Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Continental Shelf Research 24 (2004) 461–482

CONTINENTAL SHELF RESEARCH

www.elsevier.com/locate/csr

Contrasting styles of the Holocene highstand sedimentation and sediment dispersal systems in the northern shelf of the Gulf of Cadiz

F.J. Lobo[a,*], R. Sánchez[a], R. González[a], J.M.A. Dias[a], F.J. Hernández-Molina[b], L.M. Fernández-Salas[c], V. Díaz del Río[c], I. Mendes[a]

[a] *CIACOMAR/CIMA, Universidade do Algarve, Avenida 16 de Junho s/n, Olhão 8700-311, Portugal*
[b] *Departamento de Geociencias Marinas y Ordenación del Territorio, Facultad de Ciencias, Universidad de Vigo, Vigo 36200, Spain*
[c] *Instituto Español de Oceanografía (IEO), Centro Oceanográfico de Málaga, Puerto Pesquero s/n, Fuengirola 29640, Spain*

Received 14 January 2003; received in revised form 30 October 2003; accepted 5 December 2003

Abstract

An approach to the interpretation of the Holocene highstand depositional systems and the influence of shelf circulation patterns on sediment dispersal in the northern Gulf of Cadiz shelf (SW Iberian Peninsula) is reported. The study area comprises the transition from the southern Portuguese shelf, lacking major fluvial input, to the Guadiana and Guadalquivir shelves, receiving sediments from fluvial sources. An integrated study using high-resolution seismic profiles and meteorological and physical oceanography data was undertaken to reach the proposed goals.

A lateral transition of shelf environments is evidenced during the most recent sea-level highstand period. The Portuguese shelf can be considered as a moderate to high-energy environment, where the dominance of storm events led to the construction of a significant infralittoral prograding wedge, as a consequence of normal incidence of storm waves and steep shelf profile. The Guadiana shelf shows a distinct partition of depositional systems, as a result of a moderate fluvial supply and significant reworking wave and current activity over morpho-structural highs. Proximal facies are attributed to poorly developed prodeltas, whereas distal facies are interpreted as muddy belts. The Guadalquivir shelf is a fluvially dominated environment, as the most prominent feature is a thick, widespread prodelta whose formation has been controlled by significant fluvial supply, moderate hydrodynamic regime and smooth shelf topography.

The comparison between sediment transport patterns evidenced in geophysical records and shelf circulation patterns enables us to propose a model for the sediment dispersal during the Holocene highstand period. Sediment dispersal is controlled by an intermittent counter current system, which seems to be intimately linked with the wind regime. Eastward dispersal on the middle to outer shelf is led by the general anticyclonic circulation, dominant under the influence of westerly winds. Westward dispersal occurs in the inshore zones, mainly led by the entrance of warm water tongues on the shelf under the action of easterly winds. These two opposing patterns of sediment dispersal are bounded by zones of current shear (Huelva Front and Strafford Shear).

Keywords: Gulf of Cadiz shelf; Seismic stratigraphy; Highstand systems tract; Depositional systems; Sediment dispersal; Current patterns

---

*Corresponding author. Tel.: +351-289-707087; fax: +351-289-706972.
E-mail addresses: pacolobo@ualg.pt (F.J. Lobo).

0278-4343/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2003.12.003

1. Introduction

Most studies of shelf depositional systems during the Holocene highstand focus on relatively homogeneous shelf environments influenced to some extent by fluvial supplies, either in prodeltaic settings (Park et al., 1990; Figueiredo and Nittrouer, 1995; Díaz et al., 1996; Nittrouer et al., 1996; Kuehl et al., 1997), or in shelf muddy belts (Park et al., 1995, 1996, 1999; Lee and Chung, 2000; Lesueur et al., 2001; Yoo et al., 2002). This general trend is also applicable to the northern shelf of the Gulf of Cadiz (SW Iberian Peninsula), where research efforts concerning the Holocene highstand sedimentary processes have been concentrated on the fluvially dominated Guadalquivir shelf (Lobo, 1995; Nelson et al., 1999; Rodero, 1999). In contrast, studies concerning the Holocene highstand systems tract (HST) in the continental shelf westward of the Guadalquivir River have been fragmented. These studies have been generally limited to the Portuguese shelf located westward of the Guadiana River (Vanney and Mougenot, 1981; Roque, 1998; Hernández-Molina et al., 2000a), whereas the Holocene highstand accumulation on the continental shelf located off and eastward of the Guadiana River mouth has received much less attention (Nelson et al., 1999).

In spite of those limitations, the study of depositional styles developed during the Holocene highstand on the continental shelf northwestward of the Guadalquivir River is significant, because this area shows a lateral gradation from the sediment-starved southern Portuguese shelf to the fluvially dominated Guadalquivir shelf. This shelf sector receives sediment supplies from fluvial sources of different sizes, such as the Arade, Guadiana, Piedras and Tinto-Odiel Rivers (Fig. 1). Furthermore, this continental shelf is characterised by significant physiographic changes, such as shelf width and gradient, and by different coast orientations. These specific

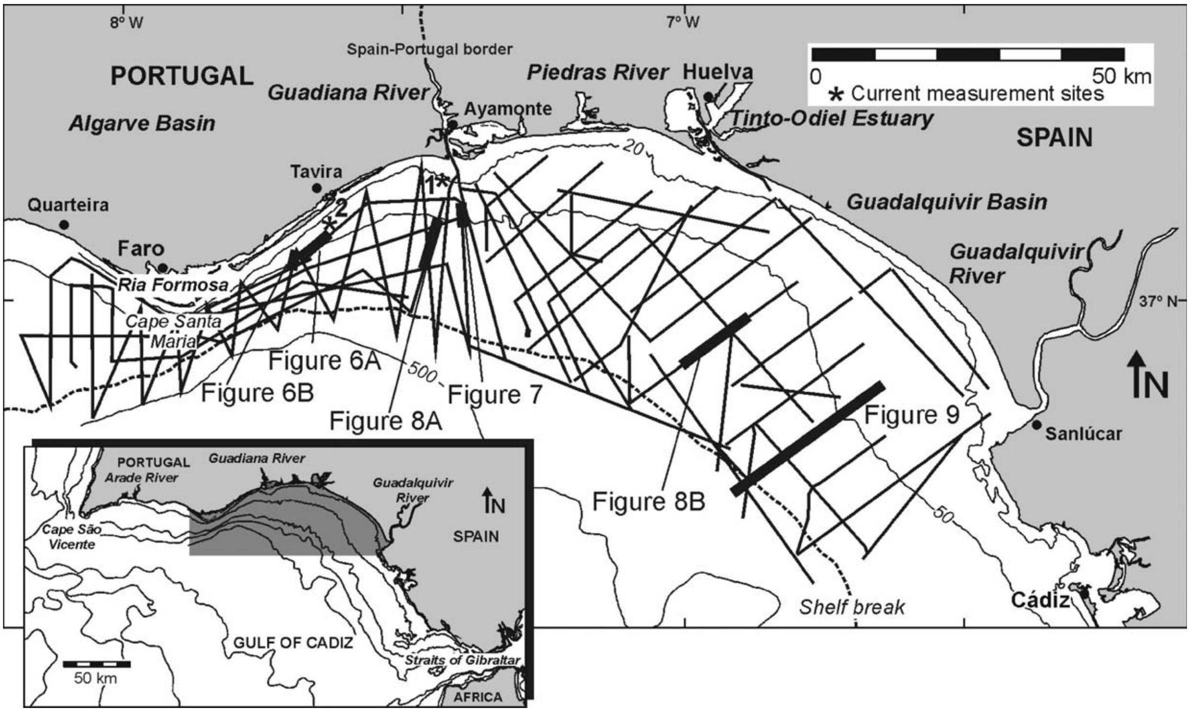

Fig. 1. Location of the study area in the Gulf of Cadiz margin, showing the position of high-resolution seismic profiles and the two sites where current measurements were made. The estimated shelf-break position and some bathymetric contours (in metres) are also indicated.

physiographic features influence the hydrodynamic processes, particularly wave activity and shelf current patterns. Therefore, the interaction between multi-sourced fluvial supplies, physiographic constraints and oceanographic agents may form complex patterns of Holocene depositional styles.

The application of this approach to the study of the complex ocenographic processes that operate on the Gulf of Cadiz shelf (Vargas et al., 2003) is particularly interesting. The traditional view assumes the influence of North Atlantic Surface Water (NASW) or Atlantic Inflow Current (Nelson et al., 1999) flowing towards the east and southeast and entering the Mediterranean Sea through the Straits of Gibraltar (Ochoa and Bray, 1991). However, evidences of a more complex shelf circulation picture have been recently provided (Folkard et al., 1997; Mauritzen et al., 2001). Therefore, the study of the sediment dispersal system from the distribution patterns and internal structure of Holocene HST and its comparison with shelf oceanographic patterns may emphasise the influence of meteorological conditions, shelf current patterns and current boundaries on the dispersal patterns of shelf sediment.

Consequently, the aims of this study are to: (a) document the different styles of shelf depositional systems developed during the Holocene highstand to the east and west of the Guadiana River; (b) determine the influences of wave regime, current patterns, sediment supply, shelf physiography and coastal configuration on the depositional styles of the Holocene HST; and (c) establish the relationships between the shelf circulation patterns and the Holocene sediment dispersal system.

2. Geological and oceanographic setting

2.1. Physiography

The study area is the northern part of the Gulf of Cadiz located between Quarteira (Portugal) and the Guadalquivir River mouth (Spain) (Fig. 1), characterised by contrasting physiographic features. The Portuguese margin shows an infralittoral domain extending up to 30–35 m water depth with a mean gradient of 0.21°. The seaward boundary with the continental shelf is marked by a break of slope. The shelf shows width values ranging from 5 km off Faro to 20 km off the Guadiana River, whereas gradient values range between 0.32° and 1.27°. The shelf edge is located at water depths between 120 and 140 m. Seaward, the upper slope extends up to 500–700 m with an average gradient of about 4° (Roque, 1998). Between the Guadiana and Guadalquivir Rivers there is no clear boundary between the infralittoral domain and the continental shelf. The shelf width increases eastward from 20 to 25 km off and eastward of the Guadiana River to more than 30 km off the Guadalquivir River. Average shelf gradients are lower than 0.3° in front of the Guadiana River and lower than 0.2° in front of the Guadalquivir River. The shelf edge is located at water depths of 100–130 m. Seaward, the upper slope extends up to 400 m water depth, with gradients up to 3° (Lobo, 2000).

2.2. Fluvial input

The most prominent feature of the Portuguese coast is a large barrier island-lagoon system (Ria Formosa). This coast is characterised by minor fluvial input. The most significant fluvial supply is provided by the Arade River, which generates a small prodelta located westward of the study area (Moita, 1986). The Spanish coast is characterised by several rivers forming estuaries partially closed by spits, such as the Guadiana, Piedras, Tinto-Odiel and Guadalquivir (Fig. 1). Their mean water discharge has been evaluated by van Geen et al. (1997): 80 m^3/s for the Guadiana, 20 m^3/s for the Tinto-Odiel and 160 m^3/s for the Guadalquivir. Although the Guadalquivir River is the main fluvial input of the Gulf of Cadiz margin, its associated muddy sedimentary wedge is deflected southeastward far from the study area, due to the east and southeastward advection of suspended sediments by the action of the NASW (Palanques et al., 1986–1987; Lobo, 1995; Gutiérrez-Mas et al., 1996; Nelson et al., 1999; Rodero et al., 1999). As a consequence, the Guadiana River can be

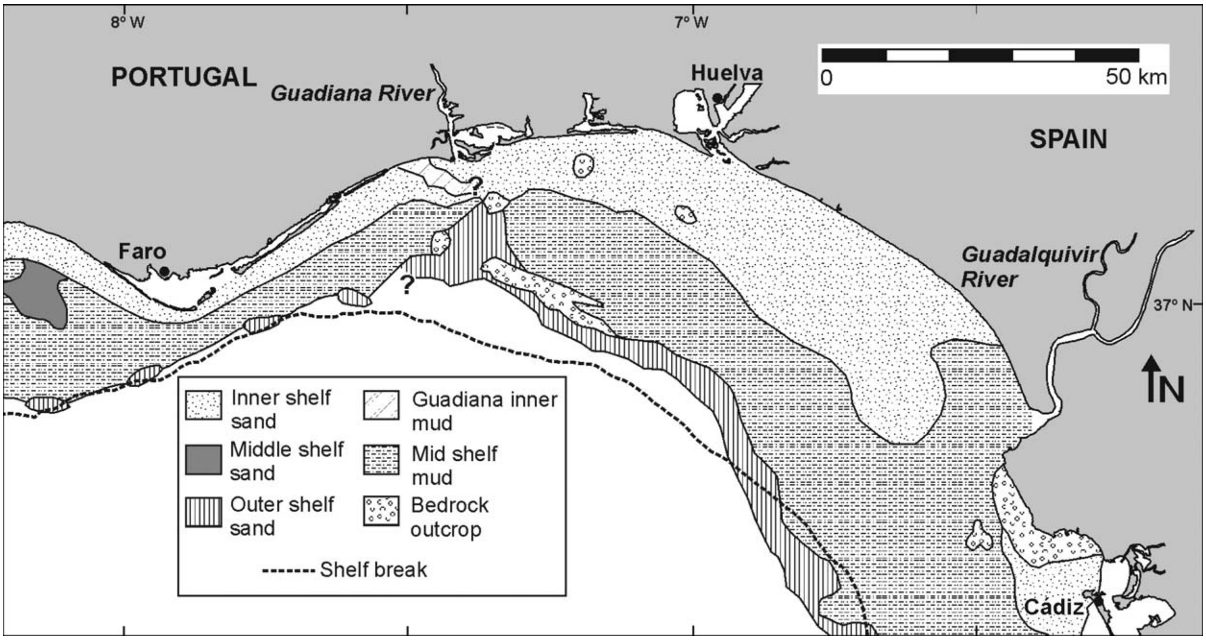

Fig. 2. Distribution map of surficial sediments in the study area, based on previous studies conducted in the Portuguese (Moita, 1986) and the Spanish (Nelson et al., 1999) shelves.

considered the main sediment source to the study area (Morales, 1997).

2.3. Modern surficial sediment distribution

The infralittoral domain is covered by a continuous belt of sands (Moita, 1986; Nelson et al., 1999), only interrupted by muddy deposits related with river mouth prodeltas, such as the Guadalquivir (Fig. 2). However, silts predominate in the inner shelf adjacent to the Guadiana River mouth (Nelson et al., 1999). Rocky outcrops of reduced extent are relatively frequent in inner shelf sectors, especially between the mouth of the Guadiana River and the Tinto-Odiel system (Rey and Medialdea, 1989; Fernández Salas et al., 1999). Most part of the middle shelf is covered by a mud layer showing an offshore and southeast gradation to finer grain size. The mid-shelf mud layer usually extends to about 100 m water depth (Nelson et al., 1999). A transgressive sand deposit is exposed at the seafloor about 100–120 m, forming a laterally continuous belt, particularly east of the Guadiana River (Moita, 1986; Nelson et al., 1999) (Fig. 2).

2.4. Shelf seismic stratigraphy

A late Quaternary stratigraphic framework has been established from the analysis of high-resolution seismic profiles (Somoza et al., 1997; Hernández-Molina et al., 2000b; Lobo et al., 2002). Sedimentation on the Gulf of Cadiz margin during the late Quaternary is marked by periods of forced regression. Since the last interglacial, several shelf wedges accumulated in response to periods of sea-level fall and lowstand related to fifth-order sea-level changes (periodicity of about 20,000 years). Each wedge is constituted by a forced wedge regressive systems tract (FWRST) and a lowstand systems tract (LST). The most recent of those marginal wedges is related with the Last Glacial Maximum (Somoza et al., 1997; Hernández-Molina et al., 2000b).

Post Last Glacial Maximum sediments are organised in a transgressive (TST) and a highstand (HST) system tracts (Somoza et al., 1997; Nelson et al., 1999; Hernández-Molina et al., 2000b; Lobo et al., 2001). The TST is constituted by four backsteppping parasequences (Lobo et al., 2001) which are downlapped by the Holocene HST consisting of prograding subaequous deltaic facies and middle shelf muddy deposits (Maldonado and Nelson, 1999; Nelson et al., 1999; Rodero et al., 1999).

2.5. Physical oceanographic setting

2.5.1. Wave regime

Significant wave height measured off Faro is 0.92 m. The coastal stretch is affected by two main wave trains coming from W to SW, with 68% of occurrences, and SE, with 25% of occurrences. Westerly waves have significant height of 0.8 m and average period of 4.5 s, whereas easterly waves have significant height of 1 m and average period of 4.9 s (Costa, 1994). During storm conditions (significant height >3 m), the two directions have similar occurrence, with 44% for SW waves and 43% for SE waves (Costa, 1994).

2.5.2. Shelf current patterns

The circulation in the Gulf of Cadiz appears to be forced by the water exchange through the Straits of Gibraltar. The Atlantic Inflow imposes eastward-directed current patterns on the shelf (Baringer and Price, 1999). However, some works point out a counter-current system controlled by the wind regime (i.e. Fiúza, 1983) that opposes to the classical pattern. The most frequent northerly winds are upwelling-favourable at the Portuguese coast north of Cape St. Vincent. Waters upwelled farther west can bend around Cape St. Vincent and invade the Gulf of Cadiz shelf as a coastal plume. Cold water upwells in the southern Portuguese coasts only under westerlies. In contrast, relaxation of upwelling-favourable wind and/or onset of easterlies favour the development of an inshore warm water tongue stretching westwards from the Bay of Cadiz. This picture was observed by Stevenson (1977). Water upwelled at the west coast was drawn eastwards over the outer shelf by the anticyclonic Tarif Eddy, whereas a warm water tongue featured the inner shelf. Both flows were separated by the Huelva Front.

The warm counter-current is a recurrent feature that occurred in the 45% of clear advanced very high-resolution radiometer (AVHRR) scans from 1982 to 1991 (Relvas and Barton, 2002). Fiúza (1983) and more recently Folkard et al. (1997) inferred wind control on the development of inshore counter currents. Direct measurements confirm that this dual band pattern has association with the wind stress field in the Gulf of Cadiz shelf (Vargas et al., 2003).

3. Data and methods

3.1. Shallow sub-bottom geology data

Subsurface geological information was provided by high-resolution seismic profiles (Fig. 1) recorded with a Uniboom system (Geopulse™: 280 J, shot delay of 500 ms, recording scale of 200 ms). These records were collected during three oceanographic surveys: Golca-93, Fado-9611 and Wadiana 2000. Positioning was achieved using a Differential Global Positioning System (DGPS). The high-resolution seismic records were interpreted following standard seismic stratigraphy rules (Mitchum et al., 1977). Based on the geometry and internal seismic characters, morpho-sedimentary units can be identified. We used the following convention in text and figures: water depth was expressed in metres (m) below sea surface, whereas seismic boundary depth and unit thickness were expressed in Two-way Travel Time milliseconds (ms).

3.2. Meteorological and oceanographical data

3.2.1. Wind data

SeaWinds from the NASA QuikScat satellite were retrieved from the Jet Propulsion Laboratory (http://podaac.jpl.nasa.gov/quikscat/qscat_data.html). More than 1000 daily passes (from June 1999 to March 2002) of the 0.25° × 0.25° grid for the box 13–6°W and 35–41°N were included.

The data were assembled into a 2D complex input data matrix, with the *u* wind component as the real part and the v as the imaginary part. Standard eigentechniques (in S-mode) were applied (e.g., Emery and Thomson, 1997) to obtain the Complex Empirical Orthogonal Functions (CEOFs) (cf. Münchow, 2000). CEOF analysis decomposes the input data matrix in the spatial patterns (CEOFs) and the corresponding time varying amplitudes (PCs). The PCs show how the patterns vary in intensity and direction over time. In the present analysis we only retained the leading CEOF, which explains 50% of the overall variance. This was statistically significant as assessed with the Monte-Carlo (Preisendorfer's rule N) and North's rule of Thumb tests.

3.2.2. Sea surface temperature (SST) data

Weekly composites derived from the National Oceanographic and Atmospheric Administration (NOAA) AVHRR data for 1999–2001 were included. This data set was obtained from the Deutsches Zentrum für Luft- und Raumfahrt (DLR) through the public access gateway (http://isis.dlr.de/).

3.2.3. Current data

They were obtained using two RDI 150 kHz ADCP moored on a SUBS-A2 buoy at 30 m water depth off the Guadiana River mouth (site 1) and off the sand spits at the east flank of Cape Santa Maria (site 2) (Fig. 1). The instruments measured the velocity profile on 1 m bins averaging pings at 300' intervals for 12 days (from 25 November to 6 December). A Cosine-Lanczos low-pass filter with half power point at 33.3 h (~0.7 cpd) spanning 85 h was applied to this series to extract the subinertial signal and get rid of tidal and other inertial noise. The resulting series was resampled into 3 daily values.

4. The Holocene HST on the Guadiana Shelf (from the Portuguese Shelf to the Guadalquivir Shelf)

4.1. Morphology of the maximum flooding surface (MFS)

The lower boundary of the Holocene HST has been mapped throughout the study area (Fig. 3),

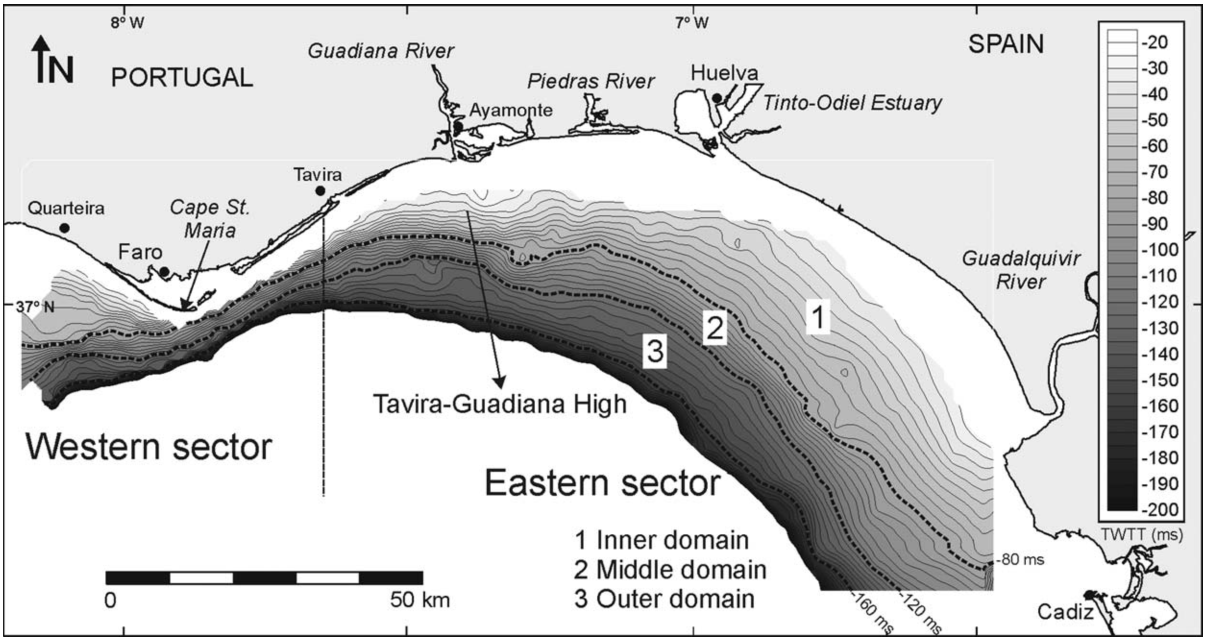

Fig. 3. Contour map (in milliseconds below the sea surface) of the lower boundary of the Holocene highstand systems tract (HST). Two contrasting sectors (western and eastern) are differentiated on the basis of physiographic characteristics, as well as the surface expression of a morpho-structural high, the Tavira–Guadiana High. TWTT (ms): two-way travel time in milliseconds.

representing −20 to −200 ms contours. The −160 ms contour marks a significant increase of the MFS gradients, because it represents the present-day shelfbreak. Two main sectors can be differentiated based on the MFS gradients (Fig. 3).

4.1.1. Western sector

It is located to the west of Tavira. This sector is characterised by an average MFS gradient of 0.95°, although it decreases in front of Quarteira to less than 0.6°. The steepest MFS occurs between Cape Santa Maria and Tavira, where it is several kilometres wide (Fig. 3).

4.1.2. Eastern sector

It is located to the east of Tavira. Three domains can be differentiated according to the gradients and contour lines pattern. An inner domain down to the −80 ms contour line shows low gradients averaging 0.12°. This domain is wider to the east of the Piedras River. Between Tavira and the Piedras River, gradients of this inner domain decrease progressively eastwards. The Tavira–Guadiana High, a shallow platform which is the surface expression of a morpho-structural high, is evidenced in front of the Guadiana River (Lobo et al., 2002). The middle domain is located between −80 and −120 ms contour lines. It displays an average gradient higher than 0.4°, although it decreases towards the Guadalquivir River mouth. Small-scale promontories occur off the Guadiana River. The outer domain is located between −120 and −160 ms contour lines, and is characterised by an average slope of 0.2°. The −160 ms contour line gives way to the upper slope, characterised by gradients higher than 1°.

4.2. Holocene HST: morpho-sedimentary units

The regional distribution of the Holocene HST is displayed in Fig. 4. Based on the seismic characters and distribution patterns, the Holocene HST is divided into four morpho-sedimentary units: (a) the Faro–Tavira wedge; (b) inner wedges; (c) shelf aggradational deposits, and (d) the Guadalquivir prodelta. Their distribution

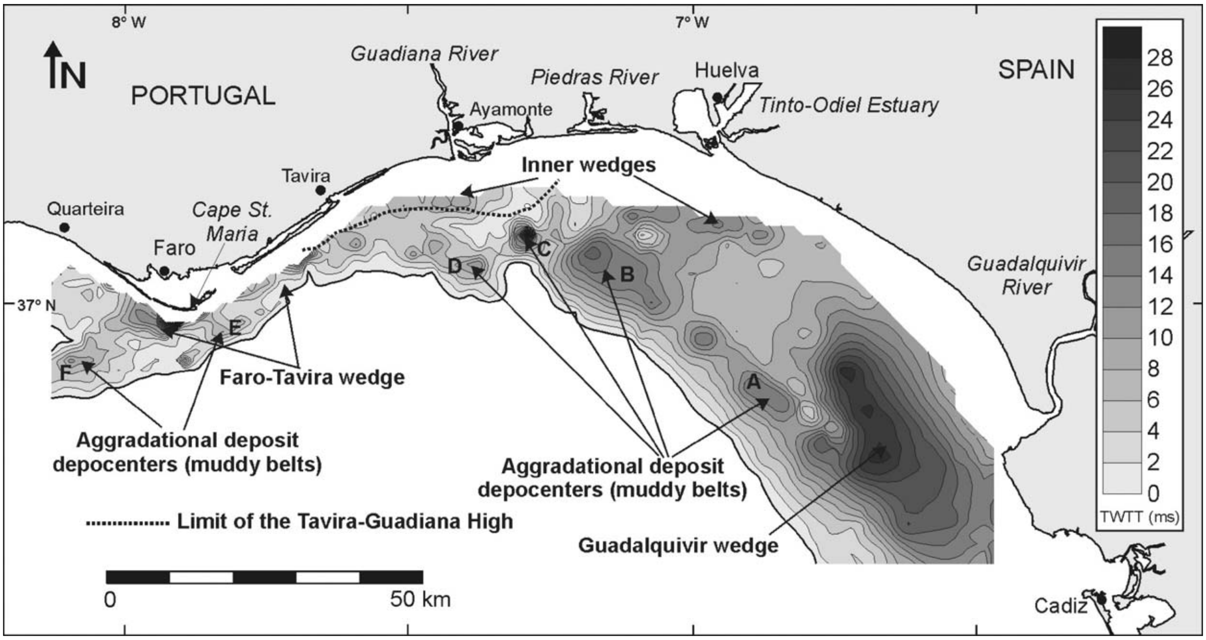

Fig. 4. Isopach map (in milliseconds) of the Holocene HST, with indication of main morpho-sedimentary units. Depocenters on the mid to outer shelf of the aggradational deposit are designated by letters (A to F). TWTT (ms): two-way travel time in milliseconds.

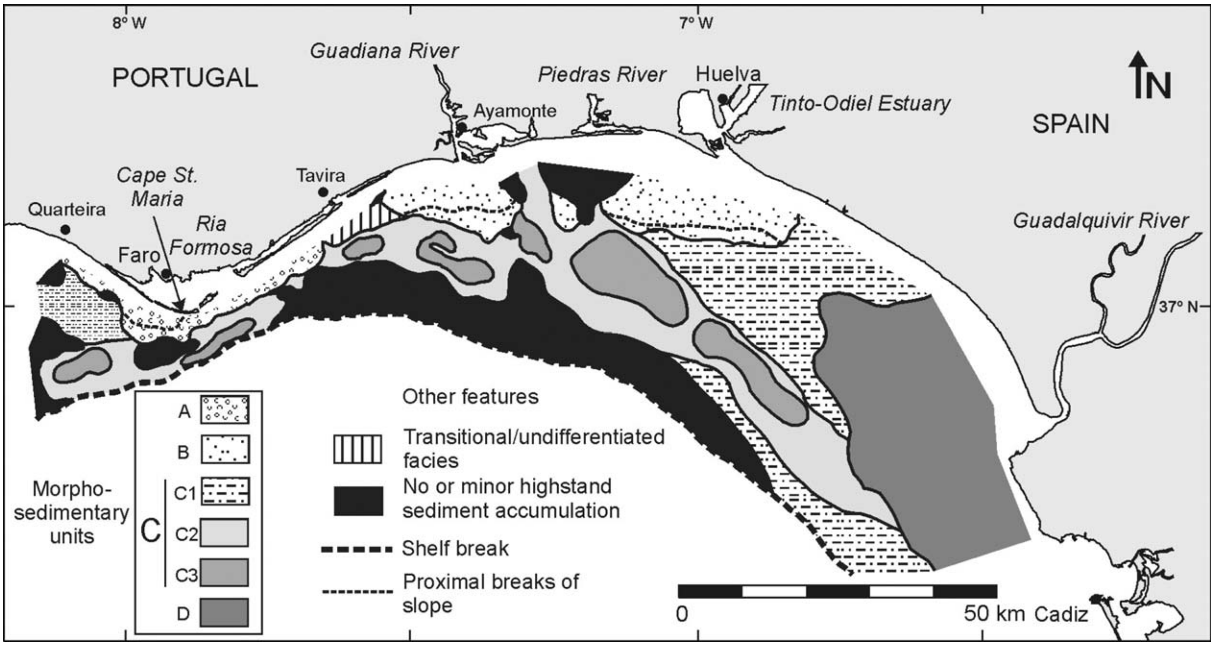

Fig. 5. Surface distribution of morpho-sedimentary units. Legend: (A) Faro–Tavira wedge; (B) inner wedges; (C) shelf aggradational deposits (C1: undifferentiated shelf aggradational deposits, C2: shelf muddy belts, or shelf aggradational deposits that show elongated patterns; C3: main depocenters of shelf muddy belts); (D) Guadalquivir wedge. Other surficial features such as transitional or undifferentiated facies between the Faro–Tavira wedge and the Guadiana inner wedge and the areas with no or minor highstand sediment accumulation are also represented.

patterns, main depocenters of shelf aggradational deposits and zones of nondeposition are represented in Fig. 5.

4.2.1. Faro–Tavira wedge

It is a prograding and seaward thickening seismic unit that shows a gently sloping upper surface (sea floor) up to 25–30 m water depth, with inclinations lower than 0.3°. An abrupt slope of about 5° characterises the seaward pinching out of the wedge at about 60 m water depth (Figs. 6A and B).

The internal structure shows progradational configuration and moderate to high reflectivity. The configuration evolves upwards from sigmoidal to oblique–tangential (Figs. 6A and B). The seaward progradation is only apparent and the true progradational trend seems to be oblique, southwestward to the west of Tavira, and towards the southeast to the west and in front of Faro. The Faro–Tavira wedge is anchored at coastal lithosomes identified to the east of Tavira that seem to have acted as barriers (Fig. 6A).

The distribution of this sedimentary wedge around Cape Santa Maria is partially imaged by the seismic grid (Fig. 4). The Faro–Tavira wedge shows an elongated pattern with two main depocenters. The first one occurs in front of Faro, where it is NNW–SSE oriented, more than 5 km long and showing maximum thickness higher than 30 ms. The second depocenter is located westward of Tavira and displays a NE–SW orientation. It is about 5 km long and the maximum thickness reaches up to 14 ms.

4.2.2. Inner wedges

These morpho-sedimentary units usually show sub-horizontal to smoothly sloping upper boundaries (sea floor) up to 20–25 water depth. The upper boundary evolves seaward to a sloping surface with a gradient up to 0.3°, and whose distal termination is located up to 40 m water depth.

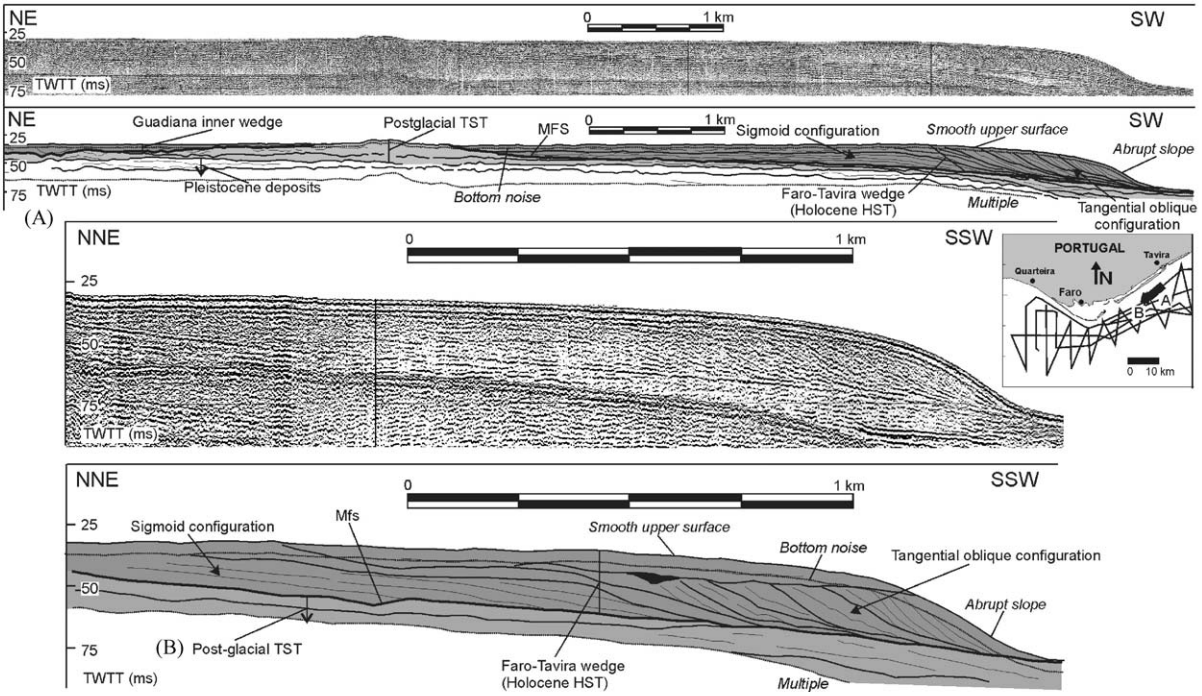

Fig. 6. High-resolution seismic sections (Geopulse) of the Faro–Tavira progradational wedge: (A) Shelf-parallel and southwestward prograding deposit in front of Tavira, detached from the Guadiana inner wedge; (B) Cross-shelf section of the Faro–Tavira progradational wedge, showing a sigmoid to tangential oblique configuration. See position of each profile in Fig. 1. HST: highstand systems tract; TST: transgressive systems tract; MFS: maximum flooding surface; TWTT (ms): two-way travel time in milliseconds.

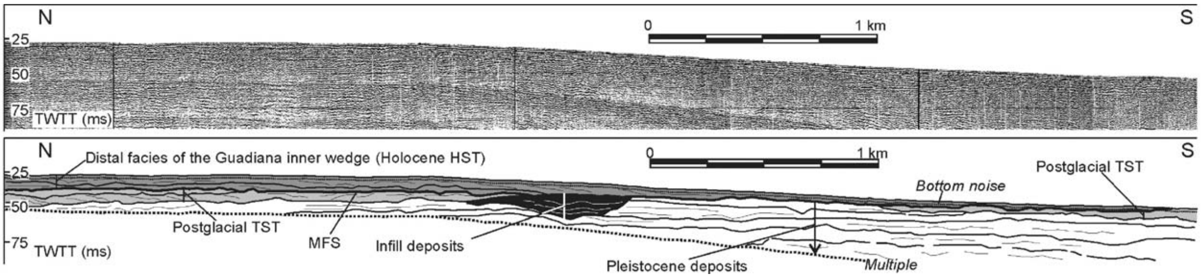

Fig. 7. High-resolution seismic sections (Geopulse) located off the Guadiana River, showing distal inner wedge facies located in front of the Guadiana River mouth. See position of the section in Fig. 1. HST: highstand systems tract; TST: transgressive systems tract; MFS: maximum flooding surface; TWTT (ms): two-way travel time in milliseconds.

The acoustic reflectivity is moderate to high. Low-angle progradational reflectors are dominant (Fig. 7). They show seaward progradations, although a slight westward prograding pattern in relation to the coast is observed to the west of the Guadiana River mouth.

In general, these inner wedges show lobate patterns in plan view, and their main axis show E–W orientations. Thicknesses are moderate, with maximum depocenters of about 8 ms. The Guadiana wedge is distributed more than 10 km offshore from the river mouth (Fig. 4).

4.2.3. *Shelf aggradational deposits*

The inner wedges are substituted seaward by aggradational, sheet-like deposits (Fig. 8), which

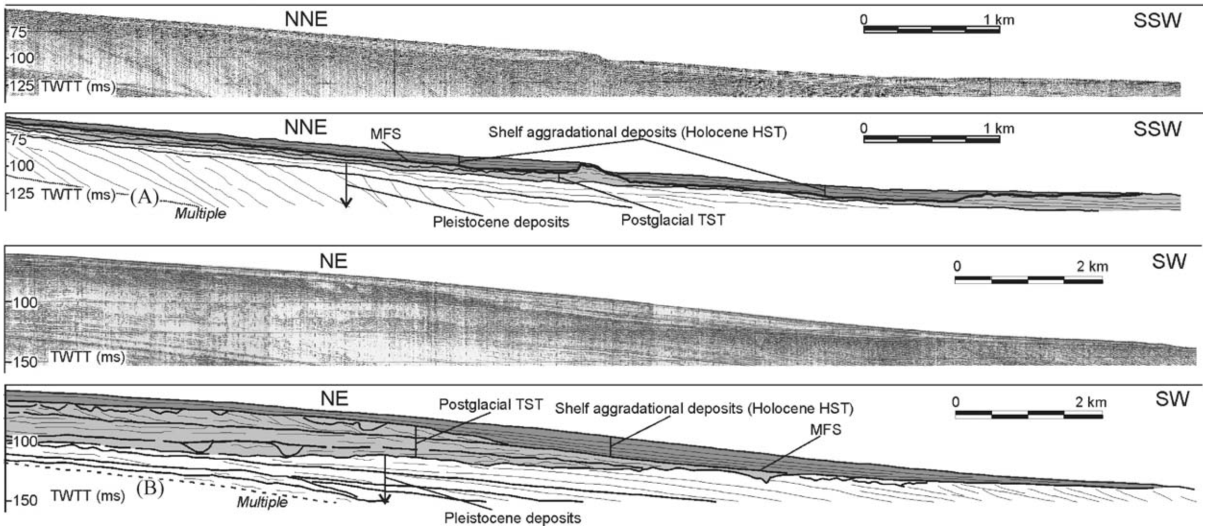

Fig. 8. High-resolution seismic sections (Geopulse) showing shelf aggradational deposits: (A) Westward the Guadiana River mouth; (B) Offshore Guadalquivir Basin. See position of each section in Fig. 1. HST: highstand systems tract; TST: transgressive systems tract; MFS: maximum flooding surface; TWTT (ms): two-way travel time in milliseconds.

are characterised by smoothly sloping upper and lower boundaries, although in places they may form lobate bodies.

These deposits show low reflectivity acoustic responses. Their internal structure is dominated by sub-horizontal, sub-parallel reflectors, with moderate to high amplitude and high lateral continuity in proximal settings evolving seaward to semitransparent configurations (Fig. 8).

These deposits occur preferentially on the middle to outer shelf detached from the inner wedges, and locally on the inner shelf where inner wedges do not occur. They tend to show elongated, parallel to shelf-break distributions on the mid to outer shelf. The most extensive deposit occurs eastward the Guadiana River, showing NW–SE orientations and lateral continuity of more than 30 km. Three main depocenters (A, B and C) are identified in this sector (Fig. 4), with thickness up to 20 ms in TWTT. Depocenter C shows even thickness higher than 30 ms, because in this zone the aggradational deposit buries an older incised valley. Less significant aggradational deposits, in extent and thickness, occur on the Portuguese shelf (Fig. 4). Three main depocenters (D, E and F) are identified from east to west. Depocenter D occurs westwards and in front of the Guadiana River. It displays a NNW–SSE orientation and maximum thickness higher than 10 ms. Depocenter E is NE–SW oriented and shows an elongated pattern. It occurs for more than 10 km eastward of Faro, showing thickness higher than 4 ms and locally about 10 ms. Depocenter F occurs on the Portuguese shelf in front of Quarteira and shows an E–W orientation and a maximum thickness of about 10 ms.

4.2.4. *Guadalquivir wedge*

The Guadalquivir-connected recent deposit is a wedge-shaped unit, which covers the entire shelf in cross-margin sections showing smooth upper and lower boundaries (Fig. 9).

A sigmoid configuration characterises the lower part of the sedimentary wedge, grading up- and seaward to a sub-parallel configuration. In proximal zones, a highly reflective acoustic response generally occurs. Seaward, internal reflectors lose amplitude and continuity, generating quasi-transparent acoustic responses on the middle to outer shelf. In front the Guadalquivir River mouth, an acoustic masking level is located 5 ms below the present sea-floor in the middle shelf (Fig. 9).

The thickness distribution map shows a main NNW-SSE oriented depocenter, extending both to

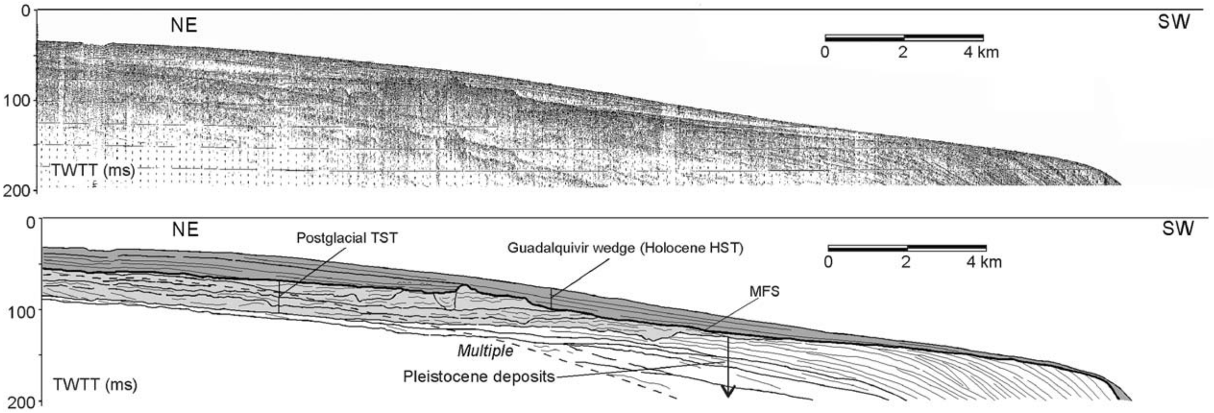

Fig. 9. High-resolution seismic profile (Geopulse) of the Guadalquivir wedge, showing its widespread distribution over the shelf. See position of the profile in Fig. 1. HST: highstand systems tract; TST: transgressive systems tract; MFS: maximum flooding surface; TWTT (ms): two-way travel time in milliseconds.

the north and to the south of the Guadalquivir River mouth. The depocenter thickness is more than 12 ms, with local maxima of about 30 ms. It seems to be more than 10 km wide in front of the Guadalquivir River mouth, but it becomes less than 5 km wide to the north. Both Guadalquivir and Guadiana-derived deposits seem to join on the middle to outer shelf, in front of the Guadalquivir River mouth (Fig. 4).

5. Shelf circulation

5.1. Wind regime

The PC time series was smoothed by a 7 day running mean to highlight trends (Fig. 10A). The PC rose plot shows that amplitude directions of this wind mode significantly altered their polarity during the studied period, showing two preferential orientations (Fig. 10A, inset), corresponding to NE and to SW wind regimes, respectively (Figs. 10C and D). Hence, the principal winds were spatially coherent over the Southern Iberian Peninsula and approximately oriented along the NE–SW axis. For the considered period the largest number of occurrences occurred for E–NE winds.

The orientation of the SW Iberian Peninsula sets interesting features concerning wind-driven ocean circulation. For the NE situation northerly wind blows leaving to its right the southern Portuguese coast (Fig. 10C). This wind regime sets onshore transport (downwelling-favourable) on the southern Portuguese coast, and the ocean response is a poleward flow to balance the onshore pressure gradient. This situation is reversed under a SW wind regime (Fig. 10D), which is upwelling-favourable on the southern Portuguese coast, forcing positive vertical velocities at the base of the Ekman layer.

5.2. Sea surface temperature (SST) pattern

In order to study the upper ocean response to the principal wind component during summer 2000, the leading CEOF (Fig. 10B) plus a series of six SST weekly composites (Figs. 11A through F) were considered. As a sub-sample of the full time series, the wind pattern showed alternating phases between westerlies and easterlies in the summer 2000 (Fig. 10B). The SST structure shows a quasi-permanent, quasi-circular, clockwise rotating warm eddy with a diameter of about 100 km anchored at the inner Gulf of Cadiz. Besides, a coastal band along the southern Portuguese coast showed differential patterns west and east of Cape St. Maria. While west of the Cape the coastal upwelling appeared with a pulsating nature, east of this cape locally upwelled waters were rarely observed (Fig. 11). Rather, a plume of cold water

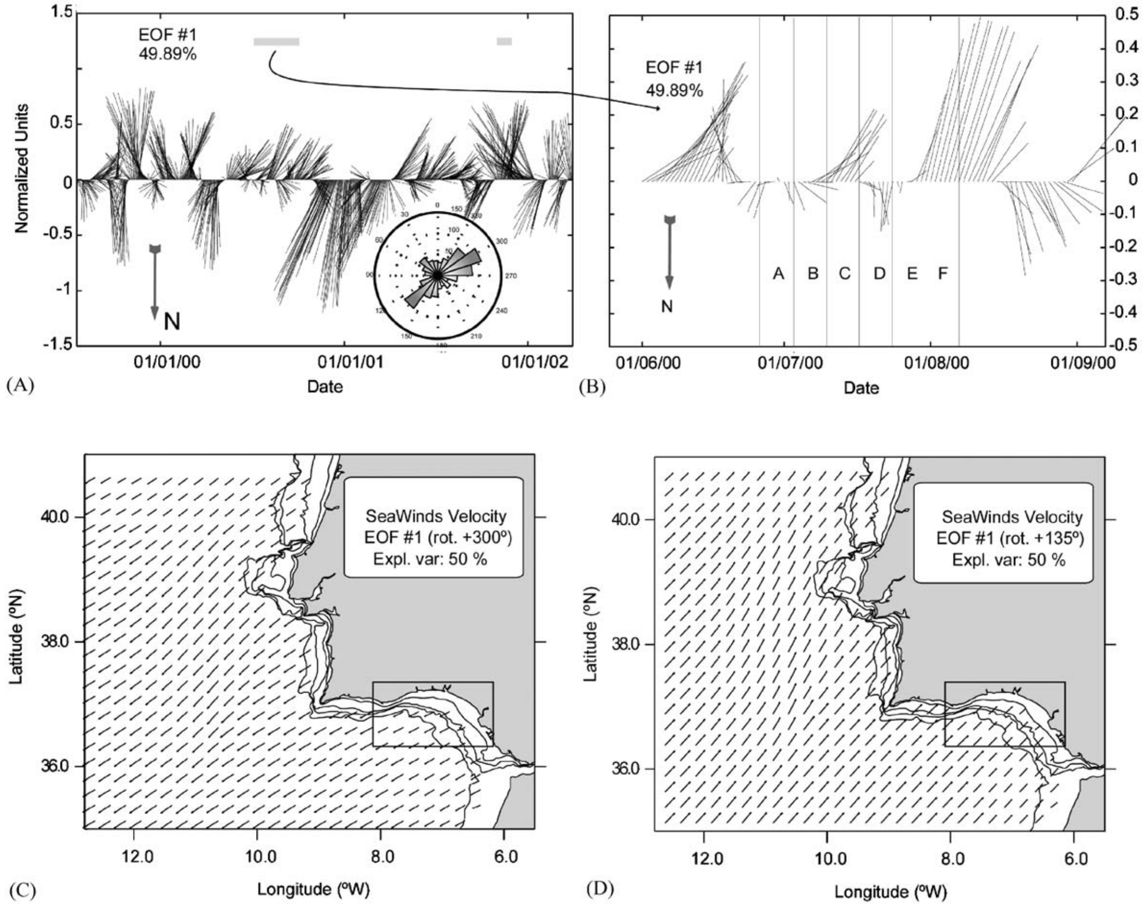

Fig. 10. Characterisation of wind regime in the study area: (A) Stick plot of daily amplitude time series (PC) of the leading mode (CEOF #1) of the SeaWinds data (in normalised units) from June 1999 to March 2002 (~50% of the variance). A downward pointing arrow marks the North for visual aid. Shadowed bars correspond to the period referred to in Figs. 8B and 9. A rose plot of CEOF #1 amplitude directions is shown in an inset for visual aid. Two main directions, corresponding to NE (+300°) and SW (+135°) are preferred. (B) Idem for the period June to September 2000. Weeks (A) through (F) referred to in Fig. 9 are labelled. (C) Reconstructed wind pattern for CEOF mode #1 directed along the preferred direction +300°. (D) Reconstructed wind pattern for CEOF mode #1 directed along the preferred direction +135°.

was drawn eastward over the mid to outer shelf along the northern border of the anticyclonic eddy. Oppositely a tongue of warm water with source in the mouth of the Guadalquivir River moved westward through the inner shelf (Fig. 11).

The surface circulation patterns are tightly linked to the wind regime during the considered period. Upwelling along the southern Portuguese shelf and retreat of the warm water tongue towards the mouth of the Guadalquivir River occurred in response to westerly winds (Fig. 10B). In contrast, coastal separation of the upwelled water and westward development of the warm coastal plume inshore the upwelled fringe occurred with fully developed easterlies (Fig. 10B).

5.3. Direct current measurements

Over the recording period, both current meters showed that the sub-inertial flows paralleled the bathymetry. Besides, mean velocities underwent a

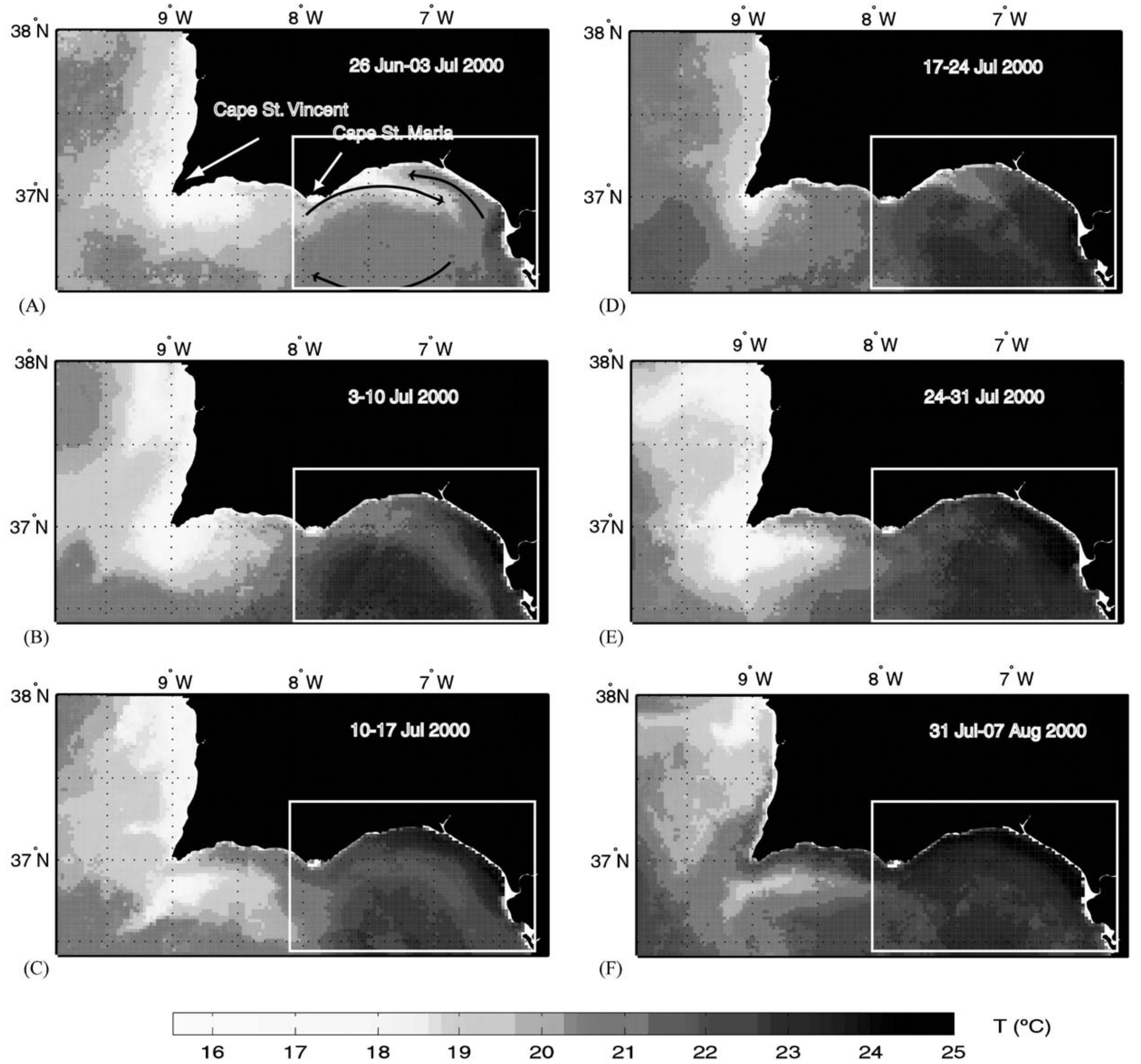

Fig. 11. Characterisation of sea surface temperatures in the study area during summer months: (A) through (F): 6 weekly Sea Surface Temperature (SST) composites for July and June 2000.

change from eastward- to westward-directed, because of the rotation of the CEOF winds from NE to E (Fig. 12A and B). Accordingly, the vertical velocity structure was modified.

From 26 November to 1 December 2001, the current pattern showed a strongly vertically sheared flow separated into an upper and a lower layer (Figs. 12C and D). Associated to the buoyant Guadiana and Guadalquivir River plumes, the upper layer velocities (~1–15 m depth) were about 0.2 m/s westward, gently deflected to the right of the prevailing NE wind. In the lower layer (~15–30 m), velocities were significantly eastward, with maximum values ranging between 0.15 and 0.2 m/s. Satellite imagery showed shoreward retreat of the Guadiana and Guadalquivir River plumes and gentle invasion

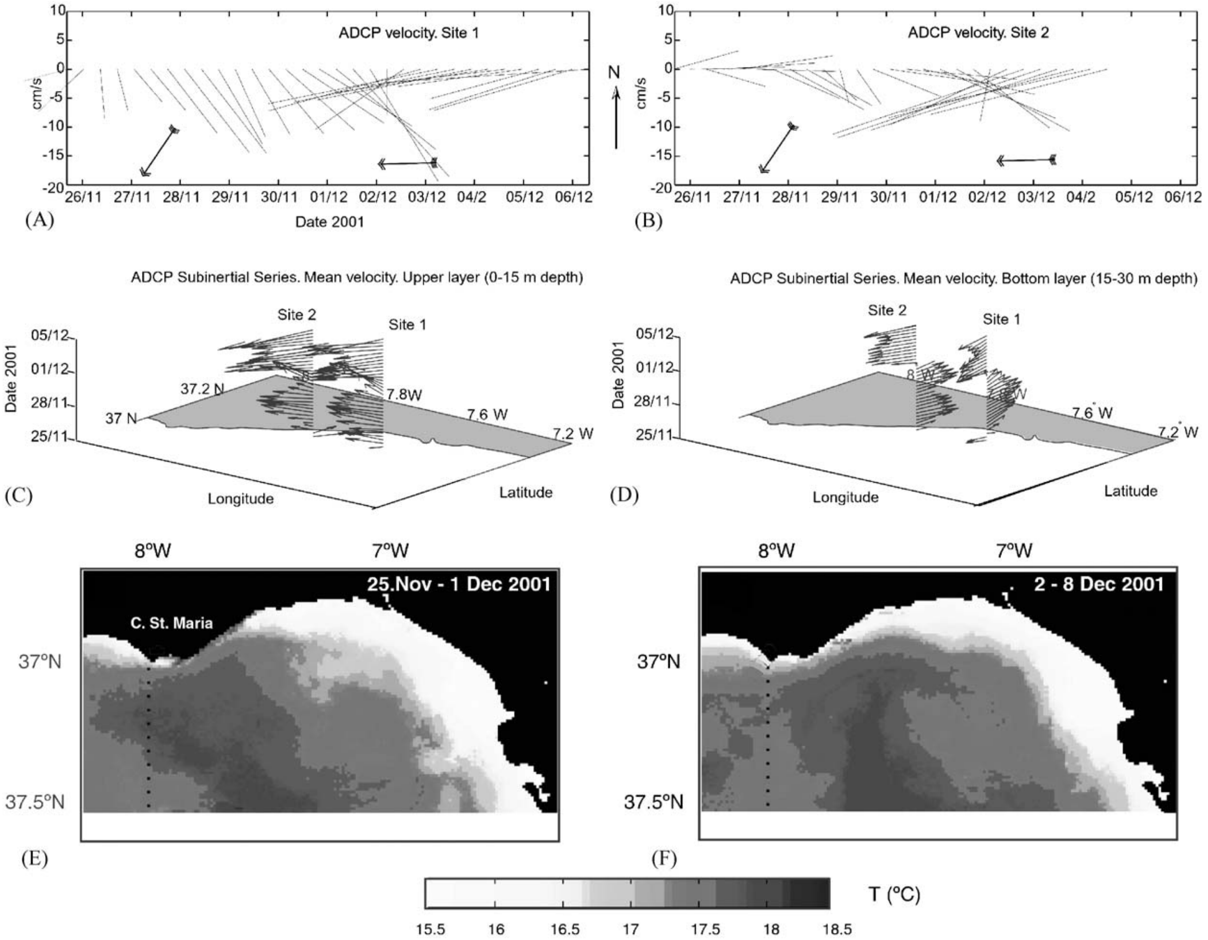

Fig. 12. Summary of direct current measurements: (A) Stick plot of depth-averaged ADCP velocity (cm/s) for the site Vila Real de Santo Antonio (in front of the Guadiana river mouth) from 26/11/01 to 06/12/01. Two arrows indicate the average wind direction for each period. (B) Idem for site Tavira. (C) Evolution of depth-averaged ADCP velocities for the upper layer (surface to 15 m depth), corresponding to the buoyant river plume. Observe that the vertical axis represent time (date 2001). (D) Idem for the bottom (15–30 m depth) layer. Maximum vector is 30 cm/s for (C) and (D). (E) Weekly SST composite for the period 25 November–1 December 2001. (F) Idem for 2–8 December 2001. Observe the westward progression of the cold fringe east of Cape St. Maria between (E) and (F).

of warmer oceanic water in the inner shelf to the east of Cape Santa Maria (Fig. 12E).

Between 1 and 2 December, ADCP velocities showed a strong westward reversal in the bottom layer (Figs. 12A and B), where maximum velocities were on the order of 0.16 m/s at both measurement sites. In the upper layer, the velocity profile showed stronger westward flow of about 0.3 m/s. Satellite imagery showed that the Guadiana and Guadalquivir River plumes were advected along the Portuguese coast (Fig. 12F).

6. Interpretation of morpho-sedimentary units

6.1. Faro–Tavira wedge

The Faro–Tavira wedge was interpreted as an infralittoral prograding wedge (IPW) (Hernández-Molina et al., 2000a) (Figs. 5 and 13A), and was considered to be linked to the erosive action of storm waves in the shoreface, and cross-shore sediment flux led by downwelling currents (Hernández-Molina et al., 2000a). The accumulation of those storm layers takes place below wave base-level (Siringan and Anderson, 1994; Novak and Pedersen, 2000; Thieler et al., 2001). Several facts support this interpretation: (a) the Faro–Tavira wedge is located in the infralittoral domain, below wave base level, estimated in this area at about 30–35 m water depth (Morales, 1997; Hernández-Molina et al., 1998, 2000a); (b) morphological features such as the break of slope and the high lateral continuity, paralleling the coastline, are characteristic of IPWs (Pomar and Tropeano, 2001); (c) the thickness (several tenths of metres) is comparable to similar storm-related deposits (Chiocci and Orlando, 1996).

6.2. *Inner wedges*

Sediment wedges similar to these inner wedges have been recognised elsewhere in relation with direct sources of terrigenous fluvial input (Ergin et al., 1992; Harris et al., 1996; Park et al., 1999; Algan et al., 2002), where they are interpreted as the result of sediment settling near river mouths, building modern subaqueous deltas (Park et al., 1990, 1999; Yoo et al., 2002). Therefore, these inner wedges are interpreted as the modern submarine portions of wave-dominated deltas (Fig. 5 and 13B).

6.3. *Shelf aggradational deposits*

The distribution patterns and acoustic facies of mid to outer shelf elongated deposits are characteristic of recent distal mud belts (Ergin et al., 1992; Jin and Chough, 1998; Chough et al., 2002; Yoo et al., 2002) (Fig. 5 and 13B). The transparent acoustic response indicates a predominance of fine sediments (Park et al., 1995, 1996; Yoo et al., 2002). Subsurface cores support this interpretation

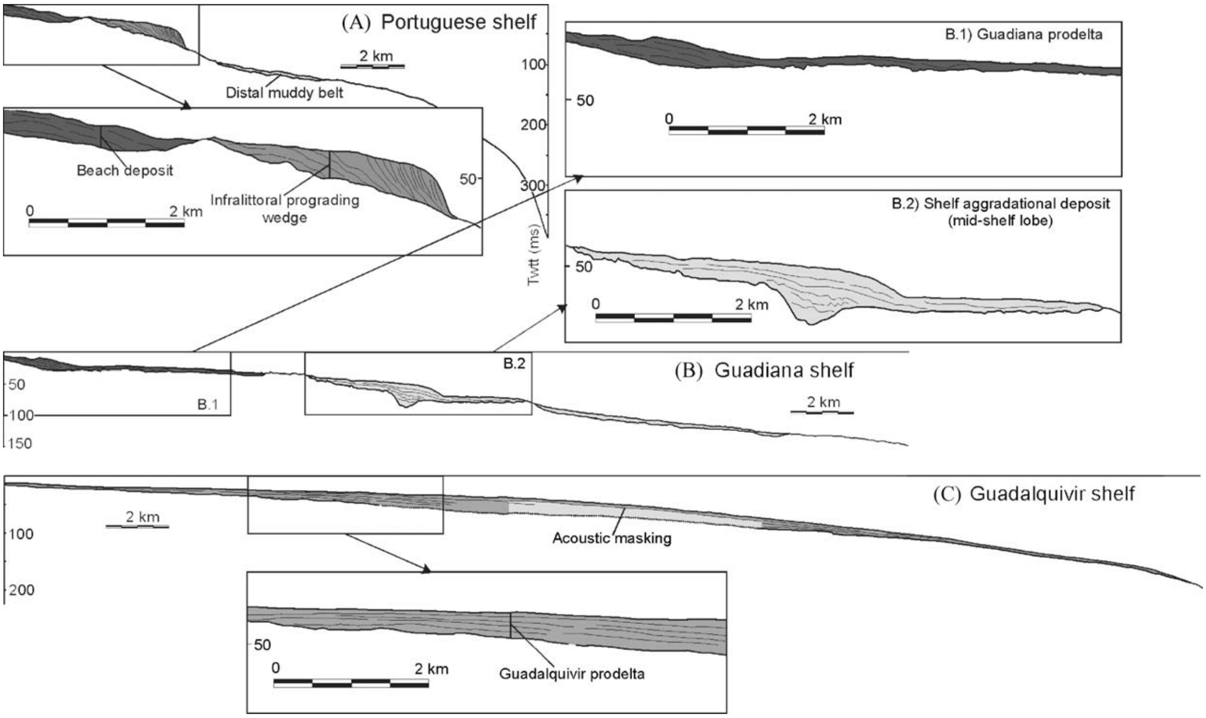

Fig. 13. Depositional profiles of contrasting shelf environments identified in the study area: (A) Portuguese shelf, dominated by the infralittoral prograding wedge; (B) Guadiana shelf, which shows a partition between proximal and distal deposits; (C) Guadalquivir shelf, covered by a single prodeltaic structure.

(Nelson et al., 1999), as the middle shelf is covered by a mud layer that becomes thinner to the inner margin and shows a southeastern gradation to finer grain size. These characteristics suggest an origin linked to the suspended sediment transport and deposition of fine-grained, fluvial sediments (cf. Park et al., 1995, 1996, 1999; Lesueur et al., 2001; Chough et al., 2002), especially during episodic flood events (Dias et al., 2002).

6.4. *Guadalquivir wedge*

This depositional body has already been described in its southwards prolongation, where a mud blanket extends into the Guadalquivir River mouth (Nelson et al., 1999). Therefore, this single stratified structure is interpreted as the Guadalquivir prodelta (Lobo, 1995; Nelson et al., 1999; Rodero et al., 1999) (Figs. 5 and 13C).

7. Discussion

7.1. *Differentiation of shelf sedimentary environments: controlling factors*

In the study area, it is possible to identify contrasting patterns of shelf sedimentation in the Holocene HST (Figs. 5 and 13). Three basic systems characterise the Portuguese (west of the Guadiana River), the Guadiana and the Guadalquivir shelves. The distinction between shelf environments results from different fluvial supplies, hydrodynamic conditions and physiographic constraints.

7.1.1. *Portuguese shelf*

This area is considered as a moderate to high-energy shelf environment with a reduced sediment supply (Figs. 5 and 13A), where two main morpho-sedimentary units located in proximal (Faro–Tavira wedge) and distal (shelf aggradational deposit) positions are distinguished.

(a) *Proximal unit*: The formation of wave-built depositional bodies similar to the Faro–Tavira wedge (IPW) is related with steep sea-floor slopes and lack of fluvial supply (Chiocci and Orlando, 1996). These two conditions occur in this area. Besides, the normal orientation of the coastlines (NW–SE and NE–SW to the west and east of Faro, respectively) in relation with the dominant storm approaches (SW and SE) would have also favoured a higher activity of storm events in the shoreface.

(b) *Distal unit*: Shelf aggradational deposits occur distally, although with poor development. Their occurrence in this area is related to a reduced local fluvial supply and to lateral advection of suspended sediments from source points located far from this area. The sediment dispersal would be controlled by along-shelf currents (Milliman et al., 1982; Chough et al., 2002; Yoo et al., 2002).

7.1.2. *Guadiana shelf*

As well as in the Portuguese shelf, two different morpho-sedimentary units (proximal and distal) compose the Guadiana depositional system.

The proximal unit is represented by the Guadiana inner prodeltaic wedge (Fig. 13B), whose moderate development and even the local occurrence of bedrocks (Nelson et al., 1999) could be related to: (a) moderate to low fluvial sediment supply, being only significant during flooding events (Lobo et al., in press); (b) intense hydrologic regime dominated by waves, storm activity and long-shore currents, which causes high reworking and does not favour significant deposition (Vanney and Mougenot, 1981; Nelson et al., 1999); and (c) influence of the Tavira–Guadiana High, as the lack of accommodation space over topographic highs prevents from significant recent sedimentation, as evidenced in other shelf settings (cf. Chin et al., 1997).

The formation of the distal unit, represented by shelf aggradational deposits attributed to muddy belts (Fig. 13B), has been controlled by: (a) the mixture of sediments from several rivers draining onto this shelf, especially from the Guadiana and to minor extent from the Tinto-Odiel and Piedras Rivers (Fig. 5); (b) the efficient activity of wave and storm events over the inner domain, particularly over the Tavira–Guadiana High, which would cause resuspension of fine-grained sediments (Nelson et al., 1999) and seaward export of the finer sediments, as evidenced in other shelves (Lesueur et al., 2001). The influence of the Tavira–Guadiana High is highlighted, because this morphological high behaved as a by-pass zone; and (c) lateral redistribution by prevailing shelf currents.

7.1.3. Guadalquivir shelf

The southeastern part of the study area is dominated by a single prodeltaic body (Fig. 13C), in contrast to the Guadiana shelf. Several factors would explain the wide distribution and high thickness of this prodelta: (a) high fluvial supply, as the Guadalquivir River is the main fluvial source draining into the Gulf of Cadiz margin (Maldonado and Nelson, 1999; Rodero et al., 1999) and (b) gentle shelf profile, which probably favoured energy dissipation and a reduced reworking activity of oceanographic agents.

7.2. Relationship between shelf circulation patterns and sediment dispersal

The integration of geological and oceanographical data permitted to evaluate the influence of shelf current patterns on sediment dispersal during the Holocene highstand in the study area. Sediment transport patterns were inferred from the analysis of: (a) progradational trends observed in proximal wedges, particularly evident in the Faro–Tavira wedge. There is substantial evidence that storm-generated deposits can be laterally redistributed by along-shelf currents below wave base level (Bradshaw et al., 1994; Siringan and Anderson, 1994; Thieler et al., 2001). Similarly oblique progradational trends identified in the study area are thought to indicate the imprint of long-term along-shelf currents and (b) distribution patterns of the distal muddy deposits, as transport of fine-grained deposits are highly influenced by current patterns (Park et al., 1996; Yoo et al., 2002).

On the basis of oceanographic data, an alternating current pattern on the Gulf of Cadiz shelf is evidenced, linked to the intermittent formation of a counter-current on the inner shelf of the Gulf of Cadiz. This current opposes the eastward flow of Atlantic Surface Water over the mid to outer shelf. The establishment of the bi-directional current pattern seems to be related with the wind field, which shows a bimodal pattern (westerlies and easterlies) and undergo changes of direction in short (3–4 days) time scales. Analysis of ADCP velocities at two locations east of Cape Santa Maria in winter 2001 also confirmed the alternating circulation pattern in agreement with reversal of the wind regime.

Estimates of sediment transport trends show a reasonable correlation with the observed shelf flow patterns, supporting the existence of a counter current system on the Gulf of Cadiz shelf. These flow conditions have possibly controlled the Holocene highstand dispersal system, which is characterised by a bi-directional pattern (Fig. 14).

7.2.1. Eastward dispersal

Most of the elongated HST depocenters found on the mid to outer shelf can be linked to significant southeastward transport of fine-grained sediments supplied by the main rivers, especially by the Guadiana, although the same interpretation could be applied to elongated depocenters located west of Cape Santa Maria, where shelf deposits would be possibly laterally advected from fluvial sources located to the west, such as the Arade River. The high lateral continuity of these depocenters suggests the persistence of the east and southeastward-directed flows (Fig. 14). The dominant east to southeastward sediment dispersal has been linked east of the Guadiana River to the influence of the Atlantic Inflow current system (Nelson et al., 1999), and is attributed to the large-scale anticyclonic circulation pattern off the Gulf of Cadiz shelf. This pattern features eastward advection of the upwelled, cold water plume into the Gulf of Cadiz following the mid to outer shelf bathymetry. This dominant circulation pattern is enhanced under the influence of southern Portuguese coast upwelling-favourable (westerly) winds.

7.2.2. Westward dispersal

According to previous works (Nelson et al., 1999), inner shelf facies would have been affected by a lower energy Atlantic Inflow current, in contrast to the more intense distal flow. However,

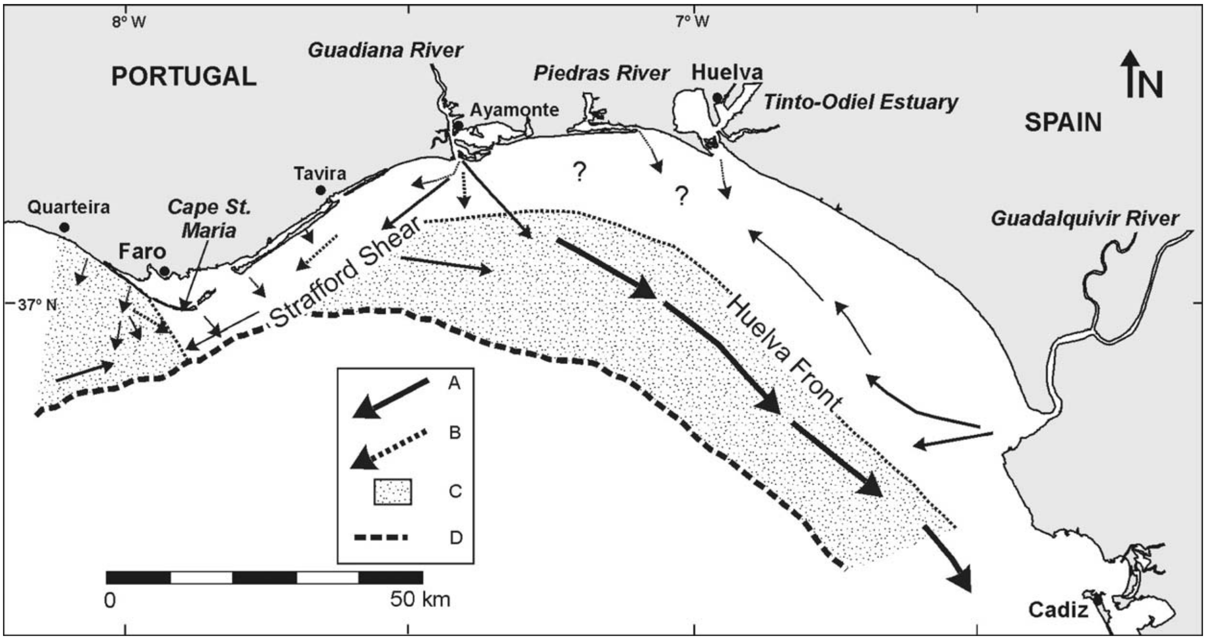

Fig. 14. Main trends of Holocene highstand sediment transport, inferred from progradational trends of proximal bodies and from distribution patterns of distal shelf deposits. The intensity of sedimentary transport is expressed by the size of the arrows. These trends feature two zones of current shear, known as the Huelva Front and the Strafford Shear. Legend: (A) long-term sedimentary transport trends of fine-grained sediments; (B) long-term sedimentary transport trends of proximal sediments (coarser); (C) zones influenced by the dominant eastward and southeastward transport and (D) present-day shelf break.

several evidences support that the action of an inshore westward counter-current has also been imprinted in Holocene highstand sedimentary deposits (Fig. 14). For example, the distribution of the Guadalquivir prodelta suggests that part of the Guadalquivir-derived sediments are also redistributed to the northwest, especially in the inner–middle shelf, where the main depocenter would join with the Guadiana-related depocenter. Besides, the identification of depocenters of the muddy aggradational deposit on the inner to middle shelf westward of the Guadiana River and the lack of fluvial supply to the west would indicate that a certain amount of fine-grained sediments were transported westward. Additionally, the observed southwest progradation of the Faro–Tavira wedge also indicates the possible influence of a westward-directed current in this area, which would be less influenced by the dominant anticyclonic circulation, due to the margin orientation (NE–SW) and to the narrowness of the shelf. The observed westward-directed sediment dispersal in the inshore zones would be linked to the westward flow of the inshore warm water tongue over the Spanish shelf (Fig. 14). This situation is enhanced under the influence of southern Portuguese coast downwelling-favourable (easterly) winds. The existence of southwestward-directed current flows and the control of wind patterns was confirmed by ADCP measurements in the inner shelf westward of the Guadiana River.

7.2.3. *Identification of oceanic boundaries*

The resultant bi-directional dispersal system seems to reflect two main zones of current shear which were described in the study area (Stevenson, 1977). The Huelva Front is recognised in the Spanish shelf, where inner deposits are redistributed northwestwards, whereas outer deposits are redistributed southeastwards. Westward of the Guadiana River mouth, the Strafford Shear, which is a strong current shear associated with a cold-warm boundary, is also evidenced. Hence, most of the deposits tend to be southwest-directed, but east of Tavira, where the shelf widens significantly, outer deposits seem to have been redistributed eastward (Fig. 14).

8. Conclusions

Contrasting pattern of depositional styles during the Holocene highstand in a sector of the northern Gulf of Cadiz shelf provides a model for transitional shelves in which starved shelves are substituted laterally by fluvially and current-dominated shelves. The Portuguese shelf is considered as a moderate to high-energy environment, where deposition was primarily controlled by high-energy events, leading to the construction of significant infralittoral prograding wedges, and secondarily by lateral redistribution of fine-grained sediments. This depositional regime is governed by a lack of fluvial supply and by the interplay between margin physiography and wave regime. Thus, the existence of a narrow, steep shelf and the normal orientation of the margin in relation with prevailing wave trends favoured erosive activity in the shoreface. Eastward, the Guadiana shelf receives more sediment than the Portuguese shelf from multiple river sources and shows a distinction between proximal and distal submarine fluvially-derived wedges. The differentiation of depositional bodies is the result of a moderate fluvial supply and a significant reworking activity of waves and currents over morpho-structural highs. Eastward, the Guadalquivir system presents a different depositional scheme characterised by a single prodeltaic structure. This shelf sector is fluvially dominated, as a consequence of high fluvial supply and moderate to low reworking activity of waves and currents, probably conditioned by smooth shelf gradients.

The integration of geological and oceanographical data enabled us to characterise the Holocene highstand sediment dispersal, which differs from previous work in the area. A counter current system has been detected. Eastward sediment dispersal mainly occurs west of Cape Santa Maria and east of Tavira, where the shelf widens significantly. These zones are governed by the dominant large-scale anticyclonic circulation pattern, which is enhanced under the influence of upwelling-favourable (westerly) winds on the Portuguese coast. A westward-directed sediment dispersal in the inshore zones is reported here for the first time. The partial northwestward redistribution of the Guadalquivir prodelta and the identification of southwestward-directed progradational patterns on the inner Portuguese shelf have been related to the intermitent westward entrance of warm water tongues on the shelf under the action of easterly winds. As a result of this complex shelf circulation pattern, the sediment dispersal system shows a cyclonic circulation between Cape Santa Maria and the Guadalquivir River mouth, which can be considered as a dispersal system expression of two zones of current shear, known as the Huelva Front and the Strafford Shear. Besides, the identification of shallow-water wedges migrating in opposite directions implies that along-shelf flows tend to converge around the Ria Formosa system.

Acknowledgements

The geological database was collected through several oceanographic surveys (Golca, Fado and Wadi Ana), jointly organized between several institutions: the universities of Algarve and Cádiz, the Instituto Español de Oceanografía, the Instituto Geológico y Minero de España and the Disepla group. The research benefited from the following projects: Emerge (Odiana Program), PB-91-0622-C03/Golca and PB-94-1090-CO3/Fado (Spanish Marine Science and Technology Program). F.J. Lobo was funded by a Post-Doctoral FCT Research Grant (Reference SFRH/BPD/5616/2001) and by a Marie Curie Individual Fellowship, under contract no HPMF-CT-2001-01494 between the Universidade do Algarve and the European Comission. R. Sánchez was funded by the ATOMS project (FCT contract

PDCTM/P/MAR/15296/1999). Journal referees Dr. M.R. Tesson and Dr. S.H. Lee are sincerely thanked, by their constructive comments and suggestions. Helpful comments of P. Relvas are also appreciated. The participation of Francisco González, Lola Godoy, Marga García and Jorge Miranda in the Wadi Ana 2000 survey is particularly acknowledged, as well as the Instituto Hidrográfico and the crew of R/V Andrómeda. This study is part of the research project IGCP no. 464 entitled "Continental Shelves during the Last Glacial Cycle: Knowledge and Applications".

References

Algan, O., Gökaşan, E., Gazioğlu, C., Yücel, Z.Y., Alpar, B., Güneysu, C., Kirci, E., Demirel, S., Sari, E., Ongan, D., 2002. A high-resolution seismic study in Sakarya Delta and Submarine Canyon, Southern Black Sea shelf. Continental Shelf Research 22, 1511–1527.

Baringer, M.O., Price, J.F., 1999. A review of the physical oceanography of the Mediterranean outflow. Marine Geology 155, 63–82.

Bradshaw, B.E., Healy, T.R., Nelson, C.S., Dell, P.M., de Lange, W.P., 1994. Holocene sediment lithofacies and dispersal systems on a storm-dominated, back-arc shelf margin: the east Coromandel Coast, New Zealand. Marine Geology 119, 75–98.

Chin, J.L., Karl, H.A., Maher, N.M., 1997. Shallow subsurface geology of the continental shelf, Gulf of the Farallones, California, and its relationship to surficial seafloor characteristics. Marine Geology 137, 251–269.

Chiocci, F.L., Orlando, L., 1996. Lowstand terraces on Tyrrhenian Sea steep continental slopes. Marine Geology 134, 127–143.

Chough, S.K., Kim, J.W., Lee, S.H., Shinn, Y.J., Jin, J.H., Suh, M.C., Lee, J.S., 2002. High-resolution acoustic characteristics of epicontinental sea deposits, central-eastern Yellow Sea. Marine Geology 188, 317–331.

Costa, C., 1994. Wind Wave Climatology of the Portuguese Coast: Final Report of Subproject A, NATO PO-WAVES Report 6/94-A, 80pp.

Dias, J.M.A., Jouanneau, J.M., González, R., Araújo, M.F., Drago, T., Garcia, C., Oliveira, A., Rodrigues, A., Vitorino, J., Weber, O., 2002. Present day sedimentary processes on the Northern Iberian shelf. Progress in Oceanography 52, 249–259.

Díaz, J.I., Palanques, A., Nelson, C.H., Guillén, J., 1996. Morpho-structure and sedimentology of the Holocene Ebro prodelta mud belt (northwestern Mediterranean Sea). Continental Shelf Research 16, 435–456.

Emery, W.J., Thomson, R.E., 1997. Data Analysis Methods in Physical Oceanography. Pergamon Press, Oxford, 634pp.

Ergin, M., Okyar, M., Timur, K., 1992. Seismic stratigraphy and late Quaternary sediments in inner and mid-shelf areas of eastern Mersin Bay, Northeastern Mediterranean Sea. Marine Geology 104, 73–91.

Fernández Salas, L.M., Rey, J., Pérez-Vázquez, E., Ramírez, J.L., Hernández-Molina, F.J., Somoza, L., De Andrés, J.R., Lobo, F.J., 1999. Morphology and characterization of the relict facies on the internal continental shelf in the Gulf of Cadiz between Ayamonte and Huelva (Spain). Boletín del Instituto Español de Oceanografía 15, 123–132.

Figueiredo Jr., A.G., Nittrouer, C.A., 1995. New insights to high-resolution stratigraphy on the Amazon continental shelf. Marine Geology 125, 393–399.

Fiúza, A.F., 1983. Upwelling patterns off Portugal. In: Suess, Pt.A.E., Thiede, J. (Eds.), Coastal Upwelling. Plenum Publishing Corporation, New York.

Folkard, A.M., Davies, P.A., Fiúza, A.F.G., Ambar, I., 1997. Remotely sensed sea surface thermal patterns in the Gulf of Cadiz and the Strait of Gibraltar: variability, correlations, and relationships with the surface wind field. Journal of Geophysical Research 102, 5669–5683.

Gutiérrez-Mas, J.M., Hernández-Molina, F.J., López-Aguayo, F., 1996. Holocene sedimentary dynamics on the Iberian continental shelf of the Gulf of Cádiz (SW Spain). Continental Shelf Research 16, 1635–1653.

Harris, P.T., Pattiaratchi, C.B., Keene, J.B., Dalrymple, R.W., Gardner, J.V., Baker, E.K., Cole, A.R., Mitchell, D., Gibbs, P., Schroeder, W.W., 1996. Late Quaternary deltaic and carbonate sedimentation in the Gulf of Papua foreland basin: response to sea-level change. Journal of Sedimentary Research 66, 801–819.

Hernández-Molina, F.J., Somoza, L., Fernández-Salas, L.M., Lobo, F.J., Llave, E., 1998. Late Holocene infralittoral wedge: a large-scale progradational lithosome in shallow marine environments. Proceedings of the 15th International Sedimentological Congress, Abstracts Book, pp. 421–422.

Hernández-Molina, F.J., Fernández-Salas, L.M., Lobo, F.J., Somoza, L., Díaz del Río, V., Alveirinho Dias, J.M., 2000a. The infralittoral prograding wedge: a new large-scale progradational sedimentary body in shallow marine environments. Geo-Marine Letters 20, 109–117.

Hernández-Molina, F.J., Somoza, L., Lobo, F.J., 2000b. Seismic stratigraphy of the Gulf of Cádiz continental shelf: a model for late Quaternary very high-resolution sequence stratigraphy and response to sea-level fall. In: Hunt, D., Gawthorpe, R.L.G. (Eds.), Sedimentary Responses to Forced Regressions. Geological Society Special Publication, Vol. 172, London, pp. 329–361.

Jin, J.H., Chough, S.K., 1998. Partitioning of transgressive deposits in the southeastern Yellow Sea: a sequence stratigraphic interpretation. Marine Geology 149, 79–92.

Kuehl, S.A., Levy, B.M., Moore, W.S., Allison, M.A., 1997. Subaqueous delta of the Ganges–Brahmaputra river system. Marine Geology 144, 81–96.

Lee, C.S., Chung, Y.H., 2000. Late Quaternary sedimentation in the Kadeok region, Korea. Geo-Marine Letters 20, 72–79.

Lesueur, P., Jouanneau, J.-M., Boust, D., Tastet, J.-P., Weber, O., 2001. Sedimentation rates and fluxes in the continental shelf mud fields in the Bay of Biscay (France). Continental Shelf Research 21, 1383–1401.

Lobo, F.J., 1995. Estructuración y evolución morfosedimentaria de un sector del margen continental septentrional del Golfo de Cádiz durante el Cuaternario Terminal. Dissertation, University of Cádiz, 200pp.

Lobo, F.J., 2000. Estratigrafía de alta resolución y cambios del nivel del mar durante el Cuaternario del margen continental del Golfo de Cádiz (S de España) y del Roussillon (S de Francia): estudio comparativo. Ph.D. Thesis, University of Cádiz, 618pp.

Lobo, F.J., Hernández-Molina, F.J., Somoza, L., Díaz del Río, V., 2001. The sedimentary record of the post-glacial transgression on the Gulf of Cadiz continental shelf (Southwest Spain). Marine Geology 178, 171–195.

Lobo, F.J., Hernández-Molina, F.J., Somoza, L., Díaz del Río, V., Dias, J.M.A., 2002. Stratigraphic evidence of an upper Pleistocene TST to HST complex on the Gulf of Cádiz continental shelf (south-west Iberian Peninsula). Geo-Marine Letters 22, 95–107.

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

Maldonado, A., Nelson, C.H., 1999. Interaction of tectonic and depositional processes that control the evolution of the Iberian Gulf of Cadiz margin. Marine Geology 155, 217–242.

Mauritzen, C., Morel, Y., Paillet, J., 2001. On the influence of Mediterranean water on the central waters of the North Atlantic Ocean. Deep-Sea Research I 48, 347–381.

Milliman, J.D., Butenko, J., Barbot, J.P., Hedberg, J., 1982. Depositional patterns of modern Orinoco/Amazon muds on the Northern Venezuelan shelf. Journal of Marine Research 40, 643–657.

Mitchum Jr., R.M., Va il, P.R., Sangree, J.B., 1977. Seismic stratigraphy and global changes of sea level, Part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences. In: Payton, C.E. (Ed.), Seismic Stratigraphy—Applications to Hydrocarbon Exploration, American Association of Petroleum Geologists Memoir, Tulsa, Oklahoma, Vol. 26, pp. 117–133.

Moita, I., 1986. Noticia Explicativa da Carta dos Sedimentos Superficiais da Plataforma. Folha SED 8, Instituto Hidrográfico, 18pp.

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

Münchow, A., 2000. Wind-stress curl forcing of the coastal ocean near Point Conception, California. Journal of Physical Oceanography 30, 1265–1280.

Nelson, C.H., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., Barber Jr., J.H., 1999. Influence of the Atlantic inflow and Mediterranean outflow currents on late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. Marine Geology 155, 99–129.

Nittrouer, C.A., Kuehl, S.A., Figueiredo, A.G., Allison, M.A., Sommerfield, C.K., Rine, J.M., Faria, E.C., Silveira, O.M., 1996. The geological record preserved by Amazon shelf sedimentation. Continental Shelf Research 16, 817–841.

Novak, B., Pedersen, G.K., 2000. Sedimentology, seismic facies and stratigraphy of a Holocene spit-platform complex interpreted from high-resolution shallow seismics, Lysegrund, southern Kattegat, Denmark. Marine Geology 162, 317–335.

Ochoa, J., Bray, N.A., 1991. Water mass exchange in the Gulf of Cadiz. Deep-Sea Research 38, 5465–5503.

Palanques, A., Plana, F., Maldonado, A., 1986–1987. Estudio de la materia en suspensión en el Golfo de Cádiz. Acta Geológica Hispánica 21–22, 491–497.

Park, S.C., Jang, K.M., Lee, S.D., 1990. High-resolution seismic study of modern fine-grained deposits: inner shelf off the Southeastern coast of Korea. Geo-Marine Letters 10, 145–149.

Park, S.C., Lee, K.W., Song, Y.I., 1995. Acoustic characters and distribution pattern of modern fine-grained deposits in a tide-dominated coastal bay: Jinhae Bay, Southeast Korea. Geo-Marine Letters 15, 77–84.

Park, S.C., Hong, S.K., Kim, D.C., 1996. Evolution of late Quaternary deposits on the inner shelf of the South Sea of Korea. Marine Geology 131, 219–232.

Park, S.-C., Yoo, D.-G., Lee, K.-W., Lee, H.-H., 1999. Accumulation of recent muds associated with coastal circulations, southeastern Korea Sea (Korea Strait). Continental Shelf Research 19, 589–608.

Pomar, L., Tropeano, M., 2001. The calcarenite di gravina formation in matera (Southern Italy): new insights for coarse-grained, large scale, cross-bedded bodies encased in offshore deposits. American Association of Petroleum Geologists Bulletin 85, 661–689.

Relvas, P., Barton, E.D., 2002. Mesoscale patterns in the Cape São Vicente (Iberian Peninsula) upwelling region. Journal of Geophysical Research 107 (C10) 3164, doi:10.1029/2000JC000456.

Rey, J., Medialdea, T., 1989. Morfología y sedimentos recientes del margen continental de Andalucía Occidental. El Cuaternario en Andalucía Occidental, AEQUA Monografías 1, 133–144.

Rodero, J., 1999. Dinámica sedimentaria y modelo evolutivo del margen continental suroriental del Golfo de Cádiz durante el Cuaternario Superior (Pleistoceno Medio-Holoceno). Ph.D. Thesis, University of Granada, 343pp.

Rodero, J., Pallarés, L., Maldonado, A., 1999. Late Quaternary seismic facies of the Gulf of Cadiz Spanish margin:

depositional processes influenced by sea-level change and tectonic controls. Marine Geology 155, 131–156.

Roque, C., 1998, Análise morfosedimentar da sequência deposicional do Quaternário Superior da plataforma continental Algarvia entre Faro e a foz do Rio Guadiana. Dissertation, University of Lisbon, 221pp.

Siringan, F.P., Anderson, J.B., 1994. Modern shoreface and inner-shelf storm deposits off the east Texas coast, Gulf of Mexico. Journal of Sedimentary Research 64, 99–110.

Somoza, L., Hernández-Molina, F.J., De Andrés, J.R., Rey, J., 1997. Continental shelf architecture and sea-level cycles: late Quaternary high-resolution stratigraphy of the Gulf of cáDiz, Spain. Geo-Marine Letters 17, 133–139.

Stevenson, R.E., 1977. Huelva front and malaga, Spain, eddy chain as defined by satellite and oceanographic data. Deutsche Hydrographische Zeitschrift 30, 51–53.

Thieler, E.R., Pilkey Jr., O.H., Cleary, W.J., Schwab, W.C., 2001. Modern sedimentation on the shoreface and inner continental shelf at Wrightsville Beach, North Carolina, USA. Journal of Sedimentary Research 71, 958–970.

Van Geen, A., Adkins, J.F., Boyle, E.A., Nelson, C.H., Palanques, A., 1997. A 120 yr record of widespread contamination from mining of the Iberian pyrite belt. Geology 25, 291–294.

Vanney, J.-R., Mougenot, D., 1981. La plate-forme continentale du Portugal et les provinces adjacentes: Analyse geomorphologique. Memórias dos Serviços Geológicos de Portugal 28, 86pp.

Vargas, M., García-Lafuente, J., Delgado, J., Criado, F., 2003. Seasonal and wind-induced variability of Sea Surface Temperature patterns in the Gulf of Cádiz. Journal of Marine Systems 38, 205–219.

Yoo, D.G., Lee, C.W., Kim, S.P., Jin, J.H., Kim, J.K., Han, H.C., 2002. Late Quaternary transgressive and highstand systems tracts in the northern East China Sea mid-shelf. Marine Geology 187, 313–328.