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Coast line evolution in Portugal since the Last Glacial Maximum until present — a synthesis

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Abstract

An effort has been made to assemble a data set on the evolution of coastal morphology of the West Iberian Continental Margin in Portugal, which has occurred since the Last Glacial Maximum. In this integrated review a particular attention was given to the analyses of coastline shaping phenomena on different time scales. Several overlapping processes such as shore erosion, local sediment supply rate, climatic changes, anthropic impacts and mean sea level rise (MSLR) were identified and their combined effects assessed. The eustatic see level rise appears as a principal factor in shaping the shore line contour until mid Holocene. Since then, the non eustatic factors namely the terrigenous sediment supply rate and the dynamics of barriers and spits systems became dominant in the evolution of the near shore morphology. Since the 15th century AD, the anthropogenic activities, namely deforestation and land cultivation contributed decisively to the positive sedimentary balance in the Portuguese coastal zone. Finally, the multiple damming of the major rivers in 20th century and exploitation of sand and gravel from the river beds led to the sediment starving of the coastal zone and generalized shore line retreat. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The systematic survey of the West Iberian Portuguese Continental Shelf started in the beginning of this century and led to the publication of 8 "Lithological submarine charts of the Portuguese coast" between 1913 and 1928. Due to this undertaking, whose principal objective was an inventory of the sea bottom destined to fishing community, Portugal became one of the first countries to posess a complete cartography of the sedimentary cover on the continental shelf. The post glacial evolution of the shelf became a pivotal idea in the sedimentological and geomorphological studies of the 1970s, following the growing economical importance of the coastal fringe and general awareness about the necessity of a better understanding of the impacts of global climatic changes on coastal zones. As a result, several tens of theses were presented and several hundreds of papers were published during the last 20 y, many of them in national journals of limited circulation and consequently of limited impact on the internationally known state of the art in the matter. Therefore, given the volume of this accumulated information it seems

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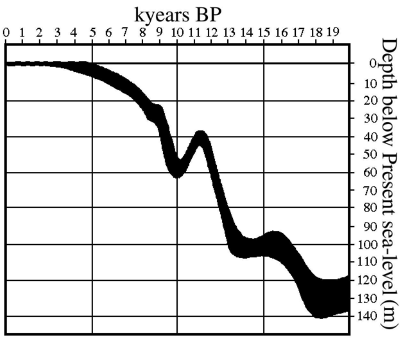

Fig. 1. Sea level rise curve for the N part of Portuguese shelf since the LGM. The curve width express the quantitative uncertitude with respect to sea level and age.

necessary now to attempt a synthetic analyses of gathered and processed data and to identify existing gaps of current knowledge.

2. The sea level changes

Since the publication of the first sea level curves (Faibridge, 1961; Jelgersma, 1961), the regional expression of this postglacial phenomenon received a lot of attention throughout the world. The first, and until now, the sole proposal of a relative mean sea level (RMSL) rise curve in Portugal (Northern Part) during the last 18 ky was published by Dias (1985) (Fig. 1). Given the scarcity of radiocarbon dating, other data were also considered to establish this curve, namely the geometry and positioning of the sedimentary bodies, geomorphological features on the shelf and their inferred genesis and relative ages. This procedure was confirmed in part by C-14 dating associated with geomorphologic analyses leading to the reconstruction of shoreline evolution events, which accompanied deglaciation and occurred after it during Holocene.

According to this curve, the sea level was situated at about −130 to −140 m during the Last Glacial Maximum (LGM) and later progressively rose to stabilise or slightly decrease at −100 m level ca 16 ky BP. Since 13 ky BP a very fast sea level rise occurred reaching −40 m between 12 and 11 ky BP, followed by an equally fast descent to −60 m in the response to the Younger Dryas event. Around 10 ky BP another period of fast sea level rise initiated, slowing down towards 8000 y BP, when the RMSL approached −20 m. The present sea level was reached ca 3500 y BP.

Other works carried out on different segments of the shelf (viz. Moita, 1971; Monteiro and Moita, 1971; Monteiro et al., 1982; Moita, 1986; Quevauviller, 1986; Quevauviller and Moita, 1986) tend to confirm the applicability of this curve to the entire Portuguese segment of the Iberian Shelf.

The Holocene sea level variations are poorly known despite the existence of published data on Sado Estuary (Moreira and Psuty, 1993) in the central zone and on the Ria Formosa Lagoon (Bettencourt, 1994) in the southern zone of Portuguese coast. New radiocarbon dating of lagoon and dune sediments from the Northern littoral, which point out on neotectonic acivity in this area, were published recently (Granja and Carvalho, 1992, 1995), however, without proposing any RMSL curve. Nevertheless, the maximum tectonically controlled vertical displacements during the Quaternary are several order of magnitudes smaller than eustatic sea level changes and therefore do not affect the applicability of the sea level rise curve.

Despite the existence of some interpretative references or mere hypotheses, historical sea level variations remain almost completely unknown. Otherwise, the sea level changes of this century were studied on the basis of an analysis of the tidal gauge record from the Cascais Station. According to Taborda and Dias (1988) and Dias and Taborda (1988, 1992), the RMSL lowered at a rate of 0.5 mm/y between 1882 and 1920. Since then the trend inversed and the observed rise reached the present rate of 1.7 mm/y and has been interpreted as essentially the consequence of thermal expansion of the ocean.

3. The Glacial Maximum

At 18,000 ky BP the shoreline was close to the shelf break (Fig. 2) corresponding to the Chappel—Shackleton minimum sea level, estimated in Portugal to be at −140 m (Dias, 1985). According to numerous authors (e.g. McIntyre et al. 1976; Molina-Cruz and Thiede, 1978), the polar front reached the latitude of Northern Portugal driving the winter coastal water temperature below 4°C. Otherwise, the open sea

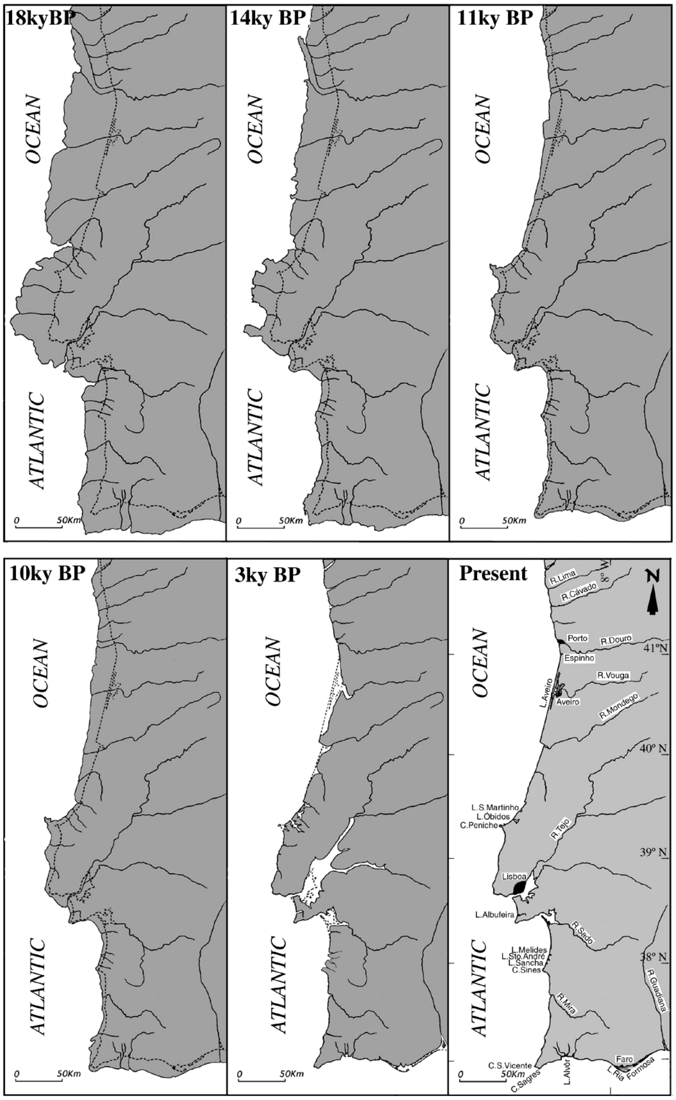

Fig. 2. Shore line evolution along the Portuguese coasts since the LGM. Based on Rodrigues and Dias (1990), Rodrigues et al. (1991) and Dias et al. (1997).

temperatures, a few kilometers off the coast remained several degrees C higher (Thiede 1977, 1978; Molina-Cruz and Thiede 1978). The distribution of cold water planctonic foraminifera assemblages points out the existence of a southern coastal current parallel to the Western Iberian Margin (Molina-Cruz and Thiede, 1978). Icebergs at the latitude of Oporto and further to the South were most probably a common feature (Guillien, 1962) indicated by the presence in abyssal sediments of frequent striated clasts of igneous rocks unknown in Iberia. Coastal upwelling was more vigorous than that observed presently (Rognon, 1980). The summital parts of the Geres and Estrela mountain chains were covered by local glaciers (Coudé-Gaussen, 1978; Daveau, 1980; Coudé et al., 1983; 1986) and close to the coast numerous evidences of frequent freezing exist (Daveau, 1973; Carvalho, 1983; Raynal, 1985, 1986).

The river catchments, which extended far to the shelf, received more rainfall due to a longer than at present wet season comprising autumn and winter (Daveau, 1980). Higher pluviosity combined with the effect of spring ice melting maintained high river discharge and consequently caused more sediment supply to the coastal zone, as recorded by sedimentary and geomorphologic features (Dias and Nittrouer, 1984; Magalhães and Dias, 1992; Abrantes et al., 1994; Cascalho et al., 1994). Lower salinity of coastal waters in the Northern area resulted from an increased influx of fresh water drained by rivers, which were mostly tributaries of one principal tectonically biased course (Rodrigues et al., 1991). This main North flowing river discharged into a hyposaline bay, as confirmed by microfaunal evidences (Nascimento and Silva, 1989). The extremely narrow shelf was a very energetic environment due to sea bottom inclination and very limited long wave refraction. The predominant western winds and waves (Pujol and Turon, 1974) induced either southward or northward longshore drift, as compared to general southwards trend observed at present. In these conditions the terrigenous load transported by rivers was almost directly discharged onto the continental slope (Dias et al., 1997).

4. Tardiglacial — towards the deglacial period

The deglaciation (phase II of Ruddiman and McIntyre, 1981) drove the littoral zone toward the mainland, and ca 16 ky BP the sea level stabilised at approximately −100 m for the next 3000 y. Several geomorphological features including abrasion platforms, sea cliffs and off shore bars could develop during this phase on the Portuguese shelf. These features were identified through geomorphologic analyses (Musellec, 1974; Dias, 1985), light seismic profiling (Musellec, 1974; Rodrigues and Dias, 1989; Rodrigues et al., 1991) and remotely operated vehicle (ROV) direct observations (Dias et al., 1991, 1992). Climatic and hydrographic conditions were similar to pleniglacial, thus, the outer shelf was covered mainly by coarse grain sediments (Dias and Nittrouer, 1984; Abrantes et al., 1994) remaining until present as relict deposits. Submarine canyons were the main ways of transfer of terrigenous sediments to the slope and continental rise. In fact, a series of cores taken along the Portuguese continental margin during the FAEGAS IV cruise (Faugères et al., 1984) revealed that between these canyons the on-slope sedimentation rates were almost nil.

At greater depth these rates were over 1.1 cm/ky and thus substantially higher than at present. Silt-clay sediments cut by erosive discontinuities predominate in these deposits and frequent turbidite and debris flow levels of clay clasts and coarse-grained sediments bear witness to a high rate of sediment flux through the canyons. Asymmetric distribution of measured sedimentation rates on the flanks of the terminal segment of Nazaré Canyon (20 cm/ky on the N flank and 1.6 cm/ky on S flank) suggests Coriolis force biased deflection of turbidity currents (Faugères et al., 1984).

5. The deglaciation

The 13–11 ky BP period brought substantial changes to climate and oceanic circulation in the North Atlantic. The reappearance of the Gulf Stream provoked the rapid vanishing of sea and continental ice in Western Europe (Ruddiman and McIntyre 1973) and a consequently northward shift of the climatic belts (Rognon, 1976, 1980; Ruddiman and McIntyre, 1981). In N. European terminology this climate warming corresponds to Bolling and Allerød stages (van der Hamen et al., 1971) or Bolling–Allerød (Mangerud, 1977; Berglund, 1979) and Ruddiman and McIntyre (1981) IIIa phase.

Palynological data from the Bay of Biscay and Atlantic deep cores of Portugal, which may be extrapolated to the entire NW Iberia (Roucoux et al., 1999), indicate a shift from predominantly grassland vegetation to arboreal vegetation (Menendez-Amor and Florschutz, 1963; Duplessy et al., 1981). During the two millenia, the ocean temperature was similar or slightly warmer than present (Duplessy et al., 1981) and the sea level rise velocity was close to its maximum. Unable to equilibrate with such a rapid rise of sea level, which approached −40 m at the end of deglaciation (Dias, 1985), the estuaries effectively became sediment traps exporting to the shelf only minor quantity of fine sediments. Such conditions also explain the striking lack of any remnant of preserved coastal morphology in the present day middle to inner shelf fringe.

6. The Younger dryas

During this cold phase (attributed to massive inflow of the ice meltwaters into the Atlantic Ocean), the polar front migrated southwards and reached the latitude of Galiza (Ruddiman and McIntyre, 1973; 1981) driving the sea surface temperature below 10°C. In NW Spain, vegetative change tracked the worsening of climatic conditions by changing once more from deciduous forest to grassland (Nonn, 1966). On the Portuguese shelf, the cool dry phase (IIIb of Ruddiman and McIntyre, 1981) left conspicuous remnants in the form of extensive coarse grain sediment bodies (Dias, 1985; Rodrigues and Dias, 1989; Rodrigues et al., 1991; Magalhães and Dias, 1992; Abrantes et al., 1994; Cascalho et al., 1994). The massive influx of these sediments on the shelf can be attributed to the renewed river erosion of the sedimentary infill of estuaries in response to the lowering sea level. Most of these sand and gravel grains are very well rounded characterised by presence of ferruginous coatings precipitated during the subaerial exposure (Dias et al., 1980–1981; Dias and Nittrouer, 1984).

The littoral zone had the characteristics of a desert as judged from the abundance of mass wasting deposits (Daveau, 1980, 1986) and consolidated (presently) aeolian deposits in Alentejo and Western Algarve (Pereira, 1985, 1992). Carbonate cemented fragments of sands are also abundant on the shelf and probably represent the remnants of calcretes and beachrocks formed during this dry climatic phase. At −40 to −60 m below present sea level, a varied and widespread widespread suite of geomorphologic features like abrasion platforms, cliffs and spits were formed and recently studied through observations by means of ROV deployed cameras and side scan sonars (Dias et al., 1991, 1992). Their generally excellent preservation is attributed to the fast rising of sea level following the Younger Dryas.

7. The Holocene

Between 10 and 8 ky BP the sea advanced very rapidly, rising about 40 m on the Portuguese shelf (Dias, 1985). The boreholes done in terminal parts of the river courses in proximity of present shoreline, revealed usually thick transgressive sequences accumulated in estuarine environments what is also confirmed by seismical profiling (Carvalho and Rosa, 1988). Boski et al. (1998) reported an accumulation of 20 m series of intertidal clayey sediments between 10 and 7 ky BP, documented by boreholes drilled through the entire Holocene sedimentary sequence in Guadiana River Estuary. However, sporadic oscillations in marine advance were occurring as documented by Galopim de Carvalho and Ribeiro (1962) in the Leça River inlet (Northern Portugal). The approach of the present sea level after 6 ky BP by the postglacial transgression (Hoffman, 1989) is reflected by a more diversified pattern of infilling of the estuaries and the sharp rising of planctonic/benthic foraminifera ratio in the estuarine record (Boski et al., 1999). New coastal features like barriers, spits and lagoons developed after 4000 − 5000 y BP at the time when the rates of sea level rise were strongly attenuated (Bao et al., 1999) and subsequently became more dependent on local factors than on the eustatic one. Hoffman (1989) observed the increase in continental erosion during the Roman times ca 2 ky BP, which led to the progradation of coastline. The shoreline remnants at the sea bottom left behind by Holocene transgression were recently surveyed using scuba diving observations in the zone of Arrábida (Groupe ERLIDES, 1992; Pereira and Regnaud, 1994; Regnauld et al., 1997) and on Algarve Shelf along the southern coast of Portugal by Teixeira (1998) who described a series of aligned shore scarps.

Data from the Sado Estuary (Moreira and Psuty, 1993) and Ria Formosa Lagoon (Bettencourt, 1994) indicate that the rising sea reached its present level between 5 to 2.5 ky BP. Notwithstanding their local importance, the above cited data does not permit the calculation of precise figures for the entire shelf. It is important to stress in this point that due to the narrowness of the West Iberian Continental Shelf the classical stratigrahic methods, which served to elaborate chronostratigrapic scale of the Holocene transgression in NW Europe are not applicable in the Portuguese case. Dating of the ancient, at present submerged coastal features and drilling in the incised estuaries of the most important rivers should bring more data on the time scale of the Holocene transgression.

Despite these limitations the inferred contour of shore line (Fig. 2) corresponding to the moment when the sea level stabilised, was completely different from the present and was characterised by the predominance of rocky cliffs, wide open estuaries and very irregularly incised coasts. Later on these features became "smoothed" through the rapid erosion of cliffs and export of sedimentary load from the estuaries, both of which provided material for the accretion of coastal sand.

8. The historical period

Among the great number of works dealing with the evolution of coastal zones, based on sources such as maps (since 14th century) and written documents, the most noteworthy are the studies of Girão (1941), Boléo (1943), Martins (1947), Castelo-Branco (1957) and Weinholtz (1978).

From the analysis of these sources and data on infilling coastal lagoons (e.g. Alves et al., 1988–1989), it appears that coastline shaping was controlled mostly by climatically biased balance between erosion and supply of terrigenous sediments to the shore, resulting eventually in a series of minor transgressions and regressions. The studies of fluvial navigation documents has led several authors to conclusions about sea level changes in historical times. However, the overlapping of local sedimentation effects with global trends as well as the small draught of ancient vessels seriously limits the applicability of these inferences. Numerous evidences indicate that one period of intense supply of terrigenous material to the shelf occurred in the 10th century AD Drago et al. (1995) observed a sharp increase of sedimentation rates in the silt deposits on the middle and external shelf at the latitude of Oporto during this time. In the Ovil lagoon, sediment infilling occurred as revealed in the dating of peat deposits (1150 ± 45 yr BP) and overlying roots (1050 ± 45 yr BP) in approximately same period (Alves et al., 1988–1989). Finally the 10th century AD maps reveal the existence of a well developed sand spit South of Espinho whose later advance closed the existing gulf and transformed it into the present day Aveiro Lagoon (Girão, 1941; Martins, 1947).

The Little Climatic Optimum between 11th and 15th centuries AD was marked by a decrease in sediment supply to the shelf and possibly also by a slight elevation of sea level (Dias, 1990). Following the worsening climatic conditions in the Little Ice Age between the 15th and 19th centuries (Font Tullot, 1986) and as well due to the deforestation and increasing agricultural land use, the shaping of the coast line became dominated once more by increased sediment supply and resulting constructive processes. In fact this period is characterised by intense sedimentation in estuaries, and formation of coastal dune fields also documented in Spain in the Gulf of Cadiz area (Borja et al., 1999). It was also at these times that the enclosing of Aveiro Lagoon came into term (Girão, 1941; Martins, 1947; Abecassis 1955; Oliveira, 1983) and formed the Alvor Lagoon (Pereira et al., 1994). Through the continuing accretion of barriers, a series of minor estuaries were transformed into coastal lagoons, like the Obidos, Albufeira, Melides, Santo André and other smaller lagoons whose tidal inlets opened only periodically and mostly due to human interventions (Dias, 1990). Several tombolos were accreted in the same period, with connections of islands with the mainland taking place as in the case of Baleal and Peniche (Calado, 1994).

From the above cited, the most spectacular example of rapid coastal evolution is the case of the Aveiro Lagoon (Fig. 2). The present lagoon evolved during ca seven centuries from a gulf approximately 70 km long and 20 km wide at the latitude of the Vouga estuary, separated from the sea only in the north by an incipient sand spit. The process of enclosing the lagoon behind the spit and barrier system involved more than $2\text{–}10^{10}\ m^3$ of sandy sediments accreted mainly since 15th century AD onwards. For the purpose of comparison it is worthwhile to note that the present rate of sediment transport by the longshore current in this area is estimated at ca 1–2 Mm^3 of sand per year. The history of the town of Aveiro is closely related to the evolution of this lagoon. In 16th century AD, it was a prosperous port, which had and easy access from the sea directly in front of the town. The southward progression of the spit and progressive infilling of the lagoon severely hampered navigation driving the original population of 15000 inhabitants in 1575 AD to a meager 3500 in 1797. This trend was reversed by the opening of an artificial inlet in the 19th century AD facilitating the reestablishment of all harbour activities and a renaissance of the town.

The perceptible anthropic impacts on coastal sedimentation date back to 15th century AD and can be exemplified by two case stories concerning the Obidos Lagoon and the Alfezeirão Lagoon.

In Obidos the agricultural activities led to accelerated sediment infilling of the lagoon and of its tributaries. This made agricultural activities progressively more difficult and flooding more frequent. Consequently extensive works, which ended in 1575 were carried out with the aim to improve drainage (Trindade, 1985). However, the removed sediments were eroded and transported to the lagoon during the subsequent period of floods and the destructive cycle of sediment removal—lagoon infilling continues until present day and is responsible for the dramatic reduction of the water depth, which is frequently less than 1 m.

Alfezeirão was an important port in 16th. century AD a with capacity to receive few tens of boats (Loureiro, 1904). But it became idle in that century due to lagoon infilling, which was accelerated by intensive land cultivation. In order to maintain commercial activity running, the facility was transferred to Salir do Porto, which was closer to the tidal inlet, but later Salir do Porto had to close its operations due to aggradation of sand. São Martinho do Porto became the next site for the port and its shipyard was very active in the second half of the 19th century AD. Over the next decades, sediment influx to the lagoon apparently was aggravated by unballasting the vessels put an end to the harbour activities. Judging from the available cartographic material the lagoon's initial surface was reduced by ca 80% over those five centuries. The examples cited above have shown that over the period documented by the historical sources, the anthropic activities became progressively a factor whose impact on coastal sediment budget equalled or even surpass the effects of natural phenomena, eustasy included.

9. Twentieth century

The present trend of coastal evolution may be defined as clearly transgressive in contrast to the regressive phase, which lasted until the end of 19th century AD (Dias, 1990). The first well-documented evidences of the coastal erosion date from the 90s of the past century (Oliveira et al., 1982). It is in Espinho (15 km south from Oporto) that the problem of coastal erosion was addressed for the first time through construction of the first shore hard protection structures in 1911. The following decades witnessed aggravation and spreading of shoreline retreat whose quantification was achieved via in situ measurements and aerial photography analysis on several stretches of Portuguese coasts, as shown in the studies of Oliveira et al. (1982), Andrade et al. (1989), Ferreira et al. (1990a), Ângelo (1991), Marques (1991), Bettencourt and Ângelo (1992), Dias and Neal (1992) and Ferreira and Dias (1991, 1992). The measured values of shoreline retreat vary greatly in space and time. However some figures with respect to recent retreat rates may be cited here, as for instance: 3.5 m/y from 1983 to 1991 with local maxima >4 m/y in Forte Novo sector, Algarve (Correia et al., 1994, 1996), 3.9 m/y with local maxima >6m/y from 1980 to 1989 in Vagueira–Areão sector, south of Aveiro, (Ferreira and Dias, 1992), 4.5 m/y with local maxima >12 m/y from 1980 to 1989 in Espinho–Cortegaça sector south of Espinho (Ferreira and Dias, 1991).

The confluence of the following factors acting on a global and regional scale are held responsible for this phenomenon: (i) secular trend of sea level rise; (ii) damming of the rivers for electric power production and/or irrigation purposes; (iii) channelisation of the river courses; (iv) sand and gravel exploitation from the river beds, estuaries, lagoons and beaches; (v) dredging of waterways for navigation; and (vi) alteration of coastal hydrodynamics and sediment transport through coastal engeneering works, namely jetties and shore protection structures (Dias, 1990).

According to the studies of Ferreira et al. (1990b) and Andrade (1991), 10–20% of coastal retreat results directly from sea level rise and the remaining 80–90% from sediment starving of the coasts.

10. Conclusions

Despite the achievements of the recent decade the understanding of the postglacial evolution of Portuguese shelf is still very incomplete. Even with the relative abundance of data from the northern segment of the shelf, the areas South of Cape Mondego lack a consistent data set and therefore should be the focus for future studies. Also, insufficient is the chronostratigraphic data set from the lagoonal and estuarine environments, which should constitute a basis for the reconstruction of Holocene events in the near shore areas. However, one must remember that due to the narrowness of W. Iberian shelf, the classic approach to Holocene stratigraphy based on peat sequences may not be applicable and should be carried out by means of the other methods such as C and O isotope stratigraphy, variations in organic carbon fluxes and palaeoecological reconstructions.

The transgressive observed presently trend results in fast shoreline retreat in several segments of the Portuguese coasts and is mostly of anthropogenic origin. The efforts to mitigate this phenomenon through hard coastal structures have proved to be costly and inefficient.

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