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Middle to Late Pleistocene dunefields in rocky coast settings at Cala Xuclar (Eivissa, Western Mediterranean): Recognition, architecture and luminescence chronology

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ABSTRACT

This study focuses on cliff-front anchored and sand-ramp aeolian dune accumulations in Cala Xuclar, Eivissa (Ibiza), Western Mediterranean, during different sea level falling stages from Middle to Late Pleistocene times. Stratigraphic mapping, conventional lithostratigraphic logging and OSL datings are used to reconstruct dune formation and evolution. Facies analyses result in the identification of six sedimentary units, three of which correspond to dune deposits formed at MIS 6 (145 ka), MIS 5d-c (~100 ka) and MIS 4 (77–73 ka) respectively. Additionally there is a beach deposit at (~2 m above present msl, which resembles the MIS 5a. This study concludes that each dune system corresponds to a relatively low sea-level stand that exposed enormous amounts of marine carbonate sands that was transported inland by migrating dunes under strong north–westerly winds. Therefore, sea-level fall and the related sediment supply owe likely to be key factors in the formation of these aeolianites systems.

1. Introduction

The Late Pliocene climate perturbation resulted in the establishment of a permanent Northern Hemisphere ice sheet and the onset of a chain of glacial and interglacial cycles (Shackleton et al., 1984; Herbert et al., 2010). In the Western Mediterranean, these cycles resulted in a serial of wet and dry periods (Martrat et al., 2004) in conjunction with an oscillating sea level (Dorale et al., 2010). This climate variation is characterized by the laying down of coastal sedimentary successions such as shallow-marine deposits (i.e. beaches), aeolianites, colluvial and alluvial deposits or palaeosols (Mckee and Ward, 1983).

Aeolianites are partially lithified former dune deposits cemented by carbonates (Fairbridge and Johnson, 1978) typically composed of fine-to medium grained, well-sorted sand. The character of the sand grains depends greatly on the local environmental setting, but the dominant constituents are quartz and feldspar grains and marine carbonate particles. The formation of coastal aeolianites occurs both during glacial and interglacial stages although there is an ongoing debate regarding the environmental conditions controlling their formation. There are Quaternary aeolianites accumulated during interglacial and interstadial sea level highstands, but it is also true that others have formed during glacial periods (Brooke, 2001; Fornós et al., 2009, 2012; Pappalardo et al., 2013).

The principal outcrops are located in the Mediterranean region, South Africa, southern Australia and the Caribbean, between 55°N and 45°S in latitude where many deposits have been documented in the last decades in order to unravel the landscape and climate evolution since the Middle-Late Pleistocene (El-Asmar, 1994; Clemmensen et al., 1997, 2001; Rose et al., 1999; Price et al., 2001; Frechen et al., 2004; Nielsen et al., 2004; Radies et al., 2004; Rodríguez-Vidal et al., 2004; Munyikwa, 2005; Andreucci et al., 2009, 2010a, 2010b, 2012, 2014; Fornós et al., 2009; Pavelic et al., 2011; Pappalardo et al., 2013).

Apart from a small number of studies, the majority of the literature has documented Pleistocene and Holocene transgressive dunefields along strandplain coastlines. Many of which have

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addressed these systems along cliffed coastlines (i.e. Andreucci et al., 2010a and 2010b or Clemmensen et al., 1997). This rocky coast physiographical setting, due to the spatial variability in a narrow area, permits a constrained evaluation of the role of sediment supply, space accommodation and environmental drivers in aeolianite stratigraphy and architecture.

Different authors have noted the existence of Quaternary aeolian and fluvial sequences along the cliffed and rugged coast of Eivissa Island (Balearic Islands, Western Mediterranean) although none have characterized or described these outcrops in depth (Henningsen et al., 1981; Rangheard, 1971; Servera, 1997; García de Domingo et al., 2009). In this study, we document the sedimentary characteristics of a transgressive dune system that crops out continuously along the northwestern cliff coasts of Eivissa (Cala Xuclar) by means of sedimentological and stratigraphical analysis, and luminescence dating (OSL).

The aims of this study are to (a) unravel the factors that promote the dune formation paying special attention to sea-level oscillations, sand supply or wind regime and (b) explore how topography and terrestrial processes (i.e. fluvial and colluvial agents) participate in shaping the dunefield. The results are discussed in the framework of the last 150ka palaeoenvironmental and landscape evolution.

2. Regional and geological setting

The island of Eivissa (Ibiza) it is located in the south-western part of the Mediterranean Sea and is the third largest (571 km^2) and the most westerly island of the Balearic Archipelago (Fig. 1). The main structure of the island is composed of a series of thrust sheets (mainly of Middle Triassic to Middle Miocene carbonate deposits) formed during the Alpine compression (Upper Oligocene to Middle Miocene) and trending NE–SW (Rangheard, 1971, 1984). These thrust sheets correspond to the northeasterly continuation of the Subbetic Mountains of southern Spain (Fornós et al., 2002). The bedrock geology of Eivissa is composed of Miocene and Mesozoic rocks (García de Domingo et al., 2009). Muschelkalk limestone and dolomite, as well as Keuper loams and clays, constitute the Triassic basement of the island, whereas Jurassic limestone and dolomite breccia, Cretaceous and Middle Miocene limestone overlie this basement and constitute the major relief of the island (Fig. 1). Quaternary fluvial, alluvial and colluvial sediments fill the central basins, whereas Pleistocene successions characterized by shallow-marine to coastal aeolian and fluvial deposits crop up patchily along the cliffed coast (del Valle et al., 2015). The Balearic Islands, and among them Eivissa, have been considered tectonically stable since the Pliocene with relatively little deformation (Fornós et al., 2002; Just et al., 2011). Small cliffy bounded bays with sandy or gravelly-boulder pocket beaches characterize the present-day coast. Holocene and recent coastal dunes developed at the south and southeastern bays of Eivissa and have been stabilized by shrub vegetation (Servera, 1997).

One of these representative Pleistocene successions is in Cala Xuclar (WGS84 39°06′16″N; 1°30′54″E), along the northwest cliff coastline of the island (Fig. 1). This outcrop extends continuously for 1 km at the bottom of a small bay, 1.34 km in width and 1.21 km in depth, bordered by cliffs 2–9 m in height of Upper Miocene limestone, Cretaceous dolostone and Lower Jurassic dolomite breccia. The Pleistocene succession rests at the bottom of the bay on Lower Jurassic bedrock with a well-developed unconformity and shows great lateral variability of coastal aeolian, shallow-marine, colluvial and fluvial deposits, with palaeosols (Fig. 2).

3. Methods

3.1. Facies analysis

The conventional method of lithostratigraphic logging has been used (Tucker, 1988), with the acquiring of additional information on cross-bed dip direction for palaeowind analyses, and samples for grain size and mineralogy analyses. The terminology for sediment deposits and the criteria for their recognition have been modified from Andreucci et al. (2009). This terminology links lithology, grain size, sedimentary structures and macrofossil characteristics. Facies have been named according to the main lithology (C: conglomerate, B: breccia; S: sandstone and P: palaeosol), dominant texture (a: sand, m: mud, s: silt), grain size (c: cobble, d: pebbles, e: medium to very coarse sand; h: fine to medium sand), sedimentary structures (l: laminated, p: planar cross-bedded, t: through cross-bedded, u: low angle cross-bedded, g: granoclassification), biogenic features (f: highly fossiliferous, r: root-races). Therefore a facies labelled as *Shu* corresponds to a fine to medium grained sandstone with low-angle cross-bedded stratification.

Seventeen vertical logs (Fig. 3) were measured in the field and correlated on the base of major unconformities and homogenous units, bounding surfaces or according to presence of continuous palaeosols. Unconformities are understood as abrupt facies change in vertical and lateral extensions at the study area. At each log major units have been characterized in terms of sediment size, composition and mineralogy. The percentage of carbonates has been obtained by hydrochloric acid etching, and grain size determined by means of thin section and digital image analyses. Images were obtained using a binocular microscope with MOTIC Image 2.0 software and the analysis of grain size was performed using the free image analysis software IMAGE_J. Mineralogy of sediments was determined with a Siemens D-5000 X-ray diffractometer using Cu Kα radiation by means of randomly oriented powders of the bulk samples of sediments after pre-treatment of samples with H_2O_2 to remove organic matter. The pressed powder diffraction patterns were recorded from 3° to 65° 2θ in steps of 0.03°, 0.3-s counting time per step, at 25 °C room temperature, and logged to data files for analysis. Phase determination and semi-quantitative analysis were made by the X-Powder ver.2010.01.09 Pro software using the DifData database (Downs and Hall-Wallace, 2003).

3.2. OSL analysis

3.2.1. Sample collection and preparation

Four sample blocks (~70 × 70 × 50 cm; ~5 kg) were collected for luminescence dating from Pleistocene carbonate aeolian deposits at Cala Xuclar and analysed in the Luminescence Dating Laboratory of Babes Bolyai University in Cluj-Napoca. The aeolianite blocks were extracted from the stratigraphic layers considered to be representative of the succession. OSL dating is based on the ability of quartz (and other minerals) to retain charges from naturally occurring radioactivity present in sediment. Many studies have shown that sand grains are effectively zeroed during wind-blown transportation and therefore can be confidentially used for OSL dating (Sivan and Porat, 2004; Roberts et al., 2008). Despite OSL has become a fundamental chronological tool of Quaternary siliciclastic successions, recent contributions have highlighted the suitability of this method for aeolian deposits poor in quartz, such as carbonate aeolianites (Murray and Clemmensen, 2000; Nielsen et al., 2004; Fornós et al., 2009).

The aeolianites collected at Cala Xuclar, contain between 1 and 8% of siliciclastic grains, primarily quartz. Blocks were detached in shadowed low light conditions and wrapped in lightproof material, labelled and documented and transported to the laboratory.

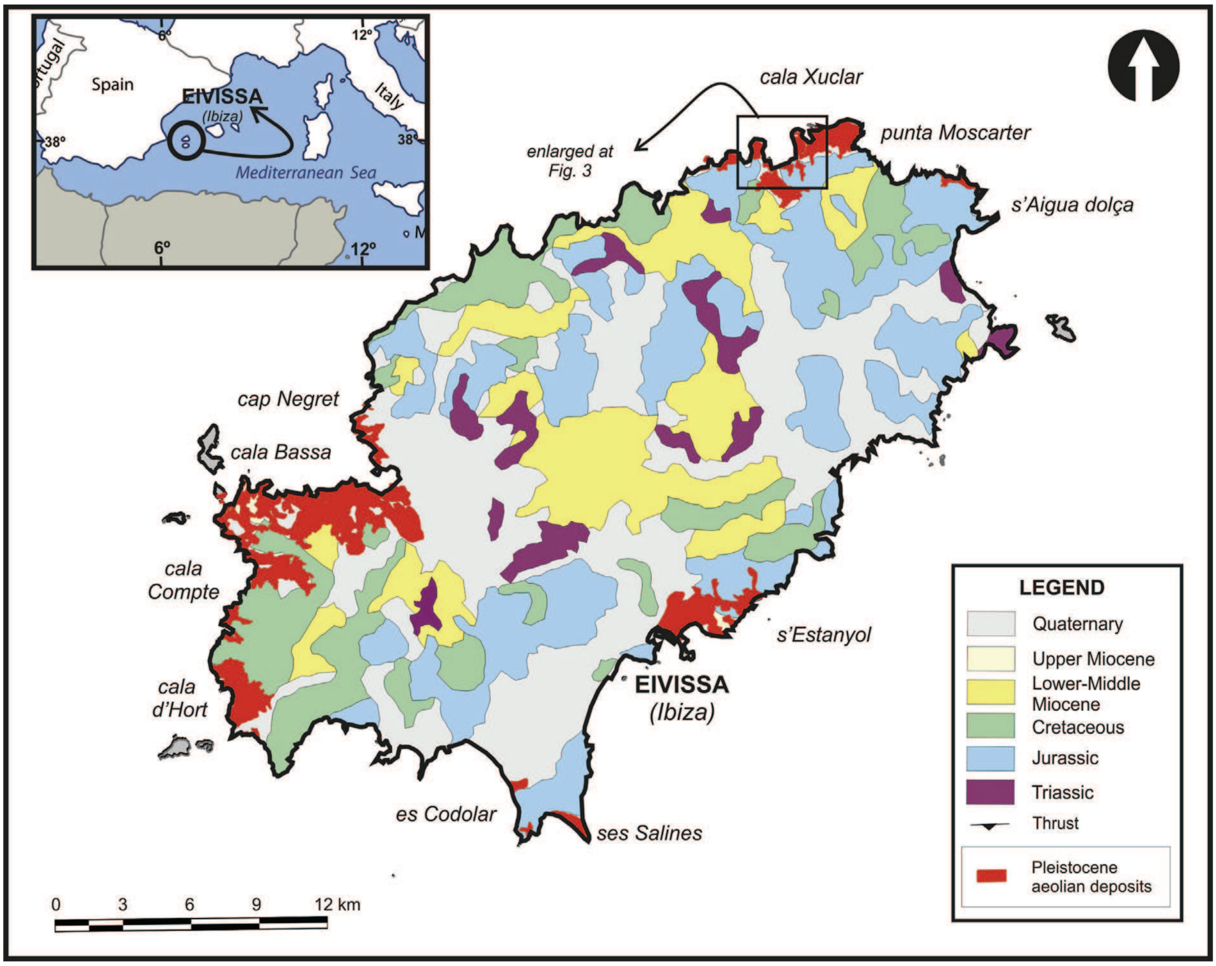

Fig. 1. General setting and geological sketch of Eivissa (Ibiza) island with the location of the study site.

Samples were also taken of the lithified aeolianites to determine their porosity, since it is important to know the sample density and the amount of carbonate influx (cement) when the OSL age is calculated. Open bulk porosity was calculated by means of a known dimension dry cube weight and the weight of the same cube after 24 h of water saturation in void conditions (Winkler, 1997). Using porosity and apparent density, mineral rock density was estimated.

The inner part of each sample was extracted in the laboratory and subsequently treated with HCl (30%) and H_2O_2 (10%) for carbonate and organic matter removal. The remaining material was sieved to obtain material <63 μm and different fractions ranging from 63 to 250 μm. The coarse fractions (>63 μm) were subsequently etched with 40% HF for 60 min. Fractions measuring less than 63 μm were prepared using published procedures (Lang et al., 1996; Frechen et al., 1996) in order to extract the fine-grained (4–11 μm) polymineral material from which the quartz grains were isolated by dissolving them in H_2SiF_6 for 10 days.

3.2.2. Dosimetry and luminescence measurement

OSL measurements have been performed on fine (4–11 μm) and mixed coarse (63/90–250 μm) quartz fraction due to the limited amount of available material. The equivalent dose measurements were undertaken using a Risø TL/OSL-DA-20 (Thomsen et al., 2006). The 90Sr-90Y beta source was calibrated using fine and coarse grains of gamma-irradiated calibration quartz supplied by Risø National Laboratory. Radionuclide concentrations were derived by high-resolution gamma spectrometry and were converted to dose rates using published conversion factors (Adamiec and Aitken, 1998). The cosmic ray contribution was estimated using published formulae (Prescott and Hutton, 1994). Water content estimation was based on the difference in weight of the material from the inner part of the blocks, before and after oven drying. Time-averaged water content was derived for each sample with a relative error of 25%. The blocks were highly cemented, allowing for little water penetration.

4. Results

4.1. Sedimentary facies and palaeosol description

Seven overlapping calcareous aeolian deposits interbedded with colluvial deposits and containing palaeosols, extend for nearly 1 km along the shoreline of Cala Xuclar bay. Stratigraphic columns and surface geological maps show that basement morphology, consisting of cliffs shaped in folded Lower Jurassic rocks, controls the overall architecture of sedimentary bodies. The morphology of these Jurassic cliffs and the position of the small catchments that reach the beach control the local processes and thereby the facies development and location. This combination results in a complex architecture with large lateral variability. From log descriptions and the data from the composition and textural analysis, seven different sedimentary facies and four different palaeosils can be distinguished (Figs. 4 and 5). Facies association relates to three main

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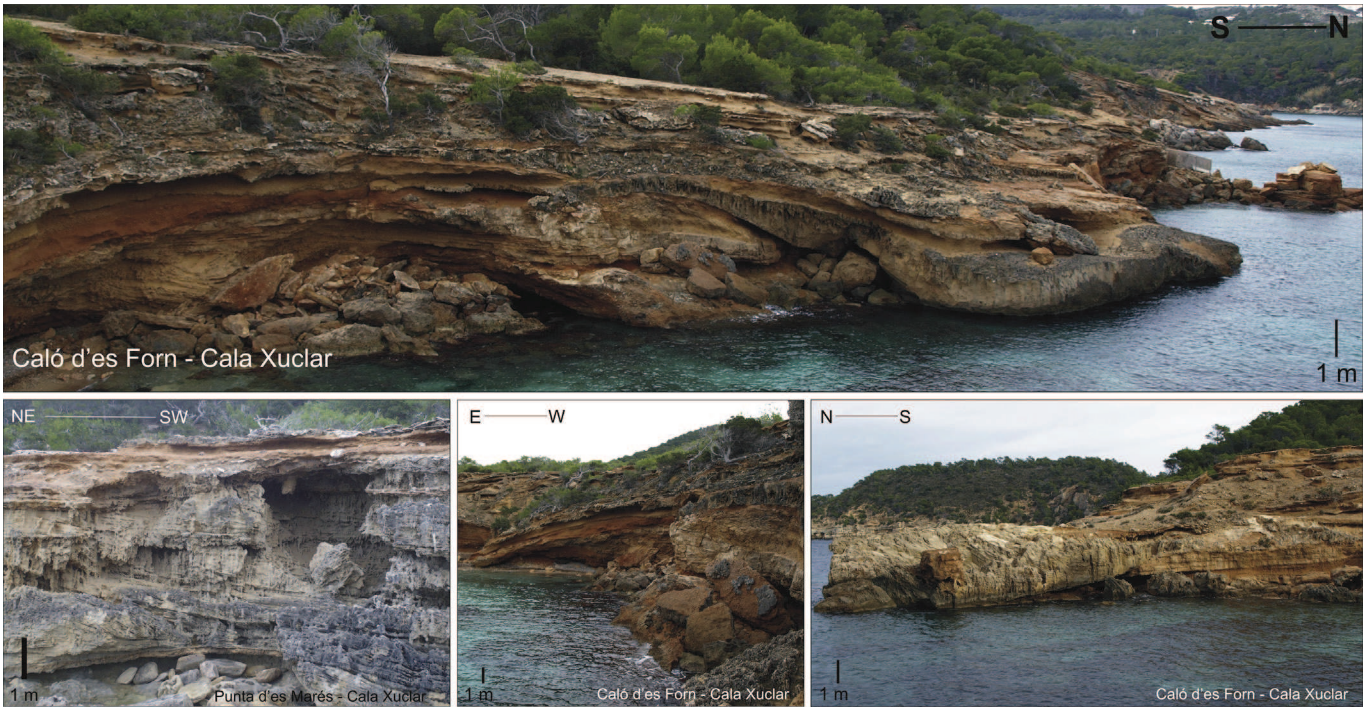

Fig. 2. Overview of Pleistocene succession at Cala Xuclar (Eivissa) (see location in Fig. 3).

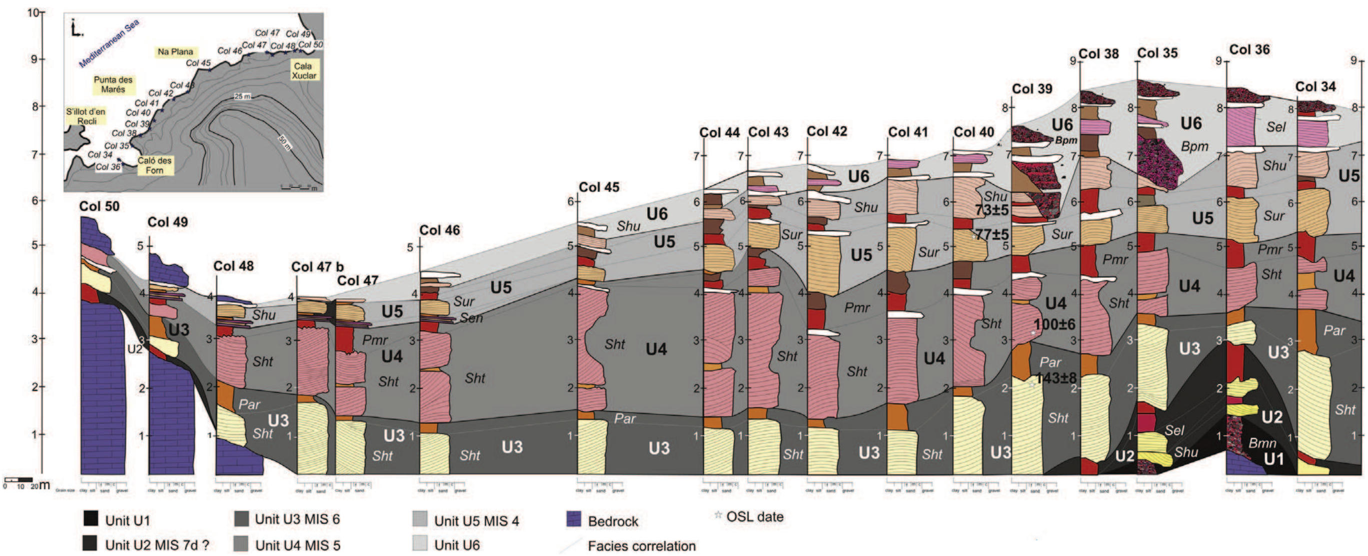

Fig. 3. Stratigraphic columns of the sediments exposed at Cala Xuclar (Eivissa).

sedimentary environments: eolic, shallow-marine and colluvial-alluvial.

4.1.1. Aeolian facies association

Facies *Sht* is characterized by very pale brown (HUE 10 YR 8/2), well sorted, fine to medium grained sandstone, with large-scale trough cross-stratification. The strata have thicknesses up to 3 m and are partially disrupted by root casts (1–7 cm width and 0.5–1 m in height), some of which are moulds and others are calcified root casts. Locally, the sediments contain abundant angular clasts, millimeter–centimeter scale in size, floating in the sand matrix. The clasts lineation follows the parallel lamination and the slope of the deposits. Their composition is mainly carbonate composed of marine bioclasts with very little terrigenous material (i.e. quartz grains). This deposit records the trapping of wind-transported marine carbonate sand in front of a steep inland cliff, as the dunes and piled up sand move forward forming cliff-front dunes and ascending dune deposits.

Facies *Sel* is composed of very pale brown (HUE 10 YR 8/2) well sorted, medium to coarse-grained laminated or sub-horizontal sands; layers are from 0.5 to 1 m thick. The facies are bioturbated by root casts lightly cemented by calcite. The sand is composed of marine carbonate particles (85%) and minor amounts of quartz and feldspar. This deposit records the upslope aeolian transport of marine carbonate sands perpendicular to the coastal cliff as a sand ramp or sand sheet deposit.

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FACIES	DESCRIPTION	INTERPRETATION	FIGURES
Sel	Very pale brown, planar-cross bedded sandstone, well sorted, with root traces.	*Aeolian sand sheep dep.*	
Sht	Very pale brown, trough cross-bedded, well sorted fine grained sandstone with root traces.	*Aeolian sand dunes dep.*	
Shu	Very pale brown, planar-cross bedded, well sorted, trough cross-bedded strongly bioturbated.	*Aeolian sand dunes dep.*	
Sur	Very pale brown, low-angle cross bedded, well sorted fine grained sandstone with root traces.	*Aeolian sand dunes dep.*	
Bmn	Pinkish silty matrix supported angular sorted pebbles.	*Colluvial dep.*	
Bpm	Sandy matrix supported angular poorly sorted cobbly-pebbly lenses, with basal erosive surface.	*Colluvial dep.*	
Sen	Coarse grained tabular sandstone. Sparserly fossiliferous.	*Sandy beach dep.*	

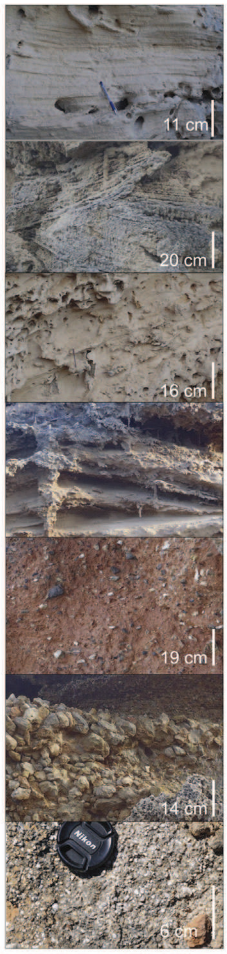

Fig. 4. Main characteristics of the sedimentary facies and their interpretation in terms of depositional processes at Cala Xuclar (Eivissa).

Facies *Shu* is characterized by fine to very pale brown (HUE 10 YR 8/2) medium-grained well-sorted sand with low-angle cross-bedded, and partially disrupted by roots casts. The laminae of the dune are 0.5–1 cm, slightly cemented by sparry calcite, and adding up to 1–2 m strata. Their composition is mainly carbonate (~80%) made up of abundant marine bioclasts. Dip strata and 3D sections where these facies has been recognized records inland migration of relative large parabolic dunes.

Facies *Sur* is composed of very pale brown (HUE 10 YR 8/2) low-angle cross bedded and well sorted medium to fine sands, strongly bioturbated. The average composition is mainly carbonate (~80%) with minor quartz components (~6%). Sheets are 0.3–1.20 m thick and there are abundant shells of terrestrial fauna (i.e. *Xerocrassa ebusitana*). This deposit also records ascending dune deposits and inland migration of relative large parabolic dunes.

4.1.2. Colluvial – alluvial facies association

Facies *Bmn* are characterized by massive reddish silty matrix-supported angular clasts forming sheets of millimetre to centimetre scale and disrupted by muddy and calcrete levels. Large clasts are aligned downslope, although the clasts rarely display a modal fabric orientation. The clasts progress from the dismantled basement and are composed of Jurassic limestone and dolomites. This deposit records episodic mass movement on sloping surfaces near a palaeocliff. Angular clasts, slope soil products and aeolian sand were mixed during these events, which most likely took place after periods of intense rain.

Facies *Bmp* is made up of pebble to cobble gravel beds interlayered with poorly sorted stratified sand beds. The largest clasts are imbricated and aligned downslope. The pebbles consist mostly of limestone and dolomites from the basement. Carbonate marine bioclasts and very little terrigenous materials comprise the sandy levels. This deposit resembles debris-flow and down-slope channelized flows involving re-sedimentation of basement material and former topographic ascending dunes. The reworking probably took place after periods of intense rainfall.

4.1.3. Shallow-marine facies association

Seaward imbricated coarse-grained sands and gravels, rich in reworked marine fauna characterize facies *Sen*. Two levels can be separated according to the relative abundance of marine fauna and lithoclasts. The upper one is richer in lithoclasts and can reach 1 m in thickness however it does not show lateral continuity at the outcrop scale. Facies *Sen* was most likely formed in a gravelly wave-dominated beach system and represents the supratidal zone of a beach with terrigenous sediment supply and a high biogenic contribution.

4.1.4. Palaeosol description

Four different types of palaeosols have been observed (Fig. 5). The first one, around 1.5 m in thickness, is characterized by massive silt and sandy deposits *(Par)* with nodular forms, and strong bioturbation. The color is very pale brown (HUE 10 YR 8/4). It exhibits abundant terrestrial fauna (i.e. the snail *Xerrocrassa ebusitana*) and angular clasts, of millimetre to centimeter scale floating in the sandy silt matrix.

The second is mainly composed of reddish (HUE 5 YR 6/8) and very plastic fine sediments banded by strips rich in iron oxide *(Pmn)*. Apart from the clay content the predominant mineral is quartz (20%).

The third one is characterized by very pale brown (HUE 10 YR 8/4) silty and muddy sediments (*Pmr)*, interbedded with sandy lenses, rich in carbonate nodules and highly bioturbated with root casts.

The fourth palaeosol is formed of reddish yellow (HUE 7,5 YR 7/6) silts with sandy layers (*Psr)* with the scattered presence of angular clasts. This level is strongly bioturbated and shows abundant roots casts (1–2 mm width and 5 cm maximum height). Clasts vary in size from boulders to cobbles and pebbles and consist of fragments of dolomites arranged in tabular or lenticular beds aligned downslope. The larger clasts are floating in a gravelly matrix.

According to the work of Rose et al. (1999) and Muhs et al. (2010) on the neighbouring island of Mallorca and dealing with similar palaeosols, most of these soils reflect periods of warmer temperatures and variable conditions of aridity and vegetation, being related to periods of sea level high-stands.

4.2. OSL dates

A total of four OSL ages have been obtained in the Pleistocene succession along the northern coast of Eivissa. The localities for sampling purposes were situated in the aeolian-dominated part of the system as the stratigraphic position of the system is easy to observe and a composite stratigraphic sketch of the architecture can be constructed (Fig. 6). Each one of the samples represents a well-defined aeolian unit from this stratigraphic sketch (Table 1). Sample D1 is from the lowermost cliff-front dune unit, sample D2 is from the middle ascending dune unit, while samples D3 and D4 are from uppermost aeolian unit. Sample D1 from aeolian dune deposits (facies *Sht*) in log col39 of Fig. 3 has an age of 143 ± 8 ka suggesting aeolian deposition in MIS 6. Sample D2 collected in the aeolian ascending dune deposits of facies *Sur* (log col39 Fig. 3) has an age of 100 ± 6 ka suggesting deposition during renewed aeolian activity in between MIS 5d and 5c. Samples D4 and D5 correspond to the uppermost aeolian deposits, from *Sur* and *Shu* facies respectively. Both have been collected from log col40 in Fig. 3 and have ages that range between 77 ± 5 ka and 73 ± 5 ka suggesting another aeolian deposition during MIS 4. There is a large consensus between the ages derived from the latter two samples.

Table 1
Optically stimulated luminescence dates, Pleistocene aeolianites, Cala Xuclar (Eivissa).

Sample code	Depth (cm)	Grain size (μm)	Water content (%)	ED (Gy)	U–Ra (Bq/kg)	Th (Bq/kg)	K (Bq/kg)	Total random error (%)	Total systematic error(%)	Total dose (Gy/Ka)	Age (Ka)	Weighted average age (Ka)
D1	350	4–11	1.4	78 ± 1 $_{n=7}$	11.6 ± 0.1	1.39 ± 0.16	14.4 ± 1.2	1.86	9.79	0.54 ± 0.007	143±4	143±8
		90–250		64 ± 6 $_{n=14}$				9.44	6.24	0.45 ± 0.005	142±16	
D2	160	4–11	0.6	63 ± 1 $_{n=9}$	12.3 ± 0.2	1.55 ± 0.2	18.0 ± 1.4	2.09	9.57	0.62 ± 0.008	102±10	100±6
		63–250		50 ± 1 $_{n=8}$				2.36	6.46	0.51 ± 0.01	97±7	
D3	105	4–11	3.5	52 ± 1 $_{n=9}$	12.2 ± 0.1	2.9 ± 0.1	40.6 ± 1.3	2.71	8.82	0.72 ± 0.014	72±7	77±5
		63–250		50 ± 3 $_{n=7}$				6.05	6.24	0.60 ± 0.004	83±7	
D4	10	4–11	3.6	61 ± 1 $_{n=9}$	11.0 ± 0.5	3.80 ± 0.22	67.0 ± 2,1	2.88	8.07	0.87 ± 0.02	70±6	73±5
		63–250		57 ± 3 $_{n=10}$				5.44	6.63	0.75 ± 0.01	76±6	

4.3. Stratigraphy

The log correlations and sections along the study area (Fig. 3) show the presence of six unconformity-bounded units, termed U1, U2, U3, U4, U5 and U6.

The lower units only crop out westward, close to the Caló des Forn creek (Figs. 2 and 3). Unit 1 is composed of facies *Bmn* that are colluvial deposits on lapping the basement (Fig. 7c). At the top, it is bounded by an unconformity from which Unit 2 evolves. This unit is made up of one association of aeolian facies (*Shu* and *Sel*) and one palaeosol facies (*Pmr*). The aeolian subunits change in thickness and, occasionally, are separated by different paleosoil lenses (log Col.36 in Fig. 3). They correspond to aeolian sand ramps and sand dunes moving inland and the high bioturbation suggest a humid climate suitable for vegetation. The aeolian deposition was interrupted by colluvial deposits formed of alternating clast-rich and matrix-supported breccia. Unfortunately, for logistical reasons these deposits could not be dated. However, on the basis of regional OSL chronologies, stratigraphy and mineralogy this unit could likely be related to the sub-stage MIS 7d (Del Valle et al., 2015; Pomar et al., 2015).

Unit 3 (Fig. 7b) is continuously present throughout the study area although the thickness decreases eastwards (Fig. 3) and is composed of the aeolian facies *Sht* and palaeosol Par. The succession architecture shows a dune field with active migration inland associated to a NW (340°) palaeowind direction. This wind created a climbing dune that reached topographic levels around 6 m above the present mean sea level. Additionally, forests show an average SE dip direction, indicating that the dune slope face migrated parallel to the hillslope orientation being pushed by the dominant NW wind direction. This aeolian deposit is overlain by a sandy palaeosol with abundant nodules and some angular clasts proceeding from the upslope. On the basis of OSL age, Unit 3 is 143 ± 8 ka and refers to the MIS 6.

Unit 4 crops out throughout most of the study area and it is bounded at the base by an erosive contact that deeply cuts the underlying deposit. This unit is composed by two aeolian levels, *Sht* facies association, separated by a sandy palaeosol and represents a coastal dunefield advancing inland (Fig 3). Dune forests show an average SE (170°) direction. The base of the dunes are well preserved and it is possible to notice the asymptotic basal stratification, whereas the upper levels are altered due to bioturbation resulting in abundant root-casts 2–10 cm in width. On this aeolian surface of erosive unconformity, there is a reddish palaeosol

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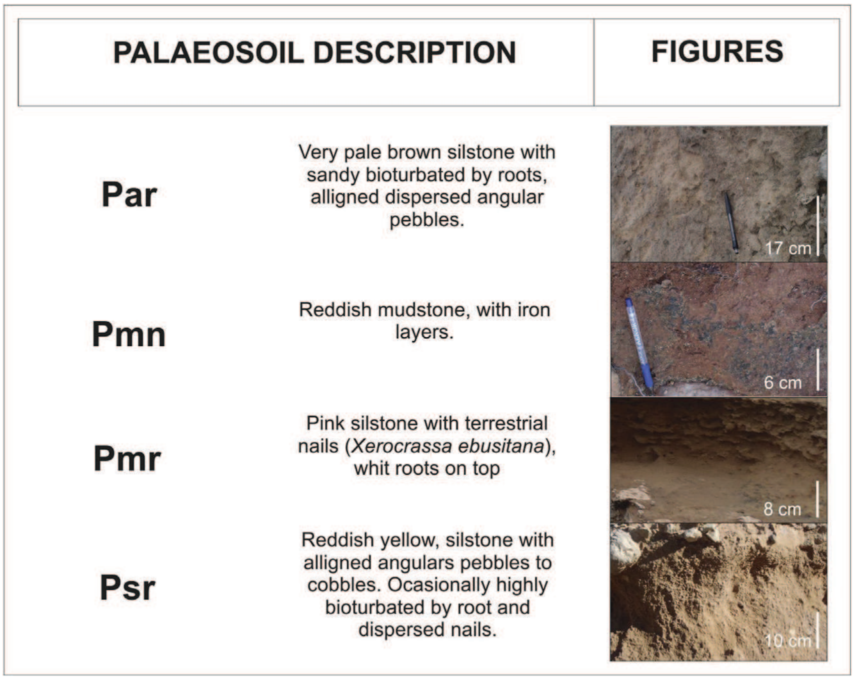

Fig. 5. Main characteristics of palaeosols at Cala Xuclar (Eivissa).

banded with strips rich in iron oxide with a marked lateral continuity. Although the aeolianite OSL age is 100 ± 6 ka, and taking into account the short interval between MIS 5c and 5d their deposition was probably triggered by the sediment exposure during the regressive sub-stage of MIS 5d.

Another erosive unconformity separates Unit 4 from Unit 5 (Fig. 7a), which is composed by the association of *Sen, Shu, Sel, Pmn* and *Psr* facies. In the western sections, the morphology of the unconformity resembles a transgressive surface developed during a period of higher sea level. In logs col46, 47 and 48 (Fig. 3), below the base of the Unit 5, there is one subunit formed by *Sen* facies that corresponds to a beach deposit. Because of their grain size, they could not be dated using OSL techniques and the fossil content does not allow the deposit to be assigned to a specific sea-level highstand. Unit 5 is also present throughout the study area although it tends to thin out westward. It rests on an erosive bounding surface and it is made up of the facies associations *Shu, Sel, Sur, Pmm* and *Psr*. The first three facies are interpreted to have built up a sand-ramp system that was interrupted by colluvial events forming the clast-rich sheets and the palaeosol formation. The facies architecture and the sequential patterns of the deposits show two clear aeolian subunits separated by red-iron rich (terra rossa) palaeosol (Fig. 7d). On the basis of the OSL ages (Table 1) the lower dune is 77 ± 5 ka and the upper dune 73 ± 5 ka.

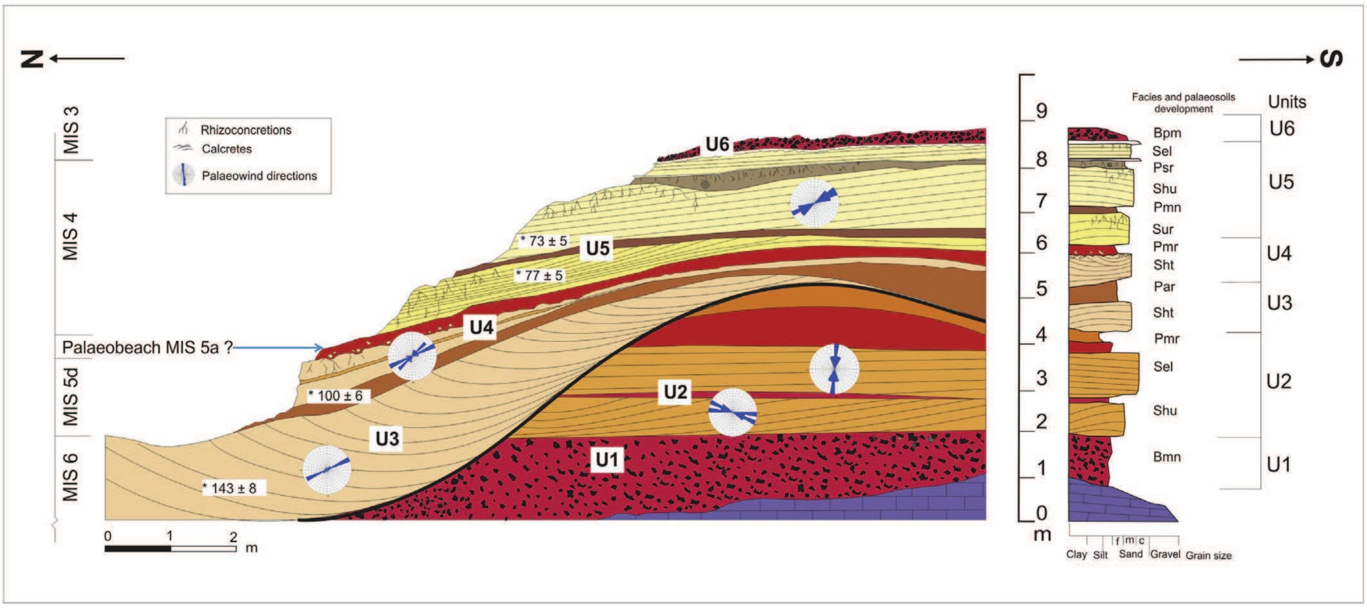

Fig. 6. Synthesis of the stratigraphical architecture and chronology of Cala Xuclar (Eivissa) of Pleistocene deposits.

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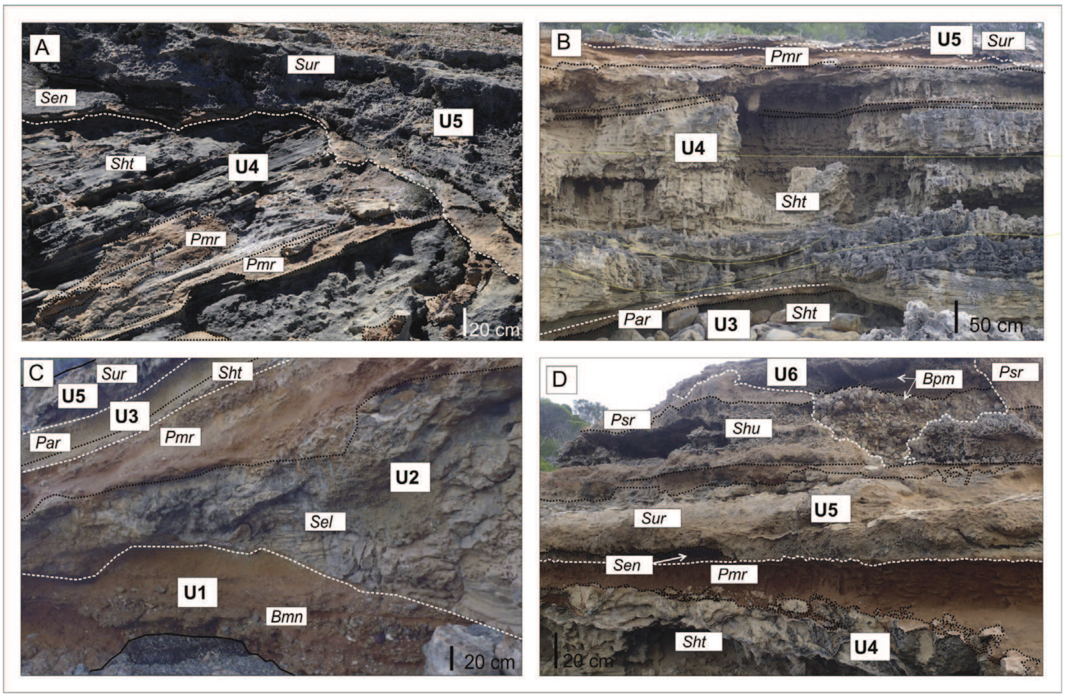

Fig. 7. General overview of sedimentary facies present in Cala Xuclar (Eivissa), with details concerning to the contact of different units and facies disposition.

The last unit is bounded at the base by an erosive unconformity that deeply cuts the underlying deposits. Colluvial and alluvial deposits, facies association *Bmm* and *Bpm* show a large lateral and vertical variation, characteristic of U6. The lower deposits correspond to colluvial gravity debris-flow deposits, whereas the upper deposits are interpreted as a sheet flood deposit.

5. Discussion: implications for landscape evolution

The sedimentological observations and the OSL data allow for constrained aeolian episodes and the reconstruction of the landscape history of Northeastern Eivissa between 143 and 73 ka (MIS 6 to 4). There are former episodes of aeolian activity (Units 1 and 2) however their OSL dates are unavailable. The first period of dated aeolian activity took place during MIS 6 and corresponds to a large-scale dune formation in terms of sediment volume accumulation and lateral presence along the Pleistocene succession. During MIS 6, which represents a cold episode, the sea level was at least 38 m below the present mean sea level (Gallup et al., 2002; Andreucci et al., 2009), leaving large amounts of sand to be transported by wind inland from the shelf. This scenario fits within the nature of MIS 6 dunes at Cala Xuclar because they are constituted by a large amount of marine carbonate particles and they contain only 8% of detrital mineral grains, primarily quartz. Directional data from the fossil dune deposits indicate sand transports towards the SE. Martrat et al. (2004) and Andreucci et al. (2010a, 2010b) notice similar wind directions for the same period and highlight that winds were probably as strong or even stronger that the present ones.

A second period of aeolian activity and dune formation is observed at Cala Xuclar in MIS 5d-c at about ~100 ka. This was a period of intermediate sea level (−10 to −20 m in the neighbouring island of Mallorca; Tuccimei et al., 2006 and Dorale et al., 2010). According to Martrat et al. (2004) sea temperatures were around 15 °C, and land temperatures were between 17 and 14 °C while modern day temperature is about 17.3 °C. During the MIS 5, there is strong evidence of two highstands 5a (~82 ka) and 5e (~131–120 ka) both a few metres above the present sea level, with an intervening period of lowstands where sea level was 10 and 20 m below from present sea level (Dorale et al., 2010). Once again, the formation of Unit 4 corresponds to a period with the sea level lower than the Eemian and the modern day where large amounts of sand could be mobilized due to the minor shelf extent exposed to wind activity. The unit thickness and its continuity along the Pleistocene succession indicate minor sediment availability compared to the previous unit. The upper limit of Unit 4 corresponds to an erosive surface covered by a beach deposit (Facies sen) ~ 2 m a.p.s.l. suggesting a connection with the relatively short-lived MIS 5a high stand.

A third period of aeolian activity and dune formation is seen between MIS 5a and MIS 4 at about 77 and 73 ka. According to Dorale et al. (2010), this was a period of low sea level; the shoreline of the neighbouring island of Mallorca was −16 m asl or about 1 km seaward from the present one. This was a period with mean sea surface temperature around 12 °C (Martrat et al., 2004) and mean annual land temperatures were moreover between 5 and 8 °C (Rose et al., 1999). This dune phase recorded the transition from highly bioturbated ascending and parabolic dunes to less or poorly bioturbated and laminated ascending dunes. The disappearance of upward root traces has also been noticed by Andreucci et al. (2010a, 2010b) and Fornós et al. (2009) in similar Mediterranean environments such as Sardinia and Mallorca and could indicate a decrease in vegetation cover. This interpretation is supported by the presence of semi-arid vegetation in the southern Mediterranean associated to a drastic reduction in temperatures and precipitation during cold climate intervals (Bout-Roumaeilles et al., 2007).

Despite the uncertainties and the low number of OSL ages, our results suggest that episodes of aeolian activity and dune formation were probably linked to periods of low sea level (Fig. 8). During these periods, an extensive part of the shelf would have been exposed to wind erosion and transport. These periods tend to correspond to cold climatic intervals with limited vegetation cover and an active erosive role of rivers (Rose et al., 1999). All of these conditions favoured the carbonate marine sand transport and

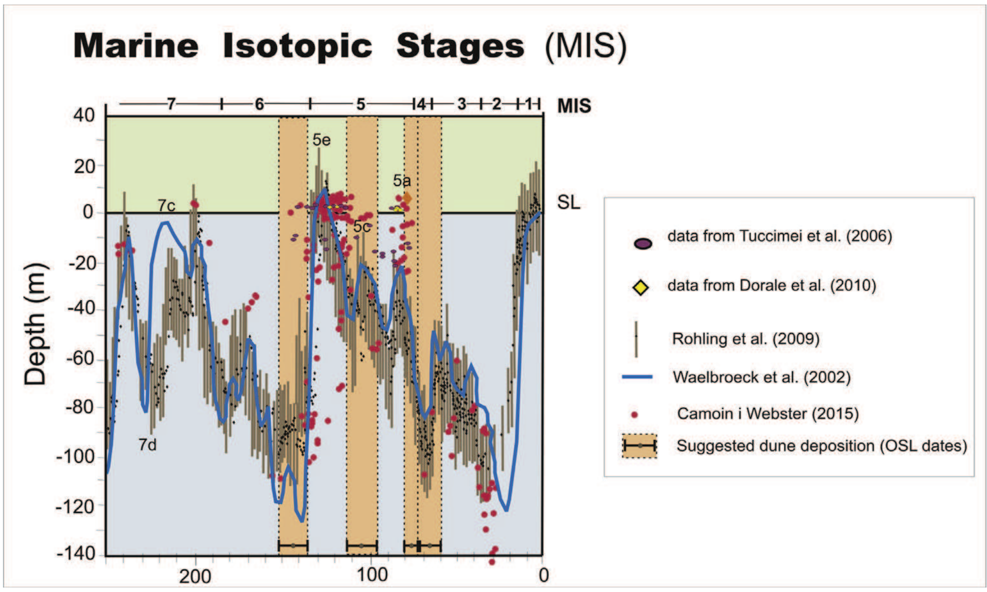

Fig. 8. Sea-level curve (modified from Camoin and Webster, 2015) and Pleistocene aeolian events deposition at Cala Xuclar (Eivissa) inferred from OSL dates (Rohling et al., 2009, Waelbroeck et al., 2002).

deposition in front of inland cliffs where they were trapped. Additionally recent OSL ages of aeolianites from Sardinia (Pascucci et al., 2008; Andreucci et al., 2010a, 2010b) and from Mallorca (Fornós et al., 2009) also indicate that the lower sea level and the cold climatic intervals seem to be the main drivers of aeolian accumulation during the Pleistocene. However other authors such as Brooke (2001) or Pappalardo et al. (2013) insist that aeolianites were mainly accumulated during interglacial and interstadial stages.

6. Conclusions

Middle to Late Pleistocene sedimentary successions of northern Eivissa (Balearic Islands, Western Mediterranean) have been studied. A chronological survey of the area has been established using OSL methods on aeolian dune deposits providing ages from the penultimate glacial (MIS 6) to MIS 4. All of the aeolian deposits are lithified and predominantly composed of marine carbonate particles that were transported inland by strong winds from nearby coasts or exposed shelf areas. The succession is characterized by three major dune phases separated by periods of soil formation and colluvial deposits. This study suggests that sand supply derived from exposed shelf areas occurred during lowstands and sea level falling stages and cool-arid climate conditions. The volume of sand accumulation seems to be related to the availability of sand during the cold-glacial low-stand phases. Inland space is also a key factor, as we need enough space in the embayment for dune formation.

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