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COMPARATIVE STUDY OF INNER SHELF SEDIMENTS (PLIO-PLEISTOCENE AND PRESENT DAY COVER) IN THE WESTERN PORTUGUESE MARGIN

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Key words: Grain-size distribution, Modal size, Inner shelf, Portuguese Continental Margin.

ABSTRACT

A comparative study between Pliocene-Pleistocene and present day inner shelf deposits, considering both grain-size distribution and the present day hydrodynamic conditions, at west Portuguese Coastal Margin, is conducted. The modal grain-size analysis indicates that the west Portuguese Plio-Pleistocene inner shelf sediments are made of a mixture of several populations. The coarser populations (mode >0.5 mm, 1Ø) result from reworking of previous shoreface and beach deposits after storm events or are related with transgressive ravinement lags. The intermediate population, with modes around 0.125 to 0.250 mm (3 to 2Ø), should be in equilibrium with the hydrodynamic storm conditions in the inner shelf. This population is also the main constituent of the present day inner shelf cover between 10 and 25 meters depth. The finer population, with modes around 32µm (5Ø), is probably deposited from suspension during fair-weather periods. Under the high hydrodynamic winter storm conditions this population remains in suspension and tends to be mobilized to outer shelf locations by downward currents. It is expected that the mud size population proportion in bulk sediment should increases basinward, but this proportion may as well be influenced by post-depositional processes in ancient deposits.

INTRODUCTION

Grain-size distributions of sediments are usually polymodal, reflecting the mixture of various populations. These populations can be derived from different sources and/or transported to the depositional site by different processes. In this work we interpret the significance of grain-size distributions of the present day sediment cover, collected offshore of Areão Beach, and of non-consolidated Pliocene to Pleistocene units, The late Cenozoic of the West Portuguese Margin of Iberia has long been known to have an onshore succession of fine siliciclastic inner shelf sediments, containing fossil faunas correlative of the Piacenzian stage (Zbyszewski, 1949; Teixeira,

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1979). Given their polymodal character, these inner shelf deposits must result from mixing of different populations. The constituent populations may be in hydraulic equilibrium with the hydrodynamic conditions at the depositional site. Nevertheless, they may also be determined by the grain-size of parent sediments or related to post-depositional processes. For this reason, in sedimentological studies it is advised to focus on the constituent populations instead of the bulk grain-size distribution.

The studied grain-size distributions show several well defined modes in a wide range of particle sizes, from clay to gravel, which allows a visual partitioning of some possible populations. As stated by Dias and Neal (1990), although the populations partitioning of a grain-size distribution by the grain-size modes is a less rigorous method and cannot be mathematically validated, it is much more pragmatic and needs fewer calculations. For this reason and because of the wide grain-size distributions, requiring different techniques, in this work there will be no attempt to statistically validate the modal analysis. The interpretations of grain-size data are attempted from the integration of the Pliocene-Pleistocene facies and present day inner shelf sediment texture and hydrodynamic conditions.

MATERIALS AND METHODS

Pliocene and Pleistocene samples were collected in 17 sections, with up to 20 metres of inner shelf sediments, scattered in the central west Portuguese coastal margin (Fig. 1). In thick homogeneous layers a sample was collected at least every 1m. Otherwise, all levels thicker than 0.2 m were sampled. 44 samples were selected for this work. Sand and gravel size was determined by sieving in 1/4Ø increment column for grain-size between -2Ø (4mm) to 4Ø (0.063mm) and in 1/2Ø increment column for grain-size coarser than -2Ø (4mm). Sub samples of grain-size below -1Ø (2mm) were also analysed in a Coulter LS 320 instrument that uses laser diffraction for particle size analysis.

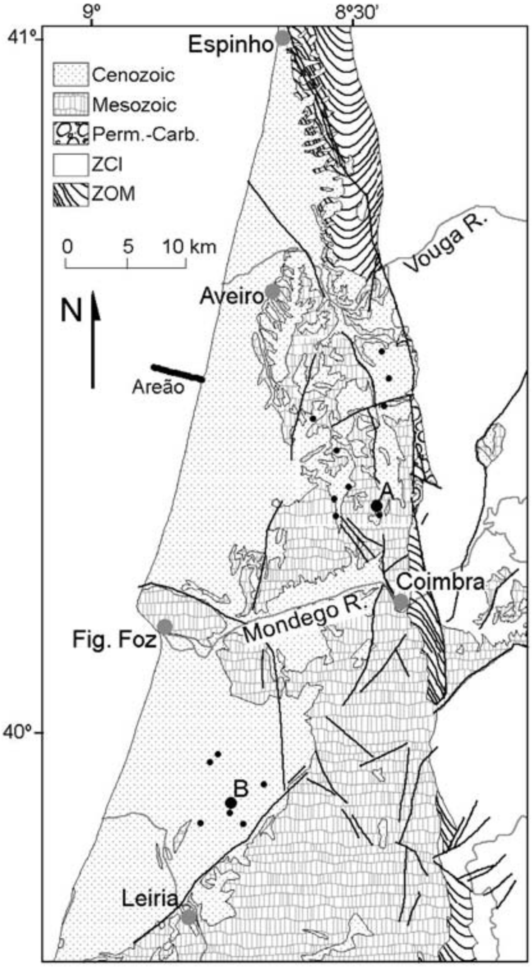

Figure 1:
Geological framework and location of the studied sections (bold dots) and the profile transversal to the shoreline at Areão Beach. A and B are the sections presented in Fig. 6. ZCI: Central Iberian Zone; ZOM: Ossa-Morena Zone.

Present day inner continental shelf samples of the Areão beach on the Northwest Portuguese coast are also reported (Fig. 1). Superficial sediments samples were collected using a Smyth McIntyre grab sampler along cross-shore profiles, from near the breaker down to 30 m depth, under spring high tide conditions. 39 samples collected in July 2001, March 2002 and June 2002 were selected for this paper. The surf zone was not possible to survey because of its

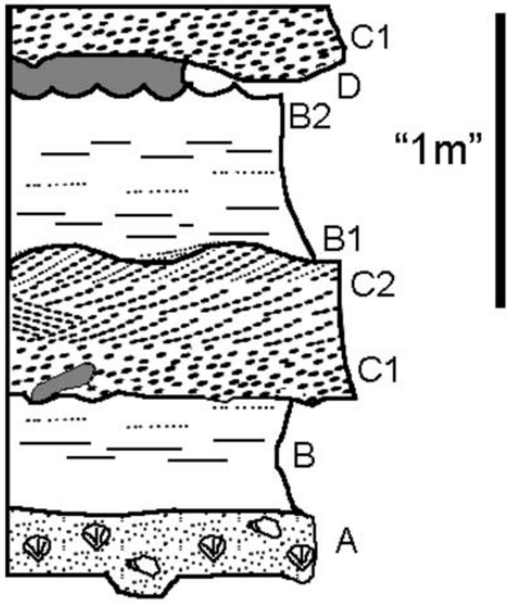

Figure 2:
Schematic log of an inner shelf coarse grained storm sequence (adapted from Cheel and Leckie, 1992 to the studied deposits). The sequence may start with a ravinement lag, usually of gravel size, sometimes with shell enrichment (A). Fine to very fine sand deposits are the most common facies. These sediments may be structureless, show parallel lamination (B1) or oscillation ripples (B2). There are also decimeter thick granule to pebble rich massive beds (C1) that may show megaripples at the top (C2). Sometimes a sequence ends with a thin mud level (D).

high hydrodynamism. Topo-bathymetric profiles data were registered with specific hydrographic survey software connected to an echo-sounder system and a GPS. Elevation data were referred to mean sea level with tidal corrections being made taking into account the Aveiro harbour tidal predictions. All samples were sieved using standard sieves with 1/2Ø intervals. For comparative purposes with the Pliocene and Pleistocene, the present day inner shelf sediments were also analyzed by laser diffraction.

As expected, some deviations between the results of sieving and laser diffraction were detected. Several authors have shown that the average results of laser beam diffractions reaching platy particles indicate a bigger size than the actual volume of these particles (Jonasz, 1991; Konert and Vandenberghe, 1997; Blott and Pye, 2006). Thus, the major deviations arise when platy shaped particles, like mica and clays, are present.

DEPOSITS DESCRIPTION

Pliocene and Pleistocene sedimentary facies

Plio-Pleistocene inner shelf transgressive sediments are widespread on the western Portuguese continental margin. These deposits usually constitute the lowermost Neogene unit, lying on angular unconformity over the basement. Although fairly rare, these sediments may also be found intercalated with prograding gravelly sand coastal sediments. Based on nannofossil content, the lower portion of one of the studied sections has been assigned to the early Piacenzian (biozones *CN 12a* of OKADA and BUKRY and NN16 of MARTINI, *in* Cachão, 1989). Subsequent works over this section pointed to upper Zanclian to lower Piacenzian age (Silva, 2001).

The inner shelf deposits consist of stacking meter scale sediment sequences limited by sharp erosional surfaces. Sequences are dominated by fine sand beds with intercalations of coarse sand to conglomerates and rare mud sediments (Fig. 2). Sometimes the depositional unit starts with a coarse-grained, several decimetre thick, conglomerate bed, with gastropod and bivalve shell debris (Figs. 2 and 3A). The fossil content points to an infralitoral setting of Pliocene age. This coarse grained bed is interpreted as a ravinement lag. Overlying the conglomerate bed the depositional units are dominated by yellow or light grey meter scale beds of well sorted fine to very fine sands with planar lamination (Figs. 2 and 3B), or oscillation ripples. The depositional structures may be obliterated by bioturbation or diagenetic processes and structurless sands are the most common sediments. Sometimes the sands are intercalated with decimetre thick beds of structurless gravels or gravelly sands (Figs. 2 and 3D). In places these coarser beds show normal gradation and pass upwards to gravelly sands

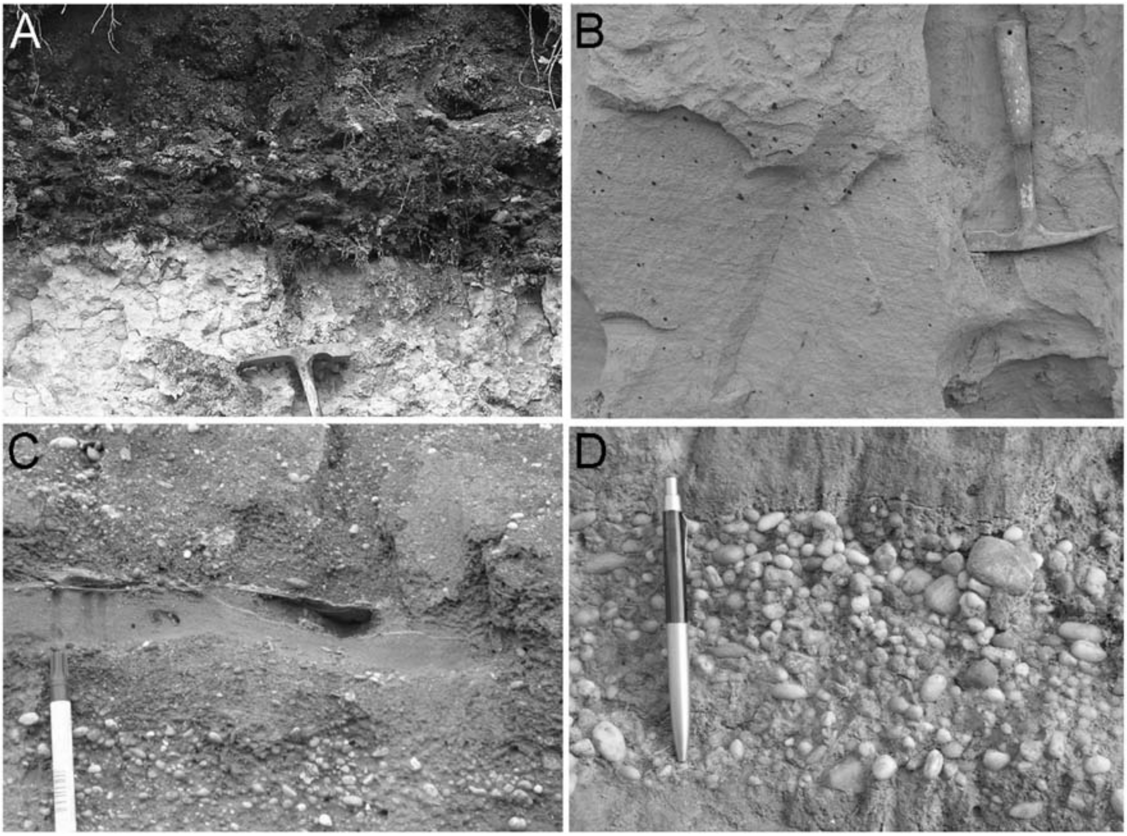

Figure 3:
Pictures of inner shelf Plio-Pleistocene deposits. (A) Coarse-grained ravinment lag with shell enrichment. (B) Well sorted fine to very fine sands with parallel lamination. (C) A contact, outlined by a mud veneer, between inner shelf and coastal plain deposits. The coarse-grained bed shows normal gradation and its upper part has oscillation ripples. (D) Interbeds of well sorted fine to very fine sand and massive granule to pebble-size gravel.

with unidirectional or oscillation ripples (Figs. 2 and 3C). The basal contact of the gravel rich beds may be gradational or a sharp erosive surface. A decimetre to centimetre mud level is occasionally found at the top of the depositional sequence, though these sediments are quite rare.

These sequences resemble several present day inner shelf deposits affected by storm events (Kumar and Sanders, 1976; Howard and Reineck, 1981). The rich macrofaunal content of one of the studied sections also suggests the existence of shallow depositional environments, propitious to the development of allochtonous storm generated coquinas. The sediment sequence with intercalated conglomerate and gravelly sands with ripples and horizontal lamination (Fig. 2) is similar to some coarse grained storm event beds deposited in inner shelf settings (Cheel and Leckie, 1992). The interbedded fine sand and sandy gravel deposits may be related to different hydrodinamic conditions. The coarse grained sediments are supposed to be delivered from the shoreface after intense storm erosion. The planar laminated sands should be deposited short after the storm peak under unidirectional flow conditions. The oscillation ripple sands, present near the sequence top, may be related to the waning storm phase (Cheel and Leckie, 1992). The coarse-grained bed at the bottom of these

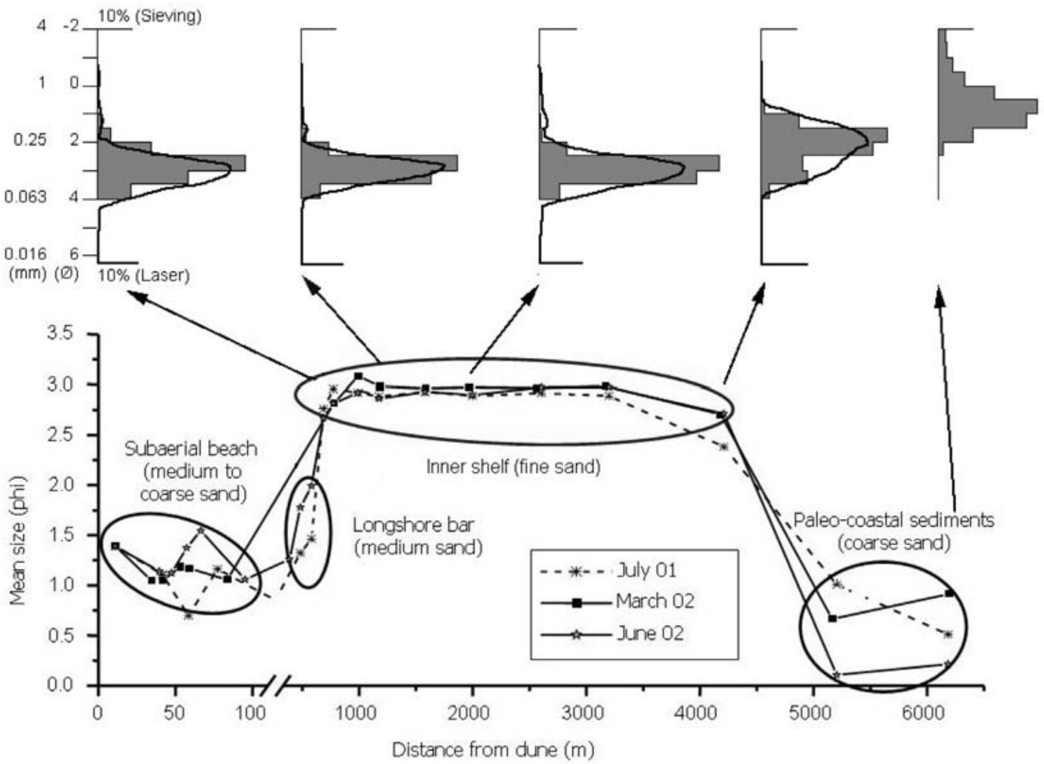

Figure 4:
Textural characteristics of the present day inner-shelf cover and shoreline deposits offshore Areão beach. Note the wide zone with monotonous fine sand sediments, between 500 and 4000 meters from the dune field, and the presence of relatively coarse-grained deposits at approximately 5000 meters from the dune field. The grain-size distributions of selected samples are also represented (histogram for sieving and frequency curve for laser diffraction).

deposits is related with a transgressive ravinement surface, because it is in erosional contact capping the basement formations or more proximal sediments (Cattaneo and Steel, 2003).

Present day analogue

One of the significant features of the present day inner shelf cover deposits, concerning the character of the hydraulic regime, is the distribution of grain sizes of the nearshore bar (Fig. 4). Bathymetric data reveals a well developed and permanent longshore bar, located at 300 m offshore at a water depth of 4.5 m (Rey and Bernardes, 2002). Waves break at the longshore bar and reform in the shoreward prior to successive breaking and dissipation on the beachface (Rey and Bernardes, 2004). Bar height varies alongshore and between the bar and the beach differences in channels width were observed.

Grain-size gradients on the Areão stretch vary with the local shelf topography. Bar crest consists of well sorted medium sand and the flanks are covered with fine sand. From the end of the bar (10 m depth) to 4000 m (22 m depth) the inner shelf cover consist of very fine to fine sand-size sediments, well to moderately sorted. Sediment characteristics suddenly change at depths greater than 25 m (5000 m from

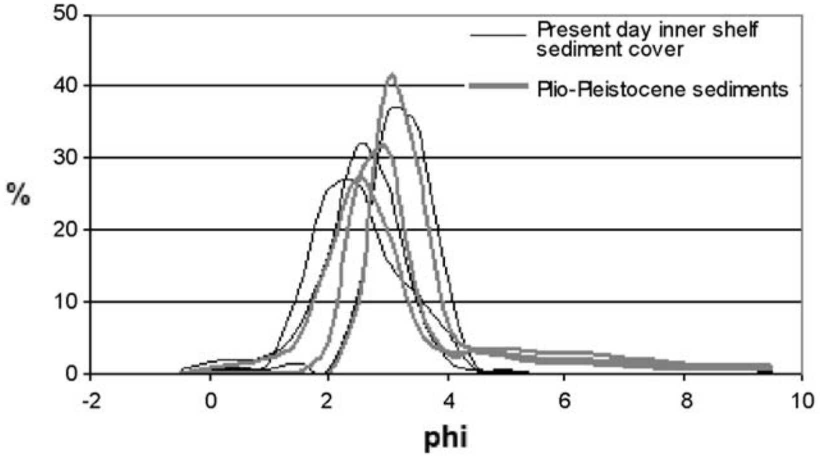

Figure 5:
Typical grain-size distribution of well sorted fine to very fine sand-size inner shelf deposits. Note the similarity between the grain-size distribution curves of the two sediments. The main difference is the higher mud content in the Plio-Pleistocene units.

shoreline) to coarse grain sizes. This is in total disagreement with today prevailing dynamics (Rey and Bernardes, 2002).

The northern Portuguese continental shelf is characterised by high energy wave conditions. Significant waves are moderate during summer (significant wave heights of 1 to 3 m and wave periods of 11 to 13 s, according to Costa, 1994) and large during storms (significant wave heights often exceeds 7 m and wave periods 13 s, according to Costa, 1994). The mean wave direction is from NW (73%) and induces an important longshore surface current drift from north to south with an associated net sand transport (Taborda, 1993). The semidiurnal mesotidal regime in the region presents a maximum tidal range of 3.2 m and a minimum tidal range of 0.9 m. Extreme water level fluctuations induced by storm surges usually exceed 40 cm (Gama *et al*., 1994). The shelf is affected by the slope Canaries Current and by the associated upwelling current. According to Vitorino *et al*. (2002) the shear velocities during summer usually are not able to put in motion the silt deposits. During storm winter conditions the circulation may be inverted and downwelling currents tend to prevail (Drago, *et al*., 1998; Dias *et al*., 2002).

GRAIN-SIZE MODES

Fine to very fine sand is usually the most frequent size-fraction in inner shelf deposits (Figs. 5 and 6). Exceptions occur in some conglomerate and mud levels. However, all Plio-Pleistocene inner shelf sediments show several ubiquitous features, namely: a) the grain-size distributions are always polymodal; b) there is always present a mode of very fine sand size and a mode of silt size.

From the analysis of the modal size of these sediments it is possible to consider three groups of modes of different grain-sizes (Fig. 7). The first modal group (group 1) is of medium sand to gravel size. Still two clusters may be identified in this group. The coarser cluster (Group 1a) was determined exclusively by sieving. It is represented by modes coarser than -4Ø and occurs exclusively in the coarser conglomerate beds found at the bottom of inner shelf deposits (facies A of fig. 2). These beds are interpreted as ravinement lags (Fig. 6). The finer cluster (Group 1b) was detected by sieving and partially by laser diffraction. It is characterized by modes between 1 and -3Ø. These modes are present in levels of coarse sand and gravelly sand intercalated with fine to very

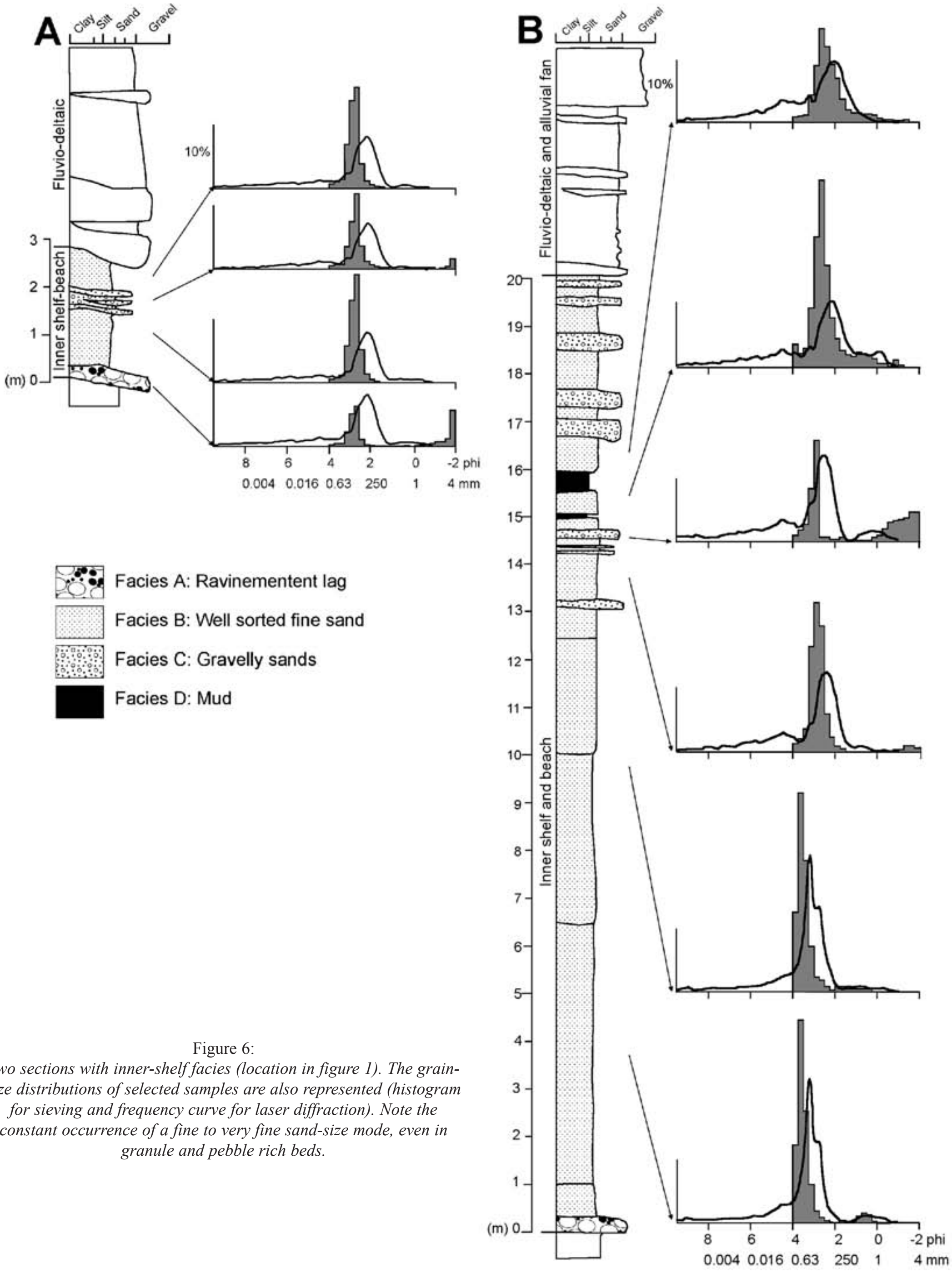

Figure 6:
Two sections with inner-shelf facies (location in figure 1). The grain-size distributions of selected samples are also represented (histogram for sieving and frequency curve for laser diffraction). Note the constant occurrence of a fine to very fine sand-size mode, even in granule and pebble rich beds.

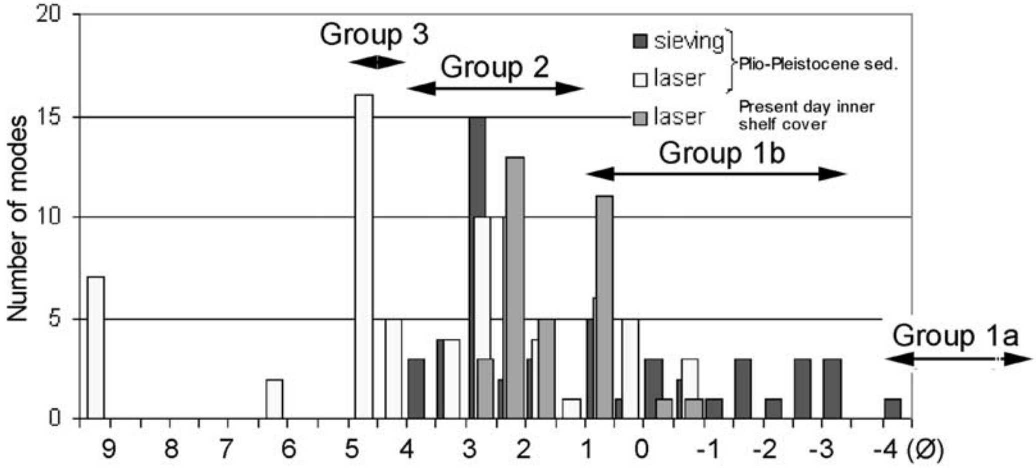

Figure 7:
Number of modes of different grain-sizes determined by laser diffraction (in present day and Plio-Pleistocene deposits) and by sieving (in Plio-Pleistocene deposits). It is possible to identify three groups of modes in Plio-Pleistocene deposits. Here, the silt-size modes are always present and the most common sand-size modes are of fine sand-size (slightly coarser when determined by laser diffraction). There is higher variability in the grain-size of the coarser modes.

fine sands (facies C of fig. 2). In these sediments they can be the most important mode or be supplanted by modes of fine to very fine sand-size.

The second modal group (group 2), of very fine to fine sand size, was detected both by laser diffraction and sieving. These modes have relatively low variability, as they are always positioned between 1.5 and 4Ø. Group 2 modes are the most frequent and are present in all inner shelf facies regardless of bulk grain-size. The distribution around these modes is narrow, indicating that they are related to well sorted populations.

The third modal group (group 3), of silt size, was determined exclusively by laser diffraction. These modes are positioned between 4Ø and 5Ø and the size class of 5-4.5Ø is the most frequent. They are present both in sand and gravel bed, although representing a low proportion of bulk sediment. The relatively rare mud deposits are dominated by particles of this size. In some samples it is still possible to interpret a mode finer than 6Ø, though rather unclear. Like the fine to very fine sand modes, the group 3 modes are always present.

There are two groups of modes in present day inner shelf sediments (Fig. 7). In several samples a mode of 1-0.5Ø grain-size class was detected. Though, this modal class has relatively low proportion in bulk sediment. The finer mode, of very fine to fine sand size, is similar to the group 2 modes of the onshore record. It is positioned between 3Ø and 1.5Ø, being the modal class of 2.5-2Ø the most common. These classes are always the most frequent and are associated to well sorted grain-size distributions.

DISCUSSION

The grain-size distribution, characterized by the presence of several modes in Plio-Pleistocene deposits, must result from the mixture of different grain-size populations (Fig. 8). The coarser Plio-Pleistocene modes (group 1a) are found in gravel beds at the base of the inner shelf sequences, which are interpreted as transgressive ravinement lags (facies A of fig. 2). Those size modes must be determined by the coarser sediments that were not transported offshore during the transgressive event, remaining as a lag deposit. Some coarse grained beds with

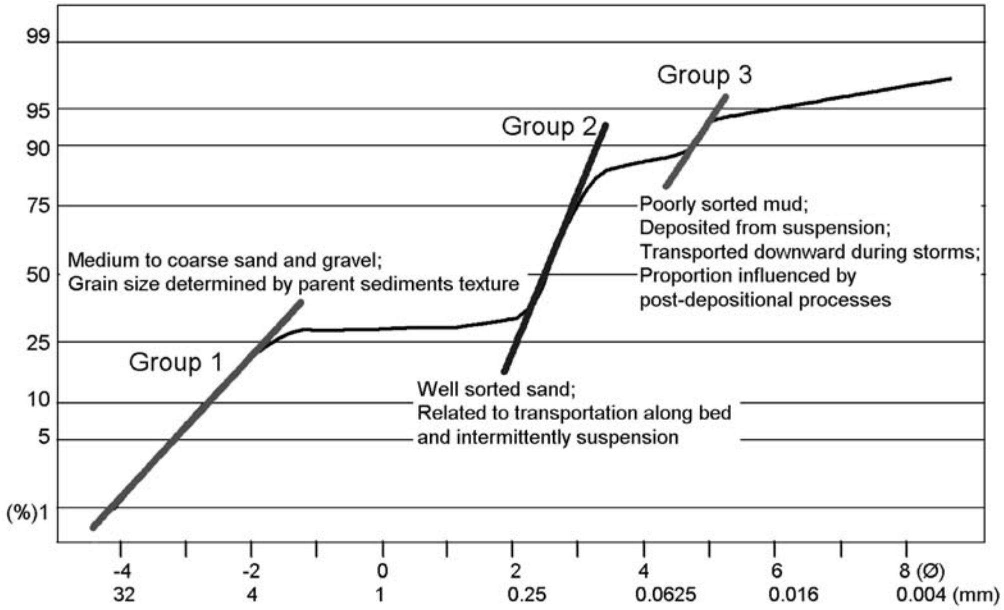

Figure 8:
Example of a normal probability plot of the grain-size distribution that results from the mixture of three populations in the inner shelf environment. The well sorted sand and the poorly sorted mud populations have limited variability, as they are located, respectively, around 2-3Ø (250-125mm) and 5Ø (0,032mm). The former must be in hydraulic equilibrium with the inner shelf storm conditions. The latter may be deposited from suspension during fair-weather periods, though, during storms it tends to be resuspended and transported to outer shelf locations by downward currents. The proportion of the mud population may increase due to post-depositional processes. Unlike the sand and mud populations, the mean of the coarser population is quite variable (between medium sand and pebble-size), depending mostly on the grain size of the parent sediments.

modal sizes between fine and very fine sand (facies C of fig. 2) are also characterized by the presence of a coarse sand to granule-size population (group 1b modes). These beds were probably deposited during peak dynamic conditions generated by storm events (Cheel and Leckie, 1992). Storms and Hampson (2005) considered that shifts in the wave height affect the inner shelf and are the primary mechanism responsible for the discontinuity surfaces. Because the bottom of these levels is usually an erosive discontinuity surface it is probable that the coarser components of these levels (group 1b modes) were delivered from the shore after storm erosion. Thus its grain-size should be dependent from the grain-size of the more proximal parent sediments. These components are mixed with a fine to very fine sand size population (group 2). Meanwhile, in the present day inner shelf the coarser grained deposits are found at depths greater than 25 m (>5000m from foredune) and are interpreted differently (Fig. 4). Taking into account the textural characteristics and their depth, these sediments are considered as relict and may be associated with a paleo-coastline (Dias, 1987). However, they may be distinguished from the coarse grained Plio-Pleistocene facies (A and C of fig. 2) by their unimodal character, since there is no mode at the fine to very fine sand-size fraction.

The homogeneity in the fine to very fine sand-size population (group 2 modes) over a vast area (more than 1000 km^2) must be related to rather uniform bottom hydrodynamic conditions. A hydrodynamic cause for the group 2 is also supported by the high frequency of heavy minerals in the finer size fractions (reach 15% of 3-4Ø size fraction) and of mica in the coarser size fractions

(Dinis, 2004). Present day inner shelf grain-size distributions at 10 to 22 m depth (500 m to 4000 m from the shoreline) are quite similar to the fine sand-size population of the Pliocene-Pleistocene units (Figs. 5 and 7). Given the similarity of these facies to some sediments in coarse grained storm sequences (Cheel and Leckie, 1992) it is proposed that group 2 population is in equilibrium with the hydrodynamic conditions during winter. The slight changes noted in its grain-size may reflect the storm intensities or the position (proximal vs. distal) along the shelf. Several authors have proposed that modal size may be used as water depth estimator (Swift and Thorne, 1991; Tamura, 2004). According to the sediment dispersal system the probability of sediment resuspension is lower for coarser particles under particular dynamic conditions (Swift and Thorne, 1991). Inasmuch, proximal station will have coarser sediments due to the higher energetic level of these reaches. The negligible differences between seasons in the present day inner shelf suggest that the textural features related to fair-weather periods is likely to be obliterated during the subsequent storm events. Hence, the record of the more energetic conditions tends to prevail.

The proportion of the mud population (group 3 modes) may be explained by depositional and post-depositional processes. Dunbar and Barrett (2005) proposed that inner shelf deposits should hold sand and mud populations. These populations result, respectively, from transportation along bed and intermittent suspension and from deposition from suspension. The mud size particles would remain in suspension near the shore due to the wave action and their proportion in bulk sediment should progressively increase toward more distal shelf locations. In the NW Portuguese shelf the mud population tends to be removed from the proximal locations during storm periods by downward currents (Drago *et al*., 1998; Dias *et al*., 2002; Jouanneau *et al*., 2002).

Dunbar and Barrett (2005) suggested that the quantities of mud particles may be correlated with the shelf depth. However, given the sub-archosic character of the Plio-Pleistocene sediments, it may be argued that the proportion of silt size modes could be also influenced by the process of feldspars weathering. This would explain the higher proportion of mud particles in the Plio-Pleistocene onshore record. But this process can hardly explain the invariable presence of modes concentrated around 5Ø. Actually, it is more likely that post depositional processes would contribute to increase the frequency of a silt and clay size tail in the grain-size distribution.

CONCLUSIONS

The grain-size distributions of inner shelf deposits result from mixing of several populations that are not necessarily in equilibrium with the hydrodynamic conditions at the depositional site. In the studied inner-shelf deposits of Plio-Pleistocene age it was possible to discriminate three populations from the analysis of their grain-size distributions, with analogues in the present day sediment cover of the inner shelf. These populations are:

- A coarse sand to gravel size populations fed from more proximal deposits during storm peak conditions, if intervened with fine to very fine sands, or related to ravinement lags, if at the bottom of an inner shelf depositional sequence. The coarser sediments are found in ravinement lag beds. These populations seem highly dependent from the texture of the parent sediments and are not in hydraulic equilibrium with prevalent hydrodynamic conditions.

- A well sorted fine to very fine sand size population transported and deposited in traction and intermittent suspension. The grain-size distribution of the present day shelf sediments found from 10 to 22 m depth is quite similar to this population. This population may be in hydraulic equilibrium with the prevalent inner shelf conditions during winter season. For this reason, its grain-size can be used to approximate the location (proximal vs. distal) within the shelf.

- A poorly sorted mud population deposited from suspension during fair-weather periods. These sediments tend to be transported by downwelling currents to outer shelf locations during storm conditions. Hence, its proportion in more proximal location would be minimal. Nevertheless, several post-depositional processes may be responsible for an increase in the proportion of this population in the Plio-Pleistocene sediments.

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