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Temporal evolution of the sand-spit between Torreira and Furadouro (NW Portugal)

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ABSTRACT

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Dune systems comprise about 60% of the Portuguese coast but they are best developed in northern areas, where they form an extensive sand plain. The dunes display several stratigraphic evidences for a long period of sand accumulation during the Holocene, related with sea level rise. Morphological aspects have shown that coastal systems progradated to the shelf but it is not clear if they migrated great distances prior to doing so.
Between Torreira and Furadouro beach, three main genetic units have been recognised which are separated by major surfaces. The first unit, unit A, defines the top of a depositional cycle that marks a period of estuarine lagoonal condition stabilities and the inversion of the depositional trend. Radiocarbon data suggests that the lagoon was formed before 1997 years BP (calibrated ages). The sedimentation of unit B favoured the development of sand ridge systems. Unit C marks a new period that leads to the reworking of coastal sediments by wave and wind action in a landward direction. The evolution of this sector may be attributed to sea level fluctuations induced by local factors such as periods of intense supply of sediments to the shelf.

ADDITIONAL INDEX WORDS: *Coastal dunes, Stratigraphy, Late Holocene*

INTRODUCTION

In the north-western coast of Portugal, coastal dunes contain indicators that show evolution related with sea level rise and probably local tectonic uplift during the Holocene. Geomorphological and lithostratigraphical studies concerning the characterisation of the Pleistocene-Holocene (GRANJA and CARVALHO, 1993, 1995) and Holocene deposits are available for this area (GRANJA and CARVALHO, 1992; GRANJA and DE GROOT, 1996; GRANJA *et al*., 1996). The chronology of dune formation is supported by radiocarbon data (tree trunks, peat, fragments of coal and shells). The stratigraphic framework is based on local lithostratigraphic units. However, the regional correlation of the mechanisms of dune emplacement is not clear, in particular with the southern areas, due to the diachronic character of the depositional systems.

Coastal dunes occur at several locations along the west Portuguese coast, most notably between Nazaré and Porto and south of Lisbon. Smaller dunes are localised on other sections of the coast but they are poorly developed (figure 1). The expression of the dunes may be related to several factors: characteristics of the continental shelf, coastal morphology and sediment supply.

The continental shelf shows contrasting features north and south of Nazaré. In the north, the shelf has a maximum width of 40 Km, 15 Km minimum and presents a gentle steep. South of the Nazaré, the shelf widens to a maximum of 30 Km and decreases at times to a minimum of 10 Km, showing a steep gradient (PEREIRA, 1987).

The coastal morphology also presents some differences. North of Porto, the coast is characterised by the presence of Pleistocene cliffs associated with abrasion platforms presenting estuaries and spits (GRANJA, 1989). South of that point, the coast exhibits a flat morphology dominated by dune complexes and lagoons.

The sediment supply is derived from the most important river in the north, Douro River, and the entire area appears to have been a long-term sink for sediment which drifted southwards along the continental shelf.

Differences in morphological and sedimentary characteristics associated with weathering profile development indicate that several episodes of dune building are represented at most sites. Truncated trailing arms suggest that some of them were originated at any distance seaward of the present shoreline, possibly at a time of lower sea level (PEREIRA, 1987).

In several places, coastal erosion has exposed sequences of weathered coloured sands, representing podzolized dunes extending back into the Holocene (GRANJA and CARVALHO, 1995).

In the study area, localised between Torreira and Furadouro beach, the coast is characterised by an extensive NW-SE sand plain that covers tertiary deposits (Figure 1). The dunes are stabilised and form an undulating surface which included several degraded areas. Air photographs revealed the dominance of parabolic ridges associated with some transverse dunes and foredunes, similar to that described by HESP (1988). However, due to natural and anthropogenic causes the dunes present eroded forms, especially the foredunes, with topographic variability, large blowouts and partially vegetated ridges. The result of this process is clearly seen, in some places, where periods of coastal erosion

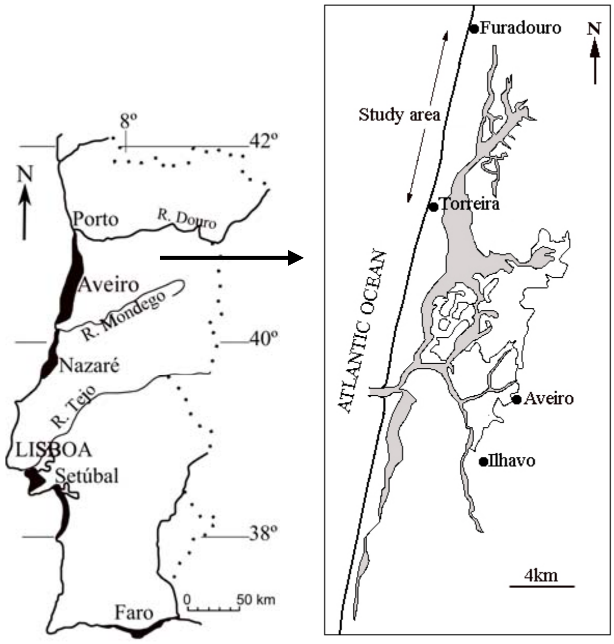

Figure 1. Location of no consolidated dunes systems, in black, in the west coast of Portugal (left) and study area (right).

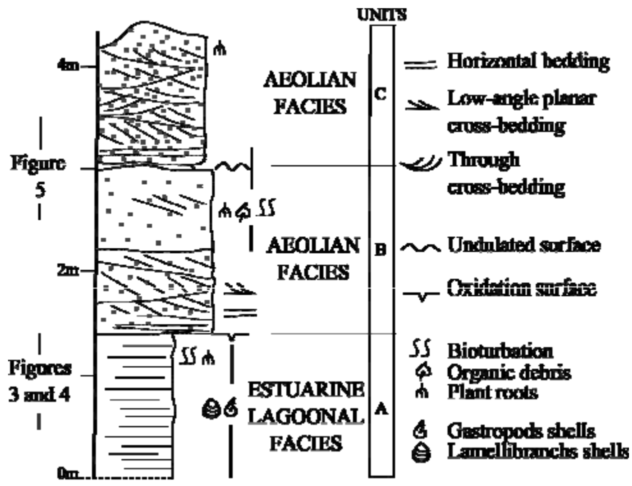

Figure 2. Schematic vertical facies sucession of the Torreira-Furadouro outcrop.

and overwashing pushed back tongues of dune sand moving landward and reworking the underlying beach deposits.

The aim of the present study is to describe a section along the actual sand-spit between Torreira and Furadouro, exposed after a storm event coincident with a spring tide. The objective is to discuss the evolution and the potential relationships of sea-level control on major periods of dune development, in the west Portuguese coast, during the late Holocene.

METHODS

The mineralogical composition, both qualitative and semi-quantitative, of muddy sediments, particularly of their silt (<63 µm) and clay (<2 µm) fractions, was determined by X-ray diffraction (XRD), carried out on non-oriented and oriented mounts. XRD measurements were performed using Philips PW1130/90 and X'Pert PW3040/60 equipments using Cu Kα radiation. Scans were run between 2° and 40° 2θ (non-oriented silty mounts) and between 2° and 20° 2θ (oriented clay mounts), the later in the air-dry state and after glycerol saturation and heat treatment (300 and 500°C).

Semi-quantitative mineralogical analyses did follow the criteria recommended by SCHULTZ (1964), THOREZ (1976), MELLINGER (1979) and PEVEAR and MUMPTON (1989). For the semi-quantification of the identified principal minerals, peak areas of the specific reflections were calculated and weighted by empirically estimated factors (GALHANO *et al*., 1999; OLIVEIRA *et al*., 2002).

Radiocarbon determinations were obtained in the Institut Royal du Patrimoine Artistique, Bruxelles (laboratory code: KIA).

RESULTS

In the Torreira - Furadouro sector, the stratigraphic framework has suggested that coastal change and dune formation has been episodic in the last few thousand years with episodes of dune activity separated by periods of relative stability (soil formation). Coring and outcrops exposed after a storm event have shown that the dunes have composite features consisting of successive aeolian accumulations. Three main genetic units can be recognised according to their decreasing age: Units A, B and C. Those are separated by two major surfaces of different hierarchy: surfaces 1 and 2 (Figure 2).

UNIT A. The total thickness of the unit is unknown. It is composed by estuarine lagoonal facies that in some places are interbedded within aeolian sands. These tabular edge levels can be observed in the actual shoreface zone, between Torreira and Furadouro, after storm episodes or due to the erosion process in the nearshore zone (Figure 3). Estuarine lagoonal deposits are composed of dark grey shelly mud and muddy sand which is laminated to structureless, bioturbated and sometimes very rich in organic matter and preserved lamellibranch and gastropod shells (Figure 4). The unit is limited by an undulated oxidation surface (Surface 1).

The mineralogical composition of the mud sediments, particularly of their silt and clay fractions, shows a predominance of detritic minerals (quartz, feldspars and phyllosilicates). In addition to the most common minerals, opal C/CT, gypsum, anhydrite, zeolites (mainly clinoptilolite-heulandite), pyrite, siderite, calcite and dolomite are also present.

This mineral association, quartz + feldspars + phyllosilicates, followed by minerals typical of reducing conditions, pyrite and siderite and/or evaporitic minerals (such as opal C/CT, gypsum, anhydrite and zeolites) point to lagoonal depositional environments.

With regards to clay minerals, illite and kaolinite are predominant, chlorite and smectite are also common (BERNARDES *et al*., 2003). Table 1 shows the mineralogical composition of the clay fractions (<2 µm).

This mineral association (illite + kaolinite + smectite, followed by chlorite) points to a weak detrital supply in a confined littoral environment. Around the Central Portugal littoral region, Holocene mud levels occur which are dark and micaceous and exhibit a very similar mineralogy (ROCHA and GOMES, 1992;

Table 1: Mineralogical composition of the clay fractions

	Chlorite	Illite	Kaolinite	Smectite
FUR	4	78	15	3
TLAM	3	75	18	4
TL1	3	80	16	1
TL2	3	70	23	4
TL3	4	75	18	3
TL3cr	4	80	14	2

ROCHA, 1993); they are considered to be estuarine and/or lagoonal deposits.

The mineral associations confirm conditions of a discontinuous supply of detritical sediments which were submitted to fluctuations of the water table. This process could have been induced by periodic marine water flooding of protected or interdune areas driven by storm or tidal events.

Radiocarbon dating of freshwater lamellibranch and gastropod shells indicate 1997 to 1992 years BP (calibrated ages). These ages are comparable to others published for similar deposits occurring north and south of the studied area. The Silvade-Paranhos Formation lagoonal deposits, located northwards, show ages of 2310±90 to 2200±80 years BP (GRANJA *et al*., 1996), and in the south, Leirosa mud levels present similar mineralogical characteristics and sedimentological context (ROCHA and BERNARDES, 1997), showing ages of 2060±90 years BP (BERNARDES *et al*., 2001). Mud levels found in Aveiro urban subsoil, at a depth of 3 to 5 m, showed ages of 1960±90 years BP (ROCHA *et al*., 1999).

UNIT B. This unit caps the underlying topography of Surface 1 in most of the sites. This feature is not present in the whole zone, due to the discontinuous character of the unit and is related to the overlying topographic bounding. It is composed of aeolian units limited by undulated surfaces (Figure 2). The unit thickness varies from a few centimetres in interdune areas to 2 m on the crest of the higher forms.

Aeolian facies consist of lenticular and sharp forms of yellowish fine-grained sands, crudely large-scale, cross-bedding to structureless. The sand is, in general, bioturbated and weathered but without indurated humate horizons. Concentrations of organic matter and muddy sand are found in some interdune depressions or capped and interfingered with dune forms.

UNIT C. The youngest unit includes all actual dunes (Figure 2). They are recognised by their slight degree of podzolization and weathering. The contact between Unit C and the underlying unit is a sharp boundary with bioturbation, roots or organic rich horizons. This limit (Surface 2) appears to be undulated, preserving the dune morphologies and could be identified in the extension of the study trench (Figure 5).

Below the actual organic horizon of the surface, the aeolian facies consists of grey, fine to medium-grained sands. Internal structures included horizontal and planar lamination at the base, and through cross-bedding to the top, which reflect different evolutionary phases.

DISCUSSION

Morphological evidence in the Portuguese coastal area has shown that sedimentary systems progradated to the shelf but it is not certain whether or not they migrated great distances. At the north and to the south of the study area the presence of probably older dunes in a submerged beach has been mentioned (PEREIRA, 1987). Those were possibly formed during the last marine regression (Holocene), indicating that sediment would have been transported onto what is now the shoreface. Nevertheless, there is no positive stratigraphic evidence for dune instability accompanying marine regressions. The morphological responses associated with this process are formation of beach ridges and barrier spits; in both situations, dune formation is restricted to superficial capping foredunes (PYE, 1984).

In northern Portugal, the rising sea level began in the last 18

Figure 3. Outcropping of estuarine lagoonal deposits observed in the actual shoreface.

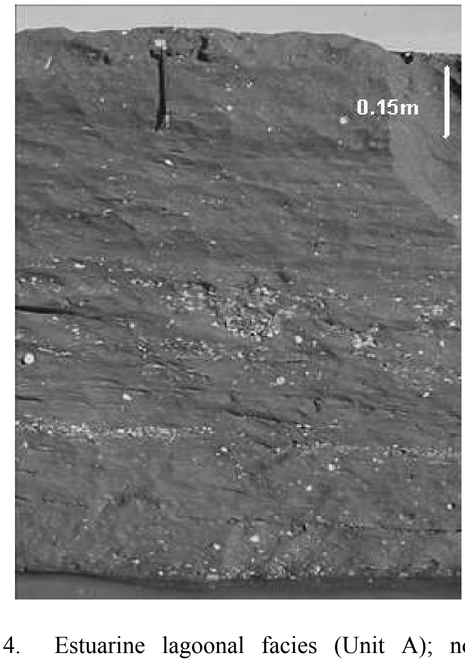

Figure 4. Estuarine lagoonal facies (Unit A); note shell concentration.

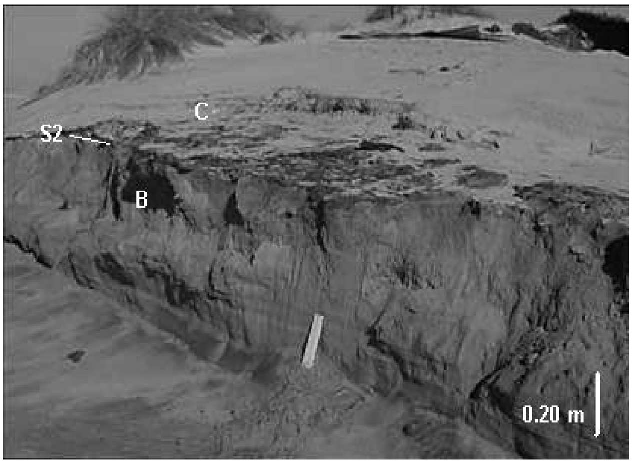

Figure 5. Contact between units B (B) and C (C); the surface 2 (S2) is undulated and shows accumulation of organic matter.

Kyears BP interrupted by periods of temporary regressions associated with important climatic changes (DIAS, 1985). DIAS *et al.* (2000) points out that the initial transgression (10 Kyears BP) was quite rapid, about 40 m in 2000 years, followed by a slow stabilisation occurring between 5 and 2.5 Kyears BP and leading to the present sea level. As a consequence of the initial rapid rise of the sea level, the shoreline transgressed the continental shelf so quickly that coastal deposits were buried slightly (DIAS *et al.*, 1997). Other authors believe that the sea level rose to its position in 10-8 Kyears BP and experienced a rise afterwards with a maximum still stand in the early Holocene (6.5 Kyears BP).

The evolution of the Torreira-Furadouro area is characterised by three units and it is possible that eustatic factors in the Late Holocene have controlled the design of their architecture, like in the other coastal areas.

The Unit A, although incomplete, may define the top of a depositional cycle. In this way, the estuarine lagoonal deposits reflect the most marine deposits, developed in conditions of stationary sea level and form part of a retrograding system. The deposits are weathered and show oxidation which suggests that the sedimentary conditions were stable for some period of time. The Surface 1 might be taken for an exposure/reactivation surface and its occurrence in similar topographic and stratigraphic positions at different locales indicates regional expression.

Radiocarbon data and the stratigraphic position of the shelly mud levels suggest that the lagoon was formed prior to 1997-1992 years BP. In this way, the marine conditions were set at some distance seaward of the present shoreline by at least 2000 years BP.

The establishment of estuarine lagoonal conditions may be compared with other situations observed. In the north of study area, south of Espinho, in the lower Silvade - Paramos Formation, lagoonal beds aged 2310±90 years to 2200±80 years BP (200 years older than Torreira-Furadouro) were described (Granja *et al.*, 1996).

The sedimentation of Unit B favoured the development of sand ridges that progradated landwards. The building activity may be associated with a minor sea rising.

The Unit C dunes require a period of shoreline stability or progradation that leads to reworked coastal sediments by wave and wind action in a landward direction. However, the nature of Surface 2, which overlies Unit B, raises some doubts. The surface may be considered as a reactivation surface. This boundary appears to have developed as a result of the end of a sand input phase, leading to a deflationary surface. On the other hand, the presence of organic matter and bioturbated horizons indicate a previous short period of relative dune stability. This is most likely due to climatic influence or to a response to shoreline changes, thus shifting the surface windflow dynamics. A minor sea level fluctuation may have led to stabilisation of the dune by vegetation, when zones comprising the local surface windflow pattern may have shifted in response to a temporary change in the position of the shoreline.

CONCLUSIONS

Data from a number of Portuguese coastal sites (estuarine and lagoonal deposits) indicate that rising sea levels reached its present level between 5 and 2.5 Kyears BP (DIAS *et al.*, 2000), and it is possible that sea level has fluctuated both above and below the present level since that time. The minor transgressions seem to be responsible for initiating phases of aeolian instability. Nevertheless, dune formation may have occurred during either transgressive and regressive marine phases or exhibit a periodicity which is completely unrelated to sea level fluctuations (PYE, 1984). Sea level changes are not the only factors capable of initiating dune instability; shoreline erosion and degradation of vegetation may also be caused by variations in the prevailing wind direction in the wave climate and in the pattern of nearshore sediment supply.

In Portugal, coastal systems such as barriers, spits and lagoons developed after 4-5 Kyears BP at a time when the rates of sea level rise were strongly attenuated (BAO *et al.*, 1999) and local factors are more influential than eustatic control. HOFFMAN (1989) observed that the increase in continental erosion during the Roman times ca 2 Kyears BP led to the progradation of Portuguese coastline.

The evolution of the Torreira-Furadouro sector may be attributed to sea level fluctuations induced by local factors such as periods of intense supply of sediments to the shelf. This scenario was repeated during the historical period (10^{th} century AD) and was responsible for the development of a sand spit south of Espinho, whose later advance closed the exiting gulf and transformed it into the present day Aveiro lagoon.

However, some authors pointed to the local neotectonism uplift as an effective control for the coastal sedimentation playing an important role, either in combination with or independently from, the sea level rise conditions (GRANJA and DE GROOT, 1996).

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