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Processes behind the Longshore Variation of the Sediment Grain Size in the Ebro Delta Coast

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ABSTRACT

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The longshore variation of the sediment grain size in the Ebro Delta coast was investigated to estimate which processes control its distribution. Thirty-two control points along the coast were used in which a representative sample was obtained by averaging four samples taken in the inner part of the surf zone during eight field campaigns (32 samples per control point). The obtained distribution was related to the longshore variation of a set of parameters characterising beach processes: shoreline evolution trends, net longshore sediment transport rates and nearshore wave power. The beachface presents a narrow range of sediment sizes due to the existence of a single external source of sediment (Ebro River) supplying a low amount of homogeneous sand. These supplies are mainly restricted to the northern hemidelta, where the sediment is finer than in the southern part. The sediment grain size distribution along the Ebro Delta coast shows a non-monotonic longshore sorting process of sediment related to the alongshore variations of the main driving agents (longshore transport and wave power). In general, coarser sediments are present in erosive zones, with high wave power and positive longshore transport gradients. Finer sediments are characteristic of depositional areas, with lower power and negative longshore transport gradients. However, the littoral dynamics along the Ebro Delta coast cannot be fully inferred from sediment grain size distribution because several parameters control the sediment distribution. In this way, some coastal stretches showing similar grain sizes under different patterns of longshore transport rates and incident wave power were identified.

ADDITIONAL INDEX WORDS: *Grain size distribution, longshore transport, wave power, erosion/accretion.*

INTRODUCTION

Sediment grain size distributions contain information about their source and the mechanism and intensity of transport (Liu and Zarillo, 1989). This information is hard to interpret because transport processes include random variables of difficult valuation (Gessler, 1976). For instance, the grain size distribution of a sediment sample is the result of transport conditions during the sampling as well as pre-existing conditions during a "certain period" of time prior to the sampling (Davis, 1985). The interpretation becomes more complex when different transport processes coexist, as in littoral areas.

Littoral sediment shows longshore and cross-shore spatial variations due to wave, tidal and aeolian induced transport. Longshore variations of beach sediment are mainly related to variations in wave energy, selective transport rates and the influence of different sediment sources along the beach (Komar, 1976; Nordstrom, 1981). In general, in sequential deposits, two possible trends in the longshore distribution of beachface sediment have been identified (see among others Gao and Collins, 1992; Masselink, 1992): (1) fining sediment in the transport direction (MacCarthy, 1931; Self, 1977; Nordstrom, 1989) and (2) coarsening sediment in the transport direction (Schalk, 1938; McCave, 1978; McLaren, 1981; Bryant, 1982). One of the few attempts to systematically explain the relationship between transport direction and sediment characteristics has been provided by McLaren and Bowles (1985) (the "McLaren model").

Longshore sediment transport gradients control the sediment volume changes along the coast. A negative longshore transport gradient (decrease in the longshore transport capacity) results in a potential deposition zone, whereas a positive gra-

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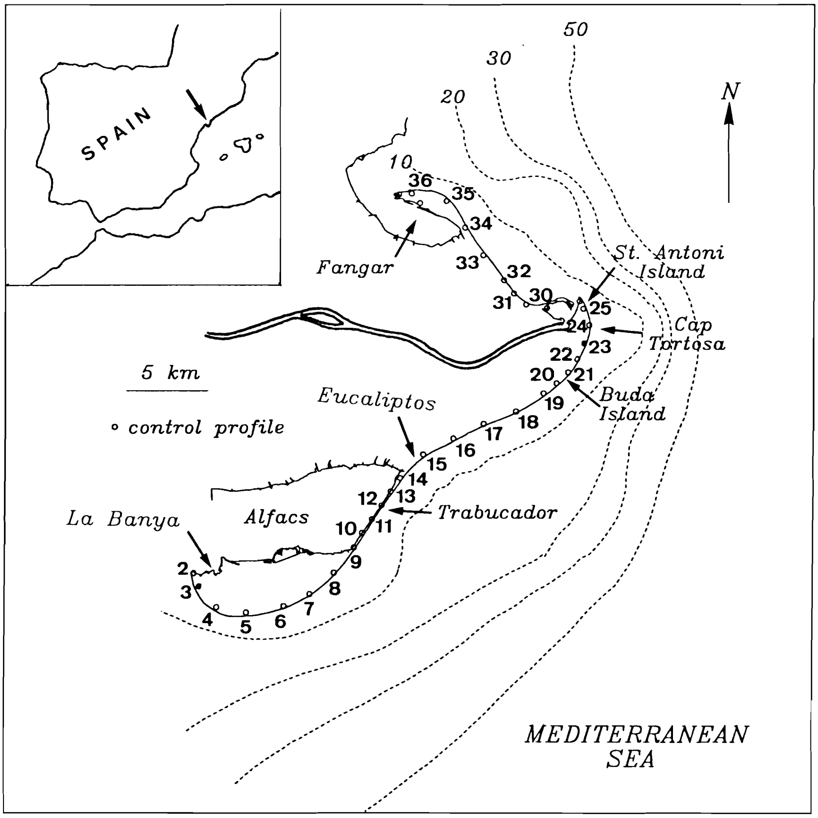

Figure 1. The Ebro Delta coast and profiles location.

dient indicates a potential erosive zone. This will be reflected by the sediment grain size.

Moreover, the incident energy level reaching the coast (usually associated to waves) is a main factor to determine the sediment grain size distribution in the beachface. Usually, finer sediments are found in lower energy, depositional zones, whereas coarser sediments are associated with high-energy erosive zones (TRASK and HAND, 1985; DUBOIS, 1989). However, the inverse relationship between the grain size and the energy level has also been observed in areas with important sediment inputs from external sources (NORDSTROM, 1977).

The main aim of this paper is to analyse the relationship between the sediment grain size distribution along the beachface of the Ebro Delta coast and the longshore distribution of a set of parameters characterizing the littoral dynamic: shoreline displacements, net longshore transport rates and nearshore wave power. This analysis enables the identification of the factors which control the longshore sediment grain size distribution. Moreover, this study will show the value of the use of sediment grain size as an index of erosion/accretion processes in the beachface.

STUDY AREA

The Ebro Delta coast is a 50 km long sandy shoreline developed during the last five centuries by the sediment supplied from the Ebro River (Figure 1). After several centuries of growth, the deltaic trend evolution changed a few decades ago (MALDONADO, 1972, 1986), in such a way that the present delta became a wave-dominated coast. This is mainly related to the drastic decrease in the solid river discharge due to the construction of dams in the course of the Ebro River and its tributaries (PALANQUES *et al.*, 1990; GUILLEN and PALANQUES, 1992). The present solid supply is

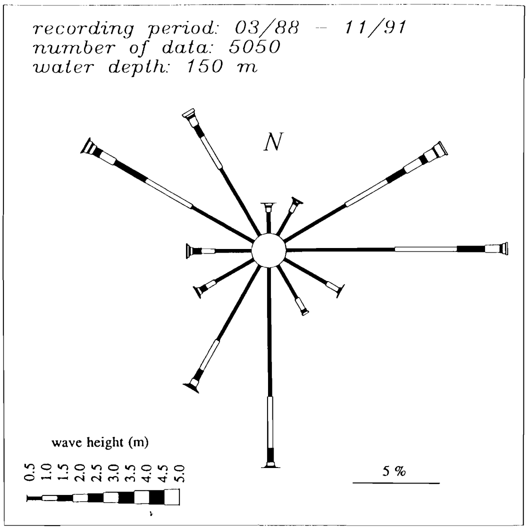

Figure 2. Offshore wave height directional distribution at the Ebro Delta coast (JIMENEZ *et al.*, 1992).

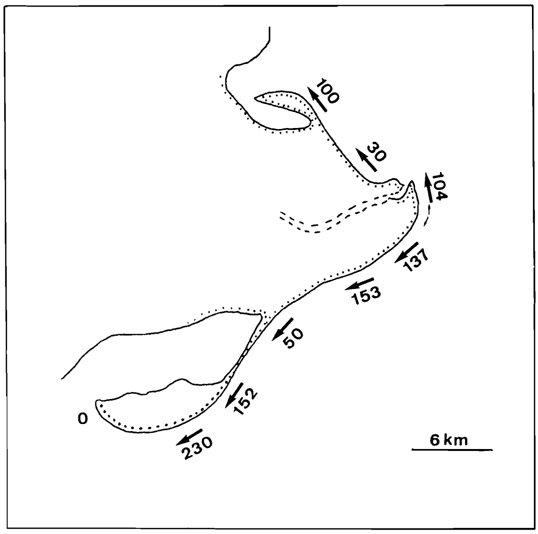

Figure 3. Net longshore transport rates (thousands of m^3/yr) in the Ebro Delta coast (adapted from JIMENEZ and SANCHEZ-ARCILLA, 1993).

now less than 5% of that during the later 19th century, representing a total amount lower than 250,000 metric tons/year (GUILLEN and PALANQUES, 1992). Only the sand fraction of these supplies will contribute to the littoral dynamics. The mean grain size of the bottom sediment in the lower Ebro River ranges from 1.8 to 7 phi (GUILLEN, 1992). During the present river conditions, the sand supplies to the Ebro coast have been estimated at about 50,000 metric tons/year (GUILLEN *et al.*, 1989, 1992; JIMENEZ *et al.*, 1990).

As a result of the drastic decrease in the solid river discharges a very intense reshaping of the nearshore deltaic area began to take place some decades ago (CALLIS *et al.*, 1988). Thus, the central part of the delta has experienced the largest erosion, with a maximum shoreline retreat of more than 1,500 m at Cap Tortosa between 1957 and 1990. Spits have experienced a big accretion due to the deposition of the eroded material. The southern spit has prograded around 700 m while the northern spit has advanced about 1,000 m during the same period (JIMENEZ and SANCHEZ-ARCILLA, 1993).

Like most of the Mediterranean coast, the Ebro Delta is a microtidal environment, with a maximum astronomical tidal range of 0.25 m. The main morphological features along the coast are longshore bars and trough systems. These systems are present throughout all the year, although they change as a function of energetic conditions (GUILLEN and DIAZ, 1990; GUILLEN, 1992).

An average offshore significant wave height (H_s) of 0.72 m, mean wave period (T_m) of 3.9 sec and peak period (T_p) of 5 sec have been estimated by JIMENEZ *et al.* (1993b) using data recorded by a directional wave-rider buoy and calibrated visual wave data. Figure 2 shows the offshore wave height directional distribution for the Ebro Delta coast. Three main components can be distinguished: east (E and ENE), south and northwestern waves. Eastern waves are more determinant in morphological terms because they are the highest and most energetic waves. Southerly waves will mainly affect the southern part of the delta; northwesterly waves will have a limited role in coastal processes due to the coastline orientation (Figure 1).

The presence of the two spits (Fangar to the north and La Banya to the south) indicates a net longshore sediment transport directed towards the south in the southern hemidelta and towards the north in the northern part. The net longshore transport scheme obtained from beach evolution data can be seen in Figure 3. A zone of divergence in the transport direction can be seen at Cap Tortosa. From Cap Tortosa to the mouth, the net transport is directed towards the north at a rate of around 100,000 m^3/yr, decreasing progressively to zero near the mouth, where a partially emerged bar has been developed. To the north of the river mouth, the net transport rate increases from south to north, reaching a maximum rate at the Fangar spit (around 100,000 m^3/yr), where part of the sediment is deposited, while the remaining sediment is transported towards the bay by locally generated N and NW waves. Southwards of Cap Tortosa, the net sediment transport is directed towards the south, although two transport cells can be differentiated. The transport increases from zero in Cap Tortosa up to 150,000 m^3/yr southwards of Buda Island. Beyond this point, the transport rate decreases down to a minimum value of 50,000 m^3/yr attained at the northern part of the Trabucador Bar. Along the Trabucador Bar, the transport rate increases up to a maximum value of 230,000 m^3/yr. To the south of this point, the transport rate decreases down to zero at the apex of the spit (JIMENEZ and SANCHEZ-ARCILLA, 1993).

DATA AND METHODS

Three data sets have been used in this work: sediment samples, beach profiles surveys and wave climate data.

Sediment sampling and beach surveys were carried out in 32 profiles separated by 1 to 2 km along the Ebro Delta beachface (Figure 1). In each profile, 4 samples of surface sediment were taken, corresponding to dune, swash, trough and crest of the inner bar. This sampling was carried out in 8 surveys (June and October 1988; March and July 1989; March and July 1990; March and July 1991). The grain size distribution of sediment was analysed using a settling tube. The mean, standard deviation and skewness were calculated by the moments method (FRIEDMAN, 1967) following the procedures described in GIRO and MALDONADO (1985). The settling tube technique enables the equivalent diameter of particles to be determined and it has a hydraulic significance, since it includes variables such as the density and the morphology of the grains.

Because we are investigating the longshore distribution related to integrated littoral processes such as the net longshore sediment transport, the shoreline evolution trend and the nearshore wave climate, all samples for each profile were averaged to obtain a "surf zone sample". The sediment grain size representative of the mean conditions was obtained by time-averaging the "surf zone samples" over the period of study. In total, 32 samples were used to estimate the textural characteristics for each point. Finally, a three-point running average along the coast was applied to smooth the data. The longshore distribution of textural parameters obtained can thus be considered to be the result of all agents acting on the coast during the sampling period (1988–1991). This can, therefore, be compared in a coherent manner with net longshore transport rate, beach evolution trend and total incident wave power.

Beach profiles were surveyed using standard levelling and bathymetric techniques. Each recorded depth was referenced to a datum of a nearby fishing harbour. A total number of 9 surveys were made between June 1988 and July 1991. To characterize the evolution of the beachface of the Ebro Delta coast during the period of control, shoreline displacements were used. The actual shoreline position was defined as the mean water level position. To calculate the shoreline rate of change, the end-point-rate (EPR) and linear regression technique (LR) were used. The former uses only the last and the first surveys to estimate the shoreline rate of change. The latter filters out short-term variability of the data, and the calculated rate can be considered to be the evolution trend of the shoreline during the period of study (DOLAN *et al.*, 1991).

The total incident wave power was used to characterize the wave action along the coast. It was evaluated at a depth of 1.5 m, which was the offshore limit of sediment samples. Shallow-water approximation for linear waves was used (this depth represents the limit for shallow waters approximation for waves with a T_p value of 5 sec), which is given by the relationship

$$P = \frac{1}{8}\rho g H^2 \sqrt{gh} \qquad (1)$$

where P is the wave power, ρ is the density of water, g is the gravitational acceleration and H is the wave height evaluated at a depth h. Since all the variables are constant except for wave height, the term H^2 will be representative of the wave power magnitude. The resulting wave power was evaluated by integrating all the waves acting on the coast and is given by

$$P_t = \sum_{i=1}^{N} P_i f_i = \sum_{i=1}^{N} H_i^2 f_i \qquad (2)$$

where P_i is the wave power associated with waves

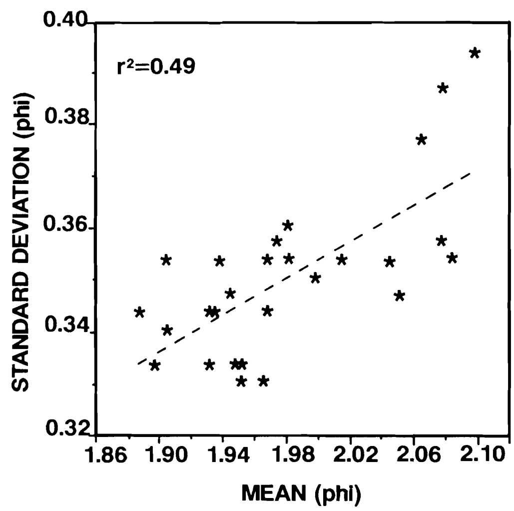

Figure 4. Standard deviation *versus* mean grain size.

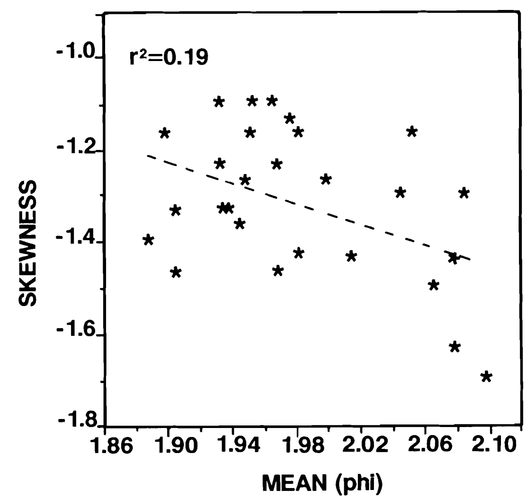

Figure 5. Skewness *versus* mean grain size.

which have the frequency f_i, N is the total number of wave characteristics and P_t is resulting wave power.

Wave heights at a depth of 1.5 m were calculated using a wave-ray model to simulate refraction from the offshore buoy location to the nearshore zone (depth = 14 m). From this point to the selected depth, a wave energy decay model was used which includes the wave energy changes due to refraction, shoaling, bottom dissipation and wave breaking (see BATTJES and JANSSEN, 1978; BATTJES and STIVE, 1985).

RESULTS

Sediment Distribution

The average textural parameters of beachface sediment in the Ebro Delta show a mean grain size of 1.99 phi, a standard deviation of 0.36 phi and a skewness of −1.37. Bivariate plots between textural parameters indicate a poor relationship between the mean grain size and the standard deviation and the skewness. The standard deviation increases and the sediment is slightly more negatively skewed (more poorly sorted) when the mean grain size value increases (finer sediment), with coefficients of determination (r^2) of 0.49 and 0.19, respectively (Figures 4 and 5). The poorly sorted sediment has a more negative skewness (r^2 = 0.62) (Figure 6).

The Ebro River mouth, located near Cap Tortosa, marks a discontinuity in the sediment distribution along the beachface of the Ebro Delta: the sediment located in the north part of the delta is considerably finer than the remaining sediment (Figure 7). This differentiation is caused by the distribution of sand supplies from the Ebro River, the only external source of sediment on the Ebro Delta coast. Most of the sand supplies of the Ebro

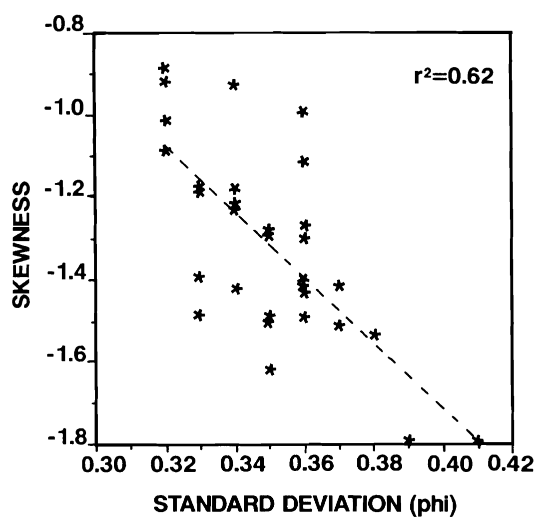

Figure 6. Skewness *versus* standard deviation.

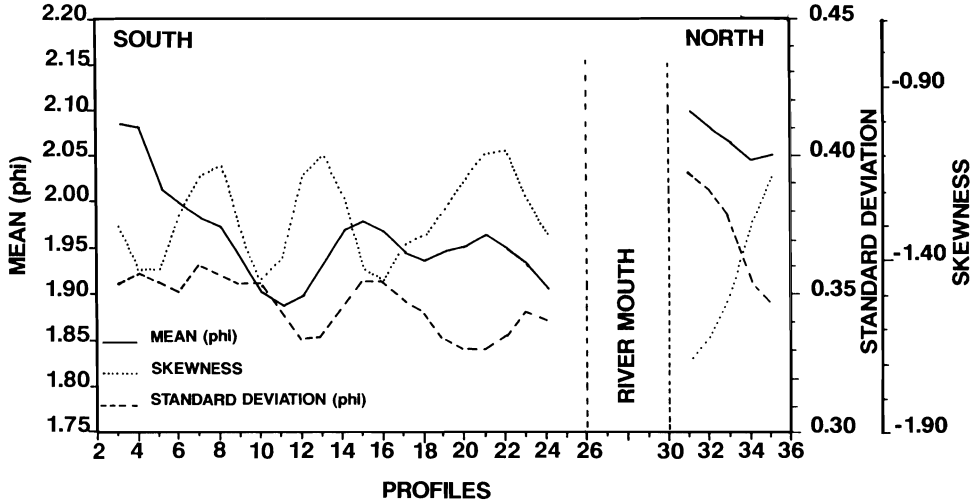

Figure 7. Longshore textural parameters distribution (mean grain size, standard deviation and skewness).

River are transported towards the north, because of the orientation of the present mouth and the dominant wave climate (easterly waves). The mixture of sand supplies with the pre-existing beachface sediment in the north part causes a mean grain size finer than that in the remainder delta, where new sand supplies do not arrive from the river. Towards the south of the river mouth, the sediment characteristics and their distribution are the result of the reworking of earlier deposited sediment in the nearshore.

The longshore distribution of textural parameters indicates the existence of several areas with different grain size trends (Figure 7). The mean sediment grain size enables the definition of six textural trends along the Ebro Delta beachface: three coarsening and three fining longshore trends in the transport direction (Figure 7). Coarsening trends are located in the Fangar, Migjorn and Trabucador Bar areas, with longshore grain size variation rates of about -0.83×10^{-2}, -0.99×10^{-2} and -2.17×10^{-2} phi/km, respectively. Fining trends are observed in Buda Island, Eucaliptos Beach and La Banya areas with grain size variations of 1.66×10^{2}, 0.78×10^{2} and 1.54×10^{-2} phi/km, respectively. Usually, coarsening longshore trends are accompanied by a better sorting of sediment (lower deviation) and fining trends correspond to a worse sorting of sediment (Figure 7). The longshore variation of the skewness indicates that coarsening and fining trends can be accompanied by a more positive or negative skewness. The most usual trends of sediment in the downdrift direction along the beachface based on the longshore distribution and bivariate plots of textural parameters would be: a) the sediment is coarsening, better sorted and more positively skewed, and b) the sediment is fining, with less sorting and more negatively skewed.

Relationship Between Shoreline Displacements and Grain Size

Figure 8 shows the shoreline rates of change along the Ebro Delta coast during the period of study. The main erosive zones are Cap Tortosa (profiles 22–24) and the Trabucador Bar (profiles 10–11) in the southern hemidelta and practically the whole northern hemidelta coast. The largest erosion rate is present in Cap Tortosa. The apices of the two spits and the Eucaliptos Beach are depositional zones. In general, it can be seen that finer sediments are present in prograding zones, while coarser sediment is present in erosive ones. Correlation between grain size and rates of shoreline change obtained using LR define two well differentiated data groups corresponding to both hemideltas (Figure 9). Since the sediment in the northern hemidelta is finer than in the southern one, the correlation has been separately analysed. For the sediment of the southern hemidelta a co-

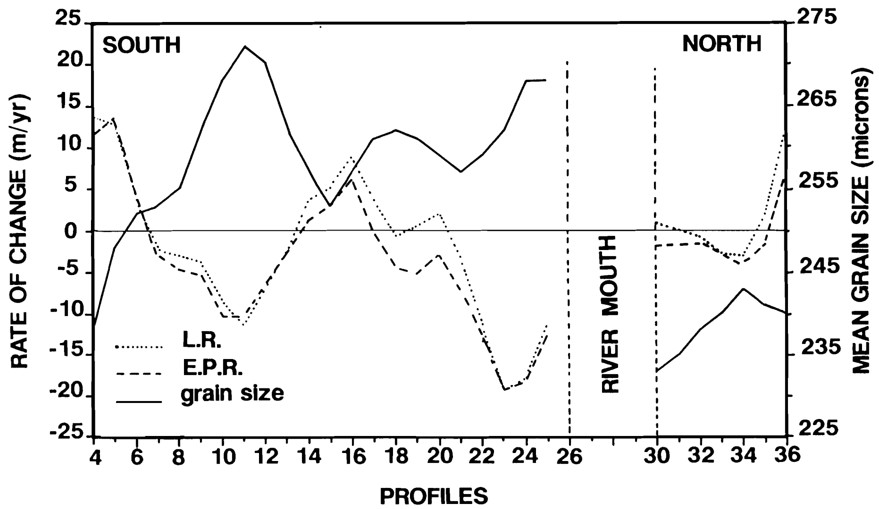

Figure 8. Shoreline rates of change and mean grain size along the Ebro Delta coast (LR: rate obtained using a linear regression technique; EPR: rate obtained using the end-point-rate method). (Microns units are used in what follows for a better visualization.)

efficient of determination of 0.57 is obtained. If the grain size values of the Cap Tortosa (profiles 22–24) are removed, r^2 increases up to 0.70. This zone is characterized, as mentioned before, by the presence of a divergence in the net longshore sediment transport. Therefore, it behaves as a source zone where the sediment is continuously removed by waves. As the sediment is not replenished, the resulting sediment distribution will be a function of the native sediment only. In the northern hemidelta, with a limited number of profiles, the value of r^2 is low (0.30).

Relationship Between Longshore Transport Rates and Grain Size

Figure 10 shows net longshore transport rates and grain size distributions along the Ebro Delta coast. This transport scheme corresponds to that presented by JIMENEZ and SANCHEZ-ARCILLA (1993). It is representative of the medium-term conditions for the Ebro Delta coast, where the medium-term shoreline evolution of the Ebro Delta is explained on the basis of the longshore transport scheme.

A high correlation between shoreline rates of change for the period of study and longshore transport gradients has been obtained, with $r^2 = 0.84$ for the whole data set (Figure 11). This high value indicates that most of these changes can be explained by the longshore transport gradient pattern. Moreover, if we remove the values of profiles 10 and 11 (located at the centre of the Trabucador Bar), this value increases up to 0.92. The values of the shoreline rate of change in these two profiles are influenced by a breaching process

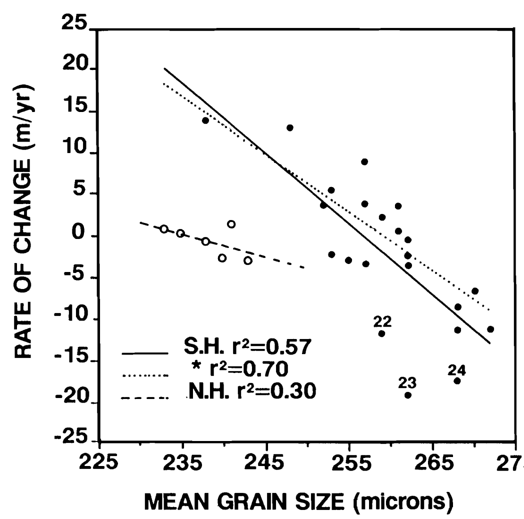

Figure 9. Shoreline rates of change *versus* mean grain size (SH: whole southern hemidelta; *: southern hemidelta without profiles of the Cap Tortosa zone (22, 23, 24); NH: northern hemidelta).

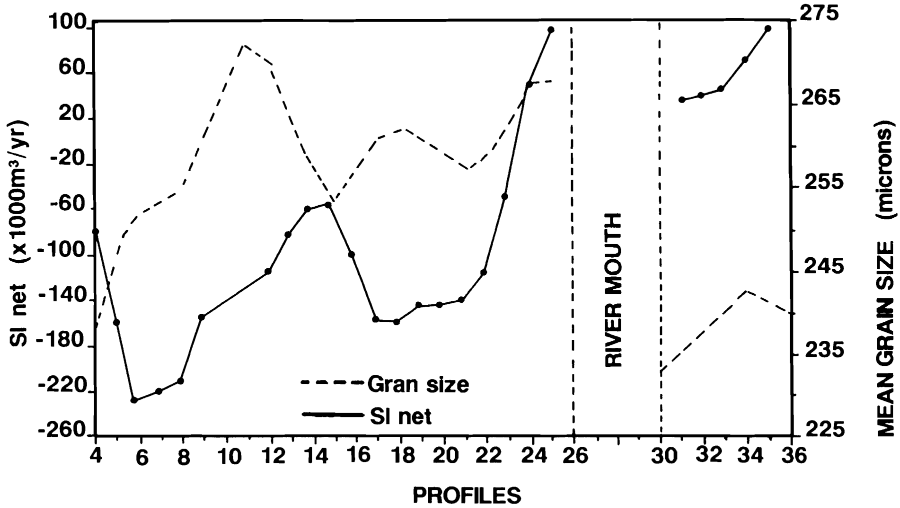

Figure 10. Net longshore transport rates and mean grain size along the Ebro Delta coast (negative values indicate a southward transport; note—profiles are not equidistant).

which occurred during a storm in October 1990 (Jimenez *et al.*, 1991, 1993a; Guillen *et al.*, 1993).

Looking at Figure 10, it can be seen that, in general, coarser sediments are present in zones with positive longshore transport gradients (increasing longshore transport rates); zones where longshore transport rates decrease are characterized by a progressive fining of the sediment grain size.

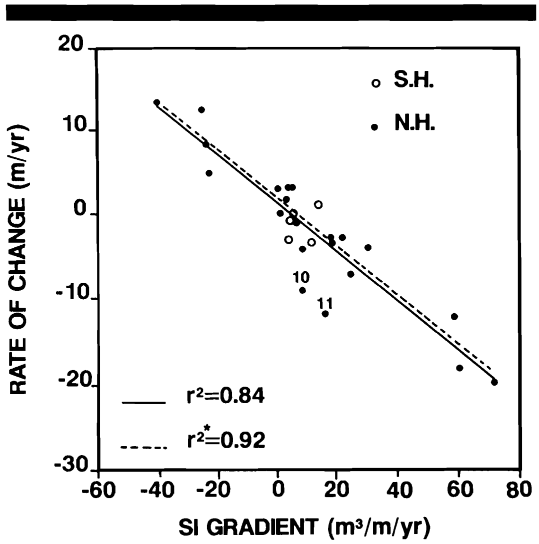

Figure 11. Shoreline rate of change *versus* longshore transport gradients (*: without profiles 10 and 11).

In the northern part of the delta, a uniform and simple pattern can be identified; the sediment becomes coarser towards the north as the longshore transport rate increases. To the south of the river mouth, the coarsest sediment is located at Cap Tortosa (profiles 22–24) where longshore transport rates are not too high. This is probably due to the existence of a large gradient in the longshore transport rate, because the transport direction diverges in this area (Figure 3). Southwards of Cap Tortosa (profiles 17–22) the longshore transport rate is nearly constant, and the sediment grain size shows small variations. In the Eucaliptos Beach (profiles 15–17), the longshore transport rate rapidly decreases and the sediment clearly becomes finer. Along the Trabucador Bar, although transport rates increase towards the south, the sediment does not exactly follow the transport pattern. The sediment coarsens towards the south, reaching the maximum grain size in the central part of the Trabucador Bar. In the south part of the Bar, although the transport rate grows, a progressive fining of the sediment can be observed. In the southern spit, between profiles 3 and 7, the grain size decreases because this is an active sink zone, where the longshore transport decreases and the sediment updrift removed is deposited.

Figure 12 shows the mean grain size *versus* longshore transport gradients. The r^2 values obtained for both northern and southern hemideltas are 0.42 and 0.34, respectively. The low value of the coefficient for the southern hemidelta can be considered to be surprising. The correlations for shoreline displacements and transport gradients as well as those between shoreline changes and mean grain size were high. This low value is a result of considering the southern coast as a single system. However, two longshore transport cells can be identified (Figure 10), coastal stretches delimited updrift by a positive transport gradient (transport rates increasing) and downdrift by a negative transport gradient (transport rates decreasing). The first cell extends from Cap Tortosa (profiles 22–23) to the Eucaliptos Beach (profile 15) and the second from the north part of the Trabucador Bar (profile 14) to the La Banya spit (profile 4).

If the analysis of correlation is done separately for both cells, the value of the coefficient significantly increases. In the Trabucador-La Banya cell a value of $r^2 = 0.61$ is obtained. Moreover, in the samples of profiles 10 and 11 (located at the centre of the Trabucador, where the above mentioned breach occurred), r^2 increases to 0.74. For the Cap Tortosa-Eucaliptos Beach cell, a value of $r^2 = 0.76$ was obtained. This last value does not take into account the samples of profiles corresponding to the largest gradient zone (22–24) because, as previously mentioned, this sediment is a function of the native sediment.

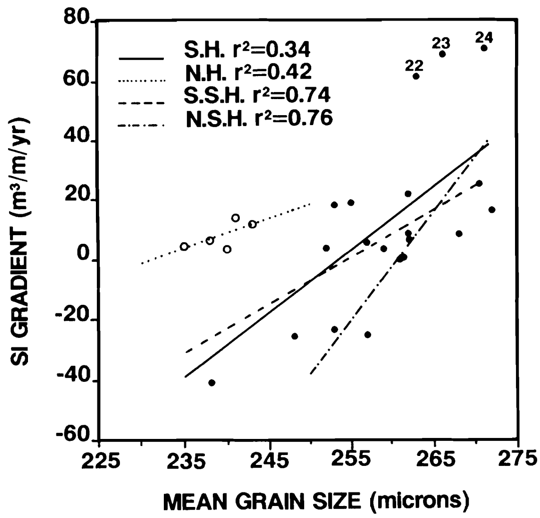

Figure 12. Longshore transport gradients *versus* mean grain size (SH: whole southern hemidelta; SSH: south transport cell in the southern hemidelta; NSH: north transport cell in the southern hemidelta; NH: northern hemidelta).

Relationship Between Wave Power and Grain Size

The incident wave power distribution along the Ebro Delta coast can be seen in Figure 13. The wave power magnitude in the northern hemidelta is lower than in the south because southerly waves are unable to reach the northern coast. In the northern hemidelta (profiles 30 to 35) the wave power increases from the river mouth area towards the Fangar spit. The river mouth area presents the lowest value of wave power due to the sheltering effect of St. Antoni Island which protects the zone from the dominant east waves, whereas the Fangar coast is fully exposed to the wave action.

In the southern hemidelta, a more complex pattern is observed in the wave power distribution due to the wave refraction. The wave power decreases between Cap Tortosa and the Eucaliptos Beach. From this point, it increases to the middle part of the Trabucador Bar and from here it decreases southwards. The peak observed in wave power at the centre of the Trabucador Bar is caused by a local increase in wave height (JIMENEZ, 1991).

Sediment grain size and wave power are well correlated (Figure 13): the higher the wave power, the coarser the sediment. In the northern hemidelta (profiles 30–35), a northwards coarsening sequence follows the increase in the wave power. In the southern hemidelta, the grain size distribution is more complex, as is wave power, although the same behaviour is present. Only in Cap Tortosa (profiles 22–24) is a different pattern observed. Although the wave power is low at this point (due to the local coastal orientation with respect to the south waves), the sediment is coarser.

Figure 14 shows the mean grain size *versus* the resulting wave power for each profile. In the southern hemidelta, if all samples are considered, the obtained value $r^2 = 0.28$ is too low to assume a relationship between the analysed parameters. However, this low value is mainly produced by the samples of Cap Tortosa (profiles 22–24). If these samples are removed from the analysis, the value of the coefficient of determination increases

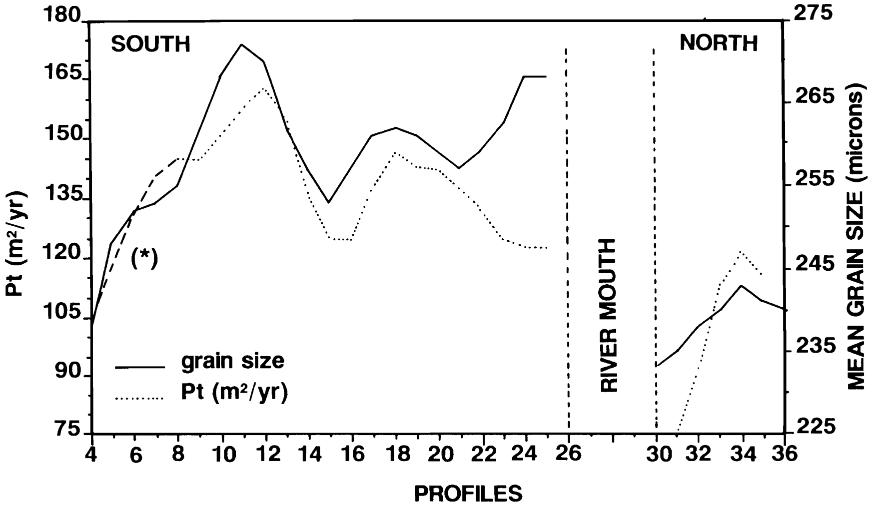

Figure 13. Wave power and mean grain size along the Ebro Delta coast (*: portion of the curve induced from coastal orientation, not used in the analysis of correlation).

to 0.68, indicating a good correlation between grain size and wave power. In the northern hemidelta a r^2 value of 0.95 has been obtained. This high value, although expected, must be taken as indicative because of the lack of sufficient data.

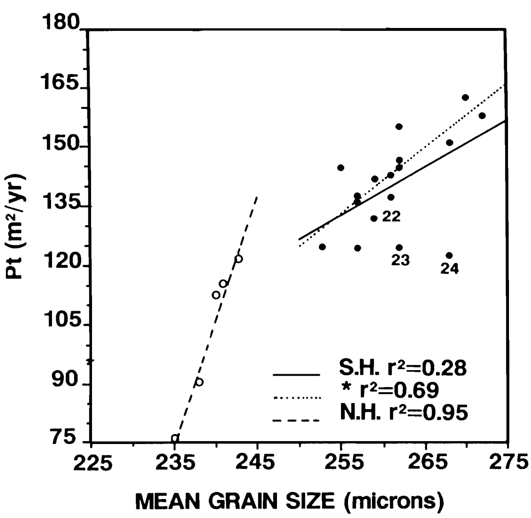

Figure 14. Wave power *versus* mean grain size (SH: whole southern hemidelta; *: southern hemidelta without profiles of Cap Tortosa (22, 23, 24); NH: northern hemidelta).

DISCUSSION

The average grain size values of the beachface sediment along the Ebro Delta coast ranges from 1.87 to 2.15 phi. This variation is small compared to other coasts around the world (Table 1). This narrow grain size range can be explained because the Ebro Delta coast has only one external source of sediment. The Ebro River supplies a low amount of homogeneous sand to the coast (mainly restricted to the northern hemidelta). The high number of samples enables us to consider the obtained sediment distribution to be the result of the main processes acting on the coast during the period of study (1988–1991).

The presence of coarser sediment in erosive zones can be associated with the more intense selective winnowing of the finest fractions and the progressive coarsening of the resulting lag deposit. Erosion areas supply the finer sediment, which is transported alongshore and deposited in accretional zones. The resulting sediment grain size depends not only on the shoreline rate of change but also on other factors. For instance, similar grain sizes can be found in Cap Tortosa and Trabucador Bar, although their erosion rates, longshore transport gradients and incident wave power are very different.

The results obtained in the comparison of sediment grain size and longshore transport gradi-

Table 1. *Ranges of sediment sizes in different beach faces around the world.*

Location	Range of Sizes (phi)	Source
Netherland coast	1.4–2.3	SHORT (1992)
Rhône Delta (France)	1.6–2.5	MASSELINK (1992)
Quilon coast, Kerala (India)	1.18–1.55	PRAKASH and PRITHVIRAJ (1988)
Australian coast		
(Palm)	1.10–1.65	BRYANT (1982)
(Putty)	1.24–1.65	
(Patonga)	0.95–1.78	
(Pearl)	1.10–2.03	
Coburg Peninsula (British Columbia)	−0.27–0.32	MCLAREN and BOWLES (1985)
Florida and SE Alabama	1.7–2.4	STONE *et al.* (1992)
Hook Spit, New York Bay	1.17–1.42	NORDSTROM (1977)
Eastern England	−0.9–2.8	MCCAVE (1978)
Ebro Delta	1.87–2.15	This study

ents show that, in general, sediment becomes coarser as the transport gradient increases; decreasing gradients are characterized by a sediment fining. The best correlation between the two parameters has been found when longshore transport cells are separately analysed (Figure 12).

With respect to the effect of the incident wave power, it has been observed that an increase in wave power causes a more intense winnowing of sediment and the resulting deposit becomes coarser. The incident wave power reflects the available energy for transport processes, both longshore and cross-shore.

Exceptions to the described relations have been observed in two areas presenting similar grain sizes: (1) Cap Tortosa and (2) the Trabucador Bar. These exceptions follows:

(1) If only the transport gradient is considered, which is the highest, the coarsest sediment along the entire coastline should be expected in Cap Tortosa. On the other hand, if only the wave power was considered, which is low in this zone, a fine sediment would occur.
(2) In the Trabucador Bar the magnitude of transport gradient and wave power are opposite of those in Cap Tortosa. Low transport gradient indicates a relatively fine sediment and the maximum incident wave power would correspond to the coarsest sediment.

These exceptions have been found in areas with maximum values of positive transport gradient (Cap Tortosa) or wave power (Trabucador). These two factors are the main agents which produce the winnowing of the finest fraction of the sediment and the resulting sediment grain size will be a product of their combined action.

In Cap Tortosa, the highest longshore transport gradient along the coastline is present due to a divergence in the longshore transport. This divergence converts the zone into a source area where the sediment is continuously eroded and transported along the coast. Under these conditions, the local longshore transport pattern is sufficient to produce a sediment coarser than in the neighbouring areas.

The Trabucador Bar has the highest incident wave power along the coastline, whereas the longshore transport gradient is moderate. The presence of the coarser sediment indicates that other processes different to the longshore transport may control the local sediment distribution, and they are reflected by the local wave power. Thus, the Trabucador is overwashed several times per year under storm wave action and low atmospheric pressure conditions, resulting in a net cross-shore sediment transport towards Alfacs Bay. During the period of study, this process reached maximum relevance in October 1990, when the central part of the Trabucador Bar was breached for three weeks (JIMENEZ *et al.*, 1991, 1993a; GUILLEN *et al.*, 1994). The breached stretch coincides with the highest wave power along the Trabucador Bar. The high energy reaching this area produces an intense winnowing of the finer sediment (most of which is transported to the inner bay).

The depositional areas such as La Banya, Eucaliptos Beach and the apex of Fangar spit, show different grain sizes as a function of the longshore transport cells. These areas receive sand supplies from updrift erosional zones. Consequently, the textural characteristics of the deposited sediment are controlled by the grain size of the source area. This is particularly evident when the grain size of the northern and southern part of the Delta are compared; the finer sediment of the Fangar is the result of a longshore transport scheme where very little exchange with the south part is expected.

Along the southern hemidelta coast, two transport cells are present. These cells are connected and part of the sediment removed from the Cap Tortosa zone arrives to the southern spit. This explains the similar grain size in the Cap Tortosa and Trabucador Bar zones, where the sediment is the coarsest along the Delta. The processes responsible for this are different in the two areas, and the resulting similar grain size shows that the sediment in the Trabucador Bar is partially controlled by the sediment supplied from Cap Tortosa.

From these observations, it is clear that the use of grain size parameters to determine the magnitude of littoral processes and/or the direction of sediment transport is not a trivial study. In breaches where the littoral dynamics are complex, such as those showing several transport cells and/or where the nearshore wave conditions are not uniform along the coast (*e.g.*, STONE *et al.*, 1992), using only sediment distribution is insufficient to correctly explain the dominant littoral processes. For instance, if the McLaren model (MCLAREN and BOWLES, 1985) is applied to estimate the transport direction between Cap Tortosa and the Trabucador Bar (profiles 23 to 8), a sediment transport towards the north is predicted. This transport would correspond to that defined as case C in the original model (coarser, better sorted and more positively skewed in the transport direction). However, the longshore sediment transport in this zone is directed towards the south (Figures 3 and 10). This disagreement is produced because the variations in the dynamic parameters along the coast cause changes in the sediment texture that are unpredictable by the McLaren model. That model is only applicable to sequential deposits along a monotonically decreasing energy transport path.

CONCLUSIONS

The sediment grain size shows longshore variations caused by alongshore changes in the littoral dynamics. These changes are produced by the alongshore variations in nearshore wave characteristics due to the bottom and coastal configuration.

The longshore grain size patterns along the Ebro Delta coast can be explained by the selective winnowing of the finer sediment. The importance of the winnowing is caused by the characteristics of the coast; only a single external sediment source (the Ebro River) exists and the sediment is continuously reworked in a longshore transport dominated coast. Two factors have been identified as being mainly responsible for the winnowing: the local longshore transport gradient and the incident wave power.

This analysis indicates that littoral dynamics cannot be fully explained by the sediment grain size, because it induces a simplistic description of the system. To relate sediment data with beach processes, information about wave conditions and a representative transport scheme have to be used. When this information is available, grain size variations can be related in a qualitative sense, with erosion/accretion processes along the coastline.

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□ RESUMEN □

La variación longitudinal del tamaño del sedimento a lo largo de la costa del Delta del Ebro fué analizada para estimar los procesos que controlan su distribución. Se utilizaron treinta y dos puntos de control, en los cuales se obtuvo una muestra representativa promediando cuatro muestras tomadas en la parte interna de la zona de rotura durante ocho campañas de medida (32 muestras por punto de control). Se relacionó la distribución obtenida con un conjunto de parámetros característicos de los procesos costeros: tendencias evolutivas de la línea de orilla, tasas de transporte longitudinal neto y flujo de energía del oleaje incidente. La playa presenta un rango pequeño de tamaños de sedimento debido a la existencia de una sola fuente externa de sedimento (el Río Ebro) que aporta una pequeña cantidad de sedimento homogéneo. Estos aportes están restringidos principalmente al hemidelta norte, donde el sedimento es más fino que el del hemidelta sur. La distribución del sedimento a lo largo de la costa del Delta del Ebro muestra un proceso de clasificación longitudinal no monotónico, relacionado con las variaciones longitudinales de los agentes impulsores (transporte longitudinal y flujo de energía). En general, los sedimentos más gruesos están localizados en zonas erosivas, con flujos de energía altos y gradientes de transporte longitudinal positivos. Los sedimentos más finos son característicos de areas de deposición, con flujos de energía bajos y gradientes de transporte longitudinal negativos. Sin embargo, la dinámica litoral de la costa del Delta del Ebro no puede ser totalmente inferida a partir de la distribución del sedimento porque varios parámetros son los que controlan su distribución. Así, existen varios tramos de costa con un tamaño de sedimento similar bajo diferentes esquemas de transporte longitudinal y flujo de energía incidente.