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RESEARCH

Late Pleistocene marine coastal deposits of Formentera Island and S'Espalmador islet (Balearic archipelago, western Mediterranean): climatic and geomorphological evolution

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Introduction

The Quaternary is characterised by glacial periods of the cold and arid climate, separated by interglacial periods of warm and humid (Ehlers and Gibbard 2011). One of the most significant effects of these climatic changes is the variations in the sea level on a global scale, affecting very significantly the geomorphological evolution of the coasts and the habitats of many living beings. In this sense, at the end of the last glaciation (MIS 6) an interglacial period of warm climate began, (Marine Isotopic Stage-MIS 5) (Dorale et al. 2010), which favoured the entry of intertropical marine mollusks (*Senegalese fauna*) through the strait of Gibraltar towards the Mediterranean (Vicens 2015). However, at the end of the interglacial substage MIS 5e (127–117 ka), there was a generalised drop in temperatures and Senegalese species gradually disappeared from the Mediterranean (Polyak et al. 2018). At present, they are restricted to the West African and Cape Verde coasts (Zazo et al. 2010). The presence of this fossil fauna is evident in the beach deposits along the Mediterranean coast, above the current sea level, and is considered of high stratigraphic value (Vicens 2015) and constitutes an important natural heritage (Pons et al. 2017). Outcrops of littoral deposits are very important elements for the reconstruction of the Quaternary coastal evolution in terms of the interplay of sea level fluctuations and climate changes. These marines, colluvial and aeolian successions in these coastal environments, are useful indicators of geomorphological changes that occurred during the Pleistocene, serving evidence of transgressive and regressive episodes along the coast.

Butzer and Cuerda (1962) mentioned, for the first time, the presence of Pleistocene marine fauna in the zone of Es Copinar; later, Cuerda (1984) indicates the presence of Quaternary deposits including Senegalese fauna (*Tethystrombus latus*) in the same zone. Subsequently, Gàsser and Ferrer (1997) and Gàsser (1998, 2002) indicate the presence of marine fossils attributed to the Late Pleistocene also in Es Copinar and Es Ram. These authors provide some paleontological data from some of the sites studied. In this work, the paleontological records of all the sites studied have been systematically analysed and increased, giving an overall view, correlating with stratigraphic and chronological data. In this work, both marine fauna and terrestrial fauna have been studied, the latter composed exclusively of endemic species. Del Valle et al. (2022) studied the Pleistocene deposits of Es Copinar, Caló des Mort, es Ram and Estufadors, focussing their attention on OSL dating and the chronostratigraphic fauna, considering the paleoclimatic aspects and making the environmental interpretation of the Pleistocene sequence from MIS 5e to MIS 2. In addition, this study describes for the first time the presence of a marine unit in the Es Caló des Mort. We have differentiated two beach units in these study zones, which can be assigned to different sub environments (shoreface, backshore or beachface).

The primary aim of this study is to investigate the Pleistocene climate and sea level variations in Formentera Island and in the neighbouring islet of S'Espalmador by analysing the sedimentological, compositional, and taxonomical features of their littoral deposits and correlate them with different features and the various climatic substages of the MIS 5 in the western Mediterranean.

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Geological and physiographic setting

Formentera is the smallest island of the Balearic Islands with 83.2 km^2 and belongs to the subgroup of the Pityusic Islands (Fig. 1A, B). This small island is characterised by a relatively flat physiography with small elevations, such as the Puig Guillen arising at 107 m altitude and the Pilar de la Mola at 202 m in altitude.

The materials outcropping on the island of Formentera correspond to the upper Miocene limestones and calcarenites Tortonian-Messinian in age and calcarenites from the Pleistocene in age (Rangheard 1985). Almost the entire island is covered by these calcarenites, and some calcareous Pleistocene crusts located above the Upper Miocene limestones underneath. On the island of S'Espalmador, the Early Miocene (Burdigalian) limestones crop out, but with no deposits attributable to the Pliocene (Butzer and Cuerda 1962). Formentera's coastline has undergone numerous variations based on changes in sea level that have decisively affected its geomorphological evolution (leaving evidence along its coastline). Above the Upper Miocene deposits are the present-day dune ridges that cover a wide zone; currently, some Holocene and current dunes can be found in the Illetes area or on d'es Carratge beach in Formentera. Subsequently, the Eemian transgression dismantled part of the Pleistocene dunes. The successive oscillations of the sea level have resulted in Quaternary marine deposits, aeolian deposits, silty deposits, etc., which have formed the isthmus that joins the two promontories (Eivissa and Formentera Islands). Quaternary marine and aeolian deposits, and several discontinuities are widely present on the island of Formentera (Racó de ses Ampolles, Cala en Baster, Els Arenals, Es Copinar, Caló des Mort, Es Ram, Es Estufadors and Torrent Fondo) and at S'Espalmador (Cala Boc) (Fig. 1C).

Methods

Stratigraphic sections had been done obtained in the field and correlated based on the presence of extend and continuous marine key layers. At each log, major units have been established in terms of lithofacies and the contents of marine fauna.

The sampling of the marine fauna had been done by singling and with the en-mass collection as Mitrovic (2004) in every area, during field trips in Formentera, and from the most representative levels. In the case of singling, the molluscan shells visible to the naked eye are collected from the sediments. The material for the malacological examination was extracted from the samples by washing the sediments through the mesh. The fauna was preserved, and a code has been established pending on the sector; in this way, Es Copinar sector is EC; Es Ram is ER; es Estufadors sector is ES; Els

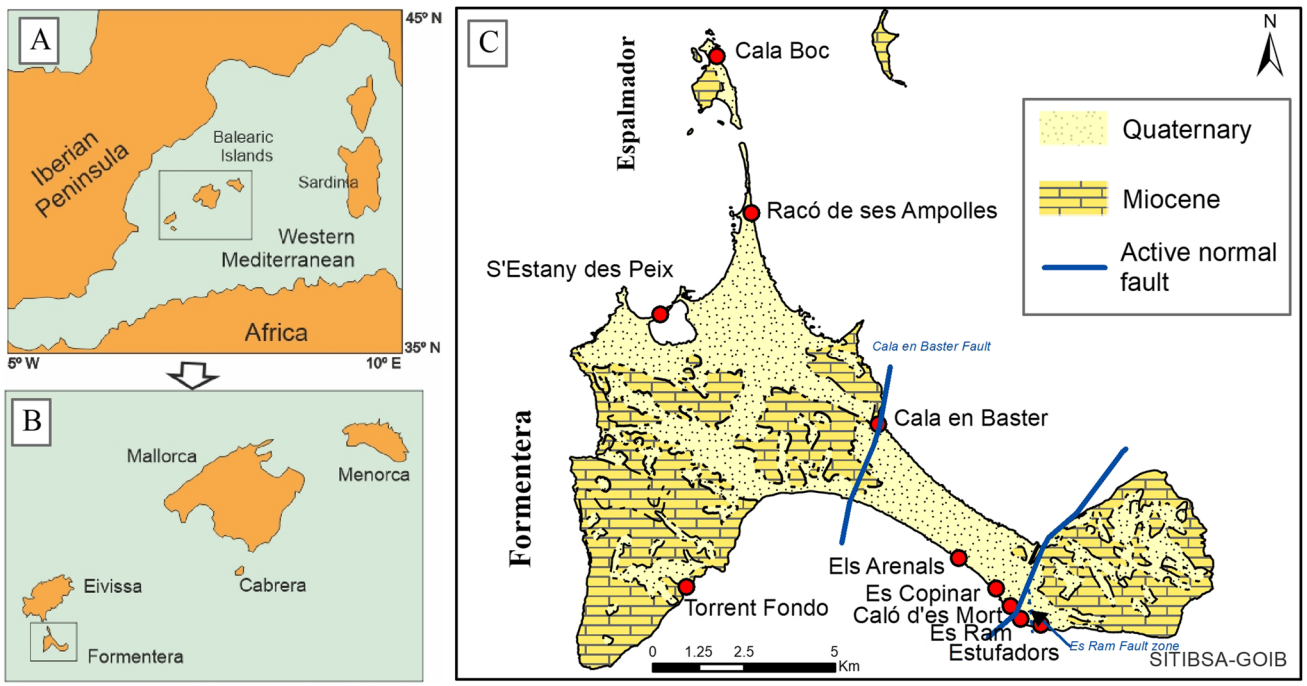

Fig. 1 Location of the study zones. **A** Location of the Balearic Islands (box); **B** location of Formentera and S'Espalmador islet (box) within the Balearic Archipelago; and **C** location of main deposits of the marine Pleistocene in Formentera and Espalmador islet (red circles)

Arenals is EA; Cala en Baster is ECB; Racó de ses Ampolles is ECSB; Cala Boc is EEB; Caló des Mort is CM; and Torrent Fondo is ETF; all the samples were deposited with these codes in the Museum of the Societat d'Història Natural de les Balears. Examination on grain characteristics and the analysis of the sediment composition were performed by point counting of 250 to 500 grains from each of the grain size fractions under a binocular microscope with the count and composition plate of *SedimPlak* (P202130758). Mineralogical content was used a Brucker D8-Advance X-ray diffractometer, using randomly oriented powders of the bulk samples. The pressed powder diffraction patterns were recorded from 3° to 65° 2Ø in steps of 0.03 s counting time. Semi-quantitative composition was based on the peak zones obtained using Difracc EVA v.4.1 software. For the taxonomic recognition of marine species, the World Register of Marine Species has been used (WoRMS 2020). For the taxonomy of terrestrial species, we followed Chueca et al. (2017).

The Pleistocene facies and fauna: antecedents and results of this study

Els Arenals, Es Copinar, Caló des Mort, Es Ram and Es Estufadors

Els Arenals, Es Copinar, Caló des Mort, Es Ram and Es Estufadors are located in the south-eastern part of Formentera (Fig. 1C). The Pleistocene deposits emerge from the sea level to 20 m at the highest point in es Caló des Mort (Del Valle et al. 2022). The Pleistocene outcrop is located over a carbonate platform mainly composed of rhodophyte algae (*Lithophyllum incrustans*) attributed to the Tortonian (Gàsser 2002).

Throughout all the profiles analysed, the eolianites always show the association of two endemic species of land snails: *Xerocrassa formenterensis* and *X. ebusitana*.

The lower beach unit (Sef-1) corresponds to a very cemented fine-medium bioclastic sand (125–250 µm), showing a very pale brown colour (HUE 10YR 8/2- HUE 10YR 8/4 according to the Munsell Chart Soil book) and 0.5 to 1.1 m thick. This unit is characterised by the presence of a high amount of marine fauna*: Thetystrombus latus*, *Conus ermineus*, *Linatella caudata*. *Acanthocardia tuberculata*, *Amonia ephipphium*, *Arca noae*, *Glycymeris nummaria*, *Striarca lactea*, *Angulus* sp., *Cerithium vulgatum*, *Columbella rustica*, *Conus ventricosus*, *Conus ermineus*, *Linatella caudata*, *Chauvetia brunnea*, *Tritia cuvieri*, *Nassarius* sp., *Semicassis undulata*, *Crisilla semistriata*, *Thetystrombus latus*, *Stramonita haemastoma*, *Truncatella subcylindrica* and *Hexaplex trunculus*. Concretely in Es Ram zone, we also found *Lithophaga lithophaga*, *Mactra stultorum*, *Pseudochama gryphina*, *Venus verrucosa*, *Diodora gibberula*, *Patella caerulea*, *Rissoa sp.*, *Tricolia pullus*. While in the Es Estufadors sector, *Bivetiella cancellata*, *Modiolus barbatus*, *Tritia cuvierii* and *Antalis vulgaris* were found.

The upper beach unit (Sef-2) consists of well-sorted fine to coarse-grained bioclastic sands (250–500 µm) showing a white to very pale brown colour (HUE 10 YR 8/1- HUE 10 YR 8/2) with sub-horizontal or low angle (± 5°) lamination dipping seaward and 0.5 to 1.5 thick. The marine fauna described are as follows: *Acanthocardia tuberculata*, *Anomia ephippium*, *Chamelea gallina*, *Glycymeris nummaria*, *Lima lima, Bolma rugosa*, *Nassarius* sp., *Semicassis undulata*, *Stramonita hemastoma*, Trochidae and *Lithothamium* sp. Local differences in the faunal contents are observed between zones. In Es Copinar and Es Caló des Mort, the huge presence of only two lamellibranches *Glycymeris nummaria* and *Acanthocardia tuberculata* is observed. Also, for the first time, we observe new faunal species: *Barbatia barbata*, *Clausinella fasciata*, *Varicorbula gibba*, *Ctena decussata*, *Chama gryphoides*, *Loripes orbiculatus*, *Ostrea stentina*, *Polititapes aureus*, *Bittium reticulatum*, *Cerithium lividulum*, *Gibberula miliaria*, *Tritia cuvierii*, *Pusia ebenus* and *Antalis vulgaris*, *Callista chione*, *Tritia pellucida*, *Diodora gibberula*, *Gibbula divaricata*, *Gibbula sp.*, *Tricolia pullus*, Scaphopoda, Poliplacophora, *Laevocardium oblongum*, *Pecten jacobeus*, *Spondylus gaederopus*, *Venus verrucosa*, *Euthria cornea*, *Ocenebra erinaceus*, *Phorcus turbinatus*, *Patella ulyssiponensis*, *Rissoa decorata*, *Stramonita haemastoma*, *Monophorus perversus*, *Turritellinella tricarinata*, *Vermetus triquetrus*, *Glycymeris bimaculate*, *Arca noae*, *Rissoa sp.*, *Poliplacophora*, *Spondylus*, *Conus ventricosus* and *Steromphala divaricata.*

Racó de ses Ampolles

Located in the northernmost part of the Island of Formentera (Fig. 1), it is characterised by a very flat pocket beach composed of Pleistocene deposits, with a maximum thickness of nearly 3 m. In general terms, it is also possible to define two beach units in this zone, like those cropping out in Es Copinar-Es Ram zones.

The lower beach unit (Sef-1) is located at 30 cm up to the present sea level, which corresponds to a very cemented fine-medium bioclastic sand (125–250 µm), showing a very pale brown colour (HUE 10YR 8/2- HUE 10YR 8/4) with a thickness around the 0.3 cm. This unit is characterised by the presence of a high amount of disorganised marine fauna species: *Glycymeris nummaria*, *Glycymeris bimaculatum*, *Cardita calyculata*, *Raphitoma linearis*, *Payraudeautia intricata*, *Acanthocardia tuberculata*, *Anomia ephippium*, *Spondylus gaederopus* and the high presence of rounded clasts (2 to 15 cm). Among the mollusc material analysed, the following species have also been identified: *Patella caerulea*, *Arca noae*, *Chamelea gallina*, *Lima lima*, *Columbella*

rustica, *Smaragdia viridis*, *Loripes lacteus*, *Stramonita haemastoma*, *Rissoina bruguieri*, *Glans trapezia*, *Barbatia barbata*, *Bittium reticulatum* and the cirripeda *Chthamalus stellatus*.

The upper beach unit (Sef-2) consists of well-sorted fine to coarse-grained bioclastic sands (250–500 µm) showing a white to very pale brown colour (HUE 10 YR 8/1-HUE 10 YR 8/2) with the huge presence of only two lamellibranches *Glycymeris nummaria* and *Acanthocardia tuberculate* and 0.5 thick.

Cala en Baster

The study zone of Cala en Baster is located in the Northeastern part of the island forming a small cove surrounded by vertical cliffs consisting of Pleistocene sedimentary rocks that descend towards the flanks covering the Miocene materials in the easternmost part of the cove.

Gàsser and Ferrer (1997) studied the fossil composition of the sediments of this zone, indicating the presence of endemic terrestrial fauna as *Xerocrassa* cf. *ebusitana ortizi,* inside the sandstone units (currently a taxonomically invalid subspecies synonymous with *Xerocrassa ebusitana*) (Chueca et al. 2017).

According to Del Valle et al. (2020a) in Cala en Baster zone, there is a marine unit (Sef-2) that consists of very pale brown (HUE 10 YR 8/3) well-sorted, fine to coarse-grained bioclastic sandstone strata with sub-horizontal or low-angle cross-stratification gently dipping seaward 1 m thick. On the top, the facies is strongly bioturbated by roots; calcretes and soft-sediment deformation structures are also present. It contains marine fossils such as *Glycymeris nummaria*, and disarticulated marine shells are common and usually aligned at the base of beds.

Es Torrent Fondo

According to Vicens et al. (1992), the outcrop under study is situated on the cliffs formed by the Tortonian, located between Punta Anguila and Barbaria cape. Specifically, it is positioned at the mouth of the Torrent Fondo, where Quaternary deposits can be found on both sides of the torrent, atop a terrace created through marine abrasion during the Pleistocene.

The observed stratigraphy from the base to the top is as follows:

(1) Basement: a massive white limestone layer (Tortonian in age) forms the base. On top of this layer, there is a flat surface and a cave formed through marine abrasion. This erosion platform is situated 2 m above sea level.
(2) Upper Pleistocene marine sediments: these sediments are present on the cliff above the marine abrasion platform, on both margins, as well as in the bed of the Torrent Fondo. The marine sediments consist of highly rounded clasts, some with a diameter exceeding 40 cm. These are embedded in a silty matrix and contain marine fauna. The sediment itself is very pale brown, with fine to medium sand particles (HUE 10YR 8/2–125–250 µm), and has an approximate thickness of 2.5 m.

The marine fauna present in the zone: Rhodophyceae: *Corallinaceae* indet.; Echinoidea: *Paracentrotus lividus*; Bivalvia: *Arca noae*, *Barbatia barbata*, *Spondylus gaederopus* and *Loripes orbiculatus*; Scaphopoda: *Antalis vulgaris*; Gastropoda: *Patella rustica*, *Phorcus turbinatus*, *Turbonilla cf. cornea*, *Cerithium vulgatum*, *Hexaplex trunculus*, *Stramonita haemastoma*, *Ocenebra edwardsii*, *Mitrella scripta*, *Columbella rustica*, *Vexillum corbicula* and *Conus ventricosus.*

S'Espalmador

S'Espalmador islet is separated from Formentera by a very narrow and shallow passage (50 m wide and 2 m depth) from the Pas cape to the Es Borronar cape. The islet is surrounded by other smaller islets (Es Porcs, Sa Torreta, Casteví and S'Alga). The eastern part of the islet features sandy beaches in the south and rocky formations with a small pocket beach called Cala en Boc in the north.

In the S'Espalmador islet, we found a marine unit (Sef-1)—Cala Boc—characterised by massive strata (maximum thickness around 40 cm) with subrounded/rounded clasts mostly discoidal form and interstices filled by medium to coarse-grained sand (250–500 µm) rich in bioclasts and marine fossils. The colour is very pale brown (HUE 10YR 8/3). The following fossils were identified: *Arca noae*, *Glycymeris nummaria*, *Spondylus gaederopus*, *Loripes lacteus*, *Melarhaphe neritoides*, *Stramonita haemastoma*, *Columbella rustica* and *Tritia cuvierii*. The mineralogical composition is dominated by calcite (55%) and aragonite (45%). Among the detected species, *Acanthocardia tuberculata* must be included.

Discussion

Two different marine units have been described (Sef-1 and Sef-2) separated by a sandy palaeosol. The lower beach unit (Sef-1) is characteristic for being located at 30–40 cm over the current sea level, composed of a high diversity of marine species and, in some cases, as Es Copinar, Es Ram or Es Estufadors with chronostratigraphic (Senegalese) species such as *Thetystrombus latus*, *Conus ermineus* and *Linatella caudata*. Also, heterometric clasts, rounded and imbricated towards the sea, have been found. This unit has only been

observed in the areas of Es Copinar, Es Ram, Estufadors and Racó de ses Ampolles; surely, we do not observe it in the other areas due to its erosion. The beach unit (Sef-2), present in all the areas, has the characteristic of having a sandy matrix, bioclastic grains of fine to medium size, in all zones except Es Estufadors, where this unit is characteristic by containing two Bivalvia species, *Glycymeris nummaria* and *Acanthocardia tuberculata*, the first being the majority, oriented towards the sea. In the case of Es Estufadors, this unit reaches its maximum height about 1.5 m above the present level, with a large number of entire marine fauna and adult species, such as *Pecten jacobeus*.

In this sense, the paleontological content (Senegalese fauna), as well as biostratigrapy data from the marine deposits of the lower beach unit (Sef-1), located 0.30 to 0.40 m above the current sea level, and the age of overlying sedimentary units (Fig. 2) dated by Del Valle et al. (2020a, b and 2022) and the characteristics of the deposits, locate them as appertaining to the upper Pleistocene (substage MIS 5e).

In detail, the lower beach unit (Sef-1) is interpreted to represent the foreshore zone of a beach characterised by intense wave energy and the constant reworking of sediment. The presence of Senegalese fauna (*Tethystrombus latus*, *Conus ermineus* and *Linatella caudata*) in Es Copinar, Es Ram, Es Estufadors, and S'Espalmador indicates warm and humid environmental conditions. During this period, the temperature was approximately 2 °C higher than the present in mid-and low latitudes (Polyak et al. 2018) and the sea level varied both temporally and spatially, ranging from + 3 to 9 m asl along the Mediterranean and globally. This sea level was associated with the first late Pleistocene highstand and is represented by the presence of warm fauna (Senegalese fauna). During MIS 5d, the climate change and thin palaeosol were formed. This fact is correlated with the presence of a thin paedogenetic level observed over the Sef-1 marine unit. In addition, this environmental change towards a more arid and colder climate caused a cooling of the Mediterranean waters, with the direct cause of the extinction of the Senegalese fauna. This is the reason why it has not been observed in other marine units with the presence of this fauna. At some locations around the Mediterranean coast, there is evidence of sea-level rise, corresponding to the isotopic stage MIS 5e, such as in Mallorca (Cuerda 1984) or Sardinia (Andreucci et al. 2010). The upper beach unit (Sef-2) represents a wave-dominated microtidal sandy beach system from the submerged zone. The presence of complete shells and most adults, with a little degree of fragmentation, aligned with a great presence of sand as a matrix, as well as a great abundance of two predominant marine fossils (*Glycymeris nummaria* and *Acanthocardia tuberculata*), suggests a calm water environment. During this period, there was a sea level rise and a relatively warm period (Warelbroeck et al. 2022) In other sites, in the western Mediterranean basin like Sardinia and Mallorca, this type of unit

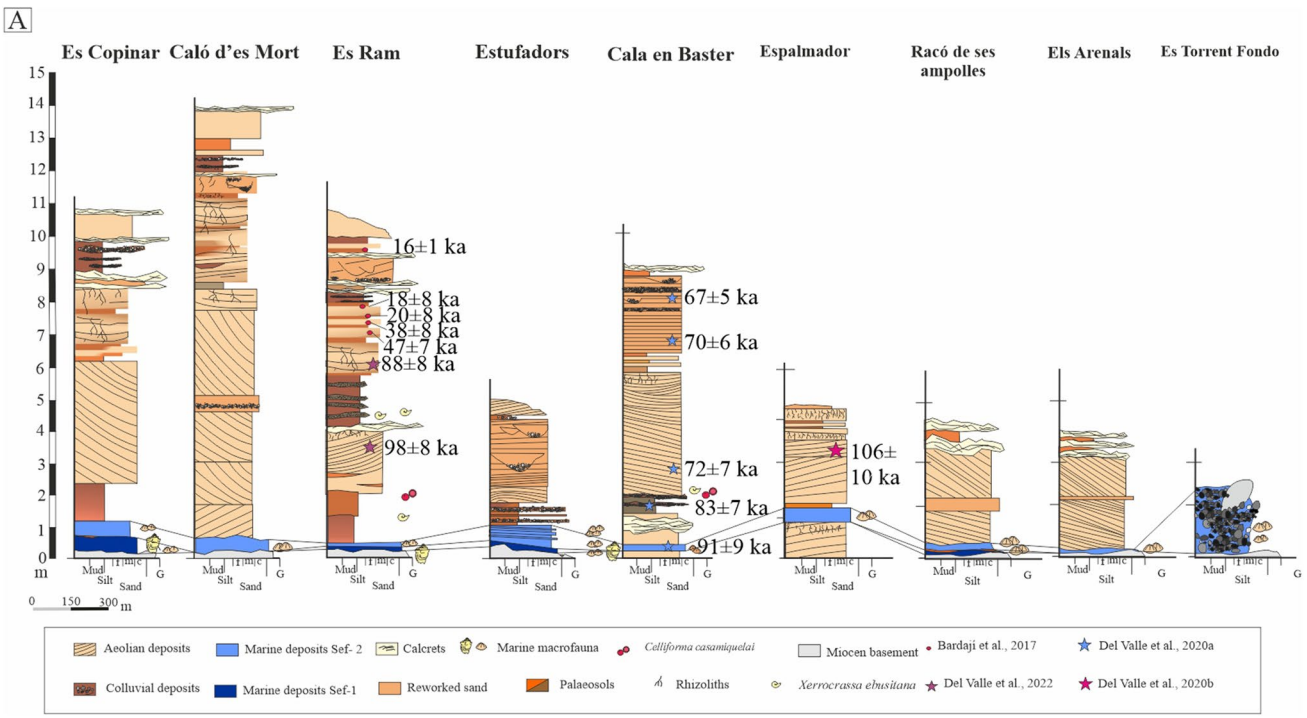

Fig. 2 Stratigraphic logs of the outcrops studied at Es Copinar, Caló des Mort, Es Ram, Es Ram, Estufadors, Cala en Baster, S'Espalmador, Racó de ses Ampolles, Els Arenals and Es Torrent Fondo

has been observed (Rose et al. 1999; Andreucci et al. 2010). Therefore, two marine units separated by a sandy palaeosol are well-differentiated that mark two ancient coastlines at 0.30–0.40 m and 1.0–1,5 m with respect to the current sea level. The first corresponds to the interglacial maximum substage MIS 5e, and the second, due to its characteristics, the content of the marine macrofauna, the stratigraphy and the dating (91 ± 9 ka) of the previous study (Del Valle 2020a), might correspond to the substage MIS 5c/a.

The geomorphological distribution of the marine units indicates that after the first highstand, the sea level suffered a relative fall. The next ascend of the sea level deposited a new marine deposit. Then, the climate gradually changed, and thick reddish soils were formed during a lowstand period. Later, suddenly, the climate changed, and strong storms occurred, as a result of which partial erosion of the upper beach unit (Sef-2) occurred, where part of these beach sediments became part of the colluvial as a consequence of the dropping of the sea level.

In general terms, the present study provides clear evidences of sea level fluctuations, which occurred during the late Pleistocene associated to climatic changes, which resulted in the extinction of thermophilic fauna (Senegalese fauna).

Conclusions

Nine outcrops of marine deposits corresponding to the upper Pleistocene, have been analysed in detail in the island of Formentera. It should be noted that two new zones are described for the first time (Es Estufadors and Caló des Mort), and a new younger Pleistocene has been described in Racó de ses Ampolles. Due to the biochronostratigraphic species observed in the lower beach unit (Sef-1) and the OSL dating of the sediments above the Sef-1 unit, it indicates that their deposition took place during the MIS 5e. The palaeosol observed over the Sef-1 unit correspond to the MIS 5d and indicate a climatic change towards more cool and arid. This decrease in the temperature caused a cooling of the Mediterranean waters, with the direct cause of the extinction of the Senegalese fauna, especially *Thetystrombus latus*. The position of the second marine highstand (Sef-2) points to a higher sea level at 117–91 ka (MIS 5c/a), but with a rapid decrease of the sea level, as evidenced by the deposition of colluvial deposits above marine sediments.

Consequently, these two fossil beach units indicate the geomorphological evidence of two highstand levels during the interglacial MIS 5, concretely during the MIS 5e (0.30–0.40 m respect to the current sea level) and during the MIS 5c/a (1–1.5 m respect to the current sea level) giving new data about the sea level oscillations and the environmental changes that occurred in this part of the Mediterranean Sea during the Quaternary.

Author contribution LdV conceived and designed the research, collected the data, performed the analysis, and wrote the paper. GXP and DV classified the fossil marine fauna and corrected the text. JJF obtained the financial support, contributed data, and revised the text.

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Code availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate All the authors of the paper give their consent to participate.

Consent for publication All the authors of the paper give their consent to publish the present paper.

Competing interests The authors declare no competing interests.

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