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# Grain-size trends associated with sediment transport patterns in Cadiz Bay (southwest Iberian Peninsula)

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**ABSTRACT**

On the inner continental shelf and coastal environments, grain-size trends make it possible to characterise ancient and modern environments, and to identify net sediment transport patterns, using grain-size distributions and factorial multivariate analysis.

In Cadiz Bay, grain-size trends are controlled by the contribution of fine sediments, coastal morphology and the suspended transport pathways due to the ebb-currents.

The main parameter able to identify grain-size trends is skewness. Three trends were determined to characterise present-day sedimentary environments: a) very positively skewed sediments with leptokurtic distributions belong to deposits with a high degree of textural maturity and reworking; b) negatively skewed sediments characterise intertidal environments (foreshore), and also make it possible to localise palaeolittoral environments; c) symmetrical and poorly sorted distributions indicate the permanent fine-settling pathways, whereas positively skewed, coarser and better-sorted sediments point to the occasional extension of suspended matter plumes.

**Key words:** Grain-size trends, sediment transport, sedimentary environments, Cadiz Bay.

***RESUMEN***

***Tendencias en los parámetros granulométricos asociadas al transporte y dinámica sedimentaria en la bahía de Cádiz (suroeste de la península Ibérica)***

*En la zona infralitoral y de plataforma interna, las tendencias en los parámetros granulométricos permiten caracterizar ambientes antiguos y modernos, e identificar trayectorias de transporte de sedimentos mediante el análisis de las distribuciones granulométricas y el análisis factorial multivariante.*

*En la bahía de Cádiz, las tendencias observadas en los parámetros granulométricos están controladas por los aportes de sedimentos finos, la configuración de la costa y las trayectorias de transporte en suspensión debidas a las corrientes de reflujo mareal. La asimetría es el parámetro principal en la identificación de tendencias granulométricas.*

*Se han determinado tres tendencias que caracterizan los ambientes sedimentarios presentes: a) asimetrías muy positivas y distribuciones muy leptocúrticas indican un alto grado de madurez textural y retrabajamiento; b) tendencias hacia asimetrías negativas caracterizan ambientes intermareales de playa y permiten localizar ambientes paleolitorales; c) distribuciones simétricas y mal seleccionadas trazan las trayectorias permanentes de precipitación de sedimentos finos, mientras asimetrías más positivas, aumento del tamaño de grano y mejor selección marcan la extension ocasional de las plumas de materia en suspensión.*

***Palabras clave:*** *Tendencias granulométricas, transporte de sedimentos, ambientes sedimentarios, bahía de Cádiz.*

## INTRODUCTION

The littoral zone of Cadiz Bay has been the subject of numerous studies focusing on sediments and on the water column. Nevertheless, it is necessary to have a global vision of the processes involved to obtain an integrated model of the sedimentary dynamic. Recently, the possible sources of supplies have been investigated (Gutiérrez Mas *et al.*, 1996, 1997; Moral Cardona *et al.*, 1996), the current distributions have been determined using natural tracers (Guillemot, 1987; Gutiérrez Mas *et al.*, 1994), and bedforms have been analysed (Parrado Román, Gutiérrez Mas and Achab, 1996).

The present paper is aimed at identifying the response of grain-size distribution and granulometric parameters in our study zone, comparing them with trends found in other zones (McLaren, 1981; Gao and Collins, 1992; Gao *et al.*, 1994; Pedreros, Howa and Michel, 1996).

The study area is located in southwest Iberian Peninsula, in outer Cadiz Bay (figure 1). The natural framework of Cadiz Bay comprises a large semiclosed bay, with a characteristic low-coast morphology; a wide bay can be differentiated to the north (external bay), as well as a barrier-island-lagoon to the south (inner bay), and an intertidal system of salt marshes to the south and southeast. The materials that constitute Cadiz Bay are fundamentally of sedimentary origin, with deposits of marsh muds, beach sands, river deposits and some conglomerate levels, dated as Plio-Quaternary (Zazo, Goy and Dabrio, 1983). The continental supplies proceed from the Guadalete and Salado Rivers and tidal inlets, and from the continuous mud transport from the marshes by ebb-currents. The hydrodynamic system is controlled by waves and tides. The prevailing winds are westerly and southeasterly. The sea waves have the same spectrum as the prevailing winds, although swell waves present a dominance of the westerly component, aided by the special north-northwest/south-southeast configuration of the coast. The mean values of significant wave heights oscillate between 0.6 m and 1 m,

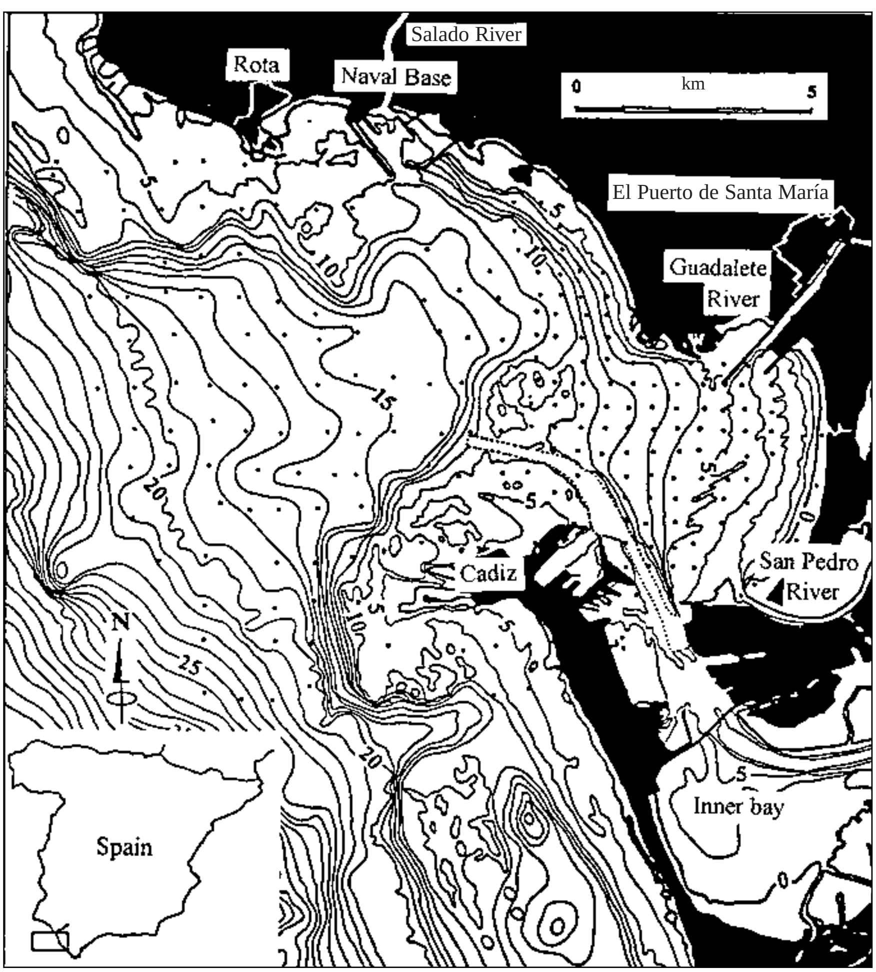


Figure 1. Location of study area and sea-bed sediment sampling sites of Cadiz Bay (bathymetry in metres)

with maximum values of 4 m (Muñoz Pérez, 1996). The tidal regime is mesotidal, with a maximum range of 3.7 m, which generates currents of up to 1.5 m/s in narrow zones (Anon., 1992).

## MATERIALS AND METHODS

The typification of seabed sediments in Cadiz Bay was based on an exhaustive surface sampling made with a Van Veen drag and GPS positioning, covering 232 stations (figure 1). Material (sand and gravel) coarser than 4 ϕ (63 μm) was dry-sieved, whilst fine-grained material > 4 ϕ (silt and clay) was analysed using the laser diffraction method, over intervals of 1 ϕ. Thus, a wide grain-size distribution was obtained, ranging from –3 ϕ (8 mm) to 13 ϕ (0.24 μm). The textural parameters were calculated using the moments method (Friedman and Sanders, 1978).

In the study zone, the main patterns of sedimentary dynamics were already known. To relate this knowledge to the observed grain-size trends, different tools were used: classification of the grain-size distributions that characterise different environments; study of the polymodal character of the distributions; and analysis of geographical profiles of variation of the parameters with the depth. Finally, a factorial multivariate analysis from the main granulometric parameters (mean, sorting, skewness and kurtosis) was made using the BMDP statistical package.

## RESULTS

Cadiz Bay's seabed showed a heterogeneous distribution, in agreement with the different depositional environments and hydrodynamic processes that control sedimentation. Two sectors were differentiated (figure 2):

a) an inner bay of shallow water constituted fundamentally by mud;
b) an external bay, which can be divided into an eastern and a western sector, whose boundary is located in the shoals of La Galera, and connects with the inner bay through the strait of Puntales. In the eastern sector, sand is the dominant fraction, being superposed by a muddy sand bed, whereas the western sector is characterised by the muddy sand that passes locally to sandy mud and mud, being configured in two branches, which reflect the trasnport path of suspended matter: the first one located to the north, with an east-northeast/west-southwest direction, the other towards the north-northeast/south-southwest. Between both branches, sand is dominant.

Ten types of grain-size distributions were found in the external sector of Cadiz Bay (figure 3), characterising different environments in the study zone.

- Type I is very scarce (2 % of the total), and is characterised by gravelly modes, and by a very poorly sorted, platikurtic and positively skewed distribution, being associated with sediments located near rocky shoals.
- Type II (7 %) appears in the southern part of the eastern sector, near the navigation channel, and following the contours of the rocky shoal near Rota, being associated with muddy-gravelly-sand facies. The samples present a bimodal character, are poorly sorted, with platikurtic and symmetrical distributions.
- Type III (7 %) is found in energetic coastal environments affected by waves, at depths lower than 5 m, and presents symmetrical, leptokurtic and unimodal distributions, with moderately- to well-sorted sediments. Some distributions present very positive skewness.
- Type IV distributions are quite frequent (17 %) and appear in the transition zones of sandy to muddy-sand facies. They present a very fine sand mode and a wide, fine tail. The granulometric spectrum is highly variable, with a leptokurtic average distribution and positively skewed or symmetrical.
- Type V (14 %) is related to sandy facies with a fine sand mode, predominates in shoreface and foreshore environments, and is characterised by well-sorted sediments that show leptokurtic and positively skewed distributions.
- Type VI distributions (5 %) are characterised by a fine and very fine sand mode, together with a fine tail. They are located in the western sector at depths higher than 15 m. They show strong leptokurtic, symmetrical and well-selected distributions.
- Type VII granulometric distributions, the most frequent (23 %), are characterised by a very fine sand mode and mesokurtic, positively

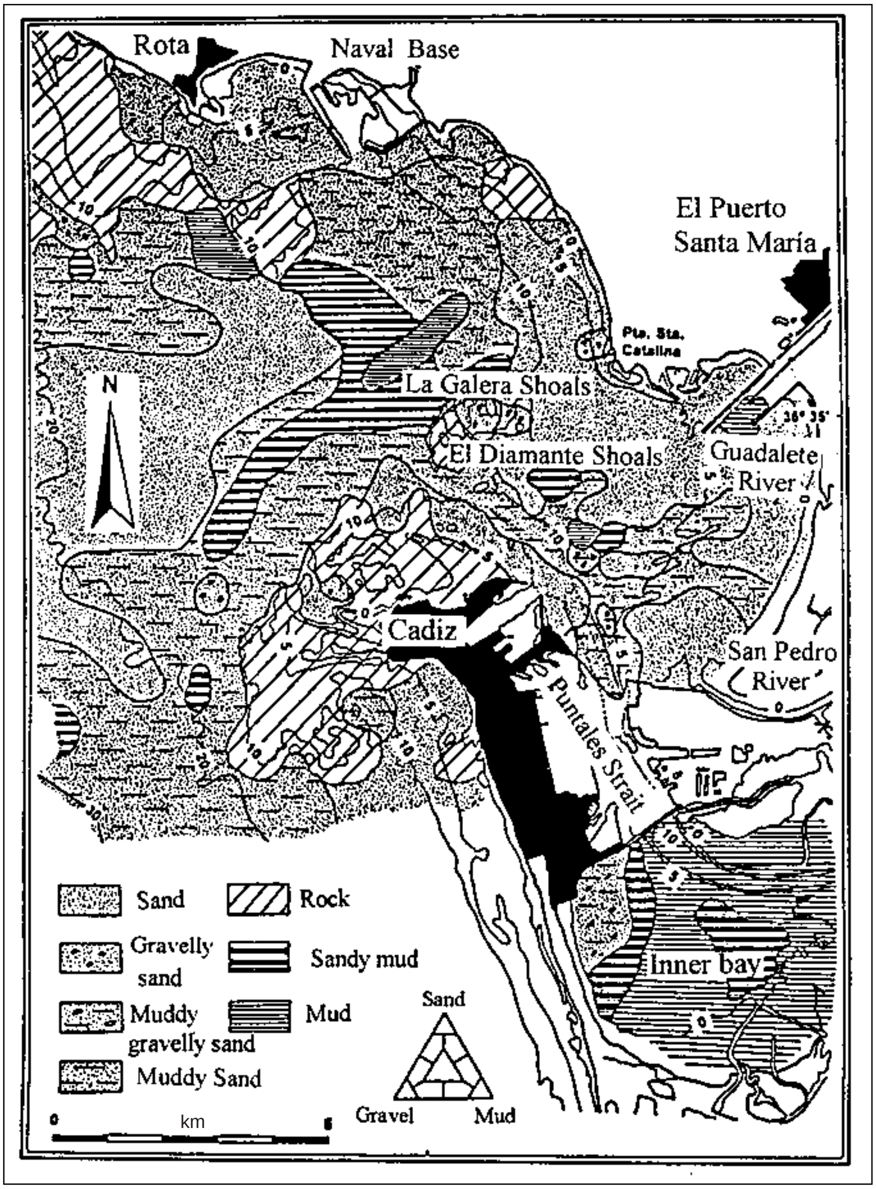


Figure 2. Granulometric distribution of sea-bottom sediments of Cadiz Bay

skewed distributions and poorly sorted sediments.

- Type VIII (16 %) has a modal class of very fine sand, which constitutes more than 70 % of the total sample. This type is located in the eastern sector, on submerged beach zones (nearshore), and at the river mouth. The grain-size distributions are extremely leptokurtic, very well sorted and very positively skewed.

The distributions where the mud content is dominant have been differentiated by their sand content.

- Type IX (4 %) presents modes of fine or very fine sand, located on sandy mud facies.
- Type X distributions (5 %) present variable modes, with silty facies. Both the grain-size distributions are very platikurtic, poorly or very poorly sorted and symmetrical.

The analysis of grain-size parameters and of the principal mode found that in the coastal zones, very fine sand is dominant, and it is the most stable size fraction for the existing energetic conditions and for the dominant transport process. The coarser modes appear in the littoral zone and near rocky shoals, and rarely at depths of 20 m, whereas the fine modes are located in the central zone of the external bay.

The polymodal nature of many distributions led us to break them down, which can be an effective in-

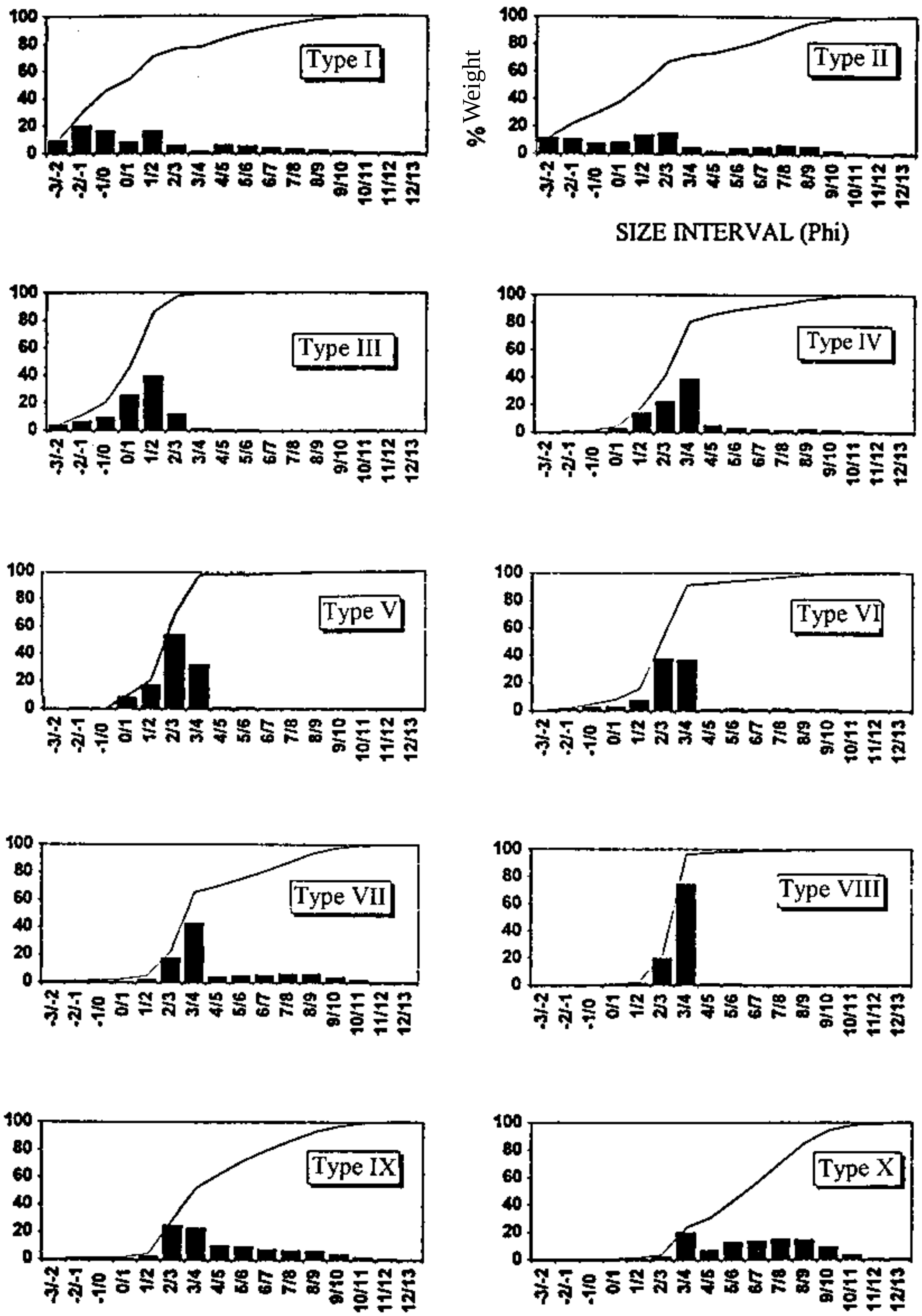


Figure 3. Different grain-size distributions found in the study area

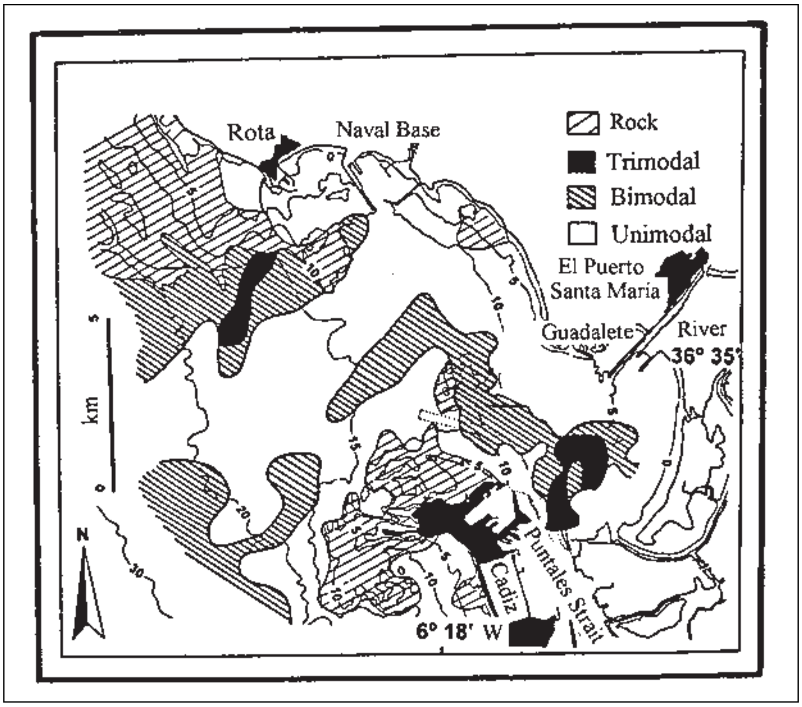


Figure 4. Distribution of the polymodal character of the sediments

strument for identifying superimposed processes and differentiating their ancient and modern processes (Alveirinho and Neal, 1990). In the external bay, the unimodal distribution of very fine sand prevails, but bimodal and polymodal distributions are also common, predominating fine sand and silts (figure 4).

The mean presents an average value of 3.4ϕ (very fine sand) (figure 5A), and shows a predominance of the very fine sand size together with a band of finest means that seem superimposed to the general trend. The coarser means appear fundamentally in the coastal zones. The sorting (figure 5B) is of 1.9ϕ, corresponding to moderately sorted sediments. Its distribution shows a high degree of heterogeneity, according to the localisation of the supply sources, to the energy of the environment and to the transport processes. An eastern sector was differentiated, with well or very well sorted sediments, especially to the north, as well as a western sector, poorly or very poorly sorted.

The skewness presents an average value of 0.9 (positive skewness). This prevails together with the

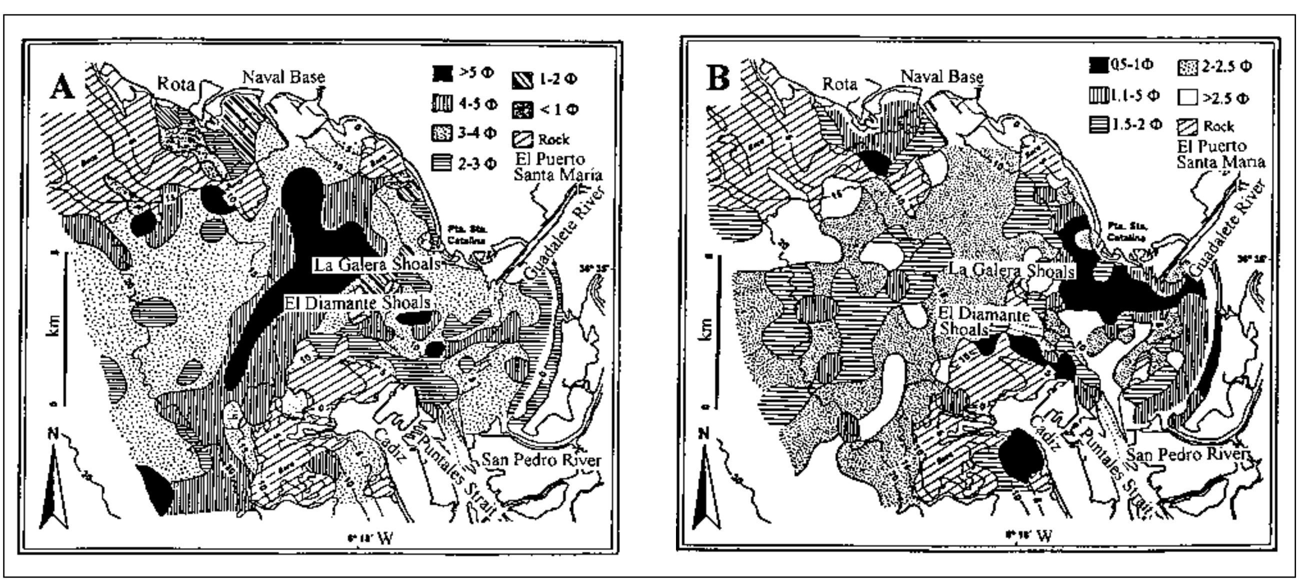


Figure 5. Distribution of grain-size parameters (in ϕ units). (A): mean grain size; (B): sorting

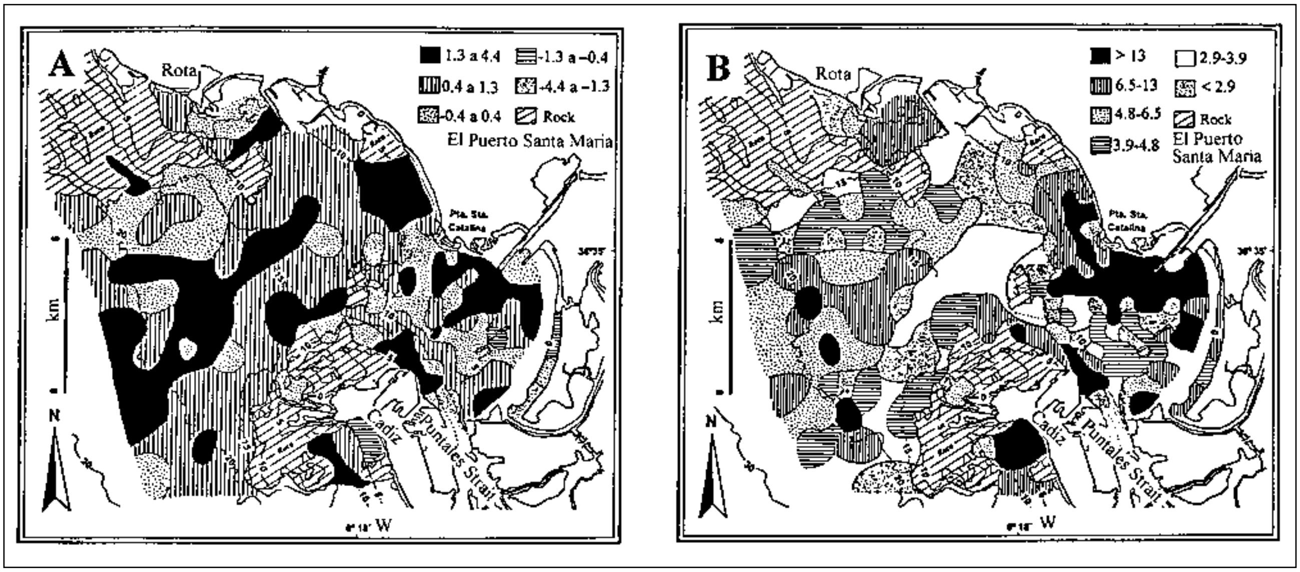


Figure 6. Distribution of grain-size parameters in sea-bottom sediments. (A): skewness; (B): kurtosis

symmetrical distributions (figure 6A). The negative skewness values are found near the coastline (foreshore).

The average value of kurtosis is about 8.4 (very leptokurtic distributions), and distribution is very heterogeneous (figure 6B).

In order to determine the variation of local trends of the main grain-size parameters (mean, sorting, skewness and kurtosis) with depth, three geographic profiles were made (figure 7).

Profile 1 is located to the north of the external bay, from Vistahermosa beach out to a depth of 20 m. The mean and the skewness show local variations, without presenting depth-defined trends (figure 8). On the other hand, the sorting (standard deviation in $\phi$) tends to increase, and the kurtosis presents a homogeneous behaviour, except for the coastal zone.

Profile 2 is located from Levante beach (Los Toruños) out to a depth of 21 m. In this section the four granulometric parameters present profiles without defined trends (figure 9).

A detailed analysis of physiographic zones makes it possible to observe a particular behaviour in the intertidal zone, characterised by coarser, well-sorted, negatively skewed and very leptokurtic sedi-

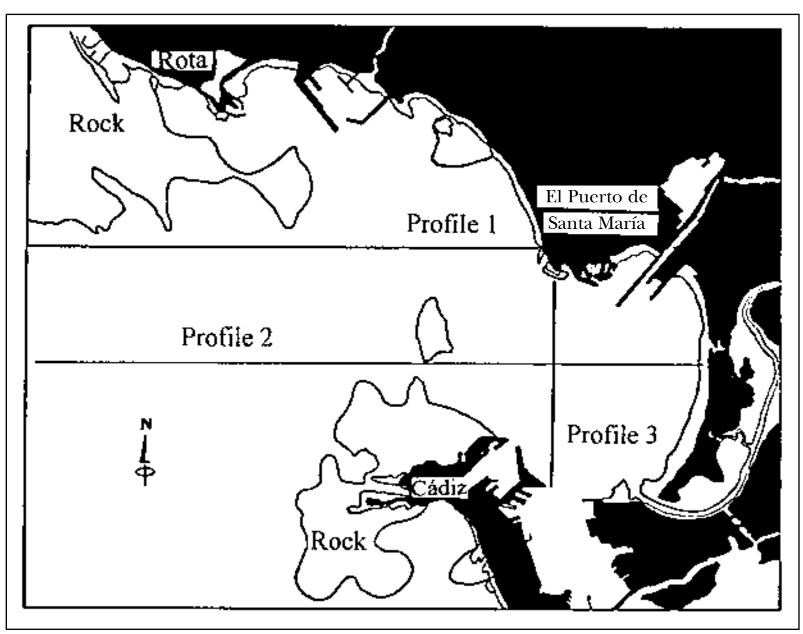


Figure 7. Location of the geographic profiles

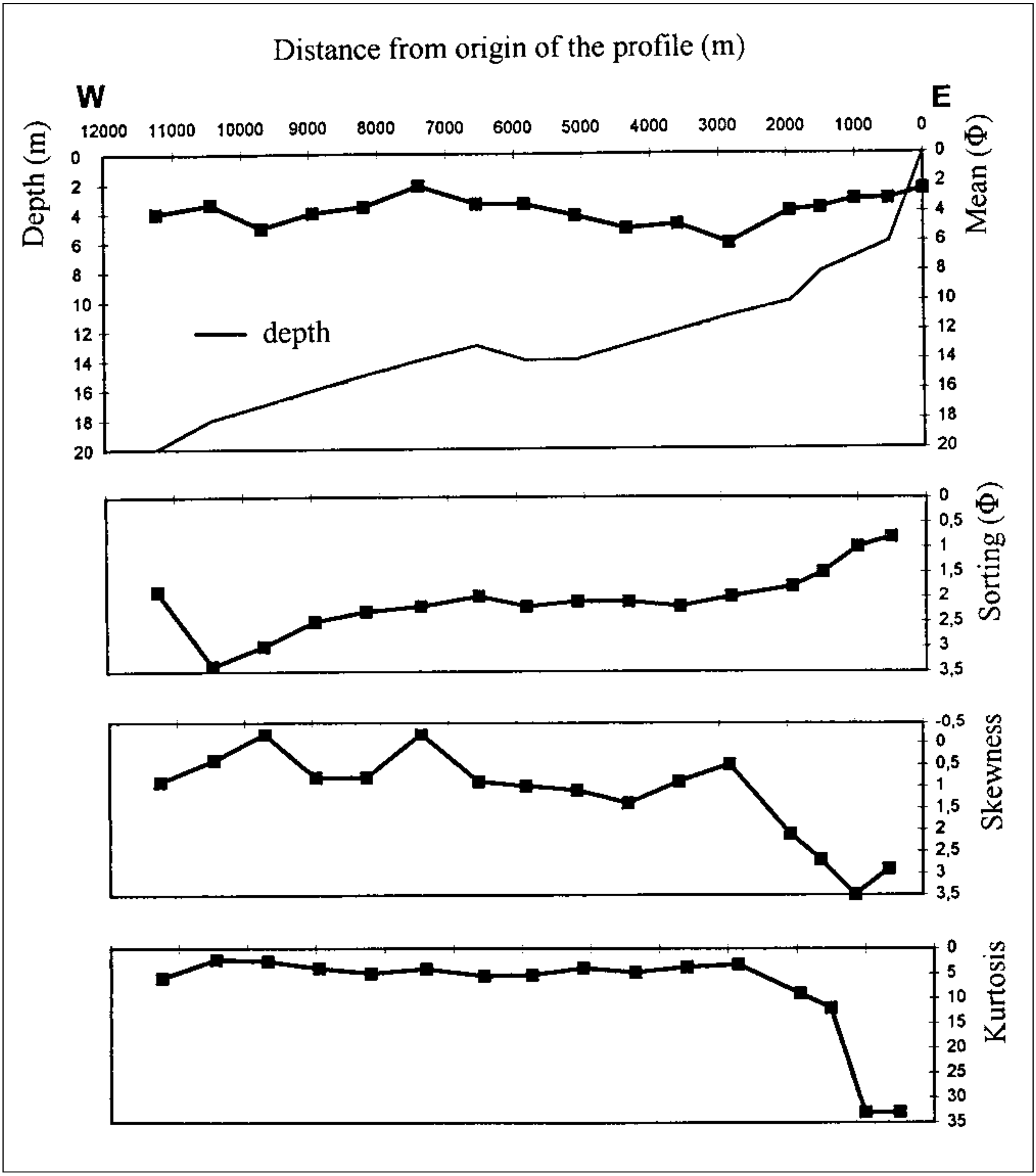


Figure 8. Grain-size parameter variation vs depth, at profile 1

ments. Then, as depth increases sediment becomes finer, poorly sorted, positively skewed and platikurtic. At a depth of 11 m, the smallest values of grain size and sorting are found near the maximum concentration of mud, with almost symmetrical distributions. At a depth of 20 m, on sandy facies, the behaviour is similar to that observed in the coastal zone, except for local variations of the skewness observed near the rocky shoal of Rota.

Profile 3 is located in the eastern sector of the external bay and runs from the Strait of Puntales towards the North; a southern part can be differ-

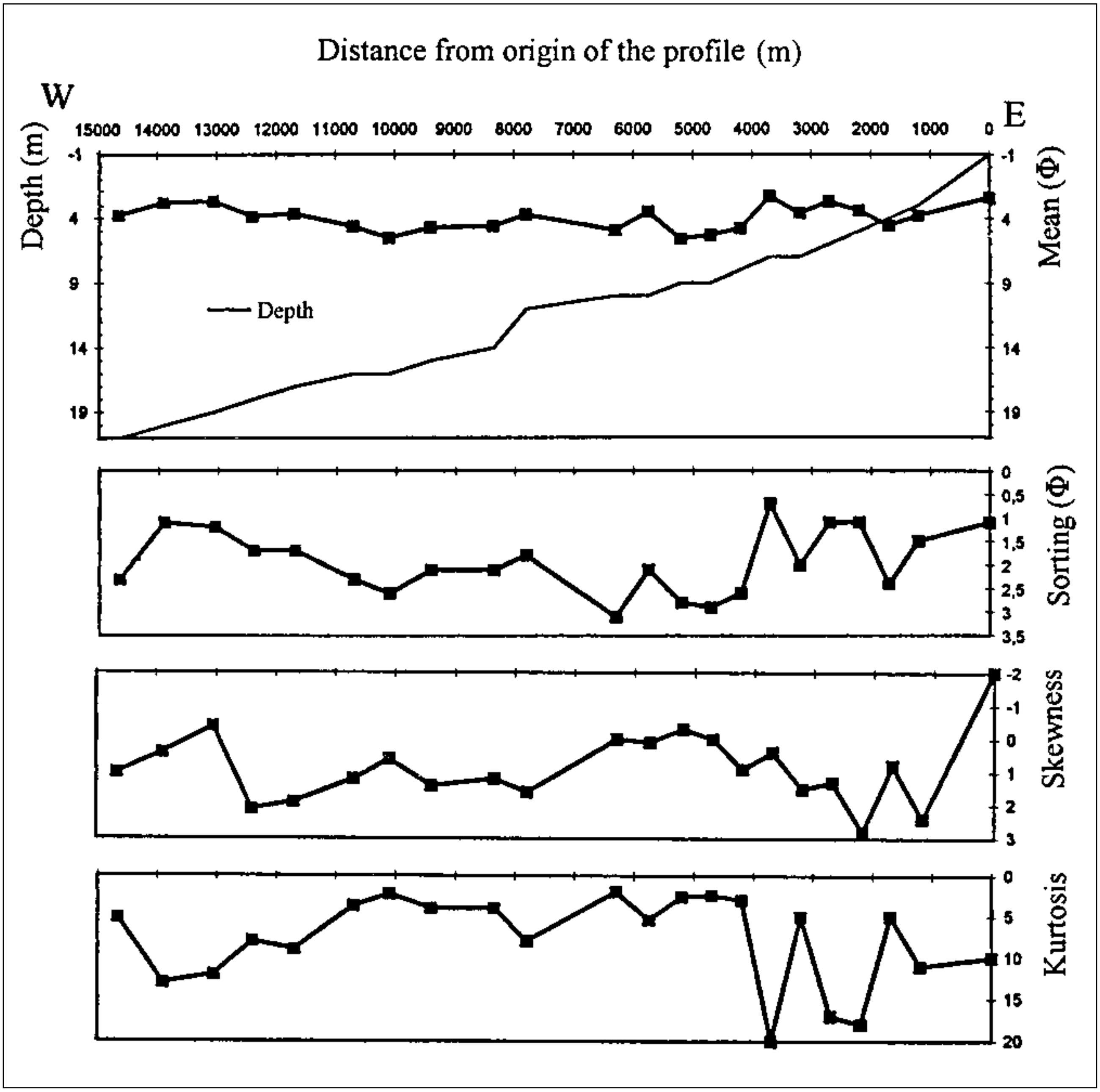


Figure 9. Grain-size parameter variation vs depth, at profile 2

entiated, with very poor skewness, and symmetrical and platikurtic distributions (figure 10). The northern sector is represented by very well-sorted sediments, an increase in kurtosis and very variable skewness, according to the sedimentary environments, ranging from very negative to very positive skewness.

Other graphic representations intend to determine general trends of the parameters with depth, so we used profiles averaged by depth interval (2.5 m).

The depth vs mean tends gently towards finer means, from the shoreline to the inner shelf (figure 11).

The average sorting presents a tendency to grow (in $\phi$) with depth (figure 11), and a wide dispersion of values was found between 2.5 m and 20 m.

Factorial multivariate analysis made it possible to determine relationships between the four 'statistic moments' of grain-sizes distribution (mean, standard deviation, skewness and kurtosis), and the sed-

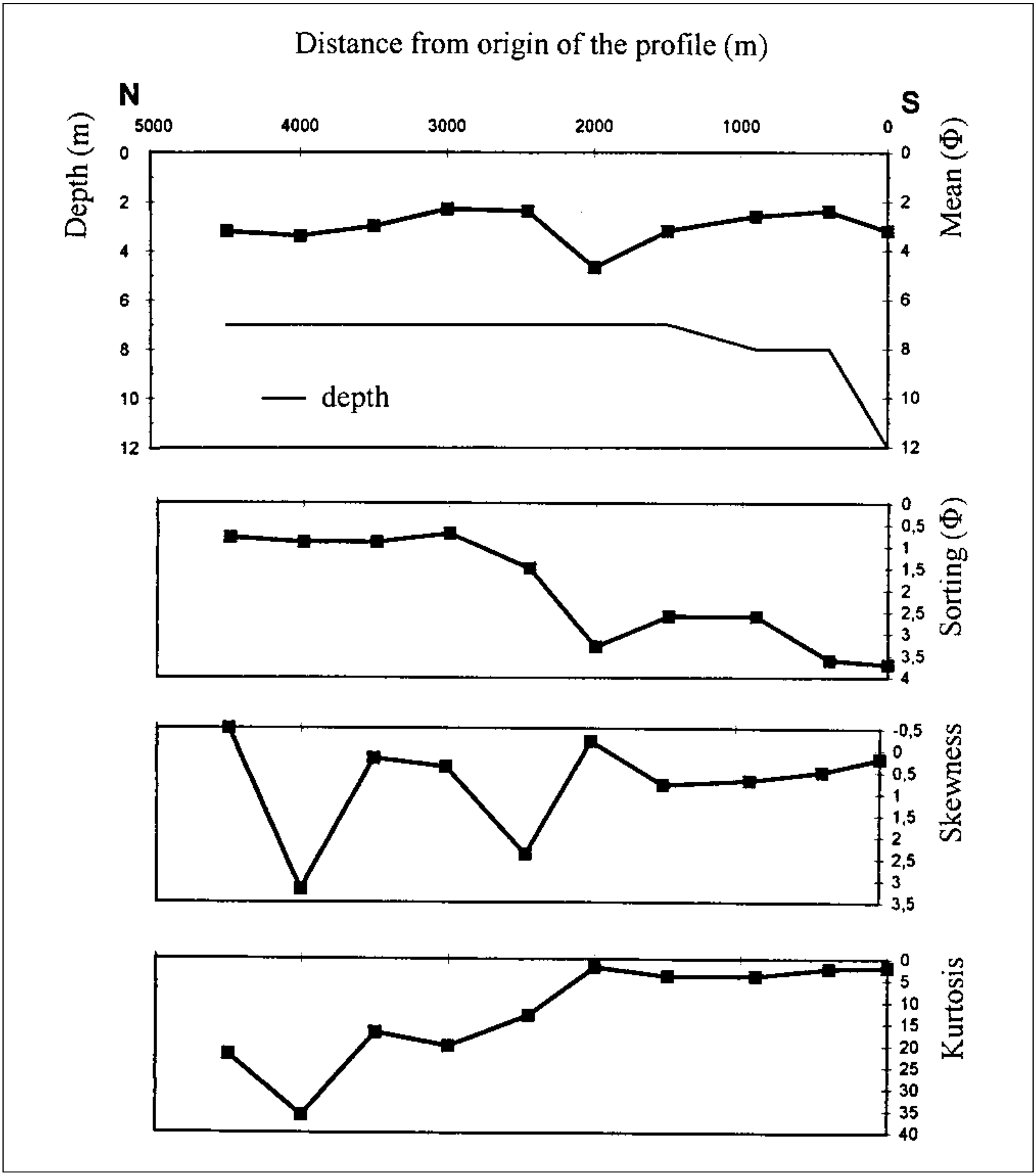


Figure 10. Grain-size parameter variation vs depth, at profile 3

iment transport and the environments characterisation. The results indicate two principal factors that explain 80 % of the total variance. The first factor explains 49 % of the variance and positively correlates kurtosis (factor loading 0.89) and skewness (factor loading 0.79). Very leptokurtic distributions present high values of very positive skewness, and sorting scores negatively (factor loading –0.32).

The zones characterised by factor 1 are located near the mouth of the Guadalete River, to depths between 5 m and 9 m, in the San Pedro River's mouth and in the outlet of Cadiz harbour (figure

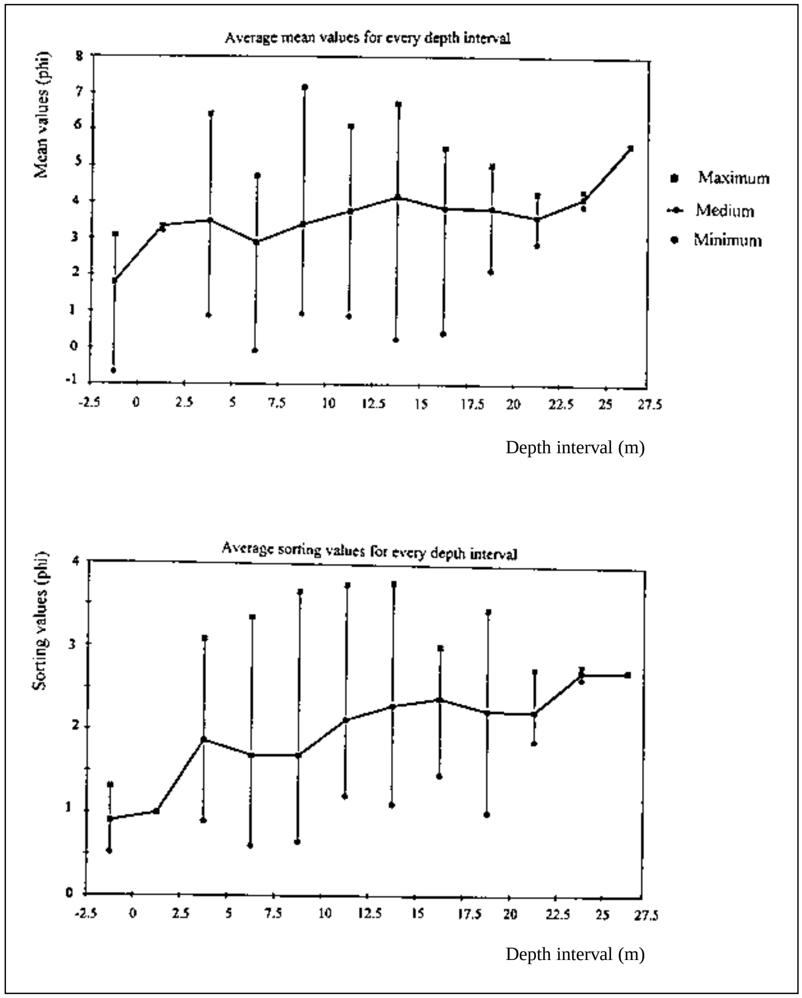


Figure 11. Variation of mean and sorting values averaged for each depth interval

12A). These zones are constituted by sandy facies, extremely leptokurtic, very well-sorted, and with very positive skewness.

The second factor explains 31 % of the total variance, and associates positively the mean and the sorting. The spatial distribution of this factor (figure 12B) represents zones where fine mean and poor sorting are associated, related to muddy sand and muddy facies.

## DISCUSSION

The surficial sediments distribution in Cadiz Bay is conditioned by the superimposition of dynamic processes such as sea, swell, tidal currents and fluvial supplies.

The mode provides information about the existence of single or superimposed transport processe, and the possibility of distinguishing grain sizes. In Cadiz Bay, the principal mode presents a high degree of homogeneity, due to the dynamic processes. However, polymodal analysis makes it possible to identify ancient and modern deposits. The coarsest modes show the presence of relict deposits (palaeolittoral environments), whereas the finest modes reflect accumulation zones or areas where the sediments are adjusting to new processes (Alveirinho and Neal, 1990). In the present study, bimodality reflects the existence of two grain-size populations: the first is constituted by sandy sediments, and it is the main component of the external bay, coming from the discontinuous supplies of rivers and the erosion of cliffs and beaches during storm events; a second population, mainly composed by mud, originates in the continuous reworking of the salt marshes, with sediments being transported in suspension by the ebb- currents.

In the study zone, there is no correlation between a decrease in mean grain size and an increase in depth, except near the littoral area. This behaviour is controlled by the tidal currents and

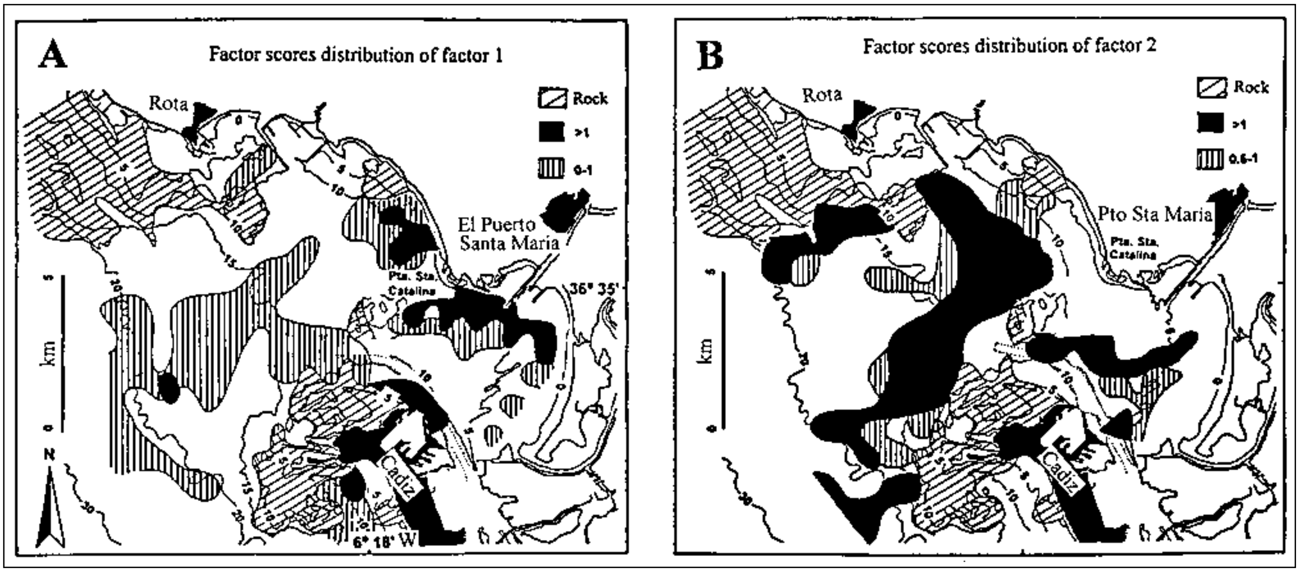


Figure 12. Distribution map of factor scores. (A): factor 1; (B): factor 2

the special shoreline morphology, whereas sorting shows a trend of increasing with depth. The skewness and kurtosis parameters have only local significance, but they are useful for the characterisation of different sedimentary environments. Skewness is a parameter that responds to transport direction and supply sources. A very negative skewness appears in the transition zones due to the mixture of fine and coarse grain sizes (Blaeser and Ledbetter, 1980).

A grain-size trend can be seen in the littoral domain, where the seaward fining of the mean grain size is controlled by transport processes related to decreasing wave energy (Sly, Thomas and Pelletier, 1983).

The sea-bottom sediments are affected by several hydrodynamic processes, which can be determined using a combination of grain-size parameters (McLaren, 1981; Gao and Collins, 1992; Gao *et al.*, 1994). The grain-size trends in outer Cadiz Bay result from both the sedimentological input and the transport pathways of fine sediments. Thus, skewness enabled us to characterise two grain-size trends. The first trend responds to the occasional fine settling upon the sand (figure 13), and it is characterised by the increase of mean grain size and well-sorted, very leptokurtic and very positively skewed sediments. But the sea-bottom sediments located under the permanent mud transport pathways are finer, poorly sorted and present symmetrical distributions.

The second trend characterises intertidal beach environments (foreshore) with a very negative skewnees. This trend appears also at depths close to 20 m.

The multivariate analysis of grain-size parameters enabled us to delimit several sedimentary environments. Factor 1 (skewness and kurtosis) correlates to very leptokurtic distributions with very positive skewness. This factor reflects a high degree of textural maturity and reworking of sediments. These are characterised by very fine and very well-sorted sand (Type VIII distribution). These deposits can be generated by the erosion of dunes and cliffs on the northern margin.

Another sandy zone is characterised by factor 1, and appears in the western sector at a depth of 20 m, where the mud settling is low (Type VI distribution) and remains outside of the fine sediment transport pathways. These deposits probably can be generated during the last transgression on an ancient littoral spit or beach.

Factor 2 (mean grain size and sorting) correlates to the finest mean grain size, with poorly sorted distributions, and is related to muddy-sand and mud facies, as well as showing the transport pathways of suspended muddy particles.

The highest settling of fine particles from suspension occurs northwest of La Galera shoal, due to the convergence of ebb-currents with a high suspended load, and to the predominance of settling processes as a consequence of the minor influence of waves at a depth of more than 11 m.

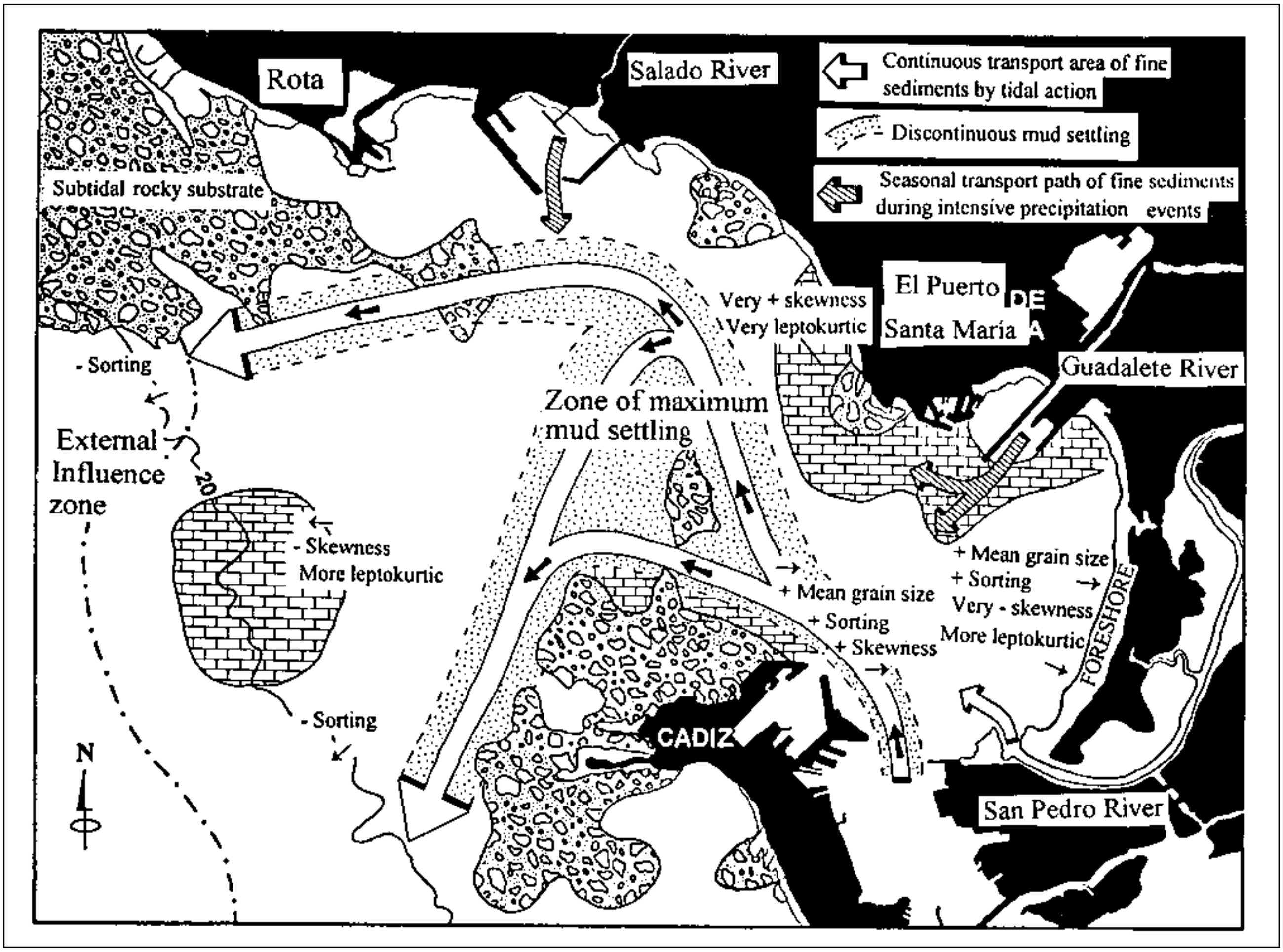


Figure 13. Interpretation map of the grain-size trends and sedimentological processes. (+): increase; (–): decrease; (+ skewness): positive skewness; (– skewness): negative skewness

The influence of peripheral water contributions (turbidity plumes of the Guadalquivir River and southeastwards littoral drift) is reflected on the inner continental shelf, where the sea bottom is characterised by poorly sorted sediments.

## ACKNOWLEDGEMENTS

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