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High-resolution architecture of late Holocene highstand prodeltaic deposits from southern Spain: the imprint of high-frequency climatic and relative sea-level changes

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Abstract

The stratigraphic architecture and recent evolution of two late Holocene prodeltas (Guadalquivir and Guadalhorce rivers) from the south of Spain are compared on the basis of a high-resolution seismic stratigraphic analysis. These sedimentary bodies display a similar internal architecture, being characterised by a thin transgressive systems tract at their bases and an overlying thick, wedge-shaped highstand systems tract (HST). The internal structure of the HST deposits shows the repetition of two progradational/aggradational cycles, whose generation seems to be related to the influence of high-frequency climatic changes during the last 6–7 ka. Those changes probably involved small amplitude (<3–4 m) sea-level oscillations and associated changes of sediment supply, conditioning the development of delta switching processes. Small differences in the distribution and characteristics of the seismic units in each area are attributed to local factors, such as physiography of the coastal plains, the wave climate and increased sediment supplies conditioned by anthropic actions.

Keywords: Holocene; Sea-level changes; Climatic changes; Gulf of Cádiz; Alboran Sea; Geographic bounding coordinates: Guadalquivir area: (36°15′N,7°15′W) (36°50′N,5°35′W); Guadalhorce area: (36°30′N,4°40′W)(36°45′N,4°23′W)

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1. Introduction

The application of sequence stratigraphy concepts to late Pleistocene and Holocene shelf and coastal deposits has shown that the large-scale architecture of deltas, defined by the geometry of progradation, aggradation and retrogradation, is mainly governed by sediment yield and relative

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sea-level change (Thorne and Swift, 1991; Postma, 1995). These deltaic sequences can be subdivided generally into three stratigraphic units (SU I, II and III) (Warne and Stanley, 1995). SU III is the most recent unit and represents the Holocene deltaic deposits. It is composed of transgressive systems tract (TST) to highstand systems tract (HST), which are differentiated by the stacking pattern of the parasequences. It is believed that eustatic changes played a major role in determining the structure of those sequences. However, their evolution may also be controlled by the rate of sediment supply and by tectonics, but those factors can only modify the relative growth patterns of such systems tracts. For example, huge sediment loads would favour the formation of aggrading TST, and early initiation of HST progradation (Goodbred and Kuehl, 2000).

The stratigraphic architecture of the HST component of the Holocene prodeltaic deposits has been studied by a number of workers. Traditionally, most of them considered a unique clinoform structure with a wedge-shaped external form and a characteristic topset–foreset–bottomset internal configuration (Nittrouer et al., 1986; Díaz et al., 1996). This wedge-shaped structure internally shows lateral transition of seismic facies, from proximal stratified facies to distal transparent facies, which is related to different sedimentary environments (Nittrouer et al., 1986; Trincardi and Normark, 1988; Díaz et al., 1990; Park et al., 1990; Díaz and Ercilla, 1993; Ercilla et al., 1995; Díaz et al., 1996; Nittrouer et al., 1996; Hart et al., 1998). The pattern of erosion/accumulation and the vertical build-up of the clinoform structure are also controlled by the intensity of oceanic processes (Nittrouer et al., 1996).

However, the detailed study of some Holocene deltas has revealed a more complex vertical structure. The cyclic character of deltaic sedimentation was described by Scruton (1960), who stated that the evolution of deltas can be subdivided in two phases: the first is constructive and progradational and the second is destructive and retrogradational. In these studies, channel avulsion and delta lobe switching are amongst the most important controlling factors in determining the internal structure of Holocene deltas (Aksu et al., 1987). Those processes were thought to be generated by rather random controlling factors, such as changes in river mouth domains, neotectonic activity and fluctuations in sediment supply (Díaz et al., 1990; Goodbred and Kuehl, 2000). However, several authors have recently suggested that the avulsion of deltaic lobes can be attributed to superimposed processes, such as climate change and sea-level fluctuations (Swift et al., 1991). In this sense, fifth-order sea-level cycles ($1–2\times10^3$ years), associated with major climatic fluctuations during the middle to late Holocene, would have favoured delta lobe switching (Lowrie and Hamiter, 1995).

Some authors (Hernández-Molina et al., 1994; Fernández-Salas, 1996; Somoza et al., 1998) have suggested that Holocene highstand deposits do not constitute a unique sedimentary body, but are made up of an assemblage of minor sedimentary bodies. The internal structure of HST deltaic deposits has been linked to the role of fifth- and sixth-order sea-level oscillations. Progradational events are caused by the fifth-order cycles, whereas the modification of deltaic lobes has been attributed to the influence of sixth-order cycles. These cycles have been used to explain the depositional architecture of many coastal and shelf deposits in different areas, as the Mississippi delta (Boyd et al., 1989; Lowrie and Fairbridge, 1991; Lowrie and Hamiter, 1995) and abundant Mediterranean deltas, such as the Nile delta (Stanley and Warne, 1993), the Rhône delta (Gensous et al., 1993), the Tiber delta (Bellotti et al., 1994), the Ebro delta (Checa et al., 1988; Díaz et al., 1990; Somoza et al., 1998) and the Alboran Sea deltas (Hernández-Molina et al., 1994; Fernández-Salas, 1996; Fernández-Salas et al., 1996), among others.

In this paper, we examine the stratigraphic architecture and recent evolution of late Holocene highstand deposits associated with deltaic bodies from the southern Iberian margin, from a high-resolution seismic stratigraphy perspective which has been supported by sedimentologic analysis. According to this, the main goals of this work are: (1) to determine the governing forces and processes which have controlled the resulting stratigraphic pattern and internal structure of middle to late Holocene deltaic sequences; (2) to test the relative significance of autocyclic (sediment supply) and allocyclic (climatic, glacio-eustatic changes) factors, and; (3) to explain the existence of regional variability of such deposits.

2. Regional setting and oceanography

Our research has focussed on two sectors of the continental shelf of the southern Iberian Peninsula. The Guadalhorce prodelta is located in the northeastern Alboran Sea (Mediterranean Sea) and the Guadalquivir prodelta is located in the Gulf of Cadiz (Atlantic Ocean). Both regions are connected by the Straits of Gibraltar (Fig. 1a).

2.1. The Alboran Sea continental shelf

The Alboran Basin is located in the westernmost Mediterranean Sea. We have studied a sector of the Spanish continental shelf of the Alboran Basin, located between the city of Malaga and Calaburras Cape (Fig. 1c). The coastal plain is very narrow, because the Betic Mountains are very close to the shoreline. As a consequence, several relatively steep and small rivers (Guadalhorce, Guadalmedina and Fuengirola rivers), characterised by a pronounced seasonal variability in the sediment supply regime, feed this sector of the Alboran shelf. The most important is the Guadalhorce River, which is 160 km long and has a drainage basin that extends for about 3158 km^2.

The total width of the continental shelf area ranges between 8 and 12 km, its average gradient ranges between 0.34° and 0.46° and the shelfbreak is located at 110 m water depth (Hernández-Molina, 1993; Hernández-Molina et al., 1994). The inner-middle shelf is covered by modern prodeltas related to the main rivers and infralittoral prograding wedges. The sea floor of the Guadalhorce prodelta displays an average gradient of 1.22°.

Coastline configuration induces a dominant W-SW littoral drift. The main current affecting the studied continental shelf is the Atlantic Inflow (AI), which flows between 0 and 150–200 m water depth (Gil, 1990). After entering the Mediterranean Sea through the Strait of Gibraltar, the pathway of the AI describes two anticyclonic gyres, generating a mean east-northeastward flow over the shelf (Cano and García, 1991).

According to Ercilla (1992), Ercilla et al. (1992), Hernández-Molina (1993) and Hernández-Molina et al. (1994), the late Quaternary depositional sequences in the northern margin of the Alboran Sea is made up of the following deposits, from bottom to top: (1) A lowstand progradational wedge in the shelfbreak, interpreted as the lowstand systems tract (LST); (2) A set of two backstepping units, one progradational and another aggradational associated with the TST; (3) A progradational wedge attributed to the HST composed of four units which represent prodeltaic bodies.

2.2. The Gulf of Cadiz continental shelf

The studied sector of the Gulf of Cadiz is located between the Guadalquivir river mouth to the north and the town of Zahara de los Atunes to the south (Fig. 1b). The most important river feeding this shelf is the Guadalquivir river, whose mouth is located at the northern edge of the study area. It is 560 km long and its basin covers over 57,121 km^2, with a mean water discharge of 160 m^3/s (Van Geen et al., 1997). The coastal plain of the Guadalquivir river is characterised by wide salt marshes with very low gradients.

The continental shelf of the Gulf of Cadiz located offshore from the Guadalquivir river mouth and covered by the Guadalquivir subaqueous deltaic deposits displays an average sea-floor gradient of 0.25°, locally up to 0.4°. The average width of this shelf is 26 km, and the shelfbreak is located at 120 m water depth (Lobo, 1995; Lobo et al., 2000).

General circulation patterns in the Gulf of Cadiz are controlled by water mass exchange in the Strait of Gibraltar. Shelf hydrodynamics is dominated by a water flow of Atlantic origin, which moves southeastwards 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; Lobo et al., 2000).

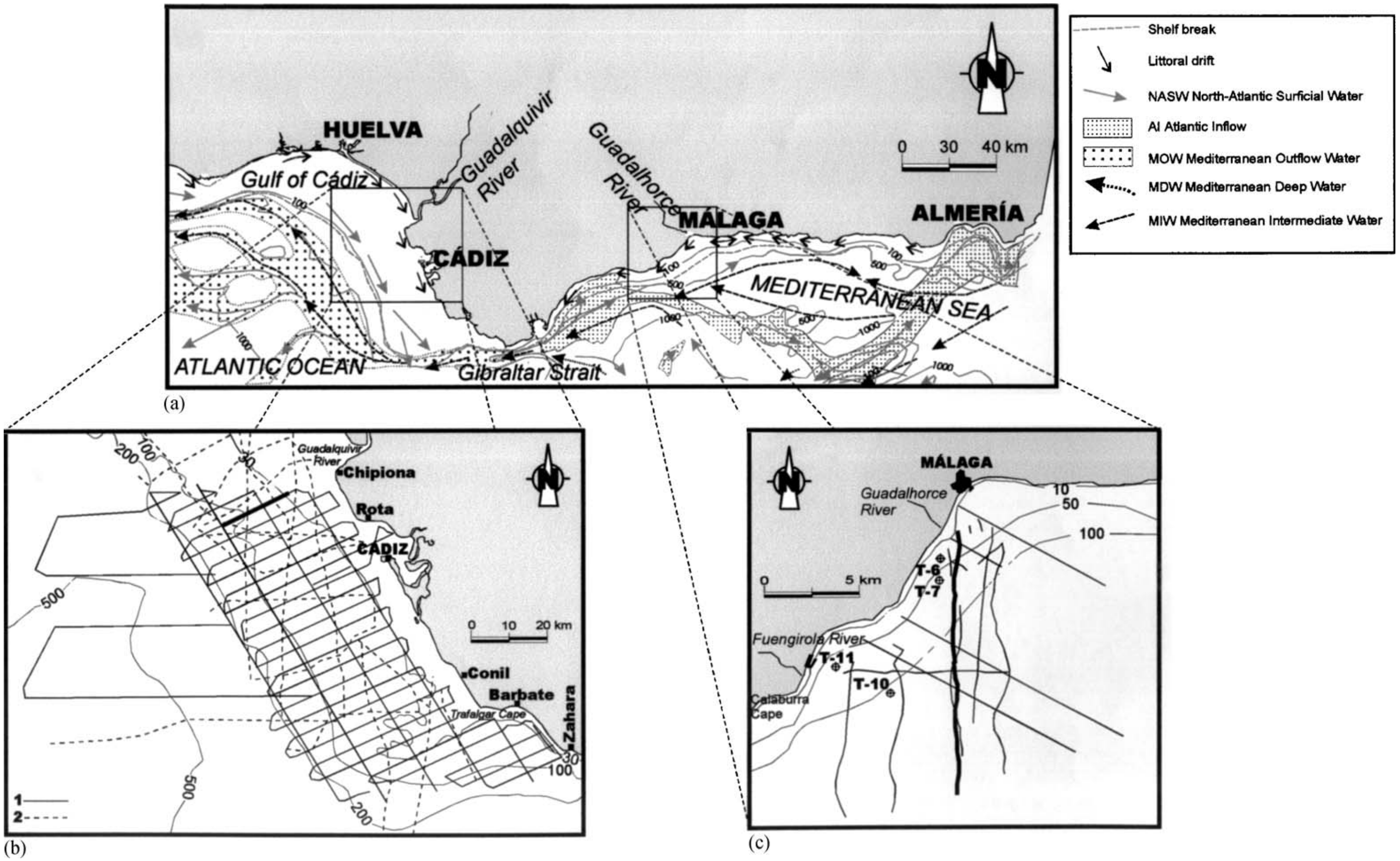


Fig. 1. General location of the study areas: (a) geographical setting of the study areas; (b) location of geophysical surveys in the Gulf of Cadiz area (Legend: (1) G-86-1 seismic survey, (2) GC-86-1 seismic survey); and (c) location of seismic profiles and vibrocores in the Alboran Sea area. In both areas, the interpreted seismic sections are represented in bold lines.

The most recent late Quaternary depositional sequence has been described in the Gulf of Cádiz (Gutiérrez-Más et al., 1996; Somoza et al., 1997; Rodero et al., 1999; Lobo, 2000; Hernández-Molina et al., 2000; Lobo et al., 2001). From bottom to top, it consists of: (1) a thick regressive wedge comprising the forced wedge regressive systems tract and the LST; (2) a set of four backstepping parasequences attributed to the post-glacial TST; (3) a recent progradational wedge mainly represented by prodeltic bodies, and which is associated with the Holocene HST.

3. Material and methods

The present study of the late Holocene sequence stratigraphy and depositional architecture of the deltas is based on the following datasets:

(1) High-resolution seismics, consisting of three geophysical surveys in the Mediterranean area and two surveys in the Atlantic area. These surveys collected very high- and high-resolution seismic profiles (3.5 kHz and Geopulse, 175 J) (Fig. 1b and c). High-resolution seismic interpretation has been based on the recognition of minor seismic discontinuities and seismic facies changes. Isopach maps have been constructed for the identified seismic units in both settings.

(2) Data from four vibrocores drilled on the delta of the Guadalhorce river (Fig. 1c), which were described by Fernández-Salas (1996).

4. Seismic stratigraphy analysis

The seismic stratigraphy analysis of both prodeltaic deposits evidences a similar stratigraphy stacking pattern. Total thickness of the Guadalhorce prodelta averages 22 m, reaching more than 30 m offshore the Guadalhorce river mouth (Fig. 2 and 3a). The Guadalquivir prodelta is wedge-shaped and extends 30 km along-shelf (Nelson et al., 1999). The thickness exceeds 20 m in the proximal areas and then gradually decreases in a south-eastwards and seaward direction (Fig. 4 and 5a).

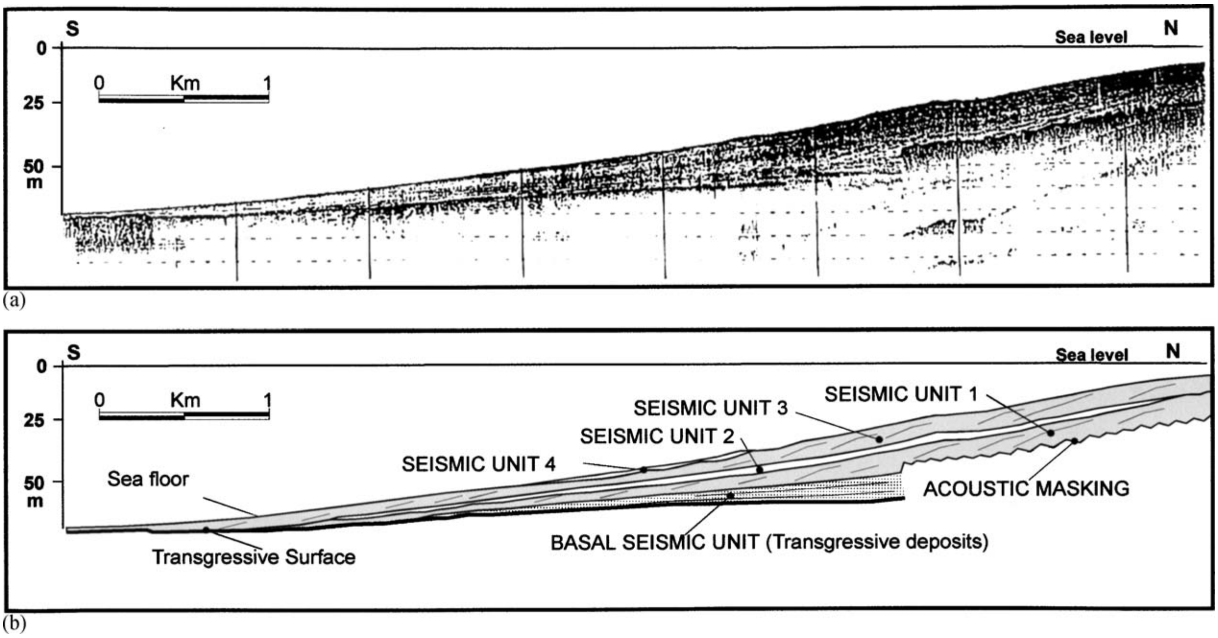
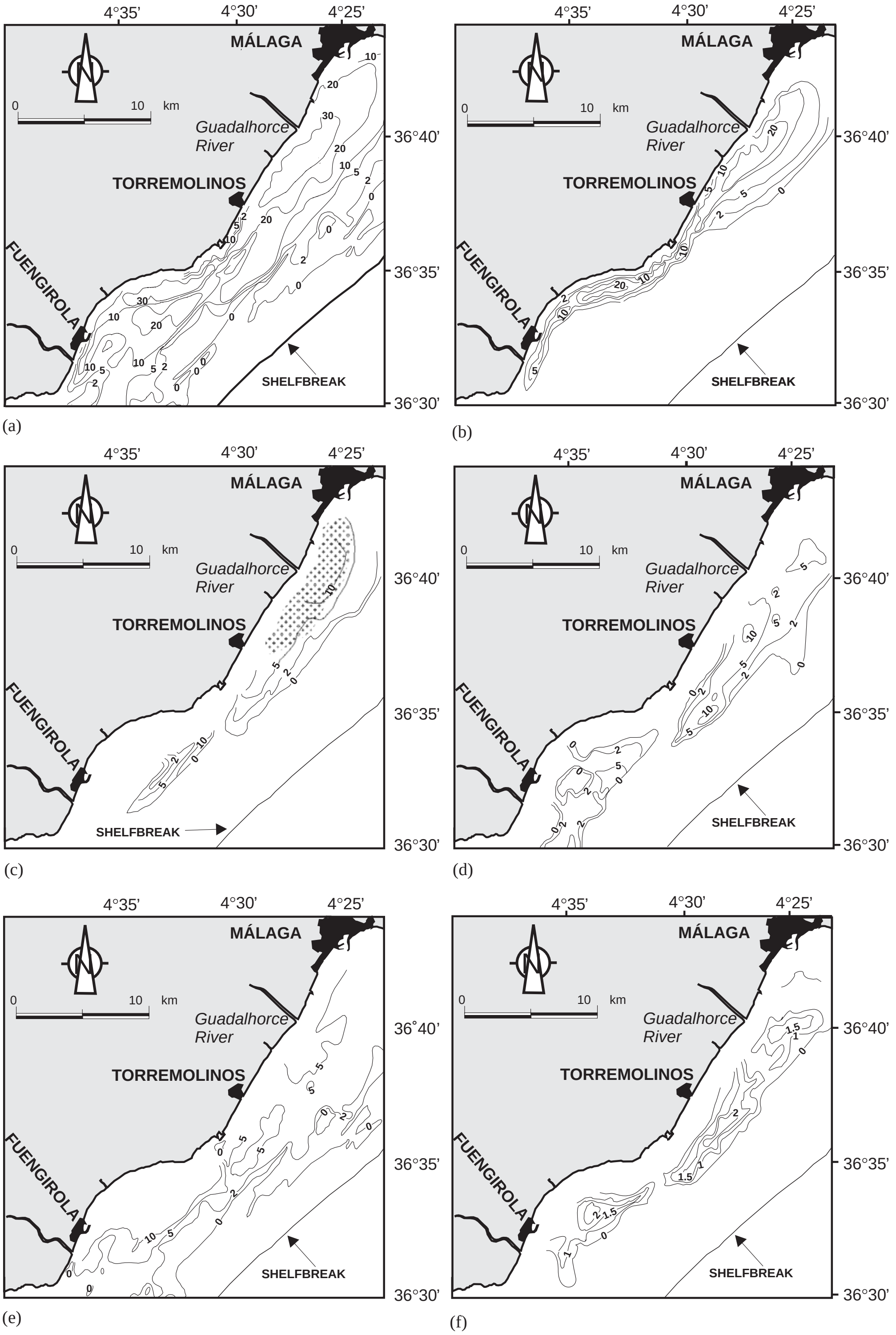


Fig. 2. Uninterpreted (a) and interpreted (b) seismic profile (3.5 kHz) of the Guadalhorce prodelta. The prodelta is composed of four seismic units (1–4) which overlay BSU. Acoustic masking is related to seismic unit 1. See location in Fig. 1.


4°35'
4°30'
4°25'
36°40'
36°35'
36°30'
MÁLAGA
Guadalhorce River
TORREMOLINOS
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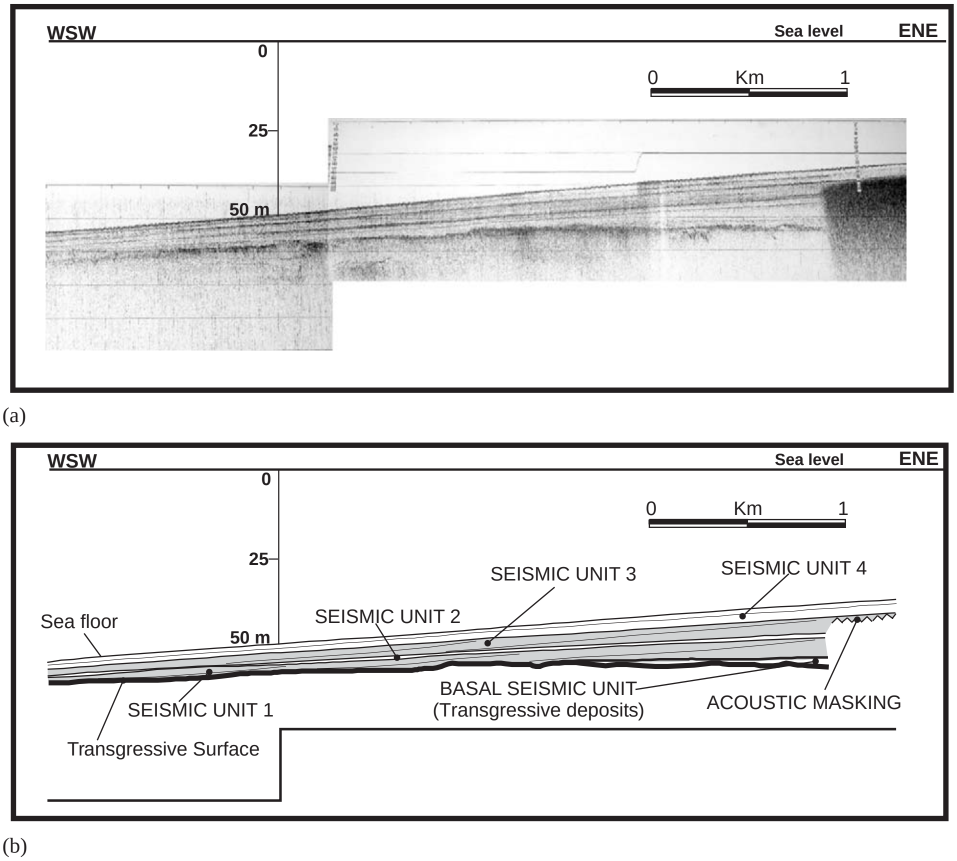

Fig. 4. Section of a Guadalquivir prodelta seismic profile (uninterpreted (a) and interpreted (b) 3.5 kHz seismic lines), which shows the internal structure of this prodelta (seismic units 1–4 overlaying BSU). Acoustic masking is related to seismic unit 3. See Fig. 1 for location.

North of the study area, the prodelta is up to 25 m thick (Rodero, 1999). As a general trend, in both areas they migrate in a shore-parallel direction (Figs. 3 and 5), apparently under the influence of shelf dynamics; e.g., southeastwards on the Gulf of Cadiz shelf and southwestwards on the Alboran Sea shelf.

Five distinct seismic units have been identified (Basal and seismic units 1–4), which have a more reflective character towards the coast (Figs. 2 and 4).

The prodeltas are underlain by a discontinuous, seismic unit named basal seismic unit (BSU), located above a high-amplitude seismic discontinuity. This is a wedge-shaped, aggradational unit with some discontinuous internal reflections that show downlap and onlap terminations, whereas the overlying units clearly downlap onto it. It is 6–12 m thick (Fig. 2 and 4). On the Alboran shelf, this seismic unit extends parallel to the coastline extending downshelf to 5 km offshore the Guadalhorce River and thinning toward the southwest

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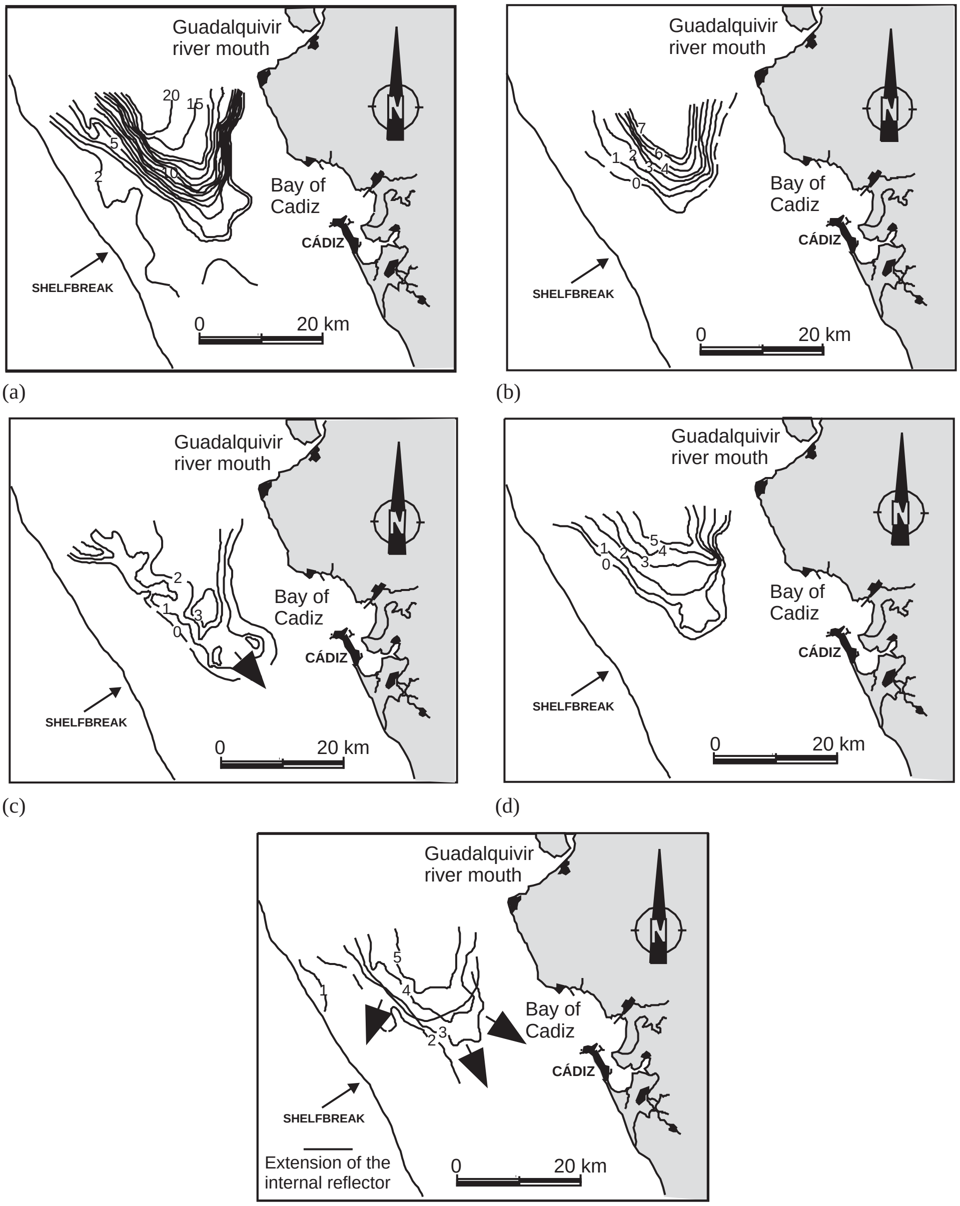
Fig. 3. Contour maps of the transgressive deposits (BSU) and the Guadalhorce prodelta seismic units (1–4): (a) total thickness of the BSU and seismic units 1–4; (b) BSU (transgressive deposits); (c) seismic unit 1, where the areal extent of the acoustic masking is shown in a dotted pattern; (d) seismic unit 2; (e) seismic unit 3; and (f) seismic unit 4. The isopach values are given in meters.



(a) (b) (c) (d) (e)

Fig. 5. Contour maps of the Guadalquivir prodelta seismic units: (a) total thickness of highstand prodeltaic deposits (seismic units 1–4); (b) seismic unit 1; (c) seismic unit 2; (d) seismic unit 3; and (e) seismic unit 4. The isopach values are given in meters.

(Fig. 3b). On the Gulf of Cadiz shelf, it has only been identified offshore the Guadalquivir River reaching up to 6 m thick (Fig. 4).

Seismic Unit 1 is a wedge-shaped unit which displays an oblique-parallel configuration and a reflective pattern, becoming transparent seaward. Reflection terminations are downlap (lower boundary) and erosional truncation that evolves seaward to toplap (upper boundary) (Fig. 2 and 4). On the Alboran shelf, this seismic unit has a mean thickness of 5 m, and it extends 5 km offshore the Guadalhorce River mouth, and pinches out in a southward direction. On this shelf, this seismic unit is characterised by the presence of a well-developed level of acoustic masking at its lower boundary (Fig. 3c). On the Gulf of Cadiz shelf this seismic unit has maximum thickness of 7 m in proximal areas and decreases abruptly to the southeast. It extends 18 km along-shelf to the latitude of the Bay of Cadiz. Seaward, it extends more than 20 km in a cross-shelf direction, pinching out at the outer shelf (Fig. 5b). This unit is composed of two minor subunits bounded by a minor discontinuity: 1a (convex oblique-parallel configuration) and 1b (concave oblique-parallel configuration) (Fernández-Salas, 1996; Fernández-Salas et al., 1996).

Seismic unit 2 has a lensoidal to sheet external shape, with average thickness values 3–4 m. On the Alboran shelf, it shows some internal aggradational reflections of low lateral continuity. It displays a laterally variable thickness as a consequence of erosional truncation at its upper boundary (Figs. 2 and 4). Its landward limit is located 3 km from the coastline, and it pinches out 5–6 km from the coastline in a seaward direction (Fig. 3d). On the Gulf of Cadiz shelf, it displays a transparent acoustic response and a thickness up to 5 m that decreases in a southeastern direction. It extends more than 30 km along the shelf to the latitude of the Bay of Cadiz (Fig. 5c). It is more than 25 km wide near the northern limit of the study area, but tapers to 10 km wide at the Cadiz Bay latitude.

Seismic unit 3 is a wedge-shaped unit with a sigmoid-oblique configuration and a reflective seismic pattern. The reflection terminations are a downlap on the lower boundary and concordance to toplap in the upper boundary. The upper boundary of this seismic unit is the present sea floor where it is not overlain by the shallowest seismic unit 4. It averages 4 m thick (Figs. 2 and 4). The distribution of this seismic unit is highly irregular on the Alboran shelf, its seaward termination is located near the shelfbreak, about 10 km from the coastline (Fig. 3e). On the Gulf of Cadiz shelf, the thickness exceeds 5 m in proximal zones, but decreases rapidly seaward and more steadily southeastwards (along-shelf). It extends along-shelf to the latitude of the Bay of Cadiz (Fig. 5d). It is 25 km wide in the northern limit of the study area and 10 km wide at the Cadiz Bay latitude. Acoustic masking is identified very close to the boundary between seismic units 2 and 3 on the Gulf of Cadiz shelf, appearing at a nearly constant level 4 m below the seafloor and covering an area of approximately 100 km^2. It is composed of two minor subunits bounded by a minor discontinuity: 3a and 3b, which have been sedimentologically characterised: (1) Subunit 3a: sigmoid unit composed of two minor fining-upward facies sequences. (2) Subunit 3b and it is composed of one fining-upward facies sequence (Fernández-Salas, 1996; Fernández-Salas et al., 1996).

Seismic unit 4 has a lensoidal to sheet external shape. It is an aggradational seismic unit with a general transparent acoustic response, but with some reflectors in proximal zones, which show concordance with the upper and lower boundaries (Figs. 2 and 4). The upper limit is the present-day sea floor. On the Alboran shelf, it displays a variable thickness (0.5–2 m) and a horizontal distribution similar to seismic unit 2 (Fig. 3f). On the Gulf of Cadiz shelf, the thickness of this unit is nearly constant, being 4 m in the proximal areas but decreasing to 2 m in both landward and seaward directions (Fig. 5e). This unit extends over the entire shelf offshore the Guadalquivir River mouth outside our study area, and continues southward. It is characterised by the presence of an internal reflector in proximal zones (Lobo, 1995). It is sedimentologically characterised by a lower coarsening-upward sequence and an upper finning-upward sequence (Fernández-Salas, 1996; Fernández-Salas et al., 1996).

5. Discussion

5.1. Choosing a sequence stratigraphy framework

The stratigraphic pattern identified in both prodeltaic deposits of southern Spain resembles the general stratigraphic architecture of Holocene deltas described by Warne and Stanley (1995), and can be correlated with other nearby deltaic stratal patterns. The BSU would correlate with unit E of Hernández-Molina (1993), Hernández-Molina et al. (1994), with the unit a_1 of Somoza et al. (1998) of the Ebro delta (Fig. 6), and with the lower portion of the Stratal Unit III of Warne and Stanley (1995). The following criteria support that this unit corresponded with the final stage of the post-glacial TST: (a) The upper boundary of the BSU is the most pronounced downlap surface as the overlying units clearly prograde over it, and can be interpreted as the Maximum Flooding Surface, which establishes the boundary between transgressive and highstand deposits; (b) the age of the first prograding deposit (seismic unit 1) that composes the subaqueous delta ranges between 6.8 and 5.2 ka BP (Fernández-Salas, 1996; Fernández-Salas et al., 1996), an age that is younger than the transgressive maximum reached ca. 6.9 ka BP along the southern coasts of Spain (Zazo et al., 1994; Lario et al., 1995). The BSU is just older than this maximum and should be included into the late Quaternary TST. By correlating with other coeval sedimentary units described in other continental shelves, the deposition of the BSU took place very close to the maximum highstand position about 7–6.8 ka BP (Hernández-Molina et al., 1994; Zazo et al., 1996; Somoza et al., 1998).

Thus, the wedge-shaped deposits that overlie BSU are interpreted as the Holocene HST, and they can be considered the upper portion of the Stratal Unit III, according to the nomenclature of Warne and Stanley (1995). This HST of the Guadalhorce and Guadalquivir prodelta deposits shows an alternation of progradational (seismic units 1 and 3) and aggradational units (seismic units 2 and 4). This stratigraphic pattern of Holocene prodeltas has been identified in other areas of the Spanish continental shelf (Hernández-Molina et al., 1994; Somoza et al., 1998). Progradational units 1 and 3 were correlated with units F1 and F3 of Hernández-Molina (1993) and Hernández-Molina et al. (1994) for the Alboran shelf and with units d1 and d3 + d4 of Somoza et al. (1998) for the Ebro delta. Accordingly, units 2 and 4 were correlated with units F2 and F4 of Hernández-Molina (1993) and Hernández-Molina et al. (1994), and with units a3 and a5 of Somoza et al. (1998) (Fig. 6). This pattern shows the existence of two couples of seismic units, which can be related to a repetitive or cyclic pattern observed inside the marginal deltaic deposits. Units 1 and 3 display similar attributes (Figs. 2 and 4): (a) reflective seismic character; (b) internal reflections which downlap the lower boundary; (c) high to moderate thickness in proximal areas; (d) they pinch out very rapidly in a seaward direction; (e) wedge external shape. Their progradational internal pattern and wedge external shape is indicative of a regressive phase, in which accommodation was reduced and sediment supply came from a local source; this is also confirmed by the reflective character, which suggests the prevalence of coarse grain size sediments. Based on the seismic and sedimentologic data, in the Guadalhorce prodelta those units have been subdivided into two subunits, which correspond to regressive and lowstand deposits in a higher-order cycle (Fernández-Salas, 1996). This differentiation has not been made in the Guadalquivir prodelta, and for comparison those units will be considered as the sum of regressive and lowstand deposits. The discussion about the origin, nature and significance of this internal boundary is beyond the scope of this paper.

In contrast, seismic units 2 and 4 display different characteristics, indicative of deposition in a different sea-level change trend (Figs. 2 and 4): (a) transparent or semitransparent seismic facies; (b) low-amplitude internal reflector showing poor lateral continuity; (c) constant and moderate thickness through the entire distribution area; and (d) sheet external shape. Unlike seismic units 1 and 3, those characteristics suggest that they are mainly composed of fine sediments which escaped from the nearshore, because fine-grained sediments are dispersed more widely than coarse-grained sediments (Hart and Long, 1996), and also that they were deposited when sea level was transgressing and/or in a highstand position.

The stacking pattern of those seismic units shows the repetition of a progradational to aggradational cycle (seismic units 1–2 and 3–4), which is related to the existence of two relative sea-level cycles. Progradational units (1 and 3) are characterised by a higher thickness and wider distribution than semi-transparent units (2 and 4),

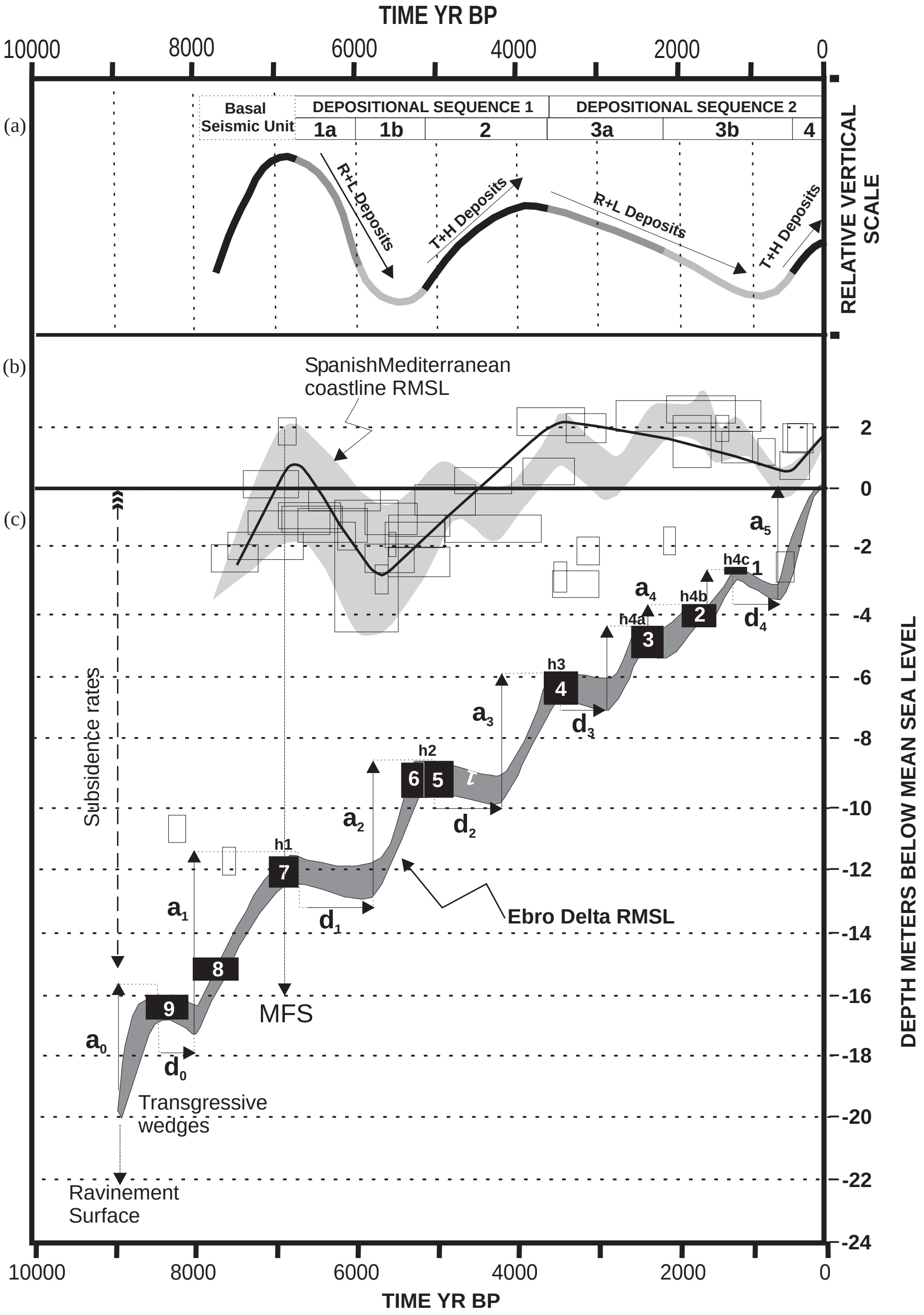


Fig. 6. Proposed curve of relative sea-level changes in the Alboran Sea and correlation with the high-frequency depositional sequences: (a) curve of relative sea-level changes in the Alboran Sea; (b) curve of relative mean sea level for the Spanish Mediterranean coastline; and (c) curve of relative mean sea level for the Ebro Delta (Somoza et al., 1998).

suggesting that the associated cyclicity is asymmetric, in the way that probably regressive intervals were continued longer than transgressive/highstand intervals.

5.2. The influence of small amplitude, high-frequency relative sea-level changes

The question that arises here is to explain the factors which control the high-resolution architecture of the studied deltaic HST. It has been suggested that high-resolution sequence stratigraphy analysis on recent deltas should shed light on centennial to decade-scale sea-level trends for the Holocene (Warne and Stanley, 1995). There is controversy about the nature of the sea-level change during the middle to late Holocene (Baker and Haworth, 2000a), because some authors argue that it has oscillated during the last 6 ka (Tooley, 1993), whereas others claim for a gradual fall since sea-level reached a highstand position 1–2 m above present (e.g., Chappell, 1983). However, recent works using a wide spectrum of techniques are providing evidence of the existence of fluctuating sea levels during the Holocene, ranging from millenial to century scale (Banerjee, 2000; Baker and Haworth, 2000b). Specifically, two Holocene sea-level cycles of amplitude of several meters have been evidenced in several distant locations, such as the Mauritanian coasts (Einsele et al., 1974), along the east coast of India (Banerjee, 2000), and on the east Australia coast, Pacific Islands and Brazil locations (Van Andel and Laborel, 1964; Baker and Haworth, 2000b). The exact timing of those two sea-level cycles is different according to the locations, possibly due to differences in dating methods and to the significance of local sea-level histories or local geological factors. However, these data suggest a broad similarity in the timing of environmental events and a remarkably widespread sea-level trend in mid-latitudes after the Holocene highstand (Baker and Haworth, 2000b). Besides, it is suggested that those records might either be absent or escape detection in other localities. The most recent sea-level cycle is related to the Medieval Warm Period-Little Ice Age oscillation, and culminated with a rise of the sea level during the last few centuries (Banerjee, 2000).

Some studies carried out on the coasts of southern Spain report the influence of recent climatic/eustatic changes on coastal progradation and deltaic sedimentation. After the transgressive maximum reached ca. 6.9 ka BP, two major phases of progradation have been reported in spits systems (Zazo et al., 1994, 1996; Lario et al., 1995; Goy et al., 1996; Rodríguez-Ramírez et al., 1996), and they have also been described in prodeltaic deposits of the Spanish continental shelf (Hernández-Molina et al., 1994; Fernández-Salas et al., 1996; Somoza et al., 1998). The older one extended from 6.9 to 2.7 ka BP, and the younger one lasted from 2.4 ka BP to the present. Both phases are separated by a "gap" or episode of no progradation. At least at the short-term, there is a link between the generation of spit bar systems and periods of slightly fluctuating sea-levels (gentle "highstand" and "lowstand") (Zazo et al., 1994; Lario et al., 1995). Cycles of higher sedimentation and enhanced progradation are related to slight falls of sea-level after highstands, whereas during slight rises in sea-level coastal erosion was dominant (Dabrio et al., 1995; Goy et al., 1996; Rodríguez-Ramírez et al., 1996).

The structure and evolution of some distant deltaic and/or estuarine sequences also reflects the existence of two main cycles of delta build-up during the recent highstand interval. Particularly, a transgressive period at about 3 ka BP has been documented in several estuarine environments of northern Spain (Cearreta, 1994; Pascual et al., 1998), and in the Gironde Estuary, southwestern France (Massé et al., 2000). Besides, the development of deltaic sequences has taken place during two consecutive evolutionary steps in the Gulf of Mexico, the first one from the last eustatic maximum to about 3 ka BP, and the second one from 3 ka BP to the present (Donoghue, 1993). This trend has also been reported from the Han River Delta (China), where the development of deltaic stratigraphy was linked to sea-level changes during the post-glacial period (Zong, 1992). Specifically during the Holocene highstand, two main sea-level cycles have been recognised. The amplitude of those minor sea-level changes is supposed to be of 2–3 m. During positive movements of sea level, transgressive deposition was favoured, whereas during negative movements, regressive deposits overlay previous transgressive formations.

In the light of these data, we propose that the high-resolution stratigraphic architecture of the HST of the deltaic systems of southern Iberian Peninsula is highly controlled by the influence of two relative, very high frequency sea-level changes that have taken place during the Holocene highstand. Those changes can be characterised as two cycles of small amplitude (few meters) and with a periodicity of about 3 ka, and they are supposed to be responsible for the generation of two repeated cycles of deltaic build-up on the coasts of southern Spain. The seismic units described can be interpreted inside a context of high-frequency sea-level changes that have taken place during the last highstand period, providing evidence of the imprint of those minor sea-level oscillations in the highstand deltaic deposits (Hernández-Molina et al., 1994; Fernández-Salas, 1996; Somoza et al., 1998). Seismic units 1 and 2 would be generated during the first sea-level cycle, whereas seismic units 3 and 4 during the second one (Fig. 6). Therefore, the late Quaternary HST of the Guadalhorce and Guadalquivir prodeltas record two regressive phases, each displaying a similar internal structure. The regressive deposits are separated by intervals of abandonment and more condensed deposition. This leads us to conclude that these two highstand cycles are imprinted in coastal and shallow marine deposits of southern Spain, regardless of their location in the Mediterranean Sea or in the Atlantic Ocean, supporting the idea that they were driven by small amplitude relative sea-level cycles. In both areas regressive deposits are thicker, probably because the sea-level cycles were asymmetrical, with regressive periods having longer duration, and with higher sediment supply along these stages.

5.3. *Climatic controls, delta lobe switching and neo-tectonic movements*

The influence of regional climatic changes on those progradational events and specifically on the deltaic architecture seems to be focussed on their effect on relative sea-level changes (Lowrie and Fairbridge, 1991; Zazo et al., 1994; Lario et al., 1995). It seems clear that the climatic oscillations had an effect on relative sea-level cycles, and in this sense it has been suggested that a proxy record of climatic conditions along stable coasts can be represented by oscillating sea-levels in the last few thousand years (Tooley, 1993). Specifically, cold events reflecting lower solar intensity are related to lowered mean sea-levels, whereas the periods of overall warming and elevated temperatures in the North Atlantic region are correlated with elevated mean high water levels (Lowrie and Fairbridge, 1991). Many high-frequency climatic changes have been described in the Holocene epoch; the most significant of Late Holocene climatic variability are the Dansgaard-Oeschger oscillations (Broecker, 2000). The most recent sea-level changes are related to the climatic cycle determined by the Early Medieval Warm Period and the following Little Ice Age Maximum (Roberts, 1998; Broecker, 2000).

Other alternative interpretations that would consider sediment supply changes and delta lobe switching rely on the fact that more surely those factors are ultimately dependant on high-frequency climatic fluctuations. Somoza et al. (1998) described that in the case of the Ebro delta, short cool/humid events should produce a sea-level fall and an increase in sediment supply by increasing precipitation within the Ebro drainage basin. Specifically in the Atlantic–Mediterranean linkage area, climatic changes would affect sediment supply rates by increasing the littoral drift and flooding events caused by heavy rains (Zazo et al., 1994; Lario et al., 1995). This relation has been reported for the initial phase of Early Medieval Warm Period that coincides with an epoch of reduced progradation, whilst the Little Ice Age witnessed anticyclonic conditions, with strong rains and high sediment supply to the coasts (Goy et al., 1996).

The existence of delta lobe switching processes seems to be determined by the control of the sea-level cycles. In this sense, during the Middle to Late Holocene, the existence of sixth-order sea-level cycles ($1–2 \times 10^3$ years), associated with major climatic fluctuations, would have favoured delta lobe switching. During falls in relative sea-level (e.g., as the Little Ice Age, 0.5–1 m of sea-level change), river gradients steepening took place. In contrast, during rises in relative sea-level (e.g., as in the Warm Viking Cycle, sea-level variation of 0.5–0.6 m) reduction of those gradients would have taken place (Lowrie and Hamiter, 1995). Under these considerations, it seems that climatic changes produce a double control on eustatic sea-level changes and also on sediment supply changes, but both factors are supposed to interact in the same way. Other possible explanations that would take into account the delta lobe switching related to recent neotectonic movements are not favoured, because no evidence of neotectonic activity has been detected on seismic profiles, and also because the progradational events seem to be widespread and not concentrated on a specific area. Furthermore, at least for the case of the Guadalquivir area, it is supposed to be an area of tectonic stability for the last 14,000 years (Rodero et al., 1999).

5.4. *Regional variability*

Total sediment thicknesses are not comparable, because in the Guadalquivir area the main depocenter is located northwards, where maximum thickness of the Holocene layer is approximately 25 m (Nelson et al., 1999), whereas in the Guadalhorce area the whole prodelta is located in the study area. However, the relative significance and distribution patterns of seismic units are different in both areas; therefore, local factors controlling the stratigraphic architecture of the Holocene highstand prodeltaic deposits must be invoked. Sediment supply, coastal physiography and sediment dispersal processes are other factors which control the morphology and stratigraphy of these kind of deltaic systems (Hart and Long, 1996). Those differences could be summarised as follows:

(a) In both areas, the persistence of the present-day current flow regime during the Holocene highstand interval is confirmed by the distribution of the seismic units, which clearly shows lateral redistribution in the direction determined by mean shelfal currents in both settings. However, the influence of those current systems over the prograding/aggrading deposits determined by the small amplitude sea-level changes is different. In the Guadalquivir area, aggrading deposits (seismic units 2 and 4) associated with small sea-level rises display an evenly distributed pattern and are clearly affected by the dominant current regime (southeastwards), whereas prograding deposits (seismic units 1 and 3) associated with small sea-level falls are developed in a well-defined wedge external shape. By contrast, the differences in the current influence between both kinds of deposits are smaller in the Guadalhorce area. This can be explained by considering contrasting shoreline changes led by small amplitude sea-level changes in both areas. The higher gradients of the Alboran Sea coasts would have determined lower changes of the shoreline and sediment entry points, and also more uniform sediment input during the highstand interval. Large coastline migrations would have occurred in the Guadalquivir area, due to the smooth gradient of the coastal plain. Besides, higher tidal influence would have conditioned enhanced sediment redistribution during rising sea-levels.

(b) Aggrading deposits reach a higher thickness in the Guadalquivir area, especially the most recent unit. This could be explained by the existence of a greater sediment supply driven by anthropogenic influence in this area, especially during the last 400 years (Lario et al., 1995; Goy et al., 1996; Rodríguez-Ramírez et al., 1996). In the Alboran Sea shelf, this unit is only present in relation with the main feeding rivers.

(c) In the Guadalquivir prodelta, the acoustic masking is related to the uppermost prograding unit (seismic unit 3), whereas in the Guadalhorce prodelta the acoustic masking is related to the deepest prograding unit (seismic unit 1). So, the generation of this effect, primarily caused by the degradation of organic matter inside the sediments, has been enhanced during the last prograding interval in the Guadalquivir prodelta. This can be attributed to a more significant sediment supply with high amounts of organic matter during the last prograding interval in the Guadalquivir prodelta, in relation to the establishment of estuarine conditions during this period (Davis, 1992; Hernández-Molina, 1993; Aqrawi, 2001).

6. Conclusions

High-resolution seismic studies conducted on two subaqueous deltaic deposits of the southern Iberian margin (Guadalhorce and Guadalquivir) drive us to conclude that the late Holocene evolution of such systems seems to be highly controlled by small amplitude, high-frequency cycles that have occurred during the recent Holocene highstand period. The bulk of such depositional systems is constituted by HST deposits, which internally show two repeated cycles of progradation/aggradation. We suggest that the generation of this complex structure is related to the effect of two small amplitude, high-frequency relative sea-level changes, which have been described in several settings around the world. Those sea-level changes seem to be intimately linked to the influence of high-frequency climatic changes. The effect of those climatic changes is also concentrated on the sediment supply rates to the continental shelf, and in this way the effects of sea-level changes and sediment supply are coupled. During relatively cold periods, small sea-level falls probably occurred joined to increased sediment supplies and concomitant deltaic progradation. Conversely, during intercalated warm periods, small sea-level rises were favoured, and aggradation of such systems took place in response to a decreased sediment supply and/or increased erosion.

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