Carnets Geol. 19 (14)

E-ISSN 1634-0744
DOI 10.4267/2042/70497

Historical review together with stratigraphical and taphonomical considerations on the upper Pleistocene deposit of Arenal de son Servera (Mallorca, Balearic Islands)

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Abstract: The upper Pleistocene deposit of Arenal de son Servera is reviewed using data from earlier works and new considerations based on its stratigraphy and taphonomical aspects of the fossils. In the present study, five different kinds of facies are identified: [1] palaeosols with pebbles from the Miocene basement, [2] aeolianites, [3] foreshore deposits with thermophilous molluscan fossil fauna, [4] palaeosols resulting from the pedogenesis of the beach units, and [5] bioclastic channelled deposits eroding the underlaying units. The detailed taphonomical analysis revealed that the fossils enclosed in these rocks remained on the sea bottom for a significant amount of time, but they were not bioeroded, perhaps because a submerged sand bar repeatedly buried and exhumed them. In addition, the fact that *Persististrombus latus* shells are in their position of maximum stability allows to infer that they were washed up on the shore during moderately energetic events, possibly comparable to present-day ordinary storms. These two last points could be of interest to the field of coastal management, as they provide insight on the scope of physical changes these systems could undergo in the present warming of the Mediterranean.

Key-words:

• Mallorca;
• stratigraphy;
• upper Pleistocene;
• MIS-5e;
• taphonomy

Citation : MATAMALES-ANDREU R. (2019).- Historical review together with stratigraphical and taphonomical considerations on the upper Pleistocene deposit of Arenal de son Servera (Mallorca, Balearic Islands).- *Carnets Geol.*, Madrid, vol. 19, no. 14, p. 277-285.

Résumé : ***Rappel historique et aspects stratigraphiques et taphonomiques du gisement pléistocène supérieur d'Arenal de son Servera (Majorque, îles Baléares).-*** Le gisement pléistocène supérieur d'Arenal de son Servera est révisé grâce aux données d'études antérieures et à de nouvelles considérations sur sa stratigraphie et les aspects taphonomiques de ses fossiles. À l'occasion de cette étude, cinq différents types de faciès ont été reconnus: [1] des paléosols avec galets provenant du socle miocène, [2] des éolianites, [3] des dépôts d'estran à faune de mollusques fossiles thermophiles, [4] des paléosols issus de la pédogenèse des dépôts de plage, et [5] des dépôts bioclastiques chenalisants érodant les unités sous-jacentes. L'analyse taphonomique détaillée montre que les fossiles contenus dans ces roches ont résidé sur le fond marin pendant un laps de temps considérable, mais qu'ils n'étaient pas bio-érodés pour autant, peut-être parce qu'un banc de sable marin les a recouverts et découverts à de nombreuses reprises. De plus, le fait que les coquilles de *Persististrombus latus* sont retrouvées dans leur position de stabilité optimale laisse penser qu'elles aient été drossées sur la côte lors d'événements d'énergie modérée, vraisemblablement comparables aux tempêtes ordinaires actuelles. Ces deux derniers points pourraient présenter un intérêt dans le domaine de la gestion côtière, car ils permettent d'observer les changements physiques que ces systèmes peuvent enregistrer à l'occasion du réchauffement actuel de la Méditerranée.

Mots-clefs :

• Mallorque ;
• stratigraphie ;

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Published online in final form (pdf) on October 10, 2019
[Editor: Bruno GRANIER; language editor: Stephen EAGER]

• Pléistocène supérieur ;
• MIS-5e ;
• taphonomie

1. Introduction

The coastline of the island of Mallorca (Balearic Islands, Western Mediterranean) comprises an outstanding representation of upper Pleistocene littoral deposits (GINÉS *et al.*, 2012). Aeolianites and palaeosols are perhaps the most widespread facies in most of the localities, and were mainly formed during the glacial periods, but they may also occur as lateral variations of beach deposits during interglacial intervals (DEL VALLE, 2015; VICENS, 2015). Comparatively rare as they may be, foreshore deposits are usually the most fossiliferous, and have been attributed to the Marine Isotopic Substages (RAILSBACK *et al.*, 2015) MIS-5e or MIS-5c (CUERDA, 1975; VICENS, 2015). The MIS-5e represents the warmest interglacial peak of the last 150 thousand years (*e.g.*, RAILSBACK *et al.*, 2015; LORSCHEID *et al.*, 2017; MAUZ *et al.*, 2018; POLYAK *et al.*, 2018), and has classically been widely recognised along the coasts of the Mediterranean sea (see CUERDA, 1975, for references). A plethora of fossiliferous MIS-5e deposits have been described on Mallorca since the first detailed studies by CUERDA and MUNTANER (1952), CUERDA (1957) and MUNTANER (1957), especially on the south-west of the island (see VICENS, 2015, for an exhaustive review). Subsequent work on the northern and eastern coasts led to the discovery of many, yet usually small, fossiliferous outcrops (MOREY, 2008; VICENS, 2015). However, some of them are often covered by modern beach sands, thus remaining mostly unstudied.

The aim of the present work is to review the upper Pleistocene deposit of Arenal de son Servera both stratigraphically and taphonomically. All earlier works dealing with nearby outcrops are reviewed in order to minimise the ambiguity on the name and extension of this deposit. Detailed stratigraphic description allows identification of subtle lateral changes in the different facies, providing a clear context for all the fossils recorded. Finally, a taphonomical analysis is conducted on the fossils, in order to distinguish any relevant patterns or particularities. This will contribute to the increase the knowledge of the Mallorcan upper Pleistocene fossiliferous deposits, and especially the ones located on the east of the island, which have been traditionally more poorly studied. Moreover, this new insight will allow comparisons between the upper Pleistocene and the modern coastal dynamics of that beach.

2. Historical background

BUTZER and CUERDA (1962) were the first to study the marine Quaternary deposits on the East of the island of Mallorca. "Arenal de son Servera" is one of many toponyms that has a vast sandy beach, of about 1.7 km of maximum length, located near the Son Moro and Cala Millor residential areas (Fig. 1). The aforementioned authors claimed that the modern dunes covered post-Thyrrenian consolidated littoral deposits, perhaps equivalent to the ones described almost at the same time by SOLÉ-SABARÍS (1962) in Cala Millor. BUTZER and CUERDA (1962) found a calcarenite boulder among the modern sand, which was deemed older by the presence of a fragmentary specimen of *Persististrombus latus*. No other author considered this deposit again until VICENS (2015). In 2014, a storm ravaged the coastline and removed the sand covering of the northern part of the beach, where VICENS (2015) found fossils of the bivalve species *Arca noae*, *Barbatia plicata*, *Glycymeris* sp., *Donax* sp., *Acanthocardia tuberculata*, *Cardita calyculata*, *Chamelea gallina*, and the gastropod species *Persististrombus latus*, *Hexaplex trunculus*, *Stramonita haemastoma* and *Gemophos viverratus*. They were embedded in the rocks that BUTZER and CUERDA (1962) had considered as post-thyrrenian. However, the finding of the gastropods *Persististrombus latus* and *Gemophos viverratus* allowed VICENS (2015) to assign the newly found outcrops to the MIS-5e, and thus in the euthyrrenian *sensu* CUERDA (*e.g.*, 1975). VICENS (2015) assumed that the boulder found by BUTZER and CUERDA (1962) should also belong to these beds. LORSCHEID *et al.* (2017) were the first to construct a stratigraphic profile of this outcrop, which they called Cala Millor. The outcrop they studied is also located at the southern half of the beach (see Fig. 1). They illustrated a specimen of *Persististrombus latus*, tentatively assigning the deposit to the MIS-5e. JUÁREZ and MATAMALES-ANDREU (2018) described another deposit bearing *Persististrombus latus*, but this time at the southernmost edge of the beach (see Fig. 1). They named it Cala Nau 3, and admitted that it could be a lateral equivalent of the Arenal de son Servera as described in VICENS (2015) because they could not study the precise stratigraphic succession of the deposit nor correlate it to bordering areas as they were covered by modern sand.

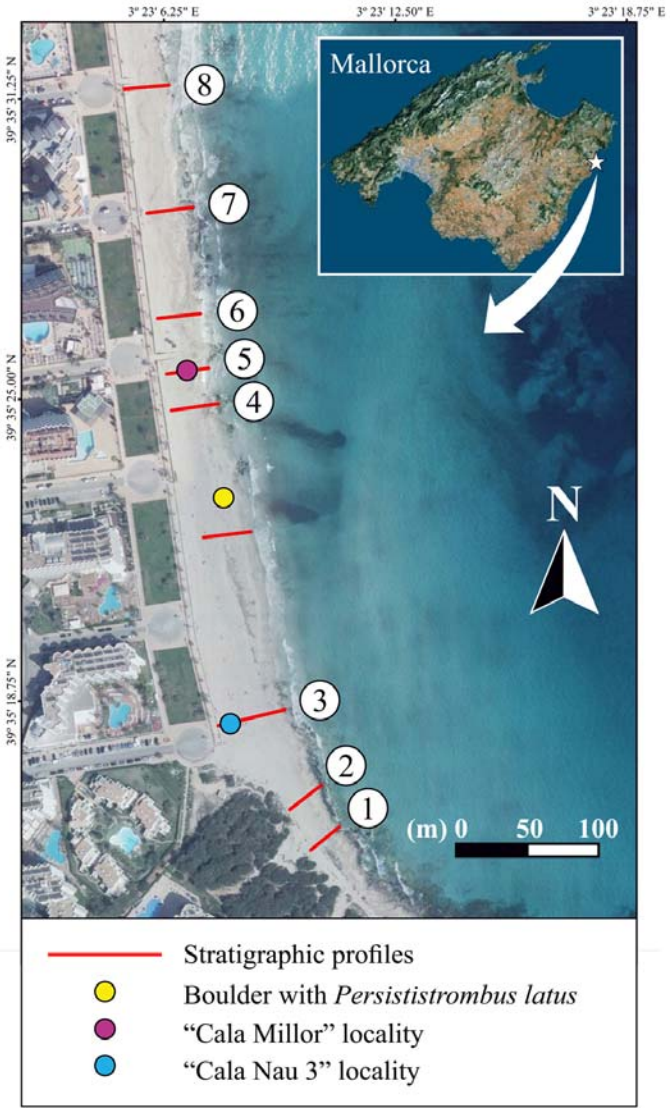


Figure 1: Geographical location of Arenal de son Servera deposit, with indication of the stratigraphical profiles studied and other remarkable features. In the localities of Cala Millor (LORSCHEID *et al.*, 2017) and Cala Nau 3 (JUÁREZ & MATAMALES-ANDREU, 2018), *Persististrombus latus* fossils were also reported. Maps taken from IDEIB (2017).

During the winter of 2017, a series of great storms overran the southern half of the beach, removing all the sand and completely clearing the outcrop for the first time in years (Fig. 2.A). This allowed the author of the present work to thoroughly study the stratigraphic lateral variations of the deposit, as it remained newly exposed. A loose calcarenitic boulder with a fragmentary specimen of *Persististrombus latus* was found somewhere around the southern half of the beach (Fig. 2.B, see Fig. 1 for its location). The remote possibility of its corresponding to the one described by BUTZER and CUERDA (1962) is herein suggested because: 1) there are no fossils from this locality in the CUERDA-SHNB (Societat d'Història Natural de Balears) collection (thoroughly reviewed by VICENS, 2015; pers. obs.), which probably means that the fragmentary specimen of *Persististrombus latus* found in 1962 was never collected; 2) the specimen bears modern bioerosion traces (*Entobia* isp.), on the exposed region only. This implies that the boulder remained on the sea bottom for some years until these last gales washed it off again on the shore.

3. Material and methods

For the present study, stratigraphic profiles of the deposit were made at intervals where the outcrop was particularly well-exposed (marked in Fig. 1). Thickness of the strata were measured with a tape. The base of each profile was determined by the base level of the wave energy on the 5th of March of 2017. The fossils recovered were deposited in the Museu Balear de Ciències Naturals (Sóller, Balearic Islands, Spain), abbreviated MBCN.

4. Results

4.1. Stratigraphy

Figure 3 represents the correlation of the eight profiles. Seven kinds of facies were recognised:

- [A] Basement. In Arenal de son Servera, the upper Pleistocene sediments overlay the upper Miocene limestones, by means of an erosion surface. Although the upper Miocene rocks are poorly exposed, they can be assigned to the Reefal Unit (POMAR *et al.*, 1983; GÓMEZ-PUJOL *et al.*, 2007).
- [B] Palaeosols. Beds constituted of reddish lutites, with common sharp pebbles from the Miocene basement and rare rhizocretions and fossil remains of land snails (*Xerocrassa* sp.). This unit is a lateral equivalent of Cala Nau 2 (JUÁREZ & MATAMALES-ANDREU, 2018: Fig. 9). It also corresponds to the infilling of fissures and depressions in the upper Miocene rocks. Exceptionally, at Cala Nau 2, it bears small marine shells.
- [C] Aeolianites. Beds constituted of yellowish calcarenites with cross-stratification, sometimes with rhizocretions present. These facies have only been located at the southernmost edge of the beach, conformably overlying the palaeosols (B). They are a lateral variation of the beach deposits (D and E).
- [D] Foreshore deposits. Beds consisting of yellowish calcarenites with very small, unidentifiable shell fragments. These sediments can sometimes be of reddish colour due to the increase in the proportion of silt. They possess low-angle parallel lamination, with interbedded lenticular laminae with coarser shell fragments. This corresponds to level "a" in LORSCHEID *et al.* (2017: Fig. S 17). Rhizocretions are often present, and become increasingly dominant towards the top of the unit. Shells of the bivalve species *Acanthocardia tuberculata* and the gastropod species

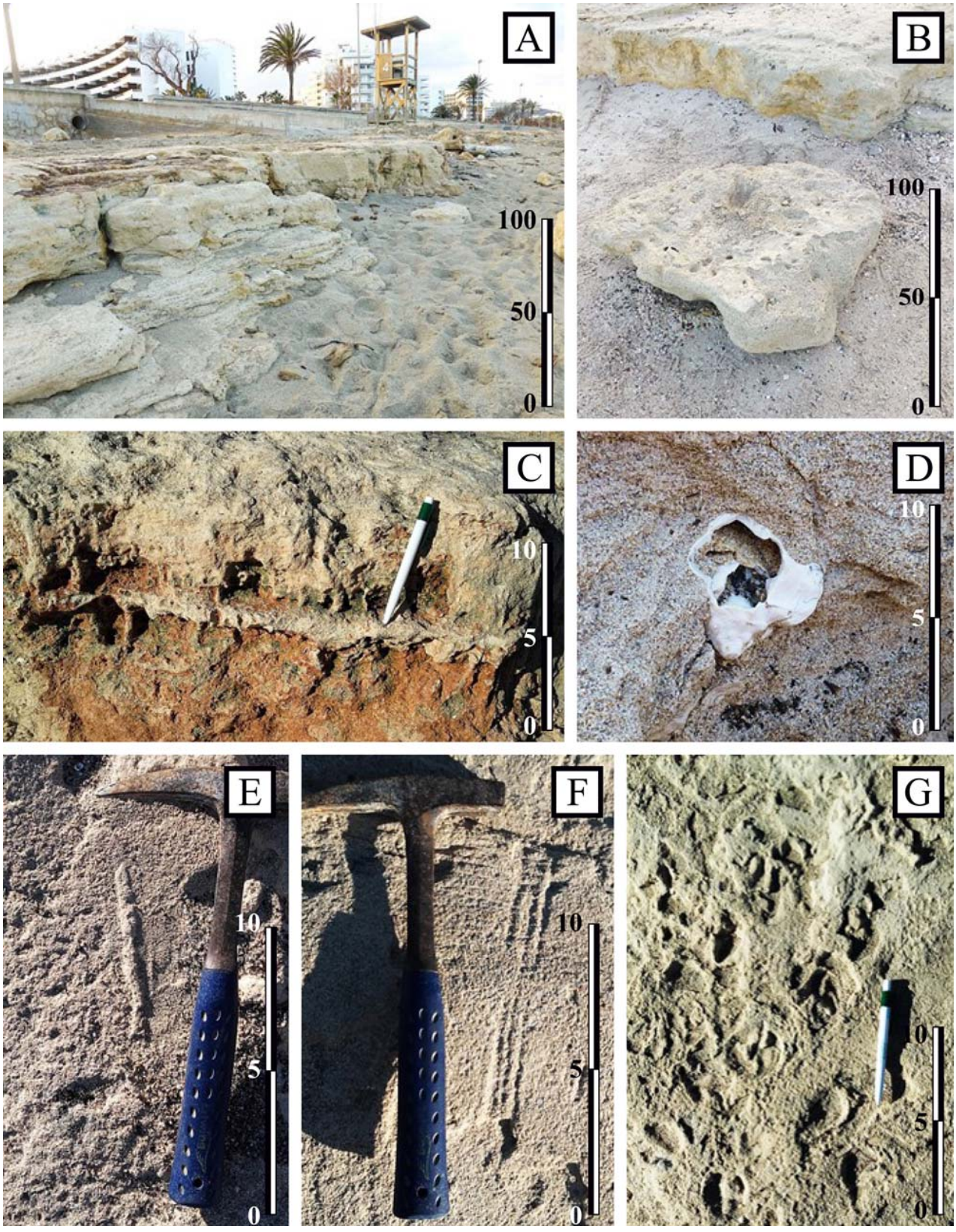
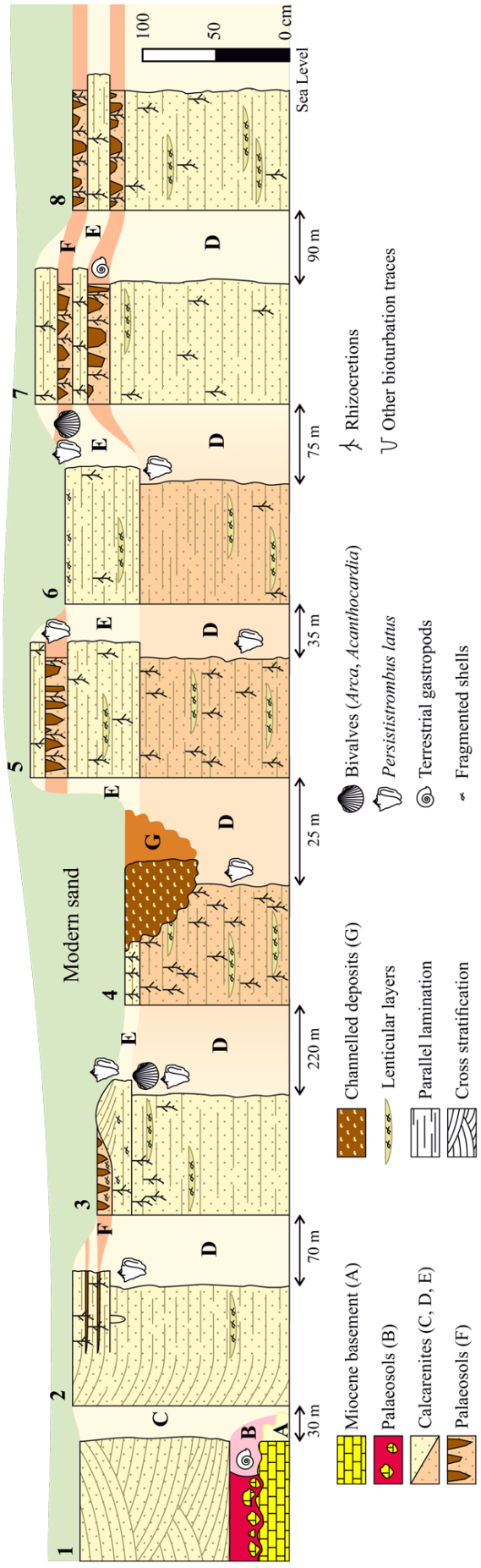


Figure 2: A: General picture of Arenal de son Servera deposit, uncovered after the storms (winter-spring 2017). **B:** Loose calcarenitic boulder in which a partial specimen of *Persististrombus latus* with modern *Entobia* bioerosion traces was found. **C:** Limit between the two foreshore units, with abundant rhizocretions. **D:** In situ specimen of *Persististrombus latus* in the lower foreshore unit. **E:** *Thalassinoides*-like burrow in the upper part of the upper foreshore unit. **F:** Bichorded bioturbation trace in the upper part of the upper foreshore unit. **G:** *Bifidipes aeolis* in the upper part of the upper foreshore unit. Scale bars in cm for all the pictures.



◀ **Figure 3:** Stratigraphical correlation of all the profiles (1-8) located in Figure 1, indicating the lateral distance between each of them.

Persististrombus latus (Figs. 2.D, 4.A) have been found within these beds. Near the top of this unit, at the southernmost part of the beach, several different traces of bioturbation have been observed: horizontal *Thalassinoides*-like burrows (Fig. 2.E), horizontal bichorded burrows (Fig. 2.F), and *Bifidipes aeolis* Fornós *et al.*, 2002 (Fig. 2.G). This unit is separated from the next by a calcareous crust with abundant rhizo-cretions (Fig. 2.C).

- [E] Foreshore deposits. These correspond to the level "b" of Lorscheid *et al.* (2017: Fig. S 17) and are characterised by yellowish, well-cemented calcarenites, bearing very small shell fragments. These beds possess low-angle parallel lamination, with sporadic interbedded lenticular laminae with coarser shell fragments. Mostly complete shells of the bivalves *Arca noae* (Fig. 4.C) and *Acanthocardia tuberculata* (Fig. 4.B), and the gastropods *Stramonita haemastoma* (Fig. 4.D) and *Persististrombus latus* also occur. This unit is often affected by pedogenetic processes, resulting in the palaeosol (F) beds. Rhizocretions appear frequently, especially near the palaeosols.
- [F] Palaeosols. These facies represent the top of the beach unit affected by processes of pedogenesis, such as nodulisation and brechification. The cracks in the calcarenites are filled with reddish lutites with abundant rhizocretions, associated with rare terrestrial gastropods (*Tudorella ferruginea*). Marine mollusc shells reworked from the beach units also occur.
- [G] Channelled deposits. Rudstones constituted by coarse carbonated sands and reddish silts, with many shell fragments. Its contact with the two beach units (D and E) is erosive. The only identifiable fossil shell belongs to the bivalve species *Chama gryphoides*.

4.2. Taphonomy

The Arenal de son Servera deposit, or at least is southern half, is one of the poorest upper Pleistocene littoral deposits in Mallorca in terms of species richness. For the present study, only specimens of the bivalves *Arca noae* and *Acanthocardia tuberculata*, a fragment of the gastropod *Stramonita haemastoma* and several shells of the gastropod *Persististrombus latus* have been found. This last species is the most abundant, with around the 70% of the total identifiable fossil content.

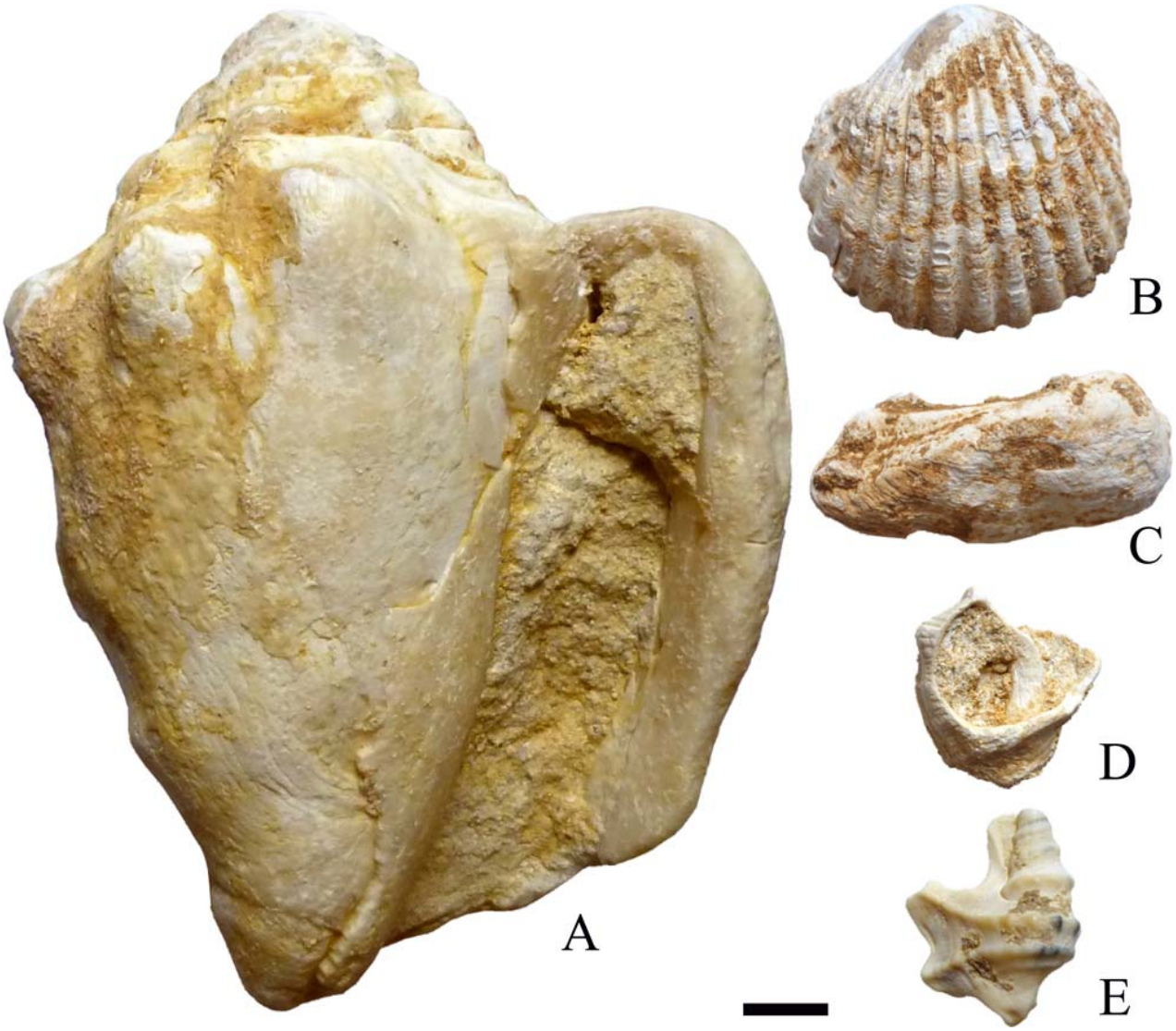


Figure 4: Fossil molluscs of Arenal de son Servera deposit. **A:** *Persististrombus latus*, lower foreshore unit. **B:** *Acanthocardia tuberculata*, upper foreshore unit. **C:** *Arca noae*, upper foreshore unit. **D:** *Stramonita haemastoma*, upper foreshore unit. **E:** *Aporrhais pespelecani*, found *ex situ*. Scale bar: 1 cm.

The fact that all the fossils are affected by abrasion, or some of them are even shattered, points to a sustained interval of underwater exposure before they were finally washed ashore. However, this is a curious case of a upper Pleistocene deposit on Mallorca in which *Persististrombus latus* shells do not show any traces of bioerosion. The only comparable situation would be the specimens in the Freu de ses Covetes deposit, which do not possess any kind of bioerosion trace either (Matamales-Andreu *et al.*, 2017). Therefore, although the biostratinomic phase seems to have spanned a significant amount of time, no organisms were able to colonise the shells.

In addition, all the *Persististrombus latus* shells were found in their position of maximum stability, *i.e.*, with their aperture facing downwards. Therefore, in the final burial event, shells were probably transported off the sea by a moderately low energetic episode. Studies on modern littoral dynamics (Tintoré *et al.*, 2009; Gómez-Pujol *et al.*, 2011) asserted that, in Cala Millor, the mean height of waves in normal climate ranges between 0.25 and 1 m, and in storms they can rise up to about 2.5 m. Assuming that coastal dynamics were somewhat similar during the upper Pleistocene, the episodes that washed off the *Persististrombus latus* shells should be of comparable importance to the hydrodynamic regimes in modern ordinary storms.

Besides, a loose shell of the gastropod *Aporrhais pespelecani* was found among the sand and debris on the shore (Fig. 4.E). This species was recently recorded for the first time in the Mallorcan upper Pleistocene (Juárez & Matamales-Andreu, 2018). The specimen found at Arenal de son Servera is partially surrounded by a thin layer of well-consolidated greyish calcarenite. It is herein considered to be very recent in age (*i.e.*, Holocene), the calcarenitic crust being formed in fast diagenetic processes such as beachrock or calichification.

5. Discussion

The upper Pleistocene succession at Arenal de son Servera consists of several units laying unconformably above the Miocene basement. A basal lutitic stretch is overlain by two foreshore units composed of yellowish calcarenites, rich in thermophilous fauna (*Persististrombus latus*). The fact that there exist two, well-marked foreshore units may not be trivial, as they have also been recognised in other Mallorcan deposits of similar age, such as Es Carnatge or Ses Covetes (VICENS, 2015); however, it is beyond of the scope of the present paper to discuss this aspect any further. Bioturbation occurs frequently: rhizocretions, *Myotragus* tracks (*Bifidipes aeolis*) and other traces. Pedogenesis processes are also usual at the top of the beds. These units change laterally to aeolianites when approaching the southern edge of the beach, because the Miocene basement provided a slightly higher ground for the dunes to settle.

The lack of any kind of bioerosion traces in the *Persististrombus latus* shells was not the result of fast burial after the death of the organism. The biostratinomic phase lasted long enough, as demonstrated by the moderate degree of abrasion that affects all the fossils studied. They correspond to the degree 1 of abrasion in the sense of DOMÈNECH *et al.* (2009). MATAMALES-ANDREU *et al.* (2017) studied the incidence of different kinds of bioerosion traces on *Persististrombus latus* shells on every upper Pleistocene Mallorcan deposit. The result of the Principal Component Analysis (MATAMALES-ANDREU *et al.*, 2017: Fig. 4) suggested that the presence of *Entobia* was nega-tively correlated to the presence of traces of other suspension-feeders such as polychaetes, vermetids or lithophagous bivalves. It was then tentatively interpreted to be related to the clearness of the water: because *Cliona* needs clear, well-lit waters to thrive (BROMLEY & D'ALESSANDRO, 1984) and the rest of borers feed on suspended detritus, the lack of *Entobia* and subsequent relative abundance of *Caulostrepsis* and *Gastrochaenolites* could indicate more turbid waters. However, the specimens considered herein do not show any kind of boring. That indicates an unstable sea bottom, which either [1] periodically buried and exhumed the fossils, which never remained exposed long enough to allow the settling of bioeroders, or [2] although on the sea floor, the orientation of the shells was modified too often to permit the establishment of the borers. Although both phenomena could have played a role in avoiding bioerosion on the studied shells, the first situation might have been dominant.

In other Mallorcan upper Pleistocene deposits of higher energy (*e.g.*, Punta Negra locality, see VICENS, 2015; JUÁREZ & MATAMALES-ANDREU, 2018), the *Persististrombus latus* shells appear with random orientations, and yet the bioeroders only colonised part of the shell (own data), pointing to the fact that those heavy shells remained relatively still on the sea floor, even in relatively high-energy conditions. Thus, the second situation seems unlikely in favour of the first one, as today there are submarine sand bars in the area, that migrate and change in size and shape over the year (GÓMEZ-PUJOL *et al.*, 2011). These sand bars could also have operated during the upper Pleistocene, covering and exposing the shells, and therefore impeding any kind of bioerosion process to occur. Hence, in this case, the absence or presence of certain bioerosion traces cannot be related to such factors as clarity of the water as pointed out by MATAMALES-ANDREU *et al.* (2017) for other localities on the island, but to a particular sedimentary environment.

6. Conclusions

Arenal de son Servera (BUTZER & CUERDA, 1962; VICENS, 2015), Cala Millor (SOLÉ-SABARÍS, 1962; LORSCHEID *et al.*, 2017) and Cala Nau 3 (JUÁREZ & MATAMALES-ANDREU, 2018) are parts of a same deposit. Because most of the time it is covered by modern sand, authors have subsequently referred to each outcrop with different toponyms. It is herein suggested that all of them should be named under the oldest designation, Arenal de son Servera, to avoid ambiguity in future work. The comprehensive stratigraphical study of this locality allowed the present author to recognise lateral variations of the foreshore deposits: from dunes at the southernmost edge of the beach, to beds of plant colonisation, pa-laeosols and probably more modern channelled deposits with different faunal assemblages. It has been established that *Persististrombus latus* shells are distributed ubiquitously in all the foreshore beds, and therefore they all can be considered as part of the MIS-5e interglacial warm peak. Taphonomical analysis of the *Persististrombus latus* specimens concluded that all of them underwent a biostratinomic phase exposed on the sea bottom, which resulted in a similar abrasion degree on all the shells. However, unlike other contemporary deposits in Mallorca, bioerosion did not occur. The presence of a submerged, changing sand bar could explain repeated burials and exhumations of the shells, making it very difficult for the bioeroders to settle. This would support the idea that some of the variables regarding the coastal dynamics of that beach during the upper Pleistocene, namely, the presence of submerged sand bars, were similar to the present. Moreover, those shells were finally washed ashore in mode-rately energetic episodes, because all the *Persististrombus latus* fossils are orientated with the aperture facing downwards, in their position of maximum stability. Those events were most probably comparable to local ordinary modern storms in intensity. These two last points allow, up to some extent, the comparison of the coastal dynamics of the modern Cala Millor beach with a warmer environment (MIS-5e), which could pro-

vide insight on the range of expected changes that Mallorcan beaches may undergo in the present context of global warming.

Acknowledgments

To Sebastià Matamalas and to Sebastiana M. Andreu for aid in fieldwork. To Pierre Lozouet (Muséum National d'Histoire Naturelle, Paris, France) and to Thomas Lorscheid (MARUM - Center for Marine Environmental Sciences, Bremen, Germany), reviewers of this paper, for their thoughtful insight that contributed to improving the final version of the manuscript. To Bruno Granier and Stephen Eager, editors of the paper, for their constructive comments and effort editing the manuscript.

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