Geo-Mar Lett (2002) 22: 95–107
DOI 10.1007/s00367-002-0103-0

**F.J. Lobo · F.J. Hernández-Molina · L. Somoza**
**V. Díaz del Río · J.M.A. Dias**

# Stratigraphic evidence of an upper Pleistocene TST to HST complex on the Gulf of Cádiz continental shelf (south-west Iberian Peninsula)

Received: 4 December 2001 / Accepted: 15 May 2002 / Published online: 18 June 2002


**Abstract** A composite backstepping seismic unit located from the middle shelf to the upper slope on the Gulf of Cadiz margin was identified and characterised through the analysis of high-resolution seismic profiles. The composite seismic unit is made up of two seismic units representing a complex transgressive systems tract to highstand systems tract. Their deposition probably took place during the sea-level rise which occurred between marine isotopic stages 4 and 3, and during the following relative highstand. The seismic stratigraphic evidence suggests that, although the upper Pleistocene sedimentary record of this margin consists mainly of sediments deposited during falling sea levels and lowstands, the deposition of transgressive and highstand deposits can occur under specific circumstances.

## Introduction

The glacio-eustatic sea-level curve during the late Quaternary describes an asymmetric fourth-order cycle (periodicity of about 100,000 years) in which the fall of sea level occurred from the last interglacial to the last glacial maximum during marine isotopic stage (MIS) 2, at about 22–18 ka B.P. Subsequently, sea level rose very rapidly up to 6 ka B.P. in response to glacial melting. The last 6,000 years have been characterised by a sea level in a highstand position (Imbrie et al. 1984).

The upper Pleistocene can be considered a cold stage beginning at 115–120 ka B.P. and ending at around 10–11 ka B.P. The fourth-order sea-level cycle was not simple, but was itself modulated by fifth-order asymmetric cycles with a periodicity of about 23,000 years and also dominated by intervals of falling sea level (Chappell and Shackleton 1986; Chappell et al. 1996). The existence of these fifth-order cycles was possibly controlled by short-lived warm episodes occurring at approximately 103, 79, 55 and 50 ka B.P. (Martinson et al. 1987).

In general, the Quaternary sedimentary record of terrigenous continental shelves is characterised by prograding wedges generated during forced regressions and lowstand intervals (Chiocci 2000; Tesson et al. 2000; Trincardi and Correggiari 2000). Furthermore, the late Quaternary record almost exclusively reveals prograding wedges of the regressive and lowstand system tracts (RST and LST respectively; Gensous and Tesson 1996; Yoo and Park 1997; Hernández-Molina et al. 2000), because the sedimentary processes were dominated by deposition during falling sea levels and lowstands occurring during 65% of the time interval (Chiocci et al. 1997). Transgressive and highstand systems tracts (TST and HST respectively) were preserved in the upper Pleistocene sedimentary record of continental shelves only under specific circumstances (Ashley et al. 1991; Carey et al. 1998; Sheridan et al. 2000). It has been suggested that the preservation potential of TSTs and HSTs in continental shelf deposits increases as their order of cyclicity decreases (Chiocci 1994). Consequently, the preservation potential of such systems tracts during fifth-order cycles is thought to be very low.

The seismic stratigraphic architecture of the Gulf of Cadiz has been described in general terms in several

F.J. Lobo (✉) · J.M.A. Dias
CIACOMAR-Universidade do Algarve,
Avenida 16 de Junho,
s/n 8700-311 Olhão, Portugal
E-mail: pacolobo@ualg.pt
Tel.: +0351-289-707087
Fax: +0351-289-706972

F.J. Hernández-Molina
Dpto. de Geociencias Marinas y Ordenación
del Territorio, Universidad de Vigo,
36200 Vigo, Spain

L. Somoza
Instituto Geológico y Minero de España (IGME),
Sección de Geología Marina, Río Rosas 23,
28003 Madrid, Spain

V. Díaz del Río
Instituto Español de Oceanografía,
Centro Oceanográfico de Málaga,
Puerto Pesquero, s/n 29640
Fuengirola, Malaga, Spain

recent studies (Somoza et al. 1997; Lobo 2000; Hernández-Molina et al. 2000; Lobo et al. 2001), but specific aspects of its sedimentary structure remained unpublished. The sedimentary record of the Gulf of Cadiz continental shelf reflects an asymmetric pattern of sea-level fluctuations. An asymmetric fourth-order depositional sequence has developed from the last interglacial period to the present. Regressive and lowstand deposits accumulated from 125 to 14 ka B.P., transgressive deposits from 14 to 6 ka B.P., and highstand deposits during the last 6 ka. This sequence is asymmetric because regressive and lowstand deposits are better preserved than transgressive and highstand deposits. This fourth-order depositional sequence is composed of fifth-order, type-1 depositional sequences, equally of asymmetric character (Somoza et al. 1997; Hernández-Molina et al. 2000). Transgressive and highstand deposits are relatively well represented in the post-glacial sedimentary record, but they are poorly preserved or absent in previous fifth-order depositional sequences occurring between MISs 5 and 3 (Hernández-Molina et al. 2000).

The main objective of this paper is to document the existence of some deposits on the Gulf of Cadiz shelf which are probably related to transgressive and highstand intervals prior to the last glacial maximum (Würm). A chronostratigraphic approach, using sequence stratigraphic interpretations and a comparison with similar stratigraphic patterns found on other shelves, was applied to reconstruct the general sedimentary conditions and to determine the main controlling factors for the formation and preservation of these deposits.

## Study area

The work focuses on a sector of the Gulf of Cádiz continental shelf (south-western Iberian Peninsula) located between the Guadalquivir River mouth in the east (6°30′W) and the Portuguese town of Quarteira in the west (8°W; Fig. 1). This region is under the influence of mixing water masses originating from the Atlantic and the Mediterranean through the Straits of Gibraltar. The fluvial input to this margin is controlled by the discharge of the Guadiana, Piedras, Tinto-Odiel, and Guadalquivir river basins. Of these, the contributions of the Guadiana and Guadalquivir rivers are the most significant, reaching average yearly water discharges of up to 160 $m^3/s$ (Morales 1997; Van Geen et al. 1997).

The northern continental shelf of the Gulf of Cadiz is characterised by variable seafloor gradients. The Portuguese shelf has a mean slope of 0.5°, ranging between 0.32 and 1.27° (Andrade 1990), whereas the mean slope of the Spanish shelf is mostly lower than 0.3° (Lobo 1995). Shelf width varies from 5 to 50 km. The widest section is located on the Spanish side where the average width is 30 km, becoming progressively narrower both towards Portugal and the Straits of Gibraltar where shelf width is lower than 10 km (Heezen and Johnson 1969; Baldy 1977; Vanney and Mougenot 1981; Lobo 1995; Roque 1998). The shelf-break is located at variable depths of 100–130 m, giving way to an upper slope located at water depths of 130–400 m with an average width of 10 km and a variable gradient of 1–3° (Heezen and Johnson 1969; Nelson et al. 1993).

The main morpho-structural features of the study area have been described in Lobo (2000). Five sectors can be distinguished on the basis of the distribution of stratigraphic surfaces, stacking pattern of seismic units, and main neotectonic features (Fig. 2): (1) the shelf west of Faro, characterised by moderate seafloor gradients ranging from 0.4 to 0.6°; (2) the shelf between Faro and Tavira, characterised by higher seafloor gradients ranging between 0.75 and 1.20°; (3) the shelf offshore from the Guadiana River mouth, where a morpho-structural

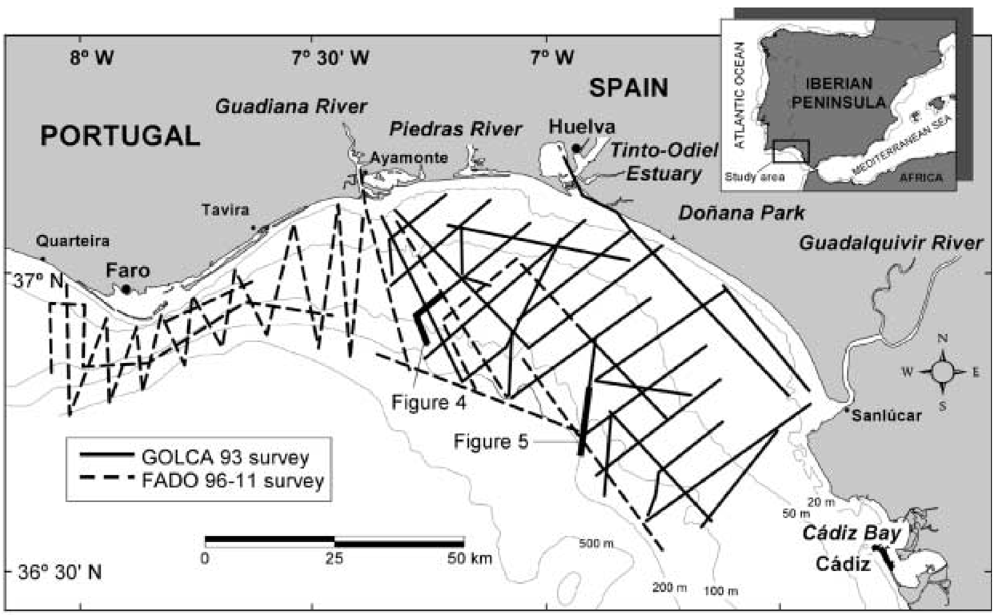



**Fig. 1** Geographical location of the study area and position of high-resolution seismic profiles

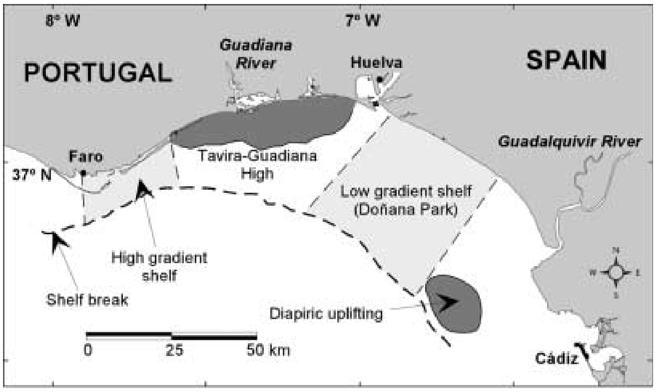



**Fig. 2** Simplified sketch showing the main morphostructural sectors of the Gulf of Cadiz continental shelf, between Quarteira town (Portugal) and the Guadalquivir River mouth (Spain) (extracted from Lobo 2000)

high extending from Tavira in the west to the Piedras River in the east (the "Tavira-Guadiana High") has been identified and which has been present at least during late Quaternary times; seafloor gradients are lower than 0.3° at the top of the Tavira-Guadiana High on the inner shelf, increasing on the middle shelf to an average of 0.5°, to finally decrease again on the outer shelf to less than 0.3°; (4) the shelf off the Doñana Park, which is a subsiding sector characterised by stratigraphic surfaces with very low gradients, usually lower than 0.2°; and (5) the shelf off the Guadalquivir River mouth, characterised by uplifting as a consequence of diapiric-like intrusions.

The dominant littoral drift is directed towards the east, generated as a consequence of the influence of the westerly waves occurring in the Gulf of Cadiz 74% of the time. Wave orientation ranges between N-20°-E and N-30°-E, and the significant wave height is 0.4 m (Morales 1997). During storm conditions the values can reach >1 m with an average period of 4.6 s. Together with the oblique orientation of the coastline, the littoral drift has generated a series of east-oriented spits along the coast (Dabrio et al. 1980; Morales et al. 1994). In the Portuguese sector, the coastal current flows at depths of up to 30 m with velocities below 0.25 m/s, sporadically reaching values more than 0.5 m/s (Moita 1986). In the Spanish sector, current velocities of 0.70 m/s have been reported (Melières 1974). Sediment transport induced by littoral drift has been estimated as ranging between $180\times10^3$ (Cuena 1991) and $300\times10^3$ $m^3$/year (CEEPYC 1979). Easterly waves are less frequent, although the significant wave height is slightly higher than 0.7 m and the period is 5.08 s. Highly energetic waves can be generated during winter storms, reaching maximum heights of 6 m and significant heights up to 3.80 m (Morales 1993).

The shelf oceanography is dominated by the so-called Atlantic inflow current (Nelson et al. 1999) which receives contributions from the surficial Atlantic water, formed as a consequence of atmospheric phenomena in the Gulf of Cadiz, and from the surficial North-Atlantic water which is an isolated water mass derived from the Portugal current (Caralp 1988). The Atlantic inflow water flows south-eastwards over the shelf of the Gulf of Cadiz from Cape Saint Vincent to the Straits of Gibraltar in a clockwise fashion (Martínez et al. 1998; Nelson et al. 1999), eventually entering the Mediterranean Sea through the Straits of Gibraltar. The velocity of this shelf current is variable but a general south-eastward increase is observed. Average velocities of 0.1–0.15 m/s have been measured over the shelf (Nelson et al. 1999).

## Materials and methods

A seismic stratigraphic analysis of the Gulf of Cadiz continental shelf between Faro (Portugal) and the Guadalquivir River mouth (Spain) was carried out in order to better understand the processes controlling the sedimentary build-up during late Quaternary times. To reach this goal, two high-resolution seismic surveys were carried out (Fig. 1): 790 km of seismic profiles were collected during the Golca 93 survey. Additionally, 690 km of high-resolution seismic profiles were obtained during the Fado 96-11 survey, covering almost exclusively the Portuguese continental shelf off the coast of the Algarve in southern Portugal.

The seismic source was a Uniboom (Geopulse) system which provides good resolution for the uppermost 100–200 m of the sedimentary record (Chiocci 1994). Positioning during both seismic surveys was achieved using a differential GPS.

The high-resolution seismic profiles obtained were interpreted following well-established criteria for seismic stratigraphy analysis. The seismic evaluation was followed by a sequence stratigraphic interpretation in which identified seismic units were correlated with standard curves for sea-level changes which have been reported for the late Quaternary, and with equivalent deposits identified on other continental shelves. For the sequence stratigraphic analysis we followed a fourfold division of systems tracts in which the initial threefold scheme of Posamentier and Vail (1988) for a type-1 depositional sequence (LST, TST, and HST) was expanded to include an RST (or forced wedge regressive systems tract, FWRST) as proposed by Hunt and Tucker (1992).

## Results

### Seismic stratigraphy

The general seismic stratigraphic scheme (Fig. 3) shows a dominance of wedge-shaped units occurring from the middle shelf to the upper slope. It was sometimes possible to identify sheet-like units which cover the entire shelf (e.g. seismic units 1 and 5). The stratigraphic pattern is characterised by alternating inner-middle shelf

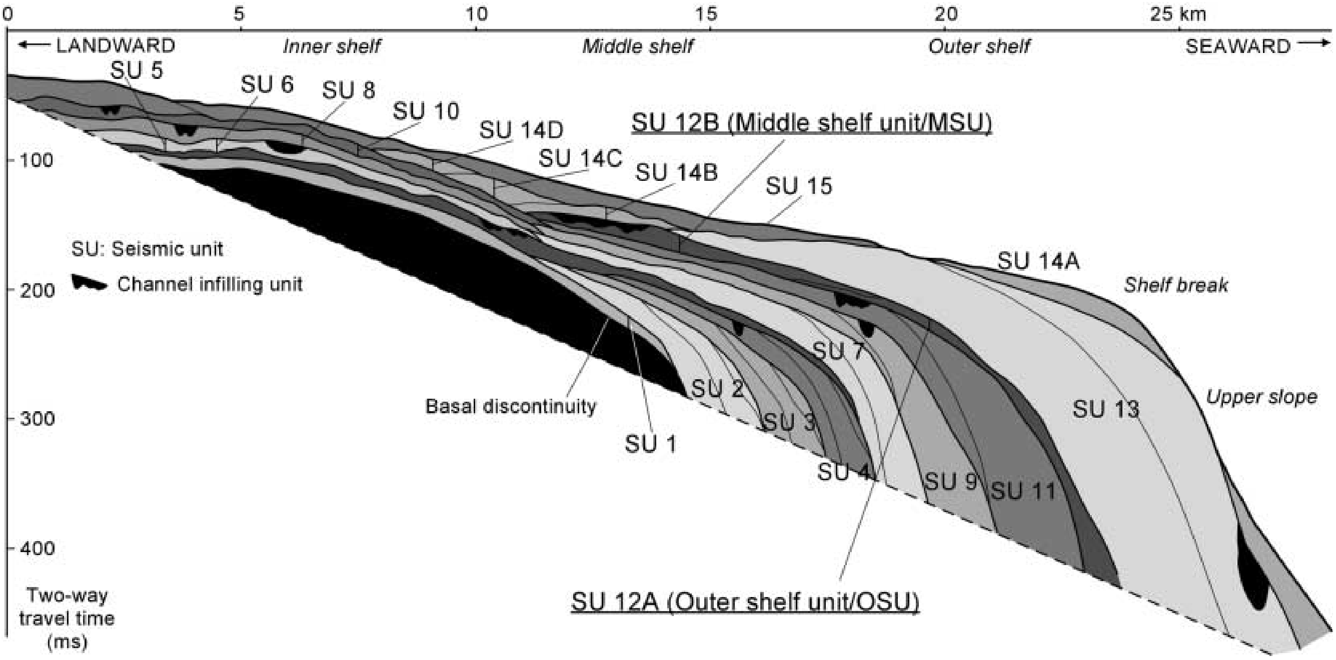
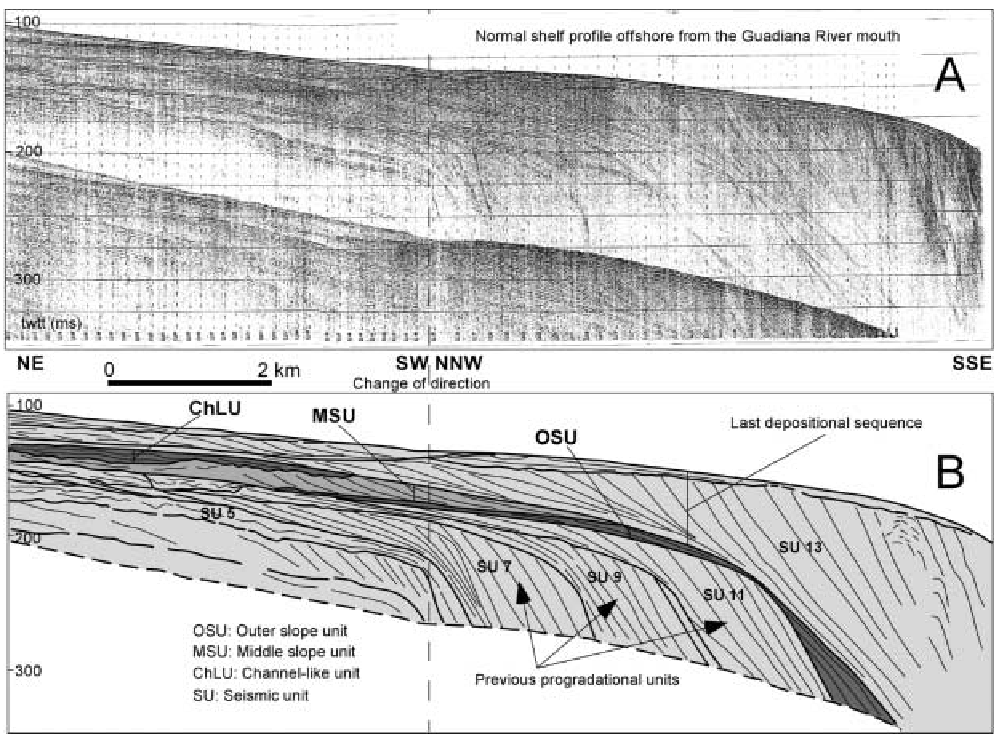



**Fig. 3** General seismic stratigraphy interpretation of the Gulf of Cadiz continental shelf (extracted from Lobo 2000)

units and outer shelf-upper slope units overlying seismic unit 5 (see also Lobo et al. 1999). The inner-middle shelf units (e.g. seismic units 6, 8 and 10) show a complex arrangement of seismic facies but in general are characterised by extensive subparallel seismic facies without internal subdivisions. The outer shelf-upper slope wedge-shaped units are characterised by prograding clinoforms with occasional internal discontinuities (e.g. seismic units 7, 9, 11 and 13). This general trend is interrupted by a composite seismic unit (seismic unit 12 in the scheme) showing a backstepping stacking pattern caused by the existence of two seismic subunits (12A and 12B). Seismic unit 12A is located on the outer shelf to upper slope, and seismic unit 12B is located on the middle to outer shelf (Fig. 3). The composite seismic unit 12 is stratigraphically located between two outer shelf-upper slope wedge-shaped units, i.e. seismic unit 11 beneath and seismic unit 13 above (Figs. 4 and 5). As seismic unit 12 represents a change in the general trend

**Fig. 4** **A** High-resolution seismic section (Geopulse source) and **B** interpretation of the middle shelf to outer slope of the Gulf of Cadiz continental shelf, focusing on the CDBU off the Guadiana River mouth. A channel-like unit affects the middle shelf unit at its top boundary (see position in Fig. 1)



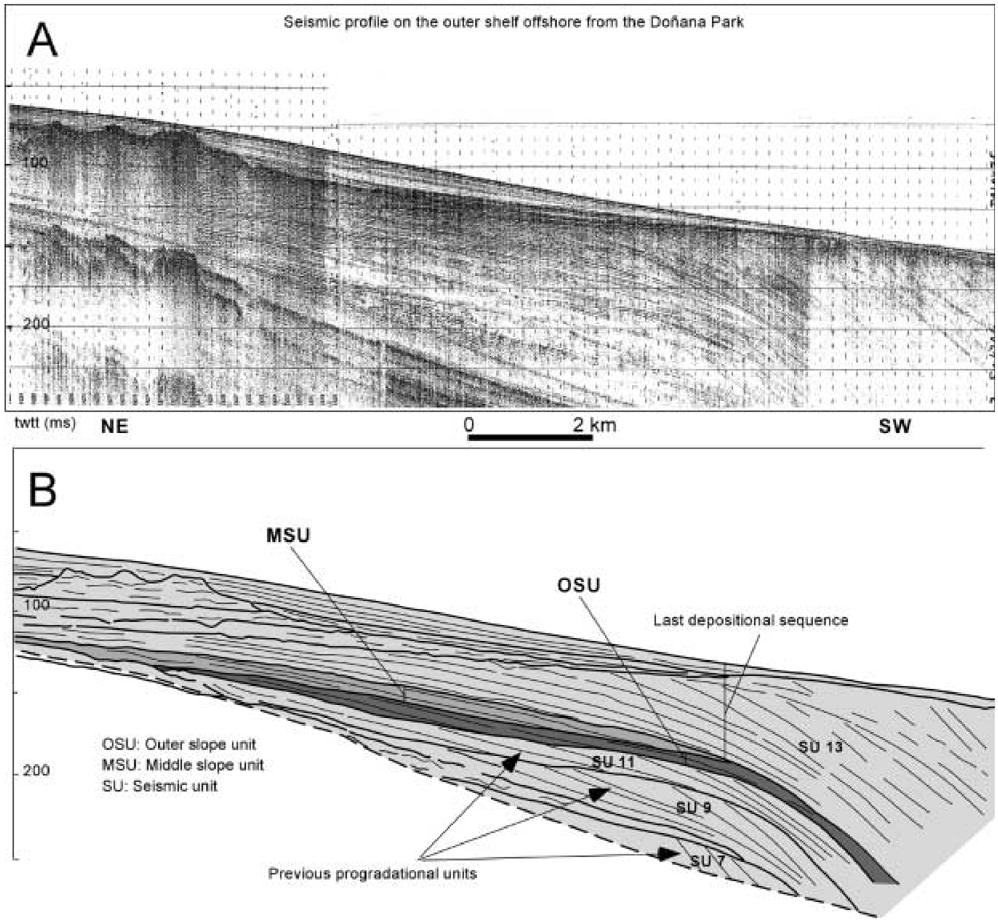



**Fig. 5** **A** High-resolution seismic section (Geopulse source) and **B** interpretation of the middle shelf to outer slope of the Gulf of Cadiz continental shelf, focusing on the CDBU off the Doñana Park. The OSU and MSU are characterised by low-angle prograding seismic configurations (see position in Fig. 1)

of the depositional architecture, its study provided several clues for the sea-level history and the recent evolution of the local continental margin. This composite seismic unit has been allocated number 12 following the terminology of Lobo (2000). It is equivalent to seismic unit 9 of Hernández-Molina et al. (2000). For the purpose of this study, it will be named composite distal backstepping unit (CDBU). Seismic unit 12A is considered an outer shelf unit (OSU), whereas seismic unit 12B is considered a middle shelf unit (MSU).

## Boundaries

The lower boundary of the CDBU is a downlap surface in the middle to outer shelf. The seafloor gradients of this discontinuity show a general eastward reduction (Fig. 6A): mean slopes of 1.13° on the Portuguese shelf, 0.55° off the Tavira-Guadiana High, and 0.27° on the continental shelf off the Doñana Park. The most prominent feature on the inner shelf is the Tavira-Guadiana High, whereas the isobaths show a convex pattern on the continental shelf off the Doñana Park. The middle-outer shelf is characterised by gradients lower than 0.5°. The depth lines run parallel to the present-day coastline off the –100 millisecond (ms) contour, being interrupted only by the presence of two promontories, one on the Portuguese shelf and the other off the Guadalquivir shelf. The shelf-break is located at an approximate depth corresponding to the –200 ms contour (Fig. 6A).

The upper boundary merges landwards with older discontinuities, and can be considered a toplap surface in relation to internal reflectors of the CDBU. This discontinuity is characterised by a gentle inner and outer shelf and by a relatively steep slope (Fig. 6B). The following sectors can be distinguished: (1) the shelf between Faro and Tavira, with relatively steep slopes (up to 1°); (2) the shelf off the Guadiana River mouth between Tavira and the Tinto-Odiel Estuary, characterised by a low-gradient inner and outer shelf ($<0.3°$) and a middle shelf with a higher seafloor gradient (up to 0.6°); and (3) the shelf off the Doñana Park, where the seafloor gradients are very low ($<0.3°$). The break of slope of the continental shelf is defined by the –180 ms depth contour (Fig. 6B).

## Distribution, thickness and internal structure

The landward termination of the CDBU is variable (Fig. 6C) but is generally located on the middle shelf at distances ranging between 15 and 18 km from the present-day coastline. Occasionally it can also be found

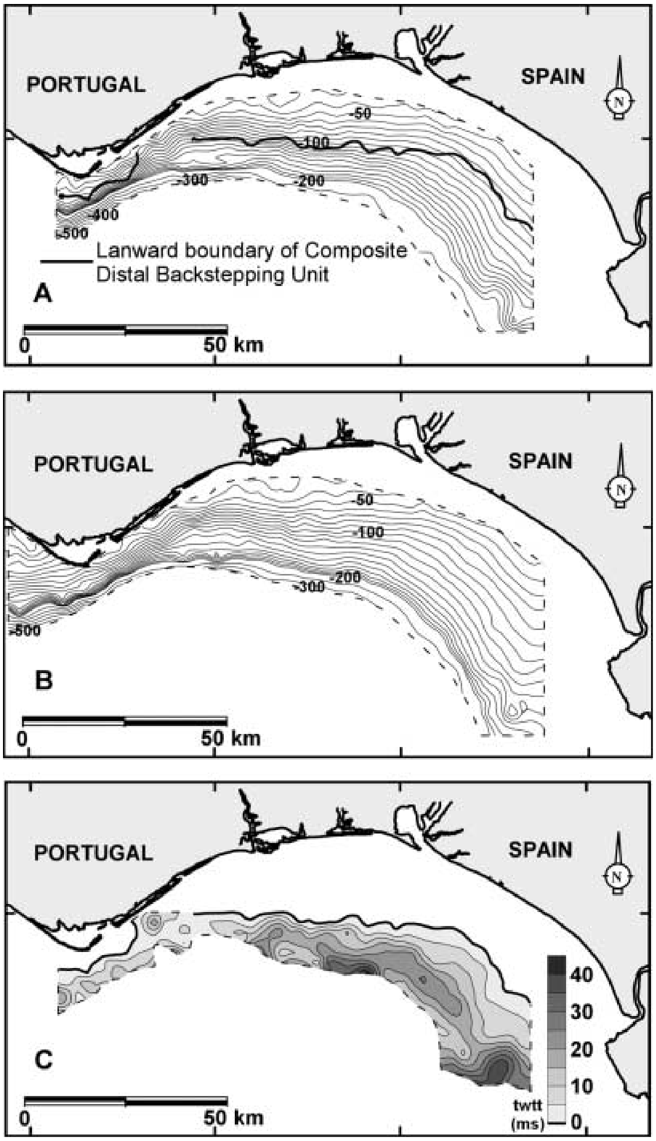



**Fig. 6A–C** Main characteristics of bounding surface and distribution of CDBU. **A** Distribution map of the lower boundary (given in ms). **B** Distribution map of the upper boundary (given in ms). **C** Contour map of the CDBU (given in ms)

on the inner shelf, e.g. the Faro shelf. The thickness of this unit is variable, alternating between zones where the thickness increases progressively seawards and other zones where the depocentres are located on the outer shelf. The CDBU is characterised by moderate thicknesses increasing towards the upper slope (up to 10 ms) on the Portuguese continental shelf. On the outer shelf, the main depocentre is located between the Guadiana River and the Doñana Park. This depocentre is oriented parallel to the present-day coastline and extends laterally for over 60 km, with a sediment thickness exceeding 20 ms. This depocentre continues to the upper slope with a WNW–ESE orientation and a sediment thickness higher than 35 ms off the Guadiana River (Fig. 6C).

The CDBU is composed of two seismic units (OSU and MSU) disposed in a backstepping pattern (Figs. 4 and 5).

*Outer shelf unit (OSU)*

The OSU extends from the outer shelf 15–20 km from the present-day coastline to the upper slope. Its seaward limit is not well defined (Fig. 7A). The landward limit is located at depths ranging between 135 and 160 ms. Two main depocentres have been identified: (1) an outer shelf depocentre of lenticular shape, and (2) an upper slope depocentre increasing seawards in thickness, especially to the west of the Tinto-Odiel Estuary where the thickness is greater than 60 ms. The thickness on the upper slope rarely exceeds 20 ms off the Tinto-Odiel Estuary, but it increases again towards the east, reaching values higher than 50 ms (Fig. 7A). The OSU is characterised by low-angle, oblique-parallel reflectors with slopes ranging between 0.47 and 1°, and locally by divergent reflectors on the upper slope (Fig. 7B).

*Middle shelf unit (MSU)*

The MSU extends across the outer shelf, pinching out both in a landward and seaward direction (Fig. 7C). The landward limit is located on the middle shelf and in places on the inner shelf, but mostly it is situated 15–20 km from the present-day coastline. The seaward limit is located at variable distances from the present-day coastline, generally ranging from 28 to 35 km, and at water depths of 90–120 ms. Occasionally, the MSU may also occupy the upper continental slope, for instance, to the east of Faro and between the Piedras River and the Tinto-Odiel Estuary. Maximum thicknesses are observed on the middle to outer shelf between the Guadiana River and the Doñana Park shelf. The depocentre of the MSU is aligned parallel to the present-day coastline, and it is wider towards the east, reaching a width of 7 km off the Guadiana River and more than 20 km off the Doñana National Park. It extends onto the upper continental slope to the west of the Tinto-Odiel Estuary. The thickness generally exceeds 8 ms, and in places is higher than 20 ms (Fig. 7C).

With the exception of the zone located off the Piedras River where distal tangential-oblique facies and proximal subparallel facies have been identified, the MSU is dominated by low-angle, oblique-parallel reflectors with variable slopes of 0.47–1°. Some proximal zones feature high-reflectivity oblique-parallel facies with variable slopes and irregular facies (Fig. 7D).

A channel-like unit (Figs. 4 and 7C), characterised by a reduced depth/width ratio and an erosional base showing several irregularities, affects the MSU at its upper boundary. This unit is located on the middle shelf between the mouths of the Guadiana and Piedras rivers, 18 km from the present-day coastline. It is aligned in an east to west direction, reaches a length of at least 15 km,

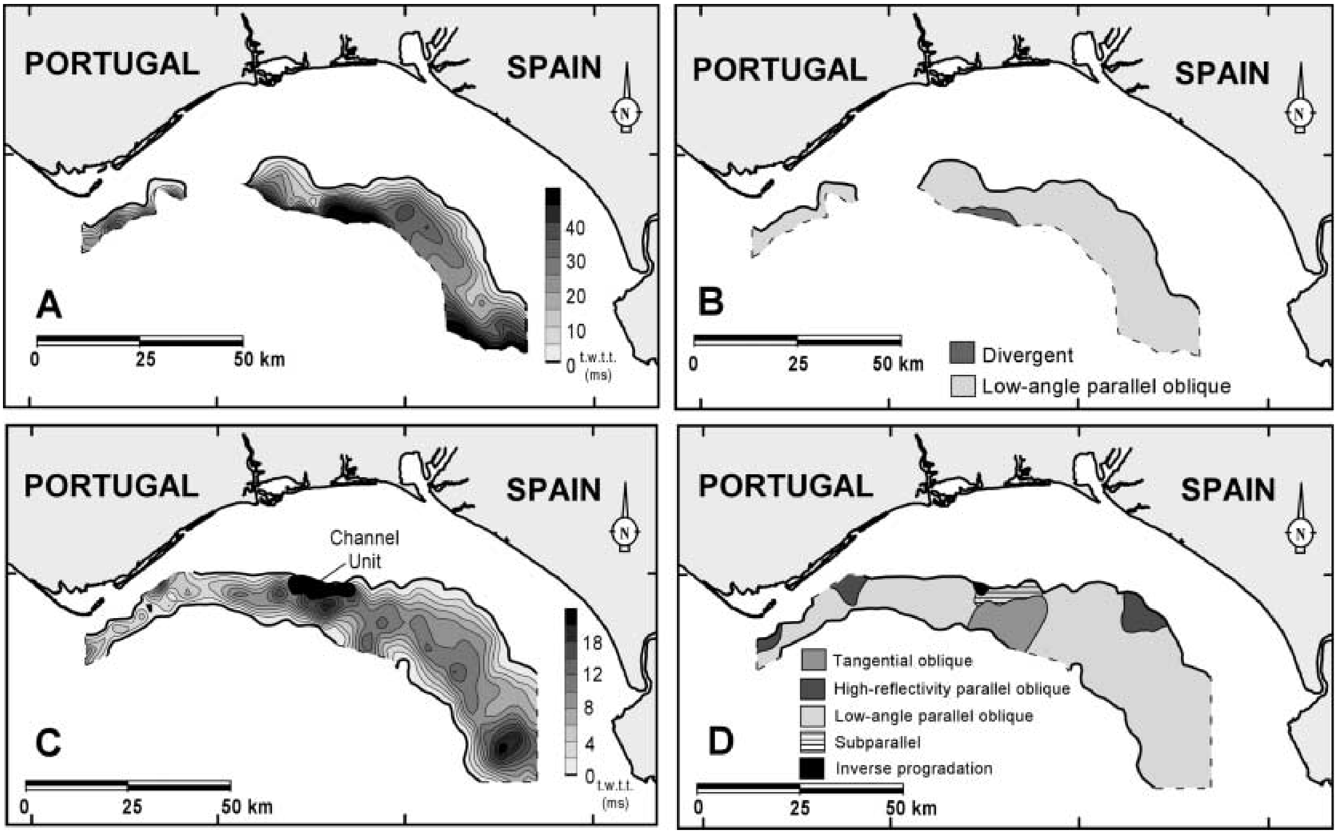



**Fig. 7A–D** Distribution and seismic facies maps of the OSU and MSU. **A** Distribution map of the OSU (given in ms). **B** Seismic facies map of the OSU. **C** Distribution map of the MSU (given in ms). **D** Seismic facies map of the MSU

and is several kilometres wide in cross section. Its upper boundary is located at variable depths of 100 to 140 ms. Although the thickness of this channel-like unit is generally small, it reaches 15 ms along the channel axis.

### Morpho-structural controls

The regional distribution of the OSU and MSU is only partially controlled by the main morpho-structural elements of the shelf. In general, the OSU and MSU are aligned parallel to the shelf with elongated depocentres, whereas the shelf itself displays alternating sectors characterised by different gradients. In this sense, the seismic units are poorly developed on the relatively high-gradient Portuguese shelf. The main depocentres are situated off the mouths of the Guadiana and Guadalquivir rivers. These shelf sectors are uplifted relative to adjacent sectors.

## Discussion

### Sequence stratigraphy and relative sea-level changes

The stratigraphic position and backstepping internal architecture of the CDBU reveals significant information about sea-level change and sequence stratigraphy. Backstepping units have been routinely interpreted as reliable indicators of relative sea-level rises with stabilisation intervals, because the prograding character of the sedimentary bodies can be explained by assuming occasional stillstands during a generally rising sea level (Boyd et al. 1989). The moderate thickness of the deposits is used as another indicator of their genesis (Boyd et al. 1989; Farrán and Maldonado 1990). Besides, this composite seismic unit is stratigraphically located between two wedge-shaped, outer shelf-upper slope units which have been interpreted as RST–LST complexes generated during periods of falling sea level followed by sea-level lowstands (Fig. 8).

Taking these considerations into account, it seems that the CDBU was deposited during a period of relative sea-level rise to highstand defining the boundary between two consecutive periods of falling sea level. The composite seismic unit is consequently interpreted as a TST to HST complex (Fig. 8). Stabilisation intervals which occurred during the last post-glacial sea-level rise have been described by Díaz et al. (1990), Hernández-Molina et al. (2000), and Lobo et al. (2001). However, the formation of composite seismic unit 12 seems to be related to a sea-level rise prior to the last post-glacial transgression.

Considering the OSU first, the upper boundary of this unit represents an erosive surface which was probably generated by shoreface erosion during a rise in sea-level, as it represents the transition from a lowstand

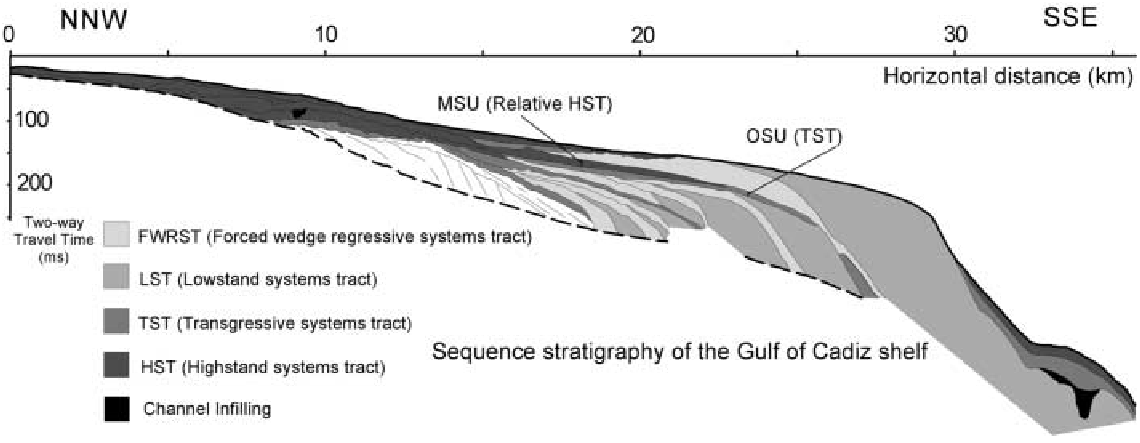



**Fig. 8** Interpretative profile of the sequence stratigraphy of the Gulf of Cadiz continental shelf

wedge (seismic unit 11) to an MSU. The onlapping character and divergent nature of the upper slope depocentre of the OSU suggests that it may represent a "healing phase" in the sense of Posamentier and Allen (1993), probably originating from the advection of nearshore sediments by shoreface erosion and seaward transport of fine sediments during sea-level rise. Healing phases are common components of TSTs and, based on this consideration, we interpret the OSU to have been deposited during a relative sea-level rise. It can thus be considered to be the TST component of the TST–HST complex (Fig. 8). The internal configuration (oblique progradation) and distribution of the MSU is indicative of deposition at a relative high sea-level stand because it is stratigraphically located between a TST (OSU underneath) and an FWRST–LST complex (seismic unit 13 above; Lobo 2000; Hernández-Molina et al. 2000). Thus, the MSU is considered an HST deposited during a relatively high sea-level stand (Fig. 8).

## Chronostratigraphy

Any sequence stratigraphic interpretation must be integrated into a global chronostratigraphic framework. Glacio-eustatic sea-level curves for the late Quaternary show an alternation of stadial and interstadial intervals. During the late Quaternary, three major sea-level highstands have been identified between individual interglacial intervals, namely marine isotopic substages (MISSs) 5c, 5a and 3.3. Since these periods were of short duration, the deposit-generating potential was relatively low. Apart from the last post-glacial transgression, the sea-level rise of highest amplitude (several tens of metres) and longest duration (about 10,000 years) occurred during the transition between MISs 4 and 3. This sea-level rise culminated in the relative highstand of MIS 3, which is the highstand prior to the last sea-level cycle (Shackleton 1987; Bard et al. 1990; Chappell et al. 1996).

In general, transgressive and highstand deposits are poorly represented in the late Quaternary sedimentary record, excluding the last post-glacial transgressive interval (from the last glacial maximum to the present). However, the stratigraphic record of MIS 3 is dominated on some shelves by TSTs and HSTs (Fig. 9). The most typical example is the New Jersey shelf where the integration of marine geological data has enabled the correlation of late Quaternary sequences from the coastal plain to the continental slope (Ashley et al. 1991; Wellner et al. 1991; Esker et al. 1996; Sheridan et al. 2000). On this shelf, some authors have related the preservation of late-highstand deposits to stadial/interstadial sea-level fluctuations occurring between major glacial/interglacial cycles (Carey et al. 1998). Two TST to HST complexes have been distinguished underlying the last depositional sequence (Carey et al. 1998; Sheridan et al. 2000).

1. A buried shoreface (unit 3c) interpreted as a combination of TST to HST deposited 65–50 ka B.P. This complex is apparently related to the migration of a barrier-island system during the sea-level rise between MISs 4 and 3 (Ashley et al. 1991). An equivalent deposit has been described in the eastern Bohai Sea by Marsset et al. (1996). According to these authors, a seismic unit (U7) developed during the transgressive interval which occurred between 65 and 53 ka B.P., the upper part of the unit being formed in the interval between the transgression and the onset of the subsequent regression.
2. A highstand shoreface (unit 3a) interpreted as a TST to HST with an estimated age of 28–45 ka B.P. The equivalent in the Bohai Sea would be a shallow-marine deposit (U5) associated with the sea-level rise before MISS 3.0 (39–22 ka B.P.; Marsset et al. 1996).

In contrast to the New Jersey margin, the Gulf of Cadiz margin is characterised by the dominance of RST–LSTs. The presence of a TST to HST complex would thus represent a significant stratigraphic marker for the late Quaternary record of this shelf. Considering the above interpretations, two different chronological scenarios can be proposed to explain the generation of the TST to HST complex on the Gulf of Cadiz shelf: (1) formation linked to the sea-level rise and relative

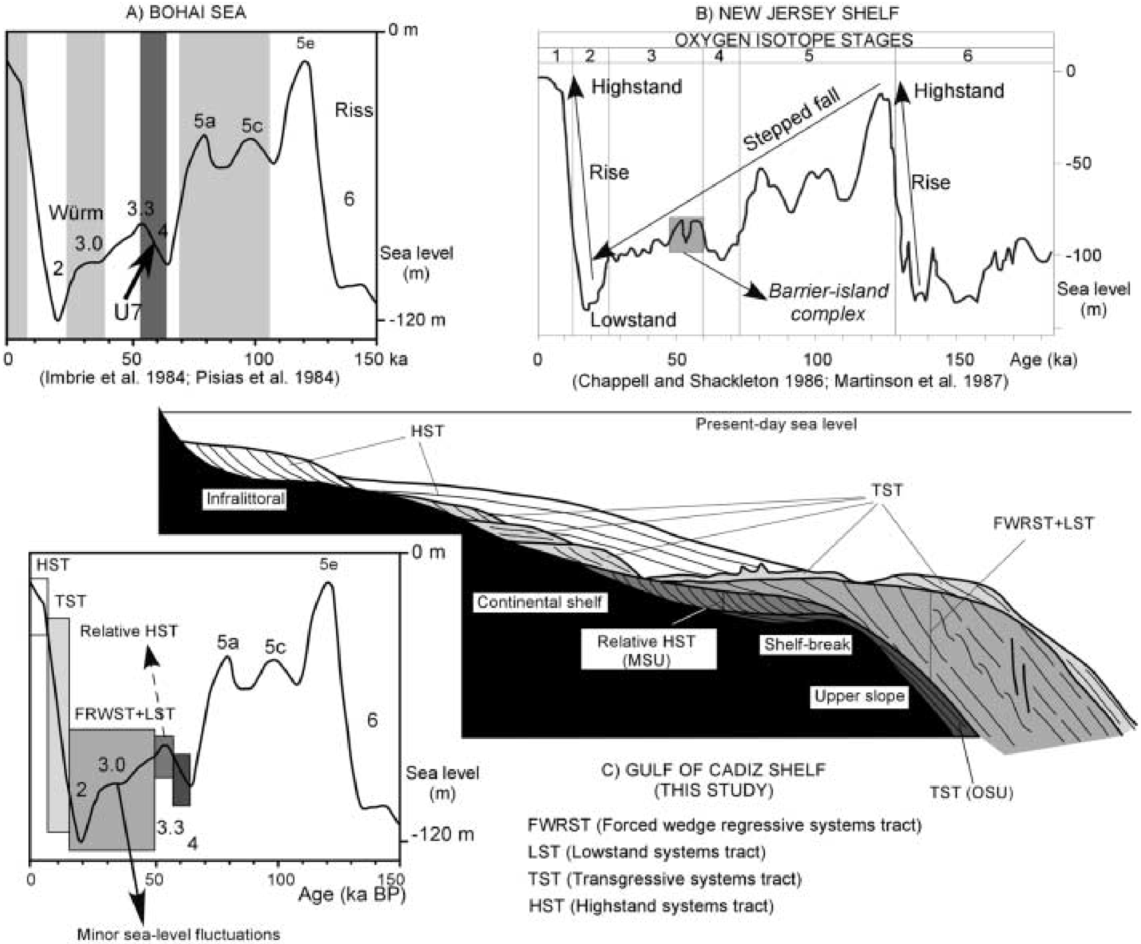



**Fig. 9A–C** Proposed chronostratigraphic scenarios for upper Pleistocene TST to HST complexes on various continental shelves (**A**, **B**), and application to the Gulf of Cadiz shelf (**C**)

highstand between MIS 4 and MISS 3.3, and (2) formation linked to the transgressive to highstand interval during MISS 3.0.

Estimated depths of late Quaternary relative highstands during MIS 3 are –80 m for MISS 3.3 and –95 m for MISS 3.0 (Imbrie et al. 1984; Pisias et al. 1984; Martinson et al. 1987). Minimum depths related to the MSU (68–80 m below present-day mean sea level) are thus more compatible with a generation during MISS 3.3. However, values of 20–30 m below present sea level for relative highstands during MIS 3 have been proposed for the New Jersey margin (Sheridan et al. 2000). Since our estimates can only be considered as a rough guide, not accounting for the post-depositional erosion and tectonic/sedimentary subsidence, a comparison with the New Jersey situation does not seem to be very useful. Sedimentary subsidence must have been significant on the Gulf of Cádiz margin, since a very thick regressive wedge overlying the TST to HST complex was deposited during the sea-level fall and lowstand of sea level associated with MIS 2 (Somoza et al. 1997; Lobo 2000; Hernández-Molina et al. 2000). By contrast, isostatic rebound processes on the New Jersey margin could at least partially explain the shallower water depths during MIS 3 highstands.

According to the above reasoning, it seems more appropriate to suggest that the difference in water depths between the OSU and the MSU (about 30 m) give a rough estimate of the magnitude of the sea-level rise. This value is more compatible with the sea-level rise proposed for the transition from MISs 4 to 3, i.e. an absolute value of at least several tens of metres (Ashley et al. 1991; Marsset et al. 1996; Carey et al. 1998; Sheridan et al. 2000) and, in some cases, even more than 30 m (Shackleton 1987; Bard et al. 1990; Chappell et al. 1996). By contrast, according to some authors (Shackleton 1987; Bard et al. 1990; Chappell et al. 1996) the sea-level rise during MISS 3.0 was much lower ( $<$ 20 m) and probably less than half that of the transition between MISs 4 and 3 (Sheridan et al. 2000).

This interpretation is in accordance with the chronostratigraphic framework for the Gulf of Cadiz shelf proposed by Somoza et al. (1997) and Hernández-Molina et al. (2000) obtained using a sequential approach. These authors interpret the deposits overlying the TST to HST complex as a depositional sequence developed from MIS 3 to the present, since they conclude that the progressive sea-level fall which followed the relative sea-level highstand reached after the MIS 4–3 transition was registered by the deposition of an RST. This sea-level fall was also modulated by other sea-level cycles of lower magnitude. The MIS 4–3 sea-level rise therefore represents the final part of a fifth-order cycle which occurred prior to the last sea-level cycle (Fig. 9).

Finally, several emerged coastal deposits along the Iberian coast are related to the relative highstands of MIS 5, during MISSs 5e, 5c and 5a (Zazo et al. 1993; Zazo 1999). Those deposits comprise terraces and escarpments located at different heights (up to 14 m above present mean sea level). However, no emerged deposits related to the relative highstand of MIS 3 have been found. It should thus be expected that such deposits occur on the shelf. The information extracted from the analysis of estuarine valley fills along the Gulf of Cadiz (Dabrio et al. 2000) suggests that the conglomerates in the estuaries were deposited during a sea-level highstand some 25–30 ka B.P. during MISS 3.0, which was a relatively humid period in the area. This highstand phase did not reach the topographic elevation of the present sea level. The deposits probably relate to the small-scale sea-level fluctuations mentioned above which occurred between MISS 3.3 and the last glacial maximum.

## Lateral variations: sedimentary model and controlling factors

Seismic facies analysis and regional distribution patterns provide information about sedimentary environments related to deposition of the TST–HST complex (Fig. 10). The OSU probably represents the distal leftovers of prodeltaic deposits which were not affected by coastal erosion. Divergent reflectors on the upper slope are related to healing phases in the sense of Posamentier and Allen (1993), probably originating from shelf progradation associated with shoreface erosion and seaward transport of fine sediments induced by storm-surge currents during sea-level rise (Fig. 10). The MSU is interpreted to represent delta front to distal deposits, similar to the OSU but showing a higher preservation of proximal coastal facies in several locations. In this context, the seismic facies of the MSU located off the Piedras River are interpreted as a barrier island-coastal lagoon system with landward progradation features interpreted as washover fans or flood tidal deltas. Very

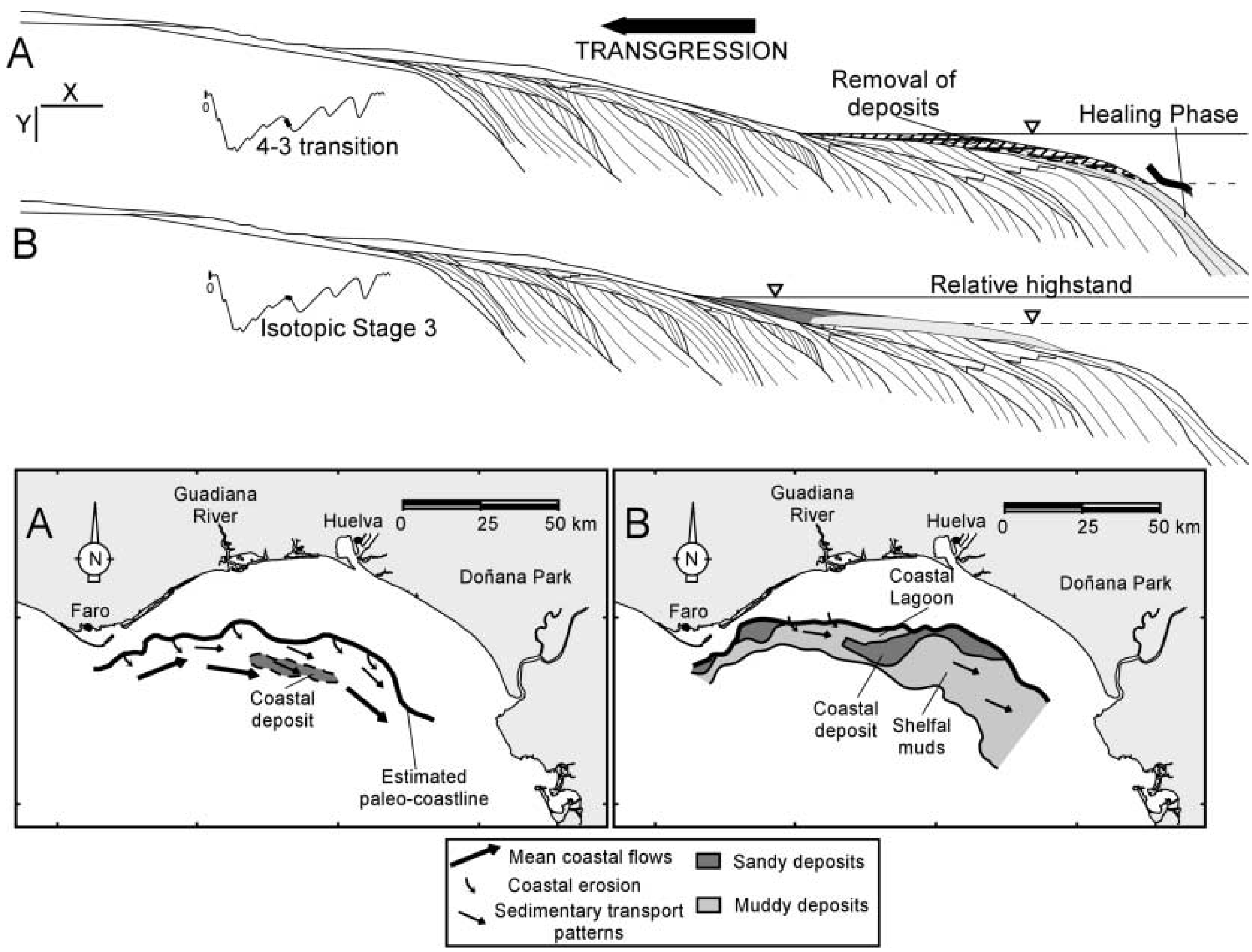



**Fig. 10A, B** Proposed genetic model for **A** the OSU, and **B** the MSU, and related palaeogeographical configurations pronounced but irregular reflectors are attributed to coastal or shallow marine sands deposited in a high-energy environment. On the basis of the coast-parallel orientation and its landward location relative to sandy coastal barriers, the channel-like unit on top of the MSU is interpreted as the sedimentary infilling of a lagoonal environment.

The variability of these seismic units along the coast has been attributed to variations in sediment supply (Hernández-Molina et al. 2000). The distribution of both deposits shows that the main depocentres are located off the main streams draining onto the continental shelf (Fig. 7A, C), particularly the Guadiana and Guadalquivir rivers, suggesting that they are the main sediment sources. However, both seismic units are also characterised by elongated depocentres indicating that shelf dispersal processes were very active during their deposition (Fig. 10). This inference is reinforced by the fact that they are mainly characterised by low-reflectivity seismic facies, suggesting that they are mainly composed of fine sediments. Under these conditions, it is reasonable to assume that coastal and shelf dynamics were similar to the present-day situation, being characterised by a very active, eastward-directed littoral drift and the influence of Atlantic swells on the shelf, as a result of which the depocentres located off the Guadiana River are deflected towards the east while reducing in thickness. The fluvially derived sediments were probably transported laterally along the coast, especially during the relative highstand situation when the coastline stabilised and modern oceanographic conditions were established on the shelf (Fig. 10). During the transgressive interval, storm events promoted the export of most sediment to the upper slope. Sediment remaining on the shelf was also redistributed laterally. A similar situation probably exists off the Guadalquivir but the absence of data south of the river mouth prevents confirmation at this stage. The small deposits on the Portuguese shelf suggest that fluvial input was quite low and also that part of the sediment was laterally redistributed.

Another factor which could be invoked is the influence of the morpho-structural setting, in particular the fact that the main depocentres are off coastal sectors which have been uplifted, e.g. the zone of diapiric uplifting off the Guadalquivir and the Tavira-Guadiana High. It therefore appears that the uplifting has triggered progradational processes in combination with the sediment input by the main rivers. By contrast, the progradation of the deposits was mainly induced by alongshore currents redistributing the sediments in subsiding areas such as the shelf off the Doñana Park.

### Preservation potential

Factors which favoured the formation and/or preservation of a TST–HST complex on the Gulf of Cádiz shelf during MIS 3 in comparison to other similar sea-level trends during the upper Pleistocene, namely, during MISSs 5c and 5a, and which can also be considered to represent relative highstands (Fig. 9) can be the following.

1. Duration and magnitude of relative sea-level rise and highstand associated with MIS 3. Assuming that deposition of the TST–HST complex found on the Gulf of Cadiz shelf is related to the MIS 4–3 transition (a sea-level variation of about 30 m in approximately 15,000 years), then the resultant rates of sea-level change are much lower than those which occurred during the post-glacial transgression (a sea-level rise of about 120 m in 10,000–15,000 years) when widespread deposition occurred on the shelf (Fig. 9). Besides, the eustatic position of the sea-level highstand related to MISS 3.3 is lower than the positions reached by the relative highstands during MISSs 5c and 5a (Imbrie et al. 1984; Pisias et al. 1984; Chappell and Shackleton 1986; Martinson et al. 1987). The preservation potential of these deposits would thus be higher, especially as they have been subjected to much shorter subaerial exposure.
2. Higher sediment supply, related to glaciation or associated climatic changes, has been used to explain the generation of shelf deposits during MIS 3 (Carey et al. 1998; Sheridan et al. 2000).
3. Distribution in an area of tectonic stability (Carey et al. 1998; Sheridan et al. 2000), and low gradients of the middle to outer shelf (lower than 0.3° in the study area) which would have favoured the recording of small sea-level changes (Marsset et al. 1996). Another controlling factor is the seaward subsidence of the margin as revealed by the stacking pattern of the seismic units (Lobo 2000).

## Conclusions

Although deposition on the continental margin of the Gulf of Cadiz during the upper Pleistocene has preferentially occurred during regressive and lowstand intervals, the formation of sedimentary deposits may also have taken place during specific intervals of sea-level rise and highstand. A backstepping deposit extending from the middle shelf to the outer slope of the Gulf of Cadiz is interpreted as a TST to HST complex. It was possible to correlate this deposit with the sea-level rise and relative highstand which occurred during the MIS 4–3 transition and MISS 3.3. Other periods of sea-level rise and relative highstand occurring during MIS 3 were of lower magnitude and probably did not favour the formation of significant shelf deposits.

The general distribution pattern of these deposits is controlled by fluvial input, a very active current dispersal system, and the influence of morpho-structural features. The preservation potential of such deposits is probably higher than similar deposits related to other well-known upper Pleistocene periods of sea-level rise and highstand. The identification of similar deposits on shelves where no chronostratigraphic framework is available could benefit from this interpretation by providing a correlation tool.

**Acknowledgements** This research has been supported by the projects DGICYT PB94-1090-C03 and CICYT MAR-98-0209 of the Spanish Research Programme. The first author received financial support from the Fundação para a Ciência e Tecnologia (FCT, reference SFRH/BPD/5616/2001). The crews of the oceanographic vessels Odón de Buen and Francisco de Paula (IEO, Instituto Español de Oceanografía) are gratefully acknowledged, as well as the efficient onboard work of the technician Francisco González. A.G. De Figueiredo, an anonymous referee and the editor Burg Flemming made useful suggestions to improve the manuscript. Ramón González and Brad Morris (Universidade do Algarve) reviewed the language style of the manuscript. This work is a contribution to the 464 IGCP Project Continental Shelves during the Last Glacial Cycle.

## References

Andrade CA (1990) O Ambiente de Barreira de Ria Formosa, Algarve-Portugal. PhD Thesis, University of Lisbon

Ashley GM, Wellner RW, Esker D, Sheridan RE (1991) Clastic sequences developed during late Quaternary glacio-eustatic fluctuations on a passive margin: Example from the inner continental shelf near Barnegat Inlet, New Jersey. Geol Soc Am Bull 103:1607–1621

Baldy P (1977) Géologie du plateau continental portugais (au sud du cap de Sines). 3rd Cycle Thesis, University of Paris VI

Bard E, Hamelin B, Fairbanks RG (1990) U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130,000 years. Nature 346:456–458

Boyd R, Suter J, Penland S (1989) Sequence stratigraphy of the Mississippi delta. Trans Gulf Coast Assoc Geol Soc XXXIX: 331–340

Caralp M-H (1988) Late glacial to recent deep-sea benthic Foraminifera from the northeastern Atlantic (Cadiz Gulf) and western Mediterranean (Alboran Sea): Paleoceanographic results. Mar Micropaleontol 13:265–289

Carey JS, Sheridan RE, Ashley GM (1998) Late Quaternary sequence stratigraphy of a slowly subsiding passive margin, New Jersey continental shelf. Am Assoc Petrol Geol Bull 82:773–791

CEEPYC (1979) Plan de estudio de la dinámica litoral de la provincia de Huelva. Inf Dir Gen Puertos Costas, Madrid

Chappell J, Shackleton NJ (1986) Oxygen isotopes and sea level. Nature 324:137–140

Chappell J, Omura A, Esat T, McCulloch M, Pandolfi J, Ota Y, Pillans B (1996) Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth Planet Sci Lett 141:227–236

Chiocci FL (1994) Very high-resolution seismics as a tool for sequence stratigraphy applied to outcrop scale – examples from Eastern Tyrrhenian margin Holocene/Pleistocene deposits. Am Assoc Petrol Geol Bull 78:378–395

Chiocci FL (2000) Depositional response to Quaternary fourth-order sea-level fluctuations on the Latium margin (Tyrrhenian Sea, Italy). In: Hunt D, Gawthorpe RLG (eds) Sedimentary responses to forced regressions. Geol Soc Spec Publ 172:271–289

Chiocci FL, Ercilla G, Torres J (1997) Stratal architecture of western Mediterranean margins as the result of the stacking of Quaternary lowstand deposits below 'glacio-eustatic fluctuation base-level'. Sediment Geol 112:195–217

Cuena GJ (1991) Proyecto de regeneración de las playas de Isla Cristina. Servicio de Costas, MOPT, Madrid

Dabrio CJ, Boersma JR, Fernández J, Martín JM, Polo MD (1980) Dinámica costera en el Golfo de Cádiz: Sus implicaciones en el desarrollo socioeconómico de la región. I Reunión Nacional del Grupo Español de Geología Ambiental y Ordenación del Territorio, 1980, Santander

Dabrio CJ, Zazo C, Goy JL, Sierro FJ, Borja F, Lario J, González JA, Flores JA (2000) Depositional history of estuarine infill during the last postglacial transgression (Gulf of Cadiz, southern Spain). Mar Geol 162:381–404

Díaz JI, Nelson CH, Barber JH Jr, Giró S (1990) Late Pleistocene and Holocene sedimentary facies on the Ebro continental shelf. Mar Geol 95:333–352

Esker D, Sheridan RE, Ashley GM, Waldner JS, Hall DW (1996) Synthetic seismograms from vibracores: a case study in correlating the Late Quaternary seismic stratigraphy of the New Jersey inner continental shelf. J Sediment Res 66:1156–1168

Farrán M, Maldonado A (1990) The Ebro continental shelf: Quaternary seismic stratigraphy and growth patterns. Mar Geol 95:289–312

Gensous B, Tesson M (1996) Sequence stratigraphy, seismic profiles, and cores of Pleistocene deposits on the Rhône continental shelf. Sediment Geol 105:183–190

Heezen B, Johnson L (1969) Mediterranean Undercurrent and Microphysiography west of Gibraltar. Bull Inst Oceanogr Monaco 67:1–49

Hernández-Molina FJ, Somoza L, Lobo FJ (2000) 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 RLG (eds) Sedimentary responses to forced regressions. Geol Soc Spec Publ 172:329–361

Hunt D, Tucker ME (1992) Stranded parasequences and the forced regressive wedge systems tract: deposition during base-level fall. Sediment Geol 81:1–9

Imbrie J, Hays JD, Martinson DG, McIntyre A, Mix AC, Morley JJ, Pisias NG, Prell WL, Shackleton NJ (1984) The orbital theory of Pleistocene climate: support from a revised chronology of the marine O-18 record. In: Berger A, Imbrie J, Hays J, Kukla G, Saltzman B (eds) Milankovitch and climate, part I. Reidel, Dordrecht, pp 269–305

Lobo FJ (1995) Estructuración y evolución morfosedimentaria de un sector del margen continental septentrional del Golfo de Cádiz durante el Cuaternario Terminal. Dissertation, University of Cádiz

Lobo FJ (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. PhD Thesis, University of Cádiz

Lobo FJ, Hernández-Molina FJ, Somoza L, Díaz del Río V (1999) Palaeoenvironments, relative sea-level changes and tectonic influence on the Quaternary seismic units of the Huelva continental shelf (Gulf of Cadiz, southwestern Iberian Peninsula). Bol Inst Esp Oceanogr 15:161–180

Lobo FJ, Hernández-Molina FJ, Somoza L, Díaz del Río V (2001) The sedimentary record of the post-glacial transgression on the Gulf of Cadiz continental shelf (southwest Spain). Mar Geol 178:171–195

Marsset T, Xia D, Berné S, Liu Z, Bourillet J-F, Wang K (1996) Stratigraphy and sedimentary environments during the Late Quaternary, in the Eastern Bohai Sea (North China Platform). Mar Geol 135:97–114

Martínez M, Cotos JM, Arias J, Tobar A (1998) Cálculo de corrientes superficiales marinas a partir de imágenes térmicas NOAA y estimación de la influencia de los vientos en su aparición: aplicación al suroeste de la Península Ibérica. Rev Teledetec 9:5–14

Martinson DG, Pisias NG, Hays JD, Imbrie J, Moore TC Jr, Shackleton NJ (1987) Age dating and the orbital theory of ice ages: development of a high-resolution 0 to 300,000-years chronostratigraphy. Quat Res 27:1–29

Melières F (1974) Recherches sur la dynamique sédimentaire du Golfe de Cadix (Espagne). PhD Thesis, University of Paris VI

Moita I (1986) Noticia explicativa da carta dos sedimentos superficiais da plataforma. Folha SED 8, Instituto Hidrográfico, Lisboa

Morales JA (1993) Sedimentología del Estuario del Río Guadiana (SW España-Portugal). PhD Thesis, University of Sevilla, Serv Publ Univ Huelva 1995

Morales JA (1997) Evolution and facies architecture of the mesotidal Guadiana River delta (SW Spain-Portugal). Mar Geol 138:127–148

Morales JA, Pendón JG, Borrego J (1994) Origen y evolución de flechas litorales recientes en la desembocadura del estuario mesomareal del río Guadiana (Huelva, SO de España). Rev Soc Geol Esp 7:155–167

Nelson CH, Baraza J, Maldonado A (1993) Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. Sediment Geol 82:103–131

Nelson CH, Baraza J, Maldonado A, Rodero J, Escutia C, Barber JH Jr (1999) Influence of the Atlantic inflow and Mediterranean outflow currents on Late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. Mar Geol 155:99–129

Pisias NG, Martinson DG, Moore TC, Shackleton NJ, Prell W, Hays J, Boden G (1984) High resolution stratigraphic correlation of benthic oxygen isotopic records spanning the last 300 000 yr. Mar Geol 56:119–136

Posamentier HW, Allen GP (1993) Variability of the sequence stratigraphic model: effects of local basin factors. Sediment Geol 86:91–109

Posamentier HW, Vail PR (1988) Eustatic controls on clastic deposition II. Sequence and systems tracts models. In: Wilgus CK et al. (eds) Sea level changes – an integrated approach. Soc Econ Paleontol Mineral Spec Publ 42:125–154

Roque AC (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

Shackleton NJ (1987) Oxygen isotopes, ice volume and sea level. Quat Sci Rev 6:183–190

Sheridan RE, Ashley GM, Miller KG, Waldner JS, Hall DW, Uptegrove J (2000) Offshore-onshore correlation of upper Pleistocene strata, New Jersey coastal plain to continental shelf and slope. Sediment Geol 134:197–207

Somoza L, Hernández-Molina FJ, De Andrés JR, Rey J (1997) Continental shelf architecture and sea-level cycles: Late Quaternary high-resolution stratigraphy of the Gulf of Cádiz, Spain. Geo-Mar Lett 17:133–139

Tesson M, Posamentier HW, Gensous B (2000) Stratigraphic organisation of Late Pleistocene deposits of the western part of the Rhone shelf (Languedoc shelf) from high resolution seismic and core data. Am Assoc Petrol Geol Bull 84:119–150

Trincardi F, Correggiari A (2000) Quaternary forced regression deposits in the Adriatic basin and the record of composite sea-level cycles. In: Hunt D, Gawthorpe RLG (eds) Sedimentary responses to forced regressions. Geol Soc Spec Publ 172:245–269

Van Geen A, Adkins JF, Boyle EA, Nelson CH, 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 géomorphologique. Mem Serv Geol Portugal 28

Wellner RW, Ashley GM, Sheridan RE (1991) Seismic stratigraphic evidence for a submerged middle Wisconsin barrier: implications for sea-level history. Geology 21:109–112

Yoo DG, Park SC (1997) Late Quaternary lowstand wedges on the shelf margin and trough region of the Korea Strait. Sediment Geol 109:121–133

Zazo C (1999) Interglacial sea levels. Quat Int 55:101–113

Zazo C, Goy JL, Dabrio CJ, Bardají T, Somoza L, Silva PG (1993) The last interglacial in the Mediterranean as a model for the present interglacial. Global Planet Change 7:109–117