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Sea-Level Rise and Neotectonism in a Holocene Coastal Environment at Cortegaça Beach (NW Portugal): A Case Study

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ABSTRACT

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The northwestern coastal zone of Portugal (north of the Serra da Boa Viagem---Mondego Cape) is a flat region with extensive dune systems, many of which have paleosoils attributed until recently to the last Quaternary glaciation.

The rapid beach erosion and the retreat of the coastline—accelerated by the building of the groin field of Espinho—allowed the revision of concepts, about not only the genesis of the deposits, but also their chronostratigraphy. The study of the outcrops in the cliffs have led to the description of lithostratigraphic units belonging to the Praia de Cortegaça Formation.

From base to top, this formation consists of the following units, expressing clear facies changes: (1) lagoonal deposits, with a dated top between 6830 ± 60 and 5500 ± 160 years BP; (2) subtidal deposits; (3) intertidal deposits; (4) foreshore deposits; (5) structureless, probably acolian deposits, covered by a podzol with truncated horizons dated about 3490 ± 100 years BP; (6) foreshore deposits; (7) aeolian deposits of medieval age.

A model correlating sea-level rise, neotectonism, and facies variation in this area is discussed. Interpretation of the data provided by the evidence, indicate tectonic uplift of about 15 m at most during the last 6000 years.

ADDITIONAL INDEX WORDS: Lagoon, dunes, podsol, coastal erosion, and facies changes

INTRODUCTION

The 1:25 000 topographic maps as well as the 1:50 000 geological maps show the presence of several dune systems in the coastal zone north of the Mondego Cape. This area includes the sector between Espinho-Cortegaça and the Furadouro beach which is the subject of this paper (Figure 1). For several years, the idea prevailed that the sandy deposits of this coastal zone, assumed to be of Pliocene or Plio-Quaternary age (TEIXEIRA, 1978; RIBEIRO *et al.*, 1979), predominantly represented aeolian deposits arranged in several dune fields. In earlier papers concerning the problems raised by the dune fields, a criterion of distinction based on the existence of dunes with or without pedological paleo-horizons (locally known as "sorraipa") was established by CARVALHO (1954, 1964), later adopted by ARAŬJO (1986, 1991) and assigned to the Würm (Weichselian) glaciation (CARVALHO, 1964); because the dunes were associated with wind-worn pebbles and Palaeolithic artefacts, as well as periglacial deposits. More recently, the dunes were placed in a wider time frame, ranging from the end of the Weichselian to the Holocene (GRANJA & CARVALHO, 1992).

The northwestern coastal zone of Portugal is subject to severe erosion (GRANJA, 1991b), partly due to human interference (GRANJA, 1991a; GRANJA & CARVALHO, 1991). In the area between Espinho and Furadouro, the construction of groins between 1980 and 1989 led to severe coastal retreat (locally more than 9 metres in two weeks as a result of storms) and seriously threatened human settlements and eroded dune fields. This severe and rapid coastal erosion, however, has made

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Figure 1. Location map of the area under study.

it possible to study Holocene sedimentary sequences in the exposed cliffs.

The study of the cliffs between Esmoriz and Furadouro has shown that the podzol, observable in, for example, the Cortegaça beach is not situated in an exclusively aeolian context, but also occurs in association with marine foreshore sediments. Furthermore, the podzol is recognized as being much younger than was previously thought (GRANJA, 1991b). A new lithostratigraphic framework based on this new evidence was described as the Praia de Cortegaça Formation (GRANJA, 1991b). Farther inland, a truncated podzol (lacking the A horizon) is associated with a dune system (ARAÚJO, 1991). In our opinion, these two podzol profiles are contemporaneous and laterally related to the foreshore environment found at the Cortegaça beach.

The outcrops along the beach cliff show a Holocene sequence with a height of about 10 m (Figure 2), exposed above the present day mean high water level (MHWL). The cliff is interrupted only by a branching, shallow, NW-SE oriented valley, extending behind the beach (Figure 3). In the middle of the valley, two small hills still represent



Figure 2. General view of the cliff at Cortegaça beach.

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Figure 3. Sedimentary cross-section along Cortegaça beach and location of the sections.

Table 1. Radiocarbon dates.

References	yr BP	Laboratory		
Podzol-horizo	on A1			
GSC-5512 GSC-5418 GSC-5471	$1,970 \pm 110$ $2,700 \pm 50$ $2,540 \pm 50$	Geological Survey of Canada Radiocarbon Dating Labo- ratory, Canada		
KSU-2205	$2,070~\pm~30$	Kyoto Sangyo University, Faculty of Sciences, Japan		
ICEN-752 ICEN-751	$2,090 \pm 30$ $2,780 \pm 50$	Instituto Nacional de Engen- haria e Tecnologia, Labora- tório de Isótopos Ambien- tais, Lisboa, Portugal		
I-16675	3,490 ± 60	Teledyne Isotopes, West- wood, USA		
Lagoon				
I-16891	5,500 ± 160	Teledyne Isotopes, West- wood, USA		
ICEN-750	6,850 ± 60	Instituto Nacional de Engen- haria e Tecnologia, Labora- tório de Isótopos Ambien- tais, Lisboa, Portugal		

the remains of a dune system. The valley itself represents the morphological relict of a small river course, filled in by the most recent dune formation.

SEDIMENTARY SEQUENCES

Sedimentary Units

The most complete vertical sequence observable South of Espinho, at the Cortegaça beach (Figure 3), is formed by seven sedimentary units. This sequence was studied in detail in two vertical sections (Section 1 and 2, Figure 3). From bottom to top:

Unit 1. Greenish silty sand, outcropping just above MHWL of the present beach, at the base of the cliff. Radiocarbon assays performed on charcoal inclusions in the unit give an age ranging between 6850 ± 60 and 5500 ± 160 years BP (Table I). In the absence of alternative datable material, the charcoal is assumed to be approximately contemporaneous with the deposits. This assumption is validated by the lower stratigraphic units (with



Figure 4. Detail of Unit 3, showing the cross-laminated and climbing ripple sets.

charcoal) which are systematically older than the higher ones. In this case, the youngest available age represents the most recent deposition of the unit. The unit has an average thickness of about 80 cm. Environment: subtidal part of a lagoon (GRANJA, 1990).

Unit 2. Wedge-shaped, tabular, SE-oriented cross-bedded sands (decimetre scale sets). The maximum exposed thickness of the unit is about 90 cm. Environment: tidal bars or washover deposits filling the lagoon. No signs of scouring into unit 1 were observed.

Unit 3. Tabular cross-laminated sands (centimetre scale sets), bidirectional (N-S), with a dominant southward-oriented flow direction (Figure 4). Some of the sets show climbing ripple lamination. Reactivation surfaces are common. Locally, the unit overlies Unit 1 at an erosional contact (clay pebbles are present in the unit). The unit has an average thickness of about 95 cm. Environment: shoreface around mean low water level (MLWL), wave and tide dominated, with local runnels.

Unit 4. Parallel-laminated sands, with graded bedding and thin heavy mineral laminations (Figure 5). Some sets show bubble sand (swash zone) and adhesion ripples, characteristic of a beach facies (Figure 6). The average thickness of the unit is about 150 cm. Environment: foreshore between MLWL and MHWL to supratidal backshore.



Figure 5. Detailed overview of the sedimentary units present between Sections 1 and 2.

Unit 5. Structureless, heavily rooted sands, covered by Al and A2 podzol horizons. These horizons are partially overlain by unit 6 at an erosional contact. Roots and root traces sometimes reach down into Unit 2. The A horizons of the podzol are bioturbated (see Unit 6). Radiocarbon datings from included pieces of charcoal give a maximum age of 3490 ± 100 years BP (Table I). The A1 and A2 horizons generally dip slightly northward. The average thickness of the unit is about 50 cm. Environment: vegetation-covered backshore deposits, with an aeolian component.

Unit 6. Parallel to low-angle laminated sands, with thin heavy-mineral laminations. Bioturbation is present at the base of the unit, and is common within the unit. The average thickness of the unit is about 125 cm. Environment: foreshore between MLWL and MHWL.

Unit 7. Cross-bedded to parallel-laminated sand. Environment: aeolian dunes.

Sections

The outcrop along the cliff of Cortegaça beach was studied in detail in six sections (Figure 3). The succession of sedimentary units changes laterally along the outcrop as a result of erosion. Without discussing each section in detail, some particular features are reviewed here.

Sections 2, 3, and 4

In a southerly direction, a decreasing number of units are retained in the coastal section until, at the location of Section 4, the aeolian Unit 7 lies directly upon unit 1 (Figure 3). This is the location of the small fluvial valley behind the most westward coastal dune ridge. The lowest part of this valley has an unknown erosion depth through Unit 1. The time of activity of the river valley is unknown but, considering the sedimentary succession, it seems that activity was at least contemporaneous with the formation of unit 5 (see also Section 5). It is not known whether the valley had already been active as an older tidal inlet.

Section 5

On the southern slope of the paleo-valley, about 470 meters south of the Cortegaça beach groin (Figure 11), there is a slump structure (Figure 7). A NW-SE-oriented block composed of elements from units 2 to 5 subsided when the valley was



Figure 6. Detail of adhesion ripple lamination within Unit 4.



Figure 7. Detail of Section 5 showing the slump structure.

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Figure 8. Detail of Section 5 showing contorted bedding inside the slump structure.

still active. The slump was deposited as a wedge upon Unit 1. The primary sedimentary structures were contorted (Figure 8). Directly overlying the slump, the dune field (Unit 7) was formed, indicating that the active discharge within this portion of the paleo-valley ended with the formation of the aeolian dunes.

HOLOCENE NEOTECTONISM AND SEA-LEVEL RISE: A DISCUSSION

The neotectonic history of the NW coastal zone of Portugal is very poorly known. CARVALHO (1953, 1954, 1964) and, more recently, GRANJA *et al.* (1992), suggested that neotectonism played an important role in the deformation of Quaternary deposits in NW Portugal. Given the sea-level curve of DIAS (1987) (Figure 9) derived from the Portuguese continental shelf, the oscillatory fluctuation of sea level about 8000 years BP may be considered to be of tectonic origin, because this part of the curve covers a general period of rapid global sea-level rise.

When the vertical facies changes in the outcrop of Cortegaça beach are studied, it is possible to discriminate between changes due to sea-level rise and those due to tectonic movements. The sedimentary evidences indicating sea-level rise or vertical tectonic movements are summarized in the following two sections.

Evidence for Sea-Level Rise

The facies evolution from Unit 1 (lagoon, subtidal) to Unit 4 (foreshore, intertidal) is dominated by sea-level rise as reflected by coastal retreat. A similar evolution has been described in detail from the western Netherlands (BEETS et al., 1992). Changes in coastal geometry and sediment accommodation space after about 5000 years BP may-due to the slowing rate of relative sealevel rise, which started as early as about 6000 years BP-have led to temporary coastal progradation and the formation of dune systems (Unit 5); this set of circumstances presently exist on the western coast of The Netherlands (BEETS et al., 1992). Alternatively, it is postulated here that neotectonism played a more important part in this process than in the example of the Netherlands (see below).

The facies change from Unit 5 (dunes, supratidal) to Unit 6 (foreshore, intertidal) too, was



determined by relative sea-level rise and renewed coastal retreat. Storm and wave action drowned and partially eroded the dune system. The traces of bioturbation and the sedimentary structures are good indicators of an extensive and permanent foreshore facies.

Evidence for Vertical Tectonic Movements

The best evidence of vertical tectonic movement is the present position of Unit 1 (lagoon, subtidal), *i.e.*, 5 to 6 m above the MHWL (Figure 3). For the time-depth diagram (see Figure 10), a generalized eustatic sea-level curve for the coastal zone was extrapolated from the continental shelf curve (DIAS, 1987), in the absence of a corresponding curve for the coastal zone of NW Portugal over the last 6000 years (Figure 9). Sedimentation of Unit 1 was still occurring at the time of the youngest radiocarbon date $(5500 \pm 160 \text{ years BP})$. In view of the depth of deposition of fine-grained subtidal lagoonal sediments within the presentday lagoons of NW Portugal (e.g., at an average depth of about 2 m inside the Aveiro lagoon), the palaeo level of deposition must have been at least about 9 m below the present-day MSL (Figure 10). This would mean a tectonic uplift of at most about 15 m, represented by the vertical arrow (Figure 10), since about 5500 years BP. This amounts to an average uplift of about 2.5 mm/ year.

Further evidence indicating vertical tectonic movements is the slight northward tilting of unit



Figure 10. Time-depth diagram showing the relationship between Holocene sea-level rise and local tectonic uplift at Cortegaça beach.

1, between an index point of 6 m at Cortegaça beach, and 3 m at Esmoriz (Figure 11). This is also shown by units 2 to 4.

Small-scale folding in Units 1 to 4, and the podzol on top of unit 5 at Esmoriz (Figure 11), have been attributed to neotectonism (GRANJA, 1991b).

In accordance with the general trend, the podsol level of unit 5 also tilts towards the north between an index point of 7.5 m at Cortegaça beach and 4 m, over a distance of about 800 m, at Esmoriz beach (Figure 11). However, the neotectonic implications of this tilting are vague since it could be the expression of the natural palaeo surface.

The evolution from a foreshore facies (Unit 4) to a supratidal aeolian facies (Unit 5) is postulated here to be the result of tectonic uplift rather than of changing environmental conditions related to a declining rate of sea-level rise, or a combination of both processes.

The podzol of Unit 5 was in a supratidal position at about 3500 years BP. This means that the lowest possible position of the top of Unit 5 would have been about 1 m below the present-day MSL (Figure 10). Shortly after this time, at the earliest about 3200 years BP, the podzol was flooded and partially eroded, and Unit 6 (foreshore, intertidal) was formed. The sedimentary structures and the



Figure 11. Cross-section between Esmoriz and Cortegaça beach, showing the tectonic tilting of the sedimentary sequence.

presence of bioturbation are clear evidence of a permanent foreshore environment, not the result of temporary deposits after storm set-up. Furthermore, at the present vertical position of Unit 6, the unit is out of reach of the highest present storm set-up (about 6 m). In the absence of datable material, the period of deposition of Unit 6 is uncertain and might range between 3200 and approximately 1000 years BP (Figure 10). In view of the present position of Unit 6 (about 7 to 8 m above MSL, Figure 3), the amount of tectonic uplift would be at most about 9 m (Figure 10).

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PALEOGEOGRAPHIC RECONSTRUCTION

Vertically, the evolution of the sedimentary sequences can be presented in terms of sea-level rise and vertical tectonic movements, as summarized in Figure 12. A relatively rapid sea-level

Tectonic uplift	Sea level rise	Coastal dynamics	Units	Sedimentary facies	C14 dates (yrBP)
\sim		Retreating coastline	7	Dune sequence	>XV cent.
			6	Shoreface, erosional base	
		Prograding coastline	5	Podzol	950 ± 80 3490 ± 100
pt starte			4	Foreshore .	
			3	Shoreface; local runnels	
		Retreating coastline	2	Washover fans	
	/		1	Lagoon behind barrier	5500 ± 160 6850 ± 60

Figure 12. Review of coastal evolution at Cortegaça beach during the Holocene.

rise during the first half of the Holocene, induced an over-all coastal retreat in NW Portugal (see also GRANJA, 1990; RODRIGUES, et al., 1991). The lagoon (Unit 1) which existed at about 6000 years BP was probably protected by a sandy barrier or shoal on the ocean side. Coastal retreat destroyed the barrier or shoal; its sediment was reworked and shifted inland (Unit 2). Facies changes migrated inland with a probable north-south component, as is shown by the predominantly southward flow direction of the sedimentary structures within the sets. This is the direction of the present-day coastal drift as well. Tectonic uplift during this period was largely overprinted by the rate of sea-level rise.

The decreasing rate of sea-level rise, starting between 6000 and 5000 years BP (JELGERSMA, 1961; VAN DE PLASSCHE, 1982; DIAS, 1987; FAIR-BANKS, 1989), possibly had the same effect as in The Netherlands (BEETS *et al.*, 1992), *i.e.*, temporary coastal progradation. This was probably enhanced by the effects of tectonic uplift, since the average rate of sea-level rise between 5000 and 3000 years BP was about 1.5 mm/year, as compared with the average tectonic uplift of 2.5 mm/year. Facies evolution indicates decreasing water depths: shoreface deposits (Unit 3), followed by upper foreshore to backshore (beach) deposits (Unit 4), and terrestrial aeolian deposits (Unit 5).

However, tectonic uplift was probably not a continuous process. Eventually, sea-level rise dominated again, resulting in coastal retreat once more. During this phase, the top of the podzol was eroded (large-scale scouring seems to have occurred) during the formation of the foreshore deposits of Unit 6. After that, tectonic uplift exceeded sea-level rise again, and a new dune system was formed (Unit 7) by reworking of the older units. This last dune system can be dated as postfifteenth century, because it covers a burial site from that period (GRANJA, 1990). Continuing tectonic uplift led eventually to the high position of the whole sedimentary sequence at Cortegaça beach, relative to the present MSL.

CONCLUSIONS

Study of the outcrops in the sandy cliff of the Cortegaça beach, resulting from very strong erosion south of the Cortegaça groin, challenges the concepts put forward in earlier reports on the sedimentary units in this area.

The cliff is composed of a succession of Holocene subtidal to supratidal sedimentary units. The sequence under study is presented as a first attempt to model the sedimentation process of the area and includes the Holocene sea-level rise and local neotectonism.

Prior to about 5000 years BP, an over-all coastal retreat occurred solely as a result of the Holocene sea-level rise. Tectonic uplift was subordinate to the rate of sea-level rise. Coastal progradation was dominant until about 3000 years BP, a time during which aeolian reworking took place and a podzol profile was formed. The main causes of the coastal progradation were the decreasing rate of sea-level rise, starting between 6000 and 5000 years BP, combined with simultaneous tectonic uplift. Coastal retreat recurred after about 3000 years BP, with the flooding and partial erosion of the podzol landscape nearest to the coastline and the formation of an intertidal foreshore facies. Tectonic uplift became again dominant over sea-level rise around or after 1000 years BP, and the foreshore facies was covered in turn by a post-fifteenth century dune sequence. Total neotectonic uplift in relation to sea-level rise amounts to maximally about 15 m for the lagoonal deposits of Unit 1, and about 9 m for the youngest foreshore deposits of Unit 6. This means an average uplift of about 2.5 mm/year over the last 6000 years. However, neotectonism was probably not a continuous process and variable rates alternated with periods of tectonic quiet.

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