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Patterns of bottom current flow deduced from dune asymmetries over the Gulf of Cadiz shelf (southwest Spain)

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Abstract

The analysis of dune-like morphologies on the Gulf of Cadiz continental shelf, using high-resolution seismic reflection profiles and sediment samples, reveals a well-defined distribution pattern controlled by the area's hydrodynamics. These bedforms are considered to be modern features from the Holocene, and therefore they provide information about the bottom circulatory patterns established over the continental shelf. Most of the submarine dunes have been identified over a shallow physiographic feature named the Barbate High. The current flows that generate the bedform fields can be attributed to a complex interaction of several hydrodynamic agents, in which the process of current direction reversal related to the tidal cycle in the Straits of Gibraltar seems to be involved. Eastward-oriented submarine dunes located on the onshore zones of the inner shelf are generated by the Atlantic inflow, which over these shallow zones is mainly orientated towards the east during high-tide conditions in the Straits of Gibraltar. Bedforms oriented westwards and west–northwestwards in the offshore zones indicate that a previously undescribed flow occurs on the Gulf of Cadiz continental shelf. This flow is attributed to the influence of ebb tidal currents, which move preferentially towards the west over these zones. As a result of this complex bottom flow pattern, a clockwise sand transport pattern over the Barbate High is established.

Keywords: Holocene; Submarine dunes; Continental shelf; Hydrodynamics; Gulf of Cadiz

1. Introduction

The existence of two major fields of submarine dunes on the Gulf of Cadiz continental margin is well known, since they have been attributed to its complex oceanographic conditions, controlled by the occurrence of a southeastwardly inflow of Atlantic water into the Mediterranean Sea over the shelf domain (Lobo, 1995) and by a northwestwardly outflow of Mediterranean water over the slope domain (Nelson et al., 1999). One of these dunefields is located on the gentle slope west of the city of Cadiz, in water depths ranging from 500 to 1500 m, previously studied by Heezen and Johnson (1969), Kenyon and Belderson (1973) and Nelson et al. (1993) among others. The aim of these studies was

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to understand the relationship between the Gulf of Cadiz deep-water dunes and the Mediterranean Outflow Water (MOW) path. In fact, as shown by Heezen and Johnson (1969), the deep-water dunefield presents a good relationship with the distribution of the highest salinity values of bottom waters that correspond to the MOW path. Another dunefield is located on the continental shelf, in depths ranging from 15 to 30 m, associated with a shallow physiographic feature known as the Barbate High. This feature is located south of the city of Cadiz, on the inner and middle shelf between the towns of Conil and Barbate in Cadiz province (Heezen and Johnson, 1969; Lobo, 1995; Lobo et al., 1996; ITGE, in press). The present paper describes the first detailed study ever carried out on this submarine dunefield.

There is a direct link between dune morphology and the flow that created these bedforms (Ashley, 1990), because the presence of transverse bedforms over sand ridges can be used as an indicator of active bedforms, whereas moribund or relict sand ridges do not have superimposed bedforms (Stride, 1982). Bedforms' distribution, arrangement and morphology provide information about bottom currents, assuming that the bedforms are in equilibrium with present-day oceanographic current conditions (Ikehara and Kinoshita, 1994). In addition, bedload sediment transport patterns may be inferred from bedform asymmetry (Allen, 1968; Bokuniewicz et al., 1977; Swift and Freeland, 1978; Langhorne, 1982; McCave and Langhorne, 1982; Twichell, 1983; Harris, 1998a,b) and from direction and rates of bedform migration (Langhorne, 1982; Aliotta and Perillo, 1987), provided that sandwaves and megaripples have been created by present-day hydraulic conditions (Terwindt, 1971). Superimposed bedforms indicate that larger bedforms are active and migrating (Aliotta and Perillo, 1987). Large dunes are affected by major events, e.g. storm currents (Harris and Collins, 1984; Fenster et al., 1990; Houthuys et al., 1994), whereas high-frequency processes only rework and modify them (Fenster et al., 1990). Large dunes consequently have a long response time and only undergo minor changes in size and shape when they are affected by high-frequency processes, e.g. instantaneous processes and neap/spring cycles; therefore, they are good indicators of bedload transport averaged over periods of several days–months (Lanckneus and De Moor, 1991; Berné et al., 1993).

Taking these considerations into account, the study of large-scale bedforms' asymmetry on the Gulf of Cadiz continental shelf can provide information about bedload transport activity and circulatory patterns over this marine domain, as long as the bedforms are in equilibrium with the present-day oceanographic regime.

2. Area description

2.1. Geologic and physiographic framework

The Gulf of Cadiz is bounded by the Mediterranean Sea to the east, through the Straits of Gibraltar; by the Iberian Peninsula and Africa to the north and south, respectively; and on the west, it is open to the Atlantic Ocean (Fig. 1). The northern continental margin extends from Cape Saint Vincent (Portugal) to Tarifa (Spain), and its morphology shows a concave shape with a northwest–southeast orientation (Roberts, 1970; Malod, 1982; Maldonado, 1992).

The Gulf of Cadiz's tectonic setting and geological evolution have been discussed elsewhere (Argus et al., 1989; Dewey et al., 1989; Srivastava et al., 1990, among others), and very recently they have been studied in great detail (Maldonado and Nelson, 1999; Maldonado et al., 1999). The most distinctive tectonic feature of this continental margin was the emplacement of an olistostromic body in the eastern part of the Gulf of Cadiz during the Late Miocene. This tectonic process led, at the beginning of the Lower Pliocene, to the opening of the Straits of Gibraltar, and consequently, to the instauration of a new oceanographic regime. This regime has been characterised by its MOW (Maldonado et al., 1999). During the Pliocene to Pleistocene, progradation of a siliciclastic coastal wedge of fluvial origin in the ancient Guadalquivir foreland basin and the development of a mid-slope contourite drift on the Guadalquivir and Algarve margins both occurred, due to MOW influence (Maldonado and Nelson, 1999). During Quaternary sea-level changes, the formation of shelf-margin deltas and slope wedges took place during regressive and lowstand intervals (Somoza et al., 1997; Rodero et al., 1999;

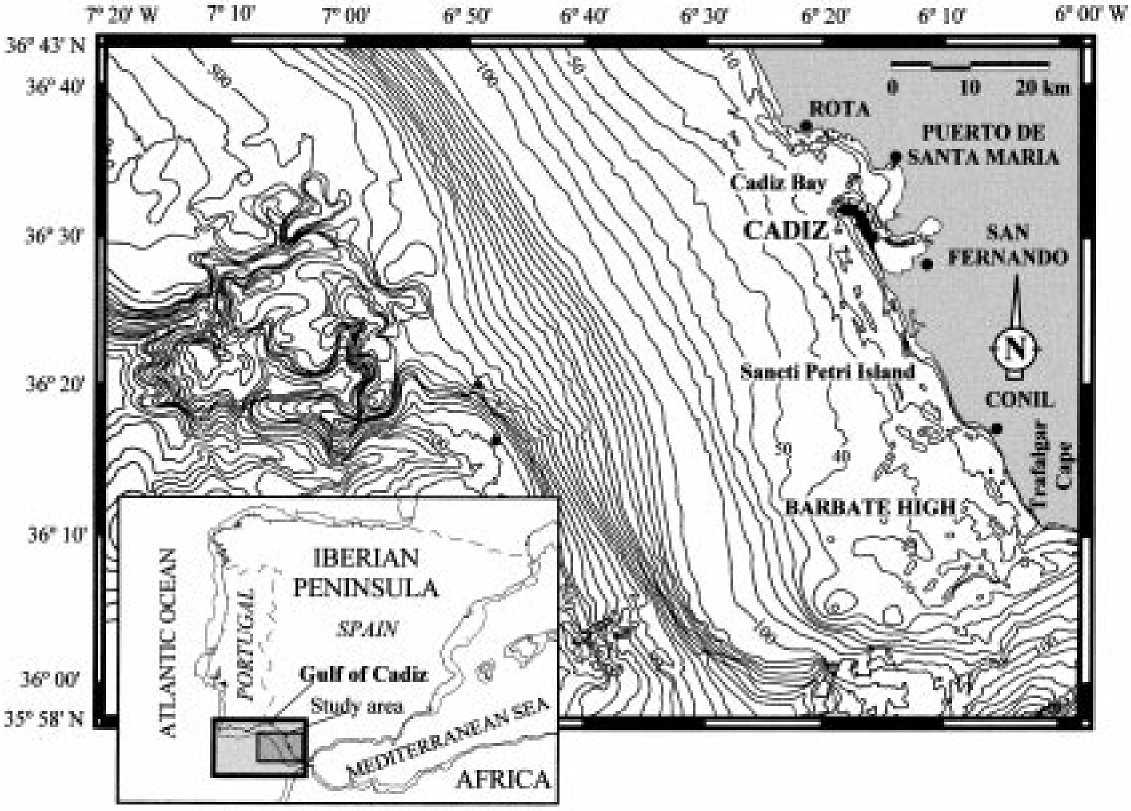


Fig. 1. General bathymetry of the study area (continental shelf and slope) and geographic location of the Gulf of Cadiz. Bathymetric contours are given in meters. A significant feature in the continental shelf is the Barbate High, which is a shallow smooth zone evidenced by the trend of the isobaths. The continental slope is incised by several submarine valleys.

Hernández-Molina et al., 2000). The Holocene is characterised by the progradation of inner-shelf deltas induced by Atlantic inflow and the development of MOW-controlled deep-water sediment drifts (Maldonado and Nelson, 1999).

The physiographic profile of the Gulf of Cadiz continental margin is characterised by a continental shelf 30–40 km wide, with the shelf-break located at a water depth of approximately 120 m, and a gentle continental slope with a low angle gradient (<1.5°), in contrast to the steep profiles of the Iberian and North African Atlantic continental margins (Heezen and Johnson, 1969). Our study area is located in a sector of the continental margin between the towns of Chipiona and Zahara de los Atunes, where the total length of the continental shelf is 100 km (Fig. 1). The continental shelf in this study area is about 30 km wide, and the shelf-break is located at a water depth of 120 m, except for south of Cape Trafalgar, where the shelf is 15 km wide and the shelf-break is located at a depth of 100 m. Sea-floor gradients on the continental shelf range between 0.2 and 0.4°, except in the inner shelf (<60 m) located between the town of Conil and Cape Trafalgar, where it drops to 0.1° in relation to the presence of a shallow, flat platform (Fig. 1). This bathymetric feature, known as the Barbate High, is bounded seaward by a submarine scarp of structural or perhaps sedimentary origin, depending on the zone (Lobo, 1995).

This sector of the Gulf of Cadiz continental shelf receives the fluvial inputs of the Guadalquivir, Guadalete and Barbate Rivers; the Guadalquivir is especially important to the shelf's sedimentation processes, because it has generated a southeastward

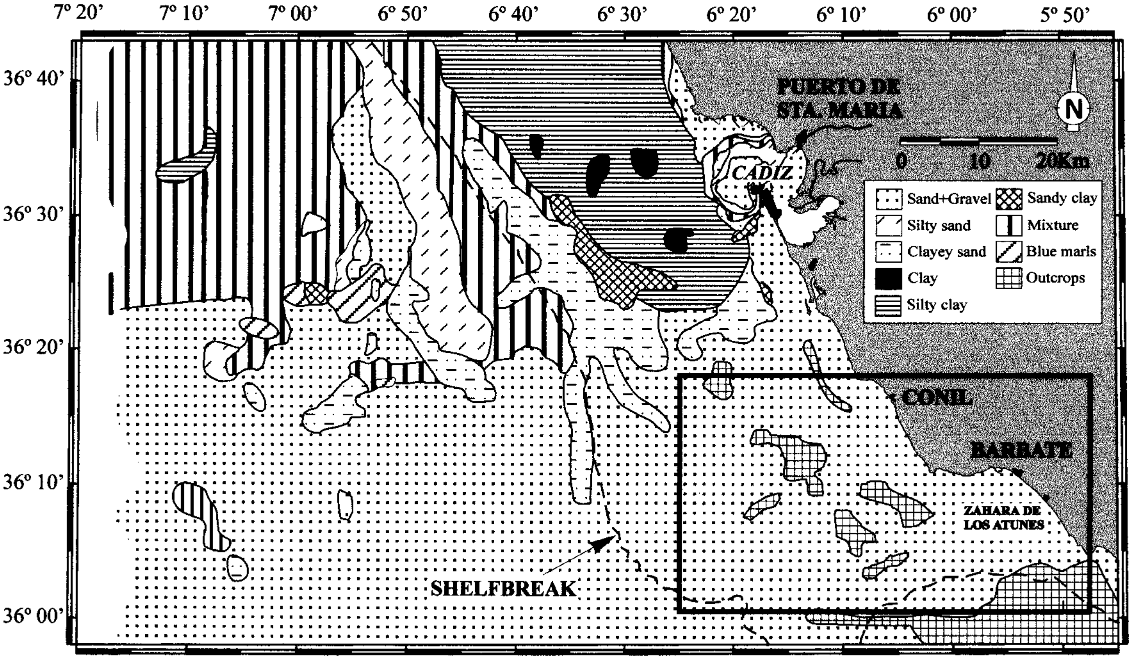


Fig. 2. Textural distribution of surficial sediments in the study area. Taken from López-Galindo et al. (1999). A more detailed investigation of the surficial sediments has been made in the meridional sector of the study area, as it is indicated by the black rectangle.

prograding prodeltaic body (Lobo, 1995; Rodero, 1999). From the characterisation of the type of surficial sediments and their regional distribution (López-Galindo et al., 1999; Rodero, 1999), two morphosedimentary sectors have been differentiated (Fig. 2). The northern sector is characterised by the presence of a large prodeltaic body generated by the Guadalquivir River's terrigenous input. This sedimentary structure progrades southeastwards, by the action of the North Atlantic Surface Current and the littoral drift (Lobo, 1995; Gutiérrez-Mas et al., 1996; López-Galindo et al., 1999; Rodero, 1999). Texturally, the prodelta sediment is composed of mud, with a sand content <10%. The sediments are characterised by very negative skewness, which indicates the presence of coarse material mixed with the sand and silt fractions. The southern sector is characterised by the occurrence of rocky outcrops and a sandy sedimentary cover that is moulded into large bedforms. The sediments are very well sorted, with 90% included in the 500–2000 μm fraction. They are composed mainly of terrigenous particles with a high quartz content (up to 60%). Another major component is biogenic calcite (foram shells), which exceeds 50% in some samples. To the north, the Guadalquivir sediment supply is significant, whereas to the south, detrital coarse material and rocky outcrops offlapped by the prodelta structure are observed.

2.2. Oceanographic setting

In the Gulf of Cadiz Alboran Sea region, the main winds are the east wind, known as the *Levante*, and the west wind, or *Poniente*. The Levante is a very constant (blowing during seven consecutive days), strong wind (average velocity of 50 km/h). The Poniente is also strong, but squally, inconsistent, and with an average velocity of 30 km/h (Calendario Meteorológico, 1991; Ramos, 1961). The waves in the Gulf of Cadiz are about 0.5–3.5 m high under sea conditions (when the Poniente is dominant) and 1.5–4.4 m under swell conditions (when either the Levantes or Ponientes can dominate) (Morales, 1993). The Gulf of Cadiz coast is considered mesotidal, with a tidal range of around 3–4 m, which decreases its

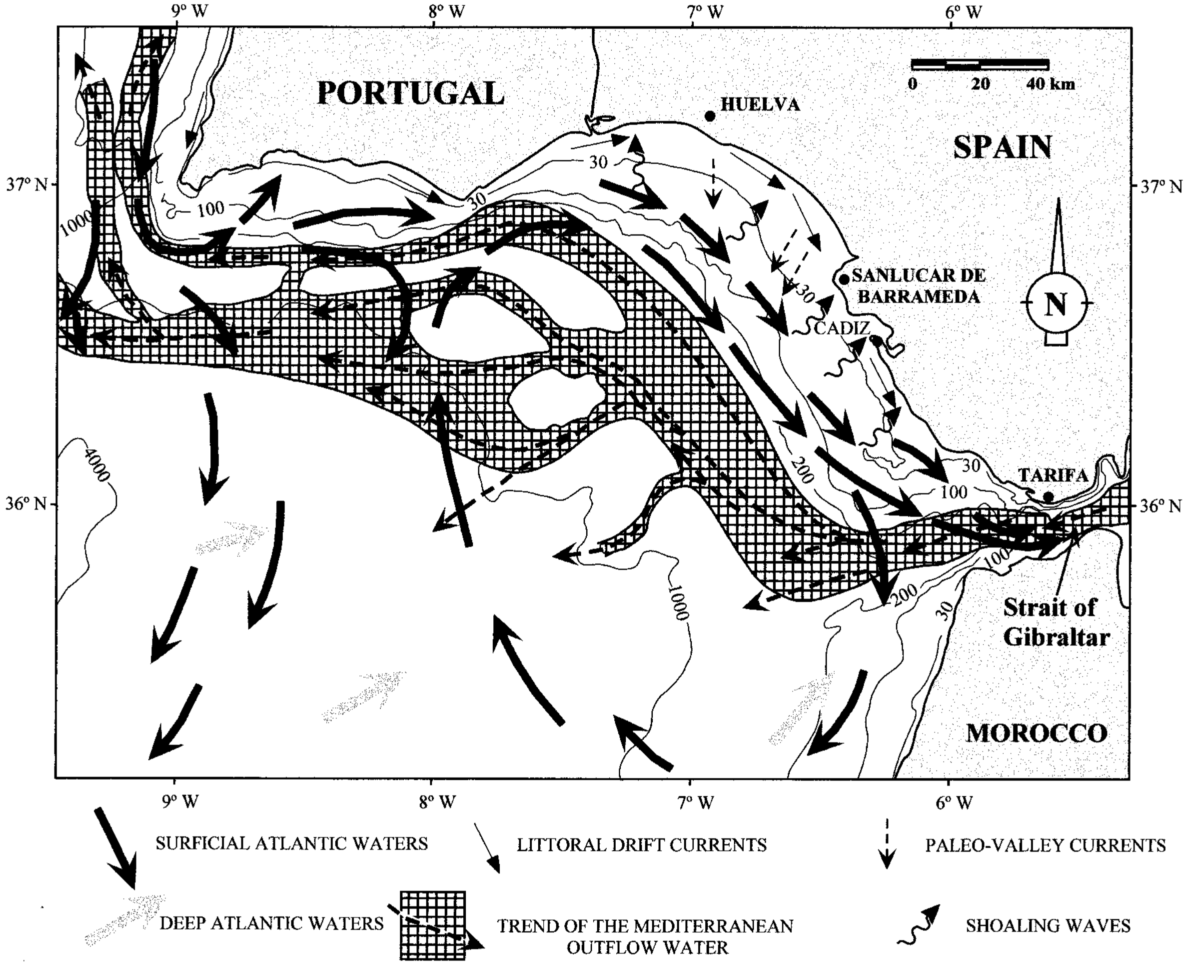


Fig. 3. General circulatory patterns of water masses in the Gulf of Cadiz. Modified from Hernandez-Molina (1993) and Nelson et al. (1999).

amplitude towards the Straits of Gibraltar (Ménanteau et al., 1983).

The Gulf of Cadiz margin's present-day circulatory patterns are controlled by the exchange of water masses in the Straits of Gibraltar, as a consequence of excess evaporation in the Mediterranean Sea, which creates an outflowing water mass (MOW) and an incoming Atlantic flow over the MOW in the Straits of Gibraltar. This process results in the existence of two counter-flows on the Gulf of Cadiz margin: the Atlantic inflow is moving southeastwards over the continental shelf, and the MOW is moving northwestwards over the continental slope (Madelain, 1970; Mélières, 1974; Zenk, 1975) (Fig. 3).

Over the continental shelf domain, Atlantic Surface Water (ASW) moves southeastwards between a water depth of 0 and 100 m, and is characterised by an isohaline of about 36.4‰ and a thermocline of 5°C/100 m. This water mass forms as a consequence of atmospheric phenomena in the Gulf of Cadiz (Gascard and Richez, 1985). North Atlantic Surface Water (NASW) moves from west to east at a water depth of 100–600 m, a temperature between 12 and 16°C and a salinity ranging from 35.7 to 36.25‰ (Caralp, 1988, 1992). These water masses of Atlantic origin move southeastwards over the Gulf of Cadiz continental shelf, and enter the Alboran Sea by the Straits of Gibraltar over the Mediterranean outflow,

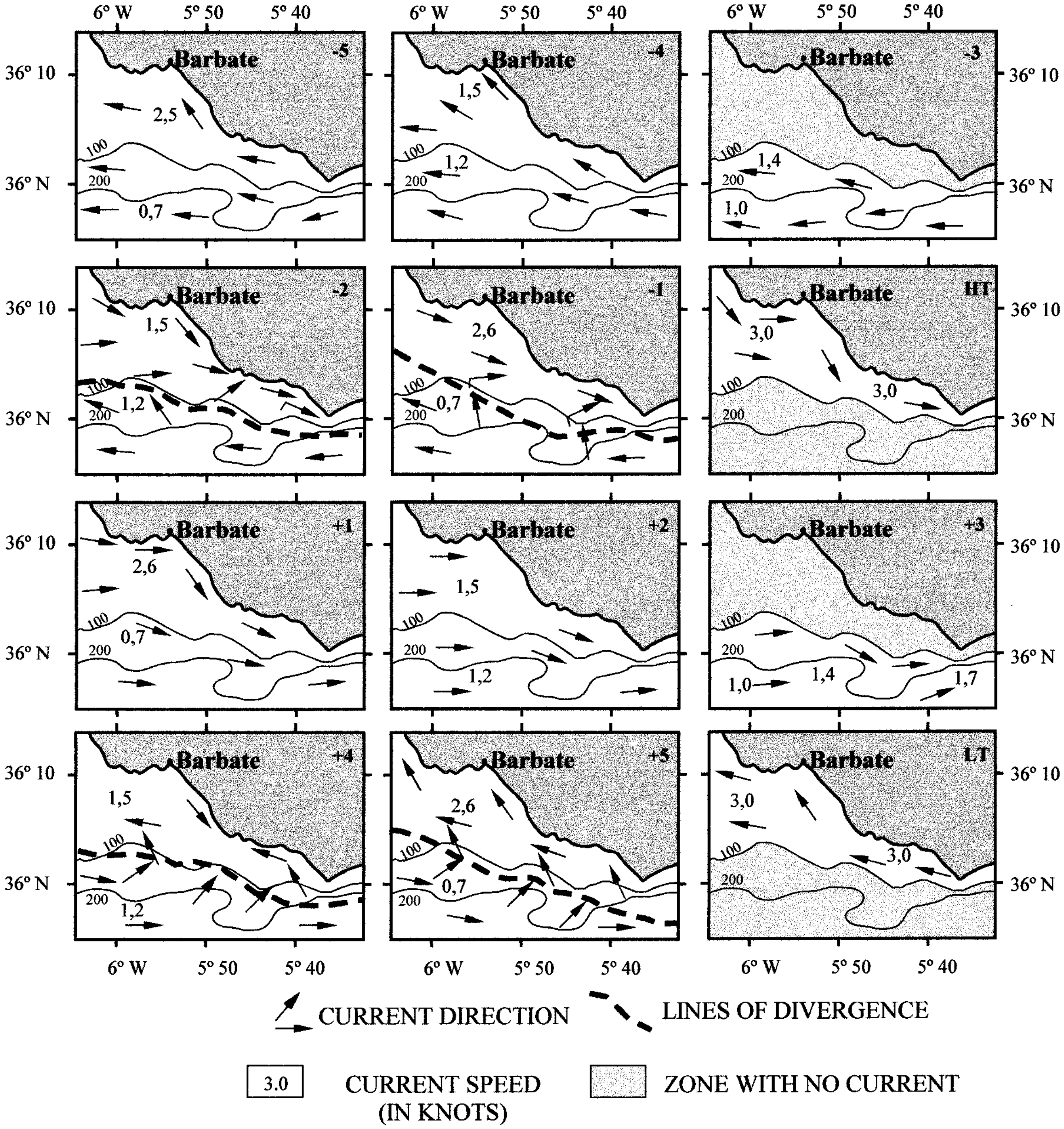
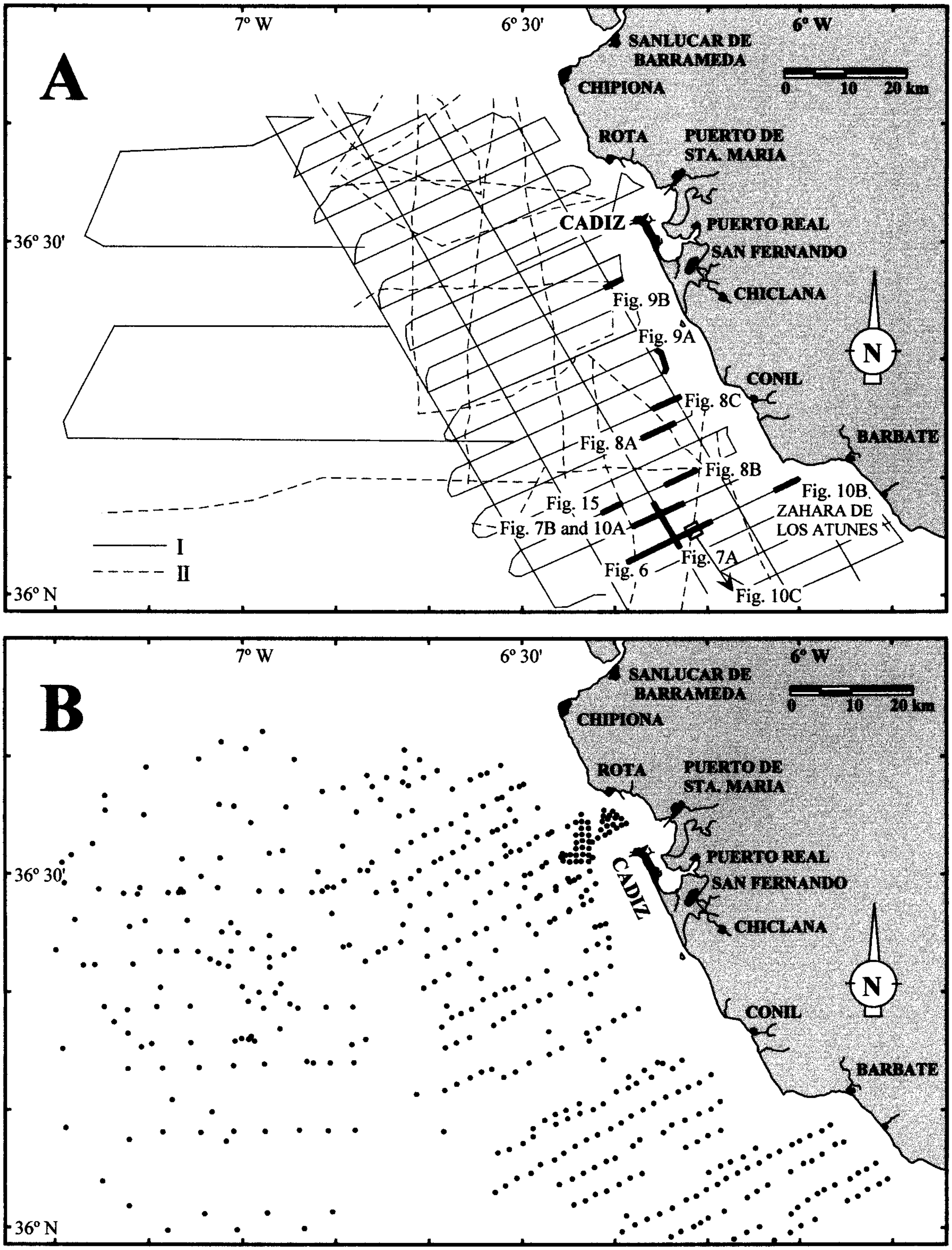


Fig. 4. Current orientation on the continental shelf next to the Strait of Gibraltar. The picture represents the evolution of current paths during a tidal cycle, beginning 5 h before (−5) the high tide (HT) up to the low tide (LT). The number located at the upper right corner of each map indicates the time in relation to the high tide in the Strait of Gibraltar. Taken from Ménanteau et al. (1983).

Fig. 5. Location of the data set studied in this work. (A) Track of seismic lines. Two geophysical surveys were considered—(I) GC-86-1 (solid lines) and (II) G-86-1 (dashed lines). The location of seismic and side scan sonar examples reported in this paper (Figs. 6–10) is also highlighted. (B) Location of surficial sediment samples in the study area.


A
7° W
6° 30'
6° W
36° 30'
36° N
SANLUCAR DE BARRAMEDA
CHIPIONA
ROTA
PUERTO DE STA. MARIA
CADIZ
PUERTO REAL
SAN FERNANDO
CHICLANA
CONIL
BARBATE
ZAHARA DE LOS ATUNES
0 10 20 km
N
Fig. 9B
Fig. 9A
Fig. 8C
Fig. 8A
Fig. 8B
Fig. 10B
Fig. 15
Fig. 7B and 10A
Fig. 6
Fig. 7A
Fig. 10C
I
II
B
7° W
6° 30'
6° W
36° 30'
36° N
SANLUCAR DE BARRAMEDA
CHIPIONA
ROTA
PUERTO DE STA. MARIA
CADIZ
PUERTO REAL
SAN FERNANDO
CHICLANA
CONIL
BARBATE
0 10 20 km
N

with a changing thickness and at velocities sometimes higher than 1 m/s (Lacombe and Richez, 1982; Parrilla and Kinder, 1987); therefore, they have been denominated the Atlantic inflow (Mélières, 1974; Ochoa and Bray, 1991). The Atlantic inflow moving towards the southeast in the Gulf of Cadiz (Martínez et al., 1998) controls the present-day sedimentary dynamics over the shelf environment, causing the migration of prodeltaic structures (Gutiérrez-Mas et al., 1996; López-Galindo et al., 1999). This inflow current is intensified near the Straits of Gibraltar due to bathymetric reduction, which causes a decrease in the section and a subsequent flow acceleration (Lobo, 1995; Nelson et al., 1999; Rodero, 1999).

In general, the circulatory patterns of the Atlantic inflow over the Gulf of Cadiz continental shelf are poorly understood, because most studies of physical oceanography in this area have focussed on characterising MOW over the slope domain. However, tidal currents change their orientation over the continental shelf from east–southeast to west–northwest (US Hydrographic Office, 1959; Ménanteau et al., 1983), so that the flow is towards the east–southeast from 2 h before to 2 h after high tide in the Straits of Gibraltar and towards the west–northwest from 4 h before to 4 h after high tide in the same location, with peak velocities reaching 3 knots in both directions (Fig. 4). The shelfal oceanographic regime of the Gulf of Cadiz is also characterised by shoaling waves and storm currents in the inner shelf environment and by seaward currents flowing along cross-shelf paleovalleys located on the continental shelf north of our study area (Mélières, 1974; Ochoa and Bray, 1991; Nelson et al., 1999) (Fig. 3).

Over the continental slope, MOW moves from east to northwest at water depths of 600–1500 m. Its main characteristics are: salinity higher than 36.5‰, temperature of about 13°C, and an oxygenation level of 4 ml/l (Madelain, 1970; Mélières, 1974; Ambar and Howe, 1979; Caralp, 1988; Ochoa and Bray, 1991). MOW is formed as a consequence of the mixing of several water masses in the Mediterranean Sea, and it moves as a unique hydrodynamic body over the Straits of Gibraltar at a water depth of 200 m below the ASW and preferably along the northern part of the Straits. After passing the Straits of Gibraltar, MOW turns northward to the Gulf of Cadiz, and forms a strong contour-current moving along Spain’s continental slope (Mélières, 1974; Gascard and Richez, 1985; Ochoa and Bray, 1991; Gutiérrez-Mas et al., 1996; Baringer and Price, 1999). MOW is subdivided into several branches affected by the complex submarine canyons and valleys (Madelain, 1970; Zenk, 1975; Nelson et al., 1993) (Fig. 3).

3. Methodology

Two types of information have been analysed: geophysical and sedimentological data. These data were obtained during two oceanographic cruises, GC-86-1 (1986) and G-86-1 (1991), onboard the oceanographic vessel *Garcia del Cid* (Fig. 5). The positioning systems were Maxiram and GPS Satellite. The geophysical data consist of high-resolution seismic reflection profiles (3.5 kHz, Geopulse and Airgun systems with variable scales of 1/2, 1 and 2 s) and acoustic records of Side Scan Sonar (SSS), with which a detailed physiographic and geomorphologic analysis has been performed. The high resolution of the 3.5 kHz seismic profiles enabled us to define the external characteristics of dunes (i.e. bedform characterisation). Once the bedforms had been identified in the seismic profiles and SSS records, large dunes’ geometrical properties—height above base level (H), wavelength (L), horizontal extension and inclination of stoss (a) and lee slopes (b)—were determined following the methodology outlined by Harris (1989). An average velocity of 1500 m/s was used to determine the bedform height. Finally, bedform crests were mapped, and their orientation and horizontal extension were calculated from SSS records. The sedimentological data included sediment samples obtained by dredge, gravity and piston cores. Grain-size analyses were performed using different methods. Sieving of the sand-gravel fraction (fraction $>63\ \mu m$) and a computerised laser inspection system (CIS-1, GALACI) were used for the silt and clay fraction (fraction $<63\ \mu m$). The composition of the sand fraction was determined by optical microscopy, counting 300–400 grains from each sample. This analysis enabled us to determine each sample’s granulometric distribution curve, following current sedimentological methods.

Table 1
General characterisation of large and small dunes: (A) terms used as equivalents of large and small dunes by different authors; (B) boundaries between large and small dunes used by different authors

	Large dunes (sandwaves)	Small dunes (megaripples)
(A) *Equivalent nomenclature*		
Langhorne (1973) and Allen (1980)		Dunes
Flemming (1978)	Sand dunes	
Field et al. (1981)	Large sandwaves	Small sandwaves
Flemming (1980), Cacchione et al. (1987) and Harris et al. (1992)	Dunes	Dunes
(B) *Boundaries*		
	Large dunes	Small dunes
McCave (1971)	$L > 30$ m, $H > 1.5$ m	$L < 30$ m, $H < 1.5$ m
Field et al. (1981)	$L = 20$ m, $H = 2$ m	$L = 20$ m, $H = 1$ m
Twichell (1983)	$50 < L < 1000$ m, $1 < H < 25$ m	$1 < L < 15$ m, $H < 1$ m
Perillo and Ludwick (1984)	$L > 12$ m, $H > 60$ m	60 cm $< L <$ 12 m, $6 < H < 60$ cm
Harris (1988a)	$L > 100$ m, $H > 2$ m	$0.6 < L < 40$ m, 10 cm $< H <$ 2 m
Berné et al. (1993)	$L > 20$ m, $H > 80$ cm	$L < 20$ m, $H < 80$ cm

4. Bedform characterisation and distribution

For the present study, we made a distinction between large dunes and small dunes (Ashley, 1990), because there are two main scales of bedforms in the study area. The large-scale bedforms are apparent from seismic records and are characterised by $H > 1$ m, whereas the small ones can only be seen in SSS records. Those terms are equivalent to sandwaves and megaripples, respectively (Table 1).

4.1. Large dunes

Large dunes ($H > 1$) occur as extensive fields, unrelated to any sandbanks. Three zones have been differentiated according to the migration pattern, which can be inferred from asymmetry (Figs. 6–11). The characteristic parameters of dune dimension in each zone are described in Table 2.

Zone A is situated south of the Barbate High, located in water depths of between 15 and 30 m (Figs. 6, 7 and 11). Large dunes are asymmetrically oriented towards the west and west–northwest. Mean orientations of longitudinal axes are N 18° E, N–S and N 100° E, and the angle to the coastline ranges between 30 and 55°. Large dunes here reach the greatest dimensions found in the study area (average length, 275 m; average maximum height, 3.75 m).

Table 2
Large dune significant parameters in every zone (A–C). All values are given in meters. Legend: *d*, water depth; *L*, wavelength; *W*, horizontal extention; *H*, height; SLDH, significant large dune height; *a*/*b*, symmetry index; *S*, separation between two consecutive bedforms; *T*, thickness; MLS, maximum lee slope; MSS, maximum stoss slope

	Zone A	Zone B	Zone C
Minimum *d*	15	15	10
Maximum *d*	30	30	25
Number	44	23	18
Minimum *L*	100	50	50
Maximum *L*	850	400	350
Average *L*	275	190	145
Minimum *W*	600	800	500
Maximum *W*	4200	3400	2000
Average *W*	1600	1760	1080
Minimum *H*	1	1	1
Maximum *H*	11	6	5
Average maximum *H*	3.75	2	1.9
SLDH	6	4	4
Minimum *L*/*H*	15	25	33
Maximum *L*/*H*	133	175	175
Average *L*/*H*	58	86	80
Minimum *a*/*b*	1	1	1
Maximum *a*/*b*	5.6	7.5	6
Minimum *S*	200	300	200
Maximum *S*	1300	2000	1200
Minimum *T*	1	1	1
Maximum *T*	13	9	6
Average *T*	4.7	2.8	2.5
MLS	9	4.5	7
MSS	3	2	2

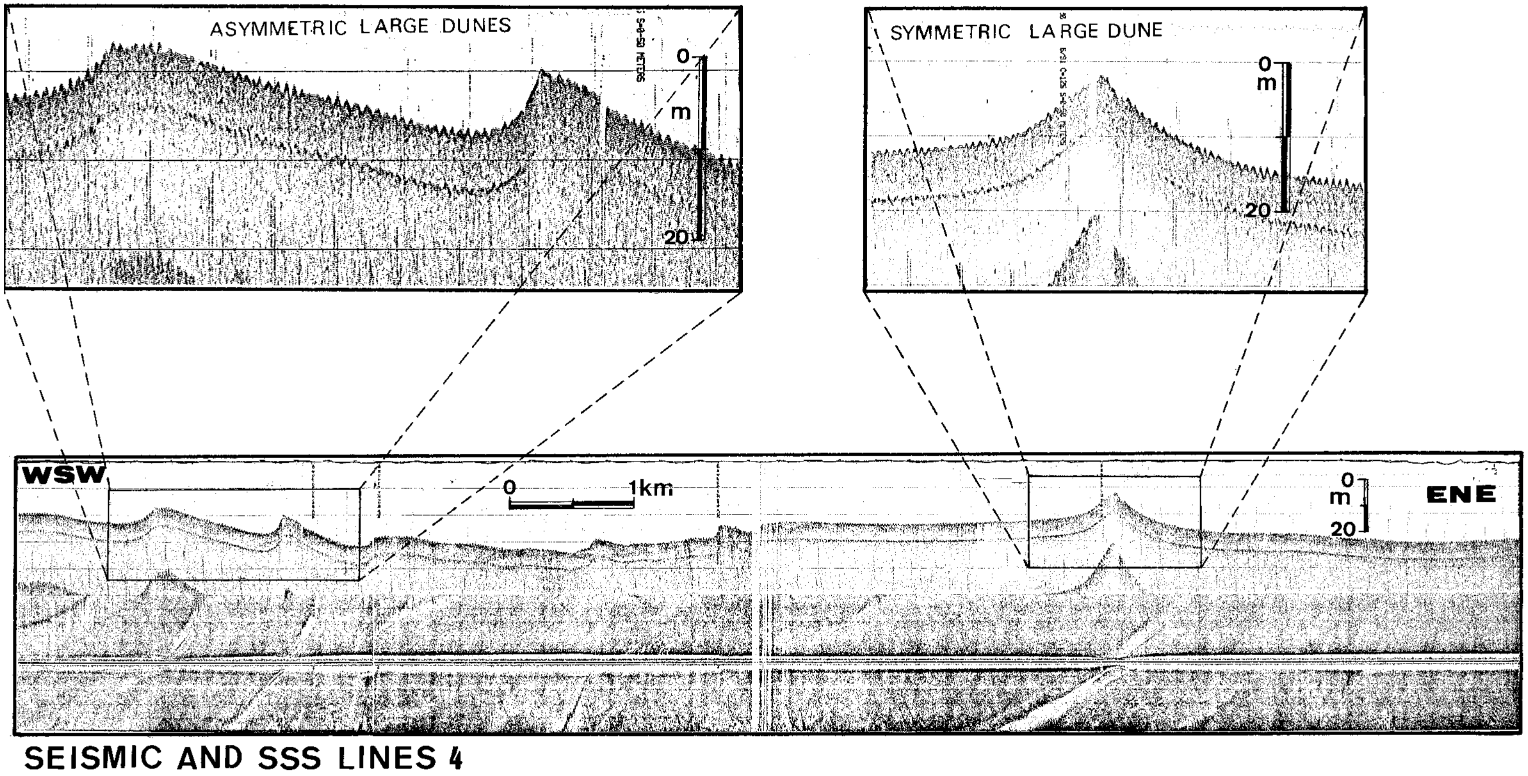
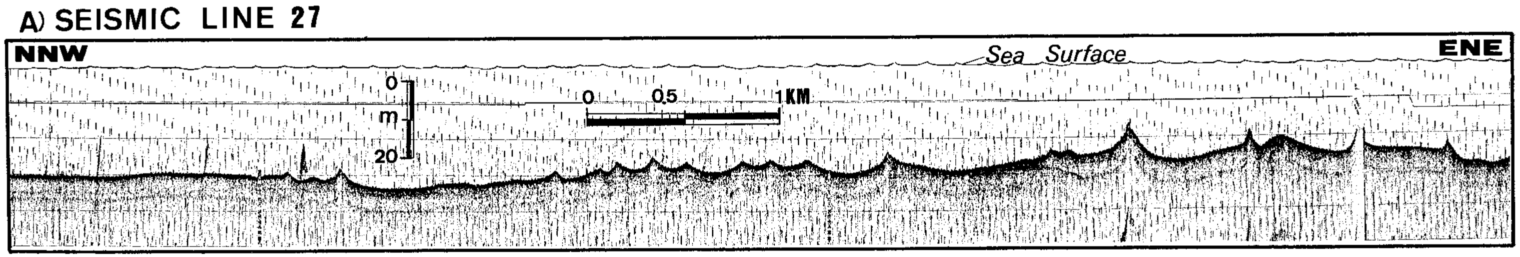


Fig. 6. Example of a 3.5 kHz seismic profile and side scan sonar record taken across the Barbate High. Symmetric and asymmetric large dunes are identified. The position of the seismic and side scan sonar section is indicated in Fig. 5.


A) SEISMIC LINE 27

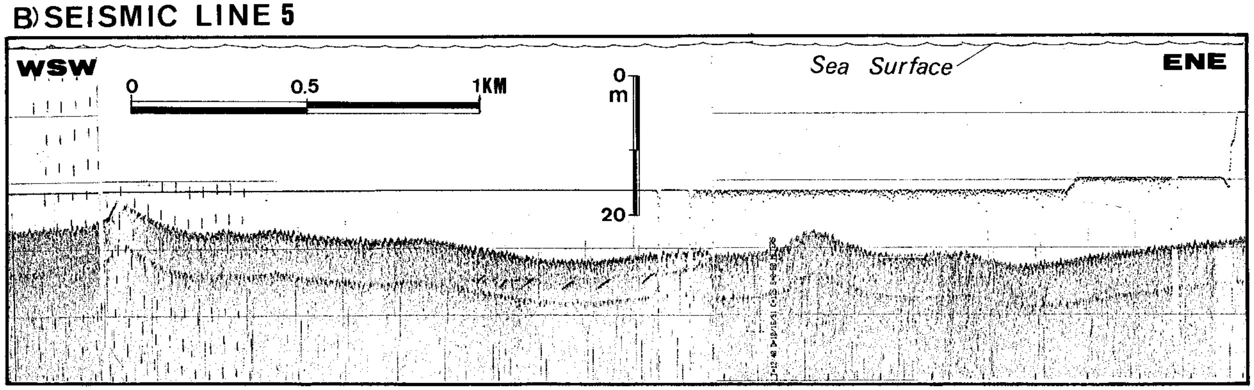

B) SEISMIC LINE 5

Fig. 7. Examples of large dunes that occur in zone A, viewed by 3.5 kHz seismic profiles. The position of the seismic profiles is indicated in Fig. 5.

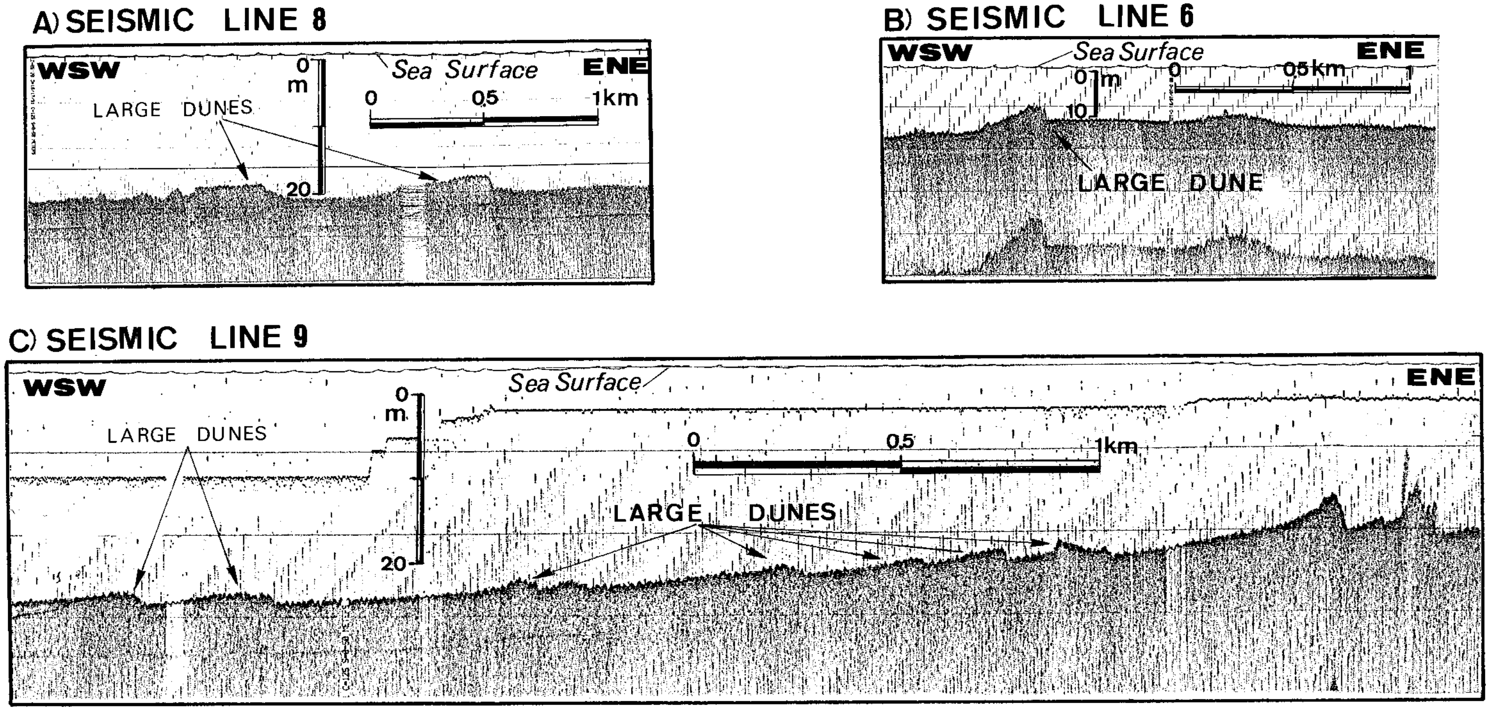


Fig. 8. Examples of large dunes that occur in zone B, viewed by 3.5 kHz seismic profiles. The position of the seismic profiles is indicated in Fig. 5.

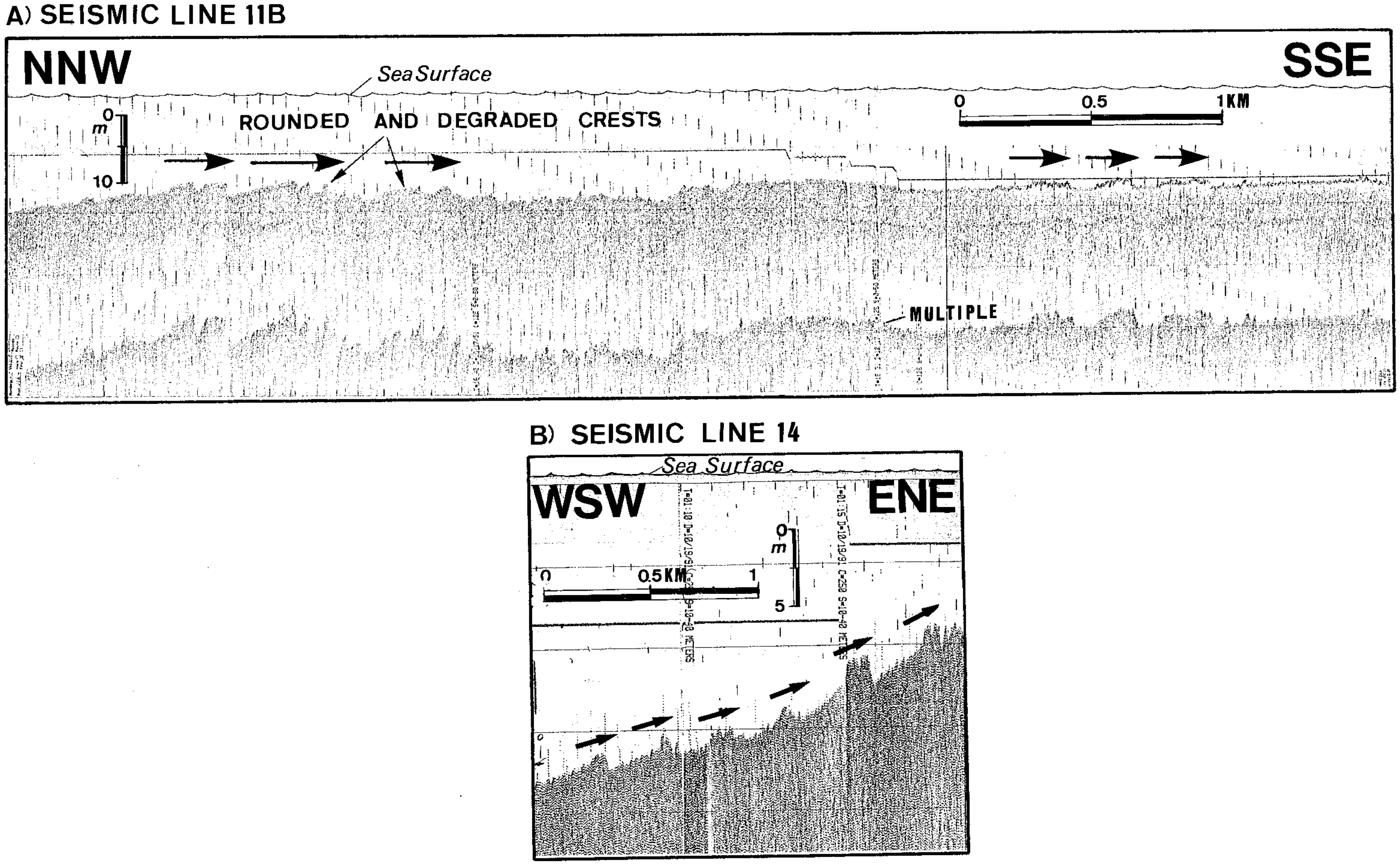


Fig. 9. Examples of large dunes that occur in zone C, viewed by 3.5 kHz seismic profiles. Arrows indicate the direction of asymmetry. The position of the seismic profiles is indicated in Fig. 5.

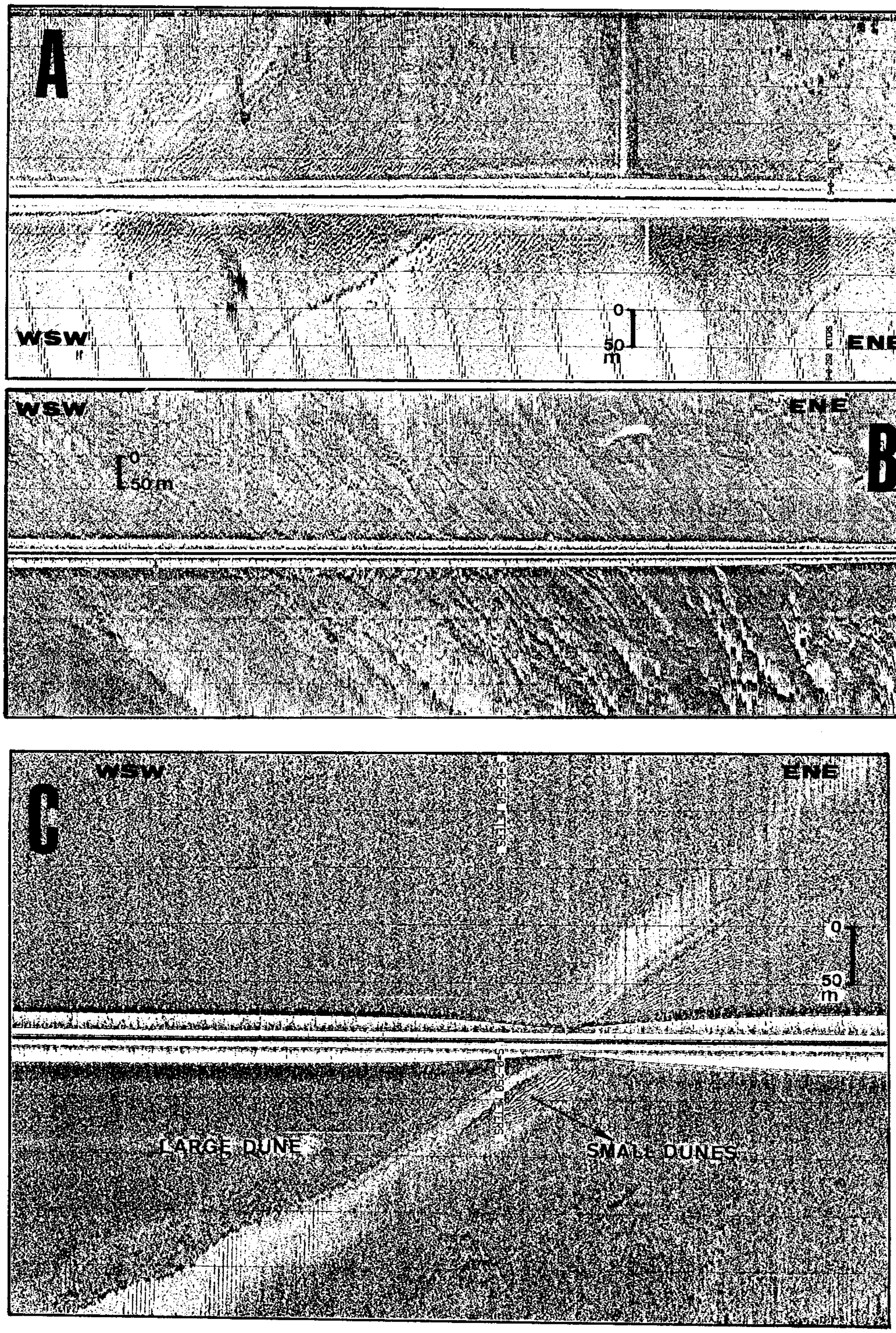


Fig. 10. Examples of small dunes identified in the study area, viewed by side scan sonar records. Small dunes superimposed upon large dunes are distinguished (10C). The position of SSS sections is also indicated in Fig. 5.

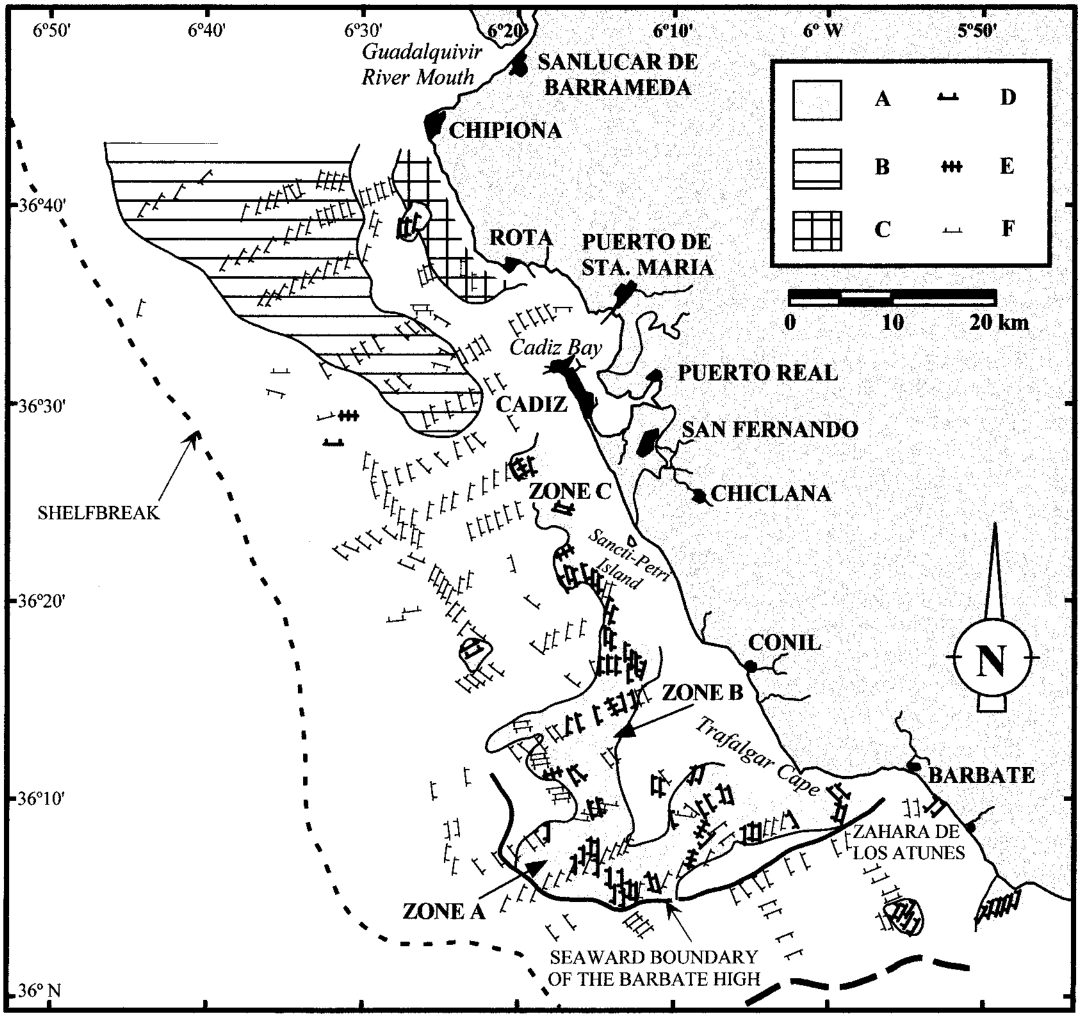


Fig. 11. Distribution map of large and small dunes on the continental shelf of the study area. Legend: (A) zones where large dune fields have been identified; (B) prodeltaic feature related to the Guadalquivir River; (C) acoustic basement outcrops; (D) longitudinal axis and lee slope orientation of asymmetric large dunes; (E) longitudinal axis of symmetric large dunes; (F) longitudinal axis and lee slope orientation of small dunes.

Maximum heights in this zone, excluding large symmetrical dunes, reach 8 m, very close to the maximum height of 7.4 m proposed by McCave (1971) as an equilibrium height in similar depths. Large symmetrical dunes were identified in the transitional area between zones A and B, and they register the maximum heights in the study area south of Cape Trafalgar, usually 8–10 m.

Zone B is located north of the Barbate High, in water depths of 15–30 m. Large dunes are asymmetrically oriented towards the east (between east–northeast and east–southeast). Mean orientations of crests are N–S, N 170° E and N 150° E, forming an angle in relation to the coastline ranging between 0 and 35° (Figs. 8 and 11).

Zone C is on the infralittoral-inner shelf between Conil and Cadiz Bay, in water depths of 10–25 m. Large dunes are asymmetrically oriented towards the east. Mean crest orientations are N 10° E, N 150° E and N 100° E, and the angle to the coastline ranges from 0 to 35°. In this zone, rounded and eroded crests are quite frequent. Large dunes here have the

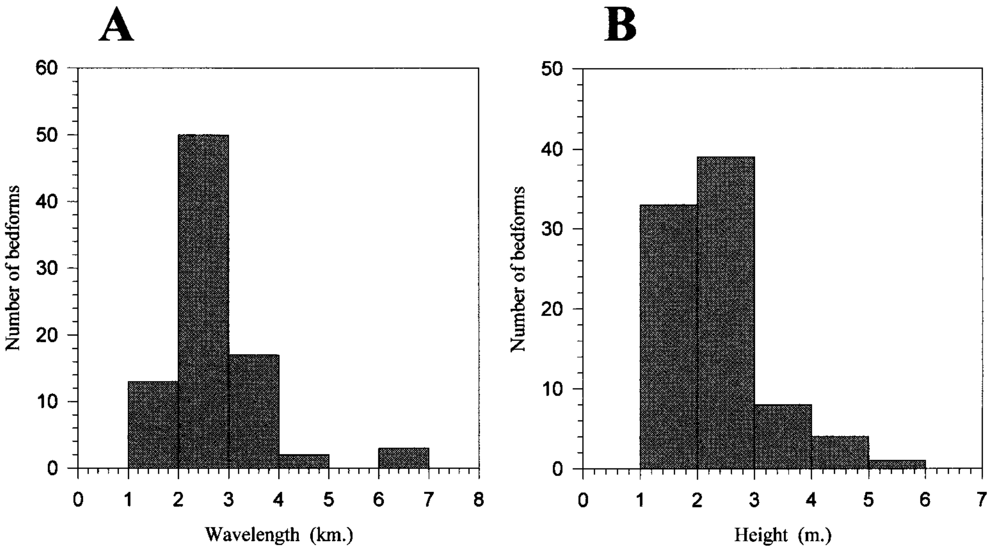


Fig. 12. Descriptive histograms of asymmetric large dunes in the study area. Legend: (A) histogram showing the distribution of wavelengths of asymmetric large dunes; (B) histogram showing the distribution of heights of asymmetric large dunes.

lowest dimensions in the study area (average length, 145 m; average maximum height, 1.9 m) (Figs. 9 and 11).

Most of the large dunes show asymmetrical cross-sections, with <10° lee slopes and <3° stoss slopes. Most subtidal large dunes have typical lee slopes smaller than 10° (Taylor and Dyer, 1977), with stoss slopes approximately half this value (Langhorne, 1973), although occasionally they may reach 30° (Berné et al., 1993). They have straight or slightly sinuous crests, being considered mainly as 2D bedforms (Ashley, 1990). The length of the large dunes' crests ranges from 500 to 4200 m. Most of them have *L* ranging between 100 and 200 m (Fig. 12A), but they display a high lateral variability in size, and most heights are smaller than 4 m (Fig. 12B). There is a good correlation between *L* and *H* (Fig. 13A), considering that this relationship is probably controlled by a mechanism common to all flow systems (Flemming, 1978), and it seems to be linear in log–log plots (Ikehara and Kinoshita, 1994). The relation $H = 0.0677L^{0.8098}$ (Flemming, 1988) acts as an upper limit of the stability field, as has been reported by several authors (Brew, 1996; Ramsay et al., 1996). Most of the large dunes on the Gulf of Cadiz shelf plot below this boundary, partially due to the fact that some of the height values do not correspond to maximum heights; except for symmetrical large dunes located in the transition between zones A and B (because they are controlled by different hydrodynamic conditions than the asymmetric ones), and for a few asymmetrical large dunes from zone A, which seem to be in non-equilibrium with the present-day oceanographic regime, probably because they are relict features.

The vertical form or steepness index *L*/*H* is variable, ranging from 15 to 175, although most of the large dunes have *L*/*H* ratios greater than 35, which characterise 2D large dunes (Terwindt and Brouwer, 1986). The minimum value agrees with that of Berné et al. (1989), who proposed that the relationship between *L* and *H* frequently varies, with ratios of 15–50. In general, the smaller bedforms have smaller vertical form indices, although there is a great deal of scattering (Fig. 13B), and so they tend to be steeper. Wavelengths increase faster than heights, so that small dunes tend to be steeper than large ones (Dalrymple, 1984).

The relationship *L*/*d* (water depth) generally falls into the range proposed by Allen (1982), $2.5 < L/d < 20$, except for very large dunes (*L* up to 900 m), some of which are symmetrical, and for other large dunes in zone C at water depths of less than 10 m, where all of them exceed the upper boundary. However, there is no

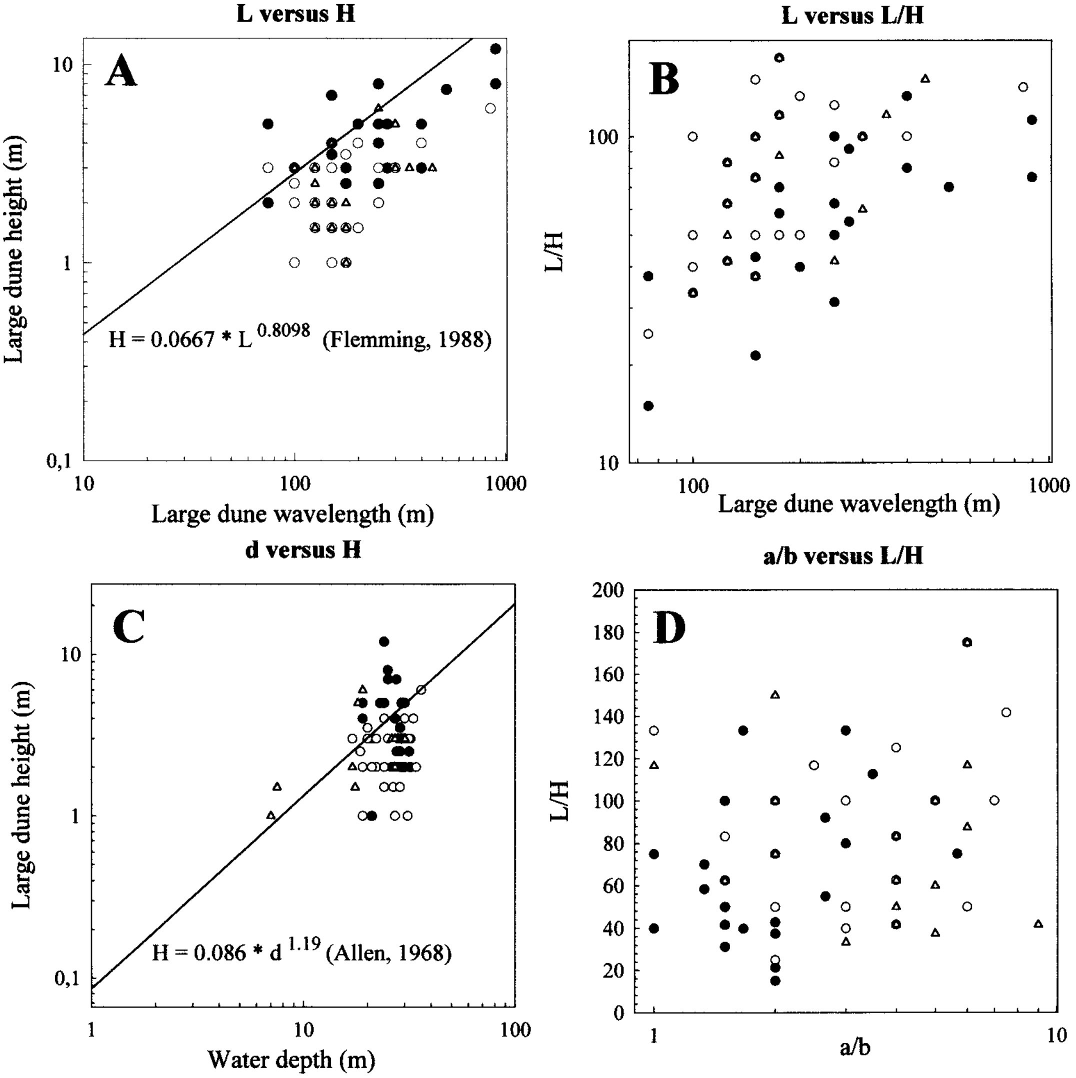


Fig. 13. Characterisation of the large dunes in every zone (A–C) by the use of morphological parameters. Legend: (A) plot of large dune wavelength against large dune height; (B) plot of large dune wavelength against the relationship between large dune wavelength and large dune height; (C) plot of water depth against large dune height; (D) plot of symmetry index (*a*/*b*) against vertical form index (*L*/*H*). Black circles represent large dunes of zone A, white circles represent large dunes of zone B, and triangles represent large dunes of zone C.

correlation between *H* and *d* (Fig. 13C), contradicting the predictions of several authors (Allen 1968; Smith, 1969; Rubin and McCulloch, 1980; Vianna et al., 1991; Brew, 1996), because other parameters, e.g. sediment size and current velocity, may vary simultaneously (Berné et al., 1993). Therefore, it seems simpler to relate bedform height to flow intensity, as in other settings on the Atlantic shelf (Swift et al., 1979). Bedforms are distributed at water depths of 15–35 m, except for those appearing in shallow water in zone C (Fig. 11). Notwithstanding, the lowest heights are found in the shallowest areas. The symmetry index (*a*/*b*; *a*, and *b* being the horizontal extensions of stoss and lee slopes, respectively) ranges between 1 (symmetric forms) and 7.5. We did not find a good correlation between *a*/*b* and the vertical form index

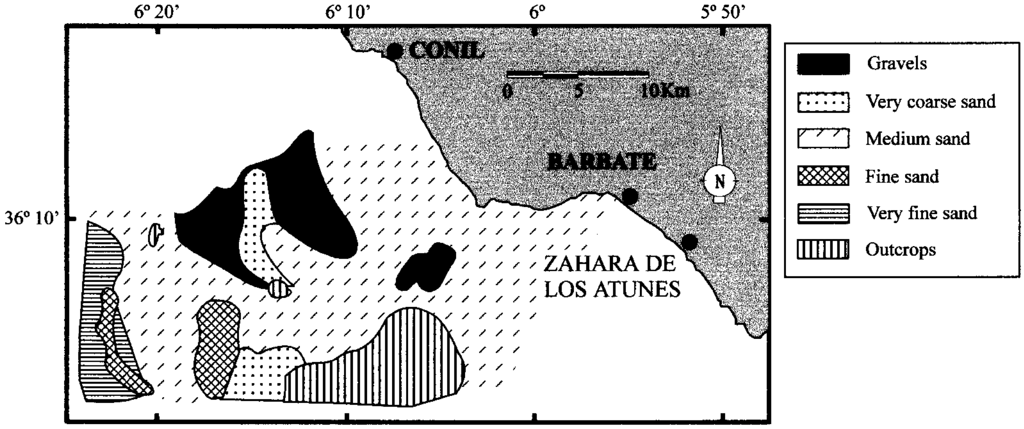


Fig. 14. Sedimentological characterisation of sea-bottom sediments over the Barbate High.

L/H (Fig. 13D), although some authors have reported a relationship between these ratios (Berné et al., 1993).

4.2. Small dunes

Bedforms with $H < 1$ m fall into this category (Table 1), and they can only be observed on SSS records, by means of the differential reflectivity character (Fig. 10). In the study area, they usually appear in flat areas between isolated large dunes, although they also appear superimposed onto stoss slopes. In zone A they show an orientation pattern opposite to large dunes, towards the east and southeast. In zone B they maintain this pattern, oriented mainly towards the east. They are very scarce in zone C, and then appear on the muddy continental shelf north of Barbate High, where they are also oriented preferentially towards the east. The distribution pattern of small dunes in the study area is shown in Fig. 11.

5. Sedimentary facies

The largest number of bedforms is located in the southern sector of the study area, where a detailed investigation was conducted to determine the type of sediment composing the seafloor features. The surficial sediments on the Barbate High are dominated by medium sands, although occasionally other sediment types are found. Over zone A, fine and very fine sand are quite common, and locally very coarse sands. Over zone B and west of Cape Trafalgar, gravels show a widespread distribution, with very coarse sands locally. Finally, there are small outcrops in the transitional area between zones A and B (Fig. 14).

There is a direct relationship between grain size and large dune morphology. A gradation of sedimentary facies can be seen, and five areas have been defined (Fig. 15). *Area 1:* the sea bottom deposits show a texture of microbreccia characterised by a high proportion of broken fragments (<1 cm) of bioclasts and the presence of rounded quartzite clasts. The surface layer is composed of very coarse sand, grading to coarse and fine sand towards the bedform crest. The main grain size range is 1.7–2 mm, and it can reach up to 95.1% of the >2000 μm fraction. *Area 2:* a transitional zone, with variable width, between Areas 1 and 3. The sediment is composed of fine sand (0.17 mm average grain size), which becomes coarser towards the crest. *Area 3:* includes the bedform crest. The sediments are composed of well-sorted medium sands (0.3 mm average grain size). On the leeward side the sediments become finer. *Area 4:* the distal part of the lee slope, where surficial sediments are composed of fine sands (0.12 mm average grain size) and poorly sorted clays. *Area 5:* the seafloor adjacent to the bedform, where the sediment is composed of very fine sands (0.088 mm average grain size). The fine sediments in this area can reach up to 10%, more than in any other.

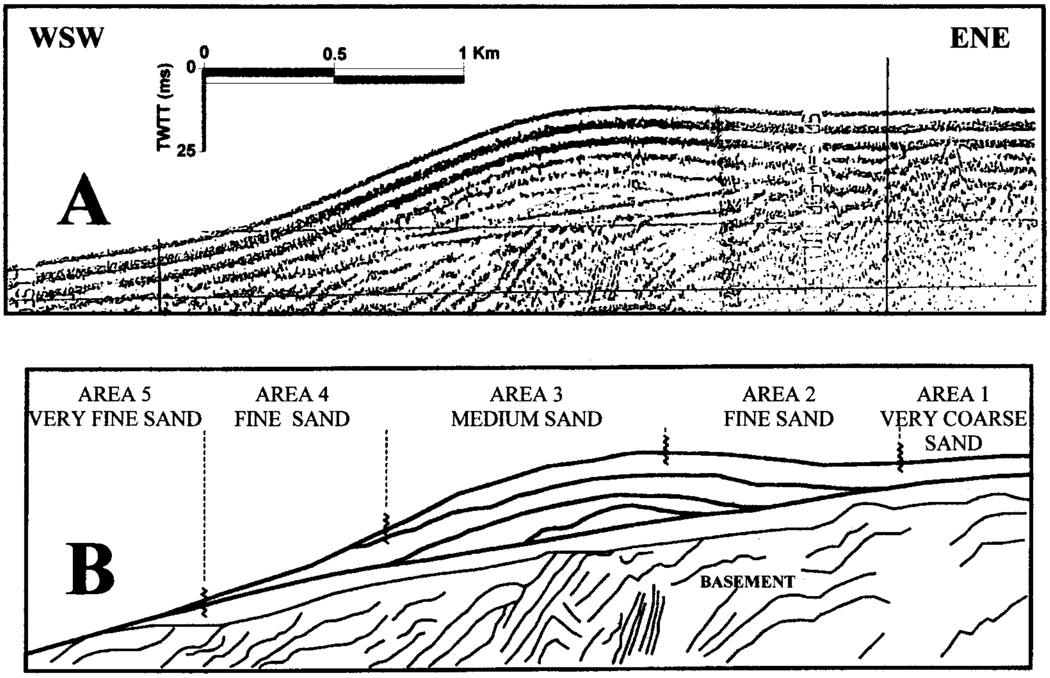


Fig. 15. Airgun seismic profile of a large-scale bedform (A) and interpretation (B), showing the distribution of surficial sediments across a dune. The position of the seismic section is indicated in Fig. 5.

6. Discussion

6.1. Controlling factors

Flow characteristics (current velocity and direction and flow depth) and duration of bedload transporting flows are the main factors controlling the geometry and scale of bedforms (Dingle, 1965; Rubin and McCulloch, 1980; Adams et al., 1986; Green, 1986), provided that water depth is deep enough (Aliotta and Perillo, 1987). The significance and origin of this controlling factor will be discussed in a following section. Other controlling factors are water depth, sediment grain size and sand thickness, whose relative importance is less.

In our study area, large dunes are restricted to the Barbate High, where water depth is less than 30 m. In deeper water, currents do not exceed a minimum velocity threshold to generate bedforms, except when sporadic flow events occur. The development of large dunes may be due to acceleration of the regional flow field when it passes across the Barbate High. On the High's northern side, water depth falls from 50–60 to 30 m, and on the southern side, the depth shoals from 100–80 to 30 m (Lobo, 1995).

Sediment grain size is another factor that controls bedform development (Allen, 1968; Aliotta and Perillo, 1987). Large dunes disappear with increasing mud content (Berné et al., 1993), and the boundaries of stable fields of large dunes have been defined by grain size changes (Bokuniewicz et al., 1977). Large dunes occur preferentially in the southern morphosedimentary sector, which is characterised by a sandy sedimentary cover. The boundaries of the fields of large dunes over the Barbate High are defined by grain size changes to the west, and by the appearance of rocky outcrops to the south. The gradation of facies that can be seen over the bedforms is related to flow interaction with the stoss side (coarse material), whereas the fine fraction is winnowed and deposited on the lee side. This is a common facies association, observed in other fields of large dunes (Aliotta and Perillo, 1987). The development of bedform fields has also been linked to the existence of a minimum value of sand thickness (Allen, 1968;

Aliotta and Perillo, 1987). The origin of the sand sheet could be associated with the presence of a transgressive lag in the Barbate High, which is related to the reworking of sediments deposited during the post-glacial Flandrian transgression (Gutiérrez-Mas et al., 1996).

6.2. Implications for bedform age

The fields of large dunes from the Late Pleistocene–Holocene identified in the study area can be regarded as relict features, generated by the action of littoral processes during the Flandrian transgression, or as modern features, created by the interaction of currents with the seafloor due to a decrease in accommodation space (Stubblefield et al., 1984; Swift et al., 1984; Correggiari et al., 1996). The second alternative seems to be the most probable, considering that the large dunes' orientation is not parallel to the coastline, and not even to the bathymetric contours. The development of large dunes is very common on continental shelves, and in the study area this process is related to the expansion of the water mass exchange across the Straits of Gibraltar during the present highstand period (Caralp, 1988, 1992; Vernaud-Grazzini et al., 1989; Nelson et al., 1993, 1999).

The ratio between L and d (water depth) tends to range between 2.5 and 20 (Allen, 1982). A discrepancy between those parameters could indicate that bedforms are not in equilibrium with present-day oceanographic conditions (Adams et al., 1986). The bulk of the large dunes identified on the study area's shelf domain have L/d ratios ranging between those values, suggesting that they are in equilibrium with the shelf's present-day hydraulic regime. There are large dunes in zone C that also have higher values, but in this case extreme deformation by wave action is a more probable explanation (Fig. 9). Large dunes have been developed over the sand sheet created during the last transgression, in a zone that presently receives a low fluvial input (Gutiérrez-Mas et al., 1996; López-Galindo et al., 1999). Therefore, it seems reasonable to believe that bedforms are modern features, generated by the interaction of present-day hydraulic processes with the seafloor. Finally, the presence of superimposed bedforms over the large dunes is another indicator of the bedforms' recent generation and development (Park and Lee, 1994), because it shows that larger bedforms are active and migrating (Aliotta and Perillo, 1987).

6.3. Hydraulic patterns

Assuming that the bedforms were generated due to the interaction of the present-day oceanographic regime and the seafloor, it is possible to obtain information about bottom flow patterns over the shelf environment, in an area where the current-flow patterns are as yet poorly understood. Dune asymmetry indicates the net direction of sediment transport by a unidirectional current or by a reversing current with time–velocity asymmetry (Johnson et al., 1982), and the lee side indicates the direction of translation (Jones et al., 1965; Aliotta and Perillo, 1987; Harris, 1988a; Berné et al., 1993). This makes it possible to use bedform asymmetry as an indicator of net bedload transport paths (McCave and Langhorne, 1982; Harris and Collins, 1984), assuming that they are not relict features, but the product of the present oceanographic regime (Harris, 1988b). Generally, the magnitude of the values is proportional to flow intensity; therefore, larger dimensions can be related to major oceanic events and hence to stronger events (Flemming, 1978; Twichell, 1983). It is generally believed that large bedforms are relatively stable, maintain their external shape, and only suffer minor changes in morphology, because they are affected by major events that act over periods of several days–months (e.g. storm currents), whereas smaller bedforms are more dynamic (Harris and Collins, 1984; Ashley, 1990; Fenster et al., 1990; Houthuys et al., 1994).

According to the large dunes' distribution and inferred migration pattern (Fig. 11), it is possible to outline the general net bedload transport in the study area—considering that the large dunes are stable features, which only change in response to large-scale events or have a very slow migration rate (Fenster et al., 1990)—and correlate those transport paths with the currents regime over the continental shelf. A main west–northwest–east–southeast to west–east direction is indicated from large dunes' inferred migration patterns, especially over the Barbate High (Fig. 16). Over this shallow marine physiographic feature, two dunefields with different asymmetry patterns are differentiated: in the southern and western areas of the Barbate High (zone A), net

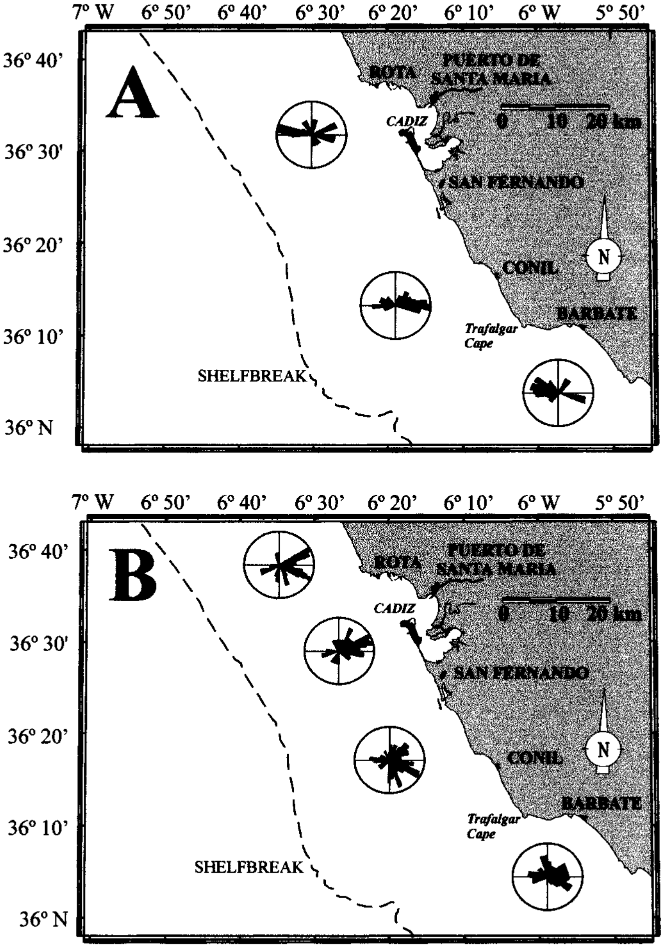


Fig. 16. Currents rose diagrams for large dunes (A) and small dunes (B), obtained from bedform asymmetry. Main current directions are W–E to WNW–ESE for large dunes in the study area. Current directions obtained from small dunes vary from WSW–ENE in the northern sector of the study area to WNW–ESE in the southern sector of the study area.

bedload transport is mainly orientated towards the west and the west–northwest, whereas in the northern and middle areas of the Barbate High (zone B), net bedload transport is mainly orientated towards the east; finally, on the inner shelf between the cities of Cadiz and Conil, net bedload transport acquires an eastern orientation (Fig. 17). The existence of a west–northwestward transport pattern over the continental shelf merits special consideration, because over this environment in the study area the hydrodynamics is dominated by Atlantic inflow, which moves southeastwardly. However, it must be considered that this asymmetry pattern is the result of peak current speeds, whereas less intense flows having different directions may also occur over the continental shelf, although they do not make their mark on bedform asymmetry. The existence of a high degree of bedform variability in a reduced area is indicative of an energetic, spatially variable flow regime (Adams et al., 1986). From all this, it follows that the current patterns over the Barbate High are substantially more complex than previously believed, and there seem to be different zones with different dominant current orientations. Considering the bedform size in our study area, and that large dunes can be used as indicators of long-term circulatory patterns, an intense flow towards the west

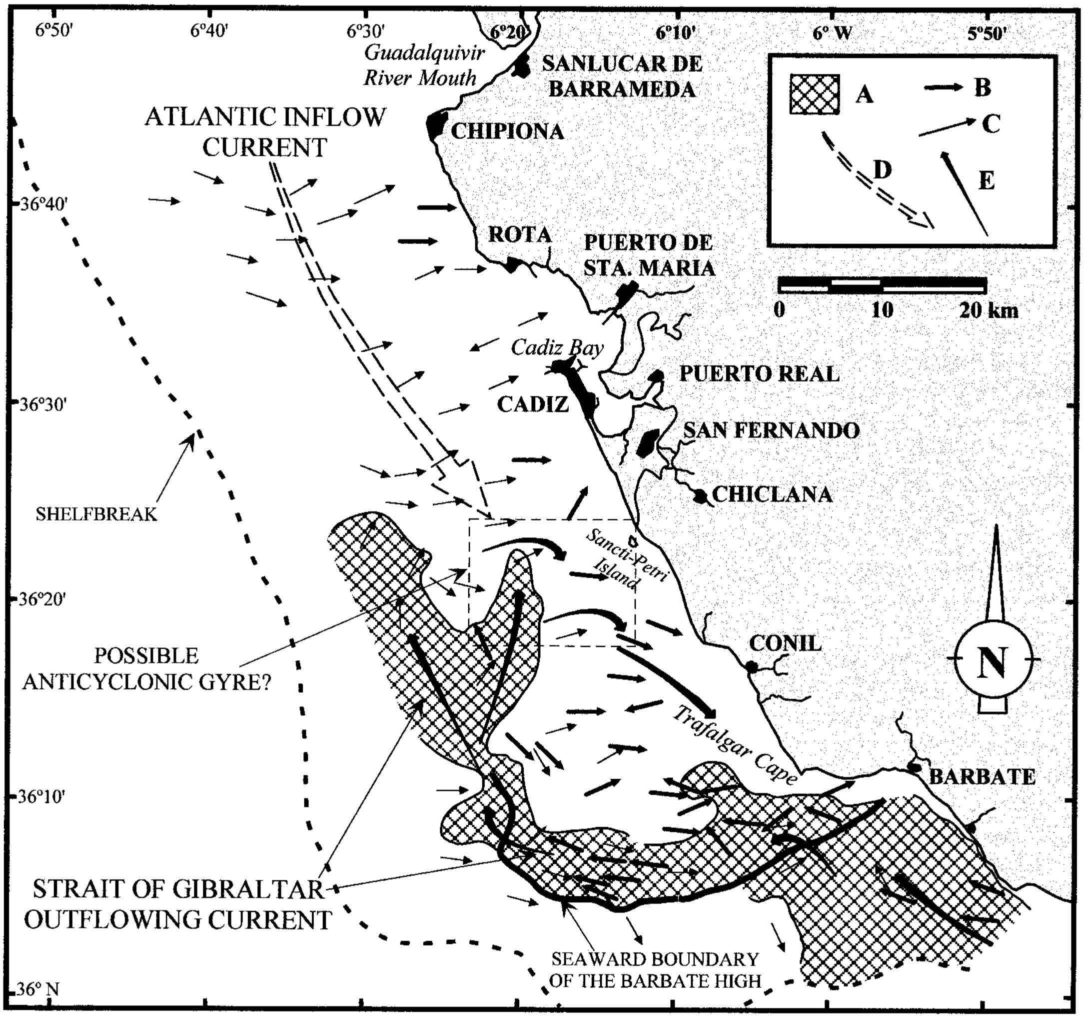


Fig. 17. Morphodynamic sketch obtained from the distribution, morphology and arrangement of bedforms in the study area. Legend: (A) zone where the existence of large bedforms suggests a dominant west–northwestward hydrodynamics; (B) sedimentary dynamics inferred from a large dune field; (C) sedimentary dynamics inferred from a set of small dunes; (D) general hydrodynamics over the shelf dominated by a southeastward flow; (E) main current directions and bedload transport paths around the Barbate High.

and west–northwest can be inferred, whereas the flow running towards the east attains a lower peak velocity (Fig. 17). Finally, it must be emphasised that our information refers to bottom flow patterns over the continental shelf, and that surface flows may vary significantly.

The scarcity of oceanographic data (currents, waves and tides) from the study area means we must consider all possible alternatives to explain the genesis of the bedforms. It seems reasonable to believe that the bottom current patterns over the Barbate High are not the result of an isolated hydrodynamic agent; rather, several factors influence flow generation. The influence of MOW over these shallow zones does not seem probable, because it is normally found at much greater depths over the slope (Nelson et al., 1993). Between zones A and B, there is a transitional zone where large dunes have a symmetric character, indicative of a bottom flow without any net direction. The presence of smaller dunes superimposed upon the large-scale dunes could indicate the influence of lower intensity water movements.

In the inshore area (zones B and C) there is a relationship between the inferred eastward migration pattern and the general southeastward Atlantic inflow over the continental shelf (Figs. 11, 16 and 17). However, over the Barbate High the net current direction is not so simple, because it seems to be influenced by the coastline configuration (Fig. 4). In this sense, the shelf current moves east–south-eastwards between 2 h before and 2 h after high tide in the Straits of Gibraltar, although in the inshore zones at the latitude of Barbate, a major eastward current direction is observed (Ménanteau et al., 1983), so it appears that these dunes are generated by the Atlantic inflow running in that direction. In zone B, the large dimensions of the dunes are indicative of an amplification of the Atlantic inflow when it passes over the Barbate High, caused by the reduction of water depth. In this sense, the bottom current velocity increases from <26 cm/s over the northern shelf of the study area to around 80 cm/s around the Barbate High (Nelson et al., 1999). During high tide in the Straits of Gibraltar, in the inshore zones of the Barbate High the flow is mainly directed towards the east–southeast, and the flow velocity varies between 1.5 and a maximum velocity of 3 knots (Ménanteau et al., 1983). Those velocities represent values ranging between 75 and 150 cm/s, which clearly exceed the minimum threshold of 60 cm/s necessary for a bottom current to generate bedforms (Middleton and Southard, 1977). This indicates that the influence of those currents is significant in the inshore zones, whereas in the offshore zones current velocity is much lower (values of 0.7 knots have been measured). The reduced dimensions of bedforms and the presence of rounded crests in zone C of the study area could be explained by considering the influence of shoaling waves in this shallow zone (Nelson et al., 1999). Rounded and degraded crests are reportedly formed in response to wave action, generating a non-equilibrium situation between bedform and flow (Adams et al., 1986), due to the influence of wind-driven currents and storm currents (Schwab and Molnia, 1987; Kuijpers et al., 1993). These features could also be influenced by a reduced sediment supply to this zone of this continental shelf, because the Guadalquivir River's prodeltaic structure progrades over the middle and outer continental shelf, and most of the sediments supplied by the Guadalete River are trapped in Cadiz Bay (Lobo, 1995; Rodero, 1999).

The existence of westward and west-north-westward-trending bedforms over the Barbate High could be related tentatively to the reversal process undergone by the shelfal currents over the Barbate High due to the influence of tidal currents in the Straits of Gibraltar. In this sense, during low tide in the Straits of Gibraltar the ebb current moves from east to west and is amplified over the sill of the Straits of Gibraltar, related to the effect of cross-section reduction. Over the study area's shelf domain, the mean current changes its direction according to the Straits of Gibraltar tidal variations (Ménanteau et al., 1983). Therefore, the shelf ebb-current is directed west–northwestwardly between 2 h before and 2 h after low tide in the Straits of Gibraltar, and tidal flows attain a maximum value of 3 knots (about 150 cm/s) during the low tide, similar to the peak velocity measured during high tide (Fig. 4). It seems that this flow is responsible for the generation of large dunes in zone A, because in the offshore zones the flow is mainly directed towards the west. This westward-directed current increases in velocity drastically when passing across the Barbate High, due to its steep physiographic profile (Lobo, 1995). In contrast, in the inshore zones the main orientation of the flow is towards the northwest, an oblique direction in relation to the north–south orientated crests of the large dunes in zone B, and therefore a slight influence on the asymmetry of those large dunes. This process means that the inshore zone (zone B) is not influenced by this reversing current, and thus large dunes in this zone are only influenced by the eastward inflow (Fig. 17).

Other processes that can be responsible for the generation of the bedforms are storms and wind-driven currents that influence the shallow zones, which could explain the bedform size (Table 2) and the bathymetric location of large dunes. When those processes are dominant, intervals of migration are restricted to short intervals every year, and infrequent major storms will largely control bedforms' net migration direction (Cacchione et al., 1987). In relation to this, the influence of southeasterly (Levantes) and northwesterly winds (Ponientes) could contribute to developing northwest- and southeast-trending currents over the Barbate High. However, the lack of data concerning those winds' influence on the generation of wind-driven currents means that this possibility is speculative.

6.4. Sediment transport

Around tidal sand banks, a net sand transport circulatory pattern is established (clockwise or counter-clockwise), because ebb and flood currents have different intensities on each side (Jones et al., 1965; Smith, 1969; McCave and Langhorne, 1982; Twichell, 1983; Harris, 1988b). In our study area, a similar pattern was detected (Fig. 17), with large dunes migrating clockwise around the centre of the Barbate High. Flood-related currents are channelled and amplified through the inshore zone of the Barbate High, whereas ebb-related currents are able to rise on top of its deepest part; in any case, they probably do not affect the inshore zone's net bedload transport.

Symmetric bedforms are considered stationary (Dingle, 1965), and they occur in the transitional boundary between two areas of bedforms moving in opposite directions (McCave and Langhorne, 1982; Berné et al., 1993), acting as a conduit for sand transport around the end of a bank (McCave and Langhorne, 1982). They have also been related to areas where net sand transport is zero (McCave, 1971). The symmetric bedforms found in the transitional area between zones A and B could act as a path for sand recirculation. In the northern part of the Barbate High, the transition from offshore west–northwest-directed dunes to inshore, east-directed dunes probably also involves sand recirculation. This being the case, the large dunes over the Barbate High reflect the existence of a system of sand recirculation around this physiographic feature (Fig. 17). Small dunes often act as vehicles for sand transport towards large dune crests, and tidal currents and wave action affect them. They have been reported as indicators of net transport directions (McCave and Langhorne, 1982). In the study area, a transversal component of sand transport across the dunefields is inferred, from west to east, because inferred currents directions range between WSW–ENE and WNW–ESE (Fig. 16).

7. Conclusions

Abundant large dunes have developed in the Gulf of Cadiz and are grouped into three significant fields. These fields are distributed in the shallow zone (Barbate High) located on the shelf domain between Conil and Cape Trafalgar, and also in the infralittoral subdomain and the inner shelf between Conil and Cadiz Bay. Water depth is one controlling factor in the development of dunes, because they are not found when water depth exceeds 30 m. The existence of a shallow physiographic feature (Barbate High) would enhance the interaction between the currents flow and the seafloor. The bedforms that have been identified in the study area seem to be modern features, generated by the interaction of present-day hydraulic processes with the seafloor.

The dunes' distribution and migration patterns on the Gulf of Cadiz's continental shelf provide information about net bedload transport and present-day bottom circulatory patterns. The large dunes are generated by the interaction of the Atlantic inflow with a sandy seafloor. This current flow changes its main direction over the continental shelf according to the tidal cycle in the Straits of Gibraltar. This current flow is directed eastwards over the inner shelf during high tide in the Straits of Gibraltar, and it is also amplified when passing over the Barbate High, creating a well developed and eastward-oriented field of large dunes in the inshore zones (zone B). In the infralittoral and inner shelf domain north of the Barbate High, the influence of shoaling waves is also important (zone C). The existence of a previously undetected westward-trending flow on the continental shelf has been determined based on dune asymmetries. This flow creates a field of large dunes over the Barbate High (zone A), and it seems to be linked to the action of strong ebb tidal currents in the Straits of Gibraltar, which would generate a westward-directed flow influencing the offshore zone of the Barbate High, whereas the inshore areas of the Barbate High would not be greatly affected by this current flow. Due to the influence of tidal currents on the sedimentary dynamics over the Barbate High, a clockwise sediment transport pattern is established there. This sedimentary pattern probably involves sand recirculation in the Barbate High, and it explains a transitional zone of large symmetric dunes between the two main fields of submarine dunes (zones A and B) which indicate zero net sand transport.

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