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Estimations of bedload sediment transport in the Guadiana Estuary (SW Iberian Peninsula) during low river discharge periods

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ABSTRACT

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The Guadiana estuary, located in the south-western part of the Iberian Peninsula, is a narrow, bedrock-controlled estuary, characterized by a seasonal fluvial regime and mesotidal conditions. Bathymetric surveys, geophysical records (Side Scan Sonar, high-resolution seismics), surficial sediment sampling, fluvial discharge data, salinity and velocity measurements were integrated to decipher the influence of tidal currents on bedload sediment transport patterns during low fluvial discharge periods. Results evidence a landward change of dominant tidal transport direction, from ebb- to flood-current dominance. The southern (seaward) estuarine stretch shows mostly seaward-directed bedload transport patterns, related to ebb-current dominance close to the river mouth. Further upstream, morphological and hydrological evidences suggest a higher influence of flood currents. The estuarine stratification seems to control the observed flood-ebb asymmetry, as higher flood dominance during neap tides is related with the establishment of stratified conditions. However, the prevailing tidal pattern is not able to produce a reversal of estuarine dune asymmetry in widespread zones of the southern estuarine stretch. In contrast, intense, landward-directed sediment transport is evidenced in the northern estuarine stretch. Flood-current enhancement in the northern stretch is probably related with channel narrowing and, consequently, with channel section decrease.

ADDITIONAL INDEX WORDS: *Estuarine dunes, bathymetry, tidal currents, fluvial discharge, estuarine morphology.*

INTRODUCTION

The influence of estuarine flows on bedload transport patterns in narrow (< 1 km wide), confined bedrock-controlled estuaries is highly controlled by the particular estuarine morphology, as general patterns of dune orientation change according to channel geometry (FENSTER and FITZGERALD, 1996; FITZGERALD et al., 2000). The influence of hydrodynamic agents in sediment transport patterns is variable. While seaward-directed transport is dominant during periods of high fresh-water discharge, landward-directed transport can prevail during periods of low fresh-water discharge (FENSTER and FITZGERALD, 1996). Strong tidal currents (above 0.4 m/s) can be associated with estuarine narrowing, usually causing a local enhancement of bottom currents by the topography (KNEBEL et al., 1999; KNEBEL and POPPE, 2000). The current enhancement may lead to intense coarse-grained bedload transport, as evidenced by bedforms (VITAL et al., 1998). Other typical geomorphological indicators of strong bottom flows are steeply incised channels (GINSBERG and PERILLO, 1999; VITAL and STATTEGGER, 2000).

The Guadiana estuary (Fig. 1), located in the southwest of the Iberian Peninsula, is characterized by a narrow valley morphology controlled by underlying Paleozoic and Mesozoic strata (BOSKI *et al.*, 2002). The river discharge is highly seasonal, with episodic flood events occurring during winter months (LOUREIRO *et al.*, 1986). The morphological configuration should have a large influence on estuarine bottom-flow patterns, especially during low-discharge periods, when tidal currents dominate the estuarine hydrology. Under those considerations, the main goals of this study are to depict the main bedload sediment transport pathways in the Guadiana estuary during low river discharge periods, and to discern the relative significance of river freshets and tidal flows as controlling factors of such transport pathways.

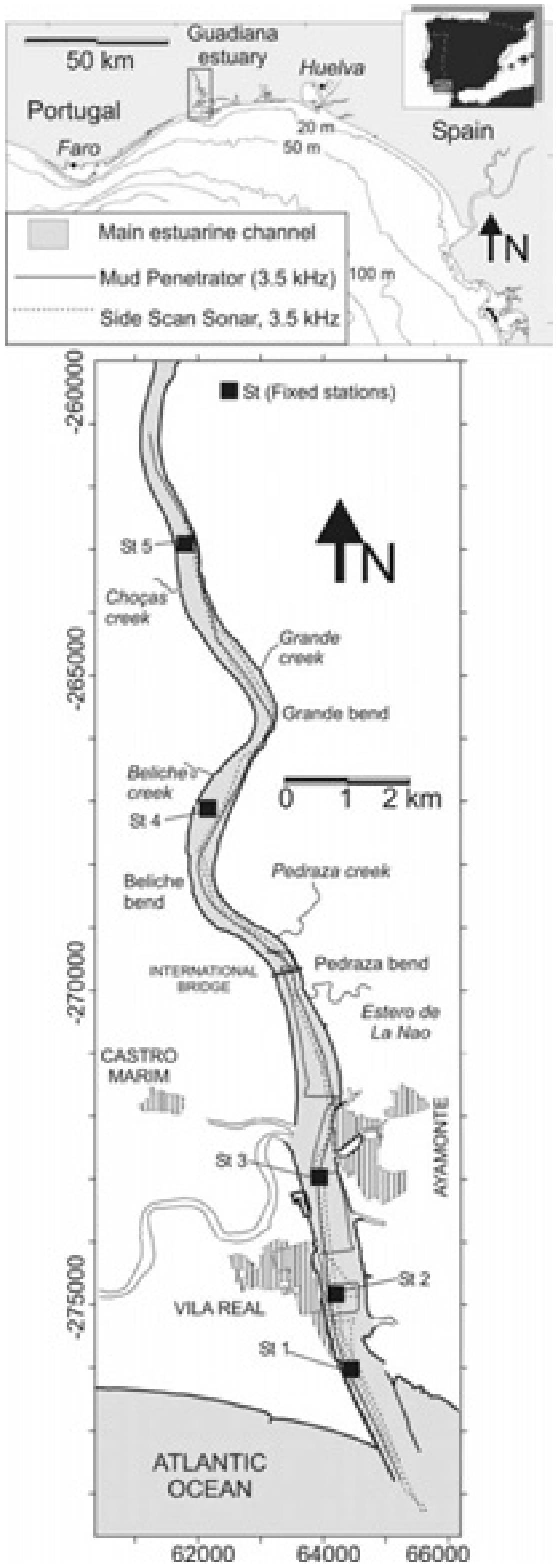

Figure 1. Geographic location of the Guadiana estuary, showing the position of geophysical records (Side Scan Sonar and Mud Penetrator) and fixed stations (St). St 6 is off the map, as it is located 35 km northward from the river mouth.

STUDY AREA

Hydrologic Characterization of the Guadiana Estuary

Fluvial Discharge

The Guadiana river is 810 km long, and its basin covers an area of 66.960 km^2, the fourth in size of the Iberian Peninsula. The flow volume is marked by changes associated with dry and wet years, as well as by large seasonal changes (LOUREIRO *et al.*, 1986). The regional climate is classified as semi-arid, with the exception of July and August (arid) and November to January (temperate-humid) (MORALES, 1993).

Fluvial discharge data are available for the period 1946-47 to 1998-99 at the hydrometric station of Pulo do Lobo, located 95 km landward from the river mouth. Values for the annually-averaged river discharge range between 170-190 m^3/s, although inter-annual variability is high. Thus, wet years show average values higher than 400 m^3/s, whereas dry years show average values ranging between 8-63 m^3/s.

Monthly-averaged river discharges show higher values in winter months (January to March), with values around 400 m^3/s, and lower values in summer months (July and August), with values around 40 m^3/s. However, inter-annual variability of monthly-averaged values is also high, as discharge values can be as high as 2000 m^3/s in winter months.

Tidal Regime

The tidal regime of the Guadiana estuary is mesotidal, with a mean amplitude of around 2 m and tidal ranges of 1.3 m for neap tides and of 3.5 m for spring tides (tide gauge in Vila Real, near the river mouth). A semidiurnal periodicity also characterizes the estuary. The tidal wave propagates following a synchronic mode, generating currents higher than 0.5 m/s (MORALES, 1997). Scarce velocity values document the occurrence of ebb dominance close to the river mouth (MORALES, 1993).

Estuarine Geology and Surficial Sediment Distribution

For most of its length the Guadiana estuarine valley cuts into the Carboniferous Lower Alentejo Flysch Group, composed of several formations characterized by thick sequences (>5000m) of pelitic shists and greywackes, with local occurrences of volcanoclastic series and conglomerates (e.g. OLIVEIRA *et al.*, 1979; OLIVEIRA, 1983). The river valley only crosses a band of

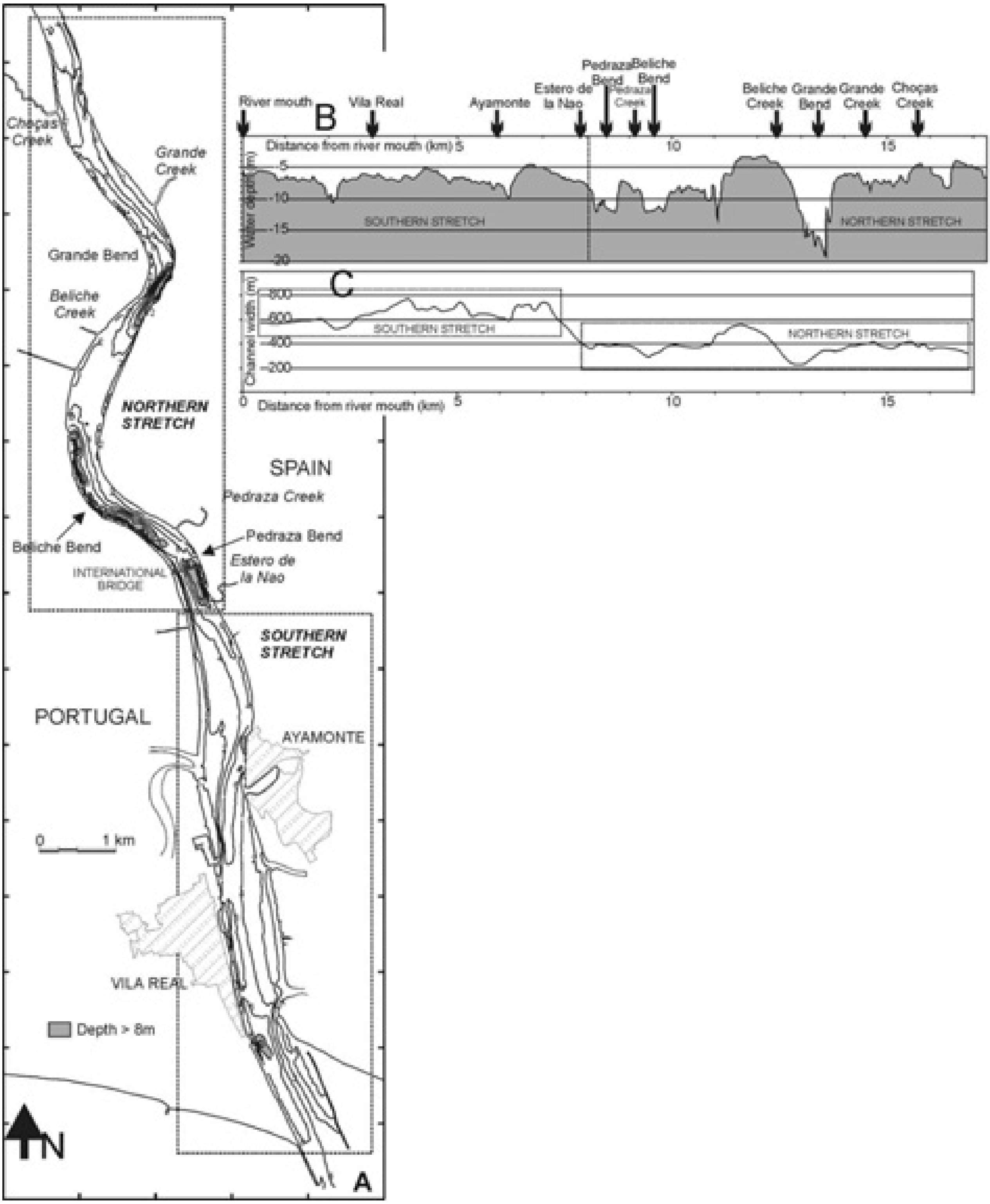

Figure 2. Physiographic characterization of the Guadiana estuary: (a) bathymetric chart of the Guadiana river estuary; (b) bathymetric profile along the estuarine thalweg; (c) channel width variation along the main estuarine channel.

Table 1: Summary of morphological and hydrological measurements conducted in the Guadiana estuary, with indication of tidal stage and fluvial discharge when available.

Dates	Equipment	Measurements	Fluvial discharge (Average daily values, m^3/s)	Tidal range (predicted, m)
September 2000	Petit Ponar dredge	surficial sediments	variable	variable
9 October 2000	echo-sounder	bathymetry	7.6	1.8
16 October 2000	echo-sounder	bathymetry	7.3	2.7
15 to 25 November 2000	ADCP	velocity	variable	variable
19 November 2000	SSS, 3.5 kHz	estuarine bottom features	5.3	1.8
20 November 2000	SSS, 3.5 kHz	estuarine bottom features	6	1.9
23 May 2001	RCM9	salinity, velocity	not available	2.7 (spring tide)
29 May 2001	RCM9	salinity, velocity	not available	1.6 (neap tide)
11 September 2001	RCM9	velocity	9.3	1.2
18 September 2001	RCM9	velocity	8.0	3.5
18 October 2001	RCM9	salinity, velocity	not available	3.2 (spring tide)
24 October 2001	RCM9	salinity, velocity	not available	1.1 (neap tide)

Mesozoic sediments of about 3-4 km width about 10 km from its mouth. These sediments are composed of arenites of fluvial semi-arid origin, evaporites, a volcano-sedimentary complex, and carbonates (e.g. MANUPELLA, 1992). South of this the river valley merges into an about 7 km wide coastal plain, composed mostly of unconsolidated sand of Quaternary and recent age. The seaward portion and areas near the main river channel of the coastal plain are dominated by marsh systems formed by the river (MORALES, 1997). The mouth of the estuary is a highly dynamic area, with considerable movement of sediments and associated morphological changes. The coastline only reached a position close to the present one about 200 years ago (MORALES, 1997; GONZÁLEZ *et al.*, 2001).

The Guadiana estuarine channel connects the fluvial channel with the open littoral domain. Fluvial sediments are transported through this channel, although they are mixed with marine sediments during tidal cycles. The deepest part of the channel is a bypassing channel, as sediments are exclusively sandy. Lateral tidal bars are composed of medium-sized fluvial sands alternating with muds (MORALES, 1997).

MATERIAL AND METHODS

The bulk of the data sets were obtained during intervals of low fluvial discharge (Table 1) and, consequently, the discussion and conclusions apply to periods with similar hydrodynamic conditions.

A bathymetric chart was elaborated from the integration of bathymetric measurements obtained in October (days 5, 6, 9, 11, 16 and 31) and in November (days 6 and 8) 2000 covering 15 km of the lower Guadiana estuary (Figure 1). Water depth was determined by means of a JMC-840 bathymetric sounder, with continuous analog recording, digital output and sub-decimetric precision. Positioning was achieved with a real-time DGPS with sub-metric precision. Bathymetric transects were executed perpendicular and parallel to the channel margins, with a mean separation of 50 m between adjacent lines.

Daily values of river discharge in m^3/s were obtained from INAG (Instituto da Agua, Portugal), covering the river volumes from January 2000 to October 2001 at Rocha da Galé, located about 80 km landward from the river mouth.

Information about salt stratification and near-bottom current velocity was obtained in November 2000 and in low river discharge periods in 2001, at several fixed stations along the estuarine valley (St 1 to St 6 at increasing distances from the river mouth). The salinity structure was defined from conductivity data obtained with several Aanderaa RCM9 current meters recording at 30 s intervals. The current meters were lowered from the surface to the near-bottom (up to 30 cm above the bottom) by means of cables marked at 1 m intervals, for sampling during 5 minutes at every depth.

An ADCP profiler was settled at St 1 (Figure 1). Data were acquired from 16:05 GMT on 14 November 2000 to 11:00 GMT on 25 November 2000. The ADCP profiler was the 'Work horse' manufactured by RD Instruments operating at 600 kHz frequency. The ADCP profiler was equipped with temperature and pressure sensors and was deployed in the self-contained mode facing upwards from the estuary bottom. The vertical resolution was 0.5 m (Depth Cell Size) and the sample interval was 5 minutes. For the purposes of this study, only near-bottom velocity values (at about 1 m above the estuarine bottom) were considered.

As limited current measurements were obtained during November 2000, additional near-bottom velocity data were collected during semidiurnal tidal cycles at St 2, St 3 and St 5 with Aanderaa RCM9 current meters during several surveys between spring and autumn 2001, in order to use them as a proxy for near-bottom tidal current behaviour under conditions of low river discharge (Table 1).

Geophysical data included bathymetric transepts collected parallel to the channel margins in October 2000, and Side Scan Sonar (SSS) records and high-resolution seismic profiling collected during 19 and 20 November 2000 between Choças creek and the Guadiana river mouth (Figure 1 and Table 1). The SSS source was a double frequency Klein system (model 422S-101HF) recording a lateral width of 75 m. The seismic source was a Mud Penetrator ORE transceptor (3.5 kHz), model 140, with a 100 ms recording interval.

Bedform analysis was executed using geophysical data collected in November 2000. Subaqueous dunes can be descriptively classified according to their height (H), which is used as an approximation to dune size (DALRYMPLE and RHODES, 1995). Thus, dunes are classified into small ($0.05 < H < 0.25$ m),

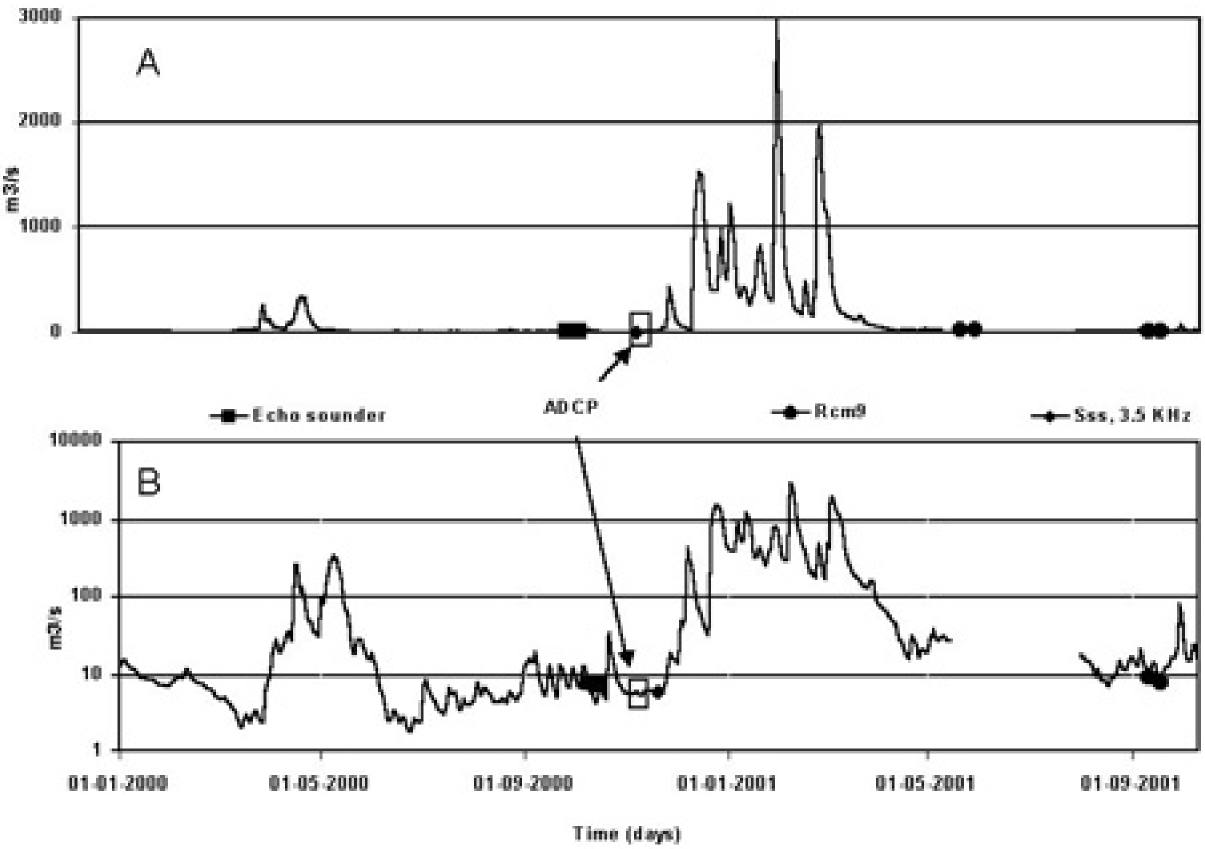

Figure 3. Summary of the Guadiana river volume at Rocha da Galé (80 km landward from the river mouth) from January 2000 to October 2001: (a) river volume in normal scale contrasting periods of flooding in winter and spring with periods of low volume in summer; (b) river volume in logarithmic scale, emphasizing variations during periods of low river discharge.

medium (0.25 < H < 0.5 m), large (0.5 < H < 3 m) and very large (H > 3 m) (ASHLEY, 1990).

The vertical profile of estuarine dunes is usually asymmetric, with a gentler stoss side and a steeper lee side. The steeper side faces in the direction of net sediment transport (BERNÉ *et al.*, 1993; VITAL and STATTEGGER, 2000), whereas symmetrical forms exist in areas where there is no net transport (HARRIS, 1988; BERNÉ *et al.*, 1993). It is assumed that asymmetrical forms generally retain a consistent facing direction over a tidal cycle, as the subordinate current does not transport sufficient sediment to reverse the profile (DALRYMPLE and RHODES, 1995). Medium and large dunes have a long response time and the reversal of asymmetry requires a long-period process (BERNÉ *et al.*, 1993; FENSTER and FITZGERALD, 1996). Consequently, the analysis of medium and large dune asymmetry enabled us to infer bedload sediment transport pathways which were representative of the dominant tidal currents, as most data were collected during periods of very low river discharge.

Two situations of bedload sediment transport were inferred. The first situation integrated along-channel echo-sounder measurements taken during 9 and 16 October 2000. Although 2-dimensional views of echo-sounder profiles only provide information about apparent dune orientation, they can be considered as good indicators of true dune orientation, as the main flow direction tends to prevail, and secondary flows only play a minor role due to the estuary narrowness. The second situation was inferred from the analysis of SSS records and high-resolution seismic profiling collected during 19 and 20 November 2000. The plan view obtained with the SSS records enabled us to confidently map the orientation of transport trends. It was observed that most of the transport patterns were parallel and sub-parallel to the estuarine margins, as documented in other estuarine channels (ALIOTTA and PERILLO, 1987; FENSTER and FITZGERALD, 1996). Another limitation was imposed by the narrowness of the deep estuarine channel, as navigation was very limited above lateral sand banks. Consequently, our investigations mainly refer to along-estuary variations of bedload sediment transport.

Surficial sediment samples were collected during September 2000 in the Guadiana estuary from Choças creek to the river mouth. These samples were collected with a Petit Ponar dredge along estuarine transepts (at least three samples for every transept) separated 150 m one from each other.

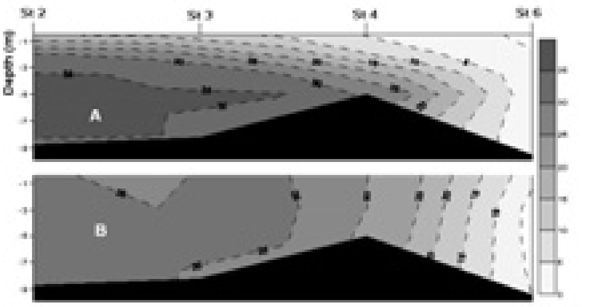

Figure 4. Salinity stratification along the Guadiana estuary an hour after the high tide during (a) neap and (b) spring tide conditions. As the main purpose of this figure is to show the vertical stratification, the horizontal axis has no scale due to the different separation between stations, particularly with regard to St 6.

RESULTS

Bathymetric Measurements

The general geological setup has strong influence on the morphological and physiographical characteristics of the main river valley (Figure 2). The river and its main tributaries have cut relatively narrow and in many places steep valleys into the terrain. While elevations in the vicinity of the main river valley do not exceed about 200-300 m, the main estuarine valley and the lower course of its main tributaries are generally well below 10 m above mean sea level. The main estuarine channel within the study area is narrow, with an average width of 540 m, and an average depth of 7.4 m.

Where the estuarine valley cuts through Paleozoic rocks north of Estero de la Nao, it shows a meandering-like pattern in plan view featuring three main river bends (Figure 2A). Also the path of the valley thalweg shows a net meandering pattern, approximating the outer margins at channel bends. The thalweg is characterized by significant along-channel depth changes, as several scour holes with depths of 7-18 m are evidenced (Figure 2B), except in the zone south of Beliche creek where depth shallows to less than 4 m. Cross-section profiles show V-shaped valleys, with high and uniformly steep valley walls between 3-10°, reaching locally more than 25°, although south of Beliche creek a symmetrical, U-shaped profile is identified (Figure 2A). The most common width of the northern estuarine stretch is about 400 m, and in some locations reaching as little as 200 m. Southwards of Beliche creek the estuarine channel reaches its maximum width (570 m) in the upper stretch, maintaining an average width higher than 450 m along 1.2 km (Figure 2C).

The southern 8.5 km long estuarine stretch between Estero de la Nao and the river mouth crosses through Mesozoic and Quaternary sediments and is less sinuous than the northern stretch. Maximum depths are less than 10 m, generally about 6 m and locally over 8 m in some small scour holes (Figure 2B). Cross-section profiles are mainly V-shaped, but with strongly asymmetric valley walls of relatively low steepness (lower than 1.5° for the gentler and higher than 2° for the more abrupt walls, except in the scour holes, where values higher than 10° can be observed) (Figure 2A). The average width of this stretch is 600 m (Figure 2C). The main estuarine channel is 500-600 m wide at the estuarine mouth, and channel width increases to more than 750 m 2.5 km upstream. The main channel remains about 700 m wide up to 6.5 km upstream from the river mouth, and its width decreases rapidly to less than 400 m close to Estero de la Nao.

River Discharge Data

The seasonality of the Guadiana river is exemplarity shown on Figure 3, covering the river discharge volumes (daily averages) from January 2000 to October 2001. There was hardly any rainfall during summer months (June to August) in 2000, when monthly-averaged values were of about 5 m^3/s, and from September to November – the period coinciding with bathymetric and geophysical surveys – where monthly-averaged values were below 10 m^3/s. The only exception was a low peak of about 30 m^3/s that occurred on 21 and 22 October (Figure 3). Therefore, it was assumed that the hydrologic regime during field surveys corresponded to summer conditions. An additional set of hydrologic measurements carried out between May and October 2001 do also fit in this pattern of low river discharge periods. No river discharge data were recovered between 15 May and 31 July, but, as no significant rainfall occurred during this interval, it was assumed that discharges corresponded to summer values.

Two main periods of increased fluvial discharge occurred during the reported interval (Figure 3): 1) Spring 2000, when the monthly-averaged value was 110 m^3/s in May and the river volume reached daily peak values of 400 m^3/s. 2) Winter 2000-2001, when strong regional rains led to river basin flooding. Monthly-averaged values ranged between 435-665 m^3/s, and the river volume reached peak values of up to 3000 m^3/s.

Estuarine Stratification

Surveys carried out on 18 (Figure 4A) and 24 October 2001 (Figure 4B) provided a synoptic view of the estuarine salinity structure during periods of low river discharge. Figure 4 shows two longitudinal salinity contours an hour after the high tide. Runoff conditions were weak enough to allow the entrance of sea-water into the estuary. On 18 October (neap tide) a salt wedge penetrated up to St 4 within the estuary and a strong halocline developed, allowing the upper layer of fresh water to extend out of the proximity of the estuarine mouth with little mixing. The

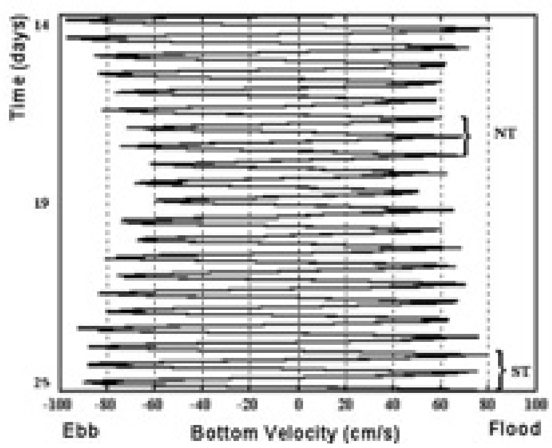

Figure 5. Near-bottom velocities obtained by ADCP from 14 to 25 November 2000 at St 1. The velocity values are projected on the estuarine longitudinal axis. NT: neap tide; ST: spring tide.

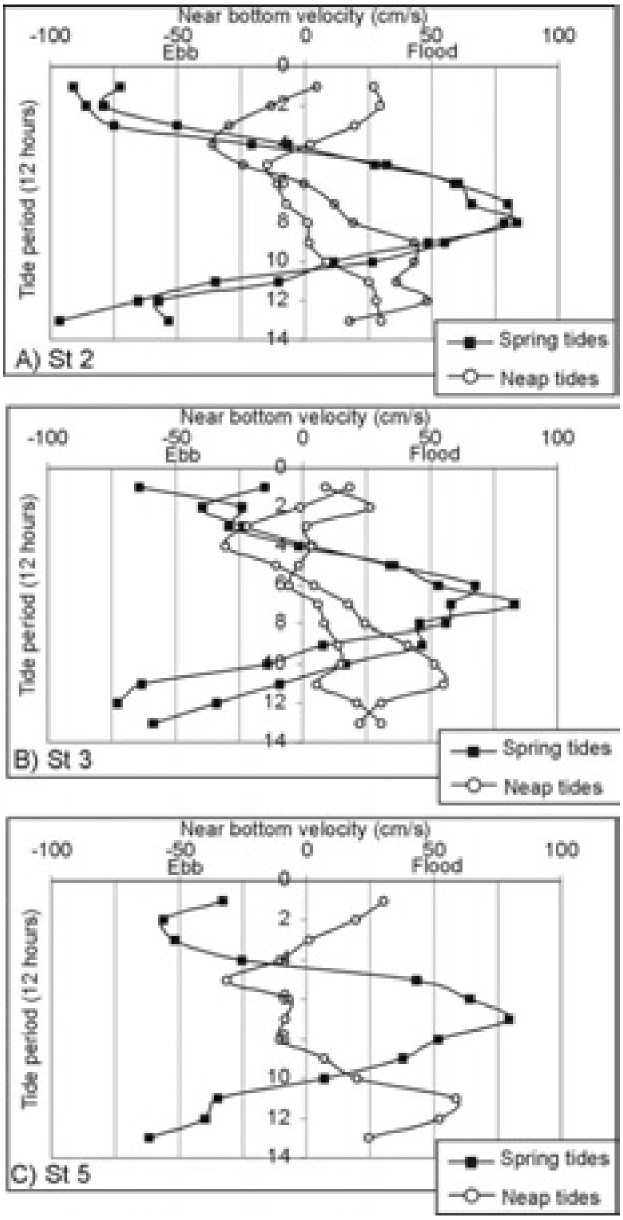

Figure 6. Near bottom velocities during semidiurnal tidal cycles at several fixed stations under conditions of low river discharge in 2001.

stratification due to the buoyancy of the fluvial input imposed an advective regime, and the fresh-water surface layer flowed over the lower layer as a gravity current. Tidal action did not break the estuarine stratification, in spite of the low fresh-water runoff (Figure 4A). On 24th October (spring tide) no vertical stratification was observed, and tidal mixing combined with low fresh-water input generated well-mixed conditions, evidenced by the vertical pattern of the isohalines up to 30 (Figure 4B).

ADCP Measurements

ADCP measurements provided current velocity data at St 1 during the period of geophysical surveying (second half of November 2000). The harmonic analysis of tidal currents (FOREMAN, 1978) determined a higher significance of the semidiurnal component M2 over the diurnal component K1. Near-bottom velocity data showed that this location was ebb dominated during the different tidal stages (Figure 5).

The first measurement days were characterized by relatively large tidal amplitudes, and ebb currents, with values close to 100 cm/s, were considerably larger than flood currents, below 80 cm/s. The transition to neap tides witnessed decreasing ebb-current values, but they remained above 70 cm/s. In contrast, flood currents decreased to values below 60 cm/s. During neap tides (18th November), ebb and flood currents were characterized by similar values ranging between 60-70 cm/s. Ebb currents increased to values around 80 cm/s during the transition from neap to spring tides, whereas flood currents were lower than 70 cm/s. The last measurement days were characterized by spring tides, when the ebb dominance was again evident, as ebb currents increased to around 90 cm/s, whereas peak flood current values were lower than 80 cm/s. Thus, ebb dominance was particularly significant during spring tide and relatively large tidal range conditions, when the difference between ebb- and flood-related velocities ranged between 10-20 cm/s (Figure 5).

Near-Bottom Current Measurements during Semidiurnal Tidal Cycles

Near-bottom current measurements were carried out at several fixed stations during periods of low river discharge and neap/spring tides in 2001 (Figure 6 and Table 1).

During spring tide conditions, St 2, located near the river mouth, was ebb dominated. There, ebb peak values were higher than 90 cm/s, whereas flood peak values were higher than 80 cm/s. In contrast, St 3 and St 5, located further up-river, were flood dominated during spring conditions. The flood-ebb asymmetry increased from St 3 (difference between peak values of about 10 cm/s) to St 5 (difference between peak values of about 20 cm/s).

During neap conditions, the three stations were flood dominated. The flood-ebb asymmetry also increased landward, from St 2 (difference between peak values of about 10 cm/s) to St 5 (difference between peak values of about 30 cm/s).

Estuarine Dunes

Dune size and shape

More than 570 medium and large dunes of $H \geq 0.25$ m were identified. Many other small dunes could be distinguished on SSS records (Figure 7). However, as they were not identified in high-resolution seismic records, their H distribution could not be studied. According to the distribution of estuarine medium and large dunes, it was found useful to characterize them in both southern and northern estuarine stretches (Figure 8 and Table 2).

In the southern stretch, seaward-directed (49%) and symmetric dunes (46.5%) were much more abundant than landward-directed dunes (4.5%). Seaward-directed dunes were higher (average value of 0.6 m) than symmetric dunes (average value of 0.4 m). In the northern stretch, landward-directed (44%) and symmetric dunes (41.8%) were more abundant than seaward-directed dunes (14%). Landward-directed dunes showed the highest proportion of large dunes (about 47%) in the northern stretch, although seaward-directed dunes showed the highest average H (0.8 m) (Figures 8A, 8B and Table 2).

Table 2: Descriptive dune size and shape morphological parameters of Guadiana estuarine dunes, based on geophysical records collected from 19 to 20 November 2000.

	SOUTHERN STRETCH			NORTHERN STRETCH		
	Seaward-directed	Symmetric	Landward-directed	Seaward-directed	Symmetric	Landward-directed
Number	98 (49%)	93 (46.5%)	9 (4.5%)	50 (14%)	149 (41.8%)	157 (44%)
Medium dunes	69 (70.4%)	87 (93.6%)	7 (77.8%)	29 (58%)	101 (67.8%)	83 (52.9%)
Large dunes	29 (29.6%)	6 (6.4%)	2 (22.2%)	21 (42%)	48 (32.2%)	74 (47.1%)
Dune height characteristics (m)						
Mean value	0.6	0.4	0.6	0.8	0.6	0.7
Max. Value	2	1.5	2	2.75	2	2
Mode	0.5	0.25	0.25	0.5	0.5	0.5
Dune wavelength characteristics (m)						
Mean value	17.8	12.4	17.2	20.7	15	17.5
Max. Value	60	50	35	50	45	45
Mode	15	10	5	20	10	15
Lee slopes (degrees)						
Min. Value	2.4		2.3	3.6		2.9
Max. Value	26.6	Not applicable	14.0	20.6	Not applicable	14.0
Average value	8.4		9.9	8.8		7.3
Stoss slopes (degrees)						
Min. Value	0.6		1.3	0.9		1.1
Max. Value	5.7	Not applicable	5.2	5.7	Not applicable	7.9
Average value	2.6		3	3.1		3.5

Wavelength (L) distribution showed similar patterns to H distribution. In the southern stretch, seaward-directed and landward-directed dunes showed similar average L values, ranging between 17-18 m. In the northern stretch, the average L value was higher than 20 m for seaward-directed dunes, whereas landward-directed and symmetric dunes showed lower L values (Figures 8C, 8D and Table 2).

The relation between dune L and H followed a similar pattern in both stretches. Although a high scattering was observed, higher Hs correlated with higher Ls, and the relationship was found to be limited by the equation $H_{max}=0.16L^{0.84}$ (after FLEMMING, 1988) (Figures 8E, 8F and Table 2).

H distribution according to water depth (h) was equally scattered, although dunes with H larger than 1 m were related to h larger or equal to 8 m. A maximum H value was associated with each specific h, suggesting that h only represents an upper boundary for H (cf. BOKUNIEWICZ *et al.*, 1977). However, in the northern stretch few dunes were located above the boundary given by the equation H=0.2h (after FLEMMING, 1988) (Figures 8G, 8H and Table 2).

The analysis of lee and stoss slopes showed that, in the southern stretch, landward-directed dunes displayed higher lee and stoss gradients than seaward-directed dunes, and therefore presented a more cuspate profile. In the northern stretch, seaward-directed dunes showed higher lee slopes but lower stoss slopes than landward-directed dunes (Table 2).

Asymmetry distribution maps

Asymmetry distribution maps were used to estimate near-bottom sediment transport paths during two specific intervals. The first situation was inferred from echo-sounding data collected during the first half of October 2000 (Figure 9), whereas the second situation was inferred from geophysical data (SSS and high-resolution seismics) collected during the second half of November 2000 (Figures 7, 10 and Table 1). Therefore, the time interval between both situations was a month. We assumed that in some zones the bedforms could be the result of previous river freshets, whereas in other zones they reflected the control of tidal flows when river discharge was low.

The first half of October 2000 showed a clear dominance of seaward-directed dunes in the southern stretch (Figures 9A and 11A), although a small zone characterized by symmetric dunes or even by landward-directed dunes was identified close to Ayamonte. The poor quality of echo-sounding records did not allow a correct identification of dune asymmetries between Vila Real and the estuarine mouth.

The northern stretch showed contrasting asymmetry patterns. Landward-directed dunes prevailed to the north of Beliche creek (Figures 9B and 11A), although zones with symmetric dunes existed. In contrast, seaward-directed dunes dominated to the south of Beliche creek (Figures 9C and 11A), although landward-directed dunes were detected between Beliche and Pedraza bends.

During the second half of November 2000 the southern stretch showed relatively weak near-bottom transport trends, but with a clear seaward-directed dominance (Figures 7A, 10A and 11B). Large seaward-directed dunes were observed in front of Vila Real. Besides, the zone between Estero de la Nao and Ayamonte was dominated by medium seaward-directed dunes. The zone between Ayamonte and Vila Real showed medium symmetric dunes or even medium landward-directed dunes, with some large dunes close to Ayamonte. Medium symmetric dunes were also found

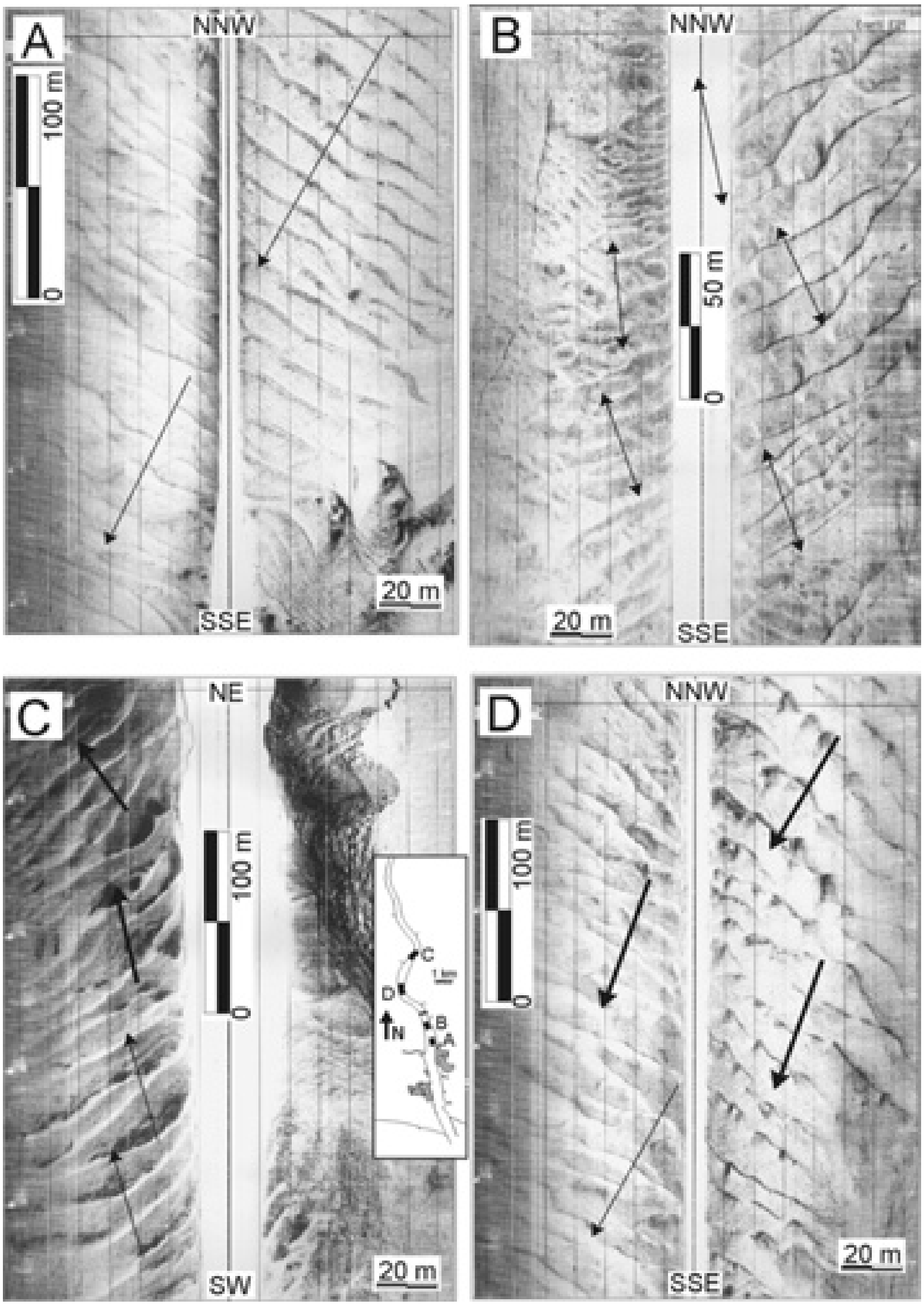

Figure 7. Examples of side scan sonar (SSS) records collected from 19 to 20 November 2000: (a) seaward-directed medium dunes in the southern stretch; (b) symmetric medium dunes with some small dunes observed to the north (in the southern stretch); (c) landward-directed dunes in the northern stretch, evolving northward from medium to large; (d) seaward-directed dunes in the northern stretch, evolving southward from large to medium.

close to the estuary mouth (Figures 7B and 11B).

The northern stretch was characterized by stronger transport trends. There, landward-directed dunes were dominant (Figures 7C, 10B and 11B), especially in four zones: 1) to the north of Grande creek; 2) between Grande bend and Beliche creek; 3) between Beliche creek and Beliche bend; 4) close to Pedraza bend. Seaward-directed dunes were only identified to the south of Beliche creek and between Beliche bend and Pedraza creek (Figures 7D, 10C and 11B). Transitional zones of symmetric dunes were identified associated with estuarine bends, such as Grande and Beliche bends (Figure 11B).

Surficial Sediment Cover

Sediments along the thalweg of the lower Guadiana estuary were dominated by sand. Exceptions generally occured where

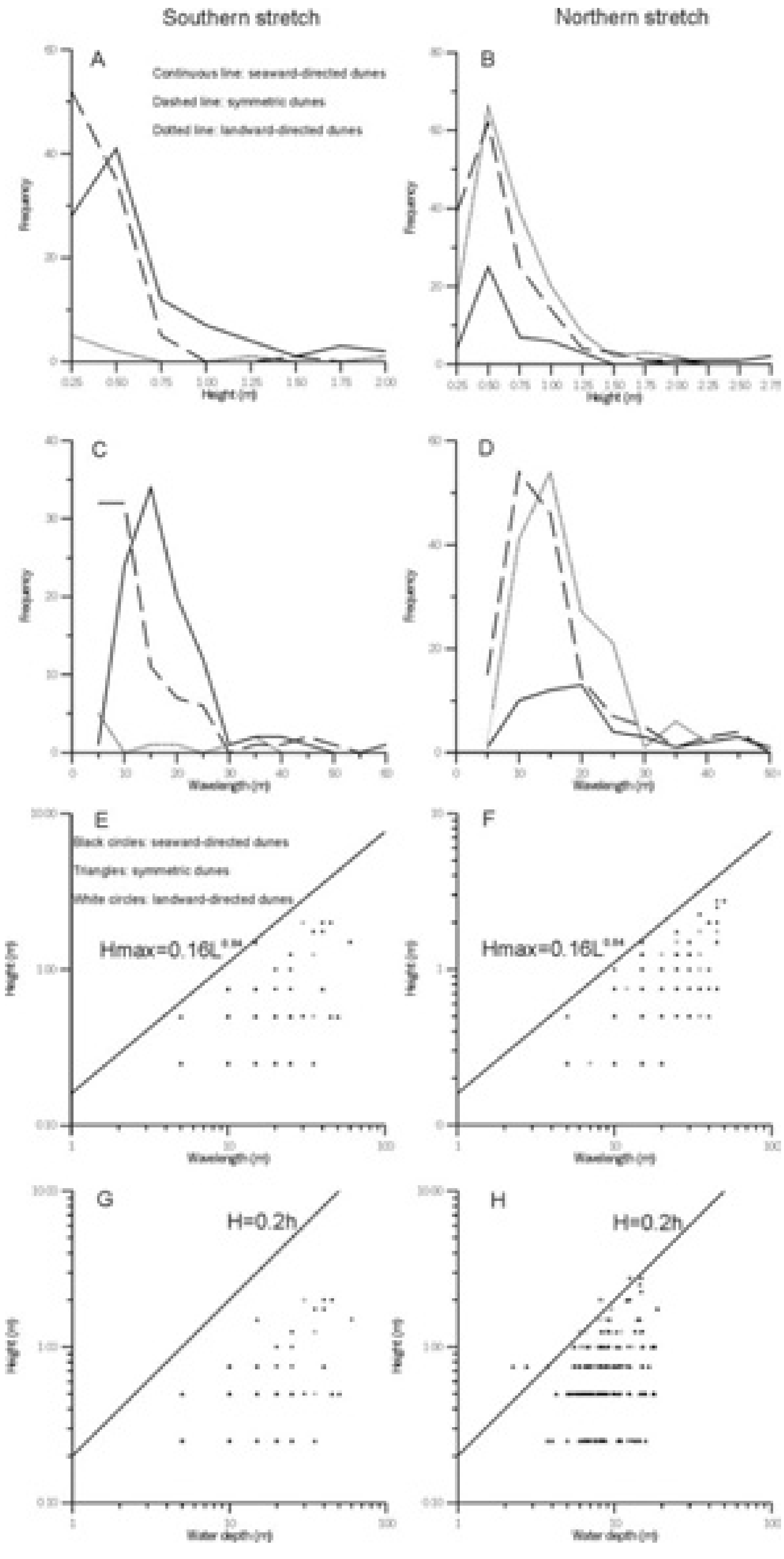

Figure 8. Morphological characterisation of subaqueous dunes in the Guadiana estuary: (a) frequency histogram of height (H) distribution in the southern stretch; (b) frequency histogram of H distribution in the northern stretch; (c) frequency histogram of wavelength (L) distribution in the southern stretch; (d) frequency histogram of L distribution in the northern stretch; (e) plot of L against H in the southern stretch; (f) plot of L against H in the northern stretch; (g) plot of water depth (h) against H in the southern stretch; (h) plot of h against H in the northern stretch.

unusually deep locations of the thalweg are located in the vicinity of creeks, for instance near the mouth of Beliche creek. In these cases fine-grained sediments <63 µm dominated. The immediate vicinity of the western jetty was dominated by gravely deposits.

The sand fraction of sediments in the study area was composed of quartz, feldspar, bioclasts, lithic components of diverse origin, with provenance primarily from Mesozoic outcrops (sandstones and vulcanites, as well as shallow marine carbonates), and shist and greywacke fragments, originating from a thick series of paleozoic turbidites, which make up large part of the interior of the south-western Iberian Peninsula.

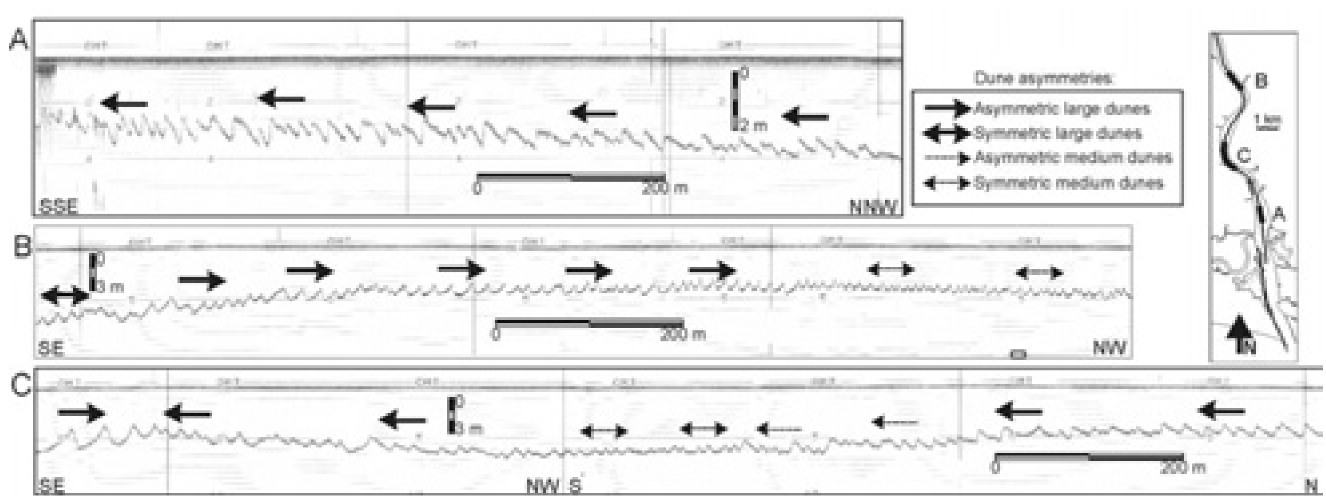

Figure 9. Echo-sounding records of estuarine dunes observed in the Guadiana estuary in October 2000: (a) seaward-oriented dunes in the southern stretch; (b) landward-oriented dunes in the northern stretch; (c) seaward-oriented dunes are locally significant in the northern stretch, as well as symmetric dunes.

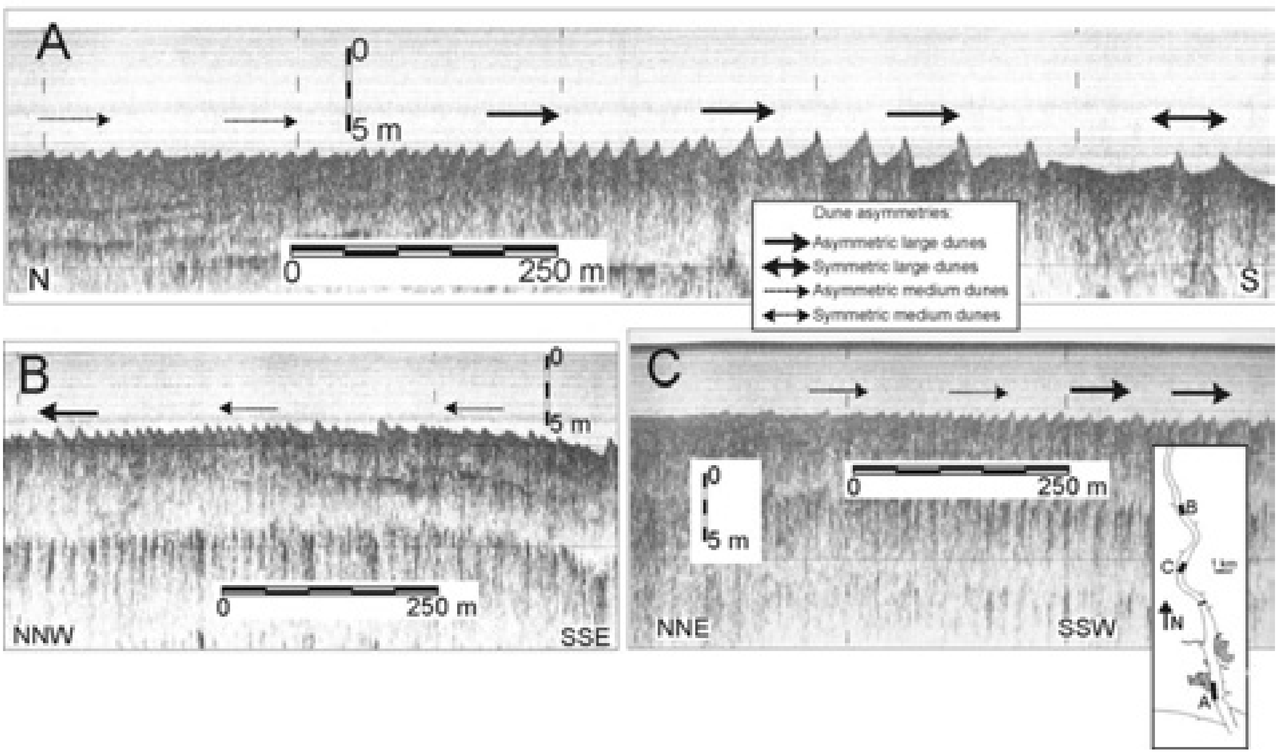

Figure 10. Examples of high-resolution seismic profiles (3.5 kHz) collected from 19 to 20 November 2000: (a) dune field in the southern stretch where seaward-oriented dunes evolve downstream from medium to large; (b) dune field in the northern stretch where landward-oriented dunes evolve upstream from medium to large; (c) dune field in the northern stretch where seaward-oriented dunes evolving downstream from medium to large.

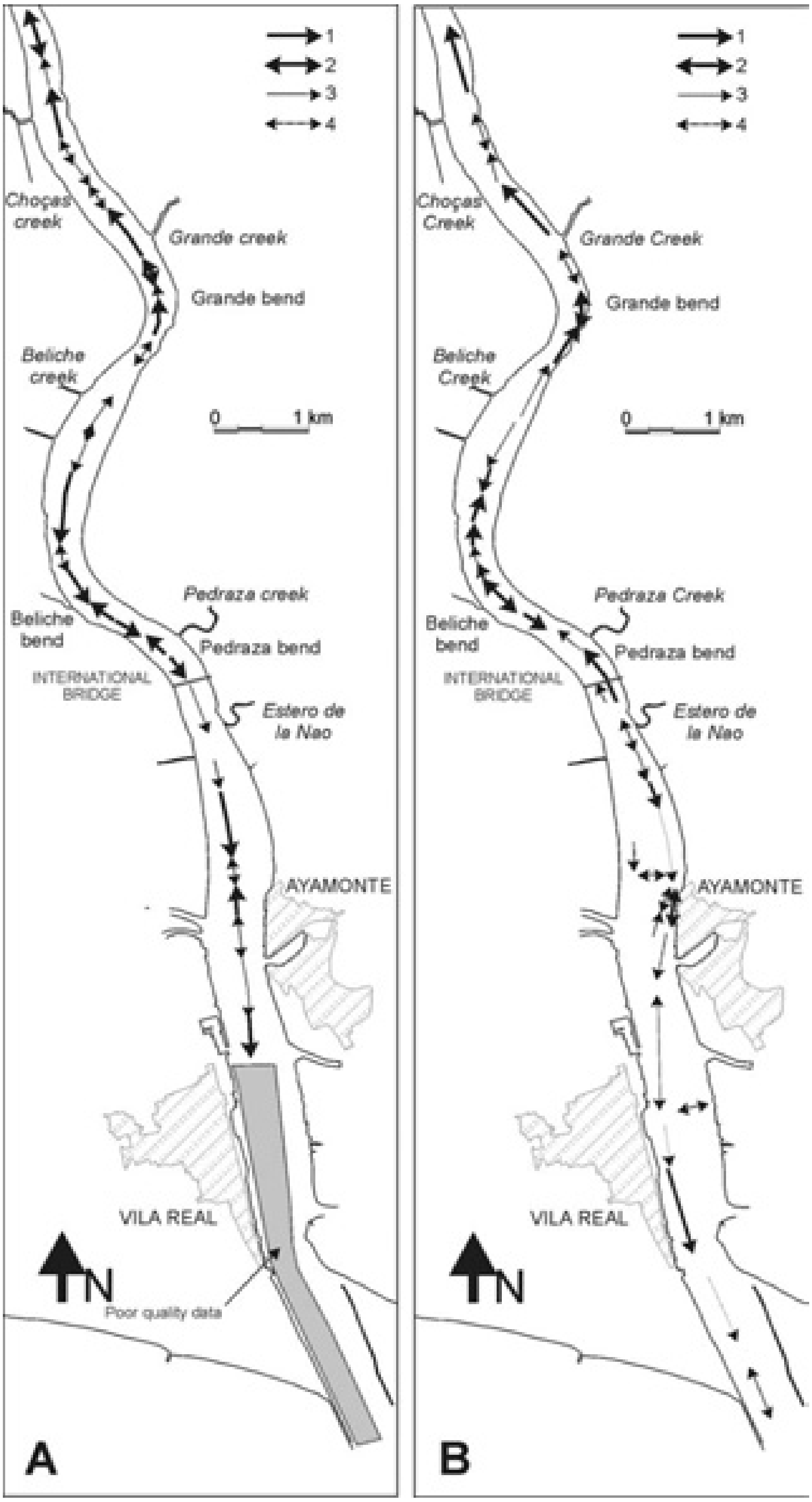

Figure 11. Estimation of near bottom sediment transport patterns deduced from dune asymmetries, from data collected in: (a) October 2000 and (b) November 2000. Legend: (1) sediment transport trends inferred from asymmetric large dunes; (2) sediment transport trends inferred from symmetric large dunes; (3) sediment transport trends inferred from asymmetric medium dunes; (4) sediment transport trends inferred from symmetric medium dunes.

DISCUSSION

Dune asymmetry distributions observed in the Guadiana estuary during two specific intervals were used to estimate trends of bedload sediment transport during periods of low river discharge, as the study of bottom bedforms in estuarine settings may provide estimates of dominant bedload transport patterns (VAN DEN BERG, 1987; PARK and YOO, 1997). Medium and large dunes are considered to be relatively stable features which only undergo major changes in response to highly energetic events (BOKUNIEWICZ *et al.*, 1977; FENSTER *et al.*, 1990), as net dune movement is unaffected by diurnal flow regime changes (FENSTER and FITZGERALD, 1996).

The differences between the two observed situations in the Guadiana estuary can be attributed to the dominant hydrodynamic regime, supposedly highly influenced by tidal currents. The transport trends were compared with limited near-bottom current velocity measurements, in order to discern the relative significance of tidal currents and fluvial freshets, as evidenced in other estuarine environments (e.g. COOPER, 1993; BERNÉ *et al.*, 1993; FENSTER and FITZGERALD, 1996). The relative narrowness of the estuarine channel probably prevented the existence of lateral reversing currents, as more intense currents tend to be conducted trough the deeper estuarine channel (cf. DALRYMPLE *et al.*, 1990).

The high proportion of medium dunes observed in the southern (seaward) stretch reflects either moderate hydrologic conditions or dune smoothing by the dominant tidal current pattern (cf. DALRYMPLE and RHODES, 1995). The dominance of seaward-oriented bedforms could be related either to ebb dominance or to the imprint of previous high fresh-water discharge events (cf. COOPER, 1993). In the zone close to Vila Real, the identified seaward-directed bedload transport could be confidently related to near-bottom ebb dominance observed in ADCP records (Figure 5). Particularly during spring tide conditions, the difference between ebb and flood currents may be as high as 20 cm/s, possibly due to the establishment of vertically homogeneous conditions. This pattern is in good agreement with the reported seaward export of sediments in the zone close to the river mouth (MORALES, 1997; MORALES *et al.*, 1997). Few data were available in the southernmost zone close to the river mouth, but the prevalence of symmetric, medium dunes indicates a low-energy hydrodynamic regime (cf. VITAL *et al.*, 1998), probably balanced between moderate tidal currents and the influence of wave action (Figure 11).

To the north of Vila Real, the interaction between bedload transport trends and near-bottom flows was more complex. Although seaward-directed dunes were still more frequent, symmetric dunes were also abundant, and local landward-directed transport also occurred. Morphological data indicate that the dominant seaward-directed transport become less evident from October to November 2000 (Figure 11). Hydrological data collected during intervals with similar hydrodynamic regime revealed a landward change from ebb to flood dominance during spring tides (Figure 6), similarly to the situation identified in other estuaries (BERNÉ *et al.*, 1993). The landward increase of flood dominance was even higher during neap conditions. The salinity structure of the estuary seems to influence the observed flood-ebb asymmetry, as the higher flood dominance during neap tides was associated with estuarine stratification. The increased flood dominance during stratified conditions could be related to a mass balance deficit of saltwater caused by its entrainment with overlying seaward-flowing fresh-water (DYER, 1973). In contrast, equal dominance of flood and ebb currents or slight flood dominance during spring tides could be related to the development of a vertically homogeneous estuary (Figure 4).

As the seaward-directed dunes identified in the northern zone of the southern stretch did not seem to be in equilibrium with the dominant tidal current pattern, it is suggested that they could reflect the influence of a previous high fresh-water discharge event (e.g, spring floods), which would increase ebb tidal flows (cf. FENSTER and FITZGERALD, 1996). The higher landward influence of flood currents during the low river discharge period might have caused a reduction of seaward asymmetry north of Ayamonte, but not a reversal of dune asymmetry. In this sense, the reversal of asymmetry during tidal dominance on sedimentation only has been reported in estuaries with very high tidal currents, such as the Gironde estuary (BERNÉ *et al.*, 1993).

The bedforms were larger in the northern estuarine stretch, indicative of a highly energetic hydrodynamic regime (cf. VITAL and STATTEGGER, 2000). The dominance of landward-directed bedload transport indicates enhanced flood currents during low river flow periods (COOPER, 1993; FENSTER and FITZGERALD, 1996). as dune migration is related with unequal flood and ebb tidal flows (cf. BOKUNIEWICZ *et al.*, 1977). According to the morphological data, the flood dominance increased landward, as no significant downstream-directed transport was identified to the north of Grande bend. The dominance of landward-directed dunes increased from October to November 2000, suggesting that the northern estuarine stretch is flood dominated during low river discharge periods. Limited hydrological data collected in the northern stretch agreed with morphological observations, as St 4 was flood dominated during spring and neap tides under conditions of low river discharge. In St 4, the flood dominance was higher than in stations located in the southern stretch. But, similarly to the situation observed in the southern stretch, the development of estuarine stratification during neap tides also led to higher flood dominance (Figures 4 and 6).

The particular estuarine morphology of the northern stretch may influence the intensity of estuarine flows, and consequently the bedload sediment transport patterns, as the bottom flow is enhanced by, and interacts with, the bottom topography (cf. KNEBEL and POPPE, 2000). This influence is presumed to be higher over tidal currents (cf. KNEBEL *et al.*, 1999). Our observations are in agreement with those statements, as the flood dominance seems to have been higher in zones where the estuarine valley becomes narrower, such as Pedraza and Grande bends (Figure 11). Thus, those narrow passages seem to cause the flood-ebb flow asymmetry.

However, the signature of local, intense seaward-directed bedload sediment transport was also evidenced in some locations, especially south of Beliche creek. The persistence of this transport pattern could indicate either the imprint of a previous high-discharge fluvial freshet (cf. FENSTER and FITZGERALD, 1996) or locally enhanced ebb tidal currents. As the seaward-directed dunes and most of the symmetrical dunes occurred in channel bends, it is suggested that seaward-directed flows accelerated when the main flow was deviated. As a result, equal influence of flood and ebb flows or even some local ebb dominance between Beliche bend and Pedraza creek occurred in relation with channel deviation.

CONCLUSIONS

Bedload transport patterns observed in the Guadiana estuary during low river discharge periods are highly complex, and probably influenced by the combined action of both tidal currents and fluvial flows. As in other estuaries characterized by a narrow, bedrock-controlled morphology, the imprints of high-energy, high fresh-water discharge events are recorded in the estuarine bottom, even under the clear dominance of tidal currents. Two estuarine stretches (southern and northern) presented contrasting patterns of bedload sediment transport.

The higher abundance of medium dunes in the southern estuarine stretch was attributed to a less intense hydrodynamic regime. The meridional zone of the southern stretch was characterized by seaward-directed bedload sediment transport, which was related to ebb dominance evidenced in ADCP recording. The seaward-directed asymmetry become less evident northward. Current measurements indicated a higher landward influence of flood currents. The higher flood dominance, especially during neap tides, was related with the establishment of estuarine stratification. Consequently, it is suggested that the dominant seaward-directed asymmetry was a remnant of a previous high-discharge fluvial event. It is noteworthy to indicate that the dominant current pattern during periods of low fluvial discharge was not able to produce a reversal of asymmetry, supporting the idea that high-discharge, fresh-water flows can be significantly imprinted in bottom morphologies of narrow estuaries.

Bedload transport patterns were mainly landward-directed in the northern estuarine stretch, indicating flood dominance that increased landward. Limited current measurements indicated enhanced flood dominance in relation to the southern stretch. Flood current enhancement especially occurred where the estuarine channel become narrower. The local identification of seaward-directed or transitional transport trends in relation with estuarine bends probably indicates seaward-directed flow enhancement by channel deviation.

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SUMMARY

O estuário do rio Guadiana localiza-se no sudoeste da Península Ibérica e apresenta uma morfologia estreita, controlada pelos afloramentos rochosos. Este estuário é também caracterizado por um regime fluvial sazonal e por condições mesotidales. Inúmeras medições geológicas e hidrológicas, incluindo batimetrias, registos geofísicos (sónar de varredura lateral, sísmica de alta resolução), amostras de sedimento superficial, escoamentos fluviais, medições de salinidade e velocidade foram integradas com o objectivo de revelar a influência das correntes de maré sobre as tendências de transporte sedimentar de fundo durante períodos de baixos escoamentos fluviais.

Os resultados evidenciam uma direcção dominante do transporte tidal de correntes de vazante no sector meridional que sofre uma mudança à montante para correntes de enchente. A dominância de transporte sedimentar de fundo dirigido a jusante no troço estuarino meridional está relacionada com uma maior influência das correntes de vazante na zona mais próxima à foz do estuário. A montante, as evidencias morfológicas e hidrológicas sugerem uma maior influência das correntes de enchente. No entanto, este regime de marés não é capaz de produzir uma reversão da assimetria das dunas estuarinas em extensas zonas do troço estuarino meridional. Pelo contrario, um intenso, transporte sedimentar de fundo dirigido a montante é dominante no troço estuarino setentrional. A maior importância das correntes de enchente neste troço superior está possivelmente relacionada com os estreitamentos do canal estuarino.