Holocene highstand deposits in the Gulf of Cadiz, SW Iberian Peninsula: A high-resolution record of hierarchical environmental changes

F.J. Lobo a,*, L.M. Fernández-Salas b, F.J. Hernández-Molina c, R. González a, J.M.A. Dias a, V. Díaz del Río b, L. Somoza d

aCIACOMAR-CIMA, Universidade do Algarve, Avenida 16 de Junho, s/n, 8700-311 Olhão, Portugal
bInstituto Español de Oceanografía, Centro Oceanográfico de Málaga, Puerto Pesquero s/n, 29640 Fuengirola, Spain
cDepartamento de Geociencias Marinas y Ordenación del Territorio, Facultad de Ciencias, Universidad de Vigo, 36200 Vigo, Spain
dInstituto Geológico y Minero de España, Ríos Rosas 23, 28003 Madrid, Spain

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Abstract

A comparison of the internal structure of Holocene highstand shallow-marine deposits with emerged spit-bar systems in the Gulf of Cadiz margin (SW Iberian Peninsula) is presented, in order to increase the knowledge about the patterns of environmental fluctuations of sub-Milankovitch periodicity during the recent highstand period. A high-resolution seismic database of boomer profiles was interpreted, focusing on shallow-marine deposits of the Gulf of Cadiz shelf, such as the Guadalquivir River prodelta, the Guadiana River depositional system and the Faro–Tavira infralittoral prograding wedge.

The results indicate that the internal architecture of recent highstand shelf deposits is complex, as the recognition of three main types of seismic unit motifs suggests the existence of a hierarchical pattern of environmental fluctuations: (a) Major-scale motifs: the most significant feature observed in the seismic records is the pervasive occurrence of two major-scale motifs (lower and upper) within the Holocene highstand systems tract. (b) Intermediate-scale motifs: each major-scale motif is composed of two intermediate-scale motifs, defining four intermediate-scale motifs (H1 to H4). (c) Minor-scale motifs: the internal structure of major- and intermediate-scale motifs reveals a high degree of environmental variability during the recent highstand, probably led by climatic cyclicities of submillenial scale. The lower major-scale motif is characterised by alternating progradational–aggradational minor-scale motifs, whereas the upper major-scale motif presents a more uniform internal structure dominated by progradational units.

The influence of two distinct trends or asymmetric cycles of sea-level change seems to have been significant in the generation of the major-scale architecture. The transition between both major phases was probably related with a major sea-

* Corresponding author. Present address: Instituto Andaluz de Ciencias de la Tierra, CSIC-Univ. Granada, Facultad de Ciencias, Campus de Fuentenueva, s/n. 18002 Granada, Spain. Tel.: +34 958 243353; fax: +34 958 243384.
E-mail address: pacolobo@ugr.es (F.J. Lobo).

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level rise. Other factors, such as changes in the magnitude and/or direction of storm events and climatically induced changes of sediment supply, are proposed to have controlled the generation of intermediate- and minor-scale architectures.

Keywords: Holocene; highstand systems tract; seismic stratigraphy; environmental changes; high-frequency sea-level changes; Gulf of Cadiz

1. Introduction

The pattern of environmental fluctuations during the recent Holocene highstand has recently received a great deal of attention due to its significance for the understanding of past and present coastal, oceanic and climatic systems (Baker and Haworth, 2000). In contrast to the traditional view that considered the Holocene climate as anomalously stable, increasing evidence suggests the existence of millennial and submillennial-scale climate shifts shorter than Heinrich events throughout the Holocene, ranging in periodicity between several hundreds to thousands of years (Bond et al., 1997; Campbell et al., 1998; Arz et al., 2001). Several main types of short time scale climatic cyclicities have been recognised:

(a) Dansgaard–Oeschger events. Those are rather irregular asymmetric climatic cycles of millennial time scale characterised by gradual cooling followed by abrupt warming (Behl and Kennett, 1996; Arz et al., 2001). Some authors have found a relationship between these cycles and iceberg calving events occurring at intervals of 2000 to 3000 yr, when pulses of sea-level rise are caused by the disintegration of icebergs (Bond and Lotti, 1995). These cycles have been mainly recognised during the last glaciation, although the variability probably extended through the Holocene (Behl and Kennett, 1996).

(b) Mini Dansgaard–Oeschger events. These are pervasive climate shifts with a periodicity of about 1500 yr, which have been operating since the last glaciation through the Holocene (Bond et al., 1997; Campbell et al., 1998; Bianchi and McCave, 1999; Viau et al., 2002). These cycles seem to coincide with abrupt global reorganisations of the Holocene climate (Bond et al., 1997) and have been related with cyclic variations in solar irradiance (Campbell et al., 1998; Bond et al., 2001), or with rearrangements of the atmospheric circulation (Viau et al., 2002).

(c) Climatic cyclicities of submillennial scale. Climatic changes of submillennial periodicity ranging from 500 to 1000 yr and marked by the alternation of cooler and warmer periods appear as a recurrent feature over the past few millennia (O’Brien et al., 1995; Campbell et al., 1998; Goodwin, 1998; Bianchi and McCave, 1999). These fluctuating environmental conditions have been revealed by several types of proxies, such as high-frequency extreme droughts (Laird et al., 1996) or repeated storm surges (Regnauld et al., 1996). The most recent of those cycles is represented by the Little Ice Age and the Medieval Warm Period.

The link between sea level and the climate–ocean system has been proposed by some authors, as sea-level fluctuations have been associated to external climatic controls (Van de Plassche et al., 1998; Morton et al., 2000). Even some of these high-frequency sea-level changes have been linked to very sudden and short-lived climatic fluctuations, such as the Little Ice Age (Banerjee, 2000). In spite of this apparent relationship, evidences of high-frequency sea-level oscillations of the order of several meters occurring during the recent highstand period are contradictory. Some authors claim for a monotonic sea-level trend after a maximum sea-level position (Fletcher and Jones, 1996; Angulo and Lessa, 1997). However, other studies suggest the modulating effect of secondary oscillations, with periodicities ranging from several thousands (Islam and Tooley, 1999) to several hundred of years (Angulo et al., 1999; Martin et al., 2003) and amplitudes of metric scale (Morton et al., 2000). As a consequence, the sea-level trend is proposed to have been stepped and/or fluctuating (Stapor et al., 1991; Baker and Haworth, 2000; Banerjee, 2000).
2. Goals of the study

Patterns of coastal progradation and/or erosion in the southern coasts of the Iberian Peninsula have been governed by regional climatic conditions and relative sea-level oscillations during the recent Holocene highstand period. Environmental changes have been particularly studied in spit-bar systems (Zazo et al., 1994, 1996; Lario et al., 1995; Goy et al., 1996). Besides, the subsurface architecture of recent highstand depositional bodies has been delineated by means of high-resolution seismic profiles in estuarine (Lobo et al., 2003) and diverse shallow-marine environments of the Gulf of Cadiz margin (Somoza et al., 1997; Hernández-Molina et al., 2000a,b; Fernández-Salas et al., 2003; Lobo et al., 2004). Up to date, the most detailed account of the internal architecture of Holocene highstand deposits has been provided for the Guadalquivir prodelta (Fernández-Salas et al., 2003). There, the highstand prodeltaic deposit is characterised by two progradational-aggradational cycles, which have been related with major coastal progradational phases. Additionally, similar depositional architectures and stacking patterns have been identified in other shallow-marine deposits of the Spanish shelves, such as Alboran Sea prodeltas (Hernández-Molina et al., 1994; Fernández-Salas et al., 2003) and the Ebro delta (Somoza et al., 1998).

Although previous studies have characterised the distribution patterns of shallow-marine deposits in the northern shelf of the Gulf of Cadiz (Roque, 1998; Lobo et al., 2004), their internal stratigraphic patterns have not been analysed in detail. For the purposes of this study, we have focussed on the analysis of the most recent shallow-water deposits observed in seismic profiles overlying the post-glacial transgressive systems tract (TST) (Hernández-Molina et al., 2000a,b; Lobo et al., 2001). Consequently, the main objectives of this study are to: 1) investigate the internal structure of shallow-marine deposits of a sector of the northern margin of the Gulf of Cadiz (Fig. 1); 2) make a comparison with the internal structure of emerged coastal spits and of other shallow-marine deposits around Iberia; 3) characterise the pattern of environmental fluctuations during the most recent highstand period; 4) discuss possible sources of environmental variability.

3. The northern margin of the Gulf of Cadiz: fluvial supply and Holocene highstand deposits

3.1. Fluvial supply and coastal deposits

The northern margin of the Gulf of Cadiz (SW Iberian Peninsula) extends from Cape Saint Vincent to the W to the Straits of Gibraltar to the E (Fig. 1A). This continental margin receives the contributions of several fluvial streams of varying significance, namely the Arade, Guadiana, Piedras, Tinto–Odiel, Guadalquivir, Guadalete and Barbate Rivers, from W to E. Within this coastal stretch, the study area extends between the Portuguese town of Quarteira to the W and the Guadalquivir River mouth to the E. The most important rivers in terms of drainage area and fluvial discharge providing sediments to the study area are the Guadalquivir and Guadiana Rivers (Fig. 1B). The Guadalquivir River is the main fluvial source draining into the Gulf of Cadiz margin, with a mean annual water discharge of 160 m³/s, whereas the Guadiana River has a mean value of 80 m³/s (Van Geen et al., 1997).

The lower courses of most of those rivers have been transformed into estuaries during the post-glacial sea-level rise (Morales, 1997). Prevailing wave conditions have led to the construction of littoral spits at the mouths of major estuaries and coastal embayments in the Gulf of Cadiz coasts, such as the Piedras, Tinto–Odiel, Guadalquivir and Guadalete River mouths (Fig. 1B) (Zazo et al., 1994, 1996; Lario et al., 1995; Goy et al., 1996; Rodríguez Ramírez et al., 1996; Dabrio et al., 2000).

3.2. Shallow-marine deposits

The most significant depositional bodies developed during the recent Holocene highstand are fluvially derived sediment wedges (Fig. 1C). The large contribution of the Guadalquivir River has led to the generation of an up to 25 m thick and mainly southeasterly extending laterally extensive submarine prodelta (Lobo, 1995; Gutiérrez-Mas et al., 1996; Nelson et al., 1999; Rodero et al., 1999; Fernández-Salas et al., 2003). In contrast to the Guadalquivir River, the depositional system related to the Guadiana River shows a distinction between proximal and distal submarine fluvially derived wedges (Lobo et al., 2004). The inner wedge is constituted by tidal bar
Fig. 1. Geographical setting of the study area: (A) geographical location of the Gulf of Cadiz margin, SW Iberian Peninsula, with indication of the main fluvial streams; (B) position of high-resolution seismic profiles used in this study; (C) surface distribution of morpho-sedimentary units simplified from Lobo et al. (2004). Legend: (1) Faro–Tavira infralittoral prograding wedge (IPW); (2) inner wedges; (3) shelf aggradational deposits; (4) Guadalquivir River prodelta. The main deposits studied in this work are highlighted.
deposits in the estuarine environment (Lobo et al., 2003), whereas off the Guadiana River mouth the modern submarine portion of a wave-dominated delta shows moderate development. The distal deposit is interpreted as a result of deposition of fine-grained, fluvial sediments (Fig. 1C). The contributions of other regional streams are less significant, and generally restricted to shallow water (Nelson et al., 1999; Lobo et al., 2004).

Apart from fluvially related depocenters, another significant deposit in terms of thickness and stratigraphic significance has been recognised on the Portuguese shelf (Fig. 1C), identified as the Faro–Tavira Infralittoral Prograding Wedge (IPW), and interpreted to be part of the Holocene highstand systems tract (HST) (Hernández-Molina et al., 2000a). The Faro–Tavira IPW is an elongated, coast-parallel deposit showing two main depocenters, off Tavira and off Faro (Lobo et al., 2004). Because of the lack of fluvial supply in this area it is thought that storm-surge currents may have played a significant role in its generation. Thus, the formation of the Faro–Tavira IPW has been linked to the erosive action of storm waves in the shoreface, and later cross-shore sediment flux led by downwelling storm currents (Hernández-Molina et al., 2000a).

4. Materials and methods

Subsurface geological information was provided by high-resolution seismic profiles (Fig. 1B). Two systems were used, a sub-bottom profiler (3.5 kHz with a 100 ms recording interval) and a boomer system (Geopulse™), of 280 J, with a shot interval of 500 ms and a recording scale of 200 ms. These records were collected during three oceanographic surveys: Golca-93, Fado-9611 and Wadiana 2000. The seismic grid covers the continental shelf and upper slope of the study area (Fig. 1B). Positioning was achieved using a differential GPS.

Available geophysical records were interpreted following standard seismic stratigraphy procedure (Mitchum et al., 1977) in order to study the internal structure of shallow-marine deposits. Particularly, the application of seismic stratigraphy principles to the recent HST is rather unfrequent, and enables the recognition of high-resolution stratigraphy with great detail (Hernández-Molina et al., 1994; Somoza et al., 1998; Fernández-Salas et al., 2003).

In order to explain the distinct stratigraphic patterns of seismic units (SUs) identified in the study area, we make a distinction between progradational seismic units (ProgSUs) and aggradational seismic units (AggSUs) composing the Holocene HST in the northern margin of the Gulf of Cadiz. ProgSUs are characterised by oblique internal configurations, downlap terminations and wedge external shapes, whereas AggSUs are characterised by concordant internal configurations and/or absence of internal reflectors and sheet-like external shapes. In the cases where no internal reflectors are observed, AggSUs may be equivalent to sheet-like drapes. Finally, it was found that ProgSUs and AggSUs are internally structured in a hierarchical pattern, so that three different seismic unit scales are distinguished: major, intermediate and minor ProgSUs and AggSUs. Major units are internally constituted by intermediate units, which in turn are internally constituted by minor units. The repetition of a basic architectural block or motif constituted by ProgSUs and/or an AggSUs is evidenced at the three scales that have been identified (major, intermediate and minor).

5. Internal structure of Holocene highstand shallow-marine deposits

The following significant shallow-marine depositional bodies have been identified in the study area: (1) a prodeltaic deposit linked to the Guadalquivir River; (2) estuarine and prodeltaic deposits related to the Guadiana River; and (3) the Faro–Tavira IPW (Fig. 1C). Previous studies have reported the distribution patterns of such deposits and their relationships with regional controlling factors, such as oceanographic regime, sediment supply and physiographic features. They have been included into the Holocene HST of the Gulf of Cadiz continental margin (Fernández-Salas et al., 2003; Lobo et al., 2003, 2004). As a whole, they show a dominance of progradational, thick forestepping wedges, in contrast to the postglacial TST, which is characterised by a typical backstepping pattern (Hernández-Molina et al., 2000b; Lobo et al., 2001). Particular attention was put on the Faro–Tavira IPW, as it provides an excellent and
rather unique example to study the internal architecture of the Holocene HST.

5.1. Guadalquivir River prodelta

The Holocene HST of the Guadalquivir River prodelta is constituted by four seismic units overlying the patchy postglacial TST (Fig. 2). Those seismic units are arranged in two ProgSU–AggSU motifs (lower and upper). Each ProgSU–AggSU motif is composed of a major ProgSU overlain by a major AggSU (Fig. 2). Major ProgSUs shows a highly reflective acoustic response and wedge external shapes, reaching more than 5 m in thickness in proximal zones and decreasing steadily towards distal zones. As gas masking occurs in the proximal zone (Fig. 2), probably the thickness may increase significantly landward. Major AggSUs are characterised by semitransparent seismic facies with low-amplitude internal reflectors showing poor lateral continuity. Thickness distribution of major AggSUs resembles sheet drapes, because they are characterised by fairly constant and moderate thickness values ranging between 2–4 m (For more detail about distribution patterns of seismic units composing the Holocene HST of the Guadalquivir River prodelta, see Fig. 5 of Fernández-Salas et al., 2003).

5.2. Guadiana River deposits

The Holocene HST is considered to be represented in the Guadiana River estuary by two major ProgSUs (lower and upper) bounded by a nondepositional surface (Fig. 3). These two major ProgSUs show seaward-directed prograding facies with a highly reflective pattern. Major ProgSUs are usually thinner than 8 m and are only locally thicker, where they infill basement depressions. Despite their moderate thickness, estuarine major ProgSUs show a widespread occurrence, which can be associated with the narrowness of the valley (Fig. 3).

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Fig. 2. Sedimentary architecture of the Guadalquivir River prodelta: (A) high-resolution seismic profile collected off the Guadalquivir River; (B) seismic stratigraphy interpretation of the Guadalquivir River prodelta, showing the repetition of two progradational–aggradational motifs. ProgSU: progradational seismic unit; AggSU: aggradational seismic unit; TST: transgressive systems tract; HST: highstand systems tract; MFS: maximum flooding surface; TWTT (ms): two-way travel time (milliseconds). Modified from Fernández-Salas et al. (2003). See position in Fig. 1.
A lobate wedge deposit located in front of the Guadiana River to a depth of 40 m is characterised by a moderate to high reflectivity and by internal low-angle progradational reflectors. The internal structure shows two major ProgSUs (lower and upper) bounded by a non-depositional downlap surface and overlying the postglacial TST (Fig. 4). The lower major ProgSU extends up to 30 m water depth and shows some internal downlapping reflectors. Maximum thickness is below 5–6 m. The upper major ProgSU is also characterised by low-angle prograding reflectors with inclinations lower than 0.5°. It presents higher seaward extension and thickness than the proximal unit, because it extends up to 40 m water depth and the maximum thickness is below 8.5 m (Fig. 4).

5.3. Faro–Tavira IPW

The Faro–Tavira IPW is a shallow-marine deposit that occurs to a depth of 25–30 m (Figs. 5 and 6), displaying an elongated pattern around Cape Santa Maria with two main depocenters located off Tavira and off Faro (Fig. 7). Each depocenter shows a distinct stratigraphic architecture (Figs. 5 and 6).

5.3.1. Depocenter off Tavira

The internal structure of this depocenter is characterised by four seismic units, which are arranged in two ProgSU–AggSU motifs dominated by ProgSUs (Figs. 5 and 6). The lower ProgSU–AggSU motif shows at the base a major ProgSU with a sigmoid internal configuration. Internal reflectors show top concordance and bottom concordance to smooth downlap. Subhorizontal topsets evolve seaward to foresets which show inclinations up to 0.5°. The maximum thickness of the lower major ProgSU is of about 12 m. It is capped by a major AggSU, represented by a sheet drape with moderate thickness ranging between 5–6 m and without internal reflectors. The upper ProgSU–AggSU motif shows at the base a major ProgSU which shows a tangential-oblique configuration, with toplap-to-erosional truncation at the top and...
downlap at the bottom. Internal foreset to bottomsets are downlap surfaces which define five minor ProgSUs. Foreset inclinations range between 3–4°, decreasing in the bottomset to about 1°. The maximum thickness value is up to 20 m. This major ProgSU pinches out dramatically at about 55 m water depth. The overlying major AggSU also appears under the form of a sheet-like drape. This recent AggSU is observed locally between 20–40 m water depth, where it shows low thickness below 5–6 m and does not show internal reflectors (Figs. 5 and 6).

5.3.2. Depocenter off Faro

The internal structure of this depocenter is very complex, because twelve minor ProgSUs (minor ProgSUs 1 to 12) and seven minor AggSUs (minor AggSUs 1 to 7) numbered from bottom to top were identified (Fig. 8). Two distinct portions are differentiated according to the stratigraphic pattern shown by minor ProgSUs and AggSUs:

(a) The lower portion is characterised by the lateral stacking and alternance of minor ProgSUs and AggSUs (Fig. 8). Minor ProgSUs are wedge-shaped units with maximum thickness in the middle parts higher than 13 m and generally ranging between 9–13 m. Minor ProgSUs depocenters show a progressive seaward migration. Lateral progradation caused by each individual minor ProgSU is generally lower than 250 m. However, in some cases a higher progradation has been detected. Particularly, minor ProgSU 1 has prograded seaward more than 1 km. Most minor ProgSUs show proximal parallel-oblique configurations which evolve distally and downward to tangential-oblique configurations. Inclinations may be as high as 10° in the foresets, decreasing to values of 1–2° in the bottomsets. As a consequence, erosional truncation is the most frequent upper termination of internal reflectors, particularly landward from successive offlap breaks. Downlap terminations frequently occur in relation to the lower boundaries. However, minor ProgSUs 4 and 7 show lenticular external shapes and sigmoid internal configurations, as the reflectors tend to toplap or even show concordant relationships in relation to the upper boundaries (Fig. 8). Minor AggSUs within the lower portion show sheet-like shapes, with maximum thickness values below 9–10 m. Minor AggSUs with higher development occur above and below
sigmoid minor ProgSUs, defining two portions characterized by increased representation of AggSUs (from minor AggSU 3 to 4, and 6 to 7). Conversely, minor AggSUs located within oblique minor ProgSUs are less developed. They mainly show aggradational or low-angle progradational internal configurations, although in places wavy configurations are also observed, as in the case of minor AggSU 7 (Fig. 8).

(b) The upper portion is composed exclusively by minor ProgSUs (from minor ProgSU 8 to 12), as no significant minor AggSUs are detected (Fig. 8). Those minor ProgSUs are wedge shaped, with maximum thickness in the middle parts generally below 15 m, particularly in relation to the three older minor ProgSUs. In contrast, the two more recent minor ProgSUs are considerably thinner, as maximum thicknesses do not exceed 8–9 m. Depocenters show a progressive seaward migration, although lateral progradation caused by those minor ProgSUs is fairly reduced. The seaward progradation of each minor ProgSU is below 200–250 m, and it decreases from older to younger units. Internal configurations are dominated by tangential-oblique progradations evolving seaward to sigmoid progradations, characterised by the preservation of topsets (Fig. 8). Foreset inclinations generally range between 7–8°, evolving seaward to bottom sets with inclinations lower than 2°.
Fig. 6. Sedimentary architecture of the Tavira depocenter, based on an along-shelf seismic section (A) and interpretation (B) showing the lateral termination of the wedge. The upper major ProgSU is composed of five minor ProgSUs, and the upper AggSU is not identified here. ProgSU: progradational seismic unit; AggSU: aggradational seismic unit; TST: transgressive systems tract; HST: highstand systems tract; MFS: maximum flooding surface; IPW: infralittoral prograding wedge; TWTT (ms): two-way travel time (milliseconds). See position in Fig. 1.
5.3.3. Comparison between Tavira and Faro depocenters

A comparison of the Tavira and the Faro depocenters was attempted, based on the existence of seismic profiles which connect both depocenters correlating the lower boundary of the Holocene HST and on the comparison of the internal architectures. The most recent stratigraphic interval in both depocenters shows a similar internal architecture, which has been evidenced in the emerged spit-bar record (Zazo et al., 1994). Thus, the upper major ProgSU identified in the depocenter off Tavira, composed by five minor ProgSUs, would be equivalent to the last architectural segment of the depocenter off Faro, which also shows five minor ProgSUs. The identification of those five minor ProgSUs is in agreement with the internal detailed architecture of the second major progradational phase identified in the emerged spit-bar record, which also shows five minor progradational sets (Fig. 9).

According to the above expressed reasoning, the lower major ProgSU–AggSU motif described in the depocenter off Tavira would be equivalent to the lower portion of the depocenter off Faro, which shows the repetition of minor ProgSU–AggSU motifs. The final part of the lower portion of the Faro depocenter shows a higher significance of minor AggSUs, as minor ProgSU 7 is intercalated within two thicker minor AggSUs (6 and 7). It may be supposed that these three minor SUs would be equivalent to the lower major AggSU. Therefore, the lower major ProgSU observed in the Tavira depocenter would be equivalent to the interval between minor ProgSU 1 and minor ProgSU 6 described in the Faro depocenter (Fig. 9).

6. Onshore–offshore comparison of Holocene highstand deposits: the record of Holocene high-frequency environmental changes

In spite of the inherent limitations of the existing database, mainly the density of seismic lines, which makes very difficult to have a strict geometric constraint at a small-scale, and the lack of direct datations in shallow-marine deposits, an effort has been made in order to increase the knowledge about the internal organisation of Holocene highstand deposits. Thus, stratigraphic patterns of shallow-marine deposits identified in the Gulf of Cadiz margin were compared with:

(a) Emerged spit-bar deposits previously characterised in the southern Iberian Peninsula, both in the Gulf of Cadiz (Zazo et al., 1994; Lario et al., 1995; Goy et al., 1996; Rodriguez Ramirez et al., 1996; Rodriguez-Ramirez et al., 2003; Dabrio et al., 2000) and the Western Mediterranean (Goy et al., 2003). In the Gulf of Cadiz, spit-bar deposits have developed since the post-glacial transgressive maximum (PTM), dated at about 6500 yr BP, under the influence of eastward- and southeastward-directed littoral drift, due to coastline orientation in relation with dominant southwest waves (Zazo et al., 1994; Lario et al., 1995; Morales, 1997). In the littoral between Guadiana Estuary and Bay of Cadiz, aeolian dune systems are associated with the spit-bar systems, particularly between the estuaries of Tinto–Odiel and Guadalquivir Rivers (Borja et al., 1999). The internal structure of coastal spit-bars shows numerous progradational phases bounded by erosion surfaces. Timing of each progradational phase has been estimated from $^{14}$C dating, archaeological and historical studies. Constructional phases have been controlled by regional climatic conditions which have influenced changes of storminess.
and of sediment supply (Rodríguez Ramírez et al., 2000; Rodríguez-Ramirez et al., 2003) and by associated high-frequency sea-level changes in connection with oceanographic changes (Zazo et al., 1994; Lario, 1996). Locally, the influence of tectonic factors has been reported (Goy et al., 1996).

(b) Contemporaneous prodeltaic deposits studied in nearby Spanish continental shelves, such as the northern shelf of the Alboran Sea (Hernández-Molina et al., 1994; Fernández-Salas et al., 2003) and the Ebro River prodelta (Somoza et al., 1998). In the shallow-marine record, progradational units have been related to stable and falling sea-levels (Hernández-Molina et al., 1994; Goy et al., 1996; Rodríguez Ramirez et al., 1996; Somoza et al., 1998), whereas aggradational units are supposed to constitute the record of sea-level rises (Hernández-Molina et al., 1994; Somoza et al., 1998).

Fig. 8. Sedimentary architecture of the Faro depocenter: (A) high-resolution seismic profile collected off Faro; (B) seismic stratigraphy interpretation of the Faro depocenter. Two main architectural segments are identified in this deposit. The lower segment (from minor ProgSU 1 to minor AggSU 7) is characterised by the repetition of a basic motif composed by minor ProgSUs and AggSUs. The upper segment (from minor ProgSU 8 to minor ProgSU 12) is characterised by the dominance of minor ProgSUs. ProgSU: progradational seismic unit; AggSU: aggradational seismic unit; TST: transgressive systems tract; MFS: maximum flooding surface; TWTT (ms): two-way travel time (milliseconds).
Although most of the works depict the shelf Holocene highstand as a single clinoform structure generated by homogeneous sedimentation processes (Hübscher et al., 2002; Yoo et al., 2002; Hori et al., 2004), some recent publications report the identification of more complex internal architectures, particularly in prodeltaic settings (Cattaneo et al., 2003; Liu et al., 2004). In those environments the overall geometry can be subdivided into minor constructional blocks. Our contribution highlights the existence of a complex internal architecture of the Holocene HST, supporting the idea that sedimentation processes have not been homogenous or continuous through time and documenting a fluctuating pattern of environmental conditions during the recent highstand period.

Besides, another significant consideration is that the units that compose shallow-marine deposits are arranged in a hierarchical pattern, as three scales of seismic motifs were identified: major, intermediate and minor scale (Fig. 10). This hierarchical pattern possibly corresponds with three different types of environmental cycles operating at different temporal scales. The major and intermediate cycles seem to have been modulated by even shorter cycles, which apparently left an imprint of alternating periods of progradation–aggradation.

6.1. Major-scale motifs: a pervasive two-fold constructional pattern

The most significant stratigraphic feature observed in the shallow-marine deposits of the Gulf of Cadiz margin is the pervasive occurrence of two major constructional phases represented by lower and upper major-scale motifs during the Holocene highstand (Figs. 10A and 11, Table 1). Major ProgSUs are recognised in all studied sedimentary environments of the Gulf of Cadiz margin, whereas major AggSUs are not recognised in the Guadiana River area (Fig. 11), probably because of reduced sediment supply (Lobo et al., 2004). The two-fold constructional pattern would indicate the existence of two major cycles during the Holocene highstand, as they have been recorded in other shallow-marine deposits around the Iberian Peninsula (Hernández-Molina, 1993; Hernández-Molina et al., 1994; Somoza et al., 1998; Fernández-Salas et al., 2003).

In spite of the lack of age dating of marine deposits, the comparison between the internal architecture of shallow-marine deposits and emerged spit-bar deposits in the Gulf of Cadiz margin during the recent highstand period reveals interesting similarities, such as:

(a) Two major-scale motifs are identified in shallow-marine deposits (Fig. 11); within spit-bar systems, two major progradational phases have been documented (Zazo et al., 1994, 1996; Lario et al., 1995; Goy et al., 1996; Rodríguez Ramirez et al., 1996; Dabrio et al., 2000).
(b) The transition between the two major scale-motifs seems to coincide with a significant change of sedimentation patterns in the shallow-marine record, being recorded by a significant aggradational deposit (lower major AggSU) or by a non-depositional surface (Figs. 10A and 11). In the emerged spit-bar system, this transition has also been related with a significant sedimentary gap of progradation, possibly related to...
intense erosion due to shoreline retreat (Zazo et al., 1994, 1996; Lario et al., 1995; Goy et al., 1996; Rodríguez Ramírez et al., 1996). In the Mediterranean region, this gap is related with a major change of littoral drift at approximately 2.7 ka (Goy et al., 2003).

(c) Progradational patterns observed within each major-scale motif show different characteristics (Figs. 10A and 11). The sigmoid progradation observed in specific locations in the lower major ProgSU would indicate the existence of enough accommodation space after the transgressive interval (cf. Posamentier et al., 1988), when open-sea conditions were dominant in the estuaries (Lario et al., 1995). In contrast, the net progradational pattern observed in the upper major ProgSU would indicate deposition when significant modifications in littoral dynamics led to the dominance of progradation over aggradation and partial infilling of estuaries started (Lario et al., 1995; Goy et al., 1996). A sedimentation change in estuaries from vertical accretion of tidal flats to lateral progradation of spit-bars has also been described (Borja et al., 1999; Dabrio et al., 2000).

(d) In places of higher seismic resolution and/or sediment thickness, the second major ProgSU in the shallow-marine record shows five minor progradational units. Similarly, the second major progradational phase in the spit-bar record is composed of five minor sets (Zazo et al., 1994; Lario et al., 1995).

Taking into account those similarities, it seems reasonable to relate the lower major ProgSU of the shallow-marine record with the older progradational phase in the spit-bar record (6500–2700 yr BP), and the upper major ProgSU of the shallow-marine record with the younger progradational phase in the spit-bar record (from 2400 yr BP to the present).

6.2. Intermediate-scale motifs

Two shorter progradational phases also bounded by erosional surfaces have been identified within each
major progradational phase of the Gulf of Cadiz coastal sedimentary record, determining four intermediate progradational phases (H1 to H4) that correspond to spit-bar units: H1 (6500–4500 yr BP), H2 (4200–2700 yr BP), H3 (2400–1100 yr BP) and H4 (1000 yr BP to present–day) (Zazo et al., 1994, 1996). The major gap occurs between H2 and H3, although two erosional gaps of similar characteristics were identified in relation with the H1–H2 and H3–H4 transitions (Zazo et al., 1994; Lario et al., 1995; Dabrio et al., 2000). H1 and H2 have been particularly documented in estuarine infills (Fig. 12). Phase H1 is represented by initial bayhead deltas and the rims of tidal flats, although spits also grew by littoral drift. A minor sea-level rise possibly promoted open marine conditions in the estuaries towards the end of phase H1. Continued spit progradation accompanied by barrier emergence probably occurred during phase H2 (Fig. 12). Spit-bar development was especially favoured during phases H3 and H4, because of littoral drift and increased sediment input (Dabrio et al., 2000). However, in the Mediterranean region up to six progradational phases, named H1 to H6 from older to younger, have been described. The duration of such H-units in the Mediterranean region suggests a quasi-millennial periodicity (Goy et al., 2003).

The intermediate progradational phases constituted the basis for the description of the coastal sedimentary record. Therefore, the coastal nomenclature was maintained in the description of the shallow-marine sedimentary record, assuming the existence of four intermediate-scale motifs recognised in the Gulf of Cadiz region and designed as H1 to H4 (Fig. 10B, Table 1). Intermediate-scale motifs H1 and H2 would
compose the lower major-scale motif, whereas intermediate-scale motifs H3 and H4 would compose the upper major-scale motif. The high-resolution architecture observed in the Faro depocenter enabled us to recognise intermediate-scale motifs H1 and H2 (Fig. 10B, Table 1). There, a dominantly aggradational interval is assumed to constitute the final part of the lower major-scale motif, but also of intermediate-scale motif H2. In addition, a dominantly aggradational interval between minor AggSUs 3 and 4 was identified within the lower major ProgSU. This interval would represent the final part of intermediate-scale motif H1 (Fig. 10B). In contrast, the distinction of intermediate-scale motifs H3 and H4 within the upper major-scale motif is not possible at this level, due to the absence of aggradational sets within the upper major ProgSU.

Taking into consideration that each major-scale motif would be composed of two intermediate-scale motifs, these intermediate cycles would have half the period of the major-scale cycles. Thus, their development could be related with mini-Dansgard/Oeschger cycles, or with H cycles of Hernández-Molina et al. (1994), with a main periodicity of about 1500 yr.

6.3. Minor-scale motifs

The detailed stratigraphic architecture observed in the Faro depocenter suggests the existence of minor-scale motifs composing intermediate-scale motifs (Fig. 10C). In the coastal spit record of the Gulf of Cadiz, the existence of minor progradational phases was identified within H1 and H4 (Zazo et al., 1994; Lario et al., 1995), but the relationships of minor progradational phases remain less known within H1 and H2 (Zazo et al., 1996). However, groups of sets composing prograding units (H units) have been documented in the Spanish Mediterranean coast during the last 7 kyr (Goy et al., 2003).

According to the information extracted from the Faro depocenter, minor-scale motifs would be composed by minor ProgUSs and AggSUs in intermediate-scale motifs H1 and H2. Thus, intermediate-scale motif H1 would be composed by four minor-scale motifs (1 to 4), whereas intermediate-scale motif H2 would be composed by three minor-scale motifs (5 to 7) (Fig. 10C, Table 1).

Detailed geomorphological analysis carried out in the emerged spit systems (Fig. 12, Table 1) (Zazo et al., 1994; Lario et al., 1995), where H3+H4 are composed of five minor progradational sets (a to e from older to younger) with a periodicity of about 400–500 yr, enabled us to study the relationship between intermediate- and minor-scale motifs within the upper major-scale motif. Those minor sets are supposed to be equivalent to the five minor ProgSUs identified within the upper major ProgSU in the Faro and Tavira depocenters. In the spit-bar record, H3 is constituted by three minor progradational sets (a, b and c), whereas H4 is constituted by two minor progradational sets (d and e). As a first approach, we propose that intermediate-scale motif H3 would be composed by three minor-scale motifs (8 to 10), whereas intermediate-scale motif H4 would be composed by two minor-scale motifs (11 and 12). Therefore, the H3–H4 transition would be represented by the boundary between minor ProgSU 10 and minor ProgSU 11, and is not represented by a distinct deposit in the shallow-marine record (Fig. 10C).

Those high-frequency cycles operating during the Holocene highstand would be equivalent to C cycles of Hernández-Molina et al. (1994), and can be related to climatic cyclicities of submillenial scale reported in the introduction. Recent morphological analysis conducted on spit-bar systems of the coastal stretch between the Guadiana and Guadalquivir Riv-

| Table 1 |
| Correlation between the major, middle and minor scale architectures recognised in shallow-marine deposits of the Gulf of Cadiz margin |
| Internal structure of Holocene highstand deposits |
| Major-scale motifs | Middle-scale motifs | Minor-scale motifs |
| UPPER | H4 | 12=e |
| | | 11=d |
| | H3 | 10=c |
| | | 9=b |
| | | 8=a |
| LOWER | H2 | 7 |
| | 6 |
| | 5 |
| | H1 | 4 |
| | 3 |
| | 2 |
| | 1 |

Minor-scale motifs 8 to 12 are considered to be equivalent to sets a to e defined in the emerged systems.

ProgSU: progradational seismic unit; AggSU: aggradational seismic unit.
ers suggest the existence of even higher frequency cyclicities (6 and 9–10 yr) leading the spit progradation during the second half of the XXth century (Rodríguez Ramírez et al., 2000; Rodriguez-Ramirez et al., 2003).

7. Driving forces of recent high-frequency environmental change

Possible causes that may have influenced the generation of high-frequency environmental changes...
recorded in shallow-marine deposits as a complex superposition of seismic units and progradational–aggradational motifs are discussed. Autocyclic mechanisms due to filling of accommodation space in the neroshore could be postulated as a possible cause, particularly in the Faro–Tavira IPW, where lateral outgrowth has occurred. However, the identification in the older major progradational phase of minor progradational–aggradational motifs suggests changing depositional conditions by external forcing. In addition, the architecture of the younger major progradational phase is evidenced in other different places, suggesting a regional control. Therefore, the ongoing discussion mainly refers to external environmental factors.

7.1. High-frequency sea-level changes and associated oceanographic changes

The influence of small-scale sea-level changes seems to be particularly evident in relation with the major-scale motifs, as this architectural level has been recognised elsewhere. Major-scale motifs have been related with two distinct sea-level cycles, or P cycles according to Hernández-Molina et al. (1994). The two-fold cyclicity pattern also could be related to two sea-level cycles recognised in different coastal environments, and summarised in Fernández-Salas et al. (2003). Besides, coastal studies conducted on the Gulf of Cadiz also support the existence of two distinct oscillations of sea-level change during the recent highstand (Zazo et al., 1996).

Within each major-scale motif, major progradational phases were followed by deposition of AggSUs indicative of significant phases of sea-level rise (Figs. 10A and 11). The transition between the two major progradational phases was characterised by a sea-level rise larger than the sea-level rise associated to the sedimentary gap between H_1 and H_2 (Goy et al., 1996). The internal structure of shallow-marine deposits shows that the transition between the two major progradational phases is represented by the lower major AggSU (Fig. 11). The record of a possibly equivalent significant intra-late Holocene highstand transgression has been reported in several estuaries of the Cantabric Sea, northern Spain (Cearreta and Murray, 1996; Cearreta, 1998; Pascual et al., 1998). Other coastal records also suggest an intra-late Holocene highstand sea-level rise of 2–3 m (Banerjee, 2000) or a high sea level (Flood and Frankel, 1989; Woodroffe et al., 1995).

In the emerged coastal record, the generation of H units has also been linked to small sea-level changes of metric or submetric scale, partially influenced by coastal current enhancement (Lario et al., 1995; Goy et al., 2003). Thus, middle-scale progradational intervals (H units) have been related with sea-level stabilization to gentle relative sea-level fall (Dabrio et al., 1995; Lario et al., 1995; Goy et al., 1996; Rodríguez Ramirez et al., 1996), whereas erosional surfaces separating spit-bar units have been related to rising sea levels, when littoral barriers underwent intense erosion, cliffs retreated and aeolian dune fields migrated landward (Zazo et al., 1994; 1996, Lario, 1996; Goy et al., 1996; Rodríguez Ramirez et al., 1996).

Finally, warm/cold climate events (Scott and Collins, 1996) have been related with rapid sea-level oscillations of metric or submetric scale and submillenial periodicity during the recent highstand (Stapor et al., 1991; Tanner, 1992; Scott and Collins, 1996; Van de Plassche et al., 1998; Yu and Ito, 1999; Morton et al., 2000). Their contribution to the generation of the small-scale architecture observed in the studied depositional morphologies remains hypothetical, as for so small-amplitude changes other local factors may interfere.

7.2. Changes in the intensity and/or the direction of storms

Storm events influence climatic variability and they have impacts in coastal areas (Regnauld et al., 1996). The possible effects of storms would be particularly applicable to the Faro–Tavira IPW, as the initial interpretation has considered a genetic link with downwelling storm currents (Hernández-Molina et al., 2000a). During the Holocene, periods of increased storminess have been related to increased bottom current energy, with enhanced sediment transport from the coastal zone to the outer shelf (Andresen et al., 2005). For the last 2000 yr, a relationship was found between winter storminess, climate-driven coastal erosion and climate dynamics in the North Atlantic. Both storminess and coastal erosion were at a minimum during the Medieval Warm Period, whereas periods of climate deterioration occurred.
both before and after that period; particularly, the most recent interval has been associated with sustained coastal erosion (Dawson et al., 2004). At a shorter scale, the influence of storm periods on the growth of beach ridges has been documented in the Gulf of Cadiz coasts for the last 40 yr, in relation with a cyclic behaviour of the North Atlantic Oscillation (Rodríguez Ramírez et al., 2000; Rodriguez-Ramirez et al., 2003). The storm periods concentrate on winter months and are associated with southwestern winds, whose influence during specific periods has favoured the accumulation of significant aeolian systems in the Gulf of Cadiz (Borja et al., 1999). Cyclonic periods accelerate erosion rates and induce the creation of new beach ridges in post-storm periods. In contrast, during prolonged anticyclonic periods the formation of swales was favoured (Rodríguez Ramírez et al., 2000; Rodriguez-Ramirez et al., 2003).

We postulate that alternating periods of increased and decreased storm influence in the shoreface could produce the observed geometry characterised by the alternance of progradational and aggradational units, particularly evident at the minor-scale level. Similarly, changes in the main direction of storms would allow the production of similar geometries, taking into account the existence of an oblique component of progradation. The change of internal architecture observed in the Tavira depocenter probably suggests a higher variability degree of those parameters (storm intensity and/or direction) during the first major constructional phase. More homogeneous conditions would have been dominant during the second major constructional phase, although downlap surfaces separating minor ProgSUs could be interpreted as the result of sediment supply fluctuations.

7.3. Regional climatic changes that can lead to sediment supply fluctuations

The possible modification of sediment supplies would be especially applicable to the prodeltaic environments considered in this study (Guadalquivir and Guadiana). By one hand, climatic phenomena may increase the magnitude and frequency of major floods, with subsequent increase in shelf sedimentation rates (Sommerfield et al., 2002). Besides, millennial-scale climatic variability has caused changes in vegetation communities during the last 14 kyr (Viau et al., 2002). The development of clinoform structures, generally of prodeltaic origin, which also show complex internal architectures has also been linked to alternating intervals of enhanced outbuilding, characterised by increased discharge and sediment load, and condensed deposition (Cattaneo et al., 2003; Liu et al., 2004). The internal architecture seems to be controlled by short-term climatic changes. As an example, substantial outbuilding has taken place during the Little Ice Age (Cattaneo et al., 2003).

In the study area, increased rates of delta progradation have been probably favoured by anticyclonic conditions, when short-lived, intense rains caused the flooding of the lower reaches of rivers and estuaries (Lario et al., 1995; Goy et al., 1996). In contrast, the boundaries of H-units have been related with short cold events in the North Atlantic, the Mini Dansgaard–Oeschger events (Bond et al., 1997), which cause periods of increased aridity and reduced sediment input (Goy et al., 2003).

7.4. Other modifications of sediment supply

As well as in the previous case, this explanation would be best applied to prodeltaic systems, where anthropogenic increases of watershed-sediment production have been documented in the recent past (Sommerfield et al., 2002). In the study area, an increase of fluvial input in relation with anthropic activities (changes of farming systems, increased deforestation) has been documented during the most recent H-units (Lario et al., 1995; Dabrio et al., 2000).

8. Conclusions

The comparison of the internal structure between emerged coastal deposits and shallow-marine deposits (Guadalquivir and Guadiana River prodeltas, Faro–Tavira IPW) formed during the Holocene highstand period in the Gulf of Cadiz margin highlights the existence of a complex internal architecture of the Holocene HST, documenting a fluctuating pattern of high-frequency environmental fluctuations linked to climatic periodicities of sub-Milankovitch scale.

The sedimentary architecture of shallow-marine deposits shows a hierarchical pattern where three
scales of ProgSUs and/or AggSUs arranged in basic motifs were defined:

(a) Major-scale motifs: the recognition of two major motifs designed as lower and upper is pervasive in shallow-marine deposits around the Iberian Peninsula. The lower major-scale motif is attributed to the first phase of coastal spit-bar progradation defined onshore by previous authors, whereas the upper major-scale motif is attributed to the second phase of coastal spit-bar progradation.

(b) Intermediate-scale motifs: the recognition of a dominantly aggradational segment within the lower major-scale motif enabled the distinction of two intermediate-scale motifs correlated with phases H1 and H2 of coastal spit-bar progradation. However, the transition between intermediate-scale motifs H3 and H4 within the upper major-scale motif was less significant. Those intermediate-scale motifs may be related with postglacial climatic shifts of ~1500 yr.

(c) Minor-scale motifs: environmental variability of sub-millenial scale seems to have operated continuously during the recent Holocene highstand period. The internal structure of the two older intermediate-scale motifs (H1 and H2) composing the lower major-scale motif is particularly interesting, as they show the repetition of minor-scale ProgSU–AggSU motifs. In contrast, the two younger intermediate-scale motifs (H3 and H4) are characterised by the dominance of minor ProgSUs.

Several driving factors are proposed to explain the generation of the observed architectures. The influence of low-amplitude sea-level fluctuations, recognised by the alternating pattern of progradation/ aggradation, seems to be particularly evident in the major-scale motifs, which were observed elsewhere. Those major-scale motifs could be attributed to two large sea-level cycles, whereas the transition between both major phases occurred through a major sea-level rise recorded by a widespread sheet drape. However, there are other factors that could significantly influence the recent stratigraphy of shallow-marine deposits. Changes in the magnitude and/or direction of storm events are thought to be a controlling factor in the generation of the small-scale architecture of the Faro–Tavira IPW, due to its genetic link with downwelling storm currents. Modifications of sediment supply by climatic shifts and/or anthropogenic activities affecting the river basins are probably a significant control on the formation of constructional blocks of prodeltaic-related deposits.

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References


