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# Palaeoenvironments, relative sea-level changes and tectonic influence on the Quaternary seismic units of the Huelva continental shelf (Gulf of Cadiz, southwestern Iberian Peninsula)

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**ABSTRACT**

A seismic stratigraphical study was conducted on the Huelva continental shelf (southwestern Iberian Peninsula) between the mouths of the Guadalquivir and Guadiana Rivers. Applying the basic concepts of seismic stratigraphy, 13 seismic units bound by erosive discontinuities have been identified.

Two main kinds of seismic units can be distinguished: a) Units that internally show a wide variability of seismic configurations and sheet to lensoidal external shape, located in inner-to-middle shelf settings. These units are considered high-energy units (HEU), deposited during intervals of rising and highstand sea levels. They represent coastal deposits comprising two main depositional systems: coastal barriers in the form of shoreface deposits and landward lagoonal and tidal deposits. b) Units displaying low-angle oblique seismic configurations, with reflectors exhibiting good lateral continuity and amplitude. Their thickness increases seaward, with the largest depocentres located near the shelf-break, displaying therefore a typical wedge external shape. These units are located very frequently from middle shelf emplacements to outer shelf and upper slope settings, and are considered low-energy units (LEU). They are believed to have been formed during periods of falling sea level, representing the distal portions of coastal and deltaic bodies that have been preserved from erosion.

The stacking pattern of the units shows three different tectonic settings: a central subsiding sector, bounded laterally by two tectonic highs, one of them structurally controlled (the western one) and the other conditioned by diapiric uplifting (the eastern one).

**Key words:** Seismic stratigraphy, seismic configuration, continental shelf, Gulf of Cadiz, Quaternary.

***RESUMEN***

***Paleoambientes, cambios relativos del nivel del mar e influencia tectónica en las unidades sísmicas cuaternarias de la plataforma continental de Huelva (golfo de Cádiz, suroeste de la península Ibérica)***

*Un análisis de estratigrafía sísmica se ha realizado en la plataforma continental de Huelva (suroeste de la península Ibérica) entre las desembocaduras de los ríos Guadiana y Guadalquivir. Aplicando los concep-*

*tos básicos de la estratigrafía sísmica, han sido identificadas 13 unidades sísmicas limitadas por discontinuidades erosivas.*

*Dos tipos principales de unidades sísmicas han sido identificadas: a) Unidades que internamente muestran una gran variabilidad de facies sísmicas y forma externa de lámina o lenticular, localizadas en la plataforma interna-media. Estas unidades son consideradas de alta energía (*high- energy units*, HEU), depositadas durante intervalos de ascenso y alto nivel del mar. Se relacionan con depósitos costeros compuestos de dos sistemas deposicionales principales: barreras costeras formadas por depósitos de frente de playa y, hacia tierra, depósitos mareales y de laguna. b) Unidades caracterizadas por clinoformas progradacionales de bajo ángulo, con reflectores de alta amplitud y continuidad. Su espesor aumenta hacia el borde de plataforma, adquiriendo una forma típica de cuña. Estas unidades están localizadas frecuentemente desde la plataforma media hasta el talud superior y son consideradas como unidades de baja energía (*low-energy units*, LEU). Se interpreta que representan las porciones distales de cuerpos costeros y deltaicos que se han formado durante periodos de descenso relativo del nivel del mar, y que han sido preservadas de la erosión que sufrieron las capas más someras. El patrón de apilamiento de las unidades muestra tres emplazamientos tectónicos diferentes: un sector central subsidente limitado lateralmente por dos altos tectónicos, uno controlado estructuralmente (sector oeste) y otro condicionado por un levantamiento de origen diapírico (sector este).*

***Palabras clave:*** *Estratigrafía sísmica, configuración sísmica, plataforma continental, golfo de Cádiz, cuaternario.*

## INTRODUCTION

The first attempt at studying the general stratigraphical architecture of the Gulf of Cadiz's continental shelf was made by Malod (1982); more recently, Somoza *et al.* (1994, 1996, 1997) and Hernández-Molina, Somoza and Lobo (in press) have outlined the Quaternary sequence stratigraphy of the Huelva continental shelf by using high-resolution seismic stratigraphy as a tool for applying sequence stratigraphy methodology.

This paper presents the results of a more detailed approach to the Late Quaternary sedimentary record of this continental shelf, using seismic stratigraphy analysis. A sedimentary characterisation of the shelf and related depositional systems are proposed for the studied area, taking into consideration the seismic facies analysis and the distribution of the seismic units. This analysis also provides information about relative sea-level changes that have taken place in this area during recent geological time, and about recent tectonic activity.

### General background

The study area is located on the Gulf of Cadiz's continental shelf (southwest Spain), between the mouths of the Guadalquivir and Guadiana Rivers, adjacent to the Huelva coast (figure 1). This arcuated coast is characterised by the presence of spit bars and lagoons in the river mouths (Guadiana, Piedras and Tinto-Odiel estuaries), generated since the last eustatic maximum due to intense sotheastward littoral drift (Dabrio, 1989). General circulation over the continental shelf runs to the southeast in relation to the advection of the North Atlantic Surficial Current and littoral drift (Ochoa and Bray, 1991).

The continental shelf morphology of the Gulf of Cadiz is very regular, with a smooth gradient and isobaths running parallel to the coast. The shelf is about 50 km wide on the Spanish side, and the shelf-break is located at a depth of 130 m (Abrantes, 1990; Lobo, 1995).

The littoral domain is characterised by the presence of sandy sediments of siliciclastic and bioclastic origin, and a high content of heavy metals, especially ilmenite. There are plio-pleistocene rocky outcrops covered by organisms in a terrace-like feature located in the 25 m isobath. The surficial sedimentary sheet is characterised on the continental shelf by the presence of muddy sediments (Bouysse and Horn, 1973). This section of the Spanish continental shelf receives fluvial inputs from the Guadalquivir (annual flux of 9 200 $km^3$), Guadiana (5 500 $km^3$) and Tinto and Odiel Rivers (517 $km^3$) (Maldonado and Nelson, 1988; Abrantes, 1990). These rivers develop nepheloid layers, which disappear due to sedimentary and advective processes (Palanques, Plana and Maldonado, 1987). In front of the Guadalquivir's mouth, the presence of acoustic masking in the recent muddy sediments has been related to sand layers with a high content in shell debris (Acosta, 1981, 1984), or more recently with the presence of intersticial gas inside

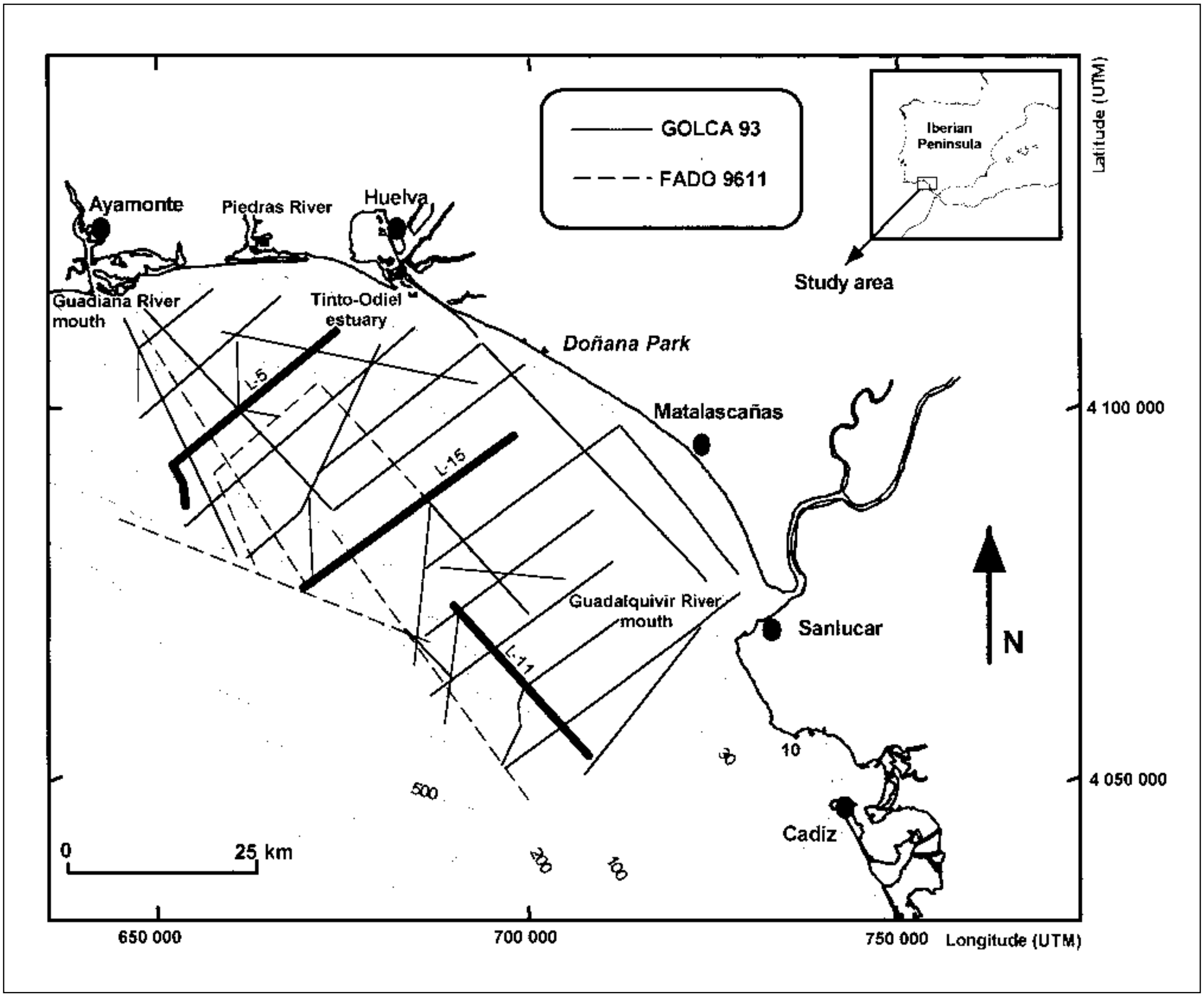



Figure 1. Geographical setting of the study area and location of seismic profiles obtained in two different seismic surveys

Nelson, 1988). During the Lower Quaternary, the compression had a northwest-southeast orientation, whereas during the Middle and Upper Quaternary this regime has not been so strong (Malod and Mougenot, 1979).

Sedimentary covering in the Gulf of Cadiz over the crust reaches 9-11 km (Medialdea *et al.*, 1986). This continental shelf has a depositional origin, and it was developed in Neogene-Quaternary times, after the Tertiary orogeny (Baldy *et al.*, 1977). Seven depositional sequences have been defined since the Neogene, related to olistostromic and erosive events; the most important of these is the regressive period that occurred during Late Messinian (Riaza and Martínez del Olmo, 1996). In the post-tectonic phase, two periods are distinthe sediment (Hernández-Molina *et al.*, 1994; Lobo, 1995; Hernández-Molina, Somoza and Lobo, in press).

This continental margin was created in Mesozoic times, when a distensive phase following two directions (north-south and east-west) was developed. Since the Late Cretaceous, the Gulf of Cadiz has been located in a compressive context between the African and Iberian plates (Malod, 1982). This movement produced during the Upper Miocene the emplacement of an olistostromic complex (Malod, 1982), in relation with the westward displacement of the Alboran microplate (Andrieux, Fontboté and Mattauer, 1971). After an extensional phase during the Pliocene, the Quaternary is again a compressional phase (Maldonado and guished (Malod, 1982): a) Late Miocene, characterised by a regular sedimentation; and b) Pliocene, when the current hydrodynamic regime was established. The Mediterranean outflow interacts with the continental slope, whereas in coastal areas the littoral drift develops eastward prograding bodies. Two Late Quaternary type-1 depositional sequences comprising a Forced Regressive Wedge System Tract, Lowstand System Tract, Transgressive System Tract and Highstand System Tract have been defined in relation to $4^{th}$-order glacio-eustatic cycles (100-110 ky). These depositional sequences comprise minor subsequences related to $5^{th}$-order cycles (22-23 ky). The geometry of the sequences reveals an asymmetric character for the glacio-eustatic cycles (Somoza *et al.*, 1994, 1996, 1997; Hernández-Molina, Somoza and Lobo, in press). Recent sediments (postglacial) reach their greatest thickness in the study area, more than 15 m, in the Isla Cristina zone, and in the zone adjacent to the Piedras, Tinto and Odiel Rivers, where the thickness increases seaward (Bouysse and Horn, 1973).

## MATERIALS AND METHODS

In September 1993, 742.5 km of seismic profiles were obtained during the oceanographic cruise Golca-93 on board the oceanographic vessel *Odón de Buen* of the Instituto Español de Oceanografía (figure 1). The seismic grid was designed with profiles across and along the continental shelf, as in a reconnaissance survey. The source employed was a 150 J Geopulse system, with an operating frequency ranging from 500-2 000 Hz. The horizontal distance between time markers was 1 km, and the vertical range was 0.25 s. The positioning system used was differential GPS. To complement the data set, another oceanographic survey (Fado 9611) was considered (figure 1), and approximately 215 km of seismic reflection profiles collected during that survey were used for this study. The seismic source employed was the same as for the first survey, and the positioning system was GPS.

The seismic stratigraphy methodology was applied following the procedures described by Vail *et al.* (1977). A number of major discontinuities have been defined, which outline genetically-related seismic units. Minor discontinuities inside seismic units separate subunits, which make up the major seismic units. Each seismic unit is characterised by a seismic facies analysis (reflector termination and characteristics, internal configuration and external shape). This analysis provides information about sedimentary environments and processes, lithology and energetic conditions (Mitchum, Vail and Sangree, 1977). Lateral changes in seismic facies within a seismic unit reflect true lateral changes in sedimentological facies. A vertical succession of seismic facies reflects changes in energy conditions (Canals, Catafau and Serra, 1988). A gradation of facies suggests that the deposition of facies are closely related (Henriksen and Vorren, 1996). This methology was initially developed using multichannel seismic data, but it has proven to be successful in its application to Late Quaternary high-resolution seismic reflection data as well (Catafau, Canals and Serra, 1987; Canals, Catafau and Serra, 1988; Hernández-Molina *et al.*, 1994). Seismic units defined by this means are characterised by a more reduced extension in time and space (Chiocci, Orlando and Tortora, 1991). The seismic units were determined by following different and laterally correlatable discontinuities. For the determination of the thickness of the units, the following values of propagation were used: 1 500 m/s for the water column and 1 650 m/s for the sedimentary record.

## RESULTS

### Seismic units and seismic facies analysis

Thirteen seismic units were defined, according to the seismic stratigraphy approach. They were numbered from 1 to 13, from bottom to top of the entire sedimentary sequence. The units are normally composed of internal subunits, according to the existence of minor discontinuities, but only when the minor discontinuities were correlated laterally did we consider the seismic subunits. For example, unit 10 is composed of 2 backstepping subunits, unit 12 is composed of 4 subunits, and unit 13 comprises 2 subunits.

A detailed seismic facies analysis was made for the recognised seismic units in the study area, following standard classifications. The main types of seismic facies and seismic attributes (amplitude, continuity, frequency, steepness and acoustic reflectivity) are summarised in table I. Seven main classes of seismic

Table I. Different types of seismic facies identified in the study area and main seismic attributes. (1): Prograding; (2): Aggrading; (3): Wavy/Irregular; (4): Transparent; (5): Chaotic; (6): Filling facies; (7): Incised valley facies

| Seismic units | | Maximum thickness (m) | Location and morphology | Internal structure | Boundaries |
|---|---|---|---|---|---|
| 1 | | Not determined | Inner-middle shelf (W sector). Wedge-shaped | Parallel oblique (LA) | Lower (L): Unknown<br>Upper (U): Toplap |
| 2 | | 20 | Inner-middle shelf (W sector). Wedge-shaped | Parallel oblique (LA) | L: Unknown<br>U: Toplap |
| 3 | | 10-15 | Shelf (W sector)<br>Sheet | Parallel<br>Semitransparent | L: Concordance<br>U: Concordance |
| 4 | | < 10 | Inner-middle shelf (W sector)<br>Sheet | Subparallel (Type 1)<br>Parallel oblique (HA) | L: Variable (Mainly concordance)<br>U: Variable (Mainly concordance) |
| 5 | | 55 | Middle-outer shelf and shelf-break (W sector)<br>Wedge-shaped | Parallel oblique (LA)<br>Divergent | L: Downlap<br>U: Toplap/Truncation |
| 6 | | 15 | Inner-middle shelf (W sector)<br>Sheet | Subparallel (1 and 2)<br>Parallel oblique (HA)<br>Irregular | L: Variable (Mainly concordance)<br>U: Variable (Mainly concordance) |
| 7 | | 55 | Outer shelf/shelf-break (W and middle sectors)<br>Wedge-shaped | Parallel oblique (LA)<br>Divergent | L: Downlap<br>U: Toplap/Truncation |
| 8 | | 20 | Inner-middle shelf (W and middle sectors)<br>Sheet | Subparallel (1, 3 and 4)<br>Parallel oblique (HA)<br>Inverse progradation | L: Downlap, concordance<br>U: Variable |
| 9 | | 65 | Middle-outer shelf and shelf-break<br>Wedge-shaped | Shingled<br>Parallel oblique (LA)<br>Divergent | L: Downlap<br>U: Toplap/Truncation |
| 10 | A | 35 | Outer shelf/Shelf-break<br>Wedge-shaped | Shingled<br>Divergent | L: Downlap<br>U: Toplap |
| | B | 25 | Middle-outer shelf<br>Lensoidal shape | Parallel oblique (HA)<br>Inverse progradation<br>Filling facies | L: Downlap<br>U: Variable |
| 11 | | 200 | Middle shelf to upper slope<br>Wedge-shaped | Tangential oblique<br>Sigmoid<br>Divergent<br>Wavy<br>Chaotic<br>Acoustic masking | L: Downlap<br>U: Toplap/Truncation |
| 12 | A | 20 | Outer shelf/Upper slope<br>Lensoidal shape | Shingled<br>Divergent | L: Onlap, downlap<br>U: Toplap, concordance |
| | B | 10 | Over the shelf<br>Variable shape | Parallel oblique (HA)<br>Inverse progradation<br>Subparallel (1, 2)<br>Semitransparent<br>Filling facies | The nature of the lower and upper boundaries of seismic subunist b, c and d are highly variable, in relation to the internal variability of seismic facies. |
| | C | 10 | Over the shelf<br>Variable shape | Sigmoid<br>Shingled<br>Paralell oblique (HA)<br>Subparallel (2, 4) | |
| | D | 10 | Over the shelf<br>Variable shape | Paralell oblique (HA)<br>Tangential oblique<br>Shingled<br>Subparallel (2)<br>Transparent<br>Semitransparent<br>Filling facies | |

Table I (continued)

| Seismic units | | Maximum thickness (m) | Location and morphology | Internal structure | Boundaries |
|---|---|---|---|---|---|
| 13 | A | 15 | Inner/Middle shelf<br>Wedge-shaped | Paralell oblique (HA)<br>Sigmoid<br>Sigmoid oblique<br>Inverse progradation<br>Irregular facies<br>Filling facies | L: Variable (mainly downlap)<br>U: Variable |
| | B | 15 | Over the shelf<br>Sheet | Subparallel (1)<br>Transparent<br>Acoustic masking | L: Variable (mainly concordance)<br>U: Concordance |

facies were identified: 1) Prograding; 2) Aggrading; 3) Wavy/Irregular; 4) Transparent; 5) Chaotic; 6) Filling facies; and 7) Incised valley facies. Each class of seismic facies has usually been subdivided into different types. An example for each type of seismic facies is given in figure 2.

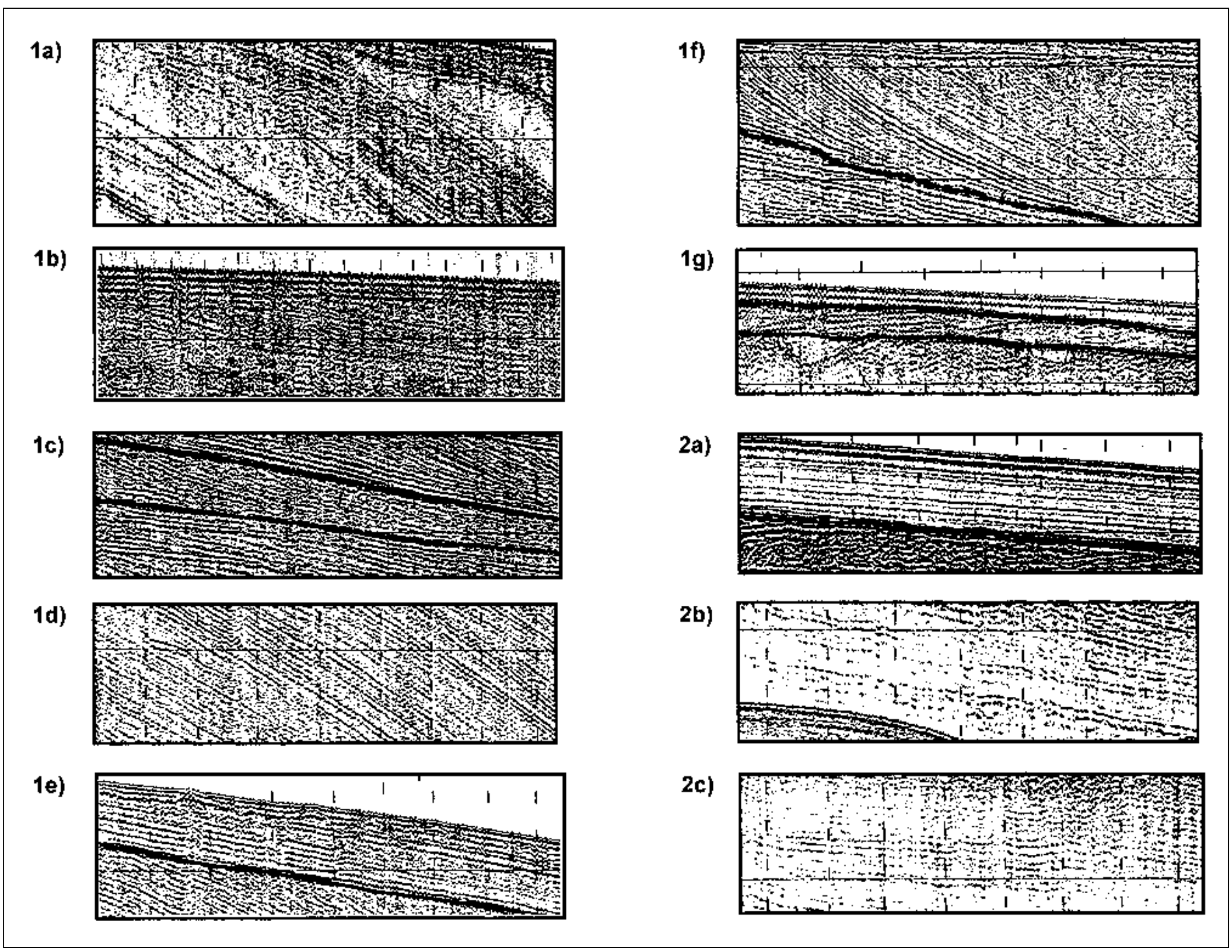



Figure 2. Different types of seismic facies defined for the identified seismic units. (1): Prograding facies: a) Sigmoid; b) Complex sigmoid-oblique; c) Parallel oblique (high-angle); d) Parallel oblique (low-angle); e) Shingled; f) Tangential oblique; g) Inverse progradation. (2): Aggrading facies: a) Subparallel (Type 1); b) Subparallel (Type 2); c) Subparallel (Type 3); d) Subparallel (Type 4); e) Divergent. (3): Wavy (a) and irregular (b). (4): Transparent: a) Semitransparent; b) Transparent. (5): Chaotic: a) Acoustic masking; b) Chaotic. (6): Filling facies. (7): Incised valley facies: a) Type 1; b) Type 2

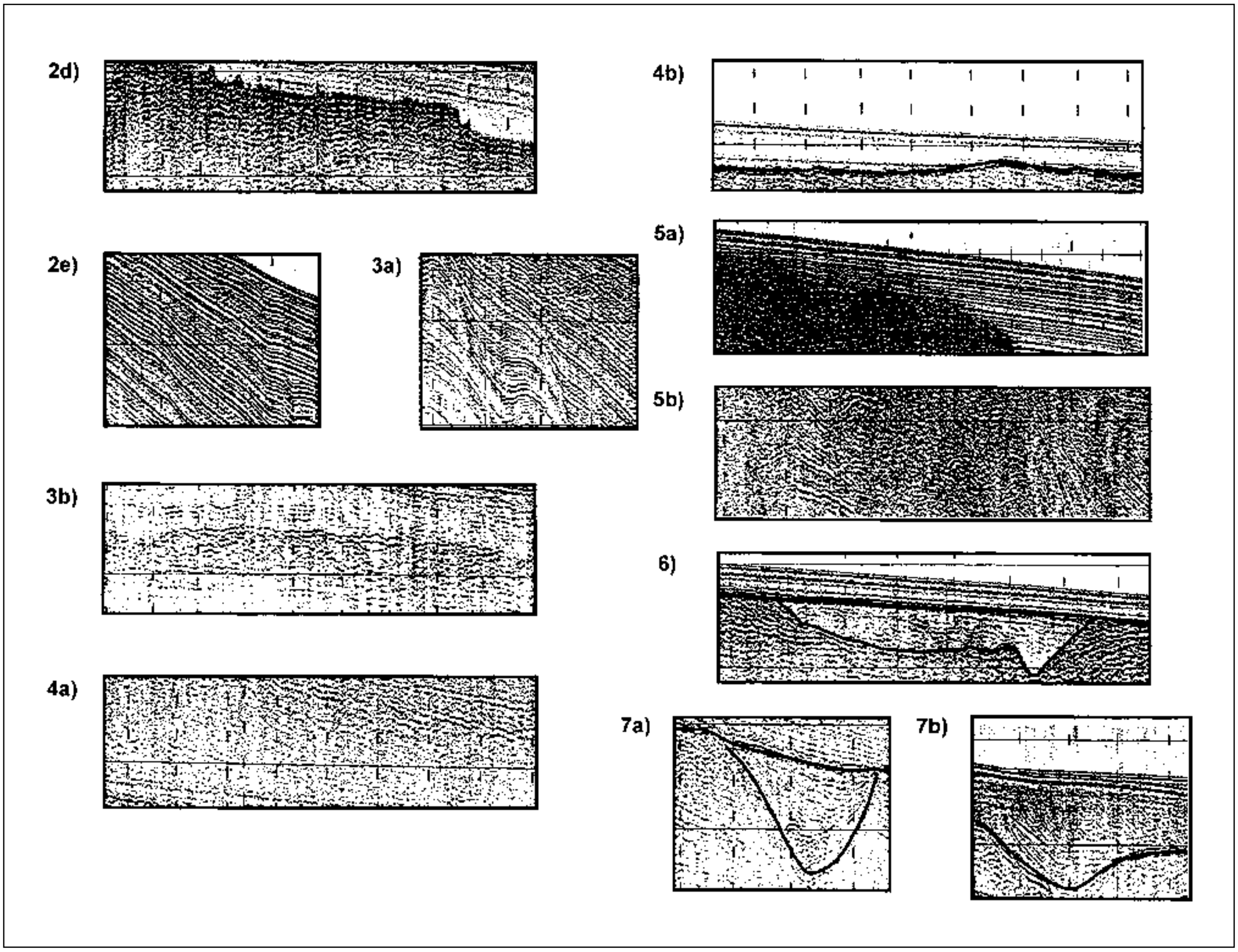



Figure 2 (continued)

Table II shows the main characteristics taken from the seismic profiles for each seismic unit. The following general considerations can be made:

a) Proximal units (4, 6, 8 and 10). Seismic units 3 and 12 (with their different subunits) share similar internal structure and general configuration. The thickness of these units is generally moderate (10-20 m, occasionally they can reach more than 30 m). The location of these units is also similar: inner and middle shelf, although occasionally they can be spread out over the entire shelf, except the for subunits of unit 10, which are found from the middle shelf to the upper slope. The typical external shape is normally sheet, but also lensoidal and wedge-shaped. The internal configuration and thus the nature of the upper and lower boundaries are highly variable, but they generally show a similar arrangement of seismic facies:

- Parallel oblique (high-angle) configurations (figure 2, Type 1c) with high acoustic reflectivity are frequent, especially in the distal portions of the seismic units, and also in the proximal sectors of several units.
- Aggrading configurations of different types (figure 2) are also very frequent inside these units, mainly in middle emplacements, although some units present a general aggrading internal configuration (i.e., seismic unit 3). This kind of facies grades laterally and vertically into transparent and semitransparent configurations, and also into filling facies, which normally are characterised by the absence or low amplitude of internal reflectors.
- Locally, other types of seismic facies can also be present such as (figure 2): inverse progradation, normally in middle emplacements and laterally related to filling or semitransparent facies; shingled facies, in the seaward termination of several units; divergent facies, in the

Table II. Main seismic characteristics of the identified seismic units in the study area

| Type of seismic facies | | Characteristics |
|---|---|---|
| 1 | 1A Sigmoid | Preservation of topset layers |
| | 1B Complex sigmoid-oblique | Lateral transition from sigmoid to oblique |
| | 1C Parallel oblique (high angle) | High steepness of climoforms and reflective acoustic response |
| | 1D Parallel oblique (low angle) | Low steepness of clinoforms and semitransparent acustic response |
| | 1E Shingled | Very slightly dipping reflectors laterally continuous |
| | 1F Tangential oblique | Reflectors become tangent to the lower boundary |
| | 1G Inverse progradation | Landward dipping reflectors |
| 2 | 2A Subparallel (Type 1) | Reflectors of high amplitude, and continuity |
| | 2B Subparallel (Type 2) | Reflectors of high amplitude, laterally discontinuous |
| | 2C Subparallel (Type 3) | Reflectors of low amplitude and continuity |
| | 2D Subparallel (Type 4) | Reflectors of high amplitude, very closely spaced |
| | 2E Divergent | Subparallel reflectors, but seaward dipping |
| 3 | 3A Wavy | Contorted reflectors inside divergent configurations |
| | 3B Irregular | Reflectors showing an irregular signature |
| 4 | 4A Semitransparent | Very low amplitude reflectors |
| | 4B Transparent | Absence of internal reflectors |
| 5 | 5A Acoustic masking | Loss of seismic resolution |
| | 5B Chaotic | Reflectors with very low lateral continuity and highly deformed |
| 6 | 6 Filling facies | Semitransparent configurations and filling external shape, very extensive but not deeply incised |
| 7 | 7A Incised valley facies (Type 1) | Aggrading facies and filling external shape deeply incised |
| | 7B Incised valley facies (Type 2) | Prograding facies and filling external shape deeply incised |

upper slope extension of several units; sigmoid and tangential oblique configurations have a reduced extension inside some units.

b) Distal units (5, 7, 9 and 11). Seismic units 1 and 2 share similar attributes. They show a global wedge external shape, with thicknesses increasing progressively towards the shelf-break. Maximum measured thickness normally exceeds 50 m, and in unit 11, more than 200 m were measured. The most significant internal structures are low-angle parallel oblique (with toplap/truncation and downlap terminations) and sometimes shingled configurations, which are characterised by very low-angle clinoforms. These kinds of configurations evolve seaward into divergent configurations, which are normally found in shelf-break and upper-slope settings. Seismic unit 11 presents a wide variety of seismic facies: prograding facies as tangential oblique and sigmoid and divergent facies in distal settings are the most common, but locally other kind of facies can be identified: wavy, chaotic and acoustic masking (see figure 2).

c) Seismic unit 13. This is the youngest seismic unit, and comprises two subunits: 13a, characterised by seismic facies similar to the proximal units; and 13b, characterised by a subparallel internal configuration, evolving seaward to transparent. In the southern sector, the presence of acoustic masking, offshore from the Guadalquivir River's mouth, related to this seismic subunit makes it impossible to recognise seismic units.

d) Filling facies (figure 2). Normally this kind of facies is related to proximal units, and they are very numerous in subunits 12b, 12c and 12d. They are normally characterised by semitransparent internal configurations and some subparallel internal reflectors, filling broad depressions but not very incised in the infrajacent units.

e) Incised valley facies. Two main kind of facies are distinguished inside the incised valleys (figure 2): subparallel reflectors of moderate to high amplitude, and prograding configurations, normally very high-angled parallel obliques. In some cases, it is possible to observe internal discontinuities that affect the infilling of the incised valleys.

## Stacking patterns of seismic units

Based on the stacking pattern of the units, three main sectors have been differenciated in the study area:

a) Western sector, between the Guadiana River mouth and the Tinto-Odiel estuary. An example from this sector is seismic profile 5 (figure 3, see position in figure 1). The seismic units are stacked vertically, and they also outbuild the margin laterally. From seismic unit 4 to the top, normally the seismic units are arranged in a repetitive pattern, with a unit on a shelfal position and the following in a distal position (i.e. seismic units 4-5, 6-7, 8-9 and 10-11). They are named proximal and distal units, respectively. Subunits 10a and 10b, and the subunits which constitute unit 12 are disposed in a backstepping pattern, whereas subunits 13a and 13b show a forestepping pattern. An important feature in this sector is the general occurrence of infilled incised valleys. They normally appear affecting the proximal units (4, 6, 8 and 10) on the inner and middle shelf, but they also have been found in some distal units (7 and 9). In the seismic profile, there is an example of an incision in a proximal unit (unit 8) and in a distal unit (unit 7). These fill-features have highly variable dimensions.

b) Middle sector, between the Tinto-Odiel estuary and the town on Matalascañas. A seismic profile from this sector is given in figure 4. In this profile, the oldest units (1-4) are not visible; the first seismic unit is unit 5. For the rest of the units, the same repetitive pattern is observed, but in general the units that are located in proximal positions are more areally developed. The distal units have moderate thicknesses in relation to the previous sector, and another remarkable characteristic is the larger areal extension in relation to the previous profile and the aggradational stacking pattern, e.g. subunits 12b, 12c and 12d. Incised valleys are not observed in this sector.

c) Southern sector, offshore from the Guadalquivir River's mouth. The most important characteristic of this sector (figure 5) is the presence of diapiric-like features on the outer shelf. The deeper units are affected by diapiric intrusions, and up to unit 12 seem to be affected by the diapiric movement. The units also seem to be affected by faulting, in relation to the diapiric intrusion. In this profile (figure 5) only the outer units are observable, because of their location on the outer shelf domain. Also, the first observable unit is unit 5, as in the middle sector. Incised valleys have not been distinguished in this sector.

## DISCUSSION

### Palaeoenvironments of deposition

The stratigraphical Late Quaternary architecture of this section of the Gulf of Cadiz's continental shelf shows a repetitive pattern, where two main kinds of seismic units can be discerned (figure 6):

a) Units that internally show a high variability of seismic configurations and sheet-to-lensoidal external shape. Usually they are located in inner-to-middle shelf settings. These units are considered high-energy units (HEU).

b) Units displaying low-angle oblique seismic configurations, having reflectors with good lateral continuity and amplitude; their thickness increases seaward, acquiring the largest depocentres near the shelf-break, displaying therefore a typical wedge external shape. Occasionally semitransparent and transparent facies are observable. These units are located very frequently from middle-shelf emplacements to outer shelf and upper-slope settings, and they are considered low-energy units (LEU).

The distribution of seismic facies inside the seismic units provides information about depositional palaeoenvironments. Taking also into account the distribution and global thickness of the units, the attributes of the two main kinds of units have been summarised as follows (figure 6):

1) Proximal units, characterised by a typical arrangement of seismic facies. The distal portions of these units are characterised by high-angle parallel oblique facies, with a very reflective character. Those features are indicators of deposition in a high-energy environment, with a coarse grain size. Highly reflective units have high sand contents, whereas transparent units are muddy deposits (Kuehl *et al.*, 1997). Steeply-dipping progradational foresets with an irregular character truncated at their top termination indicate lower shoreface facies eroded by shoreface retreat, whereas the foreshore and backshore have been removed, resting the shoreface facies as barrier islands (Ashley *et al.*, 1991; Browne, 1994). Shingled facies with a transparent character are located seaward. They are believed to represent the healing phase, composed of fine-grained marine sediments that are eroded in the coastal domain, transported seaward by the action of storms and energetic events, and deposited below fair-weather wave-base level (Ashley *et al.*, 1991; Posamentier and Allen, 1993).

Landward, there are more transparent facies, located over depressed or flat zones, which represent back-barrier palustrine environments: tidal channels, tidal flats and lagoonal conditions (Ashley *et al.*, 1991; Browne, 1994; Tortora, 1996). The presence of subparallel facies of variable continuity and

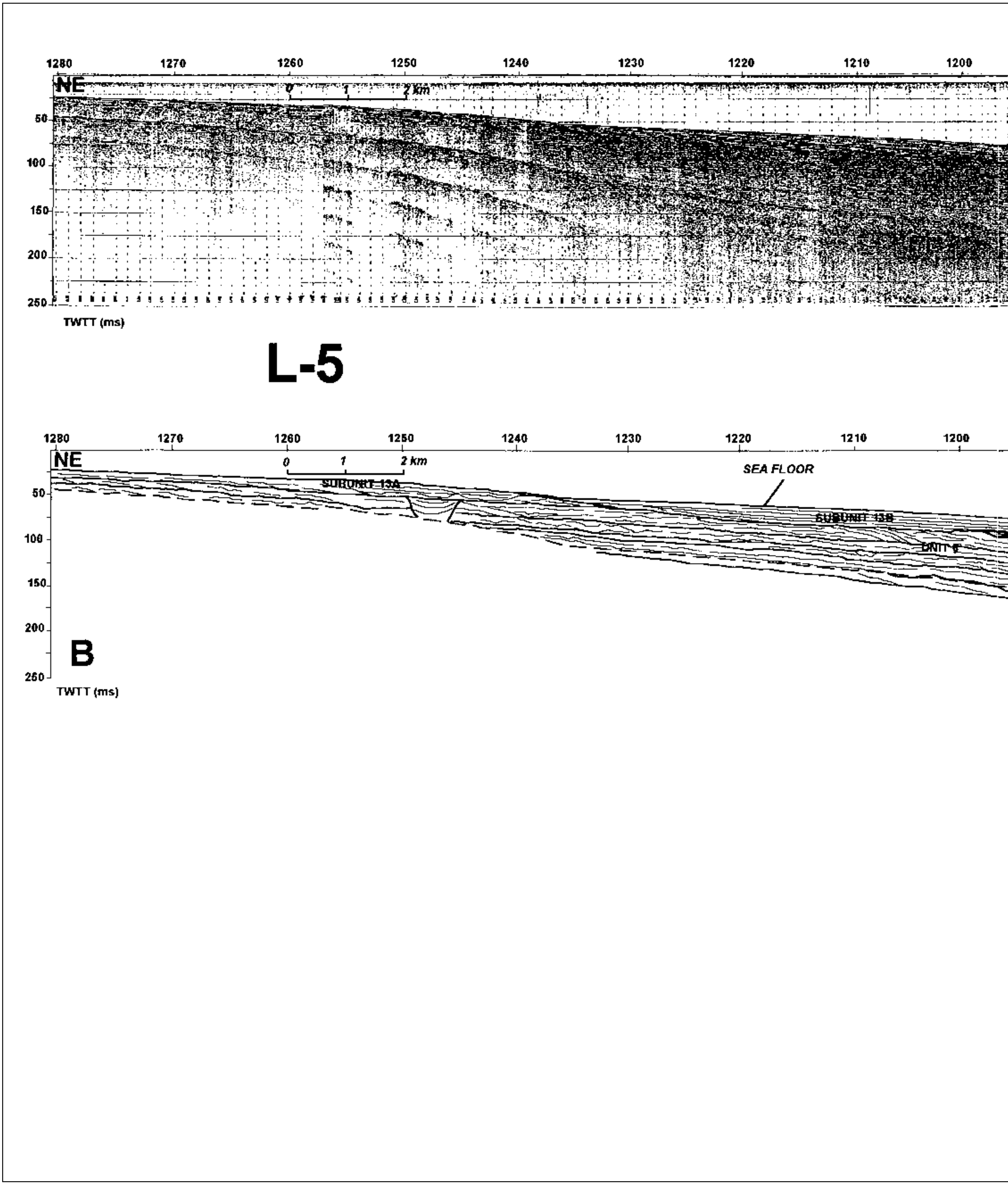
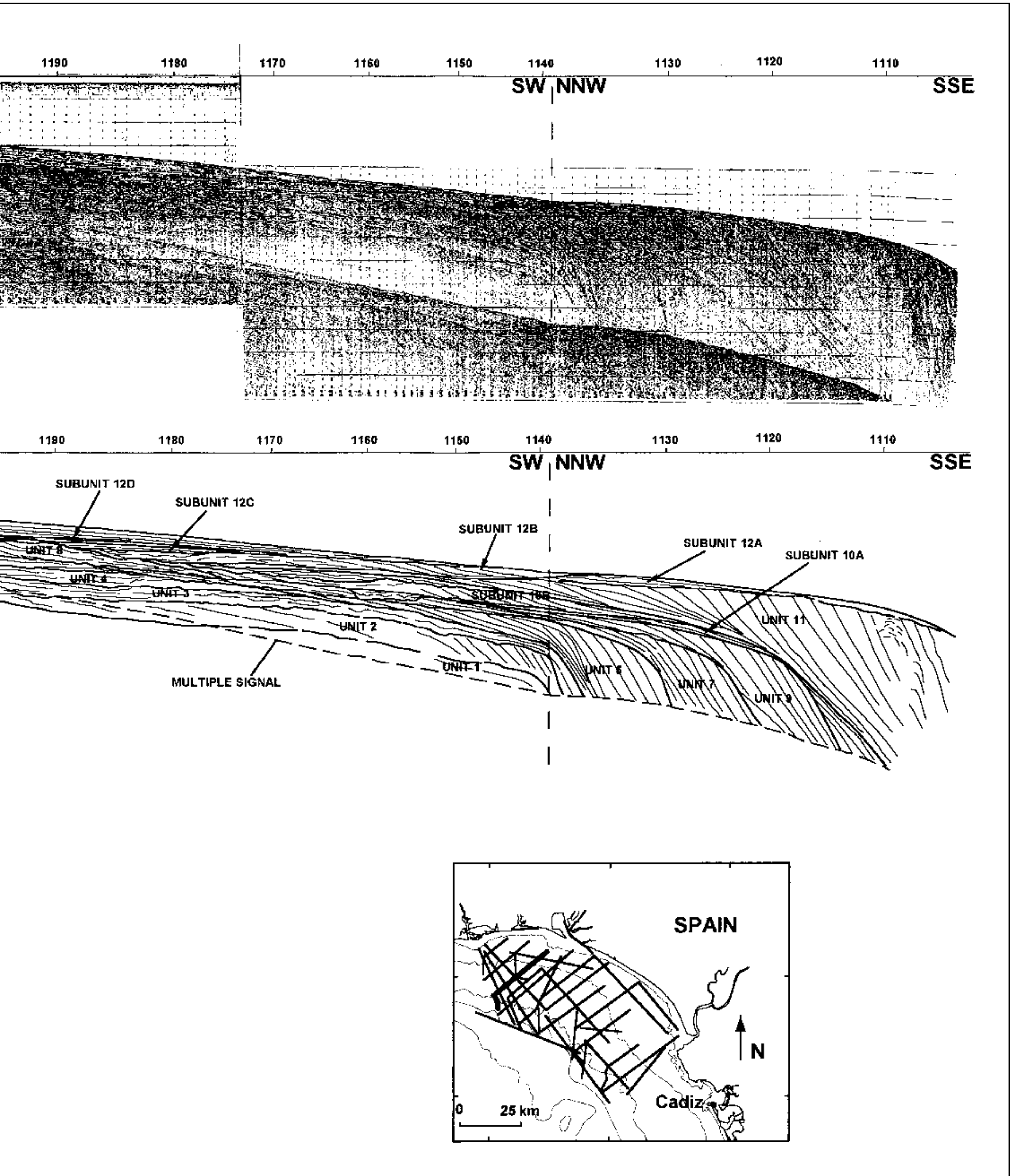



Figure 3. Uninterpreted (A) and interpreted (B) seismic section located in the western sector of the study area. All the identified seismic units are identified in this profile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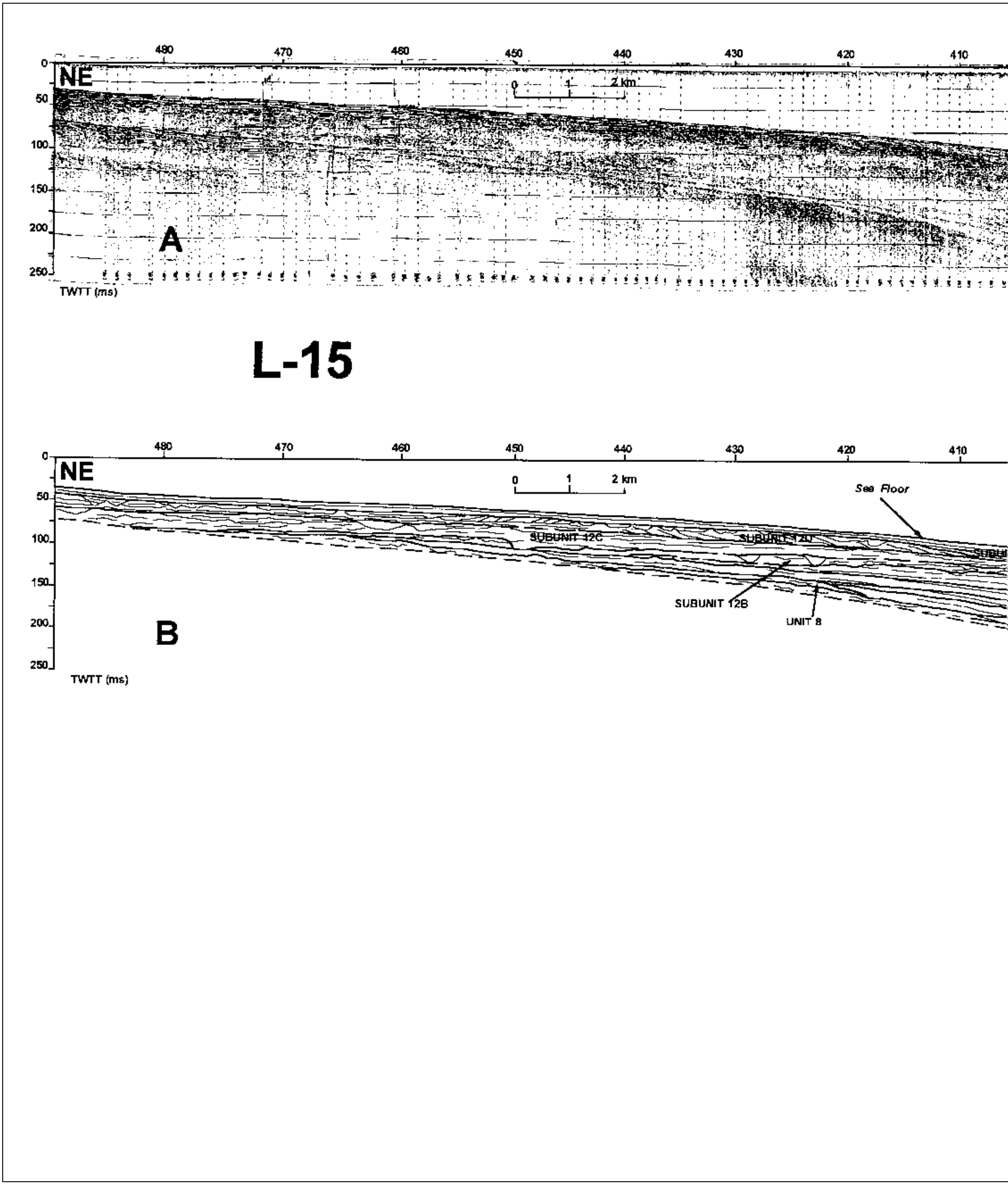
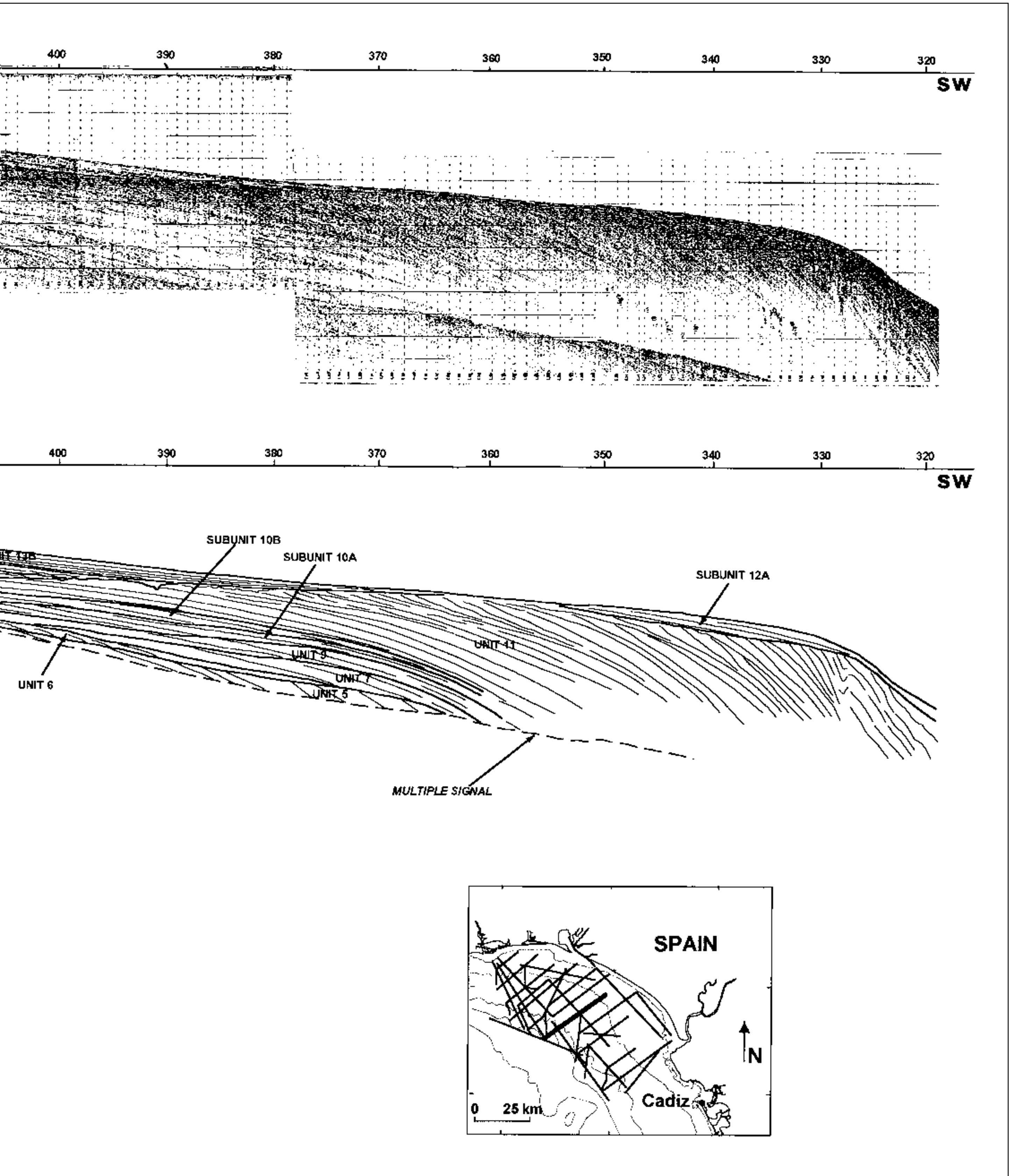



Figure 4. Uninterpreted (A) and interpreted (B) seismic section normal to the shelf profile and located in the middle sector of the study area


400
390
380
370
360
350
340
330
320
SW
SUBUNIT 10B
SUBUNIT 10A
SUBUNIT 12A
UNIT 11
UNIT 9
UNIT 7
UNIT 5
UNIT 6
MULTIPLE SIGNAL
SPAIN
N
Cadiz
0 25 km

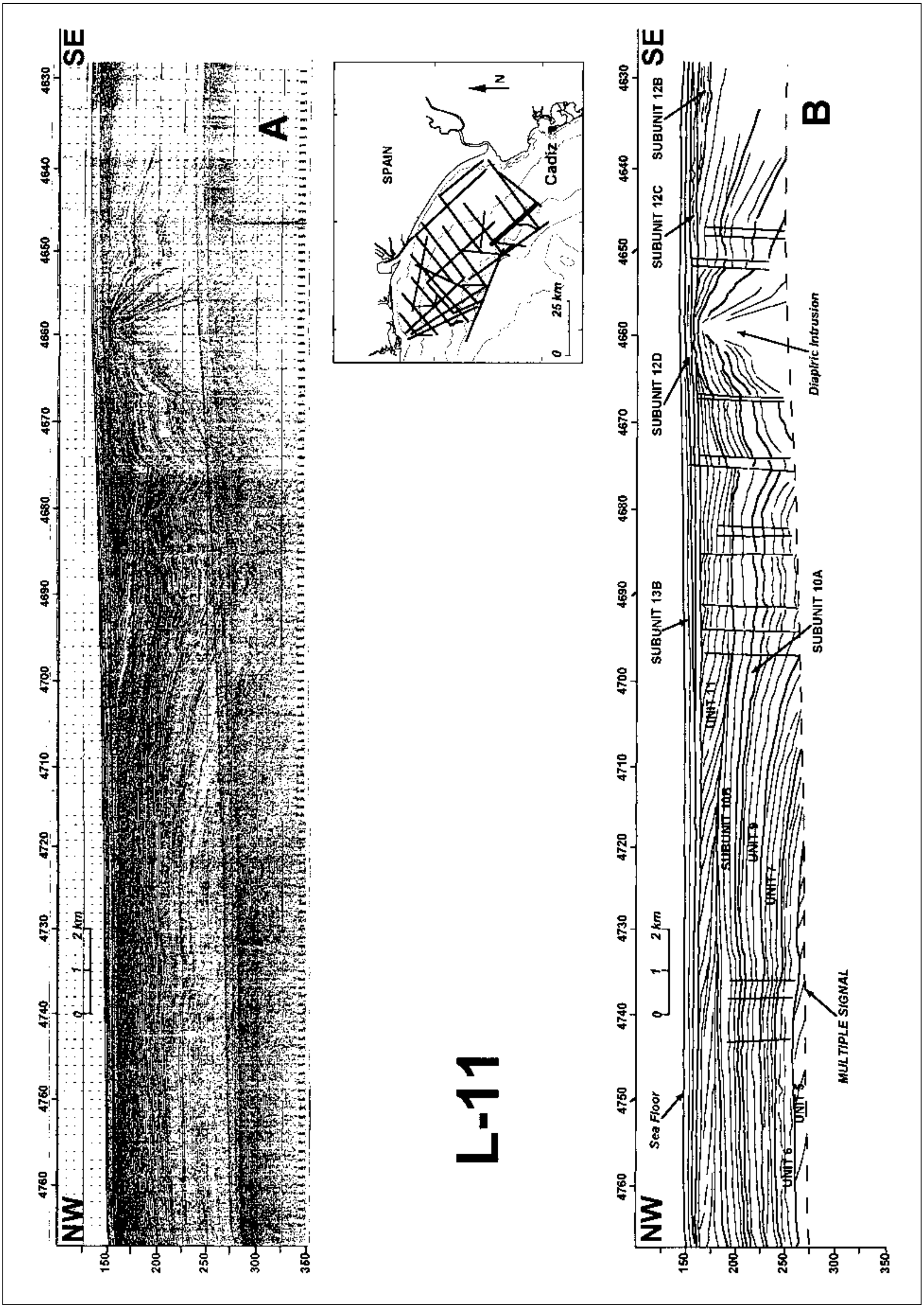



Figure 5. Uninterpreted (A) and interpreted (B) seismic section parallel to the shelf and located in the eastern sector of the study area

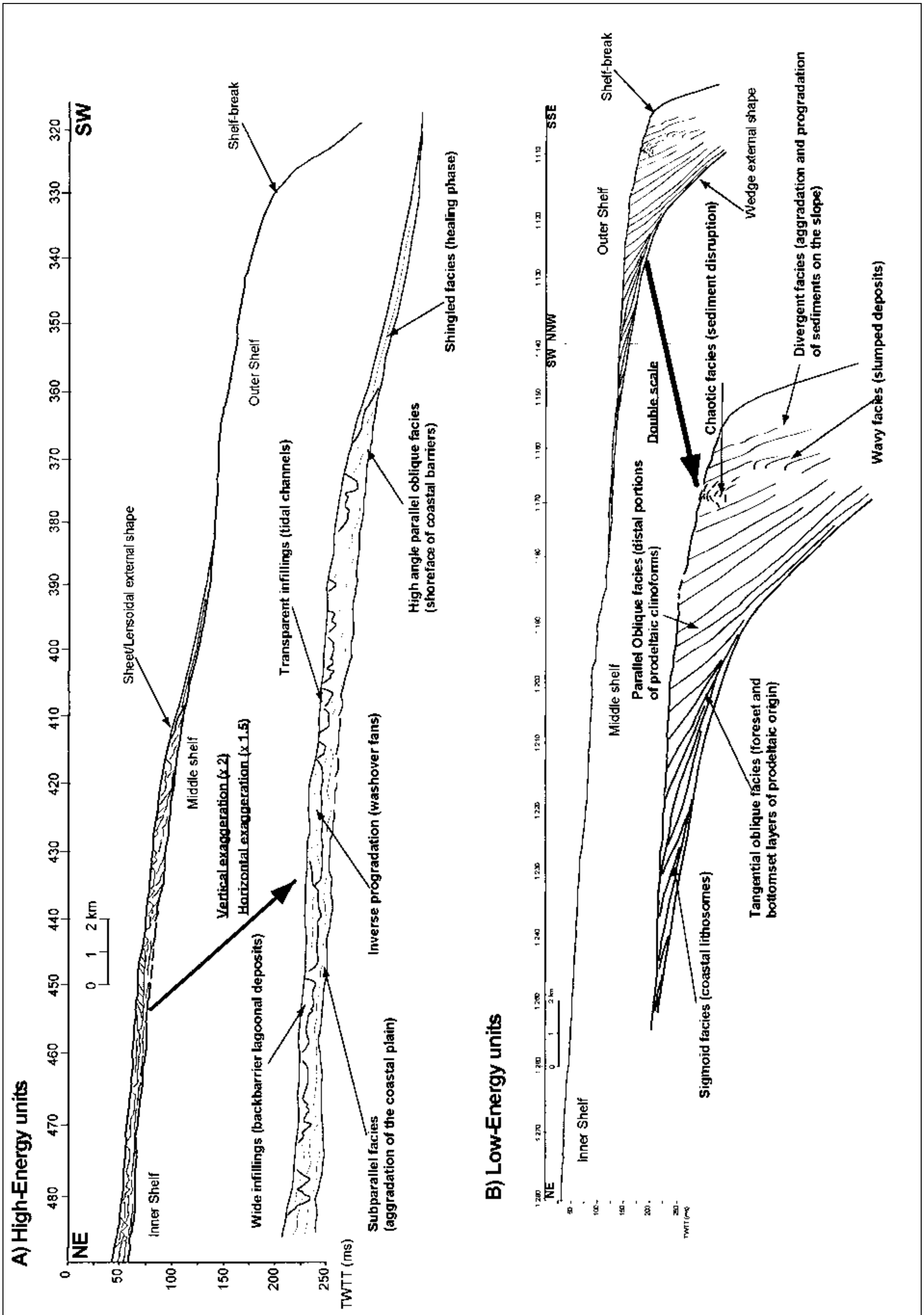



Figure 6. Main stratigraphical features of the high-energy units (proximal units) and the low-energy units (distal units) and its interpretation in terms of sedimentary processes

amplitude suggests the presence of interbedded high/low-energy deposits, in relation to the aggradation of the coastal plain.

Small progradational foresets dipping landward, located between the palustrine mud and the lower shoreface sand are considered washover fans (Browne, 1994; Tortora, 1996). Filling features that cut the architecture of shoreface and backbarrier deposits are considered tidal channels that open breaches in the littoral barrier (Tortora, 1996).

The presence of tidal channels overlying coastal deposits and toplap and truncation of shoreface deposits can indicate submarine current erosion (Evans, Stephens and Shorten, 1992). This feature represents a ravinement surface, which produces erosion inland (washover fan) and transport seaward (healing phase), whereas the backbarrier deposits have been preserved from shoreface erosion (Saito, 1994; Tortora, 1996).

These kinds of environments are typical of the present-day situation in the Gulf of Cadiz, characterised by the southeastward progradation of spit barriers (Dabrio, 1989). The sediments supplied by the rivers are redistributed and dispersed by the general dynamics, controlled by the general southeastward littoral drift and also by very effective wave action coming preferentially from the southwest.

2) Distal units, which are characterised by different types of prograding configurations (figure 6), normally oblique configurations. This kind of facies has been considered, in the Gulf of Cadiz, middle- and outer-shelf prodeltaic deposits, where topset and partially foreset deposits have been removed (Maldonado *et al.*, 1989; Baraza and Ercilla, 1996). Two types of oblique configuration can be observed: a) parallel oblique, which represent the distal portions of prodeltaic clinoforms; and b) tangential oblique, which are foreset and bottomset layers of prodeltaic origin. When clinoforms become asymtotic at the base, this indicates moderately deep-water deltaic sedimentation, where sedimentation rates are high (Morton and Suter, 1996). The existence of parallel reflectors with good lateral continuity inside nearly transparent units is related to a cyclic alternation of depositional conditions (Canals, Catafau and Serra, 1988). The origin of these deposits could be attributed to the terrigenous supply introduced onto the continental margin by rivers, especially the most significant, such as the Guadiana River and, to a lesser extent in this area, the Guadalquivir River, whose sediments are advected to the southeast. Noteworthy here is the predominant southeastward progradation of unit 11, which could be indicative of redistribution of terrigenous supply by the general shelfal circulation.

Occasionally sigmoid configurations can be observed in middle-shelf settings; these can be attributed to coastal lithosomes that have been preserved from erosion. On the upper slope, the most significant configuration is divergent, in relation to lateral variations in the rate of deposition (Mitchum, Vail and Sangree, 1977), with the progradation of shelf sediments over the slope. The clinoforms can be disturbed by chaotic and wavy facies in specific sectors near the shelf-break. This kind of facies has been related to gravitational processes (slumps) and intrastratal deformation when they occur in those settings (Ergin, Okyar and Timur, 1992; O'Leary and Laine, 1996).

Finally, although it is beyond the scope of the present paper, some observations concerning the sedimentary infilling of incised valleys can be made. Two kind of facies characterise these depositional systems: a) subparallel facies of relatively high amplitude and reflective character, which can be attributed to fluvial sands and muds; and b) prograding configurations, which can be attributed to fluvial (point bars) or coastal deposits.

## Relative sea-level changes: some reconsiderations for sequence stratigraphy analysis

Relative sea-level changes that have taken place in this area can be deduced from the analysis of internal facies and general location of the seismic units (figure 7):

1) HEUs can be considered to be deposited under relative highstand or at least landward displacement of mean sea level. This fact is supported by:

- Their location in shelf environments (normally inner-middle shelf settings)
- Characteristic seismic facies indicative of deposition in the coastal realm, under oceanographic and sediment supply conditions similar to the present. Some deposits which have been typically related to transgressive and highstand conditions have been identified inside these sedimentary bodies: i.e. healing phase, which is a common compo-

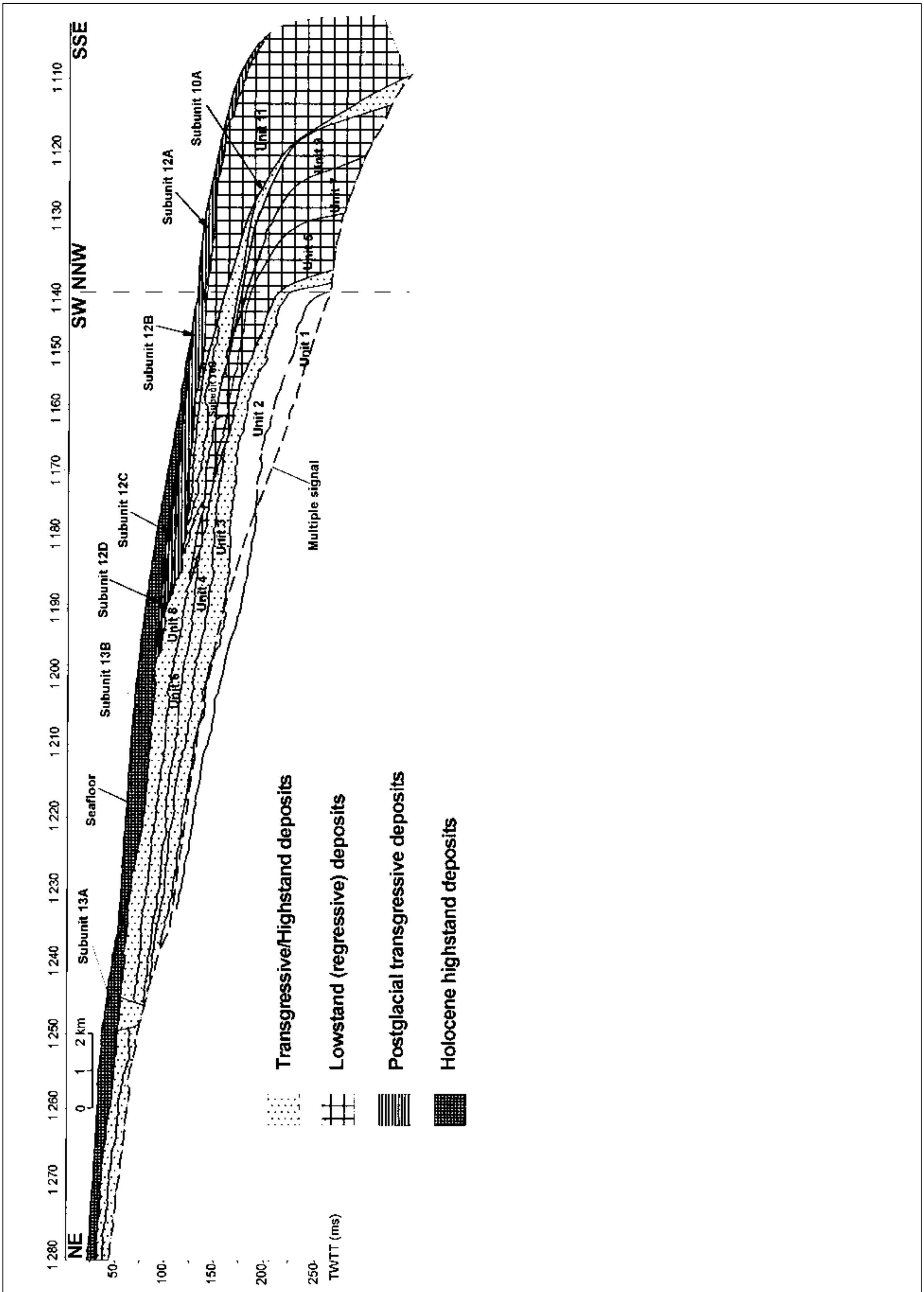



Figure 7. Interpretation of seismic units based on their location with regard to relative sea level change

nent of transgressive deposits (Posamentier and Allen, 1993)

• Transgressive deposits are normally characterised by a highly variable lithofacies in a shore normal direction (Ashley *et al.*, 1991), so that these sedimentary bodies (HEUs) can be regarded as transgressive/highstand deposits.

2) The distal units (LEUs) are believed to be deposited during intervals of lowered sea level and in lowstand periods, showing the main attributes which characterise the lowstand deposits on most Quaternary continental shelves. During these intervals, the lowering of mean sea level produces a large capability of erosion of the main streams, and large amounts of sediment are delivered to the shelf, forming coastal deposits that generate deltaic bodies. Evidence of lowering of mean sea level is also reinforced by the general occurrence of incised valleys, mostly affecting proximal units, although some of them are also in the upper part of the distal units, suggesting large seaward migrations of the coastline.

In this sense, units 1 and 2 represent regressive lowstand deposits, and they are overlain by unit 3, which is indicative of a large transgressive/highstand period. After this major event, a series of transgressive/regressive cycles are depicted by an alternation of proximal and distal units (4-5, 6-7, 8-9, 10-11). ): HEUs are located landward of LEUs, which stratigraphically are located above the HEUs. The peculiar stratigraphical architecture of unit 10 is noteworthy; it is internally composed by at least two backstepping subunits, representing transgressive deposits and probably a highstand deposit in a mid-shelf location, therefore representing a relative highstand.

Finally, the seismic subunits that constitute unit 12 are considered to be the backstepping postglacial transgressive system tract, whereas unit 13 represents the Holocene highstand deposits, showing two components, a coastal deposit (subunit 13a) and a shelfal deposit (subunit 13b) (figure 7).

The seismic evidence suggests the peculiarity of this segment of the Spanish continental shelf in terms of Late Quaternary stratigraphical architecture. The main difference, compared with other Quaternary shelves, is that on this shelf transgressive and highstand deposits display a high potential for preservation, whereas on other shelves they normally appear as thin, patchy and discontinuous. In fact, they are often undetectable with conventional high-resolution seismics.

In light of this interpretation, the stratigraphy sequence interpretation that has already been proposed for the Gulf of Cadiz's continental shelf (cf. Somoza *et al.*, 1997; Hernández-Molina, Somoza and Lobo, in press) can be improved. These previous papers have hypothesised that the forced regressive (FWRST) and lowstand deposits (LST) build up the margin, which is confirmed by the present analysis, because those deposits display the largest dimensions and a net progradational pattern. However, the FWRST normally is characterised by oblique prograding and shingled clinoforms (low energy, typical of distal portions of prodeltaic deposits and coastal wedges), being the upper part of the wedges (topsets and upper portions of foresets) eroded by subsequent drops in sea level. This more detailed approach enables us to state that the landward portions of what were previously considered forced regressive deposits represent the transgressive/highstand deposits defined in the present paper as HEUs. Concerning unit 10, its unequivocal backstepping pattern leads us to interpret it as being transgressive/highstand deposits disposed in a mid-shelf location, probably in relation to a relative highstand.

**Tectonic controls**

The stacking pattern shown by the identified seismic units in the study area (figures 3, 4 and 5) determines the existence of three different areas (western, middle and eastern sectors) characterized by a different tectonic behaviours:

1) The middle sector can be considered a very subsiding area, because: a) the oldest units have not been observed in this area, being located below the multiple signal; b) the poor development of lowstand prograding units suggests the relative importance of the subsiding process through the deposition of the units; and c) absence of incised valleys in this area is indicative of very low gradients during low sea levels and not very pronounced intervals of falling sea level.

2) The western sector is a subsiding area, since the units are stacked vertically and they also outbuild the margin laterally, but they have subsided at a lower rate than the middle sector, because all the seismic units are observed in this sector. The most

significant stratigraphical features in this area support this interpretation: presence of incised valleys in the western sector and better development of regressive/lowstand units.

3) In the eastern sector the distal units are uplifted by the action of diapiric intrusions, but also the deeper units have not been identified in this area.

Therefore, the study area can be tectonically defined by a central depressed area bounded laterally by two tectonic highs, one of them structurally controlled (the western one) and the eastern one controlled by the diapiric intrusions. The central area seems to have subsided at very high rates, probably in relation to a high sediment supply rate (sediments derived from the main rivers, e.g. the Guadiana and Guadalquivir). The rivers could have been forced to drain into this area, probably driven by a tectonic influence. A preferent direction of N 60° E for the recent tectonic deformation has been identified in this area (Vázquez *et al.*, 1998).

Another point of interest is the relevance of transgressive/highstand deposits in this area, in relation to the prograding regressive deposits. The good development and preservation of these deposits could be attributed in a first approach to the existence of a tectonic process of relatively high frequency, which causes the longer duration of transgressive and highstand intervals. The good preservation of these deposits supports the hypothesis of a mechanism of transgression by in-place drowning more effective than the erosional shoreface retreat (Browne, 1994).

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