Holocene sea level fluctuations and coastal evolution in the central Algarve (southern Portugal)

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Abstract

In Armação de Pêra Bay, southern Portugal, environmental changes during the Holocene can be interpreted based on the morphological and sedimentological similarities between older geomorphic features (cemented beach and dune rocks) and present coastal features. Using knowledge of the present beach and dune processes, we propose a two-step model for the evolution of Armação de Pêra Bay. First, during the rapid sea level rise between about 8 800 and 6 600 yr cal BP, the bay changed from a positive to a negative budget littoral cell and transgressive dunes formed, favoured by drought conditions. At about 5 000 yr cal BP, during a sea level maximum, beach width was less than the critical fetch and dunes stabilized and underwent cementation during the wetter Atlantic climatic event. The second phase of dune accumulation started at about 3 200 yr cal BP, due to a regression of sea level during which the bay changed back to a positive budget littoral cell in which beach width was greater than the critical fetch. Currently, the beach width is less than the critical fetch, dunes are inactive, and the sedimentary budget is negative due to sediment storage in local river systems.

Keywords: Portugal; Holocene; sea level; aeolianite; dune

1. Introduction and background

Dunes are the most common aeolian landforms and they occur in a wide variety of geomorphic and climatic contexts, reflecting the diversity of variables that contribute to their formation. Sediment supply and wind are requirements for aeolian accumulations and, in coastal zones, the available sediment depends on fluvial transport to the littoral zone and on biological activity in the carbonate environments as well as on longshore and cross-shore currents. However, only dry sediment can be reworked by the wind and the amount moved depends on near-shore morphology and slope, beach morphology and width, tides, wave climate, fetch, and relative mean sea level (RMSL). Climatic conditions control wind speed and energy as well as the supply of sediment to the littoral zone, while the RMSL determines the extent of the deflation area.

In coastal zones, sandy dunes can become cemented by carbonates, and are known as aeolianites (or dune rock or dune calcarenite). Aeolianites are coastal dunes composed of sand with high biogenic carbonate contents, corresponding to material reworked from shallow marine sediments (Fairbridge and Johnson,

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1978; Brooke, 2001; Price et al., 2001). Usually, the carbonate content in the aeolianites is more than 50% of the total weight of the sediment (e.g., Pereira and Angelucci, 2004; Bateman et al., 2004).

The main goals of this investigation are to correlate aeolianite development in Armação de Pêra Bay (southern Portugal) with Holocene variations in RMSL, and to determine the accuracy of aeolianite evolution as a proxy for the relative sea level history. Littoral cells such as Armação de Pêra Bay contain a complete cycle of sedimentation, and the auto-regulation of sedimentary processes in such cells responds very rapidly to climatic and sea level changes. Accordingly, paleoenvironmental evolution reflected in changes in beach-dune interactions can be solved at the millennial scale. This is the case of Armação de Pêra Bay, where changes in accretion and erosion are documented throughout the Holocene.

1.1. Variables controlling aeolianite formation

Coastal dune formation depends on sediment availability, wind activity, longshore and cross-shore currents, tides, beach and near-shore morphology and slope, climatic conditions, and sea level oscillations (Forman et al., 2001; Kindler and Mazzolini, 2001; Catto et al., 2002; Gay, 2005). Eustatic changes are frequently cited as being the primary control on dune accumulation: dune formation has been correlated with sea level rises (e.g., White and Curran, 1988; Kindler and Mazzolini, 2001; Catto et al., 2002; Arbogast et al., 2002) and falls (e.g., Rodriguez-Ramirez et al., 1996; Pereira and Angelucci, 2004), as well as with sea level fluctuation during interstadials (e.g., Bateman et al., 2004) and sea level still-stands (e.g., Mastronuzzi and Sansó, 2002). Brooke (2001) found a positive correlation between aeolianite formation and high sea level during interglacial stages, but also cited examples of aeolianites' contemporaneity with glacial climatic stages (e.g., in Australia). Nevertheless, during sea level fall, it is very difficult to mobilize carbonate sand grains due to their reactivity to diagenetic processes when in contact with freshwater, and arid conditions would be required for aeolian reworking of such sand to take place. Diagenetic processes are particularly important when carbonate content exceeds 50%, as in the case of Stocking Island (Bahamas) where lithification to a depth of 80 cm in less than 60 years due to freshwater diagenetic processes has been reported (Kindler and Mazzolini, 2001).

Studies of modern beach-dune systems reveal that the frequency of high water level occurrence and its magnitude are important factors in the reworking of sand and its accumulation in the backshore. Ruz and Meur-Ferec (2004), for example, observed that dune growth occurs mostly during summer despite the moderate wind energy compared with the strongest winds that blow in winter when dune erosion prevails due to storms, high tides, and storm surges. This is explained by the fetch effect (Svasek and Terwindt, 1974; Gillette et al., 1996; Bauer and Davidson-Arnott, 2002), which describes the increase of a particle's rate of transport starting at the upper limit of the swash zone (where the rate is zero) to a maximum downwind along the beach (where sand is dry). The distance over which this takes place is dependent on the wind's attack angle and speed. As observed in The Netherlands, the intensive wind-driven rain can mobilize sand from the beach, this mechanism having a secondary role and being irrelevant for dune construction (De Lima et al., 1992).

The genesis of the currently stabilized coastal dunefields at Denmark was correlated with spring and summer storminess which decreases at the end of the 19th century favoured the dune stabilization (Clemmensen and Murray, 2006). Storminess was also pointed as an important process on dune development between 1770 and 1905 AD at the western Portuguese coast probably correlated with negative North Atlantic Oscillation index winter (Clarke and Rendell, 2006). The research developed by Wilson et al. (2004) at the north coast of Northern Ireland aiming to correlate coastal dunefields development with sea level and climatic changes concluded that sea level change was the first-order forcing factor with superimposed climatic deterioration, some of which marking dunefield activity occurred.

Dune erosion/accretion depends mainly on the relationship between sediment supply and sand stabilization provided by vegetation or lithification. Because of sand's high permeability, high leaching capacity, and low cohesion, all attributes which result in a water deficit, precipitation is not a particularly important influence on dune vegetation decrease/increase and therefore on dune mobility/stabilization. The significant factor determining the level of dune mobility is the wind and its threshold velocity required to initiate sand grain movement. In addition, wind is the primary control on dune vegetation, with vegetation developing when climate change reduces wind speeds, making dunes less vulnerable to erosion (Tsoar, 2005).

The largest aeolianite bodies occur mainly in the latitudinal range 20°–40°. This distribution is related to climatic conditions allowing rapid cementation (Brooke, 2001). According to Short and Hesp (1999a), aeolianites occur mostly in drier tropical and temperate regions.

There are therefore two sets of processes that determine aeolianite occurrence: (a) Dune generation: sediment availability, beach characteristics, mean sea level position, wind direction and stress, and drought conditions; (b) Dune cementation: dune stabilization, wet climatic conditions, and carbonate availability/content. In modern reflective beach-shore systems, carbonate content reaches maximum values between mean sea level water and 1 m above this level, while in dissipative beach-shore systems maximum values occur between 4 and 8 m below mean sea level (Short and Hesp, 1999b). Therefore, the amount of carbonate compound in the sediment to be wind blown is higher in the most reflective systems (or during the reflective phases on mix environments), which potentially means an easier dune cementation and consequently aeolianite generation.

1.2. Timing of dune formation during the Holocene

Coastal dunes form under drought conditions when the sediment available to be blown by the wind is exposed in a beach wide enough to allow a high rate of particle transport. A review of the literature points to the mid-Holocene as a period during which dunes were widespread over many parts of the world (e.g., White and Curran, 1988; Heteren van et al., 2000; Vega Leinert et al., 2000; Arbogast et al., 2002; Mastronuzzi and Sansó, 2002; Clarke and Rendell, 2006), a period coincident with major climatic organization in the North Atlantic (Cacho et al., 2002).

In the Iberian Peninsula, a marine cooling event and dry conditions occurred at about 8 600 yr BP (Leira and Santos, 2002). In the Portuguese west coast, coastal dunes started to accumulate in the mid-Holocene during stabilization of sea level, and experienced two more phases of accumulation after about 3 000 yr BP (Noivo and Bernardes, 2000). On the Spanish Atlantic coast, close to the border with Portugal, the first generation of dunes accumulated between 7 000 and 5 000 yr BP and migrated landward during rapid rises of mean sea level at 5 500–4 000 yr BP, 3 500–2 000 yr BP, and about 1 000 yr BP (Rodriguez-Ramirez et al., 1996). Goy et al. (2003) noted that several sea level oscillations were registered along the western Mediterranean coast after 7 400 yr cal BP, and that beach ridge generation correlated positively with high RMSL periods and with increases in the amount of sediment reaching the coast.

2. Geomorphological and geographical settings

The exposed rocks forming the southerly Algarve coast young eastward and consist of limestone, marls and calcarenites spanning from Jurassic to Miocene. Those carbonate series are strongly karstified and affected by joints and faults. Coastal paleokarsts are fossilized by detrital sediments from Pliocene and Pleistocene. With rare exceptions, rivers have currently a strong seasonal hydraulic regime. A conspicuous feature at the Algarve rocky coast is the development of several bays protected from the direct wave assailing by rocky headlands. That is the case of the Armação de Pêra Bay located in the central Algarve region of southern Portugal (Fig. 1) constrained at its eastern and western ends by cliffs exposing Miocene calcarenite horizontally bedded. The bay is backed at the mainland by the Miocene calcarenite in which the paleorelief is filled by Pliocene and Pleistocene red sand intercepted by river channels (Alcantarilha and Espiche rivers) draining currently to the bay.

Armação de Pêra Bay is a zeta-shaped bay. The term zeta-shaped bay was first used by Halligan (1906) to describe bays which curvature radius decreases towards one end. The longshore transport of sand, generated by the prevailing shore currents from the WSW, is constrained by the westerly headland (Fig. 1b). The bay experiences a mesotidal regime ranging from 2.70 to 1.36 m during neap tides and from 3.82 to 0.64 m during spring tides, as measured in the Vilamoura harbour, about 30 km east of the study area (data from the Instituto Hidrográfico, 1990). Waves approach from the WSW for (on average) 90% of the year, and from the ESE during the remaining 10% of the time (Costa, 1994). Wave height ranges from 0.30 m to 1.8 m, with rare exceptional heights of more than 3.7 m. Such high waves are associated with storms from the SW, during which waves attain an average of 2–3 m height with a period of 7–8 s (Pires and Pessanha, 1979, 1986; Pires, 1989). The prevailing wind approaches the shore normal direction at angles ranging from 40 to 60°. According to Pinto and Teixeira (2002a), the Armação de Pêra beach is either reflective or dissipative for wave heights of ≤ 0.5 m and 1–1.5 m, respectively. In the latter case, there is accretion in the foreshore (about 1–1.5 m/month) leading to construction of a berm whose crest can reach 6 m during the summer. The area has a mild Mediterranean type climate and is vulnerable to droughts and desertification. Mean annual precipitation is as low as 500 mm along the Algarve coast, and mean annual temperature is between 18 and 20 °C (Miranda et al., 2002).

The beach along Armação de Pêra Bay is fed mainly by sediments from the Alcantarilha and Espiche Rivers (Fig. 1), reaching volumes of 6.9 × 1000 m^3/yr and 1.7 × 1000 m^3/yr, respectively (Pinto and Teixeira,

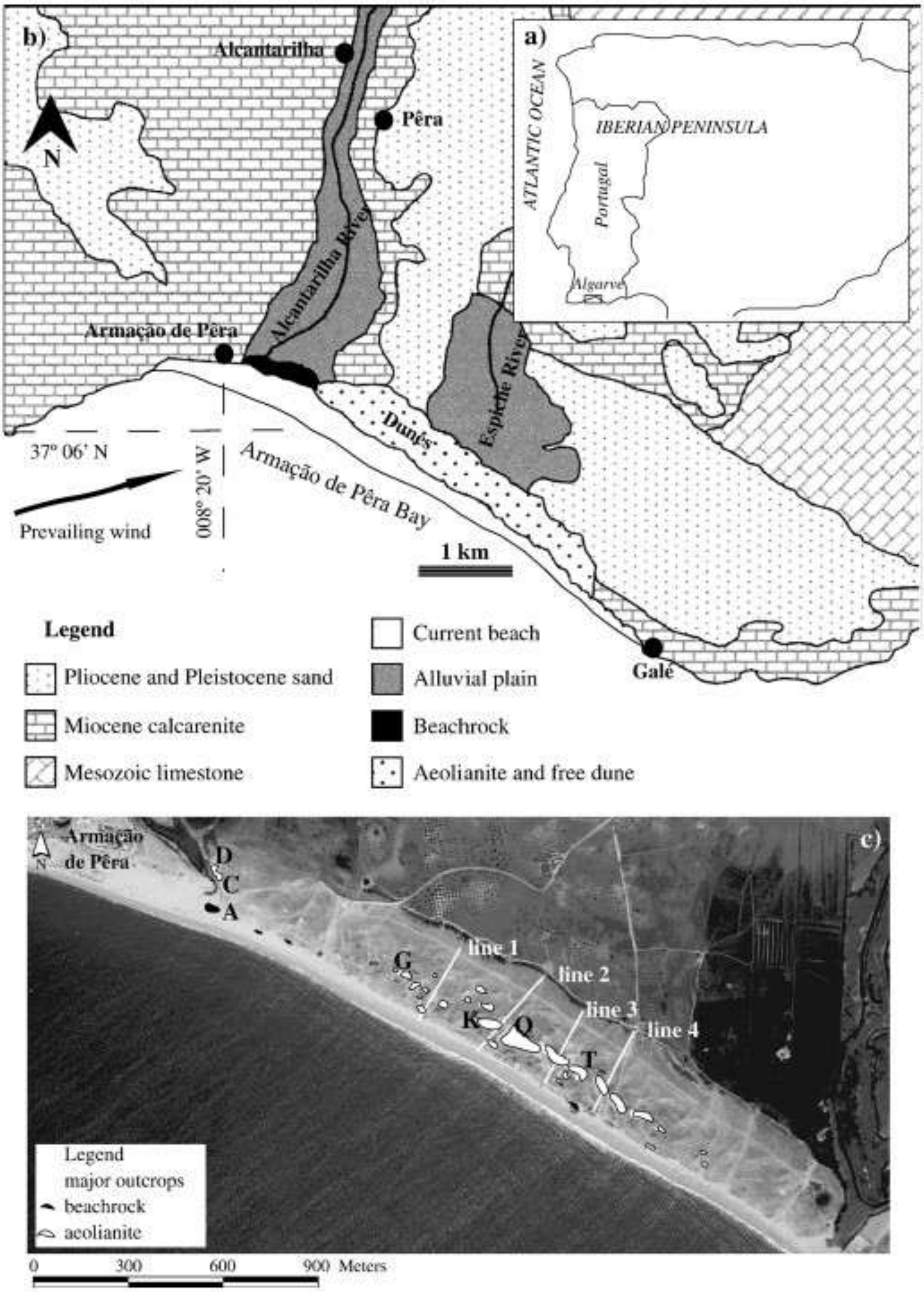

Fig. 1. (a) Location of the study area in the Algarve, southern Portugal; (b) Armação de Pêra Bay and dunefield; (c) Georeferenced Ground Penetrating Radar (GPR) lines and aeolianite outcrops (see Fig. 4). Capital letters A, C, D, G, K, Q and T designate the outcrops from which samples were collected for textural analysis and radiocarbon dating.

2002b). In this area, a free dunefield covers an older aeolianite cropping out in some sites (Fig. 1c). Free dunes are sparsely vegetated and apparently stabilized whereas foredunes are represented only by a few patches near the river mouths. The term “free dune” is used in this study to refer to dunes with uncemented sand but which are relatively stabilized, whereas “aeolianite” is applied to cemented dunes.

3. Methods

In order to ascertain the past environmental conditions responsible for the generation of aeolianites, such as the beach-dune relations (and therefore the past RMSL), we studied various aspects of the geomorphology, sedimentology, and structure of the aeolianites. Aeolianite outcrops were identified in the field, described, and sampled. Using a Global Position System (GPS), topographic maps, and aerial photographs, a contour map of the aeolianite outcrop pattern was constructed. The georeferenced outcrops were plotted onto aerial photographs using a Geographic Information System (GIS) (Fig. 1c). Outcrops exposing three dimensions of the aeolianite units were chosen for measurement of layers' inclinations and thicknesses. Internal structures of the aeolianites were described and photographed.

Samples, each weighing 0.5 kg, were taken for textural and mineralogical analyses (28 and 18 samples for the aeolianite and beachrock respectively). Samples were collected along the vertical profiles exposed at the locals A, C, D, G, K, Q and T signed in Fig. 1c. A total of 19 samples were radiocarbon dated. From these ones, nine were performed in marine shells of the bivalve Acanthocardia sp. collected in the beachrock deposits and 10 in aeolianite cement. Regarding the shell samples, the larger debris occurred in poorly cemented lag deposits with coarse texture. Aiming to separate the shells from the clastic fraction, samples were submerged in tepid distilled water during 2 months with daily water removal and hand shaking. Shells were radiocarbon dated in the Institut Royal du Patrimoine Artistique, Bruxelles (IRPA in Table 1) and in the Beta Analytic Radiocarbon Dating Laboratory, Miami, Florida (Beta in Table 1). Shells' radiocarbon ages were reservoir corrected for 400 yr as determined for the Iberian margin (Abrantes et al., in press). The other 10 samples, from aeolianite, were sent to the Beta Analytic Radiocarbon Dating Laboratory for radiometric dating analysis with extended counting. In this case the dated material was the carbonate cement that was dissolved at the Beta Analytic Laboratory. For the upper Pleistocene and Holocene paleoenvironmental studies based on dunes and aeolianites the most widespread dating methods are the radiocarbon, thermoluminescence (TL) or optical stimulated luminescence (OSL). Several workers have compared results from luminescence and radiocarbon ages and stated that the formers are usually underestimated probably due to anomalous fading (e.g., Heteren van et al., 2000) or problems related with the

Table 1
Estimated ages for samples collected in the Armação de Pêra Bay

Sample code	Laboratory code	Sedimentary body	Method	13C/12C (‰)	Radiocarbon age BP	Years cal BP (2 σ)	Mid point Cal BP
A1 □	IRPA-20059	Beachrock	AMS	+1.77	5035 ± 30	5744–5916	5853
A2 □	IRPA-20063	Beachrock	AMS	+1.15	4530 ± 30	5230–5425	5299
A3 □	IRPA-20068	Beachrock	AMS	+2.88	4685 ± 30	5441–5576	5511
A4 □	IRPA-20060	Beachrock	AMS	+1.49	4055 ± 35	4559–4802	4686
A5 □	IRPA-20067	Beachrock	AMS	+1.03	3970 ± 25	4428–4643	4540
A6 □	IRPA-20066	Beachrock	AMS	+1.48	3575 ± 25	3915–4115	4017
A7 □	Beta-185786	Beachrock	AMS	+0.6	2930 ± 40	3077–3326	3213
A8 □	Beta-185788	Beachrock	AMS	+1.8	2280 ± 40	2312–2582	2417
A9 □	IRPA-20056	Beachrock	AMS	+0.84	710 ± 20	640–726	679
C1 □□	Beta-185790	Aeolianite	Rad.	+1.1	5410 ± 50	6498–6747	6645
C2 □□	Beta-185791	Aeolianite	Rad.	− 0.5	5470 ± 50	6539–6797	6691
D □□	Beta-185792	Aeolianite	Rad.	− 1.1	5970 ± 50	7238–7418	7297
T1 □□	Beta-185793	Aeolianite	Rad.	− 0.9	7210 ± 60	8316–8544	8407
T2 □□	Beta-185794	Aeolianite	Rad.	− 3.6	7590 ± 60	8627–8992	8797
G1 □□	Beta-185795	Aeolianite	Rad.	−3.6	7080 ± 50	8170–8368	8261
G2 □□	Beta-185787	Aeolianite	Rad.	− 1.1	5470 ± 50	6533–6791	6678
K □□	Beta-185796	Aeolianite	Rad.	− 1.9	7340 ± 60	8405–8596	8498
Q1 □□	Beta-185797	Aeolianite	Rad.	− 2.8	5610 ± 50	6711–6932	6810
Q2 □□	Beta-185789	Aeolianite	Rad.	− 3.0	6410 ± 50	7565–7688	7622

Ages were calibrated using CALIB 5 program. For sample locations, see Figs. 1c and 5b. Shells' ages are reservoir corrected for 400 yr (Abrantes et al., in press).
□ Shell.
□□ Carbonate sediment.

grain size (e.g., Wallinga and Duller, 2000). However, radiocarbon dating either in organic matter or in carbonates also shows several problems. Apparent age can be too low due to contamination from younger horizons, modern roots or even to sample containers. On the contrary, apparent age can be too high due to dissolved humus from older deposits and to dissolved groundwater carbonate (Terasmae, 1984). Moreover, when deposits are heterogeneous (as it is the case in the study area) it is not possible to date the material more accurately than the likely age range of the components (Pilcher, 1991). Radiocarbon ages in this work are probably overestimated due to groundwater with older carbon from the surrounding rocks. However, the strong consistence between stratigraphic position and age gives some confidence in the results, and ages pointed in other independent works fall in the same time range (Pereira and Soares, 1994; Teixeira and Pinto, 2002).

In order to compare the aeolianite sediments with sediments of the present day environment, 11 samples from the backshore and 11 from the free dunes were also analyzed for texture and mineralogy. The $CaCO_3$ contents of samples were determined by weight difference before and after digestion in a 0.5 N HCl solution. Clastic residuals were mechanically sieved and granulometric parameters were calculated using the GRADISTAT program (Blott and Pye, 2001). In each of the granulometric class heavy minerals were separated. Accordingly, the grains were placed into centrifuge tubes filled with bromoform and centrifuged. Bromoform and light minerals (quartz) were poured off through a funnel coated with filter paper and then washed with alcohol. The remaining heavy minerals were also rinsed with alcohol and minerals were studied under the microscope after weighted and dried.

In order to understand the distribution of aeolianites under the free dunes as well as their sedimentary structures, a Ground Penetrating Radar (GPR) survey was made along four profiles perpendicular to the coast (Figs. 1c and 4).

4. Results

4.1. Features and processes of the present-day beach

4.1.1. Geomorphological features

The Armação de Pêra Bay is oriented northwest–southeast, and is thus protected from both the westerly and easterly winds (Fig. 2a). However, its central portion is exposed to the frequent winds that derive from the south and southwest and which approach the coast at shore-normal angles ranging from 40 to 60°. The beach face slopes seaward at 6° and its width is about 60 m (Fig. 2b). During spring tides the beach width is quite reduced and the high water level reaches and erodes both the free dunes and the underlying aeolianites (more frequently in the central part of the bay). This implies that dry sand on the beach is available only during short periods in a reduced deflation area. A backshore terrace up to 100 m wide and eroded only during storms has developed in the easternmost and westernmost parts of the bay close to the river mouths.

The Alcantarilha and Espiche rivers no longer enter the ocean through their natural mouths. The Alcantarilha mouth is artificially opened several times a year, while the lower portion of the Espiche has become a lagoon. During the natural closure of the river-ocean connection of the Alcantarilha, a sedimentary load characterized by a remarkable amount of heavy minerals accumulates in its lower portion. When the connection is artificially open, ocean waters enter the river during high tides and the sediment previously accumulated at the river mouth is exported to the beach (Fig. 2b).

4.1.2. Sedimentary features

The backshore is probably the most important zone contributing sand for the formation of dunes. The main sedimentary features that characterize the backshore terrace are horizontal bedding with layers composed of medium- to coarse-grained sand, and load structures (Fig. 2b–e). The backshore terrace attains a height of up to 2 m above the current beach face and is constructed by accretion under swash action during spring tides. Due to the rapid infiltration of swash water into the sand, the sediment does not return to the beach face and the terrace therefore accretes. Load structures are produced when the wind blows onto the terrace's steep seaward face, drying the coarse, poorly sorted sand more quickly than it does the fine, well-sorted sand above, thereby inducing collapse of the coarse sand layers.

4.1.3. Sedimentological characteristics

The sediment in the backshore is a moderately well sorted, medium to coarse sand (Fig. 3) composed primarily of sub-rounded quartz. The proportion of biogenic grains decreases dramatically with granulometry, from 80% to 18% for the -1.5 to -1 ϕ and 0.5 to 1 ϕ intervals, respectively. The average $CaCO_3$ content is 41%. Heavy minerals, mainly magnetite, ilmenite, tourmaline and rutile, attain their maximum occurrence in the 1–2 ϕ fractions, at about 3%.

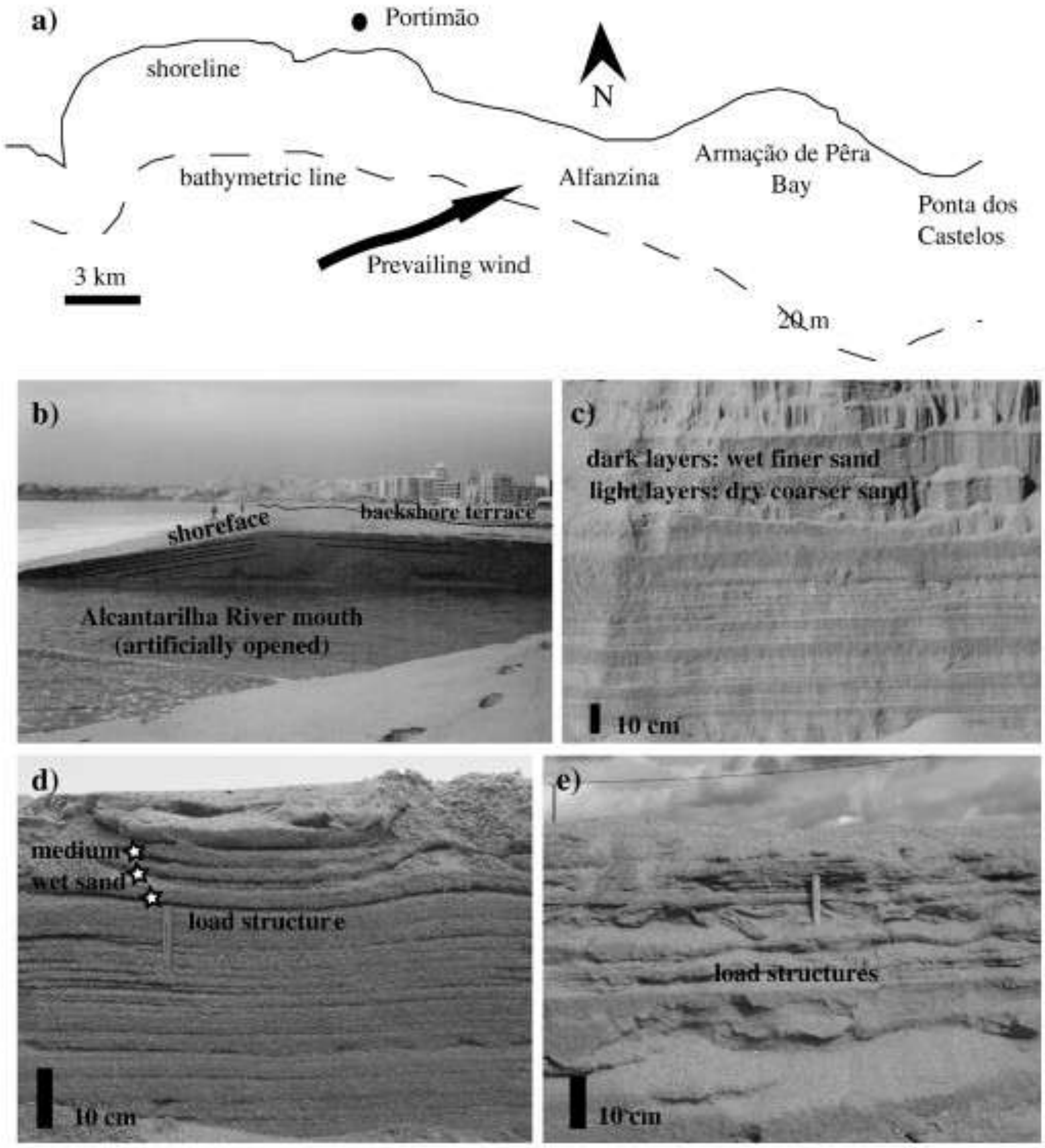

Fig. 2. (a) Morphological features of the beach in Armação de Pêra Bay; (b) stratification in the upper backshore terrace; (c, d and e) Load structures in the upper backshore terrace seaward face.

4.2. Free dunes

4.2.1. Dune morphology and sedimentology

The dunefield extends 3 km parallel to, and 0.3 km perpendicular to, the shoreline between the Alcantarilha River mouth and the Galé beach at the eastern end of the bay (Fig. 1b, c). The free dunes constitute transverse ridges parallel to the shoreline with a wavelength of about 60 m. The dunes attain heights of up to 18 m (above the current backshore) in the most landward section of the field, where they are more developed and thicker (Fig. 4). The dunes become thinner seaward, making the interpretation of the GPR signal difficult due to the lack of well defined surfaces. Dune sediment is a

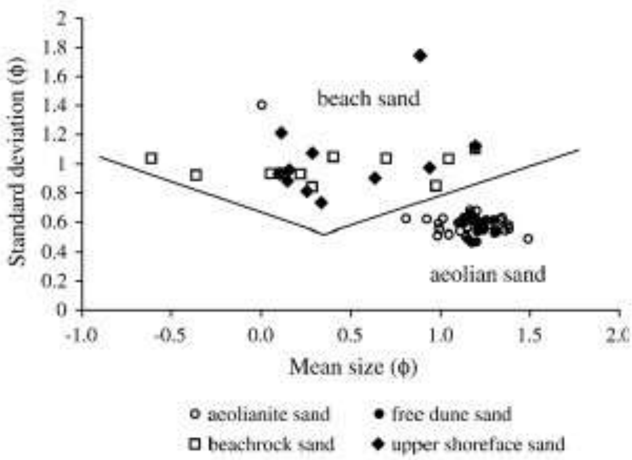

Fig. 3. Sedimentological attributes of sampled sediments in the upper shoreface, beachrock, free dunes, and aeolianites.

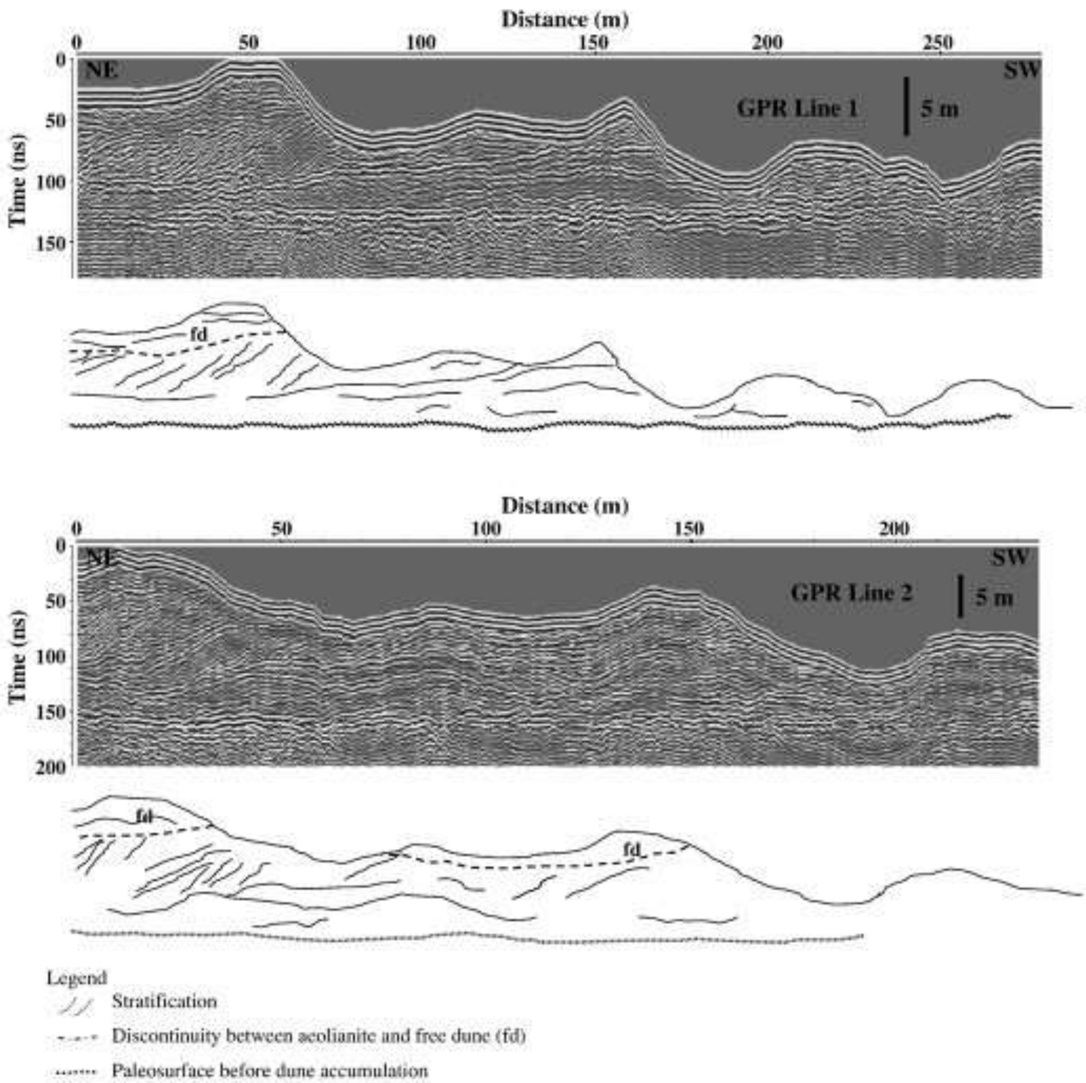

Fig. 4. GPR profiles and structural interpretations. The lack of information in the southwest parts of profiles, as in profile 2, is due to saltwater in the rock. Vertical axes are in double time. For location of profiles see Fig. 1c.

medium well sorted sand (Fig. 3) with an average of 36% $CaCO_3$.

4.3. Aeolianites and beachrock

4.3.1. Geographic distribution

Two different types of cemented sands occur in Armação de Pêra Bay: aeolianites and beachrock. The aeolianites are partially covered by the younger free dunes (Figs. 1c and 4) and, therefore, direct observations and sampling are confined to locations where free sand cover is absent. Such locations are confined to the dune and aeolianite crests that are geographically coincident, and in the cliffs carved by wave erosion. Ages of the aeolianites range from ca. 8 800 to 6 600 yr cal BP (Table 1).

In the current upper foreshore (e.g., A and B in Fig. 1c), the cemented beachrock crops out. It is dated with ages ranging from 5 853 to 4 017 yr cal BP, and is underlying other cemented sands (upper foreshore facies) which ages range from 4 017 to 679 yr cal BP (Table 1 and Fig. 5). The sedimentary paleo-facies were interpreted based on our field observations of current sedimentary environments and on other works (e. g., Hill and Hunter, 1987; Kindler and Strasser, 2002; Bezerra et al., 2003; Caldas et al., 2006).

4.3.2. Sedimentological structures and sediment attributes

The aeolianite outcrops facing the sea, which are currently undergoing wave erosion, exhibit horizontal bedding at their bases, as well as numerous load

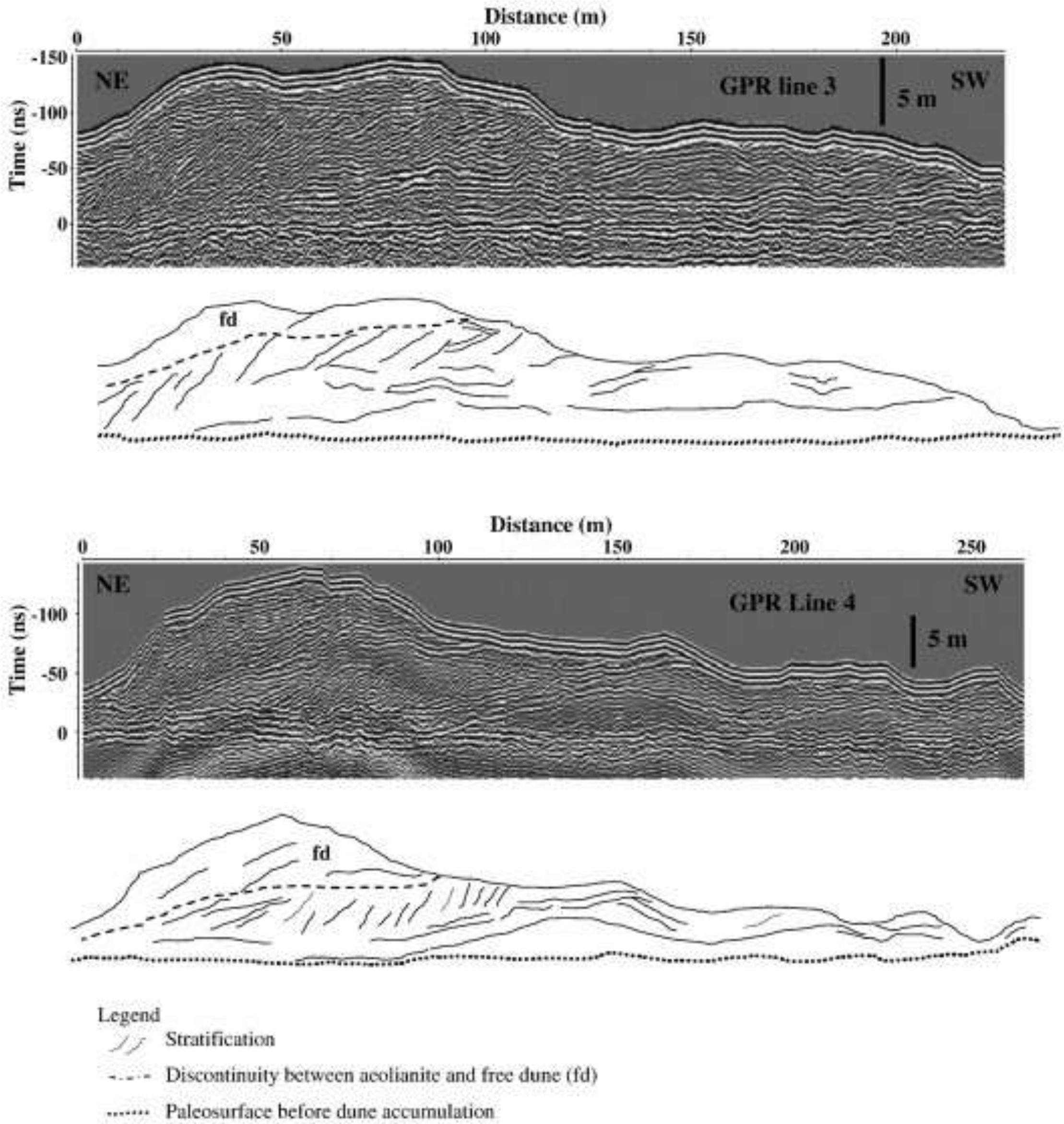

Fig. 4 (continued).

structures similar to those occurring in the present backshore terrace (Fig. 2c, d, e). Upwards from the base, centimetric layers show parallel contacts dipping 1–4° SSE and 6–28° NNE (apparent dip) in the seaward and lee sides, respectively. Cross stratification occurs but is uncommon. Landward from the backshore, aeolianite architecture evolves from sand sheets or foredunes with low angle stratification to dune forms with higher crests. Stratification changes about 100 m from the backshore, becoming markedly inclined to the NNE. This stratification is interrupted by an angular discontinuity above which repose the free dunes (Fig. 4). The aeolianite sediment is a well sorted medium sand (Fig. 3) with 48% $CaCO_3$ content on average.

Beachrock shows an upward facies variation as follows: (a) Lower foreshore facies (LFS in Fig. 5) with layers up to 10 cm thick, some of which are very shelly and contain debris shells of Acanthocardia sp. which were dated (Table 1); (b) a sequence of thinner layers (0.5–1 cm). Superposed to the beachrock sedimentological facies from the upper fore shore (UFS in Fig. 5) show: (a) a sequence of layers of thickness up to 5 cm, with frequent horizons of heavy minerals similar to those transported currently by the rivers (ilmenite, magnetite, tourmaline, rutile); and (b) layers up to 10 cm thick with scours and load structures. The first occurrence of heavy minerals in the beachrock profile is at 1 m above the present river floor, corresponding to the datum 4 017 yr cal BP (Table 1 and Fig. 5).

Beachrock sediment varies from medium to coarse moderately sorted sand (Fig. 3), and contains an average of 47.5% $CaCO_3$. During winter, some beachrock

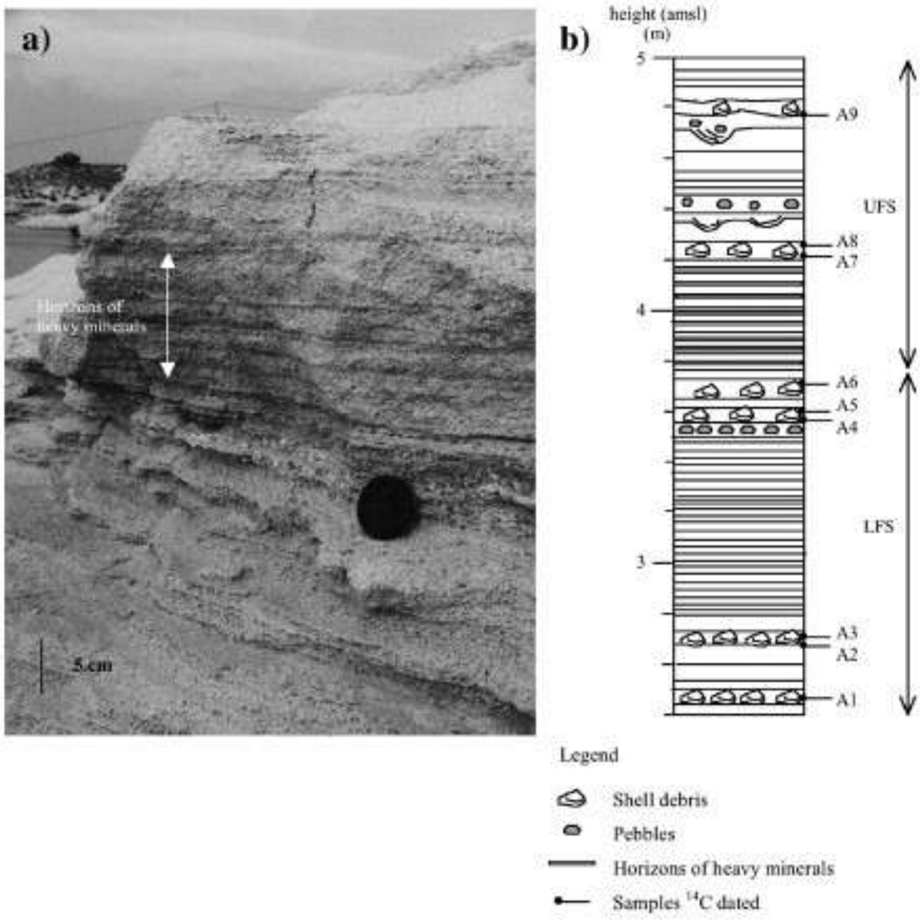

Fig. 5. (a) Beachrock cropping out in the upper foreshore; and (b) Lithologic column with the localities of samples radiocarbon-dated. Height is relative to the current mean sea level. Sample ages are shown in Table 1 and location of outcrop A is shown in Fig. 1c. “UFS” is Upper foreshore Facies and “LFS” is Lower Foreshore Facies.

fragments become exposed in the lower shore face. Also, in the central sector of Armação de Pêra Bay, karstic features in the Miocene substratum are now being exhumed by wave action, exposing a notch and lithified sands inside the karstic holes.

5. Discussion

A well-cemented beachrock formation crops out in the backshore and in the shoreface of Armação de Pêra Bay, and an aeolianite formation is exposed uncovered by a free dunefield (Figs. 1c and 4). Beachrock and aeolianite ages range from ca. 5 800 to 4 000 yr cal BP and ca. 8 800 to 6 600 yr cal BP, respectively (Table 1). The geographical, structural, and sedimentological relationships between the aeolianites and the younger free dunes point to a repetition of environmental conditions favouring dune formation during the Holocene (Figs. 1c and 4). The time interval separating these dune-forming periods corresponds to the older dunes' stabilization and cementation. The remainder of this section discusses the Holocene dune evolution of Armação de Pêra Bay, with particular reference to the role of sea level fluctuations.

Dunes are a very common geomorphic feature and therefore have advantages as environmental archives relatively to other proxies (Lawson and Thomas, 2002). To understand the processes that currently contribute to the dune development is fundamental in order to interpret past environments. The study area is a privileged site to apply this principle once it testifies the cyclic occurrence of processes including the currently acting. Therefore, the understanding of past beach-dune relations can be studied by comparison with the current dynamic processes. One merit of this work is that it interprets coastal dunes' accretion and erosion related with the beach dimensions (fetch effect), and therefore the mean sea level position. One of the variables that influences dune erosion or accretion is beach morphology, erosion prevailing when the beach is narrow and steep (Saye et al., 2005). Coastal cells such as zeta bays are relatively closed to longshore sediment transport systems. Such cells have two typologies, distinguished according to the relations between sediment supply and sink (Carter and Woodroffe, 1994). While negative budget cells experience erosion, positive budget cells usually accumulate extensive beach ridges due to the continuous sediment supply.

Adopting this nomenclature, Armação de Pêra Bay acts as a positive budget cell when riverine sediment supplies the shore, forming conditions in the bay potentially favourable for aeolian accumulation. In contrast, when fluvial sediment is trapped in the rivers' alluvial zones, due (for instance) to sea level rise, the bay becomes a negative budget cell in which erosive processes are dominant. Nevertheless, whatever the RMSL shift direction, it is necessary to have a beach large enough and containing dry sand to allow it to be wind blown. The beach in Armação de Pêra Bay is becoming narrower due to regional sea level rise of 1.5 ± 0.2 mm/yr along the Algarve coast (Dias and Taborda, 1992), and currently the fluvial sediment accumulates in the upper foreshore. The prevailing wind and waves from the WSW are oblique to the headlands protecting the bay and approach the shore normal direction at angles ranging from 40 to 60°. Therefore, cross-shore transport is the most important mechanism for sediment redistribution in the bay, and sediment availability depends almost entirely on the fluvial input. As a consequence, Armação de Pêra Bay could change into a negative budget cell should fluvial sediment become trapped in the rivers' alluvial zones.

On a beach, the transport of sand by wind increases exponentially from the swash line, where it is zero, to a maximum in the backshore, where saturation is reached. This process is the fetch effect and depends on wind speed and attack angle, constituent grain size, and beach width (Svasek and Terwindt, 1974; Gillette et al., 1996; Bauer and Davidson-Arnott, 2002). Considering the angle of approach of the wind to the shore normal direction in Armação de Pêra Bay ($\alpha = 40–60°$), the critical fetch (cf) is 72–108 m and the beach is therefore too narrow (w = 60 m) to allow the fetch effect ($\cos \alpha = w/cf$). Consequently, the sand supply to the dunes is limited (Bauer and Davidson-Arnott, 2002). This fact, together with our field observations concerning the scarcity of foredunes, the nature of the vegetation covering the dunes, and their erosion by waves, allows us to conclude that the free dunes are currently inactive. In addition, GPR facies interpretation shows that, except for the most landward sites, free dunes have a limited thickness, which, as observed in the field, was insufficient to completely cover the aeolianites.

The stabilization and cementation of the aeolianites probably occurred when RMSL and beach morphology were similar to the present, between about 8 800 and 6 600 yr cal BP (Table 1), and when the beach width was narrower than the required critical fetch. In addition, the occurrence in the upper foreshore of features such as beachrock (its meaning will be further discussed in this section) up to 4 m higher than the current mean sea level (assumed as the half of the tidal amplitude) and beach-cemented sand fossilizing the littoral karst, corroborates our hypothesis that RMSL at about 5 000 yr cal BP was close to, or slightly above, the present level. Moreover, the heavy mineral accumulations inside the cemented upper foreshore facies, lying 1 m higher than the present accumulations and whose ages are constrained to between 4 017 and 3 213 yr cal BP (Fig. 5 and Table 1), suggest that at some stage the rivers lost the capacity to transfer sediment to the lower foreshore (similar to what is observed at present), probably due to the sea level rise. The importance of the swash zone location and its shift in sympathy with mean sea level change has been observed in several regions where sediment supply and wind speed and direction are otherwise favourable to dune formation (e.g., Arens, 1996; Hesp, 2002; Ruz and Meur-Ferec, 2004).

Although dune generation can occur in either coastal, riverine, or inland settings, it usually correlates positively with drought climatic conditions (e.g., Thomas and Shaw, 1991, 2002; Forman et al., 2001; Otvos, 2001; Ivester and Leigh, 2003). During the mid-Holocene, a major climatic organization took place in the North Atlantic (e.g., Cacho et al., 2002), and a marine cooling event and dry conditions occurred at about 8 600 yr BP in the Iberian Peninsula (Leira and Santos, 2002). The mid-Holocene cooling event is also registered in the Mediterranean Basin (Geraga et al., 2000), and data gathered in speleothems reveal two cool periods in Europe at 7 800 and 3 500 yr BP (MacDermott et al., 1999). Geochemical components in the sediments from estuaries in the Algarve also point to two cool events dated at between 7 500 and 6 500 yr BP and at about 3 000 yr BP (Moura et al., 2001). Therefore we conclude that, in Armação de Pêra Bay, the first period of dune generation started during the mid-Holocene cooling-drying event. The flow and load of the rivers decreased and sediment that reached the littoral zone was deposited mainly in the upper foreshore due to the sea level rise. Storminess sometimes correlated with cool events has been referred as responsible for the dune activity phases (e.g., Otvos, 2001; Clemmensen and Murray, 2006; Clarke and Rendell, 2006). However, the wind acts in a deflation area which extension is controlled by sea level oscillations.

Mean sea level rose very quickly during the early and mid-Holocene in many parts of the globe, forcing the landward migration of coastal landforms. In the estuaries, marine influence increased and fluvial load was trapped in extensive salt marshes (Dabrio et al., 2000; Boski et al., 2002; Mastronuzzi and Sansó, 2002; Gerdes and Watermann, 2003; Andrade et al., 2004; Shennan et al., 2005). In Armação de Pêra Bay, aeolianites exhibit a typical morphology of transgressive dunes (Fig. 4). When sea level rises but sediment supply remains sufficient, the seaward side of the foredunes erodes, and crests become higher and destabilize. In consequence, landward migration occurs, forming sand sheets and a wide variety of dunes with planar or very low-angle stratification depending on the vegetation (Ritchie and Penland, 1990; Hesp and Short, 1999; Short and Hesp, 1999b; Hesp, 2002). Landward migration in the Armação de Pêra area would have been very rapid, not allowing vegetation development as no root traces were observed in the exposed aeolianites. At about 7 000 yr BP climatic conditions in Portugal were dryer than the present (Figueiral and Terral, 2002) favouring the dune activity. Therefore, dunes that later were cemented to form the aeolianites started to accumulate in the bay during the rapid marine transgression of the mid-Holocene and in climatic cold and dry conditions. The dunes became inactive when RMSL was close to, or higher than, the present level, and when available dry sediment was unable to be wind-blown because the beach width was narrower than required for the critical fetch. RMSL higher than the present level was registered in several coastal zones during the Holocene (e.g., Mastronuzzi and Sansó, 2002; Goy et al., 2003; Martin et al., 2003; Razjigaeva et al., 2004; Shennan et al., 2005). Previous work in Armação de Pêra Bay points to a bay model for about 5 000 yr BP, very similar to the present one (Teixeira and Pinto, 2002), and to a sea level stabilization close to the current level at 3 300 yr BP (Pereira and Soares, 1994). The occurrence of the heavy mineral horizon between 4 017 yr cal BP and 3 213 yr cal BP (Fig. 5 and Table 1) suggests that, during this time interval, fluvial sediments were not transferred to the lower foreshore probably due to sea level stabilization, supporting the findings of previous investigations.

However, the timings of the aeolianites' cementation and the new impulse of dune generation are more speculative. Cementation of sands with high $CaCO_3$ content can be very rapid under humid climatic conditions (Harvey, 1979; Kindler and Mazzolini, 2001) and, in the Armação de Pêra Bay, diagenetic processes probably occurred during the humid Atlantic climatic event after the dune stabilization (about 6 300 yr cal BP). This hypothesis agrees with the wetter conditions that occurred between the two dry events at about 7 000 and 5 670 yr BP as revealed by the vegetation in the Portuguese Estremadura (Figueiral and Terral, 2002).

The occurrence of beachrock in the upper foreshore at the Armação de Pêra Bay (5 853 to 4 017 yr cal BP: Fig. 5 and Table 1) supports our view that the RMSL was higher than the present of about 1 m (admitting the same tidal range) during the Late Holocene. Beachrock is a sedimentary body formed in the intertidal zone due to the rapid cementation of sandy beach (Russell, 1962; Dalongeville and Sanlaville, 1984; Neumeier, 1999). Several factors contribute to the cementation of the sand in the intertidal zone, such as the sediment immobilization to allow its cementation, water over-saturation in calcium carbonate and good permeability favouring the water percolation (Blatt, 1979; Hays, 1979; Davaud and Strasser, 1984). Other factors contributing for the beachrock generation have been reported in world wide coasts among which are: (a) temperature (Russell and McIntire, 1965), (b) microbial activity (Neumeier, 1999), (c) water degasification (Calvet et al., 2003; Rey et al., 2004). Genesis of the beachrock in the study area was favoured by the mixing of marine and fresh water as well as by the high permeability of the sediment. Beachrock occurrence has been reported mainly in lower latitudes (e.g., Moore, 1973; Strasser et al., 1989; Semeniuk, 1996; Gischler and Lomando, 1997; Webb et al., 1999; Vieira and De Ros, in press) but they can also form in higher latitudes (e.g., Kneale and Viles, 2000; Rey et al., 2004). Even for similar latitudes beachrock can or not form, depending on the environmental parameters as reported in Canaria Islands where beachrock only formed in the west coast which is dominated by a dry warm climate (Calvet et al., 2003). Whatever the region and the factors contributing to the beachrocks' genesis and since they form in the intertidal zone, they can potentially be used for the past sea level curves reconstructions (Omoto, 2001). However, the beachrock accuracy as a sea level proxy depends on the tidal regime and correlates inversely with the tidal range which makes it difficult to use as a proxy.

The beachrock lower shoreface facies (Fig. 5) underwent accumulation and cementation up to 4 017 yr cal BP, corresponding probably to the maximum sea level in Armação de Pêra Bay. After 4 017 yr cal BP, heavy mineral horizons are no longer represented in the upper shoreface facies (Fig. 5 and Table 1), implying that these minerals were transferred to the tidal zone. Thus, RMSL must have become lower, and fluvial sediment (previously trapped in the alluvial zone) started to feed a progressively widening beach. The sedimentary load placed into the littoral zone from the Alcantarilha and Espiche rivers has been calculated to have been much higher during the last 2 000 yr than before that time (Pinto and Teixeira, 2002b). The bay thus again became a positive budget cell at about 3 200 yr cal BP, thereby providing favourable conditions for a new phase of dune accumulation.

A new phase of dune activity at about 3 000 yr BP has also been described for the area of the Portuguese West Coast (Noivo and Bernardes, 2000). In addition, in the Apulian region of Italy, dunes were formed not only during the mid-Holocene Optimum under a relative sea level higher than the present, but also during the sea level low stand at about 2 500 yr BP (Mastronuzzi and Sansó, 2002). Therefore, a relative sea level lowering following the mid-Holocene sea level maximum, most likely a result of the Holocene Neoglaciation at 3 000 – 2 000 yr BP (Calkin, 1988), has been registered in several regions. However, the seaward shift of sea level could also have been forced by greater quantities of sediment reaching the littoral zone. In this respect, several investigations in estuaries of the Cadiz Gulf indicate an important phase of fluvial activity after about 4 000 yr BP (Dabrio et al., 2000; Boski et al., 2002; González-Vila et al., 2003). As Stanley (1995) asked, will a global sea level curve for the late Quaternary be an impossible dream?

The continental masses puzzling since the end of the Mesozoic Era favoured the progressive "regionalization" of the geological environments. Therefore, correlations between processes and their geological register at faraway or even neighbour regions are sometimes difficult even if the cause is global. In addition, as stated by some researchers (e.g., Pirazzoli, 1991; Stanley, 1995; Woodrofle and Horton, 2005), the dozens of proxies used to reconstruct the sea level curves and how they are interpreted are responsible for some of the their discrepancies. More recently and in opposition to the view of Fleming et al. (1998) that no significant high frequency oscillations occurred in the past 7 000 years, several high frequency oscillations were identified in world wide coasts (e.g., Morner, 1999; Goy et al., 2003; Martin et al., 2003; Razjigaeva et al., 2004; Shennan et al., 2005). However, while a mid-Holocene maximum highstand lying between 6 400 and 5 600 yr BP receives the concordance of most of previous cited authors, the following oscillations show a great disparity in their ages. This is probably due to a high diversity of geomorphological conditions, and it is necessary to understand the local responses in order to have a global vision. Far field sites as southern coast of Portugal away from direct influence of ice capes can greatly contribute to the understanding of the eustatic signal of the sea level.

The results reported here show that significant environmental transformations took place in Armação de Pêra Bay during the Holocene. The formation of dunes and their subsequent phases of stabilization or erosion are related to the bay acting as a positive or negative budget cell, respectively. The sign of the budget cell is dependent on: (a) the supply of fluvial sediment, as influenced by climatic conditions; (b) the transference of fluvial sediment from the alluvial zone to the shoreface, as controlled by RMSL; and (c) the width of the beach, reflecting both the sedimentary budget and RMSL. The aeolianites are, therefore, a good proxy for the occurrence of sea level fluctuations. Moreover, if the fetch is quantified according to wind direction and speed as well as to grain size, aeolianites can also provide the magnitude of those oscillations.

6. Conclusion

Armação de Pêra Bay (southern Portugal) has proved to be a remarkable locality in which to study Holocene environmental evolution, given that it is a littoral cell containing sedimentary source, sink, and transport path. This relatively closed and complete sedimentary cycle is recorded in the geographical, structural, and sedimentological relationships between the aeolianites and the younger free dunes. During the Holocene, the bay has acted alternately as a positive cell dominated by constructive processes, and as a negative cell dominated by erosive processes. Its behaviour depends on sea level fluctuations and on variations in sedimentary input from the Alcantarilha and Espiche rivers. The littoral zone has been strongly dependent on local fluvial sediments throughout the Holocene because the western headland of the bay presents an obstacle to the prevailing wave direction and therefore to longshore drift of sediment into the bay.

The aeolianites in Armação de Pêra Bay are transgressive dunes formed during a rapid rise in sea level between about 8 800 and 6 600 yr cal BP. The formation of these dunes was favoured by the cool, dry conditions of the mid-Holocene. These dunes stabilized at about 5 000 yr cal BP when relative mean sea level and beach morphology were similar to the present. A new phase of dune generation occurred after ca. 3 200 yr cal BP, due to a seaward movement of sea level during which beach width was greater than the critical fetch. Currently, the beach width is less than the critical fetch and the free dunes are inactive. In addition, the sedimentary budget is negative because fluvial sediment is trapped in the rivers' alluvial zones and during spring tides beach sand is transported back into the alluvial zones.

Although climatic conditions control several parameters such as sediment supply and wind energy, the relative mean sea level is the first order factor for coastal dune generation as it controls the extension of the deflection area.

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References

Abrantes, F., Lebreiro, S., Rodrigues, T., Gil, I., Bartels-Jónsdóttir, H., Oliveira, P., Kissel, C., Grimalt, J.O., in press. Shallow-marine sediment cores record climate variability and earthquake activity off Lisbon (Portugal) for the last 2000 years. Quaternary Sci. Rev., doi:10.1016/j.quasirev.2004.04.009.

Andrade, C., Freitas, M.C., Moreno, J., Craveiro, S.C., 2004. Stratigraphical evidence of Late Holocene barrier breaching and extreme storms in lagoonal sediments of Ria Formosa, Algarve, Portugal. Mar. Geol. 210, 339–362.

Arbogast, A.F., Hansen, E.C., Van Oort, M.D., 2002. Reconstructing the geomorphic evolution of large coastal dunes along the southeastern shore of Lake Michigan. Geomorphology 46, 241–255.

Arens, S.M., 1996. Sediment dynamics of a coastal foredune at Schiermonnikoog, The Netherlands. In: Jones, P.S., Healy, M.G., Williams, A.T. (Eds.), Studies in European Coastal Management. Samatra, Cardigan, pp. 137–146.

Bateman, M.D., Holmes, P.J., Carr, A.S., Horton, B.P., Jaiswald, M.K., 2004. Aeolianite and barrier dune construction spanning the last two glacial–interglacial cycles from the southern Cape coast, South Africa. Quat. Sci. Rev. 23, 1681–1698.

Bauer, B.O., Davidson-Arnott, R.G.D., 2002. A general framework for modelling sediment supply to coastal dunes including wind angle, beach geometry, and fetch effects. Geomorphology 49, 89–108.

Bezerra, F.H.R., Barreto, A.M.F., Suguio, K., 2003. Holocene sea-level history on the Rio Grande do Norte State coast, Brazil. Mar. Geol. 196, 73–89.

Blatt, H., 1979. Diagenetic processes in sandstones. Soc. Econ. Paleontol. Mineral., Spec. Publ. 26, 141–157.

Blott, S.J., Pye, K., 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surf. Process. Landf. 26, 1237–1248.

Boski, T., Moura, D., Veiga-Pires, C., Camacho, S., Duarte, D., Scott, D.B., Fernandes, S.G., 2002. Postglacial sea-level rise and sedimentary response in the Guadiana Estuary, Portugal/Spain border. Sediment. Geol. 150, 103–122.

Brooke, B., 2001. The distribution of carbonate eolianite. Earth-Sci. Rev. 55, 135–164.

Cacho, I., Grimalt, J.O., Canals, M., 2002. Response of the Western Mediterranean Sea to rapid climatic variability during the last 50 000 years: a molecular biomarker approach. J. Mar. Syst. 33–34, 253–272.

Caldas, L.H.O., Stattegger, K., Vital, H., 2006. Holocene sea-level history: evidence from coastal sediments of the northern Rio Grande do Norte coast, NE Brazil. Mar. Geol. 228, 39–53.

Calkin, P., 1988. Holocene glaciation of Alaska (and adjoining Yukon Territory, Canada). Quat. Sci. Rev. 7, 159–184.

Calvet, F., Cabrera, M.C., Carracedo, J.C., Mangas, J., Pérez-Torrado, F.J., Recio, C., Travé, A., 2003. Beachrock from the island of La Palma (Canary Islands, Spain). Mar. Geol. 197, 75–93.

Carter, R.W.G., Woodroffe, C.D., 1994. Coastal evolution: an introduction. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution. Cambridge University Press, UK, pp. 1–31.

Catto, N., MacQuarnie, K., Hermann, M., 2002. Geomorphic response to Late Holocene climate variation and anthropogenic pressure, Northeastern Prince Edward Island, Canada. Quat. Int. 87, 101–117.

Clarke, M.L., Rendell, H.M., 2006. Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal. Holocene 16 (3), 341–355.

Clemmensen, L.B., Murray, A., 2006. The termination of the last major phase of Aeolian sand movement, coastal dunefields, Denmark. Earth Surf. Process. Landf. 31, 795–808.

Costa, M., 1994. Agitação marítima na costa portuguesa. Anais do Instituto Hidrográfico (Lisboa) 13, 35–40.

Dabrio, C.J., Zazo, C., Goy, J.L., Sierro, F.J., Borja, F., Lario, J., González, J.A., Flores, J.A., 2000. Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cadiz, Southern Spain). Mar. Geol. 162, 381–404.

Dalongeville, R., Sanlaville, P., 1984. Essai de synthèse sur le beach-rock. In: Dalongeville, R., Sanlaville, P. (Eds.), Le beach-rock. Travaux de la Maison de l' Orient, vol. 8, pp. 161–167.

Davaud, E., Strasser, A., 1984. Cimentation et structures sédimentaires des beachrocks: genèse et critères d' identification. In: Dalongeville, R., Sanlaville, P. (Eds.), Le beach-rock, Lyon. Travaux de la Maison de l'Orient, vol. 8, pp. 41–50.

De Lima, J.L.M.P., Van Dijk, P.M., Spaan, W.P., 1992. Spash-saltation transport under wind-driven rain. Soil Technol. 5, 151–166.

Dias, J.M.A., Taborda, R., 1992. Tidal gauge data in deducing secular trends of relative sea level and crustal movements in Portugal. J. Coast. Res. 8 (3), 655–659.

Fairbridge, R.W., Johnson, D.L., 1978. Eolianite. In: Fairbridge, R.W., Bourgeois, J. (Eds.), The Encyclopedia of Sedimentology. Dowden, Hutchinson & Ross, Stroudsburg, pp. 279–282.

Figueiral, I., Terral, J., 2002. Late Quaternary refugia of Mediterranean taxa in the Portuguese Estremadura: charcoal based palaeovegetation and climatic reconstruction. Quat. Sci. Rev. 21, 549–558.

Fleming, K., Yokoyama, Y., Lambeck, K., Chappell, J., Johnston, P., Zwartz, D., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. Earth Planet. Sci. Lett. 163, 327–342.

Forman, S.L., Oglesby, R., Webb, R.S., 2001. Temporal and spatial patterns of Holocene dune activity on the Great Plains of North

America: megadroughts and climate links. Glob. Planet. Change 29, 1–29.
Gay Jr., S.P., 2005. Blowing sand and surface winds in the Pisco to Chala Area, Southern Peru. J. Arid Environ. 61, 101–117.
Geraga, M., Tsaila-Monopolis, St., Ioakim, C., Papatheodorou, G., Ferentinos, G., 2000. Evaluation of palaeoenvironmental changes during the last 18,000 years in the Myrtoon basin, SW Aegean Sea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 156, 1–17.
Gerdes, G., Watermann, F., 2003. Major and minor effects of Holocene sea-level rise recorded from microfossils and Ca:Sr ratios in coastal sequences of NW Germany. Holocene 13, 423–432.
Gillette, D.A., Herbert, G., Stockton, P.H., Owen, P.R., 1996. Causes of the fetch effect in wind erosion. Earth Surf. Process. Landf. 21, 641–659.
Gischler, E., Lomando, A.J., 1997. Holocene cemented beach deposits in Belize. Sediment. Geol. 110, 277–297.
González-Vila, F.J., Polvillo, O., Boski, T., Moura, D., Andrés, J.R., 2003. Biomarker patterns in a time-resolved Holocene/terminal Pleistocene sedimentary sequence from the Guadiana river estuarine area (SW Portrugal/Spain border). Org. Geochem. 34, 1601–1613.
Goy, J.L., Zazo, C., Dabrio, C.J., 2003. A beach-ridge progradation complex reflecting periodical sea-level and climate variability during the Holocene (Gulf of Almería, Western Mediterranean). Geomorphology 50, 251–268.
Halligan, G.H., 1906. Sand movement on the New South Wales coast. Proc. Linn. Soc. N. S. W. vol. 31, 619–640.
Harvey, B., 1979. Diagenetic processes in sandstones. Soc. Econ. Paleontol. Mineral., Spec. Publ. 26, 141–157.
Hays, J.B., 1979. Sandstone diagenesis—the whole truth. Soc. Econ. Paleontol. Mineral., Spec. Publ. 26, 127–139.
Hesp, P., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48, 245–264.
Hesp, P.A., Short, A.D., 1999. Barrier morphodynamics. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. Wiley, London, pp. 307–333.
Heteren van, S., Huntley, D.J., Plassche van de, O., Lubberts, R.K., 2000. Optical dating of dune sand for the study of sea-level change. Geology 28 (5), 411–414.
Hill, G.H., Hunter, R.E., 1987. Interaction of biological and geological processes in the beach and nearshore environments, northern Padre Island, Texas. Soc. Econ. Paleontol. Mineral. 167–187.
Instituto Hidrográfico, 1990. Roteiro da Costa de Portugal. Instituto Hidrográfico, Lisboa. 41 pp.
Ivester, A.H., Leigh, D.S., 2003. Riverine dunes on the Coastal Plain of Georgia, USA. Geomorphology 51, 289–311.
Kindler, P., Mazzolini, D., 2001. Sedimentology and petrography of dredged carbonate sands from Stocking Island (Bahamas). Implications for meteoric diagenesis and aeolianite formation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 175, 369–379.
Kindler, P., Strasser, A., 2002. Palaeoclimatic significance of co-occurring wind- and water-induced sedimentary structures in last-interglacial coastal deposits from Bermuda and the Bahamas: response to Hearty et al.'s comment. Sediment. Geol. 147, 437–443.
Kneale, D., Viles, H.A., 2000. Beach cement: incipient $CaCO_3$-cemented beachrock development in the upper intertidal zone, North Uist, Scotland. Sediment. Geol. 132, 165–170.
Lawson, M.P., Thomas, D.S.G., 2002. Late Quaternary lunette dune sedimentation in the southwestern Kalahari desert, South Africa: luminescence based chronologies of Aeolian activity. Quat. Sci. Rev. 21, 825–836.
Leira, M., Santos, L., 2002. An early Holocene short climatic event in the northwest Iberian Peninsula inferred from pollen and diatoms. Quat. Int. 93–94, 3–12.
MacDermott, F., Frisia, S., Huang, Y., Longinelli, A., Spiro, B., Heaton, T.H.E., Hawkesworth, C.J., Borsato, A., Keppens, E., Fairchild, I.J., Borg Van Der, K., Verheyden, S., Selmo, E., 1999. Holocene climate variability in Europe: evidence from $\delta^{18}O$, textural and extension-rate variations in three speleothems. Quat. Sci. Rev. 18, 1021–1038.
Martin, L., Dominguez, J.M.L., Bittencourt, A.C.S.P., 2003. Fluctuating Holocene sea levels in eastern and southeastern Brasil: evidence from multiple fossil and geometric indicators. J. Coast. Res. 19 (1), 101–124.
Mastronuzzi, G., Sansó, P., 2002. Holocene coastal dune development and environmental changes in Apúlia (southern Italy). Sediment. Geol. 150, 139–152.
Miranda, P., Coelho, F.E.S., Tomé, A.R., Valente, M.A., 2002. 20th century Portuguese climate and climate scenarios. In: Santos, F.D., Forbes, K., Moita, R. (Eds.), Climate Change in Portugal Scenarios, Impacts and Adaptation Measures, SIAM Project. Gradiva Publ., Lisboa, pp. 27–101.
Moore, C.H., 1973. Intertidal carbonate cementation, Grand Cayman, West Indies. J. Sediment. Petrol. 43, 591–602.
Morner, N.-A., 1999. Sea level and climate: rapid regressions al local warm phases. Quat. Int. 60, 75–82.
Moura, D., Boski, T., Veiga-Pires, C., Duarte, N., Santana, P., 2001. Variações das características químicas dos sedimentos estuarinos-tentativa de interpretação paleoambiental. V Reunião do Quaternário Ibérico, Lisboa, pp. 252–255.
Neumeier, U., 1999. Experimental modelling of beachrock segmentation under microbial influence. Sediment. Geol. 126, 35–46.
Noivo, L.M.S., Bernardes, C.A., 2000. Evolução do sistema de dunas costeiras na zona da Leirosa, Portugal. 3° Simpósio sobre a Margem Ibérica Atlântica, Faro, pp. 131–132.
Omoto, K., 2001. Radiocarbon ages of beach rocks and Late Holocene sea-level changes in the southern part of the Nansei Islands, Southwest of Japan. Radiocarbon 43 (2), 887–898.
Otvos, E.G., 2001. Late Quaternary inland dunes of Southern Louisiana and arid climate phases in the Gulf coast region. Quat. Res. 55, 150–158.
Pereira, A.R., Angelucci, D.E., 2004. Formações dunares no litoral português, do final do Plistocénico e inícios do Holocénico, como indicadores paleoclimáticos e paleogeográficos. In: Tavares, A.A., Tavares, M.J.F., Cardoso, J.L. (Eds.), Evolução Geohistórica do Litoral Português e Fenómenos Correlativos. Universidade Aberta, Lisboa, pp. 221–256.
Pereira, A.R., Soares, A.M., 1994. A estabilização do nível do mar no litoral de Armação de Pêra. Gaia 9, Lisboa, pp. 91–93.
Pilcher, J.R., 1991. Radiocarbon dating. In: Smart, P.L., Frances, P.D. (Eds.), Quaternary Dating Methods—A User's Guide. Quaternary Research Association, London, pp. 16–36.
Pinto, C.A., Teixeira, S., 2002a. Morphodynamics of the sandy barrier of Salgados coastal lagoon. Armação de Pêra Bay (Algarve-Portugal). Littoral 2002, Porto, pp. 22–26.
Pinto, C.A., Teixeira, S., 2002b. Avaliação preliminar do balanço sedimentar tardi-holocénica do litoral da Baía de Armação de Pêra (Algarve-Portugal). PANGEA'02, Évora, pp. 87–94.
Pirazzoli, P.A., 1991. World Atlas of Holocene Sea-Level Changes. Elsevier Publishers B.V, Amsterdam. 300 pp.
Pires, H.N.O., 1989. O clima de Portugal. Alguns aspectos do clima de agitação marítima de interesse para a navegação na costa de

Portugal. Instituto Nacional de Meteorologia e Geofísica (INMG), Lisboa. 34 pp.
Pires, H.N.O., Pessanha, L.E.V., 1979. Agitação marítima na costa portuguesa. Instituto Nacional de Meteorologia e Geofísica (INMG), Lisboa, pp. 1–13.
Pires, H.N.O., Pessanha, L.E.V., 1986. Wave power climate of Portugal. In: Evans, D., Falcão, A.F.O. (Eds.), Hydrodynamics of Ocean Wave-Energy Utilization, IUTAM Symposium, Lisboa, pp. 157–167.
Price, D.M., Brooke, B.P., Woodroffe, C.D., 2001. Thermoluminescence dating of aeolianites from Lord Howe Island and South-West Western Australian. Quat. Sci. Rev. 20, 841–846.
Razjigaeva, N.G., Grebennikova, T.A., Ganzey, L.A., Mokhova, L.M., Bazarova, V.B., 2004. The role of global and local factors in determining the middle to late Holocene environmental history of the South Kurile and Komandar islands, northwestern Pacific. Palaeogeogr. Palaeoclimatol. Palaeoecol. 209, 313–333.
Rey, D., Rubio, B., Bernabeu, A.M., Vilas, F., 2004. Formation, exposure, and evolution of a high-latitude beachrock in the intertidal zone of the Corrubedo complex (Ria de Arousa, Galicia, NW Spain). Sediment. Geol. 169, 93–105.
Ritchie, W., Penland, S., 1990. Aeolian sand bodies of the South Louisiana Coast. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.), Coastal Dunes Form and Process. Wiley, London, pp. 105–127.
Rodriguez-Ramirez, A., Rodríguez-Vidal, J., Cáceres, L., Clemente, L., Belluomini, G., Manfra, L., Improta, S., Andrés, J.R., 1996. Recent coastal evolution of the Doñana National Park (SW Spain). Quat. Sci. Rev. 15, 803–809.
Russell, R.J., 1962. Origin of beachrock. Z. Geomorphol. 6, 227–236.
Russell, R.J., McIntire, W.G., 1965. Southern hemisphere beach rock. Geogr. Rev. 55, 17–45.
Ruz, M.-H., Meur-Ferec, C., 2004. Influence of high water levels on Aeolian sand transport: upper beach/dune evolution on a macrotidal coast, Wissant bay, northern France. Geomorphology 60, 73–87.
Saye, S.E., Wal van der, D., Pye, K., Blott, S.J., 2005. Beach-dune morphological relationships and erosion/accretion: an investigation at five sites in England and Wales using LIDAR data. Geomorphology 72 (1–4), 128–155.
Semeniuk, V., 1996. Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 123, 49–84.
Shennan, I., Hamilton, S., Hillier, C., Woodroffe, S., 2005. A 16000-year record from near-field relative sea-level changes, northwest Scotland, United Kingdom. Quat. Int. 133–134, 95–106.
Short, A.D., Hesp, P.A., 1999a. Beach ecology. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. John Wiley & Sons, LTD,, West Sussex, England, pp. 271–278.
Short, A.D., Hesp, P.A., 1999b. Beach and dune stratification. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. John Wiley & Sons, LTD, West Sussex, England, pp. 279–291.
Stanley, D.J., 1995. A global sea-level curve for the late Quaternary: the impossible dream? Mar. Geol. 125, 1–6.
Strasser, A., Davaud, E., Jedoui, Y., 1989. Carbonate cements in Holocene beachrock: example from Bahiret el Biban, southeastern Tunisia. Sediment. Geol. 62, 89–100.
Svasek, J.N., Terwindt, J.H.J., 1974. Measurement of sand transport by wind on a natural beach. Sedimentology 21, 311–322.
Teixeira, S.B., Pinto, C., 2002. Radiocarbon ages of submerged and emerged beachrock in the Armação de Pêra Bay (Algarve-Portugal). XI° Seminário Ibérico de Química Marinha, Faro, Portugal, pp. 72–73.
Terasmae, J., 1984. Radiocarbon dating: some problems and potential developments. In: Mahaney, W.C. (Ed.), Quaternary Dating Methods, Developments in Palaeontology and Stratigraphy. Elsevier Science Publishers B.V, The Netherlands, pp. 1–15.
Thomas, D.S.G., Shaw, P.A., 1991. Relict desert systems: interpretations and problems. J. Arid Environ. 20, 1–14.
Thomas, D.S.G., Shaw, P.A., 2002. Late Quaternary environmental change in central southern Africa: new data, synthesis, issues and prospects. Quat. Sci. Rev. 21, 783–794.
Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. Physica, A 357, 50–56.
Vega Leinert, A.C, de la, K., D.H., Jones, R.L., Wells, J., Smith, D.E., 2000. Mid-Holocene environmental changes in the Bay of Kaill, Mainland Orkney, Scotland: an integrated geomorphological, sedimentological and stratigraphical study. J. Quat. Sci. 15, 509–528.
Vieira, M.M., De Ros, L.F., in press. Cementation patterns and genetic implications of Holocene beachrocks from northeastern Brazil. Sediment. Geol.
Wallinga, J., Duller, G.A.T., 2000. The effect of optical absorption on the infrared stimulated luminescence age obtained on coarse-grain feldspar. Quat. Sci. Rev. 19, 1035–1042.
Webb, G.E., Jell, J.S., Baker, J.C., 1999. Cryptic intertidal microbialites in beachrock, Heron Island, Great Barrier Reef: implications for the origin of microcrystalline beachrock cement. Sediment. Geol. 126, 317–334.
White, B., Curran, H.A., 1988. Mesoscale physical sedimentary structures and trace fossils in Holocene carbonate eolianites from San Salvador Island, Bahamas. Sediment. Geol. 55 (1–2), 163–184.
Wilson, P., McGourty, J., Bateman, M.D., 2004. Mid-to late-Holocene coastal dune event stratigraphy for the north coast of Northern Ireland. Holocene 14 (3), 406–416.
Woodrofle, S.A., Horton, B.P., 2005. Holocene sea-level changes in the Indo-pacific. J. Asian Earth Sci. 25 (1), 29–43.