Available online at www.sciencedirect.com
ScienceDirect
Estuarine, Coastal and Shelf Science 70 (2006) 117–131
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Sedimentary characterization of bed types along the Guadiana estuary (SW Europe) before the construction of the Alqueva dam

J.A. Morales [a,*], I. Delgado [a], J.M. Gutierrez-Mas [b]

[a] Department of Geology, University of Huelva, Av. Fuerzas Armadas s/n, E-21007 Huelva, Spain
[b] Department of Geology, University of Cadiz, Campus Rio San Pedro s/n, E-11510 Puerto Real, Cádiz, Spain

Received 26 May 2006; accepted 27 May 2006
Available online 8 September 2006

Abstract

The Guadiana River estuary is one of the most important mesotidal fluvio-marine systems of the south-western Iberian Peninsula. The river mouth was formed as a narrow channel that was excavated by fluvial incision during the Pleistocene lowstand and was then flooded 6500 years ago. The estuary is in an advanced state of sediment infilling in its proximal part, due to its narrow morphology, which prevents passage of sediment through to the open coast. Consequently, sediment is accumulating in the river mouth, which causes progradation. The analysis of the sediments into the estuarine channel (grain size, organic carbon content) and bedform distribution (Side-Scan Sonar) allows a distinction between two types of sedimentation to be made: a fluvial–marine sedimentation (favoured by tidal action) and an autochthonous sedimentation that is related to water mixing. The net transport of sediments is towards the sea because of the tidal current asymmetry. The autochthonous deposits and the sediments from the extreme fluvial floods that tides are unable to rework are preserved on the meandering convex margins under low tidal velocities. These areas acquire a lateral tidal-bar morphology with cohesive beds because the narrow geometry of the estuary inhibits the presence of longitudinal tidal bars, as may be expected in tide-dominated systems. The higher energy zones (deeper zones of the channel) become bypassing channels where the flocculated material cannot be settled on the bottom; this part of the channel then develops sandy beds with mesoforms as ebb-oriented two-dimensional and three-dimensional dunes (sand waves and megaripples).

Keywords: sediment dynamics; Holocene; estuarine deposition; tidal bars; progradation; Guadiana; SW Spain

1. Introduction

The study of the evolution and sedimentary infilling of contemporary estuaries is relatively complex because they are the product of the interaction between waves, tides and fluvial sediment supply. Other factors, such as sea-level stability, also have an important influence. As a result of these interactions, these phenomena can give rise to different types of processes and sedimentary dynamics (Davis and Clifton, 1987; Nichol and Boyd, 1993). Areas with subaqueous bedform fields that are related to estuaries and deltas are known from several places. In the North Sea shores, frontal sand waves have been described by Terwindt (1971), Kuijpers et al. (1993) and Zeiler et al. (2000), among others. In addition, other European estuaries have shown subaqueous dunes, as described by Langhorne (1973), Harris and Collins (1984), Duck et al. (2001), Garnaud et al. (2003) and Lancker et al. (2004). In the East and Gulf coasts of the USA, similar estuarine forms have been described by McKinney et al. (1974), Knebel et al. (1982), Sherwood and Creager (1990), Woodruff et al. (2001) and Donahue et al. (2003), among others. Particularly interesting were the works of the narrow, bedrock-controlled estuaries, such as the Kennebec estuary (Fenster and FitzGerald, 1996; FitzGerald et al., 2000), as their dynamics are directly comparable with the Guadiana estuary.

In recent years, different research teams have carried out several investigations along the Guadiana River estuary. Apart from general sedimentological studies of the estuary (Morales,

* Corresponding author.
E-mail address: jmorales@uhu.es (J.A. Morales).

0272-7714/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2006.05.049

1995, 1997; Morales et al., 1997), this estuary has been studied recently in terms of estuarine stratigraphy and postglacial evolution (Boski et al., 2002; Lobo et al., 2003), recent sedimentary processes (González-Vila et al., 2003; Lobo et al., 2004), hydrodynamic regime (Plaza et al., 2003), hydrogeochemistry (Ferreira et al., 2003) and biology (Esteves et al., 2000). In particular, the work by Lobo et al. (2004) represents the first major contribution reporting dynamic bedforms that occur along extensive areas of the Guadiana estuary.

The aim of this paper is to document the existence and spatial distribution of bed types that have been mapped of the Guadiana Mouth, and to describe the sediment texture, composition and bedforms to understand the hydrodynamic regime that is responsible for their existence. Moreover, the relationship between surface sediment grain size and bedform position has been analysed.

Field campaigns were carried out before the construction of the Alqueva dam, which significantly reduced the sediment input to the estuary and modified the estuarine water-mixing conditions. As a consequence, this work could be used as a reference point to compare the estuarine behaviour that exists after the construction of the dam.

1.1. Estuarine morphology

The Guadiana River estuary (Fig. 1) is an example of an estuary that is in an advanced state of sediment infilling, and is in a prograding phase (fluvial delta construction). This infilling is mainly due to the interaction of coastal processes that enhance sedimentation, and that provide a sufficient sediment supply and a relatively stable sea level (rises very slowly, 1 mm/year; Zazo et al., 1994). Another aspect to be taken into account

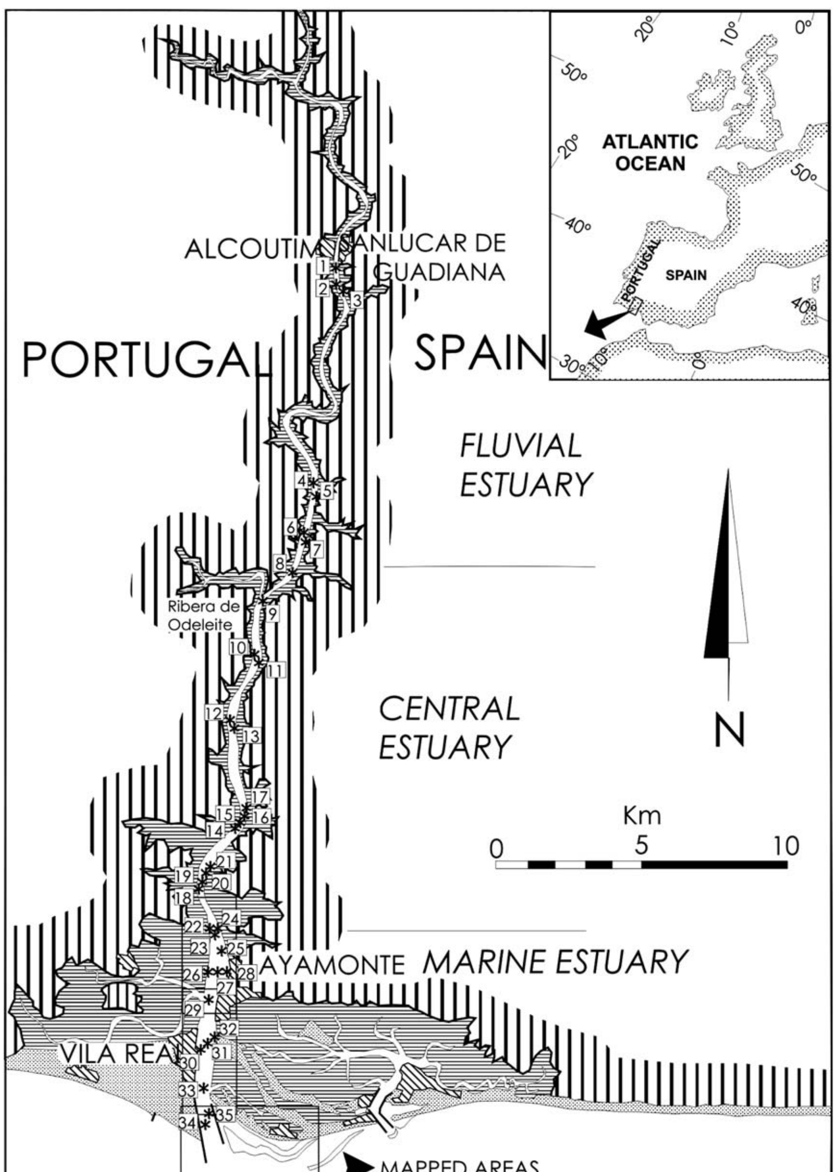

Fig. 1. Location of the Guadiana River estuary, division of the estuary in dynamic zones (Morales et al., 1997), location of the sediment samples and bedform-mapped areas.

is the inherited physiography: a narrow channel incised on Slate-Quartzitic materials of a Devonic-Carboniferous age under strong control of tectonic structures (Oliveira, 1990). This characteristic of the bedrock inhibited the river in excavating a wide funnel-shaped estuary during the Pleistocene period. As a consequence, the mouth of the Guadiana River includes three morphologically different areas (Fig. 2): (1) the narrow estuarine channel, (2) a submerged fluvial delta, and (3) a wide, barrier island/salt marshes prograding complex.

1.1.1. Guadiana estuarine channel

The estuarine channel is oriented perpendicular to the coast, connecting the fluvial channel with the open littoral zone. The channel is very narrow in the landward 50 km, but it widens in the mouth area into a funnel morphology, at which point it cuts through the friable Pliocene strata. Marsh complexes and barrier islands that are adjacent to the lower channel developed independently of the estuarine channel (Morales, 1995). Fluvial sediments are transported through the estuarine channel section, although marine sediments are mixed in this area during the tidal cycles (Morales et al., 1997). The water depth in the study area varies between intertidal areas and 8–10 m in the deeper channel. From a morphological point of view, the channel displays two distinct areas (Morales et al., 1997; Lobo et al., 2004) (Fig. 2). First, the deepest part of the channel is more than 3 m deep under the Equinox Spring Low Water level and shows a meandering morphology. The second area appears on each side of this bypassing channel and, in the areas that are lower than 3 m in depth, lateral tidal bars are present. Active sedimentation takes

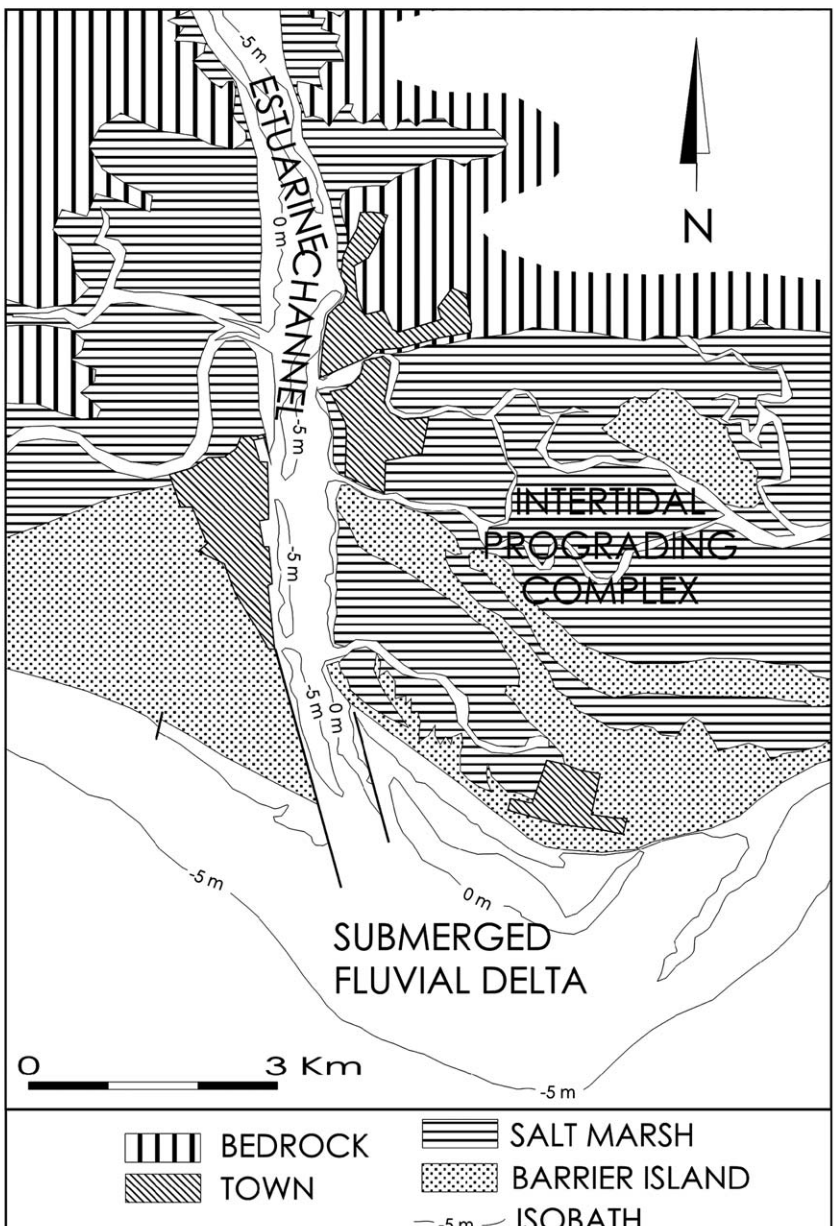

Fig. 2. Morphosedimentary zones in the marine domain of the estuary.

place on these bars, narrowing the navigable areas of the channel.

1.1.2. The frontal zone: the submerged fluvial delta

The deltaic sediments at the mouth of the main estuary channel are reworked continually by wave activity. This produces large swash platforms that, in turn, change the angle of wave approach to the foreshore of the most recent barrier islands (Fig. 2). The main ebb channel of the delta is directly connected to the estuarine channel. The fast growth and the mobility of these wash platforms, and the shifting of the main ebb channels, has made it necessary to perform artificial stabilization by jetties.

1.1.3. The prograding complex: barrier island and salt marshes

The western margin of the marine estuary (Portugal) comprises a littoral spit with transverse progradation, on which large aeolian dunes are developed, some up to 20 m high. At the seaward side of the spit, a slight foreshore slope has a high rate of sedimentation, giving rise to transverse growth of the spit in addition to swash bars. On the landward part of the spit, a large salt-marsh area drains directly into the main estuary channel. Its origin is due to exclusively marine processes that occurred when this area became protected from waves by the initial growth of the littoral spit.

The Spanish side consists of a succession of old barrier islands that have been transformed into elongate spits that are separated by wide marsh areas. These salt marshes drain directly to the sea through a feeder inlet (Carreras) via a wide complex tidal channel network (Fig. 2). The foreshore area in the front of the youngest spit is still active and has a slope of 10, which is much higher than the Portuguese spit front.

An association of sedimentary environments is present, the existence of which is controlled by: (a) wave activity or lack thereof; (b) the proximity of the main estuary channel (fluvial sediment supply); and (c) exposure/submersion levels that are related to tidal activity.

1.2. Hydrological regime

The Guadiana estuary system is semi-diurnal and mesotidal, with a mean tidal range of 2.0 m (the mean neap range is 1.22 m and the mean spring range is 2.82 m), giving rise to different period cycles (semi-diurnal, twice-weekly and half-yearly). The tidal wave along the coast moves from east to west, producing slow velocity currents (flood is 0.40 m/s to the west and ebb is 0.30 m/s to the east during a mean spring tide). In the estuary, the wave propagates following a synchronic model, generating stronger currents (floods can reach 0.80 m/s and ebb can reach 0.90 m/s during a mean spring tide). Lobo et al. (2004) describe a complex tidal current behaviour. During neap tides, flood is the dominant current, producing mainly a flood-oriented microform net migration on the mouth portion of the estuarine channel. In contrast, during spring, stronger currents are observed in the ebb sense; in addition, the falling tide is appreciably longer than the rising tide in this channel portion, which results in a net transport of sediment towards the open coastal area.

This coastal region is influenced by waves of medium and low energy, including both Atlantic swell waves (48.91% of the time) and local sea waves (51.75% of the time). Southwest waves prevail (20% of time), although they are less energetic ($H_{1/3} = 0.40$ m, $T = 4.06$ s) than the southeast ones, which are present only 8% of the time ($H_{1/3} = 0.70$, $T = 5.08$ s). The southwest waves' energy is associated primarily with swell from the Atlantic Ocean (75%) (Morales, 1995). During south-eastern winter storms, a storm surge produces exceptionally strong waves ($H_{max} = 6$ m), with significant wave heights of up to 3.80 m (Morales, 1995). These conditions produce a strong west-to-east longshore current. The potential longshore sediment transport is reported to be between 180×10^3 m^3/yr (Cuena, 1991) and 300×10^3 m^3/yr (CEEPYC, 1979).

The Guadiana River discharge shows a marked inter-annual and seasonal variability. During modal discharge periods, the tide can rework and carry all of the sediments that are brought by the river to the sea. However, during maximum instantaneous discharge, most of the sandy sediment remains in the estuary (Morales et al., 1997). There are no published data on the Guadiana sediment supply, although there is an estimation of the average suspended load (57.90×10^4 m^3/yr) and bedload (43.96×10^4 m^3/yr) over the last 44 years (Morales, 1995). Since the 1960s, the Guadiana drainage basin has experienced a strong retention due to more than 40 dams being built, which regulate about 75% of the drainage area. The most important, in this respect, is the newest of them: the Alqueva dam, which began functioning in February 2002. The result is a major decrease in the volume of water and sediment supplied from the river to the estuary, and a strong estuarine dynamic modification. This is a problem that exists in many fluvial systems around the world, e.g. The Nile, Ebro and Mississippi rivers.

2. Methods

2.1. Oceanographic surveys

Bed types and bedform distribution were studied during a campaign that was carried out on 31 July and 1 August 2001, under mean tide conditions (range: 1.84–2.05 m) and during the ebb transition. On these days, the tide evolved from spring to neap. The river discharge in Rocha da Galé (80 km to the north of the estuary mouth) during the survey was the typical summer discharge (11 m^3/s), which corresponded with null rainfall. The morphology of the subtidal and intertidal zones was analysed using a Side-Scan Sonar™ using C-MAX, with a resolution of 100 m per band. The navigation was done in parallel lines such that successive navigation lines superpose 30% of the record. The position of the sonar record was accurate and connected the sonar with a D-GPS™ (Trimble model RTK5700), which was also connected to a portable computer using an Ozi explorer navigator.

A sediment sampling survey was carried out on 30 and 31 March 1992, under similar hydrological conditions (mean tides with a range of 1.72–2.04 m and a river discharge of 8 m^3/s). A total of 37 samples were collected (Fig. 1) and were distributed at different depths in transects along the estuary. Samples were obtained using a Van Veen dredge, which is a trademark of EIJKELKAMP.

2.2. Grain size analysis

The following procedure was applied:

- Sifting with a sieve of 63 μm (4 ϕ units), to separate the sand from the mud.
- The fraction that was more than 63 μm (sands) was analysed by conventional (Udden–Wentworth) sieving, whereas the lower (muddy) fraction, which was between 2 and 70 μm, was analysed using a Coulter Counter (model ZM) with a pipe of 100 μm. This analysis allowed grouping of the samples into different types of textural distribution.
- Representation of grain size resulted in frequency histograms and accumulated curves. From these curves, some significant statistical parameters have been obtained (Folk and Ward, 1957): centil (C), mean (M), graphic average (Mz), standard deviation (σ), sorting (So), graphic skewness (Ski) and Kurtosis (Kg). Studied parameters have been paired in bivariate diagrams to observe the possible tendencies and grouping. These are (a) diagram C–M by Passega (1964), to compare maximum instantaneous energy with mean energy of the system, deducing the main type of transport of the sediment; (b) diagrams to compare a central value with values of dispersion/sorting (σ, Mz and So–Mz) or symmetry values (Ski–Mz); and (c) dynamic interpretations have been performed on the basis of the triangular diagram suggested by Pejrüp (1988) for the classification of estuarine sediments.

2.3. Organic carbon

Analysis of the organic carbon (OC) content has been carried out in all samples according to the analytical method suggested by Courau (1983).

2.4. Microfauna

A micropaleontological analysis was carried out using 32 selected samples (foraminifers and ostracods). The biocenosis was determined using a dyeing process (the method of Walton, 1955), according to the criteria of Kilenyi (1969).

3. Results

3.1. Grain size distribution

The results of the grain size analysis are shown in Table 1. According to the criteria defined by Pejrüp (1988), the particles that were 16–63 μm can be considered to be mechanical silts, whereas the particles that were less than 16 μm can be considered to be flocculation materials. Six types of grain size distribution can be distinguished in the analysed samples (Fig. 3).

Table 1
Resume of sedimentary grain size analysis

Sample	Gravels	Sands	Muds	Mech. silts	Flocs
1	0.00	88.91	11.09	3.68	7.41
2	2.43	97.57	0.00	0.00	0.00
3	95.99	4.01	0.00	0.00	0.00
4	3.39	96.61	0.00	0.00	0.00
5	19.31	80.29	0.40	0.40	0.00
6	0.66	99.34	0.00	0.00	0.00
7	91.87	8.13	0.00	0.00	0.00
8	0.00	8.50	91.50	30.22	61.28
9	36.52	51.53	11.95	1.99	9.95
10	0.00	98.15	1.55	0.30	0.00
11	15.32	73.50	7.15	2.97	1.06
12	0.12	99.56	0.32	0.32	0.00
13	23.33	64.31	12.36	5.17	7.19
14	0.00	17.91	82.09	70.46	11.62
15	0.13	24.80	75.07	33.28	41.79
16	1.56	21.04	77.41	33.63	43.78
17	1.15	41.84	57.01	2.91	54.10
18	48.80	35.26	15.94	6.54	9.41
19	0.13	99.87	0.00	0.00	0.00
20	0.00	20.09	79.91	48.98	30.93
21	0.00	2.53	97.47	43.73	53.75
22	0.00	52.42	47.58	6.41	41.17
23	0.79	18.15	81.07	5.67	75.40
24	0.00	69.67	30.33	12.98	17.35
25	3.19	54.80	42.01	2.27	39.74
26	30.43	56.52	13.05	1.43	11.62
27	5.32	94.19	0.49	0.49	0.00
28	0.00	11.81	88.19	50.62	37.57
29	18.26	81.39	0.36	0.36	0.00
30	13.93	85.05	1.01	1.01	0.00
31	0.23	99.72	0.04	0.04	0.00
32	0.77	58.52	40.71	4.46	36.25
33	1.36	98.55	0.09	0.09	0.00
34	22.68	77.30	0.02	0.02	0.00
35	0.88	22.41	76.71	9.67	67.04

SC-1 Fractions less than 6 ϕ units (very fine silts and clays) are dominant. All these particles come from flocculation processes. Very fine sands and mechanical silts are also present, indicating the relative importance of the suspended matter deposition. The coarser fractions of more than 2 ϕ units are absent. Samples with this distribution type are associated with the shallow zones of the central estuary that are near the Ribera de Odeleite (Fig. 4).

SC-2 These are samples that have abundant fractions of less than 6 ϕ units (flocculation domain). However, the coarse silts and sand populations are negligible or absent. This kind of distribution characterizes the samples that are located in the shallow zones of the marine estuary and the lower part of the central estuary (Fig. 4).

SC-3 Saltation, suspended transported matter and flocculated fractions are present. This distribution can be distinguished from the SC-2 type due to the fact that the

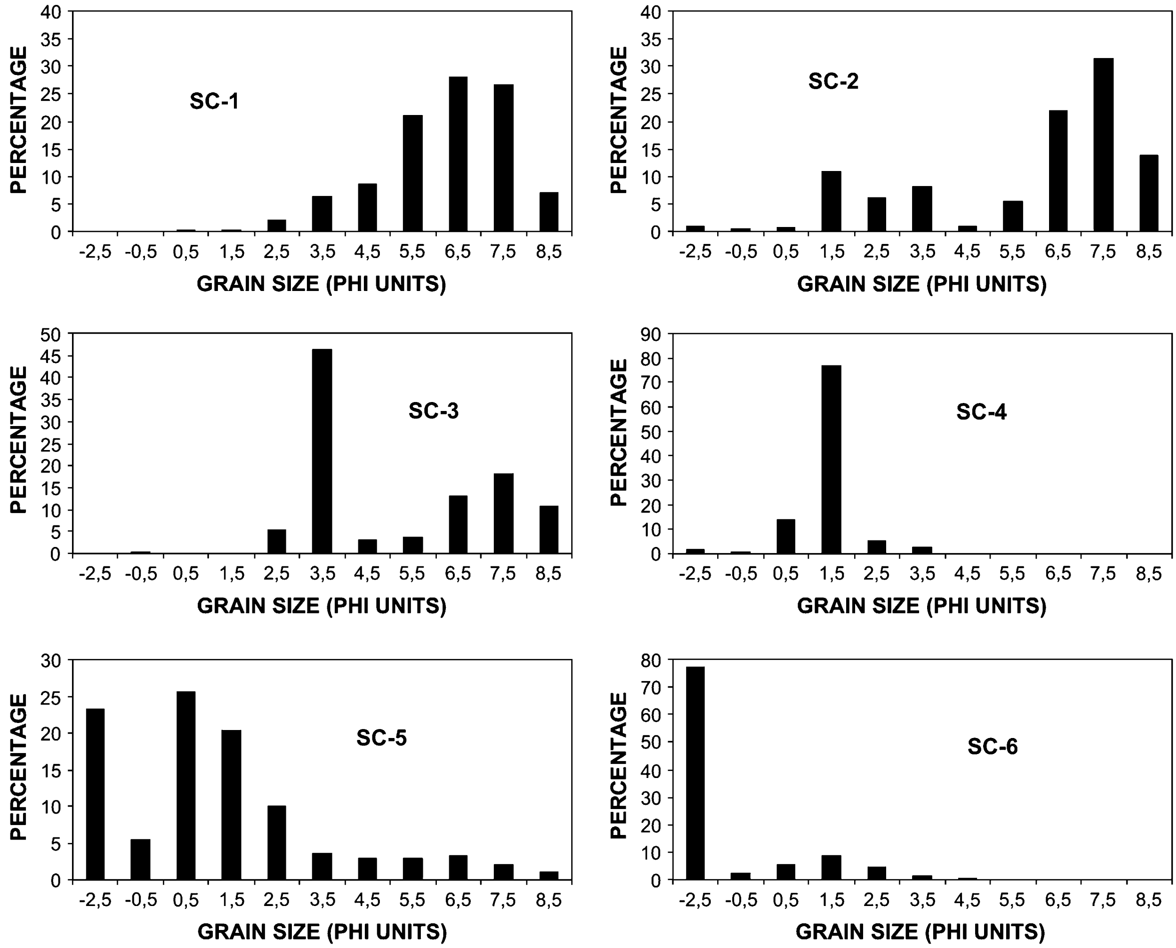

Fig. 3. Types of grain size distribution histograms in the analysed sediment samples.

sandy fractions are dominant. The sand is represented only by very fine sands (3–4 ϕ units). Samples with this distribution are located in the same places as the SC-2, but in the deeper zones of the subtidal channel.

SC-4 These are well-sorted medium sands with the dominant fraction consisting of 1–2 ϕ units. The samples with this kind of grain size distribution are typical of the deeper zones of the marine estuary and the shallower zones of the fluvial estuary. These kinds of samples also appear in the swash platforms of the frontal intertidal zones.

SC-5 These have very poor sorting, and all the grain size populations are present in this group. The dominant populations are the fractions that consist of 3 to −5 ϕ units, which are transported by saltation, rolling and traction.

SC-6 These are gravels with some percentage of sands. Samples with this kind of granulometric distribution appear in the deeper zones of the fluvial estuarine channel.

The spatial distribution of these grain size patterns on the estuarine channel bed (Fig. 4) allows observations to be made on the relationship between fields with different patterns and other variables, such as the boundaries of the estuarine sectors (Fig. 1).

According to the criteria outlined in Section 2, the studied grain size parameters have been paired in some significant bivariate diagrams. The study of these diagrams allows clouds of points to be distinguished, the shape of which may be interpreted from a hydrodynamic point of view. Therefore, the represented diagrams show four groups of points that are elongated in different senses (Fig. 5).

- The first of these includes samples of the subtidal channel from the fluvial sector of the estuary. In all the diagrams, the major axis of elongation shows a positive slope. This disposition reflects an increase in maximum size and sorting with the mean grain size (Fig. 5A and B), whereas the asymmetry stays almost constant (Fig. 5C).
- A second cloud of points includes the samples of the subtidal channel from the marine sector of the estuary. It shows a parallel elongation according to the *Y*-axis and intersects the previously described cloud. It is observed that all of the samples included in this cloud have a similar mean grain size (fine sands), but the maximum grain size, sorting and symmetry display wide variability.
- The rest of the points represent the sediments of a finer mean size. They include the samples from the subtidal channel from the central estuary and the samples from

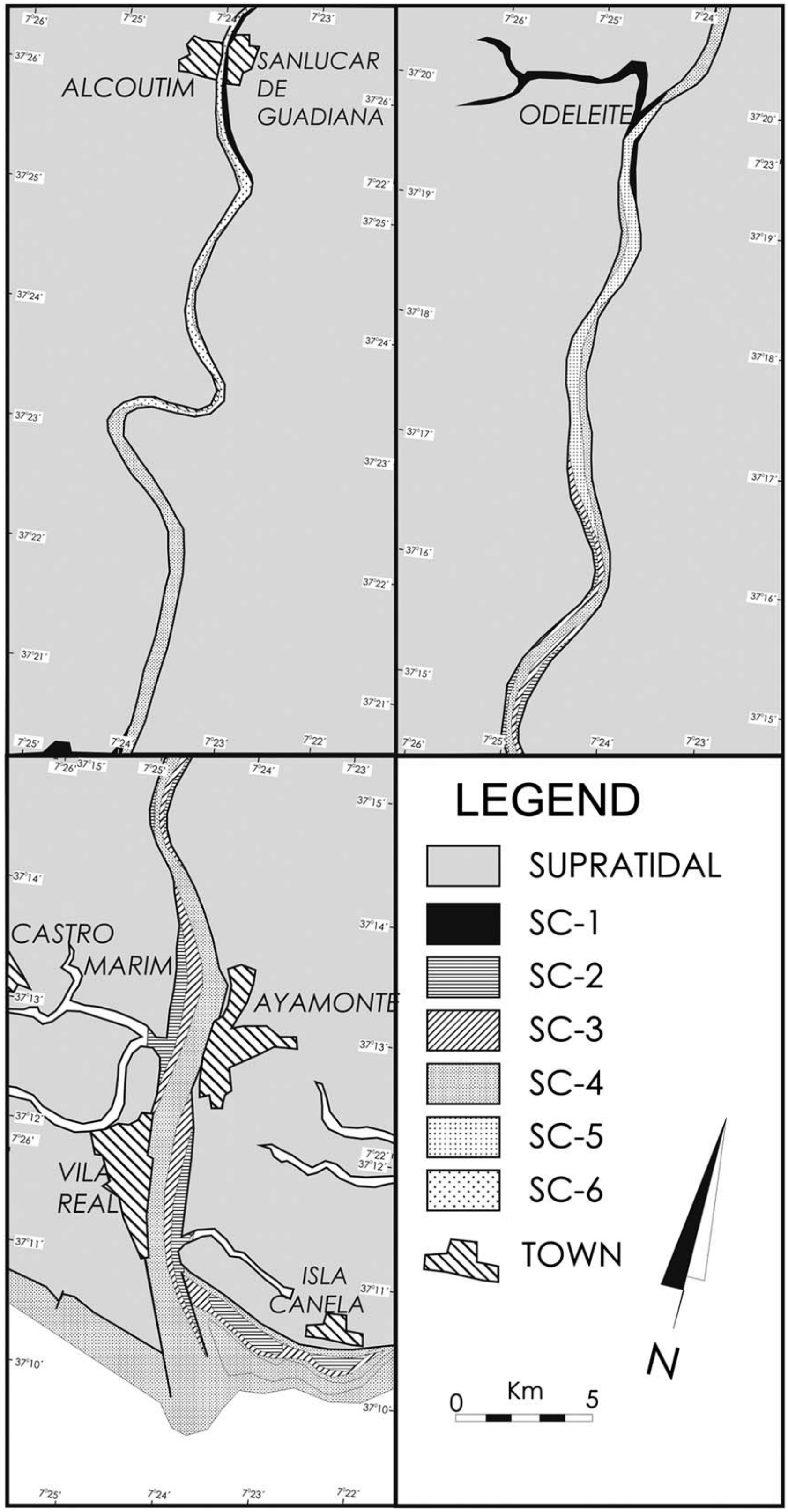

Fig. 4. Map of distribution of sediment types in the estuarine subtidal channel.

the shallow channels. These samples are grouped in different ways according to the diagram. In the diagram $C-M$ (Fig. 5A), these samples are divided into two clouds of points: the first one (cloud 3) is an elongated cloud with a positive slope, which shows a parallel of fine mean size and fine maximum size; the second (cloud 4) includes samples with a fine mean size and a high maximum size, this is due to these samples having some shells present.

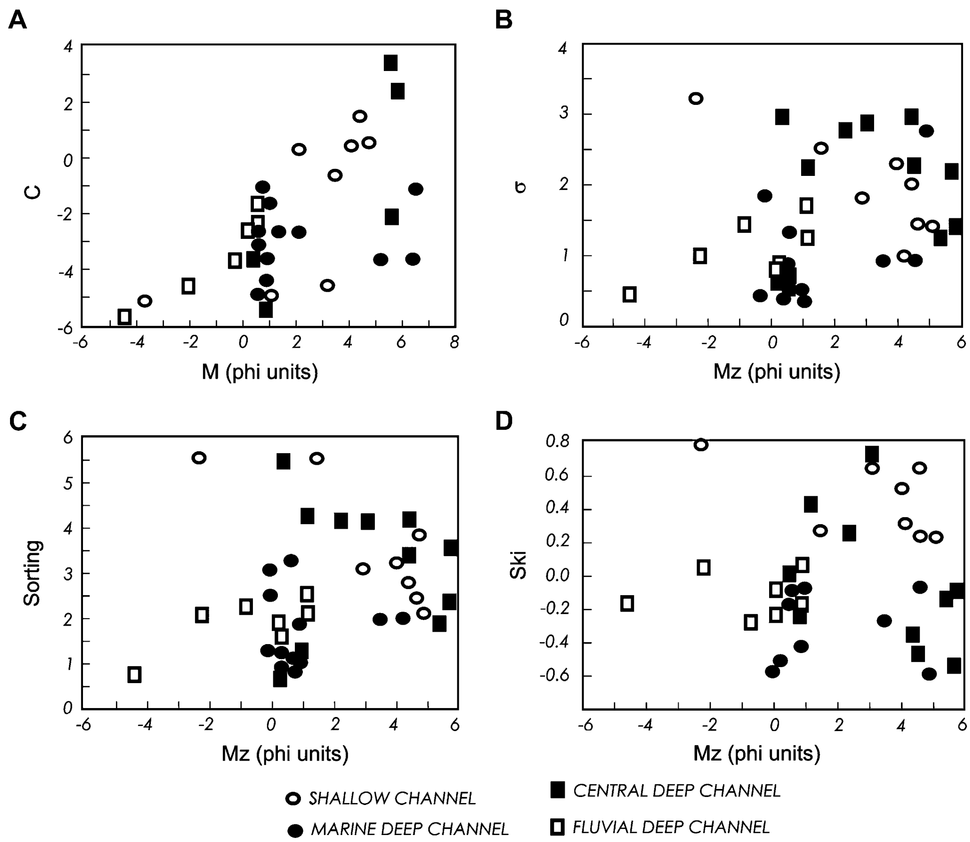

Fig. 5. Bivariate diagrams. (A) *C*–*M* by Passega (1964); (B and C) Mz–Sorting and (D) Mz–Skewness.

Similar observations may be seen with respect to the symmetry. In contrast, the sorting diagram (Fig. 5C) groups these samples into only a scattered cloud, which is elongated negatively. This shows that the sorting produces a progressive decrease in finer samples.

It is significant that the samples from the central estuary channel and the samples from the shallow channels of the complete estuary are included in the same cloud of points. This indicates that similar depositional processes occur in both zones, where the finer particles are mainly sedimented. At the same time, the samples from the deep channel in the marine and fluvial estuary display variable characteristics and there is a gradation between them.

Similar observations may be seen in the textural diagram suggested by Pejrüp (1988); however, in this case, an interpretation from a hydrodynamic point of view is also possible (Fig. 6). The samples from the deep channel of the fluvial and marine sectors of the estuary are represented in the sand vortex of the triangle as an indication of the double (fluvial and marine) provenance of sediment that circulates in the deep channel. The samples from the central estuary and the shallow channel, as well as the samples from the marine estuary, occupy the central portion of the triangle. In this case, the samples from the central deep channel and some from the shallow channel are plotted on area I, which is interpreted as of 'total calm' and corresponding to the domain of the flocculation processes. The samples from the marine deep channel occupy area II, which corresponds to a situation of 'relative hydrodynamic calm'. The rest of the samples from the shallow channels are represented in zones III and IV, which correspond to low-energy mechanical deposition (decantation).

3.2. Organic carbon content

The study of the variations of OC content (Fig. 7 and Table 2) allows the following presumptions to be made:

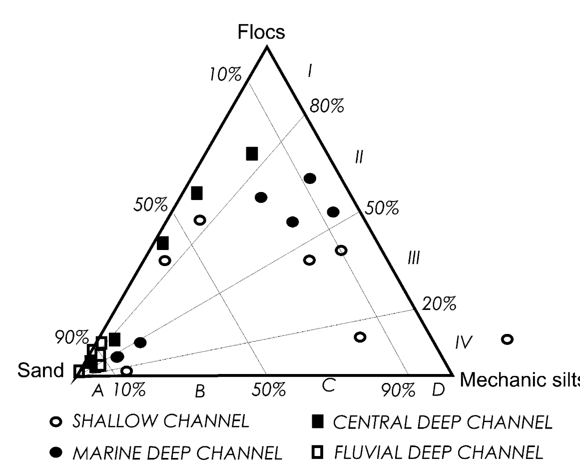

Fig. 6. Triangle diagram for classification of estuarine sediments (Pejrüp, 1988).

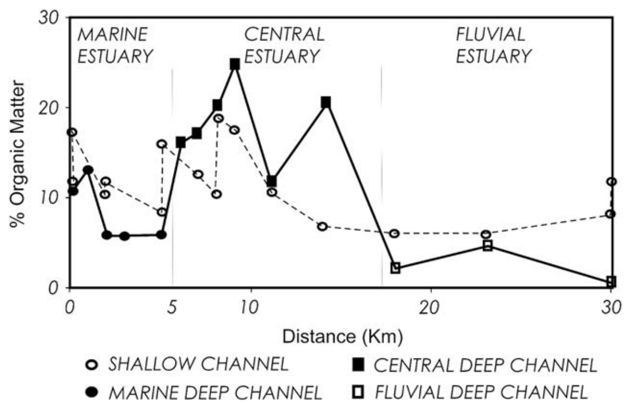

Fig. 7. Organic carbon content along the estuarine subtidal channel.

(a) *Fluvial estuary*: in this part of the estuary, the mean content in organic matter is very low (mean: 5.7%), increasing towards the central estuary. The organic content is higher in the shallow channel, where the sediment is finer.
(b) *Central estuary*: this part of the estuary presents the highest content of organic matter of the estuary (mean: 16.3%). There is a clear relationship with the depth of the estuary, as the maximum values are located in the deepest area of the channel. Nevertheless, the organic content in the shallow channel of this area is higher than the content of the rest of the estuary (Fig. 7). This high content of organic matter is not related to the higher proportion in the muddy fraction, but to the higher abundance in the whole sample.
(c) *Marine estuary*: this part of the estuary is characterized by a relatively high mean content of organic matter (mean: 9.8%). There is an inverse relationship with the depth of the estuary and the mean grain size: the organic content of the shallow channel is higher than that of the deep channel because the sediment of the shallow areas is finer. An increment in the organic content towards the estuary mouth is also observed but, in this case, the increment does not have a relationship with the higher content in the muddy fraction.
(d) *Open intertidal zone and frontal subtidal zone*: these zones have very low contents of organic matter, with a range that is even lower than that in the fluvial estuary (mean: 1.3%).

Table 2
Organic carbon contents of the analysed samples

	Deep channel	Shallow channel	Total
Whole estuary			
Mean	10.75	13.69	12.24
Minimum	0.83	9.77	0.83
Maximum	24.92	19.32	24.92
Range	24.09	9.55	24.09
Fluvial estuary			
Mean	4.67	11.99	5.71
Minimum	0.83		0.83
Maximum	8.23		11.99
Range	7.40		11.16
Central estuary			
Mean	15.57	15.56	16.27
Minimum	6.66	12.31	6.66
Maximum	24.92	19.32	24.92
Range	18.26	7.01	18.26
Marine estuary			
Mean	8.61	9.77	9.81
Minimum	5.64		5.64
Maximum	17.42		17.42
Range	11.78		11.78

3.3. Micropaleontologic content

Ruiz et al. (1996) determined 16 species of foraminifers and 14 species of ostracods but with a small number of total individuals. The samples rarely contained 100 individuals (foraminifers/ostracods) per 200 g of sediment. The foraminifer, *Cribroelphidium vadescens*, dominates the whole estuary, whereas *Astronion stelligerum*, *Ammonia inflata* and *Ammonia beccarii* are dominant in the shallow zones of the marine estuary. The dominant indigenous ostracods are *Loxoconcha elliptica*, *Cytherois fischeri*, *Leptocythere castanea* and *Leptocythere lacertosa*. The biocenosis is typical of the low-energy shallow channel of the central estuary and of the lateral shallow areas of the marine estuary.

The rest of the identified species correspond to dead organisms and those that have crawled from the open coastal area.

3.4. Acoustic records and bedform distribution

A geo-referenced mosaic has been elaborated on the basis of Side-Scan Sonar records from the marine sector of the estuary channel. This mosaic has been interpreted by mapping fields of bedforms or bed types (Fig. 8). This information has also been linked with the grain size surficial distribution (Fig. 4) to obtain a distribution of bed types. From a general point of view, four zones can be distinguished:

- *Deep zones of the estuarine channel*: these are zones that are deeper than 3 m under the extreme equinox low water level (EELW). The position of the deep channel with respect to the margins oscillates from one bank to another along the estuary, in a similar way to that of a straight river. The bed of this channel is characterized by sand waves that have different morphologies and dimensions: those with a straight crest (two-dimensional dunes) have wavelengths that oscillate between 4 and 7 m and heights of between 0.5 and 1 m (Fig. 9A). The sand waves with linguoid crests (three-dimensional dunes) are larger, with wavelengths of 7–12 m and heights higher than 1 m (Fig. 9B). All the bedforms are ebb-oriented.
- *Shallow zones of the estuarine channel*: these zones are located along the margins of the deeper channel and are less than 3 m under the EELW level. The bed of this marginal channel may have different features that vary in space and time. In some places, the bed shows marked erosional

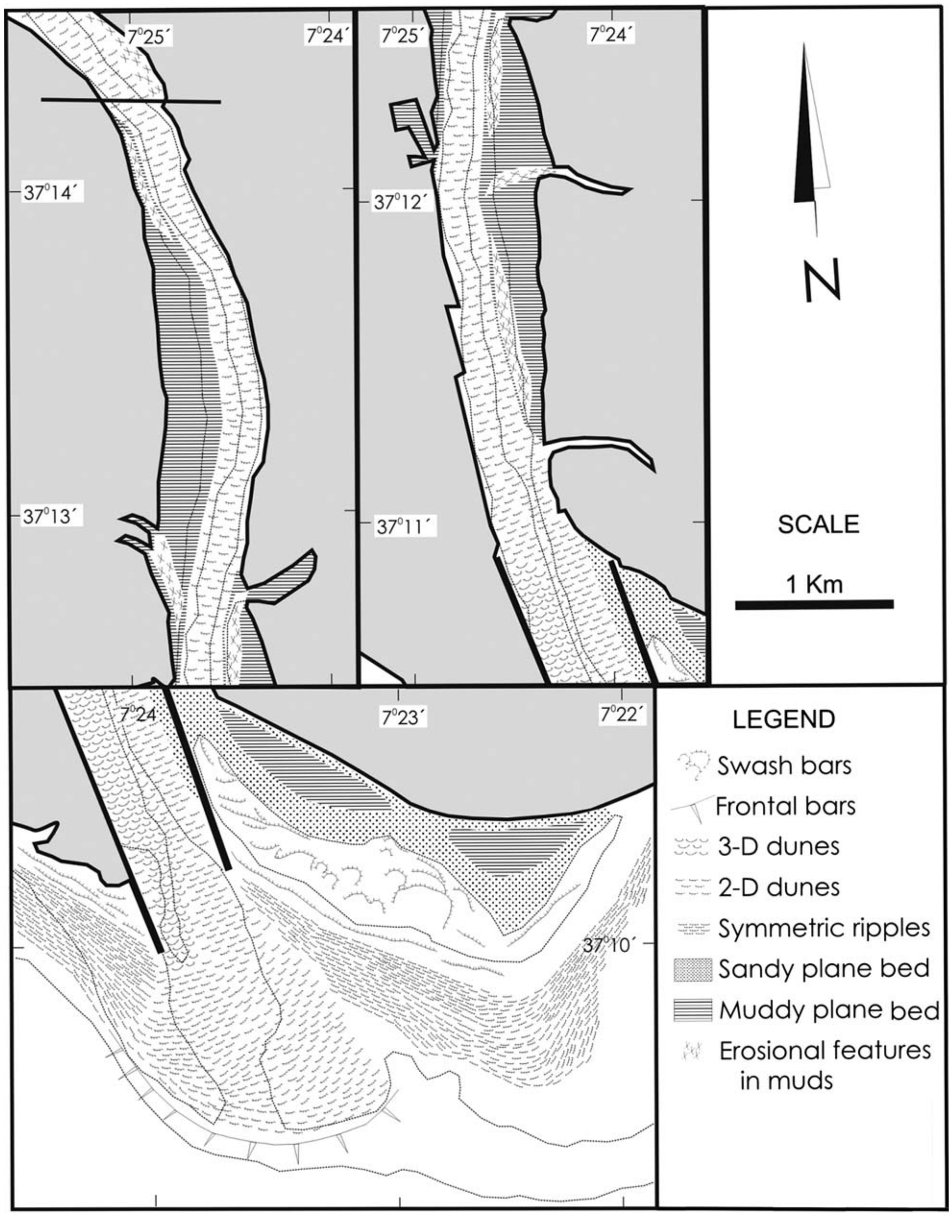

Fig. 8. Map of bed types in the marine domain of the estuary (A and B) and the frontal zone (C).

features or furrows (Fig. 10A), which are typical of cohesive sediment. In other places, which are transitional with the deep channel, flood or ebb-oriented sand waves with straight crests (two-dimensional dunes) and minor bedforms are identified. Wavelengths of almost 5 m and heights of 0.50 m are the most common dimensions (Fig. 10B).

- *Open intertidal zones*: these physiographical elements are located in the open zone of the system, under the wave action. Morphologically, the open intertidal zones consist of long sand bars with wavelengths that are almost 30 m high and 1 m high. Above those bars, ebb-oriented, straight-crested megaripples (two-dimensional dunes) are well developed. These forms have wavelengths that oscillate between 1 and 1.50 m and heights of between 0.15 and 0.30 m (Fig. 11).
- *Frontal subtidal zones*: the frontal subtidal zones are currently located in the opening of the jetties. The seabed is characterized by a long sand bar with more than 20 m of wavelength and 1.50 m high (Fig. 12A). Symmetric ripple fields are developed in the open zone of the sand bar (Fig. 12B).

4. Interpretation and discussion

The combined results of the acoustic records, grain size, organic matter analysis and microfauna content show the existence of zones that have different hydrodynamic characteristics. The

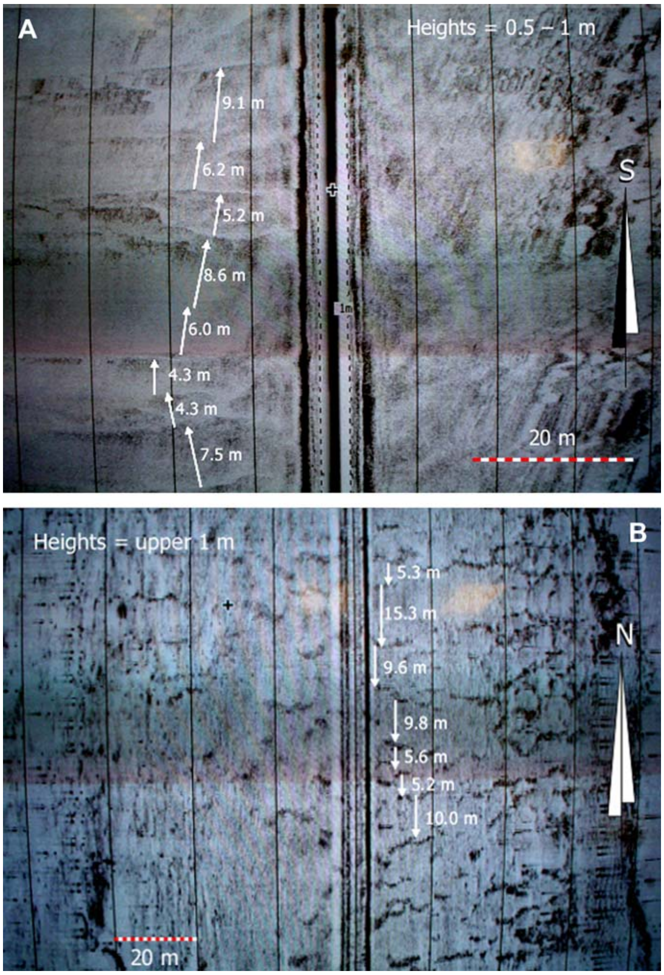

Fig. 9. Photograph of Side-Scan Sonar records in the deep estuarine channel. (A) Two-dimensional dune field. (B) Three-dimensional dune field.

first remarkable observation is the existence of two different hydrodynamic zones in the estuarine channel:

- In the deep part of the channel, a high percentage of sand and the presence of wide bedform fields may be interpreted as a zone in which the bedload transportation is dominant.
- In the shallow portion of the channel, the presence of microfauna assemblages, a high content of organic matter and a cohesive characteristic is shown by a high percentage of muddy fraction, which indicates an active deposition zone. Nevertheless, some punctual periods of erosion may affect this area, as is deduced from the presence of erosional features in the acoustic patterns.

In the deep subtidal environments, the fractions that are transported as bedload are dominant. These are bypassing areas, where the transport of sediment towards the marine area takes place. In the shallow areas of the channel, the fractions that are transported in saltation and suspension increase, with an active sedimentation that contributes to the fulfillment and narrowing of the estuary.

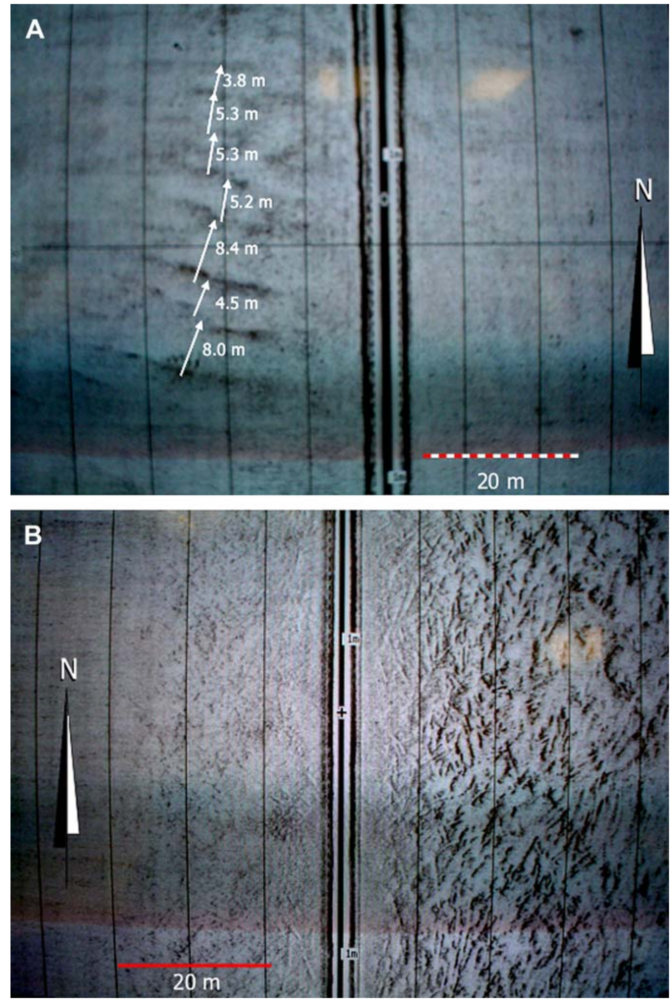

Fig. 10. Photograph of Side-Scan Sonar records in the shallow estuarine channel (lateral tidal bar). (A) Erosional features in a cohesive bed. (B) Two-dimensional dune field in a sandy bed.

On the other hand, the results offered by the grain size, organic matter and microfauna analyses show that a longitudinal energy gradient is present in the deeper part of the estuarine channel. The response to this energy

Fig. 11. Panoramic view of sand bars developed above the swash platform in the open intertidal zones.

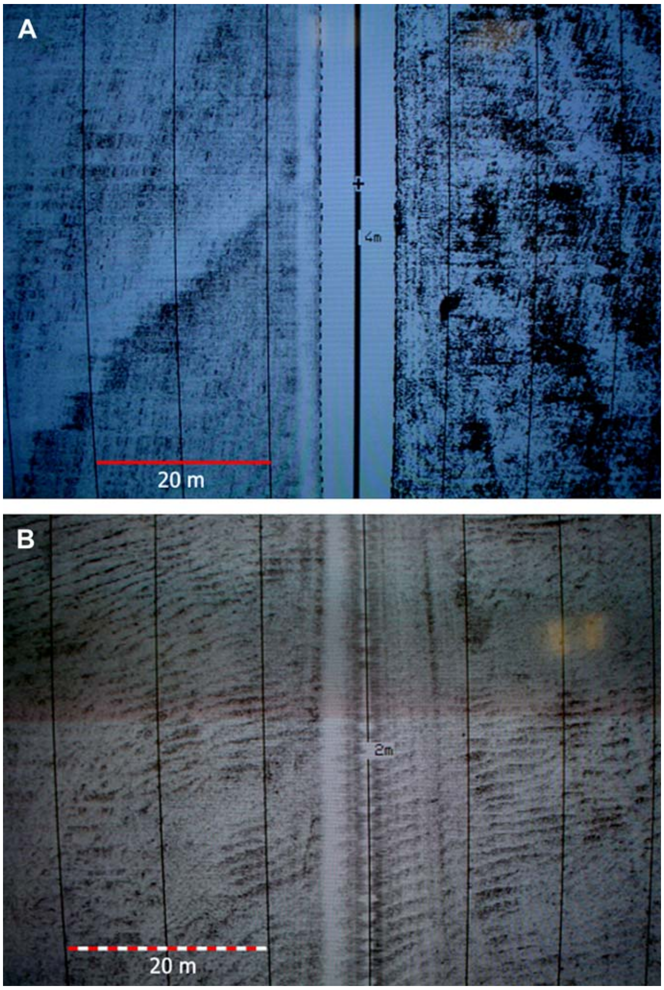

Fig. 12. Photograph of Side-Scan Sonar records in the frontal subtidal zone. (A) Frontal sand bar. (B) Symmetrical ripple field.

gradient is estuarine zonation, which is seen by the following:

(1) The samples from different zones of the estuary, which are always plotted in different clouds of points on the bivariate diagrams and on the Pejrüp triangle.
(2) The organic matter content presents radical differences between samples of different sectors.
(3) The central estuary is the only zone that presents microfauna biocenosis.

The existence of a longitudinal gradient is seen by the textural bipolarity of the estuary. This gradient has been observed in estuaries all over the world and is independent of its morphology and the balance of its processes (Fairbridge, 1980; Dalrymple et al., 1992), but it is particularly evident in bedrock-controlled estuaries (Fenster and FitzGerald, 1996; FitzGerald et al., 2000). This textural bipolarity is not only energetic, but also represents a double provenance of the sediment: the fluvial sediment is reworked from the river to the sea by the ebb current and the marine sediment is introduced into the estuary by the flood current.

The limits of the fluvial and central zones of the estuary have been localized to 1 km north of Ribera de Odeleite, whereas the limit of the central and marine zones is located in the bedrock strait of the international bridge (Fig. 1).

The deep channel of the fluvial estuary transports the sediment that is supported by the Guadiana River from its drainage area. The coarser grains (fine sands to gravels) are transported in saltation and as bedload and are deposited in the subtidal channel, as is shown by the types of granulometric distributions of the sediment (SC-3 and SC-6). The poor maturity of the gravels implies that they are in close vicinity to the source area (same margins of the estuary). The effective sorting of the sands is the consequence of the high energy and the influence of the fluvial current. The significant presence of muddy fractions in the shallow channel indicates a lack of energy in the protected sectors. In these shallow areas, the suspension transportation and the decantation process are dominant, as is deduced from the higher content of mechanical silts versus flocculation materials that are observed on the Pejrüp triangle.

The significantly low contents of organic matter in the fluvial estuary could be generated by unfavourable chemical conditions for the flocculation of organic particles, or may also be due to a cleaning process and resuspension of finer fractions during the wet season (Hennessee et al., 1986).

The appearance, in the shallow areas of the fluvial estuary channel, of resedimented shells of microorganisms that arise from the central estuary is a consequence of the action of the flow-tidal currents.

In the central estuary, the mixture of freshwater (conductivity = 275–1075 μS/cm; O_2 dissolved = 6.3–10.5 mg/l) and saltwater (conductivity = 50,000–55,000 μS/cm; O_2 dissolved = 7.8–8.3 mg/l) strongly affects the type of sedimentation that is present in this area. The loss of energy of the opposite currents starts the flocculation processes in the deep channel, with the appearance of poorly sorted sediments occurring (with distributions of type SC-5). The sorting increases notably in some shallow channel areas (granulometric distributions, type SC-4) due to the domain of the tidal transportation on the flocculation. The bordering areas of the estuary can be an additional source of sediment. Bedrock substrate outcrops in some shallow margins, as is observed in some sonar records by Lobo et al. (2004). The proportions of organic matter are also indicative of the flocculation processes that are detected in this area, although the possibility should not be rejected that re-sedimentation of organic carbon arises from cleaning of the fluvial sector. This phenomenon has been observed in other estuaries (Hennessee et al., 1986) and it would explain the higher contents that are detected in the deeper areas of the channel, in which gravelly and sandy sediment fractions are abundant. The living microfauna concentrates on these not very energetic and organic-rich environments, with associations being almost mono-specific in foraminifers (*Cribroelphidium vadescens*) or ostracods (*Loxoconcha elliptica*).

The marine estuary is the most complex of the estuarine sectors. The bedload transport of well-sorted sands is the dominant process that occurs in the deeper part of the subtidal channel, generating sediments of type SC-4, in which the organic matter is scarce and the living microorganisms are absent. In this area, these elements have not appeared in the biocenosis, due to the mobility of the sediment, the highest energy in the currents and the smallest content in nutrients in this environment (Ruiz et al., 1996). The transport of sand may take place in both, ebb and flood senses, but the ebb is the only sense that is observed in the bedform fields. Maybe the ebb is the dominant current in this sector of the estuary, as suggested by Morales et al. (1997), but the most likely explanation for the dominance of these ebb-oriented bedforms is that the acoustic survey was carried out during ebb conditions and the observed forms were active.

In the shallow channel, the loss of energy instigates the flocculation and decantation of the finer fractions, which generate sediments with a distribution of type SC-2. This process may be induced by marine phanerogams (*Zostera noltii*), such as described in other mesotidal estuaries (Sherwood and Creager, 1990). The high concentrations of organic matter are also due to the abundant activity of these phanerogams, the roots of which increase the organic content, and excavating organisms such as bivalves and crabs (Ruiz et al., 1996). The cohesive characteristics of the sediment are also observable in the acoustic records: the beds are completely flat or they may have erosional features that are typical of cohesive bottoms. The origin of these erosional features may be anthropic (fishing activities) or due to punctual events of high energy that can lift cohesive bottom fragments that will be reworked as mudclasts, as observed by Woodruff et al. (2001) in the Hudson estuary.

In the transition between the deepest channel and the shallowest channel, the bed presents hybrid characteristics: the sediment is mainly sandy, but with some content of mechanical silts (grain size distribution of type SC-3). Bedforms present a wide variability in morphology and dimensions; the sense of flow may be also variable but flood direction is more abundant. There is a simple explanation for this: the most efficient hydrodynamic tidal fluxes are not located along the same course in the ebb sense than in the flood sense, and the ebb current is not able to rework the flood-oriented bedforms in some shallower areas.

According to these data, the complex distribution of bedform orientation that has been observed by Lobo et al. (2004) along the subtidal channel of this sector of the estuary, using an echo sounding profiler, may be the result of a ship route that is not coincident with the most efficient bypassing channel during the ebb conditions.

The open intertidal and frontal subtidal zones are dominated by a mixed action of tidal ebbs and waves, but the swash action is dominant since the construction of two jetties in the mouth of the estuarine channel. Consequently, the sediment is similar to that transported by the ebb current along the marine estuarine channel (very well-sorted medium-to-fine sand). From a morphological point of view, the intertidal zones constitute long sand bars that migrate to the north above a wide swash platform. The complete swash platform migrates to the north, becoming shallower (Morales, 1997).

The frontal subtidal zone is located in the opening of the groins that receive the direct discharge of sediment from the ebb current. The sediment also consists of well-sorted sands (SC-4) but the fine sand is more abundant. The seabed is characterized by a long sand bar, which is the product of the collision of waters between the ebb (south directed) and the waves (north directed). In the open zone of this bar, symmetric ripple fields are developed. These ripples are the product of the waves swinging over the wavebase.

5. Conclusions

The data presented in this work allow us to affirm that the Guadiana River estuary channel does not work as a mere transmitter of sediments between the continent and the open coastal area when beginning the deltaic progradation. On the contrary, a mixture of fluvial and marine sediments that are favoured by the actions of the tides occurring inside the estuary, together with an autochthonous flocculated sedimentation of the estuary, concluded that this was induced by water-mixing processes.

These processes that take place inside the estuary favour the continuity of the sedimentation, although the progradation process began in the open area of the system. The processes of inner infilling produce a hydrodynamic problem: although the flocculation accumulation is dominant, the volume of water that circulates in the channel tends to maintain a sedimentary bypassing among the continent and the coast. The Guadiana River estuary ‘solves’ this problem by allowing the clays to be provided by flocculation (partially mixed with clastic, fine, suspended sands and, sometimes, even with materials that are transported in the bedload), and to be preserved in places where the average tidal currents are lower: the convex margins of the meander imposed by the bedrock morphology. At the same time, in the places where tidal currents are higher (in the deeper areas of the channel), the flocculated material is not able to remain in the bottom; these areas become bypassing channels.

Due to tidal sedimentation in the shallowest areas and bypassing in the deepest areas, a lateral tidal-bar morphology is developed in the channel. The bars concentrate the active sedimentation, whereas the deep-channel sector constitutes a mere sedimentary transmitter. In this case, the narrow morphology that is imposed by the configuration of the bedrock impedes the development of longitudinal bars, as can be expected in wider estuaries, and lateral bars are developed in its place that become hydrodynamically better suited to this inherited morphology.

Superficial distribution of processes allows sedimentary accumulation inside the estuary, although this is very limited because the dominant process is sedimentary bypassing towards the coast, which favours accumulation in the frontal deltaic zone of most of the sediments, resulting in a progradation process.

The suggested depositional model of deposition and sedimentary bypassing would continue while retaining the fluvial input of water and sediments. The construction of the Alqueva dam, in February 2002, almost 60 km up to the last tidal influence, may have changed the described dynamic conditions. This model may be a reference point to compare with future studies about the sedimentary dynamics that now occur after the construction of the dam.

Acknowledgements

This work has been funded by Research Projects PS89-0113 and REN2002-01142/MAR, supported by DGCYT, P.A.I., Group # 0276 and the University of Huelva. We acknowledge the collaboration of M.J. Morales and J. Borrego during sampling surveys and C. Lozano, J.M. Gálvez, J. Reales and A. Herrera during Side-Scan Sonar surveys. The Spanish enterprise CRÁTERA S.L. kindly provided the ship to do the Side-Scan Sonar survey.

We particularly acknowledge the contribution of Dr. F. Lobo, who carried out an intensive revision of this work and L. Chicharo for his hard work on this special volume.

References

Boski, T., Moura, D., Veiga-Pires, C., Camacho, S., Duarte, D., Scott, D.B., Fernandes, S.G., 2002. Postglacial sea-level rise and sedimentary response in the Guadiana estuary, Portugal/Spain border. Sedimentary Geology 150, 103–122.

Centro de Estudios y Experimentacion de Puertos y Costas "Ramón Iribarren" (CEEPYC), 1979. Plan de estudio de la dinamica literal de la Provincia de Huelva. Informe, Direccion General de Puertos y Costas, Madrid, 37 pp.

Courau, P., 1983. Traces metalliques: principe des methodes, reduction des contaminations. Manuel des analyses chimiques en milieu marin. C.N.P.E.O., 395 pp.

Cuena, G.J., 1991. Proyecto de regeneracion de las playas de Isla Cristina. Informe del Servicio de Costas, MOPT, 100 pp.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology 62, 1030–1055.

Davis Jr., R.A., Clifton, H.E., 1987. Effects of sea-level rise on preservation potential of wave- and tide-dominated coasts. In: Nummedal, D., et al. (Eds.), Sea-level fluctuations and coastal evolution. S.E.P.M. Special Publication 41, 167–178.

Donahue, B.T., Hine, A.C., Tebbens, S., Locker, S.D., Twichell, D.C., 2003. Late Holocene estuarine–inner shelf interactions: is there evidence of an estuarine retreat path for Tampa Bay, Florida? Marine Geology 200, 219–241.

Duck, R.W., Rowan, J.S., Jenkins, P.A., Youngs, I., 2001. A multi-method study of bedload provenance and transport pathways in an estuarine channel. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere 26, 747–752.

Esteves, E., Pina, T., Chícharo, M.A., Andrade, J.P., 2000. The distribution of estuarine fish larvae: nutritional condition and co-occurrence with predators and prey. Acta Oecologica 21, 161–173.

Fairbridge, P.V., 1980. The estuary: its definition and geodynamic cycle. In: Olausson, E., Cato, I. (Eds.), Chemistry and Biochemistry of Estuaries. Wiley and Sons, New York, pp. 1–36.

Fenster, M.S., FitzGerald, D.M., 1996. Morphodynamics, stratigraphy, and sediment transport patterns of the Kennebec River estuary, Maine, USA. Sedimentary Geology 107, 99–120.

FitzGerald, D.M., Buynevich, I.V., Fenster, M.S., McKinlay, P.A., 2000. Sand dynamics at the mouth of a rock-bound, tide-dominated estuary. Sedimentary Geology 131, 25–49.

Ferreira, A.M., Martins, M., Vale, C., 2003. Influence of diffuse sources on levels and distribution of polychlorinated biphenyls in the Guadiana River estuary, Portugal. Marine Chemistry 83, 175–184.

Folk, R.L., Ward, W.C., 1957. Brazos river bar. A study in the significance of grain size parameters. Journal of Sedimentary Petrology 27, 3–26.

Garnaud, S., Lesueur, P., Clet, M., Lesourd, S., Garlan, T., Lafite, R., Brun-Cottan, J.C., 2003. Holocene to modern fine-grained sedimentation on a macrotidal shoreface-to-inner-shelf setting (eastern Bay of the Seine, France). Marine Geology 202, 33–54.

González-Vila, F.J., Polvillo, O., Boski, T., Moura, D., de Andrés, J.R., 2003. Biomarker patterns in a time-resolved Holocene/terminal Pleistocene sedimentary sequence from the Guadiana River estuarine area (SW Portugal/Spain border). Organic Geochemistry 34, 1601–1613.

Harris, P.T., Collins, M.B., 1984. Bedform distributions and sediment transport paths in the Bristol Channel and Severn Estuary, U.K. Marine Geology 62, 153–166.

Hennessee, E.L., Blakeslee, P.J., Hill, J.M., 1986. The distributions of organic carbon and sulphur in surficial sediments of the Maryland portion of Chesapeake Bay. Journal of Sedimentary Petrology 56, 674–683.

Kilenyi, T.I., 1969. The problem of the ostracod ecology in the Thames estuary. In: Neale, J. (Ed.), The Taxonomy, Morphology and Ecology of Recent Ostracoda. Olivier & Boyd Ltd., Edinburgh, pp. 251–267.

Knebel, H.J., Needell, S.W., O'Hara, C.J., 1982. Modern sedimentary environments on the Rhode Island inner shelf, off the eastern United States. Marine Geology 49, 241–256.

Kuijpers, A., Werner, F., Rumohr, J., 1993. Sandwaves and other large-scale bedforms as indicators of non-tidal surge currents in the Skagerrak off Northern Denmark. Marine Geology 111, 209–221.

Langhorne, D.N., 1973. A sandwave field in the Outer Thames Estuary, Great Britain. Marine Geology 14, 129–143.

Lancker, V., van Lanckneus, J., Hearn, S., Hoekstra, P., Levoy, F., Miles, J., Moerkerke, G., Monfort, O., Whitehouse, R., 2004. Coastal and nearshore morphology, bedforms and sediment transport pathways at Teignmouth (UK). Continental Shelf Research 24, 1171–1202.

Lobo, F.J., Dias, J.M.A., Gonzalez, R., Hernandez-Molina, F.J., Morales, J.A., Diaz Del Rio, V., 2003. High-resolution seismic stratigraphy of a narrow, bedrock-controlled estuary: the Guadiana estuarine system, SW Iberia. Journal of Sedimentary Research 73, 973–986.

Lobo, F.J., Plaza, F., González, R., Dias, J.M.A., Kapsimalis, V., Mendes, I., Díaz del Río, V., 2004. Estimations of bedload sediment transport in the Guadiana Estuary (SW Iberian Peninsula) during low river discharge periods. Journal of Coastal Research 41, 12–26.

McKinney, T.F., Stubblefield, W.L., Swift, D.J.P., 1974. Large-scale current lineations on the central New Jersey shelf: investigations by side-scan sonar. Marine Geology 17, 79–102.

Morales, J.A., 1995. Sedimentología del Estuario del Rio Guadiana (SW España–Portugal). Tesis doctoral Univ., Sevilla, Servicio Publicaciones Universidad de Huelva, 274 pp.

Morales, J.A., 1997. Evolution and facies architecture of the mesotidal Guadiana River delta (S.W. Spain–Portugal). Marine Geology 138, 127–148.

Morales, J.A., Ruiz, F., Jiménez, I., 1997. Papel de la sedimentación estuarina en el intercambio sedimentario entre el continente y el litoral: el estuario del Río Guadiana (S.O. España–Portugal). Revista de la Sociedad Geológica de España 10, 118–135.

Nichol, S.L., Boyd, R., 1993. Morphostratigraphy and facies architecture of sandy barriers along eastern shore of Nova Scotia. Marine Geology 114, 59–80.

Oliveira, J.T., 1990. The South Portuguese Zone. Stratigraphy and synsedimentary tectonism. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 334–347.

Passega, R., 1964. Grain size representation by CM patterns as a geological tool. Journal of Sedimentary Petrology 34, 830–847.

Pejrüp, M., 1988. The triangular diagram used for classification of estuarine sediments: a new approach. In: de Boer, P.L., et al. (Eds.), Tide-influenced Sedimentary Environments and Fades, pp. 289–300.

Plaza, F., Días, J.A., Várgas-Yáñez, M., González, R., Da Silva, A.J., 2003. Variability of the Guadiana River circulation. In: Fourth Symposium of the Iberian Atlantic Margin, abstracts, pp. 169–170.

Ruiz, F., Gonzalez-Regalado, M.L., Morales, J.A., 1996. Distribution et ecologie des foraminiferes et ostracodes actuels de 1'estuaire du Fleuve Guadiana (SO Espagne). Geobios 29, 513–528.

Sherwood, C.R., Creager, J.S., 1990. Sedimentary geology of the Columbia River Estuary. Progress in Oceanography 25, 15–79.

Terwindt, J.H.J., 1971. Sand waves in the southern bight of the North Sea. Marine Geology 10, 51–67.

Walton, W.R., 1955. Ecology of living benthonic foraminifera, Todos Santos Bay, Baja, California. Journal of Paleontology 29, 952–1018.

Woodruff, J.D., Geyer, W.R., Sommerfield, C.K., Driscoll, N.W., 2001. Seasonal variation of sediment deposition in the Hudson River estuary. Marine Geology 179, 105–119.

Zazo, C., Goy, J.L., Somoza, L., Dabrio, C.J., Belluomini, G., Improta, S., Lario, J., Bardaji, T., Silva, P.G., 1994. Holocene sequence of sea level fluctuations in relation to climatic trends in the Atlantic–Mediterranean Linkage Coast. Journal of Coastal Research 10, 933–945.

Zeiler, M., Schulz-Ohlberg, J., Figge, K., 2000. Mobile sand deposits and shoreface sediment dynamics in the inner German Bight (North Sea). Marine Geology 170, 363–380.