

## **SEDIMENTARY RESPONSE TO SEA-LEVEL CHANGES OF PORTUGUESE LOWLANDS SINCE THE LATE GLACIAL – A MULTIDISCIPLINARY APPROACH**

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### **RESUMO**

Apresenta-se um estudo multidisciplinar de reconstituição paleoambiental de zonas húmidas do SW Português desde o Tardiglacial. Os dados foram obtidos em testemunhos de sondagem efectuadas em lagunas e estuários a diferentes distâncias da actual linha de costa permitindo avaliar variações laterais de fácies. Os resultados indicam sedimentação terrestre fluvial até cerca de 10000BP contemporânea de uma linha de costa distante e nível de base baixo. Durante a primeira metade do Holocénico, os vales e depressões existentes foram inundados em consequência da subida rápida do nível do mar, formando rias e golfos, nos quais o máximo transgressivo data de 5500-5000BP. Na segunda metade do Holocénico, a acentuada desaceleração do ritmo transgressivo favoreceu o desenvolvimento de barreiras detríticas, originando lagunas costeiras que evoluíram como tal até ao presente, perdendo profundidade e superfície molhada. O registo geológico correlativo corresponde a um ciclo sedimentar completo, com fase transgressiva seguida de outra regressiva, ambas associadas a eustatismo positivo de ritmo sigmoidal. O balanço entre a variação do nível médio, sedimentação e tectónica sugere que até 5500-5000BP o eustatismo global controlou a evolução das zonas húmidas do SW Ibérico; posteriormente, factores locais (disponibilidade sedimentar, permeabilidade da barreira, actividade antrópica) adquiriram papel preponderante.

### **ABSTRACT**

This work presents the results of a multidisciplinary study on the paleoenvironmental changes recorded in SW Portuguese lagoons and estuaries since the Late Glacial. Several cores have been retrieved from the lowlands, in more distal or proximal locations relatively to the present-day shoreline to account for spatial facies variability. Prior to 10000BP sedimentation is of fluvial facies, induced by a low sea level and a distal shoreline. During the Early Holocene the previous erosional depressions have been rapidly drowned, creating rias and wide gulfs, the transgressive maximum being recorded around 5500-5000BP. In the second half of the Holocene the accentuated decrease on mean sea-level rise rate triggered the development of detrital barriers transforming the drowned areas into coastal lagoons which remained as such until present, however reducing their surface and depth. The geological record represents a complete sedimentary cycle, which includes a transgression followed by regression, both associated to positive eustatism with a sigmoid rithm. The balance between sea-level, tectonics and sedimentation suggests that prior to 5000-5500BP eustasy was dominant in forcing coastal change and controlled the sedimentation patterns of SW Iberian lowlands, while after that date local forcing factors (sediment supply, barrier permeability, anthropogenic influence) became pre-eminent, exceeding those of global character.

Palavras-Chave: transgressão holocénica, regressão do litoral SW, ciclo sedimentar, lagunas e estuários

Key-words: Holocene transgression, SW Portugal Holocene regression, sedimentary cycle, estuaries, lagoons

### **1. INTRODUCTION**

During the last 18 ka important changes of global scale in climate (ranging from full glacial to interglacial) and in sea-level (from low to present-day level) occurred, driving significant transformations in the landscape in the middle latitudes of the Northern Hemisphere, where the Portuguese coast is included. The complexity of the tectonic, morpho- and bioclimatic systems, added by variations in the response of the shelf to glacio-isostatic forcing, which is to a large extent of regional to local character, inhibit the construction of a single sea-level curve of worldwide value and of a unique model of environmental evolution. Yet, it is possible to find broad similarities in the main climatic stages that followed in this period; there is general agreement in dating the last glacial maximum of circa 18 000 BP (Bell & Walker, 1994) and despite some variability in the figures reported for the contemporaneous low-stand, 120m below present-level may be taken as a reasonable or minimum estimate in both margins of the North Atlantic (Jelgersma & Tooley, 1995). Since then, climate changed in general towards amelioration but following a non-linear pattern. In fact, a

tion but following a non-linear pattern. In fact, a short-lived cooler episode, the Older Dryas Stadial (12-11.8 Ka BP) separates the earlier Bölling Interstadial from the succeeding Allerød Interstadial. Between 11 and 10 ka BP another climatic cooling occurred, referred in Europe as the Younger Dryas Stadial. Finally, a climatic amelioration began at around 10 ka BP, the beginning of the present-day interglacial (Holocene). In consequence, rates of sea-level change varied during the last 18 ka and two distinct periods can be recognized: an earlier period, from 18 ka to 6 ka, of rapid sea-level rise, during which the present-day rate of change has been exceeded by at least a factor of ten, due to transfer of water from mid and high latitude ice masses into the oceanic reservoir; in places, the Younger Dryas is marked by a temporary reversal of this trend; the period from 6 ka to the present, when sea-level rise decelerated and local and regional processes (isostasy, subsidence, sediment supply, anthropic activity) became pre-eminent (Jelgersma & Tooley, 1995).

Studies on the Portuguese coast and shelf suggest that sea-level followed this pattern in general terms. These studies began in the middle 1980's, the first tentative curve of sea-level change during the last 20ka having been proposed by Dias (1987) and improved later by Rodrigues et al., (1991). The major features shown in this model since the Lateglacial include (Fig. 1A): an episode of rapid sea-level rise that attained circa -40m at the end of the Bölling-Allerød Interstadial; a sea-level fall to circa -60m at the end of the Younger Dryas Stadial, followed by a second period of rapid rise in sea-level which reached circa -20m between 9000 - 8000BP; since then, the rate of sea-level rise decreased, the present-day level being attained after 5000BP.

From the 1990's onwards the systematic study of cores taken from SW Portuguese lowlands yielded information on their paleoenvironmental evolution and sea-level fluctuations throughout the last 14ka (e.g. Bao et al., 1999; Cruces et al., 1999; Freitas et al., 1999, 2002a, 2002b, 2003a, 2003b; Cearreta et al., 2003; Queiroz & Mateus, 1994; Santos & Goñi, 2003). More recently, similar work has been initiated in the NW estuaries (e.g. Drago et al., 2002). The sedimentary record of these lowlands keeps a signature of the afore-mentioned two contrasting periods of sea-level rise. Before 6000-5000 BP the sedimentation has been essentially controlled by global scale forcing factors with emphasis to sea-level, while after 6000-5000 BP the local forcing factors overwhelmed the global ones.

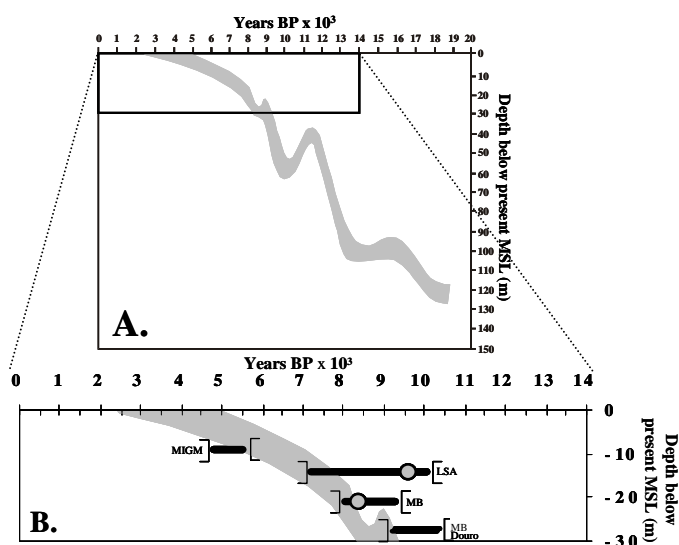


Figure 1: A – Sea-level curve of Dias (1987). B – Plot of sea-level data discussed in text. Dots represent interpolated ages.

## 2. STUDY AREA

The coast under study extends along 140km south of Cape Roca (Fig.2) and is high energy and high-mesotidal. It comprehends two broad homothetic arcuate segments – Trafaria-Espichel and Tróia-Sines – which include the coastal lagoons of Albufeira, Melides and Santo André. These barred lowlands correspond to the final stages of evolution of former river valleys or coastal embayments drowned by the Holocene transgression.

The lagoon of Albufeira is located 20 km south of Lisbon (Fig.2) and presents a flooded surface, maximum width and length of 1.3 km<sup>2</sup>, 625 m and 3.5 km, respectively. It has an elongate shape, its major axis trending northeast-southwest aligned with the Apostiça valley. The lagoons of Melides and Santo André are located 20 and 15 km north of Sines (Fig. 2). The Melides lagoon occupies an elongated flooded surface of 0.4km<sup>2</sup> while the Santo André lagoon extends across 2.5 km<sup>2</sup> and displays a more complex shape (Fig. 2). The average depth and stored volume of water vary seasonally, the Melides' lagoon being generally shallower throughout the year.

## 3. METHODS

Each area has been extensively cored and sediment samples studied for sedimentology (texture and composition), geochemistry (major, minor and trace elements, isotopes), mineralogy (clay minerals) and paleoecological content (foraminifera, ostracoda, diatoms, calcareous nannoplankton, pollen); significant levels have been dated using <sup>14</sup>C. The information obtained provided an insight into the paleoenvironmental features and local variation and allowed to select representative boreholes (LSA, cored in the alluvial plain of the main tributary of Santo André lagoon; MB, MC and MIGM, cored in the Melides lagoon, the former in the backbarrier area and the latter two in the alluvial plain of its main tributary; APO and AM in the alluvial plain of Albufeira lagoon) – Figure 2.

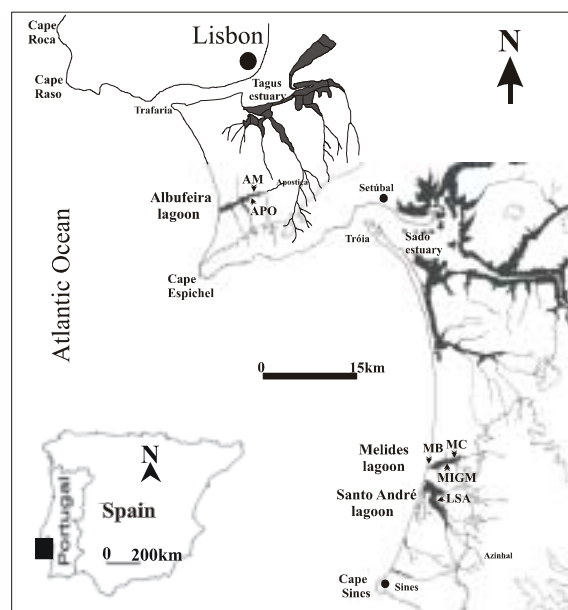


Figure 2: Location map and study area. Arrows indicate coring sites. Filled surfaces correspond to lagoonal and estuarine environments.

## 4. RESULTS

The coastal sedimentary environments of the Portuguese SW coast contain a reasonably complete sedimentary record of the last 14 ka, consisting of several lithostratigraphic units that differ according to the location of the cores relatively to the present-day coast (in a more proximal or distal position) which can be spatially

correlated (Figure 3). In the littoral (MB) and alluvial proximal cores (LSA and MIGM) four units have been considered:

Unit I – consists of 7 – 16 m of barren, minerogenic detrital material deposited under variable energy levels. These basal sediments, which yielded a maximum age of 14160 BP, accumulated while the shoreline was at some distance westward; marine-borne elements (e.g. I, Cl, Br, S) remain below detection limit and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is high (Freitas et al., 2003a).

Unit II – consists of finer sediment, the organic matter and bioclastic contents increasing in proportion, deposited in the interval post 10000 to 5500-5000 BP; marine-borne elements occur in measurable, some times significant, concentrations, and the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is consistently low (Freitas et al., 2002a; Freitas et al., 2003a). The assemblages of foraminifera, ostracods, diatoms and calcareous nannoplankton (Cearreta et al., 2002; 2003) are characteristic of marine to brackish water, show maximum abundance and diversity, the open marine influence increasing towards the top. The thickness of this unit decreases inland (7m at MB and few centimetres at MIGM).

Unit III – is formed by 7 to 9m of sediment varied in texture, with high values of organic matter and bioclasts; the paleoecological and geochemical are consistent and indicate alternating episodes of brackish with freshwater sedimentation, the latter usually associated with enrichment in pyrite denoting anoxic conditions (Freitas et al., 2003a; Cearreta et al., 2003). An erosive surface truncates the top of this unit, defining a sharp contact with the uppermost sediments.

At APO and AM, the lower unit (dated post circa 7000 BP) is made of 5m of organic mud and peat accumulated in freshwater environment, under variable water table and inundation levels, as indicated by the local pollen record (Queiroz & Mateus, 1994): maximum flooding persisted until approximately 4350 BP and was followed by pronounced terrestrialization until 3200 BP; a second rise of the water table is detected towards the top of the unit, which is diachronic possibly due to extensive erosion at APO. The pollen assemblages include those of dune species after 5140 BP and these components increase in abundance towards the top of this unit. At MC the lower unit (dated post circa 5500 BP) consists of 2m of highly organic sediment (organic matter content may reach 90%) similarly deposited under variable water table: a lower level episode is recorded between 5540 and 3500 BP and a higher level followed until 950 BP.

The upper unit capping the three cores is made of 1 to 2 m of terrigenous, essentially minerogenic sediment, similar in texture and composition to those of unit IV described in both alluvial proximal cores.

## 5. DISCUSSION

The multidisciplinary study of the cores retrieved in the wetlands of SW Portuguese coast allows the establishment of a conceptual evolutionary model for these areas since the Late glacial. Prior to 10000 BP sedimentation was of fluvial facies, consisting of floodplain and crevasse splay/levee deposits (Unit I of MB, LSA and MIGM), during a period when sea-level remained below 30m. Sediment input was terrestrial and resulting from intensive weathering and erosion in the adjacent watershed.

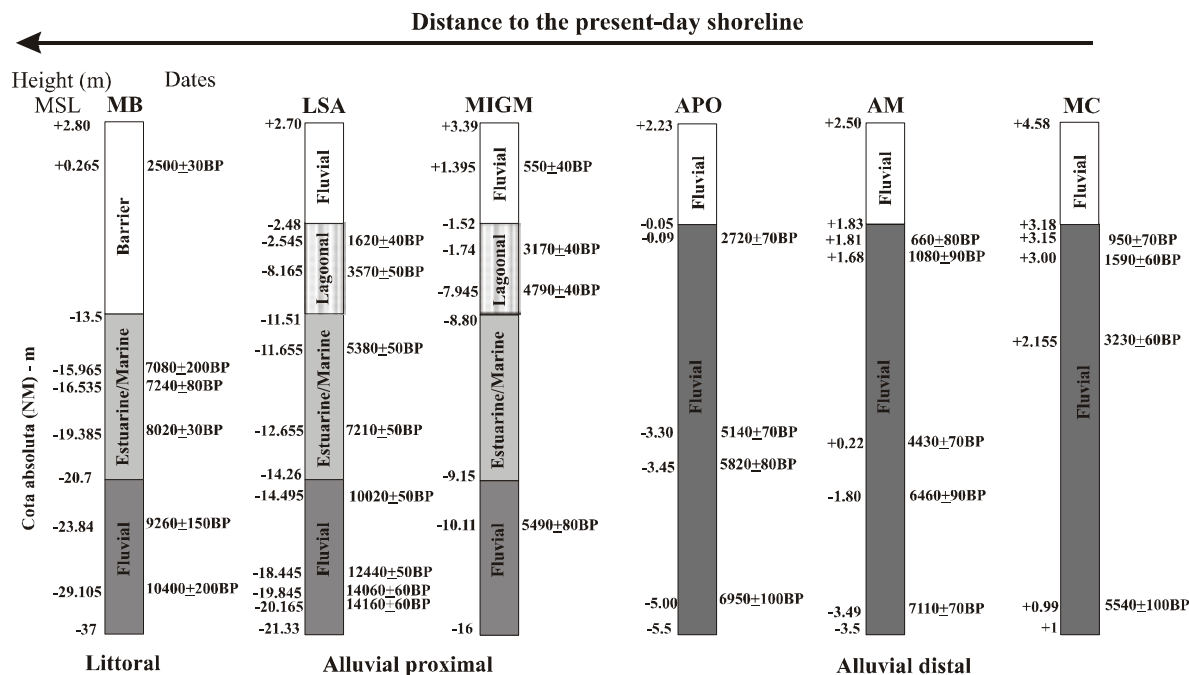


Figure 3: Schematic representation of facies succession found in boreholes referred in text. Note different scales.

Unit IV – in LSA and MIGM it consists of circa 5m of essentially detrital and minerogenic sediments which share similarities with those forming the basal unit and deposited after 3000 BP. In core MB the top unit is formed by circa 16m of monotonous coarse sand, free of organic matter and very low values of bioclasts and rests directly over Unit II.

In the alluvial distal cores (APO, AM and MC) the lithostratigraphic arrangement is simpler and consists of two contrasting units.

During the Early Holocene the inherited incised valleys and lowlands have been drowned by the sea, creating rias and wide gulfs; this flooding progressed nonlinearly in time: the first localised and ephemeral oceanic incursions alternating with fluvial discharge events gave place to persistent marine inundation which reached maximum expression around 5500-5000 BP. Unit II of littoral and alluvial proximal cores bears clear signature of marine influence, though its sedimentary expression reduces inland. Based on the studied proxies, marine water did

not reach the sites where the distal cores were taken; however, sedimentation in this time interval reflects important fluctuations of the water table which depend on the regional, marine-dependent base-level.

The occurrence of open marine flooding at LSA is clear in the sedimentary record circa -14m and was dated in the range 10020-7210BP, the interpolation procedures indicating that it most probably happened in the first half of this time interval (Fig. 1B). At MB, persistent marine inundation is recorded in sediments deposited shallower than circa -21m and dated between 9260 and 8020BP, with an interpolated more probable age located in the late half of this time interval (8390BP). In this location, this episode has been preceded by four ephemeral incursions of the sea, the lowest one occurring at circa -27m with an age in the range 10400-9260BP (Fig. 1B). At MIGM, the marine flooding is evident later, [5490 to 4790BP], at circa -9m. Although scarce, the sea-level markers obtained for the Middle Holocene seem to validate the lower boundary of Dias' (1987) curve by this time, suggesting that the present day sea-level had been probably not attained before the Late Holocene. The data may indicate a more pronounced deceleration of the relative sea-level rise rate in the beginning of the Middle Holocene than previously recognized.

In the second half of the Holocene detrital barriers developed, transforming the drowned areas into coastal lagoons. Sedimentation of lagoonal facies is represented by Unit III in LSA and MIGM while borehole MB cored the contemporaneous barrier. The lagoonal environments remained as such until present, alternating periods of complete isolation from the ocean with epochs of frequent barrier breaching; the former essentially correspond with freshwater paralic sedimentation and the latter are represented by brackish deposits. The depth and wet surface of the lagoons reduced progressively due to the progradation of the alluvial sedimentation front (in the form of alluvial fans and flood plain deposits - Unit IV) over former lagoonal deposits. Seaward, flood dominance contributed to the shoaling of the lagoonal margin but no traces of roll over have been found so far.

The Late glacial and Holocene sedimentary record of the studied lowlands indicates the existence of a complete sedimentary cycle; this cycle includes a transgressive phase followed by a regressive phase, both associated to positive eustatism (Figure 4). The occurrence of a transgression (progress of the coastline inland) or regression (progress of the coastline offshore) results from the balance between eustatism (E), tectonics (T) and sedimentation (S):

Transgression  $\Rightarrow E-T-S > 0$

Regression  $\Rightarrow E-T-S < 0$

Assuming that  $T=0$  in this section of the coast, it may be concluded that prior to 5500-5000 BP the eustatic forcing factor, translated by rapid sea level rise, dominated the pattern of coastal change in the SW of Iberian Peninsula. The deceleration of the sea level rise rate post 5500-5000 BP together with large sediment availability triggered the establishment of detrital barriers, which remained until present as important features determining the evolution of these lowlands. In this time period, the local forcing factors (e.g. sediment availability, permeability of the barrier, anthropogenic influence) become dominant. The balance between the sea level rise rate and the amount of sediment delivered to these areas is negative, leading to the regression expressed by sedimentary Units III and IV, despite the positive eustatism that persists throughout the Late Holocene. These results were recently confirmed by inedited data from a continuous record retrieved from the Mira estuary.

## 6. CONCLUSIONS

The results presented above indicate increasing complexity of sedimentation in lagoonal systems with decreasing distance to the shore; alluvial distal deposits are typically of fresh-water, low energy facies, monotonous in composition, enriched in fermented plant debris and, to a large extent, organic, carbonate free, representing confined sedimentation in paralic, open water environments that experienced pronounced changes in depth. Proximal deposits (littoral and alluvial proximal) include significant contributions of shell material and minerogenic sand, added by mud and organic mud, indicating higher energy-levels and rapid changes of the hydrodynamic controls.

In general, the facies succession records two major thresholds: the earlier separates continental, fluvial dominated sedimentation from extensive unrestricted marine flooding of the lowlands; the second corresponds with the widespread formation of detrital barriers which enclosed former gulfs, rias or estuaries and transformed them into coastal lagoons or barred estuaries that evolved as such until present.

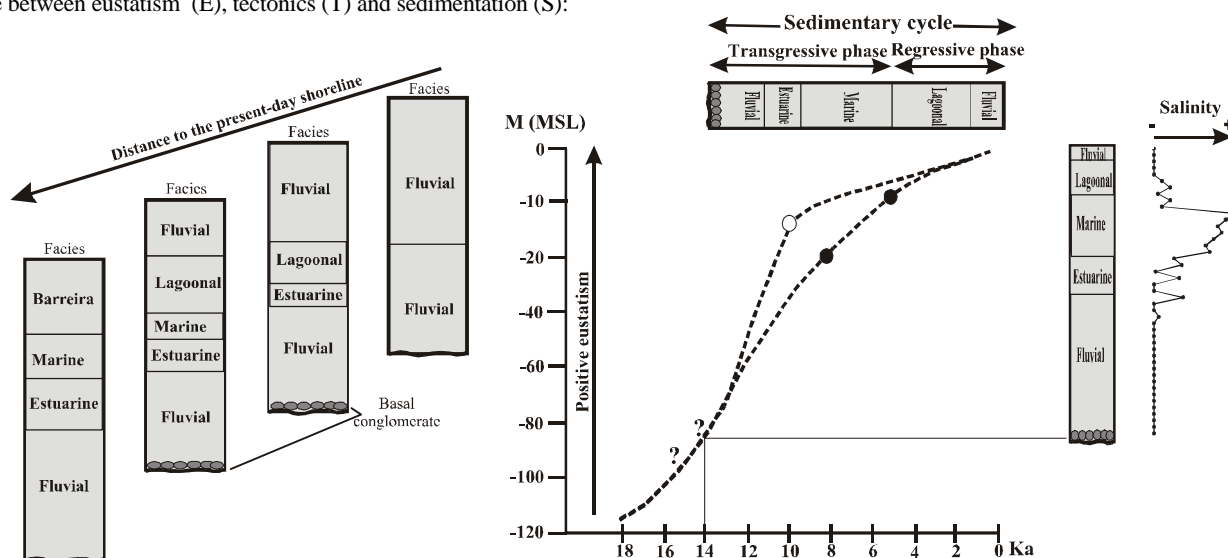


Figure 4: Schematic representation of the Late glacial and Holocene sedimentary cycle in the SW Portuguese coast and sea level curve. Filled dots represent data obtained at MB and MIGM and open dot refers to data from LSA core.

The relative sea level rise rate along the Portuguese coast increased to +1.5 mm/year (Dias & Taborda, 1992) since the early 19<sup>th</sup> century in consequence of global warming driven by anthropogenic activity (IPCC, 2001). This figure is similar to average rate of change reported elsewhere in the world and significantly higher than the one characterizing the Late Holocene. Throughout the 20<sup>th</sup> century the Portuguese coast displayed signals of increasing sediment starvation which resulted from the cut off of terrestrial sediment sources and led to widespread erosion of significant ribbons of exposed coast. However, the evolution of Portuguese southwestern wetlands is still towards siltation, therefore maintaining the regressive signal in spite of the acceleration of the sea level forcing.

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