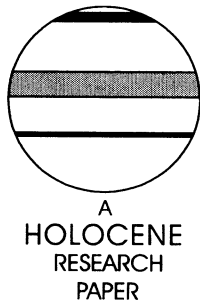


Effects of storminess, sand supply and the North Atlantic Oscillation on sand invasion and coastal dune accretion in western Portugal

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Abstract: Holocene forested coastal dunes fringe the Atlantic coast of western Portugal. Mapping of dunes in the field and using air photographs shows a range of forms reflecting dominant northwest and westerly onshore wind regimes. Planting of maritime pine forests in the thirteenth and twentieth centuries was initiated because of sand invasion causing problems for human settlement and agriculture. Early Holocene dunes have a well-developed podsol and date to 9.7 and 8.2 ka, suggesting at least some of these sands may have been emplaced during a global cooling event. Significant transgressive dune accretion at 2.2 and 1.5 ka, implies abundant sand supply and strong onshore winds. The most recent dune-building period dates to AD 1770–1905 and coincides with a predominantly negative winter North Atlantic Oscillation index (NAOi). Accretion of dunes along the Portuguese coast appears out of phase with dune development in southwest France, which may reflect different Atlantic storm tracks driven by changes in the dominance and state of the NAOi.

Key words: Sand invasion, North Atlantic storminess, North Atlantic Oscillation, luminescence dating, Holocene, Portugal, dunes, aeolian accretion, coastal processes.

Introduction

Between the Duoro and Tejo river estuaries, the littoral fringe of western Portugal is extensively blanketed by Holocene dunes and sand sheets, extending inland more than 10 km and consisting of foredunes, parabolic dunes (Granja, 1999) and E–W trending linear dunes (Figure 1). Atlantic westerlies dominate the wind regime in this coastal zone and the longitudinal forms lie at angles of ± 0 – 15° to the westerly winds that formed them (Hunter *et al.*, 1983; Figure 1). Stratigraphic evidence of episodic dune accretion, based on the degree of podsol development, suggests at least two phases of dune emplacement along the Portuguese coast (Granja, 1999). Elsewhere in northwest Europe, stratigraphical, geomorphological and chronological investigation of historical sand drift has revealed episodic sand invasion on exposed Atlantic coasts in Spain (Borja *et al.*, 1999), France (Meur *et al.*, 1992; Clarke *et al.*, 1999, 2002), Britain (Lewis, 1992;

Gilbertson *et al.*, 1999; Wilson, 2002; Sommerville *et al.*, 2003) and Ireland (Wilson and Braley, 1997; Wintle *et al.*, 1998) and on the North Sea coasts of Denmark (Christensen *et al.*, 1990; Lamb and Freyendahl, 1991; Clemmensen *et al.*, 1996, 2001a, b) and the Netherlands (Jelgersma *et al.*, 1995) (Figure 2). Along these coastlines, sand drift in historical times, causing problems for human settlement and agriculture (Lamb and Freyendahl, 1991; Lamb, 1995), has been linked to periods of increased North Atlantic storminess during the ‘Little Ice Age’ (Lewis, 1992; Wintle *et al.*, 1998; Gilbertson *et al.*, 1999; Clemmensen *et al.*, 2001b; Wilson, 2002; Clarke *et al.*, 2002; Sommerville *et al.*, 2003; Björck and Clemmensen, 2004). Periods of increased storminess have, in turn, been linked to the state of North Atlantic Oscillation (Lamb 1995; Dawson *et al.*, 2002).

Today, mean wind speed, intensity, direction and number of storms over the Atlantic are determined by the strength and state of the North Atlantic Oscillation (NAO; Hurrell and Dickson, 2004), controlled by surface pressure gradients between the subtropical Azores high-pressure system and the high-latitude Aleutian and Iceland low-pressure centres

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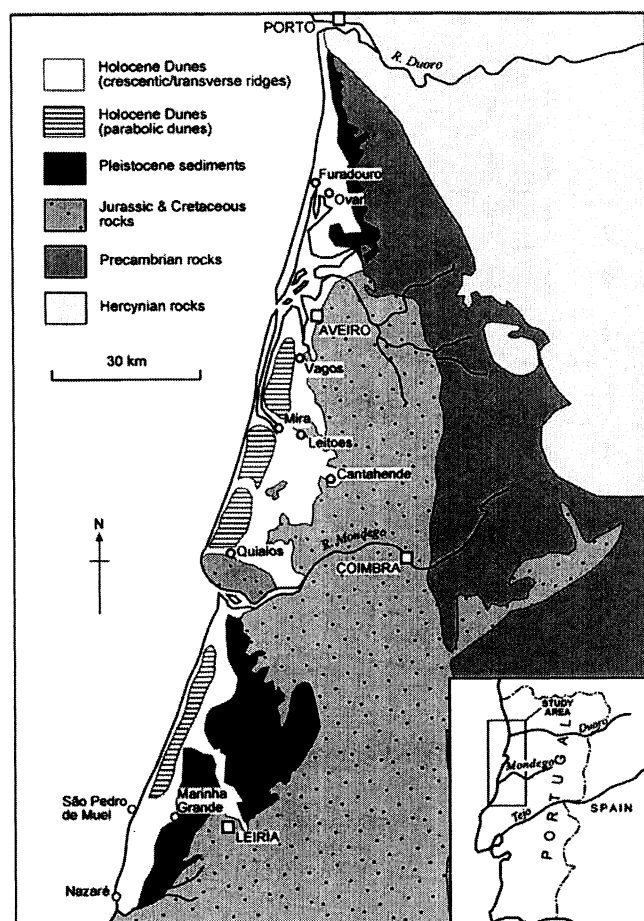


Figure 1 Location and distribution of dune types along the Portuguese coast

(Hurrell and Van Loon, 1997; Walter and Graf, 2004). During boreal winters with a positive NAO state (NAO+), higher than normal surface pressures south of 55°N combine with a broad region of low pressure throughout the Arctic and Subarctic (Figure 3a). This creates a strengthening of subpolar westerlies (Thompson *et al.*, 2000), bringing mild, wet and stormy winters to the British Isles and Scandinavia (Parker and Folland, 1988) and dry weather to the Iberian Peninsula (Dickson *et al.*, 2000) while south of the Azores high-pressure centre, enhanced easterly trade winds carry Saharan dust to the Caribbean (Moulin *et al.*, 1997) (Figure 3a). During the negative state (NAO-), both the Icelandic low and the Azores high-pressure centres are weaker than normal, with the result that both the mid-latitude westerlies and the subtropical tradewinds are also weak (Hurrell and Dickson, 2004). European wintertime temperatures are frequently lower than normal, dominated by cold air from the north and east (van Loon and Williams, 1976; Moses *et al.*, 1987), and there is an increase in the extent of sea ice in the Nordic Seas (Vinje, 2001), while a weakening of the Azores anticyclone allows the westerlies to bring rain across the Iberian Peninsula and into the Mediterranean (Rogers, 1997; Hurrell and Van Loon, 1997; Hurrell *et al.*, 2003; Qian and Saunders, 2003) (Figure 3b).

Along the Aquitaine coast of southwest France, a well-constrained chronology of Holocene dune accretion has shown that sand invasion was driven by periods of increased North Atlantic storminess (Clarke *et al.*, 2002). During positive NAO winters, northward displacement of the westerly storm tracks brings wet, windy weather to northern Europe. Aquitaine lies at the southern margin of this positive NAO influence. The

severe storms of winter 1999, which were driven by a strongly positive NAO (index values of +2.8; Hurrell, 2005), brought a number of extreme Atlantic depressions, with high winds and storm surges hitting Britain, Denmark, Germany and France (Galvin and Pike, 2001; Pearce *et al.*, 2001; Ulbrich *et al.*, 2001). The storm of 27 December 1999 affected southern France (Pearce *et al.*, 2001) with westerly gales gusting to more than 36 m/s around Bordeaux and flooding along the Atlantic coast (Ulbrich *et al.*, 2001) providing a modern analogue for historical sand drift events. Lying to the south and west of Aquitaine, Portugal is well placed to examine the synchronicity (or perhaps, non-synchronicity?) of coastal responses to NAO-related storminess. If periods of sand invasion and dune building in the coastal areas of western Portugal are related to periods of persistent storminess, from Figure 3, we would expect the timing of sand accretion to reflect dominantly negative NAO values, and to be asynchronous both with dune building episodes in the Aquitaine record and with the rest of northwest Europe.

Along the Iberian Peninsula, climatic deterioration during the 'Little Ice Age' (LIA) is believed to have driven increased sediment supply and coastal dune accretion in Portugal (Dias *et al.*, 2000a) and southern Spain (Borja *et al.*, 1999). Archival records testify to sand inundation of mediaeval cemeteries at Fão and Chafé, and mediaeval salt pans at Belinho, Sublago and Marinhas Esposende (Almeida, 1979; Abreu, 1987; Granja and Soares de Carvalho, 1992; Almeida *et al.*, 1992; Cunha *et al.*, 1993). Stabilization measures to curtail sand drift occurred as early as the thirteenth century AD (pre-'Little Ice Age') when a royal decree forced planting of maritime pine (*Pinus pinaster*) to establish the forest of Pinhal do Rei (Clarke *et al.*, 2002) and protect the town of Marinha Grande from sand invasion. Whilst it is clear that episodic sand invasion along the Portuguese coast may be climatically driven, apart from historical evidence based on eye-witness accounts there is no dating evidence for dune emplacement. Thus, without age control, it is not possible to better resolve the climate-forcing factors responsible for sand invasion. This paper presents the results of a chronological study, using luminescence techniques, to provide absolute ages for sand invasion and accretion along the Portuguese coast between Furadouro and Nazaré. The timing of dune emplacement, when compared with the timing of coastal dune development elsewhere in Europe, may provide evidence that aeolian activity is a good indicator of Holocene storminess driven by the strength and state of the North Atlantic Oscillation.

Study area and sampling locations

This research focuses on a 144 km stretch of the western coast of Portugal between Nazaré in the region of Leira and Furadouro-Ovar in the Aveiro region. This littoral zone is bisected by the Aveiro lagoon, fed by the Mira, Boco, Vougo, Antua and Caster rivers, and the Mondego river, dividing it into three sectors (Figure 4). Dune forms, currently stabilized by maritime pine forests, were mapped (Figure 5) by field survey and examination of 1:26 000-scale aerial photographs. Sampling sites for dating were selected on the basis of analysis of aerial photographs and topographic maps of the Portuguese coastline. Samples were obtained by either digging pits in the sand dunes or by cleaning back sections exposed by road cuttings. Unless otherwise stated below, the sands displayed no sedimentary structures, being dominantly massive and undifferentiated, although colour differences were notable and these

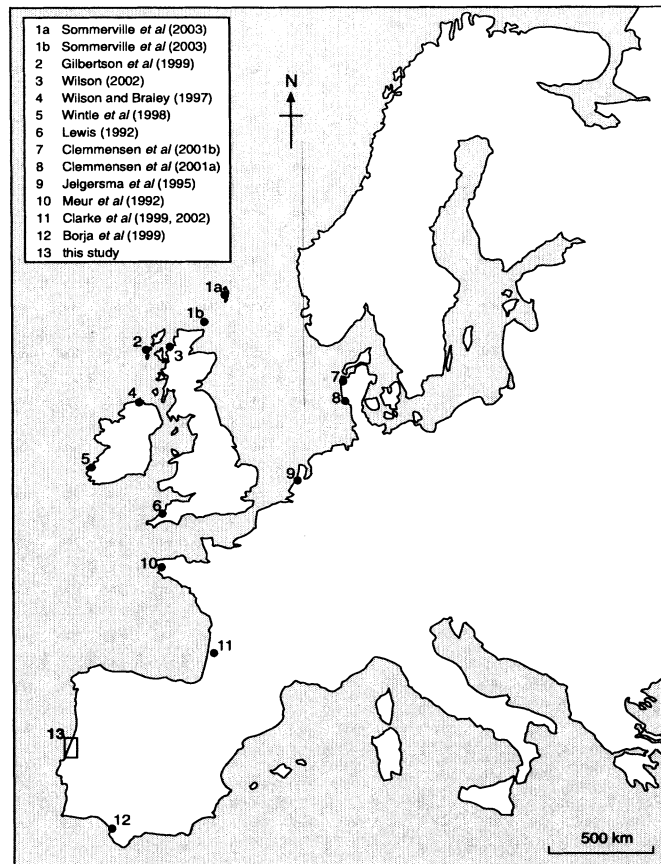


Figure 2 Map of Europe showing Portugal study site and locations of other dune study sites mentioned in the text

were described using a Munsell colour chart. After stratigraphic logging and section description, lengths of black plastic drainpipe were hammered into the cleaned sand sections and samples were transferred to opaque black plastic bags for transport to the luminescence laboratory.

Southern sector: Nazaré to Cape Mondego

In the 67 km-long southern sector between Cape Mondego and Nazaré the coastline is straight and orientated N23°E. The main source of clastic material for beach and dune building is the Mondego river at the northern end of this sector, with longshore movement of sediment predominantly north–south. Lying behind the littoral foredunes, the Dunas de Leiria are composed of transverse, crescentic ridges, which have merged with the downwind hairpin end of parabolic dunes (Figure 4). The largest crescentic dune ridge, which lies inland from São Pedro de Muel, is 104 m high. Further south, towards Nazaré, dune ridge topography is more subdued and much of the inland dune area is currently heavily forested (Figure 6a). Two locations within this dunefield were studied: an area to the north and east of São Pedro de Muel, and further inland, an area to the northeast of Nazaré.

Nazaré

Sample PT4 was taken from a road cutting through a 2–3 m high crescentic dune, 5 km inland from the current beach and 3 km southwest of Pataias (Figure 4). The dunes here are forested with pine, which is currently tapped for resin production, and eucalyptus. The cleared section consisted of a humic layer of pine needles and organic matter resting upon a light grey sand that comprised the uppermost part of a 1 m-thick, well-developed, podsol. The light sand graded downwards into

dark, yellowish-brown to brown, mottled, sand with well-developed marbling. Towards the base of the cleaned section, the sand colour lightened to very pale brown and sample PT4 was taken from this unit at a depth of 1.3 m below the surface (Figure 7a).

São Pedro de Muel

This dunefield lies on the southern edge of the Pinhal do Rei (Royal Pine Forest). The Mata Nacional de Leiria now comprises 11 029 ha of managed forest and was first established during the reign of Dom Dinis between AD 1297 and 1325. Northeast of the town of São Pedro de Muel lies the San Pedro river. To the north of this river, the dunefield consists of a series of parallel foredune ridges aligned N36°E±17° (Figure 5a) reflecting the coastline aggradation that is known to have occurred between the tenth and the end of the nineteenth centuries AD (Dias *et al.*, 2000a). Four transverse ridges lie behind the littoral foredunes, with large blowouts visible in the third and fourth ridges (Figure 5a). Analysis of aerial photographs (scale 1:25 700) reveals that behind the transverse ridges lies a parabolic dunefield (aligned N131°E±14°). The hairpin ends of many of the parabolic dunes merge into a high crescentic ridge (N35°E±10°), which occurs on either side of the San Pedro river (Figure 5a).

Samples PT1 and PT3 were taken from the same high crescentic ridge lying ~2.2 km inland, but are 1.6 km apart, separated by the San Pedro river, and from different faces of the dune. Sample PT1, derived from Ponte Novo immediately to the south of the river, consists of pale brown sand, and was sampled at a depth of 0.7 m below the surface and from 5 m below the crest of the dune ridge on the lee side. The sand at

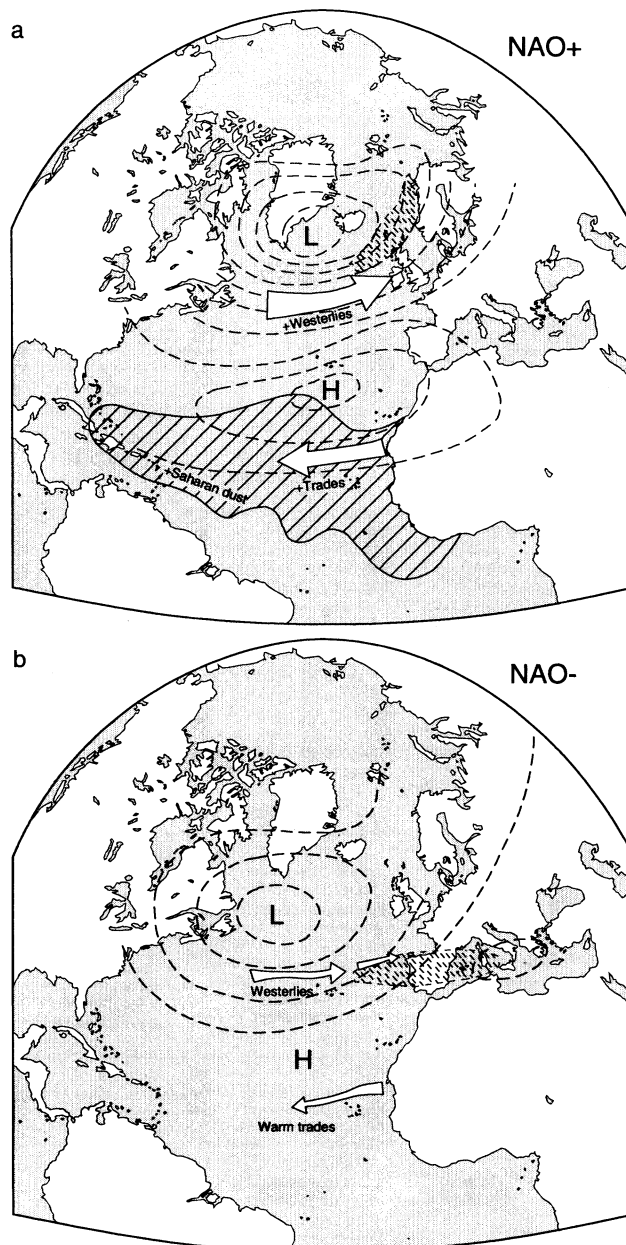


Figure 3 North Atlantic Oscillation (a) NAO+ enhanced westerlies bring rain (dashed shading) to Britain and Scandinavia, while enhanced Trades drive Saharan dust plume across the Atlantic to the Caribbean. (b) NAO- Westerlies and Trade winds reduced in strength, rain (dashed shading) over Iberian Peninsula and western Mediterranean (from Hurrell and Dickson, 2004. Reproduced with the permission of Oxford University Press)

this site exhibits some soil development with 0.4 m of dark-grey to greyish-brown soil. The area is currently heavily forested with a mixture of pine and eucalyptus with a ground cover of bracken, broom, holly and gorse and a surface mat of pine needles and sphagnum moss. Weak podsol development is apparent in the dune sand. Sample PT3 was taken from the windward side of the ridge (Figure 6b), in very pale brown sand and 8 m below the dune crest at a depth of 0.65 m below the surface. Despite in principle deriving from the same dune as PT1, soil development at this location was limited to a surface humus layer of largely leaf-litter, overlying white sand with a diffuse boundary into very pale brown sand (Figure 7a). Vegetation cover consisted of sphagnum moss, ferns, heather, broom and gorse.

Sample PT2 was taken 0.4 m below the surface of the third transverse dune ridge in the foredune series, 0.4 km from the current beach, in undifferentiated light grey sand. The surface vegetation cover comprised gorse and broom.

Central sector: Cape Mondego to Aveiro

In the 52-km-long central sector from Cape Mondego to Aveiro the coastline orientation is N14°E. The northern end of this sector includes the lagoons and barrier beaches of the Aveiro inlet. This sector is typical of the barrier lagoon coastline that has developed along the western coast of Portugal since the mid-Holocene, as sea-level rise decelerated and the clastic inputs from the main river systems increased (Bao *et al.*, 1999; Dias *et al.*, 2000a). The dunes in this region extend 5–7 km inland from the current beach and there is evidence that sand invasion has disrupted drainage patterns, with a number of freshwater lakes (eg, the Lagoa dos Bracos, Lagoa da Vela, Lagoa Salgueira and Lagoa dos Teixeiros) caused by ponded drainage. Dune forms are predominantly elongated hairpin and complex parabolic forms, 7–10 m high, up to 1 km in length, orientated between N91°E and N95°E and spaced about 200 m apart. Some, but not all of the ridges join in a u- or v-shaped

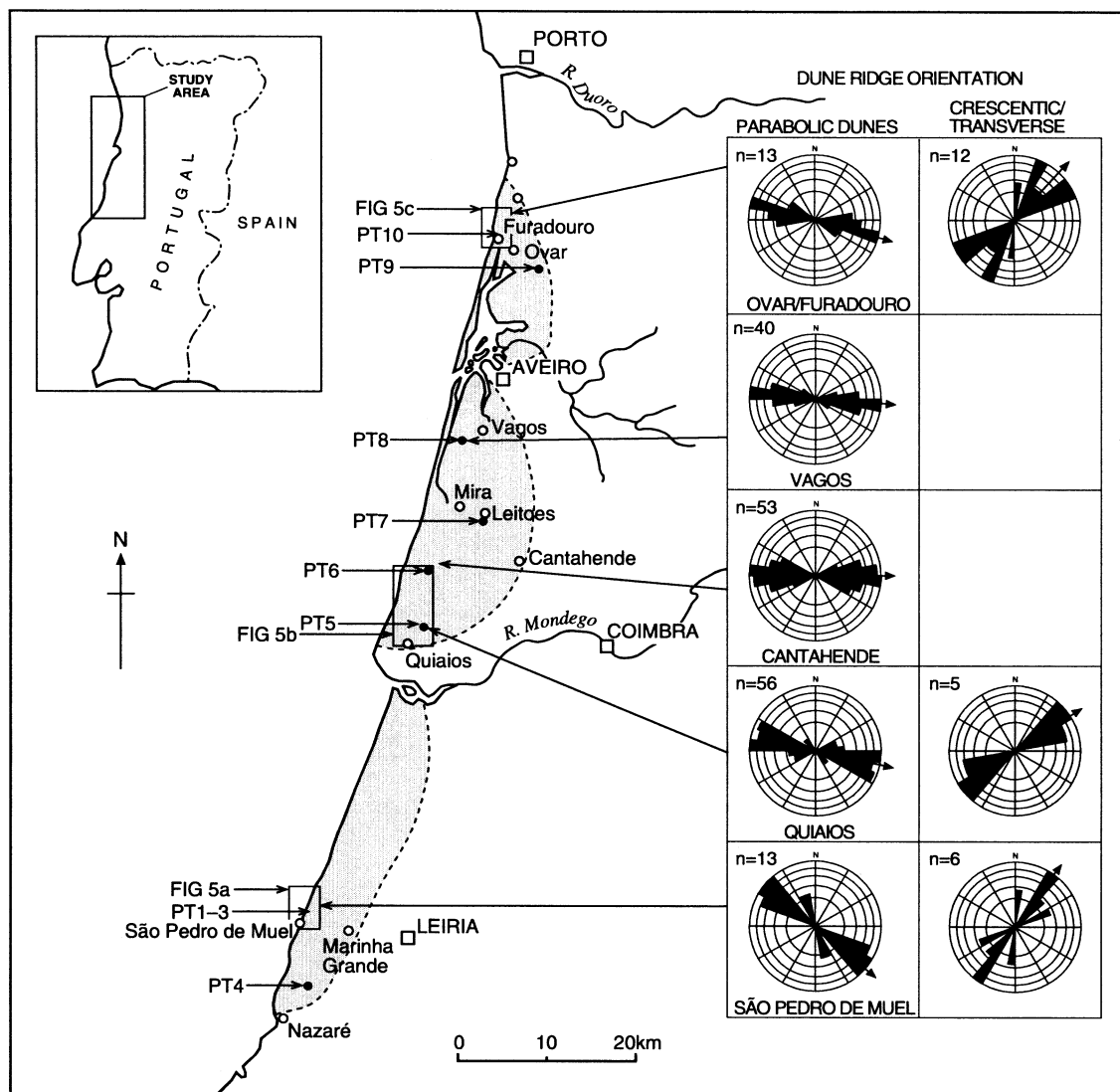


Figure 4 Location of study areas in western Portugal showing the positions of luminescence dating samples PT1–PT10. Shading indicates the extent of sand dunes and sand sheets. Inset diagram shows dune ridge orientation data for Ovar–Furadouro, Vagos, Cantahende, Quiaios and São Pedro de Muel

apex, supporting the interpretation of the dune ridges as the arms of elongate parabolics (Pye, 1993) rather than linear dunes (Tsoar *et al.*, 2004). The southern edge of the region around Quiaios also contains crescentic ridges, however within this sector samples were taken exclusively from parabolic dunes.

Dunas de Quiaios and Dunas de Cantahende

Planting of the 6425-ha Mata Nacional das Dunas de Quiaios was initiated by the Portuguese Forestry Service in 1926 with the express purpose of preventing sand invasion of cultivated areas inland. Sample PT5 was taken close to the landward end of a parabolic dune (5 km inland) near the Lagoa dos Bracos (Figure 4) in very pale brown sand, 0.5 m below the surface (Figure 5b). Vegetation cover beneath a canopy of pine trees comprised broom, heather and lavender. Immediately inland from the current foredunes, the dune forms are complex with a series of blowouts that may have been initiated by an increase in the wind energy environment or a change in vegetation density (Hesp, 2002). This complex area extends 0.25–0.5 km inland and is then succeeded by a 5 km-wide belt of elongate parabolics with a mean orientation of N102°E±13° and occasional crescentic ridges orientated

N58°E±5° (Figure 4). Numerous small freshwater ponds occupy the interdune slacks.

North of Quiaios, the Dunas de Cantahende and Dunas de Mira comprise a continuous coastal dune belt with east–west ridge orientations of N91°E±120° (Cantahende) and N95°E±9° (Mira) (Figures 4 and 5b). In addition to hairpin parabolics, some of the dune ridges exhibit complex branching similar in nature to the V-junctions found in some linear dunes. These junctions have been variously interpreted as evidence for advancing blowouts (Madigan 1936, 1946; Folk, 1971) or the asymmetrical extension of simple crescentic (barchan) dune arms (Bagnold, 1941; Tsoar, 1974; Lancaster, 1980) (Figure 5b). Sample PT6 was obtained from very pale brown sand located 0.55 m below the surface of the hairpin parabolic dune and 3.8 km inland (Figure 7b). The parabolic dune was stabilized by a pine forest with the surface cover consisting of sphagnum moss and pine needles.

Leitoes

Inland from the belt of elongate parabolic dune ridges, dune forms are more subdued. Sample PT7 was taken 10 km inland just to the east of the town of Leitoes (Figure 4). A small dune

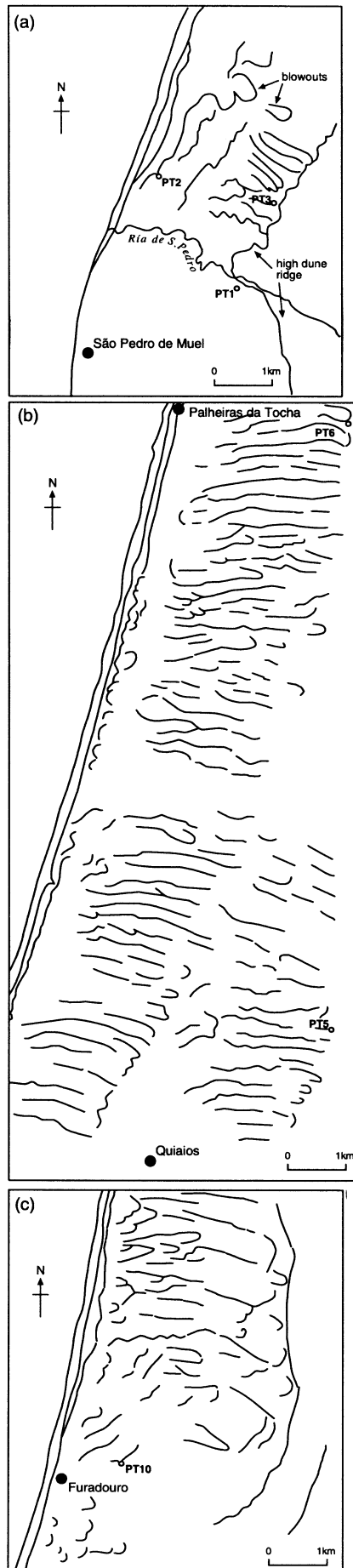


Figure 5 Orientation of sand dune ridges and sample locations for (a) São Pedro de Muel, (b) Quiaios and Tocha and (c) Furadouro

3–4 m high was exposed in a 20- to 30-m-long road cutting (Figure 6c). The sample comprised very pale brown, horizontally bedded sand from a depth of 3.0 m beneath a well-developed, brown to yellowish brown podsol (Figure 7b). The degree of podsol development has been used by Granja (1999) to differentiate between older (early Holocene) and more recent dunes in this area, suggesting that this dune is of early Holocene age.

Dunas de Vagos

North of the coastal town of Praia de Mira, the belt of elongate parabolic dune ridges is currently separated from the coastline, and from a source of sand supply, by a series of lagoons and canals that link together and eventually lead to the lagoons of Aveiro (Figure 4). The mean orientation of the dune ridges is $N94^{\circ}E \pm 10^{\circ}$. Sample PT8 is from undifferentiated very pale brown sand located 0.55 m below the flank of an elongated dune ridge (Figure 7b). As with the other dunes, the surface vegetation cover is dominated by sphagnum and broom beneath a canopy of pine trees.

Northern sector: Aveiro to Furadouro

The 25 km northern sector from Aveiro to Furadouro includes both parabolic and crescentic dune ridges. The dunes in the inland area around Ovar are separated from the coast by a large crescentic dune ridge and display a subdued topography in comparison with the littoral fringe.

Ovar-Furadouro

The Ovar–Furadouro area lies immediately north of the Aveiro lagoon system. The dunes here form a complex of crescentic ridges and parabolic dunes. The ridged arms of the parabolic dunes are orientated $N103^{\circ}E \pm 12^{\circ}$ and extend up to 4 km inland, whereas the shorter transverse ridges are orientated $N43^{\circ}E \pm 19^{\circ}$. At the back of this dunefield, forming its landward edge, is a 13-km-long, crescentic dune ridge, which rises up to a height of 37 m (Figure 5c). Sample PT10 was taken from a depth of 1.7 m in a section through a 3-m-high transverse dune close to the coastal town of Furadouro (Figure 5c). The sample was taken from very pale brown undifferentiated sand exhibiting no discernible soil development beneath a thin mat of organic material (Figure 7b).

The 13-km-long crescentic ridge forms the landward edge of the coastal dune field, landward of which agricultural land use and settlements have developed upon a topographically subdued sand sheet that is believed to comprise the older dunes of Granja (1999). Sample PT9 was taken from 2.1 m below the surface of a podsolized dune at a road section 7 km inland and southeast of the town of Ovar (Figure 4). The sample of undifferentiated, very pale brown sand was taken beneath a well-developed brown to yellowish-brown sandy podsol (Figure 6d, Figure 7b).

Luminescence methodology

Feldspars were chosen for the luminescence dosimeter to enable a direct comparison to be made with the Aquitaine coastal sequences (Clarke *et al.*, 1999, 2002), where an additive dose method (Duller, 1991; Wintle *et al.*, 1998) gave good agreement with independent age control in the form of radiocarbon-dated peat. Despite concerns regarding thermal transfer and sensitivity changes (Lian and Huntley, 2002; Blair *et al.*, 2005), infrared stimulated luminescence (IRSL) dating

of feldspars offers advantages for luminescence dating of Holocene sands because luminescence intensities are higher than for quartz allowing very young samples to be dated (Edwards, 1993; Wintle *et al.*, 1998). In addition, the dose rate contribution from within feldspar grains minimizes uncertainties associated with past water content history and its effect on the external dose rate to the grains. The accuracy of high-precision infrared stimulated luminescence (IRSL) additive dose protocols applied to feldspars has been tested in a range of aeolian contexts in which independent age control exists. Aeolian sands from Lapland (Clarke and Käykhö, 1997), and the Great Plains of the USA (Clarke and Rendell, 2003) have shown good agreement with independent age control provided by calibrated radiocarbon ages on soil organic matter. Sands bracketing the known-age Mazama tephra in Oregon also show excellent agreement with the age control (Clarke, 1994). More recently, Lang *et al.* (2003) undertook an accuracy assessment on additive dose IRSL from polymineral fine grained loess using radiocarbon-dated organic matter. They found that over the period 14–45 ka ‘good agreement ... demonstrates the high accuracy that can be obtained’ (Lang *et al.*, 2003: 958). Porat *et al.* (2003) also found good agreement between feldspars from nearshore coastal sands and an independent control on chronological accuracy in the form of radiocarbon dates on mollusc shells over the Holocene period. However, they also report overestimation from quartz ages on the same samples (Porat *et al.*, 2003). Clarke *et al.* (2003) used IRSL on feldspars from a stacked sequence of sandy colluvium and palaeosols and demonstrated excellent agreement between the feldspar ages and bracketing calibrated radiocarbon dates on soil organic matter. However, some authors have found disagreement when comparing IRSL ages with independent age control, suggesting that each site should be evaluated on an independent basis: Wallinga *et al.* (2001) found disagreement in fluvial sands when feldspar IRSL dates were compared with radiocarbon-dated macrophytes and van Heteren *et al.* (2000) found 10–20% age underestimations compared with radiocarbon dating for coastal sands. Age underestimations have been found in some feldspars that suffer from long-term loss of signal, known as anomalous fading (Spooner, 1994; Lamothe and Auclair, 1999; Huntley and Lamothe, 2001; Balescu *et al.*, 2003). Therefore, in addition to comparison with independent age control, laboratory tests for the presence and rate of anomalous fading are needed to assess the likely accuracy of the IRSL age (Lian and Huntley, 2002). Unfortunately, the Portuguese dunes do not exhibit palaeosol development to allow independent verification of the luminescence ages by comparison with radiocarbon dates, however historical evidence for sand invasion provides supporting information. Given that the additive dose IRSL protocol showed good agreement with independently dated peat in Aquitaine, as stated above, this method was chosen for the dating programme undertaken here. Tests for anomalous fading are described below.

On return from the field, approximately 50 g of sample was removed for measurement of the field moisture content. Once dried and weighed this material was then ground into a fine powder (<10 µm) for use in dosimetry measurements. A Daybreak 582 Thick Source Alpha Counter with pairs counting was used to determine the uranium and thorium contents of the bulk sample. A SURRC Thick Source Beta Counter was used to determine the external beta dose. The cosmic dose rate to the sample was calculated from the sample depth below the surface (Prescott and Hutton, 1988).

Sample preparation was undertaken in the laboratory under subdued orange light to prevent the bleaching of the

natural luminescence signal from the samples. Samples were dried and sieved and an optimum grain size (250–300 µm) was selected for mineralogical separation and luminescence measurement. All of the Portuguese sands were coarse-grained, showing modal distributions around 500 µm; the finer tail of this distribution was chosen to ensure effective zeroing of the luminescence signal. The selected grain size fraction was treated with 0.0032M hydrochloric acid and 30% hydrogen peroxide to remove carbonates and organic matter. Sodium polytungstate solutions with densities of 2.62 g/cm³ and 2.58 g/cm³ were used in succession to separate potassium-rich feldspar grains from first, quartz and heavy minerals and second, from plagioclase feldspars.

Aliquots of ~10 mg of the potassium-rich feldspar grains were then mounted on 1 cm aluminium discs using silicone oil ready for luminescence measurements. Luminescence measurements were made using an automated Risø TL/OSL DA12 Reader containing an integral ⁹⁰Sr-⁹⁰Y beta source. Luminescence was stimulated from an array of 31 TEMT484 infrared diodes (peak emission wavelength of 880±80 nm) delivering a power of 40 mW/cm² to the sample. The detection system comprised an EMI9635QA photomultiplier tube filtered with a combination of Schott BG-39 and Corning 7–59 colour glass filters. Additional neutral density filters were used during the measurements of samples PT7 and PT9 to reduce signal levels in order to prevent saturation of the photomultiplier tube. The equivalent dose (D_e) was determined for 12 aliquots from each sample using a single aliquot additive dose procedure (Duller, 1991) employing 0.5 s IR stimulation at 50°C and a preheat of 220°C for 600 s. Six aliquots were used to correct for loss of signal from repetitive heating and measurement cycles. Tests for anomalous fading were conducted using the procedure of Clarke *et al.* (2003), which is similar to the method b approach of Huntley and Lamothe (2001). No fading was observed over a period of one year.

Results

The analysis of dune forms and of the orientation of the dune ridges in the study area (Figures 4 and 5) reflects the dominance of west to northwesterly winds. The Atlantic wind environment (both strength and directionality) coupled with the large fetch, determines a wave environment that drives southerly littoral drift. It is likely that the dunefields of the northern Ovar–Furadouro sector are principally fed by sediment emanating from the Duoro river, the central sector from the Aveiro lagoon and associated rivers, and the southern sector dunefields are supplied by the Mondego river, with an additional onshore component. The predominance of parabolic forms in the central sector probably reflects the diminution of supply related to the creation of the lagoon.

The luminescence results are presented in Table 1. The D_e values comprise the mean and standard deviation of the individual aliquot D_e distribution for each sample. The coefficient of variation approach to assessing adequate zeroing at burial (Clarke, 1996; Clarke *et al.*, 1998; Fuchs and Wagner, 2003) suggests that all of the Portuguese samples were well-bleached at deposition and therefore should give accurate ages. The majority of the IRSL ages are in the range 95–230 years ago, with four samples of greater antiquity. The implications of these ages for sand accretion along the Portuguese coast are discussed below.

Discussion

Dune development

Dune development in the coastal zone is controlled by sea-level change, sediment supply and onshore winds. Postglacial sea-level rose rapidly across the Portuguese shelf from 10 ka reaching its current level *c.* 3.5 ka (Dias *et al.*, 2000a). Holocene neotectonic movements associated with movement of the Iberian plate (Granja and Soares de Carvalho, 1992), which caused episodes such as the Lisbon earthquake and tsunami in 1755 (Granja, 1999), are thought to be several orders of magnitude smaller than eustatic sea-level changes (Dias *et al.*, 2000a). Shoreline evolution, in particular the progradation of the coast around Aveiro and the formation of the spit barrier system, has impacted upon coastal dune formation. Transgressive dune forms, which include the high crescentic ridges seen at São Pedro de Muel, are known to form under conditions of disturbance, when strong onshore winds, together with rapid and significant sand supply from offshore or from littoral drift result in major sand inundation which

may bury existing vegetation (Short and Hesp, 1982). Where sand supply is limited and vegetation cover is patchy or disturbed, strong wind regimes impacting upon a vegetation-stabilized sand landscape will result in blowout formation and the creation of parabolic dunes (Pye, 1993). Therefore the changing nature of the coast, driven by changes in river sediment yield and lagoon formation will have an impact on dune form (Carter *et al.*, 1992). According to Dias *et al.* (2000a) the shape of the Portuguese coast has changed dramatically since sea level reached its current location, when it was characterized by rocky cliffs, estuaries and irregularly incised embayments. These features have become smoothed as a result of rapid erosion of cliffs and estuarine sedimentation (Dias *et al.*, 2000a, b). Until the end of the nineteenth century AD, the coastland was dominated by aggradation. In the tenth century AD a sand spit developed south of Espinho (Dias *et al.*, 2000b). Progradation of this spit southwards through littoral drift enclosed the Vougo estuary, which is fed by the Mira, Boco, Vougo, Antua and Caster rivers from the fifteenth century AD (Rodrigues and Dias, 1989) and cut off the port

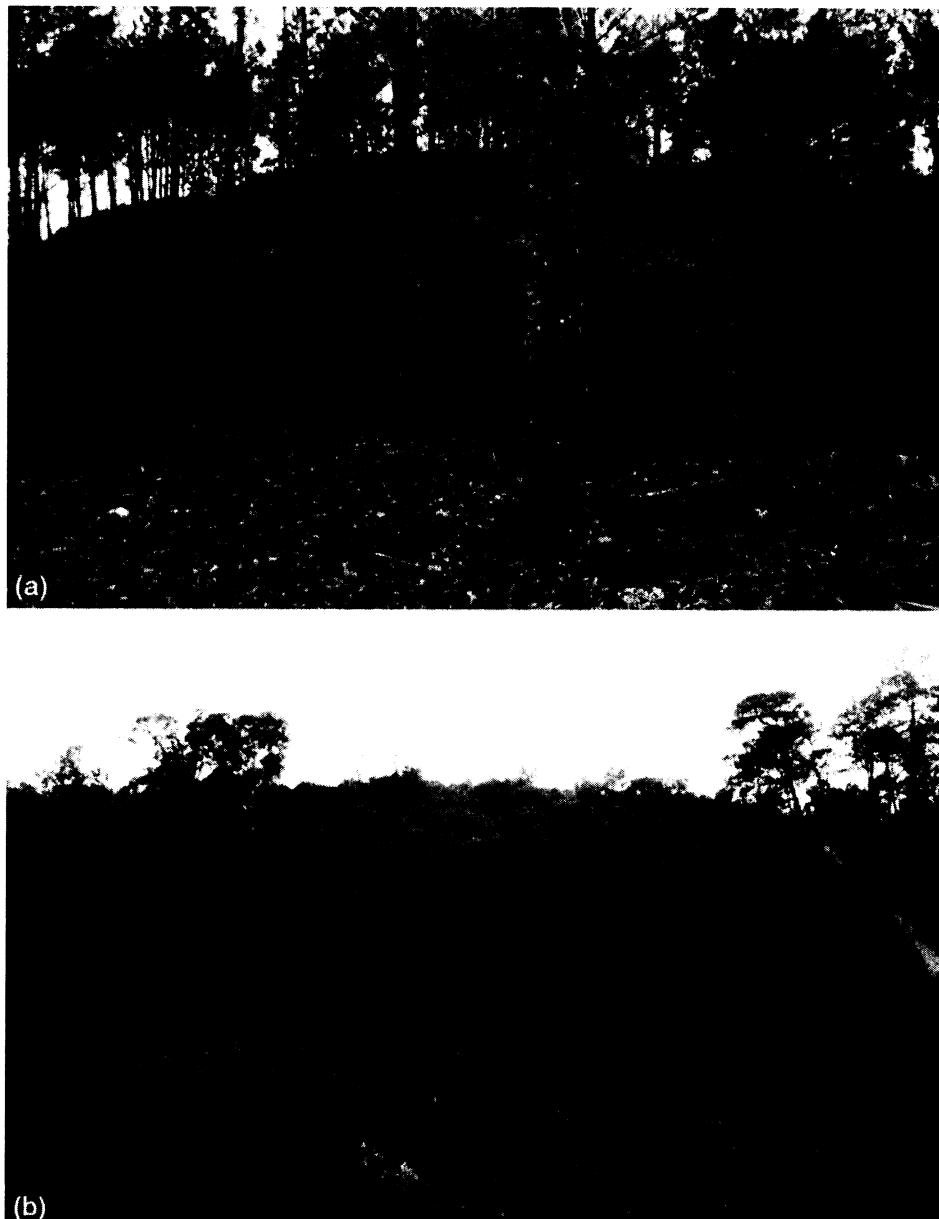


Figure 6 (*Continued*)

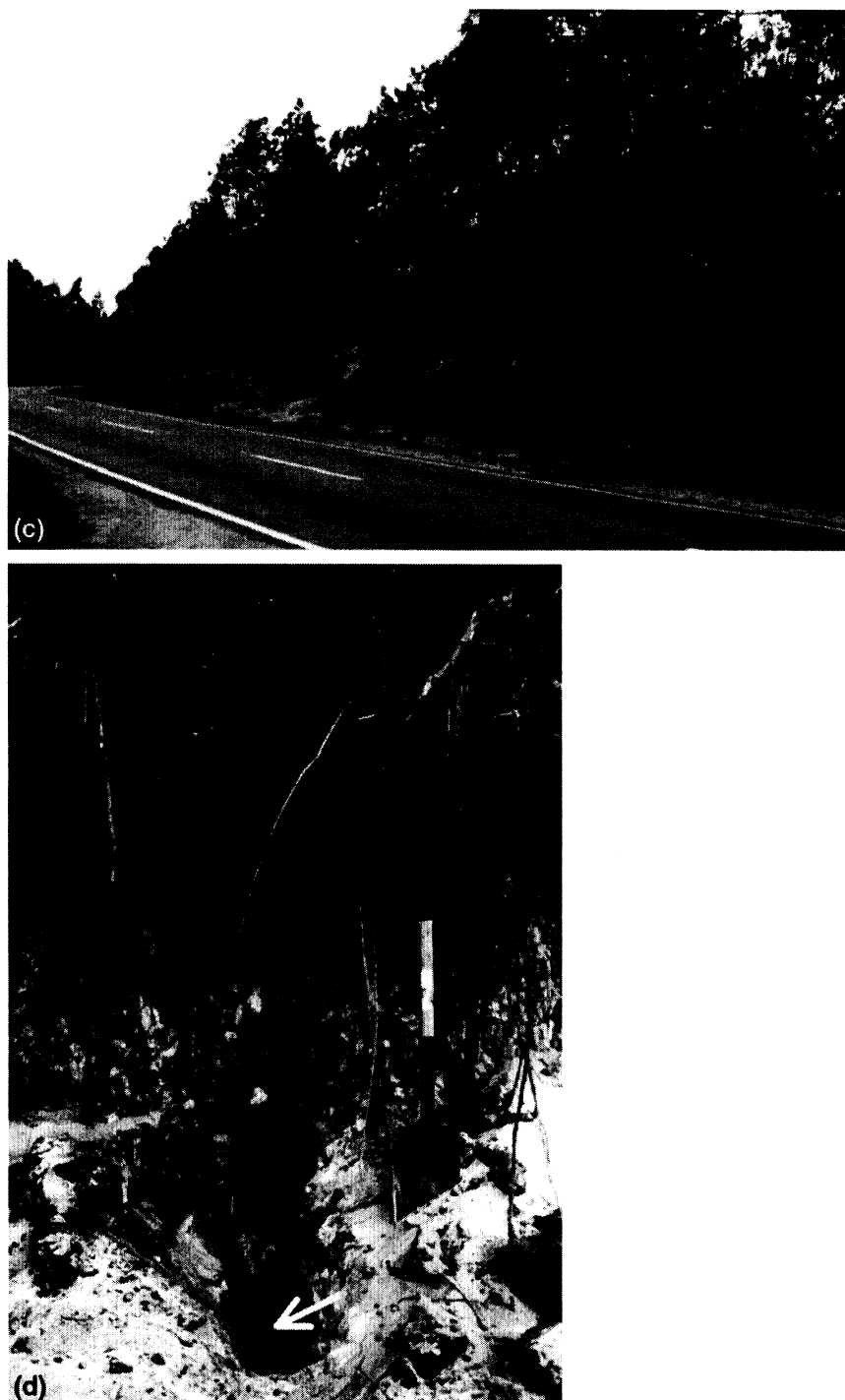


Figure 6 (a) A view of the sand dunes of Pinhal do Rei. (b) PT3 sampling location on windward side of crescentic dune ridge near São Pedro da Muel. (c) Road cutting exposure of early Holocene dune near Leitoes. (d) Podsolized sand dune near Ovar showing location of PT9 marked with an arrow

town of Aveiro from the sea until an artificial inlet was opened in 1808 (da Silva and Duck, 2001). Current estimates of average annual sediment load transported by the rivers into the lagoon are $0.24 \times 10^6 \text{ m}^3$, some of which is currently forming an ebb-tide delta outside the inlet–outlet channel (da Silva and Duck, 2001).

The podsolized low-relief dunes, which have been utilized for agriculture and settlement, gave ages of 8150 ± 790 years ago at a distance of 7 km inland at Ovar, to the northeast of the Aviero lagoon, and 9740 ± 1375 years ago at 10 km inland at Leitoes in the central sector. These ages support the interpretation of Granja (1999) that the dunes lying inland of the

forest-stabilized coastal zone are early Holocene in age and bounded to the east by the Serra de Estrela highlands. These dunes exhibit well-developed podsoles in the upper 1.5 m of the exposed sections suggesting a long phase of stability. The 8150 ± 790 year dune sands may have been deposited during the 8.2 ka cooling event, driven by the catastrophic outburst of Lake Agassiz and freshening of the North Atlantic (Barber *et al.*, 1999; Baldini *et al.*, 2002; Clarke *et al.*, 2004; Muscheler *et al.*, 2004; Alley and Ágústsdóttir, 2005), which is known to have weakened the tropical monsoon (Lachniet *et al.*, 2004) and hence increased storminess in the mid-latitudes. The uncertainties associated with estimation of the environmental

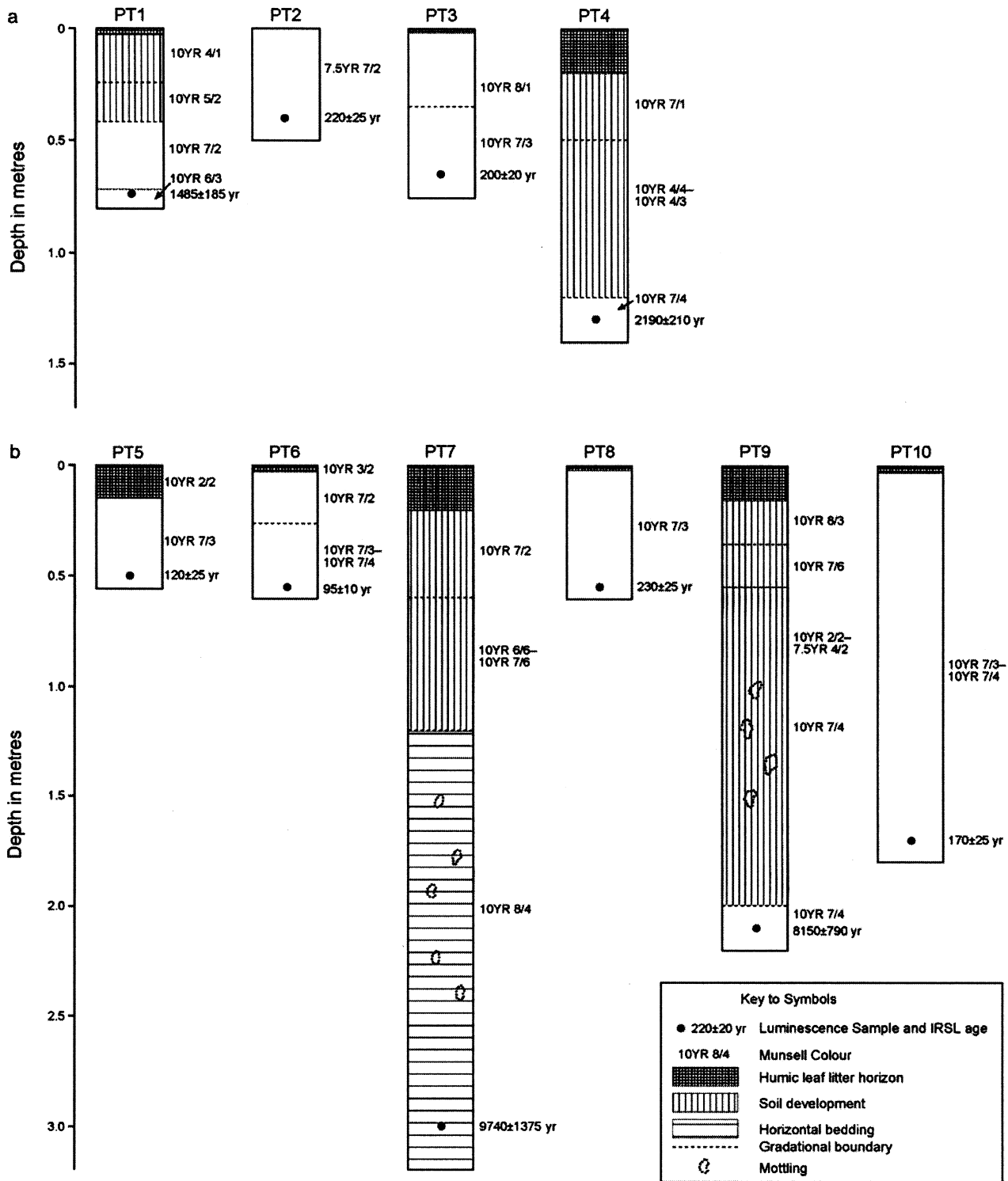


Figure 7 Stratigraphic profiles of the sampling sites in (a) the southern sector between Nazaré and Cape Mondego, (b) the central and the northern sectors between Cape Mondego and Furadouro. Whilst the dunes sampled may reach heights of > 10 m, only the sections cleared and subsequently sampled are shown here. IRSL ages are shown for each sample location.

dose rate to the sample since burial mean that whilst an association with the 8.2 ka cooling event is likely, we cannot state categorically that this is the case. The early Holocene age of the dune at Leitoes (PT7) might reflect wind activity associated with a rapidly rising sea level that controlled dune formation. Further dating is required to better resolve the timing of early Holocene dune accretion.

The younger, forested coastal dune sediments are all late Holocene in age and were formed whilst the sea was at its current level. The luminescence dates from the most landward

crescentic dune ridges in the southern sector gave ages of 1485 ± 185 years ago and 2190 ± 210 years ago. These pre-date the planting of maritime pine forests and reflect significant sand invasion creating transgressive dunefields with appreciable sand mass. Significant littoral drift, fed by river input provides an abundant source of sand for dune formation and strong onshore northwesterly winds have created ridges up to 104 m high. It is interesting to note that these transverse ridges reflect strong winds blowing from the northwest, whereas the younger parabolic dunes throughout the coastal region, are

Table 1 Attenuated dosimetry data, equivalent dose (D_e) and IRSL ages

Sample	Internal beta dose rate ($\mu\text{Gy/yr}$)	External alpha dose rate ($\mu\text{Gy/yr}$)	External beta dose rate ($\mu\text{Gy/yr}$)	Gamma dose rate ($\mu\text{Gy/yr}$)	Cosmic dose rate ($\mu\text{Gy/yr}$)	Total dose rate ($\mu\text{Gy/yr}$)	D_e (Gy)	Age (yr)
PT1	650 \pm 127	100 \pm 51	775 \pm 79	375 \pm 35	192 \pm 10	2092 \pm 162	3.11 \pm 0.30	1485 \pm 185
PT2	920 \pm 175	61 \pm 32	903 \pm 82	414 \pm 39	200 \pm 10	2498 \pm 200	0.55 \pm 0.04	220 \pm 25
PT3	927 \pm 176	61 \pm 31	669 \pm 59	338 \pm 32	194 \pm 10	2182 \pm 190	0.44 \pm 0.02	200 \pm 20
PT4	920 \pm 175	49 \pm 25	898 \pm 64	390 \pm 36	179 \pm 10	2436 \pm 192	5.34 \pm 0.30	2190 \pm 210
PT5	920 \pm 175	64 \pm 33	888 \pm 74	425 \pm 40	197 \pm 10	2494 \pm 197	0.31 \pm 0.06	120 \pm 25
PT6	920 \pm 175	62 \pm 32	963 \pm 77	435 \pm 40	196 \pm 10	2583 \pm 199	0.24 \pm 0.02	95 \pm 10
PT7	927 \pm 176	70 \pm 36	993 \pm 84	463 \pm 43	146 \pm 10	2599 \pm 203	25.32 \pm 2.97	9740 \pm 1375
PT8	927 \pm 176	77 \pm 40	1069 \pm 85	512 \pm 48	196 \pm 10	2781 \pm 206	0.63 \pm 0.05	230 \pm 25
PT9	927 \pm 176	51 \pm 26	976 \pm 82	422 \pm 39	162 \pm 10	2538 \pm 200	20.68 \pm 1.16	8150 \pm 790
PT10	920 \pm 175	58 \pm 30	1290 \pm 111	548 \pm 50	170 \pm 10	2993 \pm 217	0.51 \pm 0.07	170 \pm 25

formed by dominantly westerly winds, suggesting a southerly shift in dominant wind vector at some time within the last 1000 years. Development of the transgressive ridges in Portugal appears synchronous with sand accumulation in coastal dunefields bordering the Gulf of Cadiz (Borja *et al.*, 1999). Other independent records from the Portuguese coast are limited to a possible storm-induced breaching of a salt marsh at Ponte do Estreito near Esposende before 1780 \pm 10 years BP (Granja, 1999), and breaches of the Albufeira lagoon, dated at 1600 years BP and 1225 years BP (Bao *et al.*, 1999). Archival evidence suggests significant Mediaeval sand invasion along the Portuguese coast (Granja and Soares de Carvalho, 1992) prompting the thirteenth-century AD managed planting of the Pinhal do Rei forest to prevent sand drift. Dias *et al.* (2000a, b) suggest that the period between eleventh and fifteenth centuries AD showed a marked decrease in sediment supply to the continental shelf, implying that Mediaeval inundation resulted from reworking of existing dune forms rather than supply of new source material. None of the dunes we sampled gave luminescence ages in this timeframe, although further sampling may provide evidence for this apparent period of activity.

Post-dating stabilization measures in the southern sector, significant aeolian activity occurred throughout the coast 170–230 years ago (AD 1770–1830), during the ‘Little Ice Age’. This period is characterized by intense sedimentation in estuaries (Dias *et al.*, 2000a, b) and is equivalent to the period of sand accretion in the Gulf of Cadiz that buried seventeenth-century watchtowers (Borja *et al.*, 1999). In Portugal, sand invasion and dune accretion at São Pedro de Muel created a transverse ridge (220 \pm 25 years) parallel to the modern foredunes and also provided a blanketing sand cover (200 \pm 20 years) on the windward side of the 1.5 ka transverse dune ridge. At Vagos (230 \pm 25 years) and Furaduoro (170 \pm 25 years) parabolic dunes elongated and transverse ridges were created. Historic records from Esposende, north of Porto, report strong winds during the eighteenth and nineteenth centuries (Granja and Soares de Carvalho, 1992; Granja, 1999). Archival evidence for coastline change around the Aveiro lagoon also supports the luminescence dating of the recent dune-building episodes. The development of the barrier coastline at Aveiro continued until the nineteenth century AD (Dinas and Costa, 2004).

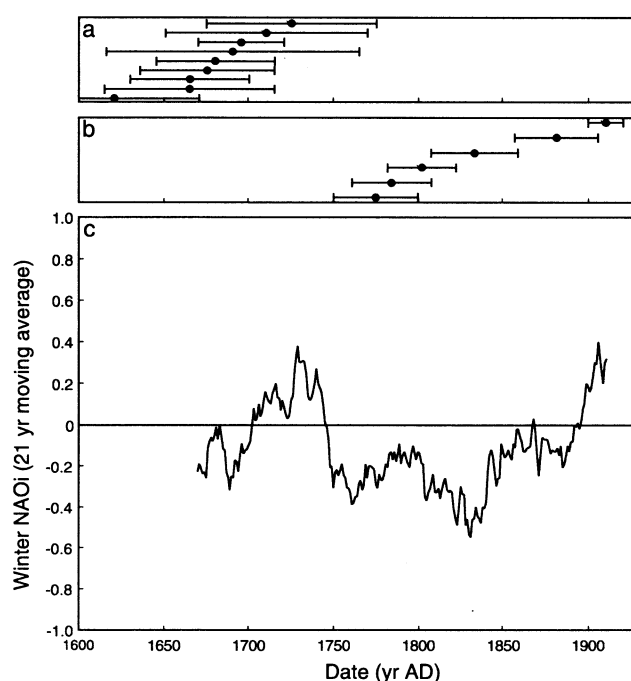


Figure 8 (a) Timing of the latest Holocene dune-building in Aquitaine. (b) Timing of the latest Holocene dune-building in Portugal. (c) Plot of the 21 year moving average for the reconstructed Winter (DJF) North Atlantic Oscillation Index (NAOI) of Luterbacher *et al.*, (2002)

The youngest dune-building phase occurred in the central sector between Vagos and Cantahende, which is dominated by multiple longitudinal dune ridges with dominant E–W orientation. These ridges conform to the classification of linear dunes on the basis of morphology, spacing and orientation, however it is likely that they comprise elongate parabolic forms that have subsequently lost their landward apex, developed as a result of more limited sand supply. It has been suggested that elongate forms result from higher wind speeds (Gaylord and Dawson, 1987). The elongate parabolic dune ridges of Quiaios and Cantahende date to the late nineteenth (120 ± 25 years) and early twentieth (95 ± 10 years) centuries AD and pre-date the planting of the 6425-ha Mata Nacional das Dunas de Quiaios in 1926. It is likely that this dunefield remained active until the stabilization measures were put in place, thus explaining the young ages for the forms.

Comparison with Aquitaine: the role of the NAO

The nearest comparable, well-dated coastal dune sequence to that of western Portugal is in Aquitaine, southwest France, where a complex sequence of forested barchan and parabolic dunes occupies the coastal plain of the Landes de Gascogne (Tastet and Pontee, 1998). Planting of maritime pines along this coast to stabilize sand drift occurred by royal decree in 1801 (Clarke *et al.*, 2002). The most recent period of dune accretion in Aquitaine spans the period AD 1480–1750, which shows synchronicity with sand accretion elsewhere in the Atlantic coasts of northwest Europe, such as Cornwall, UK (Lewis, 1992) and the Outer Hebrides of Scotland (Gilbertson *et al.*, 1999). In contrast, the most recent period of activity in Portugal occurred asynchronously from AD 1770 to 1905. The older periods of dune building in Aquitaine (Clarke *et al.*, 2002) either lead or lag the Portuguese ages, with no apparent overlap of dates.

In order to establish whether this apparent asynchronous sand activity is driven by changes in the position of storm tracks, influenced by the state and strength of the North Atlantic Oscillation (NAO), the dates of dune emplacement have been compared with the winter (DJF) NAO reconstruction by Luterbacher *et al.* (2002). This monthly NAOi series is based on instrumental records from AD 1659 to 1995. Persistent negative (winter) NAOi values occurred from AD 1750 to 1850, and around AD 1900, as indicated by smoothing the series with a 21-yr moving average (Figure 8), with periods of positive NAOi predominantly between AD 1705 and 1750 and after AD 1900.

Sand mobilization on the Aquitaine coast during the period of the Luterbacher *et al.* (2002) NAOi reconstruction is associated with a period of variable, but often positive, winter NAOi values (Figure 8). By contrast, five out of the six dates for the Portugal samples, spanning the period AD 1775–1910, are associated with negative winter NAOi values (Figure 8). Although both the reconstructed NAOi and the luminescence dates contain uncertainties, the asynchronicity of the dune-building episodes between France and Portugal does appear to be matched by the shifts in the dominance of the winter NAOi values, enabling a link to be made between episodes of sand mobilization and the inferred pattern of Atlantic storm tracks.

Abrantes *et al.* (2006) present evidence for a strong negative correlation between the mean winter discharge of the Tejo river (which reaches the sea at Lisbon) between AD 1900 and 2000 and the North Atlantic Oscillation, which indicates the influence of the NAO on river regime and sediment delivery to the coastal zone. Unlike Aquitaine, which lies on a wide sedimentary plain, the Portuguese coast is backed by the Serra

da Estrella that provide relatively steep catchments for the many rivers that feed the coastal plain. Negative NAO winters are wet (Trigo *et al.*, 2000; Rodrigo *et al.*, 2001), promoting runoff and soil erosion from the mountain catchments. Increased sediment supply to the coastal zone will promote an increase in littoral drift, which coupled with the southward deflection of westerly storm tracks and strong onshore winds, will feed dune building and sand drift along the Portuguese coast. Without mitigation measures such as forest planting, significant inundation is likely. An additional supply of sediment for aeolian deflation would have been provided by the Lisbon earthquake and subsequent tsunamis of 1 November 1755, which inundated the coastline of Portugal, Spain and north Africa (Kendrick, 1957; Baptista *et al.*, 1988a, b; Vilanova *et al.*, 2003) and resulted in erosion and re-deposition of 19 cm of sediments in the estuary of the Tejo (Dias *et al.*, 2000b).

Conclusions

Luminescence dating of vegetation-stabilized sand dunes along the western coastal fringe of Portugal from Nazaré to Furadouro demonstrates periodic sand mobilization throughout the Holocene. Analysis of dune morphology reveals a range of transverse and parabolic dune ridges with orientations implying dune development in response to dominant north-westerly and westerly air flow. The most recent dune-building episode identified in Portugal (AD 1770–1905) is asynchronous with that identified in Aquitaine, southwest France (AD 1480–1750) and other northern European Atlantic coastal regions (Lewis, 1992; Gilbertson *et al.*, 1999). Dune accretion throughout the late Holocene in Portugal appears linked to periods of predominantly negative winter NAOi and southward deflection of Atlantic storm tracks. Alluvial responses to increased rainfall and accelerated sediment input at these times (Trigo *et al.*, 2000; Abrantes *et al.*, 2006) drive an increased sand supply to the littoral drift, which coupled with strong onshore winds lead to sand invasion and dune building. The planting of maritime pine forests in the thirteenth century AD to prevent sand invasion of agricultural land appears to have been effective. The development of a longitudinal dune field between the Aveiro Lagoon and Cape Mondego, which predominantly comprise erosional, elongate, parabolic dunes, results from comparative sand starvation from alluvial sources, caused by closure of the Aveiro lagoon. Transgressive dune building creating high, crescentic ridges at 1.5 and 2.2 ka probably results from periods of strong wind activity and abundant sediment supply, causing sand invasion of existing vegetation. Further absolute dating is needed to improve the temporal resolution of dune accretion along the Iberian Peninsula and its relationship to climate forcing.

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