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Evidence for Late Pleistocene and Holocene sea-level, neotectonic and climate control in the coastal zone of northwest Portugal

Helena Maria Granja
Universidade do Minho, Departamento de Ciências da Terra, Campus de Gualtar, 4700 Braga, Portugal

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Abstract

The coastal zone of northwest Portugal can be subdivided into two geomorphological sectors: Sector 1, between the Minho River and the town of Espinho, where the coastal segments consist of estuaries, sandy and shingle beaches with rocky outcrops, and Holocene dune systems (foredunes and some migrating dunes with blow-outs). The estuaries and the foredunes in particular are very degraded by human activities. Sector 2, between Espinho and the Mondego Cape, where coastal lagoons and Holocene dune systems (foredunes, parabolic and transverse dunes) occur. This study deals with the macroscale, i.e. 100–1000 years, forcing by sea-level changes and neotectonic activity on the one hand, and mesoscale, i.e. 1–100 years, forcing by climate fluctuations on the other hand, on these (palaeo-)environments. It is shown in particular that sea-level changes and neotectonic activity play a dominant role in the evolution of the coastal zone since the Late Pleistocene. Sediment starvation on the shoreface is postulated to be one of the major causes for coastal erosion since at least the 15th century. The mesoscale role of climate is difficult to assess at the present stage of knowledge, mainly because of overprinting by the macroscale evolution of the coast. However, data on estuarine saltmarsh evolution in sector 1 point towards discrete changes in storminess, while the development of Medieval dune systems in sectors 1 and 2 are attributed to the Little Ice Age or, alternatively, to human occupation of the dune areas.

Introduction

The coastal zone of northwest Portugal is and has been subject to severe coastal erosion, at least since the second half of the 19th century (Teixeira 1980, Andrade et al. 1996). Although human influence cannot be excluded, the natural causes for this are still poorly understood but of major importance for coastal management. From previous studies during the last decade, e.g. Granja (1990), Granja & Carvalho (1994) and Granja et al. (1996), the following environmental mechanisms have been proposed as likely contributors to long-term coastal erosion in northwest Portugal: relative sea-level rise as well as neotectonic movement along pre-existing faults resulting from (plate) tectonic activities in the Iberian peninsula. These prior studies were concerned primarily with the geomorphology and the reconstruction of a Pleistocene-Holocene lithostratigraphic scale from outcrops, supported by radiocarbon dates, grain-size and sedimentary structures analysis, diatom and pollen assemblages, etc. The present work in the framework of the European project 'Climate Change and Coastal Evolution in Europe' (CCCEE, De Groot & Orford this issue) presents a more refined than previously possible macroscale (100–1000 years) reconstruction of the successive palaeoenvironments, controlled by sea-level rise, sediment starvation and neotectonic movements, while the mesoscale impacts of climate change are introduced as a new issue. During the project, boreholes to a depth of c. 45 m below surface were drilled between Espinho and Ovar (Figure 1). The upper 20 m were cored in order to obtain undisturbed samples for sedimentological analysis. The lower 25 m were counter-flushed and sampled every metre. Additional palaeoecological data were also obtained, especially from diatom assemblages. Optically stimulated luminescence (OSL) was used for the first time during the

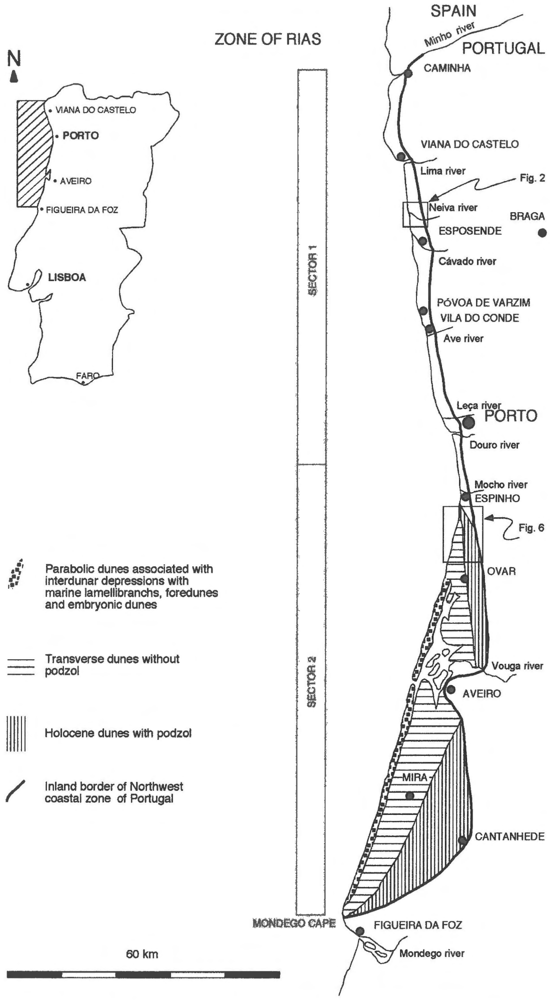

Figure 1. Schematic overview of the main geomorphological features of the Pleistocene and Holocene in the coastal zone of northwest Portugal.

project. In order to assess the neotectonic framework, a geophysical survey was made between Espinho and Ovar, using electrical soundings and shallow seismic profiling. The impact of mesoscale (1–100 years) climate changes on the coastal environments is tentatively assessed from the scarce information derived from estuarine coastal lowlands and from the developments of Holocene dunes. In a first part, an outline of the relevant geomorphological units and lithostratigraphic and sedimentological successions is given. In a second part, the sea-level, neotectonic and climatic implications for (future) coastal evolution are discussed.

Main geomorphological units

On the Portuguese Atlantic coast between the Minho River in the north and the Mondego Cape in the south, two main sectors can be defined from a geomorphological point of view (Figure 1): Sector 1, from the Minho River to Espinho, characterised by a relatively narrow coastal plain with different segments of which the one between the Neiva and Ave rivers is discussed in detail below, and Sector 2, from Espinho to the Mondego Cape, characterised by a wide coastal plain that forms the main subject of this paper, more specifically the coastal segment between Espinho and Ovar.

Sector 1: between the Minho River and Espinho

This sector has a long history of (tectonic and sea-level controlled) Pleistocene to Holocene evolution, identified from marked geomorphological features in the landscape. In the central segment between the Neiva and Ave rivers (Figure 2), Granja (1990) identified the following geomorphological units from east to west: 1) an older abandoned cliff of uncertain Quaternary age, associated with 2) a higher platform, well-above present mean sea-level (MSL), with relict Pleistocene marine deposits, 3) a younger abandoned cliff cut into this higher platform, associated with 4) a lower platform consisting of two sub-units, one with Pleistocene marine deposits on the landward side of the platform, and one with Holocene lagoonal deposits (1900 ± 40 to 920 ± 60 BP at Aguçadoura near Póvoa de Varzim) on the seaward side (cf. Granja & Carvalho 1994). The lower platform in turn, is covered to seaward by 5) dune systems of Medieval to sub-recent ages. The oldest dunes, e.g. the ones at Ofir-Fão (Esposende) and Chafé (Viana do Castelo) are attributed to the Little Ice Age as they cover Medieval burial-grounds (Abreu 1987; Granja 1990; Almeida et al. 1992; Cunha et al. 1993). At Belinho, Sublago and Marinhas (Esposende), the dunes cover Medieval salt pans (Almeida 1979). The central segment is further characterised by estuaries with degraded marshes, by sub-recent beaches and dunes (foredunes and migrating dunes), and by cliffs resulting from coastal erosion. No recent lagoons are found, with the exception of the residual lagoon of Apúlia near Esposende.

Table 1. Lithostratigraphy, sedimentology, radiocarbon and OSL datings, and environmental interpretation of outcrops and cores mentioned in the text. See also Figures 3, 4 and 9).

Table 1.

Units	Lithology	Age in years BP	Interpretation
Aguçadoura			
A4	Sands		Aeolian
A3	Bioturbated sands		Beach
A2	Fine to very fine, silty sands with diatomite and peat lenses	^{14}C:1900 ± 40 to 920 ± 60	Lagoonal
A1	Sands	OSL: 2477 ± 531	Aquatic (marine)
S. Pedro da Maceda Beach			
M9	Sands with large-scale cross-bedding		Aeolian
M8	Sands, bioturbated, mainly with parallel laminations and heavy-mineral streaks		Beach
M7	Sands with a metre-scale cross-bedded set at the base, followed by tabular decimetre-scale cross-bedding. Locally topped by a podzol		Aeolian
M6	Fine silty sands. The top represents a major palaeo-surface along the cross-section	^{14}C: 15250 ± 500 and 13 255 ± 685	Aquatic (lake or fresh-water lagoonal)
M5	Sands with locally contorted bedding, bioturbation and large clay balls		Aquatic
M4	Fine silty sands	^{14}C: 17 100 ± 200	Aquatic (lake or fresh-water lagoonal)
M3	Structureless (bioturbated) sands		Probably aquatic
M2	Fine silty sands (^{A}) with locally thin clay laminae towards the top. Contains *Pinus silvestris* (^{B}, Figure 6) and Graminae pollen	^{14}C: 26 700 ± 100^{A} ^{14}C: 27 150 ± 250^{B} to 19 910 ± 260^{B}	Aquatic (lake or fresh-water lagoonal)
M1	Structureless (bioturbated) sands with rootlets in the contact zone with unit M2		Probably aquatic
Cortegaça Beach			
C5	Sands with large-scale cross-bedding		Aeolian
C4	Sands, bioturbated, showing parallel laminations and heavy-mineral streaks		Beach
C3	Podzol, with A1 and A2 horizons	^{14}C: 3490 ± 90 to 1650 ± 160	Aeolian, also soil
C2	Sands with a partly eroded and complex sedimentary succession. The lower part (^{A}) in the area near Cortegaça Beach itself, shows a lateral change from wavy parallel to tabular, southward oriented cross-bedded sets and northwards oriented climbing ripple sets, overlain by parallel laminated sets, locally with a bubble sand intercalation (i.e. containing many air bubbles entrapped during rapid sedimentation from swash, often found on the backshore; cf. Reineck & Singh 1980). More southwards, where the unit is erosively overlain by unit C5, the contact is heavily bioturbated. The top of the unit (^{B}) is structureless due to the presence of rootlets from unit C3	OSL: 6390 ± 120^{A} OSL: 6958 ± 846^{B} to 6457 ± 937^{B}	The parallel and cross-bedded sets are interpreted as (tidally dominated) beach deposits while the upper, structureless part, may be aeolian
C1	Fine silty sands in lateral contact with unit C1A	^{14}C: 6830 ± 60 and 5500 ± 160	Lagoonal
C1A	Fine silty sands overlying white, aquatic sands	^{14}C: 17 100 ± 200 to 14 720 ± 220	Lagoonal
Silvalde-Paramos Beach			
S2	Peaty (tijuca) layer with fossil tree trunks and seeds. Diatoms: *Nitzschia scalaris*, *Synedra pulchella*, *Navicula peregrina*, *Navicula pusilla*, and many fragments of fresh-water species (e.g. *Cyclotella meneghiniana*).	^{14}C: 1700 ± 30 to 500 ± 80	Fresh to brackish, lagoonal
S1	Fine, silty, > 2 m thick sands, with brackish-water lamellibranchs	^{14}C: 2310 ± 90 to 2200 ± 80	Lagoonal ('tijuca' in strictest sense)
Paramos (RGD6) core			
P6	2.10 m depth upwards, predominantly cross-bedded sands		Aeolian
P5	2.10 to 3 m: cross-bedded and cross-laminated sands with a shell layer		Washovers
P4	3 to 3.5 m: clay with a peaty layer on top	^{14}C: 440 ± 50	Lagoonal
P3	3.5 to 7 m: alternations of fine silty sands with more or less shell-rich intervals		Lagoonal with proximal washovers
P2	7 to 12 m: clay and sandy clay with brackish lamellibranch shells	^{14}C: 4920 ± 105 and 4090 ± 220	Lagoonal with distal washovers
P1	Below 12 m: alternation of fining-upwards and coarsening-upwards, pebble-rich sands		Beach

Table 2. Diatom species and environmental interpretation of a core taken at Ponte do Estreito (Cávado River, Esposende). Depth in metres below surface, which is c. 5 m above MSL.

Zone and depth to surface	Diatom species	Environmental interpretation
Zone E 0-4.60 m	*Eunotia pectinalis* *Tabellaria flocculosa* *Gomponema acuminatum var. coronata* *Navicula pusilla*	Brackish lagoon of Zone D changes to an upper saltmarsh environment (terrestrial). When the *Eunotia* flora appears, the environment becomes fresh, oligo-mesotrophic and slightly acid (pH ≈ 5), with growth of aquatic plants.
Zone D 4.60-5.50 m	*Nitzschia obtusa* *Diploneis ovalis* *Melosira moniliformis* *Rhopalodia acuminata*	Transition towards a brackish, stagnant lagoon.
Zone C 5.50-6.80 m	*Fragilaria construens var. susalina* *Eunotia pectinalis*	Sudden flooding, increasing marine influence. Shallow, fresh to brackish water, depth ≤ 1 m.
Zone B 6.80-7.20 m	*Navicula pusilla*	Upper saltmarsh, above high tides. Increasing fresh-water influence.
Zone A 7.20-7.90 m	*Diploneis didyma* *Paralia (Melosira) sulcata* *Stauroneis gregorii* *Nitzschia punctata* *Nitzschia navicularis* *Nitzschia sigma*	Marine-brackish epipelic diatoms. Mudflats to saltmarshes at high water level.

Sector 2: between Espinho and the Mondego Cape

The morphology of the coastal plain in this sector differs markedly from that of Sector 1, particularly because of the presence of large Holocene dune fields (foredunes as well as parabolic dunes and mainly E-W transverse dunes) with some evidence of truncated podzol horizons. These dune systems limit coastal lagoons with permanent inlets, e.g. the Aveiro lagoon (although the inlet is artificial) or temporary ones, e.g. the lagoon of Esmoriz. Further inland, the dune systems isolate fresh-water lagoons with artificial drainage channels in between them or with semi-permanent sea inlets, e.g. the Braças, Vela, Salgueiro, Teixoeiros and Mira lagoons, between Mira and the Mondego Cape.

Lithostratigraphic framework and palaeoenvironmental interpretation

During the project, one site was investigated for mesoscale fluctuations in Sector 1. However, most attention of the work concentrated on the megascale evolution in Sector 2.

Sector 1: coastal segment between the Neiva and Ave rivers

At Aguçadoura, near Póvoa de Varzim, the Holocene sediments show a succession of units (Table 1), previously described by Granja (1989, 1990) and Granja & Carvalho (1989, 1992, 1994). The diatom species from the diatomites in unit A2 point to a fresh-water or slightly brackish environment, interpreted as confined lagoons in the neighbourhood of the ocean. The pollen content of the peat in this same unit shows a dominance of fresh-water aquatic plants (Granja 1990).

In the CCCEE project, and in order to investigate the mesoscale evolution of these low-energy deposits in more detail, a complete 'tijuca'[1] section was cored in an abandoned estuary-channel of the Cávado River at Ponte do Estreito, near Esposende. The core reached a depth of 11 m below surface. The samples between the surface and 7.9 m depth are rich in organic matter and well-preserved diatoms. Five palaeoenvironmental zones could be identified from these samples, indicating a fluctuating marine influence through time (Table 2): silting-up towards a supratidal marsh (zones A and B), sudden flooding prior to 1780 ± 50 ^{14}C years BP (the oldest age obtained at 4.44 m below surface, c. 0.56 m above MSL), shown by the appearance of brackish-water species like *Fragilaria* and *Eunotia* (zone C), establishment of a lagoon in the estuary (zone D), and finally, silting-up again towards a supratidal marsh (zone E). The flooding of zone C will be discussed further below in the section about climate.

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[1] 'Tijuca' is a term of Brazilian origin describing fine, silty sands deposited in coastal lagoons.

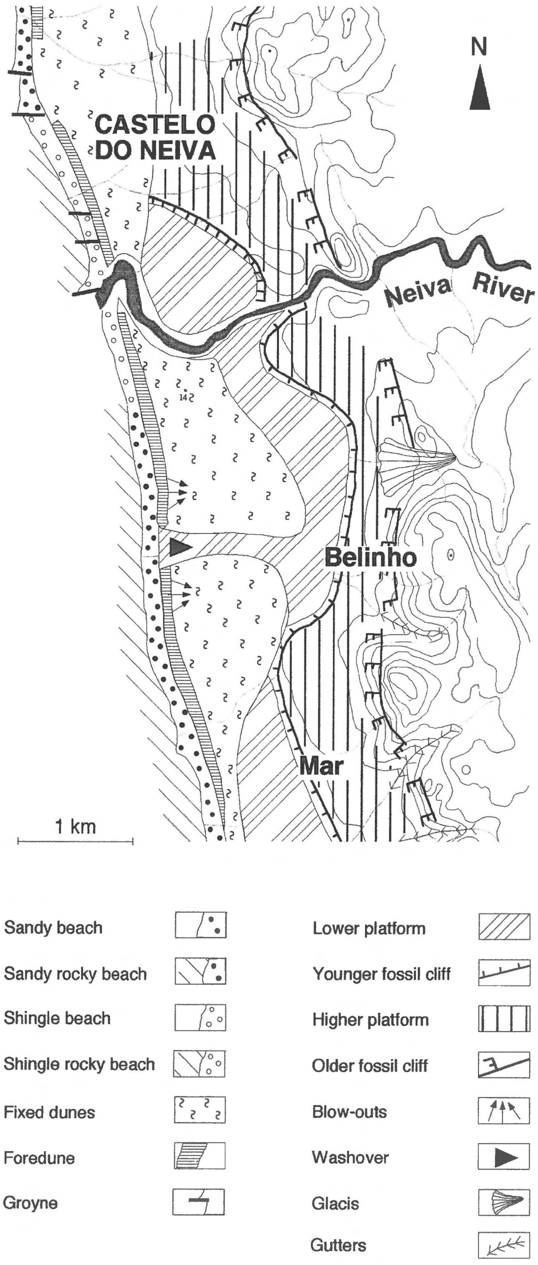

Figure 2. Geomorphological map of the Belinho (Esposende) coastal segment. See Figure 1 for location.

Sector 2: coastal segment between Espinho and Aveiro

Extensive cliff outcrops resulting from severe coastal erosion (cf. Araújo 1986) have allowed the reconstruction of a lithostratigraphic sequence, dated by radiocarbon and OSL. Geological cross-sections and cores formed the basis for the facies interpretation of this sequence, studied in detail by Granja (1990, 1991, 1993), Granja & Carvalho (1992, 1993a, b, 1994, 1995), Granja & De Groot (1996) and Granja et al. (1996).

For the purpose of the present study, three outcrops are briefly outlined: the S. Pedro da Maceda Beach, the Cortegaça Beach, and the Silvalde-Paramos Beach (Table 1).

S. Pedro da Maceda Beach: The units observed are summarised in Table 1 and shown in Figure 3 (Granja et al. 1996). The alternation of aquatic, probably nearshore to beachface and lagoonal deposits (units M1 to M6 and M8) and subaerial deposits (units M7 and M9) indicates major palaeoenvironmental changes related to sea-level rise and neotectonism (see discussion below).

Cortegaça Beach: The units observed are summarised in Table 1 and shown in Figure 4. In a previous paper derived from the project, Granja & De Groot (1996) inferred that unit C1, in existence at about 6000 years BP, was probably protected to seawards by a barrier, subsequently destroyed during coastal retreat under sea-level-rise conditions. The sediments were reworked and shifted inland by southward longshore drift and cross-shore wave action. The lagoon was infilled by beach deposits (unit C2), followed by aeolian deposits, including the formation of extensive podzol profiles, indicating a decrease in water depths and (temporary) stabilisation of the coastline (unit C3). Further south, unit C1 was eroded. Tectonic uplift seems to have played an important role in this process (see below). Subsequent coastal retreat flooded and partially eroded the top of the podzol, and deposited unit C4, after which a new dune system developed (unit C5), possibly as a result of tectonic uplift.

It should be noted that when comparing the outcrops of Maceda Beach and Cortegaça Beach, only the units M4 and C1A can be directly correlated on radiocarbon evidence (Figure 5). This implies that the units M5 and M6 were locally eroded from the Cortegaça Beach outcrop. The podzol on top of unit C3 extends southwards till approximately the groyne of S. Pedro de Maceda Beach, just north of Figure 3, where it is found at the top of unit M7. In view of this, and in the absence of other data, it is assumed that the units M7 to M9 are the lateral equivalents of the units C3 to C5.

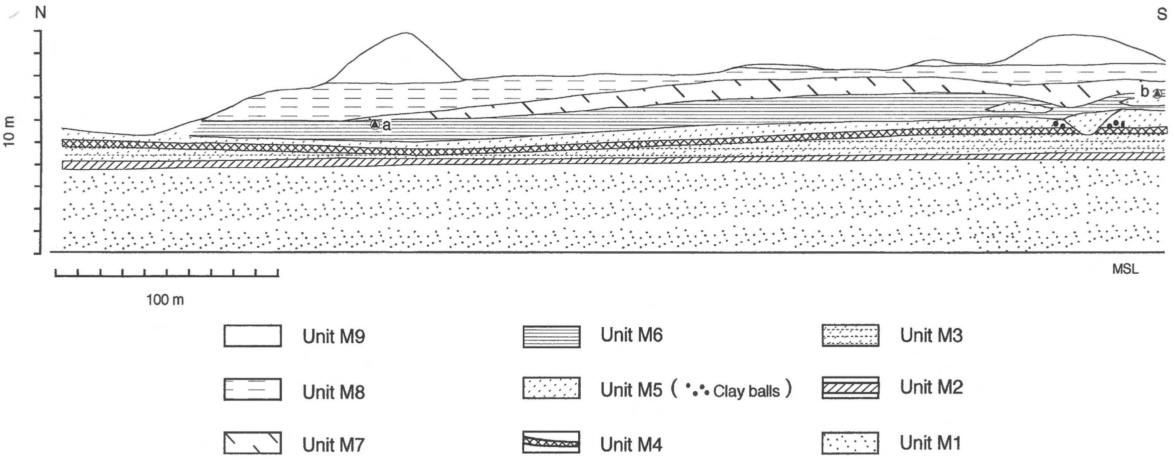

Figure 3. Geological cross-section of Maceda Beach north of S. Pedro da Maceda Beach groyne. See Figure 7 for location and Table 1 for data on units M1–M9. Altitudes in metres above MSL. (a) and (b) refer to radiocarbon sample locations: (a) 13255 ± 685 BP; (b) 15250 ± 500 BP.

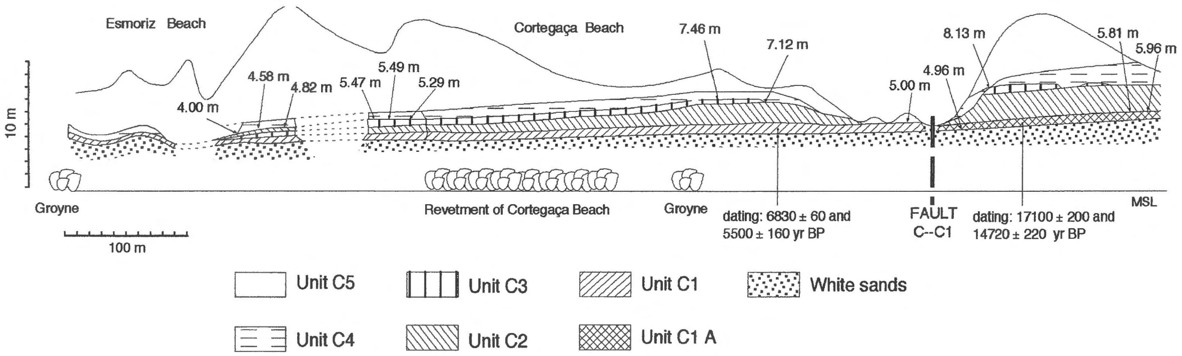

Figure 4. Geological cross-section of Cortegaça Beach south of Esmoriz Beach groyne. See Figure 7 for location and Table 1 for data on units C1–C5. Altitudes in metres above MSL.

Silvalde-Paramos Beach: Outcrops of the Silvalde-Paramos Beach show two units (Table 1) described by Granja (1996) and Granja & Carvalho (1992, 1994, 1995). In the CCCEE project, seven cores were drilled by the Geological Survey of the Netherlands (RGD)[2] in the area of S. Pedro da Maceda Beach, Cortegaça Beach, and Silvalde-Paramos Beach (De Groot & Granja 1998; Figure 7). Near Paramos Beach, core RGD 6 reached the schist bedrock at 17.30 m depth below surface, c. 11 m below MSL, crossing the units summarised in Table 1.

Evidence for the impacts of sea level, neotectonics and climate

Rationale

The recognition and interpretation of the impacts of sea level, neotectonics and climate are important for the understanding and forecasting of future coastal zone evolution (Granja & Carvalho 1994). The current explanation of coastal erosion and cliff retreat in northwest Portugal given by most Portuguese coastal researchers, invokes the following causes: 1) the construction of river dams and the decrease of the erosion rates of valley slopes after reforestation, both reducing the supply of sandy sediments to the coastal zone, 2) the sand quarrying in estuaries, beaches and dunes, 3) the trampling of dunes, increasing the remobilisation of sands and the destruction of the dunes, and 4) the global climatic change postulated to cause the con-

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[2] Since September 1st, 1997: Netherlands Institute of Applied Geoscience TNO – *National Geological Survey* (NITG-TNO).

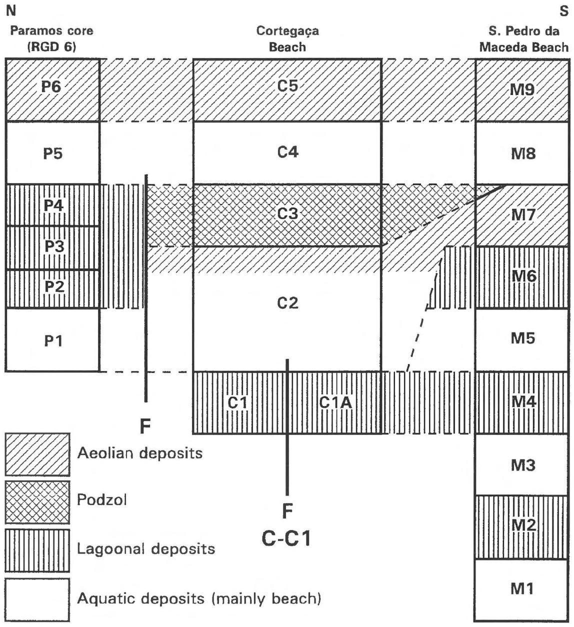

Figure 5. Lateral relationships between the different lithostratigraphic units from the outcrops of S. Pedro da Maceda Beach and Cortegaça Beach, and from core RGD 6 at Paramos Beach. Not to scale. See Figure 7 for location. F = fault.

temporary sea-level rise (Wigley 1995, Houghton et al. 1996). However, some observations in the coastal zone of northwest Portugal indicate that these causes are not enough by themselves to explain this erosion. The following arguments can be mentioned.

Erosion in sector 2 and particularly around and immediatly south of Espinho, is known at least since the second half of the 19th century. The first recorded erosional impact was reported in newspapers at Espinho in 1869 (Teixeira 1980, Andrade et al. 1996). At that time, the damming of the northern Portuguese rivers had not yet been initiated. However, although the postulated greenhouse effect from industrialisation could not yet have been perceptible, some data point towards an (accelerated) sea-level rise trend since before the 1850s (Houghton et al. 1996). As will be shown below, the following causes can be proposed for a significant contribution to the coastal erosion in this sector: sea-level rise and sediment starvation, neotectonism, and climate.

Sea-level rise and sediment starvation

In all the described outcrops and cores, relative sea-level rise can be inferred as a major controlling factor for coastal evolution, in view of the presence of erosive flooding and deposition of aquatic (nearshore to beachface) sediments, and the development of lagoons, e.g. units A3, M3 to M6 and M8, C2 and C4, P2 and P5. They indicate a macroscale, metastable evolution with periods of temporary marine retreat. However, this metastable situation seems in contradiction with the present increased erosion observed on the northwestern Portuguese coast, at least since the second half of the 19th century as was outlined above. In fact, it was the increased threat to riverine populations that furthered the development of coastal defence works in Sector 2. Unfortunately, these measures only increased further the rate of coastal retreat, which in some places reaches 9 m during storms. Thus, overall, the natural causes for sub-recent erosion are not well understood, except for the following considerations.

An important background for coastal erosion in northwest Portugal may have its origin in the shoreface per se. Sediment transport towards the coast by wave action may have ceased prior to the 19th century and at the earliest with the formation of the post-15th century dunes of unit C5. This cessation of sediment transport could have been initiated either by sediment depletion on the shoreface, or by the increasing water-depths as a result of sea-level rise. In the latter case, bottom sediments are gradually positioned below the wave-base and shoreward sediment transport decreases. In the absence of reliable data about the sediment budget on the present shoreface, it is impossible to test this at present. However, data obtained from a diving campaign initiated by the project in Sector 1 between the Minho and Ave rivers, indicate that the bedrock of the shoreface is covered by pebbles and cobbles, and that sand is practically nonexistent.

An example of coastal erosion linked to sediment starvation as a result of sea-level rise occurred in the Netherlands. After 3000 BP, the sediment availability from outside the coastal zone became non-existent (Beets et al. 1995). This supply cessation initiated the steepening of the shoreface, subsequent retreat of the coast and, especially since the Middle Ages, large-scale inundations from the estuaries landwards. As a side effect, the shoreface sediments eroded along the Holland coast and transported to the beach by wave action, became the sediment source for the Younger Dunes. However, this did not impede coastal retreat. From this example it might be assumed that Medieval dune formation in Portugal was also initiated by the erosion of the shoreface sediments, concomitant with the retreat of the coastline at that time.

Figure 6. Fossil *Pinus sylvestris* trunks in unit M2 on Esmoriz Beach. Lengths of trunks vary between c. 40 and 100 cm. See Figure 7 for location.

Neotectonism

Neotectonic movements in the coastal zone of northwest Portugal are the result of major stress patterns of plate-tectonic origin in the Iberian microplate and its passive Atlantic margin (Cabral 1993, Ribeiro 1994). It is postulated that this margin is in the process of incipient subduction (Ribeiro 1994). Stress release along this tectonic margin caused amongst others the Lisbon earthquake of 1755 (cf. Hindson et al. this issue). The stress field has important effects upon the active fault pattern of northwest Portugal, in particular on the major NNW-SSE strike-slip fault south of Porto (Cabral & Ribeiro 1989) that seems to control the orientation of the inland border of the coastal zone south of Espinho.

There are several indicators of recent tectonic movements in the northwest coastal zone and its surroundings. Examples of these are (see Figure 1 for locations):

1. The reverse fault of Monte Chão (S. Pedro da Torre, near Caminha), that caused the overthrust of the Quaternary deposits of the Minho valley by Hercynian gneiss-granites (Carvalho 1981).
2. The contorted sedimentary structures in the vicinity of faults in the Holocene fluvial deposits of the Cávado valley (1140 ± 45 to 1010 ± 80 BP). These structures are interpreted as palaeoseismicity indicators (Carvalho 1989, Granja et al. 1992).
3. The 'valeiros' (gutters), small valleys south of the Douro estuary with asymmetric transversal cross-sections (Granja 1990), assumed to be controlled by a NNW-SSE fault that runs parallel to the major strike-slip fault of Cabral & Ribeiro (1989), as their ends are situated along a line with that orientation. This line corresponds in fact to the eastern limit of the Holocene formations (Granja & Carvalho 1994).

The sedimentary succession described at Maceda Beach in sector 2 shows a marked rhythmicity (Figures 3, 5, Table 1). This is attributed to small-scale depositional cyclicity related to advances and retreats of the shoreline, possibly as a result of eustatic variations of the Atlantic water-levels. However, the relatively high positions of the units M2, M4 and M6 in relation to MSL indicate uplift of the area as coastal lagoons are formed at or below sea level. Also the relatively high position of unit M8 points to the same phenomenon. This is corroborated by the outcrops at Cortegaça Beach.

According to Dias & Boski (1995), Dabrio et al. (this issue) and Zazo et al. (this issue), palaeo-sea level reached the present one at about 6000 years BP in the Iberian coastal zone. The data presented by the first authors are based on sea-level index points on the continental shelf. However, no index points for sea level have yet been found in the coastal zone of northwest Portugal. According to the modelling of post-glacial sea-level changes (Clark et al. 1978, Pirazzoli 1991), however, sea level was still some 8 m below the present one at 6000 BP in the northern part of the Iberian peninsula. Tentatively, and in the absence of more reliable data, the modelling sea-level curve is used in this study for assessing neotectonic movements in the coastal zone. With the provision that the calculated rates of uplift may probably be too high especially for the older data, the sea-level and neotectonic data of Cortegaça Beach discussed by Granja & De Groot (1996), have been re-evaluated (Figures 4, 8). This yields the following observations:

1. In view of its age and interpreted depth of deposition of c. 3 m, unit C1 (lagoonal bed) should have been formed at least c. 8 m below present MSL. This would indicate a tectonic uplift of at most 16 m since 5500 BP to its present position c. 5 to 6 m above MHW (average uplift c. 30 cm/century).
2. The overlying tidally-influenced beach deposits (unit C2), while related to sea-level rise, have accordingly also been uplifted.
3. The podzol (unit C3), already in existence at c. 3500 BP, implies that the lowest possible position of its top, originally at least above the palaeo-mean high-water level, i.e. c. 2 m above palaeo-MSL, would habe been flooded, partially eroded and covered by unit C4 (beach deposits) shortly after

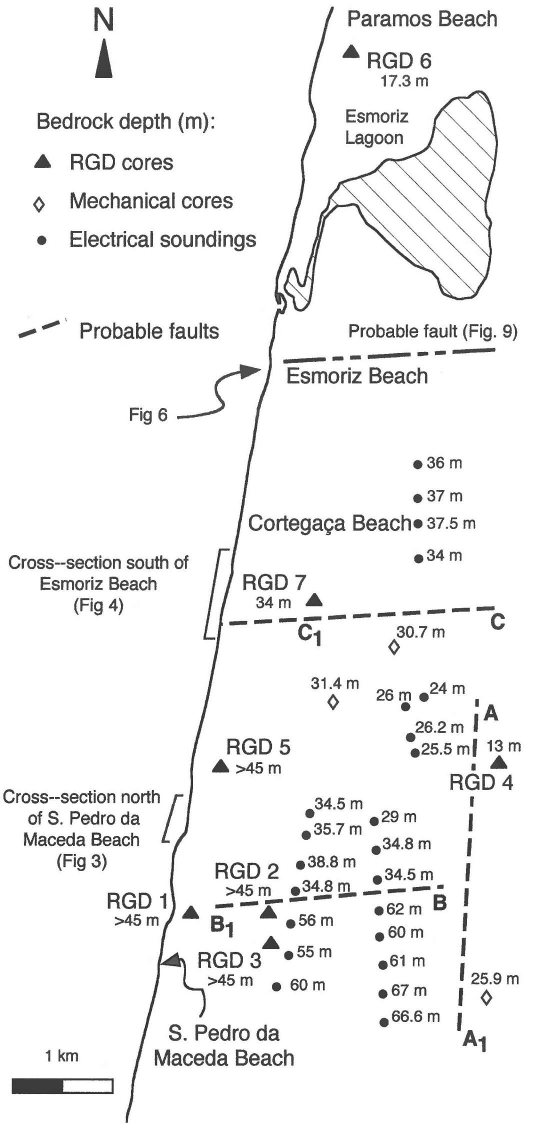

Figure 7. Location map of the geological cross-sections of Figures 3 and 4, electrical soundings, RGD and other boreholes, and the main faults (A–A1; B–B1; C–C1) interpreted from the geophysical and borehole data. See Figure 1 for location. Depths below surface; surface elevations are between c. 5 and 8 m above MSL.

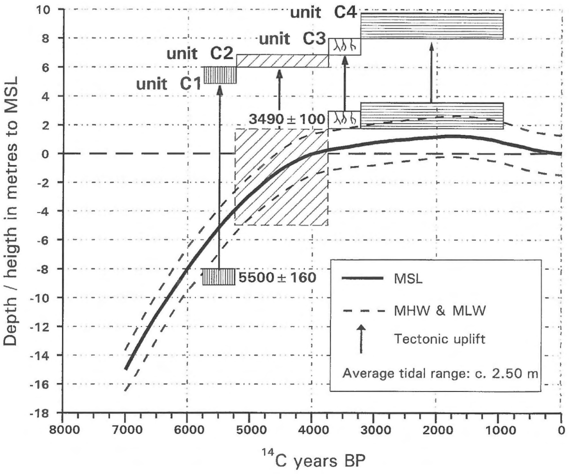

Figure 8. Time-depth diagram showing the influence of sea-level rise and local tectonic uplift on the Holocene coastal deposits at Cortegaça Beach. The upper boxes show the present-day position of the Cortegaça Beach units in relation to MSL; the lower boxes represent the inferred palaeo-depth of deposition of these units in relation to the inferred sea-level curve (after Granja & De Groot 1996). See discussion in text.

3500 BP but probably not later than c. 3200 BP, if one assumes the curve of Figure 9 to apply. In view of its present position at c. 7 to 8 m above MSL, the amount of tectonic uplift would be at most c. 5 m (average uplift ≤ 14 cm/century).

Faults are difficult to deduce from the outcrops. However, there is clear evidence of a fault in the Cortegaça Beach outcrop where units C1A and C1, formed at widely different ages, are in direct lateral contact at the top of the present beach (Figure 4, Table 1). In the framework of the project therefore, other techniques were used to locate possible faults controlling the coastal sediments. A geophysical survey consisting of electrical resistivity soundings and shallow seismic profiling was performed south of Espinho by the University of Aveiro (Figures 7, 9). Three faults were interpreted in the area delimited by the Cortegaça Beach, the S. Pedro da Maceda Beach and the Aerial Base of Ovar (Carvalho et al. 1995, Granja et al. in press).

1. A nearly N-S oriented fault (A-A1), probably the same fault that controls the ends of the valeiros. On the western side of this fault, the cores RGD 1, 2, 3 and 5 did not reach the bedrock at 45 m depth. The upper, cored beds are similar to those found in the outcrops. On the eastern side however, core RGD 4 reached the schist bedrock at c. 13 m depth (c. 2 m below MSL) and the beds crossed are different from those of the other four cores, representing a temporarily flooded environment consisting of storm-controlled channel and overwash deposits, followed by c. 3-m-thick lagoonal deposits, in turn covered by dunes (De Groot & Granja 1998).
2. An E-W oriented fault immediately south of Cortegaça Beach (C-C1) confirms the lateral contact between unit C1A and unit C1. Movements along this fault predate the deposition of the tidal

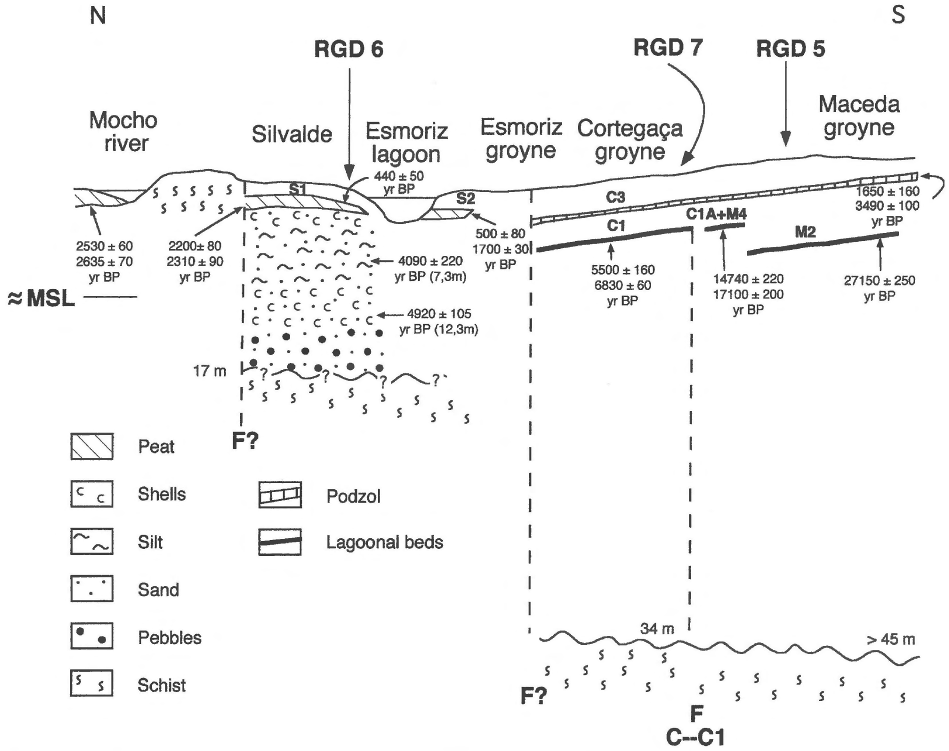

Figure 9. Schematic cross-section along the coastline, showing observed and/or inferred E-W faults (F?). Not to scale. See Figure 7 for location.

deposits (unit C2) and the podzol (unit C3) as they are laterally continuous without any break.

3. An E-W oriented fault (B-B1) located north of the S. Pedro da Maceda Beach is not visible in the outcrops. The geophysical data indicate however a downthrow of the southern bedrock block by c. 20 to 30 m.

Tectonic activity is further demonstrated by the following observations:

- Unit C1 shows small folds near the Esmoriz groyne, evidence for deformation after 5500±160 BP.
- Deposits with contorted bedding found in the southern slope of the palaeo-valley located immediately south of the Cortegaça groyne (Granja & De Groot 1996) and south of fault C-C1 (Figure 4), contain fragments from the podzol horizon of unit C3. This indicates palaeoseismic activity between 1620 years BC and 60 years AD (Granja et al. 1996). The opening of the palaeo-valley and the fragmentation of the podzol can be related to this activity.
- Core RGD 6 near Paramos Beach, reached the schist bedrock at 17 m below surface (11 m below MSL) without showing any of the beds of the Cortegaça outcrop (Figures 7, 9, Table 1). In the core, pebble-rich beach and storm-influenced lagoonal deposits cover the bedrock. Lagoonal deposits of unit P4 occur up to c. 2 m above MSL. This may indicate a fault, located southward of the Esmoriz lagoon, and possibly active after deposition of units P3 to P5 (440 ± 50 BP).

- At Cortegaça Beach, the youngest podzol date (1650 ±160 BP) of unit C3 is more or less contemporaneous with the oldest peaty beds (unit S2, 1700 ± 30 BP) at the Silvalde-Paramos Beach (Granja & Carvalho 1995, Granja et al. 1996). Furthermore, in core RGD 6, the lagoonal beds with brackish lamellibranchs of unit P2 (4920 ± 105 and 4090 ± 220 BP) indicate that tectonic activity would be older than this brackish palaeoenvironment. It is assumed that tectonic movements along faults first generated the depression where the sedimentary sequence found in core RGD 6 (brackish lagoonal deposits and peat) was deposited. During a later tectonic phase, the sequence was subsequently elevated to its present position.

Climate

Besides the macroscale forcing by sea-level and neotectonics on the palaeoenvironments in the studied coastal zone, climate is postulated to have been an important agent on the mesoscale. However, its impact is difficult to assess, mainly because of the local overprinting by macroscale marine flooding. Nevertheless, a few environmental changes that may be related to climate are recorded, particularly in the aeolian systems. Some examples are briefly discussed below.

In Sector 1, the sands overblowing and burying the Medieval cemeteries of Fão (Esposende) and Chafé (Viana do Castelo) are attributed to the Little Ice Age (Abreu 1987; Granja 1990). Local historical records report strong sand-transporting winds during the 18th and 19th centuries (Neiva 1987). However, it is impossible to assert at this stage of knowledge whether this was caused by climate or by human activities in the dunes.

Also in Sector 1, the core studied at Ponte do Estreito near Esposende (Table 2), shows a sudden flooding of the saltmarsh (diatom zone B) in the Cávado estuary prior to 1780 ± 50 BP. This flooding (zone C) is inferred to have occurred following a period of increased storminess that destroyed the protected environment. The lagoon thus formed (zone D), was subsequently filled-in again (which may be attributed to washover effects related to storms or the shifting of the estuary), and grew-up to supratidal heights.

Differences in podzolisation may also point to climatic influence. In Sector 2 in particular, the development of the podzol unit C3 from the 16th century BC to the 3rd century AD, can probably be attributed to a cool to temperate and moist climate. However, it may possibly also be related to human deforestation during Roman times and the early Middle Ages.

In the outcrops of Sector 2, the occurrence of wide-spread washover and beach deposits covering and eroding in places the aeolian units, e.g. unit C4, or filling-in the palaeo-lagoons, e.g. units M5 or C2, and the washover units from the cores RGD 4 and 6 (De Groot & Granja 1998), may be related to mesocale climatic shifts during the Holocene.

Conclusions and recommendations

The study shows that in the coastal zone of northwest Portugal, sequences of lagoonal, beach and aeolian environments were in place during the Late Pleistocene and Holocene. Neotectonic movements occurred on several occasions, i.e. shortly after the Late Pleistocene and sub-recently. It seems that the deposition in one of the youngest lagoonal palaeoenvironments at Silvalde-Paramos Beach was controlled by neotectonics. In addition, sediment starvation has been shown to be one of the possible causes for coastal erosion, at least since the 15th century.

Sea-level rise and the post-30 000 BP tectonic deformations are the fundamental, macroscale, forcing factors for coastal evolution in northwest Portugal. Sea-level rise of c. 50 cm during the next century as postulated by Houghton et al. (1996) would only increase the problems of a deficient sediment supply from the shoreface. Tectonic deformation since the 3rd century AD, the youngest age of the podzol at Cortegaça Beach, is possibly still active today. More research is needed however, to further determine the influence of neotectonics on coastal evolution in northwest Portugal.

The study shows furthermore that mesoscale, storm-induced coastal changes related to climate, e.g. the saltmarsh flooding in the Cávado estuary in Sector 1, are largely overprinted by the macroscale changes of sea level, sediment supply and neotectonics. In the studied outcrops of Sector 2, no clear traces could be found of mesoscale forcing. However, the occurrence of wide-spread washover and beach deposits covering and eroding in places the described aeolian units, or filling-in the palaeo-lagoons, may be related to mesocale climatic shifts during the Holocene. The competing meso- and macroscale processes resulted in the complex depositional systems found in the coastal zone. At the present state of knowledge, however, variations in the mesoscale rates of activities cannot be ascertained with any fair degree of confidence.

In view of the present erosion of the coastal zone of northwest Portugal, it is recommended that policy makers should be made aware that natural processes such as sea-level changes, deficient sediment supply and neotectonism are basically uncontrollable. This should be taken into consideration in future coastal zone management. New strategies for coastal conservation need to be developed, different from the contemporary local measures applied. In the absence of such new strategies, the coastal zone may likely be the stage for severe catastrophes with important environmental and socio-economic losses.

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