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A Shoreface Zonation in the Ebro Delta Based on Grain Size Distribution

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ABSTRACT

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Trends in sediments and morphology across the Ebro Delta shoreface were investigated during a three year experiment. The profile slope, the location of morphological features, the textural parameters of the sediment and the relative abundance of sand fractions were measured along the Ebro coast. The observed sediment distribution was compared with the grain size distribution calculated from simple models and with an equilibrium grain size defined from the abundance of textural fractions. On the basis of the cross-shore variations three zones were identified across the Ebro shoreface: high energy, transition and low energy zones. These zones are mainly controlled by the sediment transport processes associated with the incident wave climate. The distribution of these zones is locally disrupted by the presence of shoreface outcrops corresponding to ancient deltaic lobe deposits. The analysis of the sediment distribution is a useful tool in the definition of zones across the shoreface. Sediment distribution is complementary to other zonation criteria (based on morphology and hydrodynamics) and contributes to a better definition of the shoreface units.

ADDITIONAL INDEX WORDS: *Grain size, sediment types, shoreface zones, coastal morphology, sediment transport, coastal hydrodynamics.*

INTRODUCTION

A number of zones can be differentiated along coastal profiles, including the dune area, the upper, middle and lower shoreface and the inner shelf (DE VRIEND *et al.,* 1993). Each zone has a specific behavior caused by the processes that act across it and the positions of the boundaries of these zones relative to mean sea level vary from one area to another mainly due to the wave climate conditions. In this study, the shoreface is used with the meaning defined in STIVE and DE VRIEND (1995): it corresponds to the part of littoral profile extends from the duneface to the inner shelf. Although in other studies the nearshore zone is not considered part of the shoreface (NIEDORODA *et al.,* 1985), the evolution of the nearshore is strongly related to changes happening in the remainder part of the littoral profile (STIVE and DE VRIEND, 1995) and it can be seen as one unit when long time scales are considered. The zonation of the shoreface based on morphology, sediment distribution or hydrodynamic processes is specially important in the study of littoral profile evolution. These zonation are critical to models of the shoreface because they serve to define the "closure depth" of the profile, which is the seaward limit beyond which the profile does not change over the considered temporal scale (HALLERMEIER, 1981).

Sediment on the shoreface tends to become finer in an offshore direction (SWIFT, 1976; SLY *et al.,* 1983; NIEDORODA *et al.,* 1985). This fining of sediment across the littoral profile is mainly caused by the decreasing energy of transport fluxes offshore, although the influence of strong flood tides may disturb the seaward fining trend on the intertidal profile of some beaches (BRYANT, 1984). The seaward fining of the sediment is not monotonic, but that typically shows a more steep variation closer to the shoreline as compared to the distal offshore part of the profile (LARSON, 1991; WORK and DEAN, 1991). Following the "equilibrium profile" concept (BRUUN, 1954), the sediment will tend to move across the profile to a position in which it will be in equilibrium with the acting wave and currents (HORN, 1992a, b). The theoretical cross-shore sediment distribution could be estimated using different methods, such as the null point hypothesis, the Hallermeier equation or the Horn's method. The null point hypothesis takes into account the flow asymmetry and the downslope component of the gravitational force (CORNAGLIA, 1889). Hallermeier's equation calculates the deepest limit of sand movement produced by waves considering the annual wave climate (HALLERMEIER, 1981), whereas Horn's method is based on the hypothesis of asymmetrical thresholds under waves (HORN, 1992a). At present, none of these methods gives an accurate description of grain size distribution in the cross-shore profile (HORN, 1992b).

Since transport and depositional processes are probabilistic, the distribution of grain sizes is a probability parameter (MCLAREN and BOWLES, 1985; LIU and ZARILLO, 1989). In this way, size classes of natural sediments can be considered as natural tracers and the distribution of individual grain sizes is representative of long-term dispersal patterns on the shoreface (LIU and ZARILLO, 1989). Only a few previous studies have dealt with the cross-shore distribution of individual

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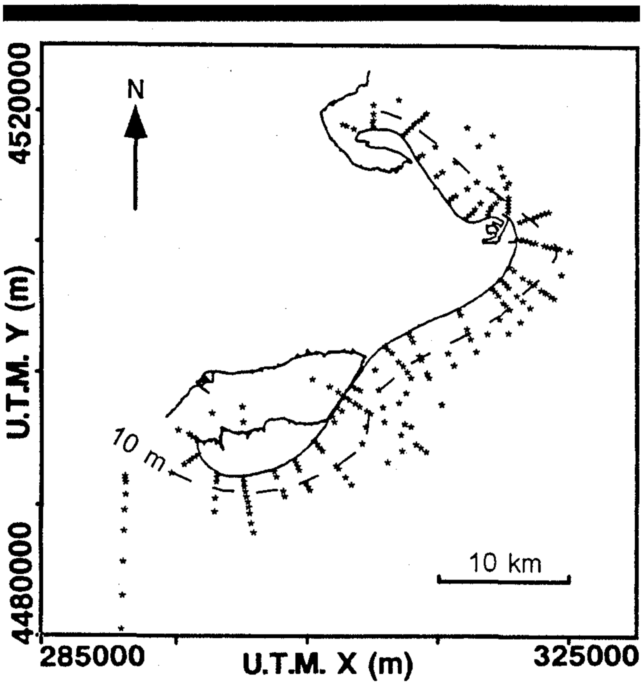

Figure 2. Location of drag samples along the Ebro Delta coast.

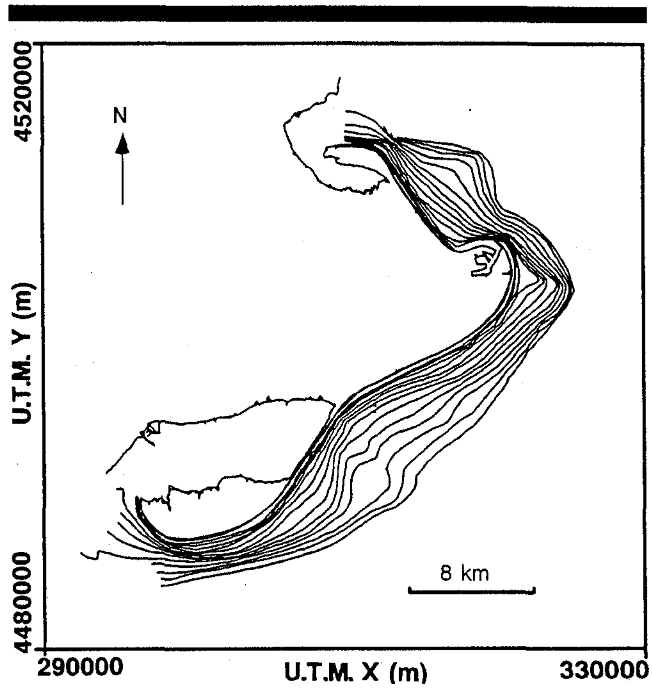

Figure 3. Bathymetrical chart of the Ebro Delta coast from the shoreline to 15 m depth (equidistance isobaths 1 meter).

In order to evaluate the differences between the observed sediment distribution and an "equilibrium" distribution from theoretical equations, the mean values of the textural grain size parameters of all the samples in relation to the depth were calculated. Theoretical sediment distribution across the shoreface of the Ebro Delta coast from the null-point hypothesis and Horn's method (**Di**) was calculated using mean hydrodynamic and morphological data (wave height (H)= 0.7 m, period (T)= 3.9 s, slope $\tau\beta$)= 0.005). In the null-point hypothesis, the equilibrium grain size across the littoral profile is calculated from equations given by JAGO and BARUSSEAU (1981). In Horn's method, the local wave height is calculated according to the solution of NEILSEN (1982). The peak near-bed onshore and offshore velocities at each point of the profile are calculated from Stokes second order wave theory using the approximation given by KOMAR (1976). Finally, the threshold grain size is calculated using the expressions of KOMAR and MILLER (1975) for both the onshore and offshore peak flows.

The depth limiting motion for sandy sediment was also calculated from the empirical equation of HALLERMEIER (1981). Hallermeier's equation calculates the deepest limit of sand movement produced by waves:

$$h = 2Hs + 11\sigma$$

where **Hs** is the mean significant annual wave height, and σ the annual standard deviation in significant wave height.

SHOREFACE MORPHOLOGY AND SEDIMENTS

The bathymetry of the Ebro Delta littoral zone is shown in Figure 3. The mean slope in the littoral zone ($\tau\beta$) ranges between 0.003 and 0.009, with the most common values about 0.004–0.006. The lower slope gradients (< 0.002) are usually in the deeper part of the shoreface profile (10 to 15 m depth) and the maximum gradients in the swash zone (> 0.032). Three characteristic slope ranges have been differentiated: 1) slopes higher than 0.005, which extend between the shoreline and 4–6 m depth; 2) intermediate slopes from 0.002 to 0.005, located in deeper areas (about 6–11 m depth); and 3) slopes lower than 0.002, located in discontinuous patches of the deepest littoral zone (> 11 m depth).

Most of the morphological elements on the shoreface of the Ebro Delta have developed near the shoreline (dunes, sand flats, berms and bar and trough systems). The inner and longshore bar systems are the most relevant morphological features in the littoral profiles (GUILLEN and PALANQUES, 1993). The nearshore profile shows from none to four bar systems, one system very close to the shoreline (inner bar) and the others located progressively offshore, up to depths of about 5–6 m and distances from the shoreline to less than 600 m (Figure 4). Offshore from the outer bar system the steeper gradients of the nearshore zone change to the smooth slopes of deeper areas, except in the middle part of both spits, around profiles 5 and 35 (Figure 3). In the deepest part of the nearshore profile only a few changes in the slope can be recognized and it is not possible to identify any major morphological element.

The sediment grain size on the shoreface of the Ebro Delta ranges between 1.6 and 8.8 phi, the standard deviation between 0.21 and 0.36 phi, the skewness between −7 and 5.2 and the kurtosis between 2 and 70. The mean grain size distribution on the shoreface profile shows a fining trend with

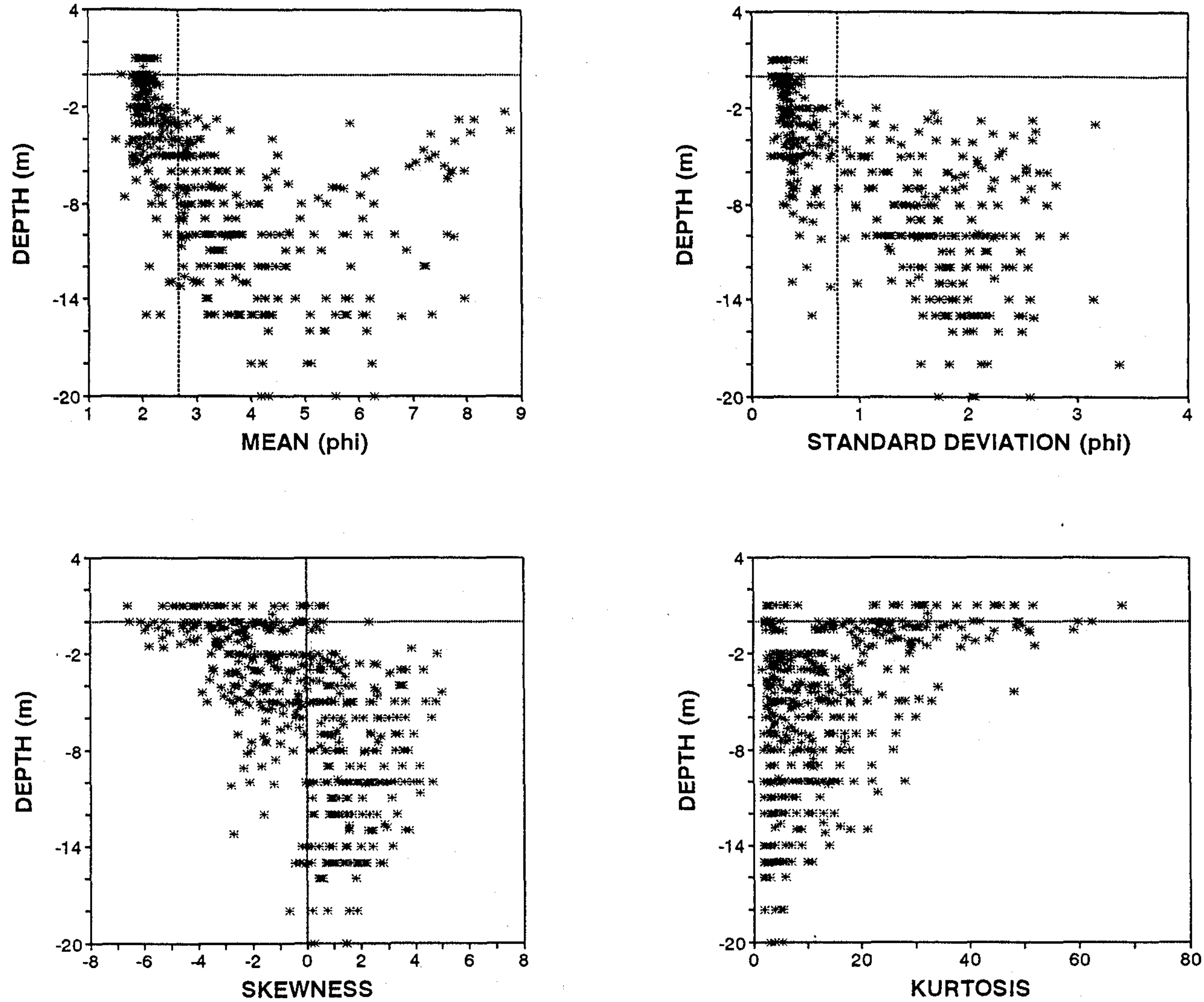

Figure 5. Bivariate plots between textural sediment parameters and depth showing the general grain size trends (0 m depth= mean sea level).

depth, from values about of 2 phi at the shoreline to finer than 4 phi in areas deeper than 6 m (Figure 5). The standard deviation of sediment increases with water depth across the profile. The distribution of the skewness ranges from very negative values at 3–6 m water depth to values of about 0 at the offshore part of the profile. The kurtosis value decreases along the shoreface with water depth (Figure 5). A general view of the sediment grain size distribution indicates some general trends seaward of the shoreline: (1) the sediment tends to be finer and more poorly sorted, (2) the sediment changes from an excess of coarser fractions to an excess of finer fractions (from negative to positive skewness), and (3) the dispersion of the grain sizes around the modal size increases (kurtosis decreases) (Figure 5). However, these trends are locally interrupted showing textural variability in all shoreface water depth.

Histograms and cumulative frequency curves of the samples indicate that the textural distributions are unimodal in the coarsest and the finest sediment of the Ebro Delta, but between the two end-members the sediment is bimodal (Figure 6).

A map of sediment grain size distribution in the littoral zone of the Ebro Delta is shown in Figure 7. Mud outcrops and relict sands have also been depicted on the map. The fining trend of sediment with depth is observed along the complete littoral zone, but the boundaries between the grain size ranges are not always parallel to the shoreline (Figure 7).

Relations between the textural parameters indicate the existence of two types of sediment (Figure 8): (1) type A or coarse sediment, which mean grain size ranges between 1.8 and 2.5 phi, is well sorted, negatively skewed and has high kurtosis, and (2) type B or fine sediment, with mean grain size lower than 3.5 phi and reverse textural characteristics (poorly sorted, more positively skewed and with a low kurtosis). The A and B sediment types identified on the Ebro

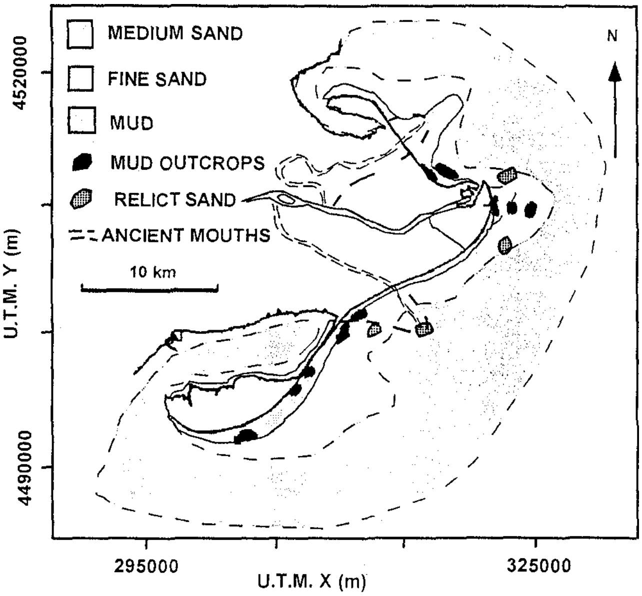

Figure 7. Sediment grain size distribution in the Ebro Delta coast and location of the ancient river mouths observed in the Ebro delta plain by MALDONADO (1972). Three grain size ranges have been differentiated: (1) sediment coarser than 2.7 phi (medium sand), located in the shallower areas, (2) sediment whose grain size ranges from 2.7 to 4 phi (fine and very fine sand), and (3) sediment finer than 4 phi (mud).

Delta coast are representative respectively of the high and low energy sediment defined from textural characteristics in other areas (SLY *et al.*, 1983). The boundary between these sediment types on the shoreface of the Ebro Delta is not clearly defined by textural relationships, but it is located in a transitional area ranging between 4 and 8 m depth. In this transitional area there is an increase of the grain size variability of the samples: the grain size decreases from 2.5 to 3.5 phi, the standard deviation increases from 0.6 to 1.3 phi and the skewness changes from negative (−0.5) to positive values (1.0) (Figure 5).

SEDIMENT DISTRIBUTION: OBSERVED AND PREDICTED

The comparison between the grain size distribution observed on the shoreface of the Ebro Delta and the prediction estimated from the null-point hypothesis and Horn's method shows important differences. The sediment grain size predicted by these models is only equivalent to the observed at about 6 m water depth, where the mean grain size averages 2.7 phi and the standard deviation 0.8 phi (Figure 9). Differences between the observed (**D**) and the theoretical (**Di**) grain size distribution indicates that the cross-shore sediment pattern in the Ebro Delta is more complex than that resulting from the action of only the mean wave climate. In the shallower part of the shoreface profile, a **Di** coarser than **D** shows that mean wave climate conditions could transport coarser material than the observed, suggesting a deficit of the coarsest sediment fractions. In the deeper shoreface profile, a **Di** finer than **D** indicates that the coarser sediment fractions (probably supplied during storms) cannot be transported during mean wave climate conditions.

Differences between the observed (**D**) and the theoretical (**Di**) sediment distribution across the profile are mainly caused by the limited range of grain size fractions available in the Ebro Delta shoreface. Other causes could be related with the simplifications involved in the characterization of the wave field and the sediment transport processes and the definition of the sediment textural characteristics, such as it has been reported in previous studies (GRAF, 1976; JAGO and BARUSSEAU, 1981; HORN, 1992a).

The presence of ancient deltaic lobes on the shoreface of the Ebro Delta is other important factor in the control of sediment distribution. The last change in the Ebro River mouth position (1937) generated a planar erosion surface in the shoreface, relict bar and trough system and mud outcrops (profile 24 Figure 4). These modifications can be used as criteria to recognize ancient delta lobes in the Ebro Delta shoreface: areas where a low-slope and an interruption of the offshore sediment fining trend are observed in the shoreface profile. The chart of the Ebro Delta (Figure 3) shows four areas with low slope where the sediment distribution is characterized by the interruption of the fining trend between 8 and 13 m water depth (profiles 12, 17 and 32 in Figure 4). These areas can be related to ancient delta lobe deposits. In some cases, ancient deltaic lobes do not develop a clear low slope surface, as occurs in the Migjorn area (profile 17), but they produce a break in the sediment fining trend. The presence of mud outcrops in the shallower part of the profiles (Figure 7) can also indicate the position of ancient delta lobes. Outcrops of compacted mud are more resistant to erosion and change the morphology of the profile. Morphological changes in the profile caused by outcrops of ancient deposits also modify the wave energy that reaches the beach: a maximum wave height along the delta is reached in the central part of the Trabucador Bar (JIMENEZ, 1996) due to the modifications in the wave propagation caused by the morphology of ancient deposit outcrops in this area. The location of ancient deltaic lobes identified in the Ebro Delta shoreface using changes in shoreface slope and presence of mud outcrops correlates well with the location of the ancient river channels identified by MALDONADO (1972) on the delta plain (Figure 7).

A concave upward profile and a continuous sediment fining trend offshore are typical characteristics of an equilibrium profile (DEAN, 1991; DEAN *et al.*, 1993). The "equilibrium" morphology and sediment distribution across the Ebro Delta shoreface is disturbed by the presence of bar and trough systems, in which the textural parameters change from the top of the bar to the trough (GUILLEN and PALANQUES, 1993), and by the outcrops of ancient deltaic lobes that break the offshore sediment fining trend. If it is assumed that each grain size fraction of the sediment tends to reach an equilibrium or zero transport position across the profile, then the equilibrium grain size can be deduced from the distribution patterns of the individual textural fractions (LIU and ZARILLO, 1989). In the Ebro Delta shoreface, the relative abundance of the coarsest fractions (1.5–2.25 phi) decreases sharply between the shoreline and the 5–6 m isobath, and the per-

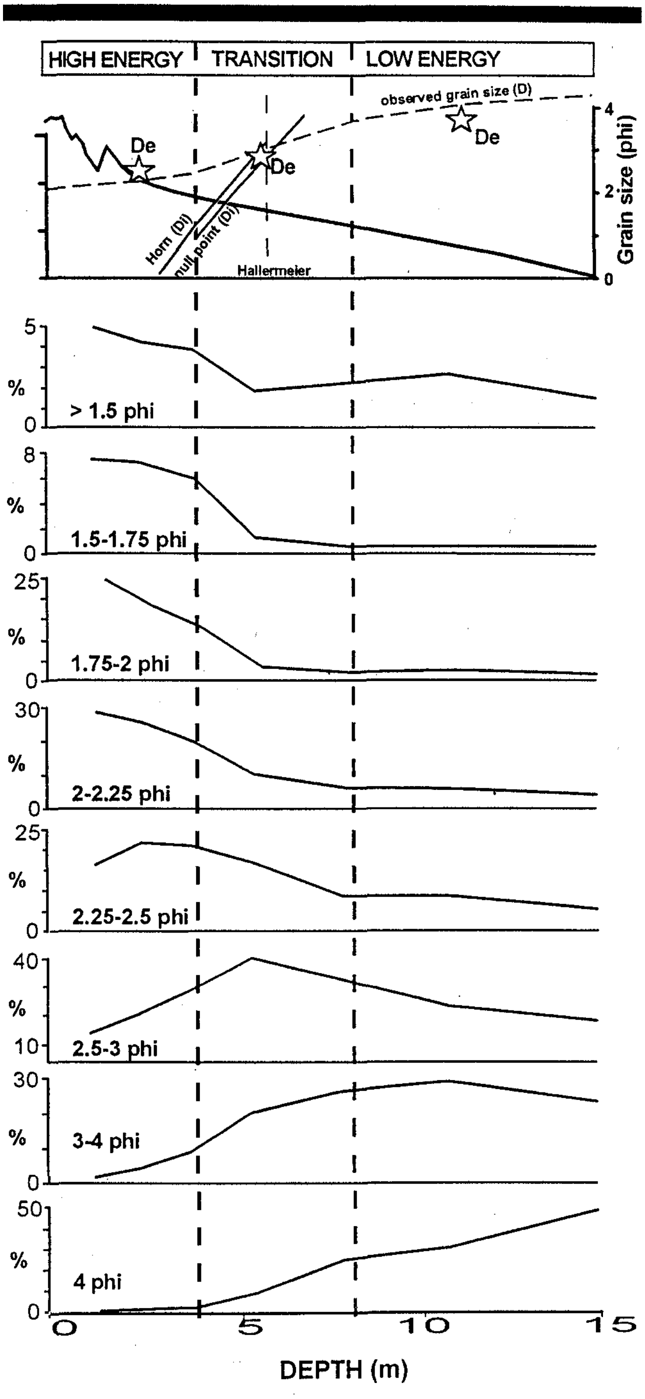

Figure 9. Idealized cross-shore profile showing the relationships between morphology and grain size characteristics on the shoreface zones identified in the Ebro Delta. The observed (**D**), predicted (**Di**) and equilibrium (**De**) grain size distribution across the shoreface profile of the Ebro Delta are compared. Mean wave conditions have been considered for theoretical calculations of **Di** and the seaward limit of sand motion based on the equation of Hallermeier. The equilibrium grain size (**De**) is estimated from the abundance of grain size fractions. Fractions of 2.25–2.50, 2.50–2.75 and 3–4 phi show a peak of maximum abundance in the profile and decreasing trends both landward and seaward.

centage of the finest fraction of sediment (>4 phi) increases gradually with depth. However, some textural fractions clearly are more abundant at positions within the Ebro shoreface profile and decrease in abundance in both onshore and offshore directions (Figure 9). Size fractions which show such patterns include 2.25–2.50, 2.5–3 and 3–4 phi, and they are inferred to be the equilibrium sediment sizes (**De**) at their depths of maximum abundance at 3, 5.5 and 11 m depth respectively. Based on the inference about these three fractions the grain size equilibrium profile during the study period (3 years) can be drawn.

The comparison between the mean grain size sediment variation observed in the profile (**D**) and the equilibrium distribution considered (**De**) indicates that the sediment is located at a disequilibrium position across most of the shoreface (Figure 9). The equilibrium distribution **De** is finer than **D** in the shallower shoreface and coarser in the deeper shoreface. There is a transition area from 4 to 8 m depth in which the relation between **D** and **De** progressively changes, intersecting both curves at 5.5 m depth. This depth almost corresponds to the offshore limit of sand motion calculated from the Hallermeier equation using the mean wave climate data (Figure 9).

SHOREFACE ZONATION

Most sediment transport models for the shoreface consider asymmetries of wave orbital velocities as the primary mechanism of sand transport (WRIGHT *et al.,* 1991). From these models, the morphology and sediment distribution of the shoreface can be estimated. In the field, however, this "ideal" pattern is modified by the action of a variety of other hydrodynamical processes, including infragravity motions, mean flows, gravity-induced transport and by other factors, such as grain size, sediment availability and the morphology and texture on the shoreface area, that also contribute to profile development (PILKEY *et al.,* 1993). All these processes and controlling factors have different impacts across the shoreface and are reflected both in the sediment distribution and in the morphological behavior across the shoreface profile. Terms such as active zone, nearshore, upper, middle or lower shoreface are frequently used to refer to zones of the shoreface with different characteristics. These zonation are defined primarily on the basis of the morphology and hydrodynamic processes, whereas the sediment distribution is usually a subordinate factor. On the other hand, some specific zonation for deltaic areas contemplate the sediment as a primordial factor. For instance, WRIGHT (1985) identifies dune, beach, delta front and prodelta deposits.

The sediment distribution on the shoreface is mainly controlled by wave energy, circulation and currents affecting the coast and to grain size fractions available. Moreover, the retreating or prograding character of the coast is other important factor (NIEDORODA *et al.,* 1985): the lower shoreface deposits on retreating coast consist of a relatively coarse lag, interrupting the seaward fining sequence, whereas on prograding coast the fining sequence passes into mud deposits in a continuous way. On the shoreface of the Ebro Delta, where available grain size fractions are the same along the transport caused by waves and the winnowing of fine material that is transported seaward. The sediment texture in the low-energy zone is the result of sporadic sand mobility occurring mainly during storm periods and mud deposition during fair weather conditions. The middle point of the transition zone can be considered as the seaward limit of significant sand transport caused by mean wave conditions in the Ebro Delta shoreface. The mud sediment located at 11 m depth indicates the deepest boundary of significant sand movement in the Ebro Delta. Detailed analysis of the sediment distribution on the shoreface allows identification of areas, where different sediment transport processes are dominant, and complements the zonation methods based on morphological and hydrodynamical criteria, contributing toward more accurate estimates of the boundaries of the shoreface zones.

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