31.

Butzer, K.W. (1975): Pleistocene littoral-sedimentary cycles of the Mediterranean Basin: a Mallorquin view. In: Butzer, K.W. & Isaac, G.L. (eds.) *After the Australopithecines*. Mouton Press: 25-71. The Hague, U.S.A.

Butzer, K.W. (1983): Global sea level stratigraphy: an apppraisal. *Quaternary Science Reviews*, 2: 1-15.

Butzer, K.W. & Cuerda, J. (1962a): Coastal stratigraphy of southern Mallorca and its implications for the Pleistocene chronology of the Mediterranean Sea. *Journal of Geology*, 70: 389-416.

Butzer, K.W. & Cuerda, J. (1962b): Nuevos yacimientos marinos cuaternarios de las Baleares. *Notas y Comunicaciones. Instituto Geológico y Minero de España*, 67: 25-70.

Cañellas, B.; Orfila, A.; Méndez, F.J.; Menéndez, M.; Gómez-Pujol, L. & Tintoré, J. (2007): Application of a POT model to estimate the extreme significant wave height levels around the Balearic Sea (Western Mediterranean). *Journal of Coastal Research*, Spec. Issue 51: 329-333.

Castro, P.; Gili, S.; González, P.; Lull, V.; Micó, R. & Rihuete, C. (1997): Radiocarbon Dating and the Prehistory of the Balearic Islands. *Proceedings of the Prehistoric Society*, 63: 55-86.

Clauzon, G.; Suc, J.-P.; Gautier, F.; Berger, A. & Loutre, M.F. (1996): Alternate interpretation of the Messinian salinity crisis: controversy resolved? *Geology*, 24: 363-366.

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

Colom, G. (1975): *Geología de Mallorca*. Diputación Provincial de Baleares, Instituto de Estudios Baleáricos. 519 pp. Palma de Mallorca.

Colom, G., Sacarés, J. & Cuerda, J. (1968): Las formaciones marinas y dunares pliocénicas de la región de Lluchmayor (Mallorca). *Boletín de la Sociedad de Historia Natural de las Baleares*, 14: 46-61.

Crabtree, K. (1978): Soils. In Rose, J. (ed.) *The Quaternary of Mallorca*. Quaternary Research Association. Field meeting guide: 17-18. Bedfordshire, U.K.

Cuerda, J. (1957): Fauna marina del Tirreniense de la Bahía de Palma (Mallorca). *Boletín de la Sociedad de Historia Natural de las Baleares*, 3: 3-76.

Cuerda, J. (1975): *Los tiempos cuaternarios en Baleares*. Diputación Provincial de Baleares. Instituto de Estudios Baleáricos. 304 pp. Palma de Mallorca.
Cuerda, J. (1987): *Moluscos marinos y salobres del Pleistoceno balear*. Caja de Baleares "Sa Nostra". 420 pp. Palma de Mallorca.
Cuerda, J.; Sacarés, J. & Colom, G. (1969): Hallazgo de terrazas pliocénicas, marinas, en la región de Llucmajor (Mallorca). *Acta Geológica Hispánica*, 2: 35-37.
De la Cruz, M.T.; Balaguer, J. & Hernando, J. (2001): Caracterización de suelos del bosque termomediterráneo del Este de Mallorca. *Bolletí de la Societat d'Història Natural de les Illes Balears*, 44: 27-39.
Egozcue, J.J. (1971): Estudio del cono de materiales alóctonos de la Cova de sa Font. *Speleon*, 18: 49-53.
Fernández-Miranda, M. & Waldren, W. (1979): Periodificación cultural y cronología absoluta en la Prehistoria de Mallorca. *Trabajos de Prehistoria*, 36: 349-377.
Fiol, L.A.; Fornós, J.J.; Gelabert, B. & Guijarro, J.A. (2005): Dust rains in Mallorca (Western Mediterranean): their occurrence and role in some recent geological processes. *Catena*, 63: 64-84.
Flint, R.F. (1966): Comparison of interglacial marine stratigraphy in Virginia, Alaska, and Mediterranean areas. *American Journal of Science*, 264: 673-684.
Fornós, J.J. & Gelabert, B. (1995): Litologia i tectònica del carst de Mallorca / Lithology and tectonics of the Majorcan karst. In: Ginés, A. & Ginés, J. (eds.) *El carst i les coves de Mallorca / Karst and caves in Mallorca*. Endins, 20 / Mon. Soc. Hist. Nat. Balears, 3: 27-43. Palma de Mallorca.
Fornós, J.J. & Gelabert, B. (2004): Baleares. In: Vera, J.A. (ed.) *Geología de España*. Sociedad Geológica de España, Instituto Geológico y Minero de España: 450-464. Madrid.
Fornós, J.J. & Gelabert, B. (2011): Condicionants litològics i estructurals del Carst a les Illes Balears. In: Gràcia, F.; Ginés, J.; Pons, G.X.; Ginard, A. & Vicens, D. (eds.) *El Carst. Patrimoni natural de les Illes Balears*. Endins, 35 / Mon. Soc. Hist. Nat. Balears, 17: 37-52. Palma de Mallorca.
Fornós, J.J.; Pomar, L. & Ramos-Guerrero, E. (2002): Balearic Islands. Tertiary. In: Gibbons, W. & Moreno, T. (eds.) *The Geology of Spain*. The Geological Society, 327-334, 405-406. London.
Fornós, J.J.; Balaguer, P.; Gelabert, B. & Gómez-Pujol, L. (2005): Pleistocene formation, evolution and retreat rates of a carbonate coastal cliff (Mallorca Islands, Western Mediterranean). *Journal of Coastal Research*, Spec. Issue, 49: 15-21.
Fornós, J.J.; Clemmensen, L.B.; Gómez-Pujol, L. & Murray, A.S. (2009): Late Pleistocene carbonate aeolianites on Mallorca, Western Mediterranean: a luminiscence chronology. *Quaternary Science Reviews*, 28(25-26): 2697-2709.
Gelabert, B. (1998): *La estructura geológica de la mitad occidental de la isla de Mallorca*. Memorias del Instituto Tecnológico Geominero de España. 129 pp. Madrid.
Gibbons, W. & Moreno, T. (2002): *The Geology of Spain*. The Geological Society. 649 pp. London, UK
Ginés, A. (1998): L'exocarst de la serra de Tramuntana de Mallorca. In: Fornós, J.J. (ed.) *Aspectes geològics de les Balears*. Universitat de les Illes Balears: 361-389. Palma de Mallorca.
Ginés, A. (1999): Agriculture, grazing and land use changes at the Serra de Tramuntana karstic mountains. *International Journal of Speleol*ogy, 28 B (1/4): 5-14.
Ginés, A. & Fiol, L.A. (1981): Estratigrafía del yacimiento de la Cova des Fum (Sant Llorenç, Mallorca). *Endins*, 8: 25-42.
Ginés, A. & Ginés, J. (1974): Consideraciones sobre los mecanismos de fosilización de la Cova de sa Bassa Blanca y su paralelismo con formaciones marinas del Cuaternario. *Boll. Soc. Hist. Nat. Balears*, 19: 11-28.
Ginés, A. & Ginés, J. (1986): On the interest of speleochronological studies in karstified islands. The case of Mallorca (Spain). *Com. 9º Cong. Int. Espeleol.*, 1: 297-300. Barcelona.
Ginés, A.; Ginés, J.; Fornós, J.J. & Tuccimei. P. (1999): Dataciones isotópicas de espeleotemas procedentes de cuevas costeras de Mallorca. Estado actual de las investigaciones. In: Andreo, B.; Carrasco, F. & Durán, J.J. (eds.) *Contribución del estudio científico de las cavidades kársticas al conocimiento geológico*. Patronato de la Cueva de Nerja. 143-152. Nerja, Màlaga.
Ginés, J. & Ginés, A. (1995): Aspectes espeleocronològics del carst de Mallorca / Speleochronological aspects of karst in Mallorca. In: Ginés, A. & Ginés, J. (eds.) *El carst i les coves de Mallorca / Karst and caves in Mallorca*. Endins, 20 / Mon. Soc. Hist. Nat. Balears, 3: 99-112. Palma de Mallorca.
Ginés, J.; Ginés, A. & Fornós, J.J. (2011): Dades sobre Paleocarst i Espeleocronologia de les Illes Balears. In: Gràcia, F.; Ginés, J.; Pons, G.X.; Ginard, A. & Vicens, D. (eds.) *El Carst. Patrimoni*

natural de les Illes Balears. Endins, 35 / Mon. Soc. Hist. Nat. Balears, 17: 213-226. Palma de Mallorca.

Gómez-Pujol, L. & Fornós, J.J. (2009): Coastal karren in the Balearic Islands. In: Ginés, A.; Knez, M.; Slabe, T. & Dreybrodt, W. (eds.) *Karst rock features. Karren sculpturing*. Zalozba Publ.: 487-502. Ljubljana, Slovenia.

Gómez-Pujol, L.; Cruslock, E.M.; Fornós, J.J. & Swantesson, J.O.H. (2006): Unravelling factors that control shore platforms and cliffs in microtidal coasts: the case of Mallorcan, Catalonian and Swedish coasts. *Z. Geomorph. N.F., Suppl. Bd.* 144: 117-135.

Gómez-Pujol, L.; Balaguer, P. & Fornós, J.J. (2007a): El litoral de Mallorca: síntesis geomórfica. In: Fornós, J.J.; Ginés, J. & Gómez-Pujol, L. (eds.) *Geomorfología litoral: Migjorn y Llevant de Mallorca*. Mon. Soc. Hist. Nat. Balears, 15: 39-59. Palma de Mallorca.

Gómez-Pujol, L.; Orfila, A.; Cañellas, B.; Álvarez-Ellacuría, A.; Méndez, F.J.; Medina, R. & Tintoré, J. (2007b): Morphodynamic classification of sandy beaches in low energetic marine environment. *Marine Geology*, 242: 235-246.

González-Hernandez, F. M.; Goy, J. L.; Zazo, C. & Silva, P. G. (2001): Actividad eólica – cambios del nivel del mar durante los últimos 170.000 años (litoral de Mallorca, Islas Baleares). *Rev. Cuaternario y Geomorfología*, 15 (3-4): 67-75.

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

Gràcia, F. & Vicens, D. (1998): Aspectes geomorfològics quaternaris del litoral de Mallorca. In: Fornós, J.J. (ed.) *Aspectes geològics de les Balears*. Universitat de les Illes Balears. 307-329. Palma de Mallorca.

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

Grimalt, M. & Rodríguez-Perea, A. (1994): El modelado periglacial en Baleares. Estado de la cuestión. In: Gómez, A.; Simón, M. & Salvador, F. (eds.) *Periglaciarismo en la Península Ibérica, Canarias y Baleares*. Monografías de la S.E.G., 7: 189-201. Granada.

Grimalt, M.; Rodríguez-Perea, A.; Servera, J. & Rodríguez-Gomila, R. (1991): *Libro-Guía de las Excursiones de las VII Jornadas de Campo de Geografía Física*. Universitat de les Illes Balears, Departament de Ciències de la Terra. 253 pp. Palma de Mallorca.

Guerrero, V.M. (2000): La colonización humana de Mallorca en el contexto de las islas occidentales del Mediterráneo: una revisión crítica. In: Guerrero, V.M. & Gornés, S. (eds.) *Colonització humana en ambients insulars. Interacció amb el medi i adaptació cultural*. Universitat de les Illes Balears: 99-193. Palma de Mallorca.

Guijarro, J.A. (1986): *Contribución a la Bioclimatología de Baleares*. Tesi Doctoral. Universitat de les Illes Balears. 232 pp & app. Unpublished. Palma de Mallorca.

Guijarro, J.A. (1995): Aspectes bioclimatics del karst de Mallorca / Bioclimatic aspects of karst in Mallorca. In: Ginés, A. & Ginés, J. (eds.) *El carst i les coves de Mallorca / Karst and caves in Mallorca*. Endins, 20 / Mon. Soc. Hist. Nat. Balears, 3: 17-26. Palma de Mallorca.

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

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

Hodge, E.J. (2004): *Palaeoclimate of the Western Mediterranean region: results from speleothems*. Ph. D. Thesis. University of Bristol. 246 pp. Unpublished. Bristol.

Hodge, E.J.; Richards, D.A.; Smart, P.L.; Ginés, A. & Mattey, D.P. (2008): Sub-millennial climate shifts in the western Mediterranean during the last glacial period recorded in a speleothem from Mallorca, Spain. *Journal of Quaternary Science*, 23 (8): 713-718.

Jenkyns, H.C.; Sellwood, B.W. & Pomar, L. (1990): *A field excursion guide to the island of Mallorca*. The Geologists' Association. 93 pp. London, U.K.

Klinge, H. & Mella, A. (1958): Los suelos de las Islas Baleares. *Anales de Edafología y Fisiología Vegetal*, 17: 57-92.

Knoche, H. (1921-1923): *Flora Balearica. Étude phytogéographique sur les îles Baléares*. Ed. Imp. Roumègous et Dêhen. 4 Volumes. Montpellier.

Köhler M. & Moyà-Solà, S. (2004): Reduction of brain size and sense organs in the fossil insular bovid *Myotragus*. *Brain, Behavior and Evolution*, 63:125-140.

Köhler, M. & Moyà-Solà, S. (2009): Physiological and life history strategies of a fossil large mammal in a resource-limited environment. *Proceedings of the National Academy of Sciences USA*, 106: 20354-20358.

Krijgsman, W.; Hilgen, F.J.; Raffi, I.; Sierro, F.J. & Wilson, D.S. (1999): Chronology, causes and progression of the Messinian salinity crisis. *Nature*, 400: 652-655.

Kubiëna, W.L. (1953): *The soils of Europe*. Thomas Murby and Company. 318 pp. London.

Mayol, J. & Machado, A. (1992): *Medi Ambient, Ecologia i Turisme a les Illes Balears*. Editorial Moll. 127 pp. Palma de Mallorca.

Menéndez-Amor, J. & Florschütz, F. (1961): La concordancia entre la composición de la vegetación durante la segunda mitad del Holoceno en la costa de Levante y en la costa W. de Mallorca. *Boletín Real Sociedad Española de Historia Natural*, (serie G) 59: 97-100.

Mensching, H. (1955): Karst und Terra Rossa auf Mallorca. *Erdkunde*, 9: 188-196. Bonn, Germany.

Morey, M. & Ruiz-Pérez, M. (2008): The Balearic Islands. In: Vogiatzakis, I.N.; Pungetti, G. & Mannion, A.M. (eds.) *Mediterranean Island Landscapes*. Landscape Series, volume 9: 271-296. Springer.

Moyà-Solà, S. & Pons-Moyà, J. (1979): Catálogo de los yacimientos con fauna de vertebrados del Plioceno, Pleistoceno y Holoceno de las Baleares. *Endins*, 5-6: 59-74.

Moyà-Solà, S.; Köhler, M.; Alba, D.M. & Pons-Moyà, J. (2007): El significado de *Myotragus batei* y *M. binigausensis* en la evolución del género *Myotragus* (Bovidae, Mammalia) en las islas Baleares. In: Pons, G.X. & Vicens, D. (eds.) *Geomorfología litoral i Quaternari. Homenatge a Joan Cuerda Barceló*. Mon. Soc. Hist. Nat. Balears, 14: 155-180. Palma de Mallorca.

Muhs, D.R.; Budhan, J.; Avila, A.; Skipp, G.; Freedman, J. & Patterson, D. (2010): The role of African dust in the formation of Quaternary soils on Mallorca, Spain and implications for the genesis of Red Mediterranean soils. *Quaternary Science Reviews*, 29: 2518-2543.

Muntaner-Darder, A. (1954): Nota sobre los aluviones de Palma de Mallorca. *Boletín de la Sociedad de Historia Natural de las Baleares*, 1: 36-48.

Muntaner-Darder, A. (1956): Nota sobre un fémur de Myotragus balearicus hallado en los aluviones de Sancellas. *Boletín de la Sociedad de Historia Natural de las Baleares*, 2: 115-117.

Muntaner-Darder, A. (1957): Las formaciones cuaternarias de la Bahía de Palma (Mallorca). *Boletín de la Sociedad de Historia Natural de las Baleares*, 3: 77-118.

Nielsen, K.A.; Clemmensen, L.B. & Fornós, J.J. (2004): Middle Pleistocene magneto-stratigraphy and susceptibility stratigraphy. Data from carbonate aeolian systems, Mallorca, Western Mediterranean. *Quaternary Science Reviews*, 23: 1733-1756.

Osmaston, H.A. (1978): Paleosols. In Rose, J. (ed.) *The Quaternary of Mallorca*. Quaternary Research Association. Field meeting guide: 39-40. Bedfordshire, U.K.

Parker, J. (1994): *Walking in Mallorca*. Cicerone Press. 256 pp. Milnthorpe, U.K.

Pérez-Obiol, R. & Yll, E.I. (2003): Quaternary palynology of Balearic islands. In: Ruiz, M.B.; Dorado, M.; Valdeolmillos, A.; Gil, M.J.; Bardají, T.; de Bustamante, I. & Martínez, I. (eds.) *Quaternary climatic changes and environmental crises in the Mediterranean region*. Universidad de Alcalá - Ministerio de Ciencia y Tecnología - INQUA. 123-131. Alcalá de Henares, Madrid.

Pérez-Obiol, R.; Yll, E.I.; Pantaleón-Cano, J. & Roure, J.M. (2000): Evaluación de los impactos antrópicos y los cambios climáticos en el paisaje vegetal de las Islas Baleares durante los últimos 8000 años. In: Guerrero, V.M. & Gornés, S. (eds.) *Colonització humana en ambients insulars. Interacció amb el medi i adaptació cultural*. Universitat de les Illes Balears: 73-98. Palma de Mallorca.

Pérez-Obiol, R.; Sáez, L. & Yll, E.I. (2003): Vestigis florístics postglacials a les Illes Balears i dinàmica de la vegetació holocènica. *Orsis*, 18: 77-94.

Pomar, L. (1979): La evolución tectosedimentaria de las Baleares: análisis crítico. *Acta Geológica Hispánica (Libro Homenaje a L. Solé Sabarís)*, 14: 293-310. (1981).

Pons-Moyà, J.; Moyà-Solà, S. & Kopper, J.S. (1979): La fauna de mamíferos de la Cova de Canet (Esporles) y su cronología. *Endins*, 5-6: 55-58.

Rodríguez-Perea, A. (1998): Ventalls al·luvials i sistemes dunars a Betlem (Artà, Mallorca. In: Fornós, J.J. (ed.) *Aspectes Geològics de les Balears*. Universitat de les Illes Balears: 169-189. Palma de Mallorca.

Rodríguez-Perea, A. & Gelabert, B. (1998): Geologia de Mallorca. In: Fornós, J.J. (ed.) *Aspectes Geològics de les Balears*. Universitat de les Illes Balears: 11-38. Palma de Mallorca.

Rose, J. ed. (1978): *The Quaternary of Mallorca*. Quaternary Research Association. Field meeting guide. 114 pp. Bedfordshire, U.K.

Rose, J. & Meng, X. (1999): River activity in small catchments over the Last 140 ka, North-east Mallorca, Spain. In: Brown, A.G. & Quine, T.A. (eds.) *Fluvial processes and Environmental Change*. John Wiley & Sons Ltd.: 91-102.

Rose, J.; Meng, X. & Watson, C. (1999): Palaeoclimate and palaeoenvironmental responses in the western Mediterranean over the last 140 ka: evidence from Mallorca, Spain. *Journal of the Geological Society*, 156: 435-448.

Rosselló-Verger, V.M. (1977a): *Les Illes Balears. Resum geogràfic*. Editorial Barcino. 198 pp. Barcelona.

Rosselló-Verger, V.M. (1977b): Screes periglaciares en la montaña mallorquina. *V Coloquio de Geografía*: 83-92.

Sàbat, F. (1986): *Estructura geològica de les Serres de Llevant de Mallorca (Balears)*. Tesi Doctoral, Universitat de Barcelona. 128 pp, 76 figs. Barcelona.

Servera, J. (1995): Distribució geogràfica del carst a Mallorca / The geographical distribution of karst in Mallorca. In: Ginés, A. & Ginés, J. (eds.) *El carst i les coves de Mallorca / Karst and caves in Mallorca*. Endins, 20 / Mon. Soc. Hist. Nat. Balears, 3: 7-16. Palma de Mallorca.

Servera, J.; Gelabert, B. & Rodríguez-Perea, A. (2009): Development and setting of the Alcudia Bay beach-dune system (Mallorca, Spain). *Geomorphology*, 110: 172-181.

Solé-Sabarís, L. (1962): Le quaternaire marin des Baléares et ses rapports avec les côtes méditerranéennes de la peninsule ibérique. *Quaternaria*, 6: 309-342.

Stearns, C.E. & Thurber, D.L. (1965): ^{230}Th/^{234}U dates of late Pleistocene marine fossils from the Mediterranean and Moroccan littorals. *Quaternaria*, 7: 29-42.

Swantesson, J.O.H.; Gómez-Pujol, L.; Cruslock, E.M.; Fornós, J.J. & Balaguer, P. (2006). Processes and patterns of erosion and downwearing on micro-tidal rock coasts in Sweden and western Mediterranean. *Z. Geomorph. N.F., Suppl. Bd*. 144: 137-160.

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

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

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

Verd, J.M. (1972): Introducción al estudio sedimentológico del Cuaternario continental del llano de Palma. *Boletín de la Sociedad de Historia Natural de las Baleares*, 17: 79-126.

Vicens, D.; Gràcia, F.; Balaguer, P.; Ginard, A.; Crespí, D. & Bover, P. (2011): Cavitats litorals de gènesi marina a les Illes Balears. In: Gràcia, F.; Ginés, J.; Pons, G.X.; Ginard, A. & Vicens, D. (eds.) *El Carst. Patrimoni natural de les Illes Balears*. Endins, 35 / Mon. Soc. Hist. Nat. Balears, 17: 227-236. Palma de Mallorca.

Waldren, W.H. (1982): A preliminary palynological report from the Muleta cave deposit. Balearic Prehistoric Ecology and Culture. Part II. *BAR International Series*, 149(2): 539-545.

Waldren, W.H. (1992): Radiocarbon and other isotopic age determinations from the Balearic Islands. A comprehensive inventory. *DAMARC*, 26. Donald Baden-Powell Quaternary Research Centre, Pitt Rivers Museum, Oxford University.

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