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Continental shelf architecture and sea-level cycles: Late Quaternary high-resolution stratigraphy of the Gulf of Cádiz, Spain

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Abstract The stratal architecture of the Gulf of Cádiz continental margin (SW Spain) has been analyzed by using single-channel, very high-resolution seismic reflection profiles. An evolutionary scheme of asymmetrical depositional sequences is proposed that was governed by the Late Pleistocene–Holocene sea-level fluctuations. Stratigraphic analysis defined 14 seismic units, that are configured into two major type-1 depositional sequences related to 4th-order eustatic sea level changes (100–110 ka). Within these sequences, minor asymmetrical depositional sequences have been recognized related to 5th-order eustatic cycles (22–23 ka) superimposed and modulated by the regressive trends of 4th-order cycles. In 5th-order depositional sequences, the forced regressive and lowstand deposits are volumetrically dominant. They cause the main progradation of the margin in such a way that they form the margin structure almost entirely.

Introduction

Single-channel, very high-resolution seismic profiles allow the study of the youngest depositional sequence during the last sea-level hemicycle, identifying high-frequency cycles that have modulated the eustatic trend during the last 20 ka BP (Suter et al. 1987; Boy et al. 1989; Swift et al. 1991; Gensous et al. 1993; Chiocci, 1994; Hernández-Molina et al. 1994). However, there are no high-resolution stratigraphic detailed studies of depositional sequences on the continental margins older than 20 ka that can be correlated with sea-level fluctuations recognized on emerged deposits. The objectives of this paper are to: (1) describe the present seismic units that made up the southern Spanish continental shelf during the Late Pleistocene–Holocene, (2) apply the concepts of sequence stratigraphic analysis to high-resolution seismic profiles to interpreting the data, and (3) establish a model of stratal architecture of this continental margin controlled by superimposed eustatic cycles of different frequency. The resulting model is compared with both the main eustatic cycles that affect the Quaternary sequences, specifically the 4th- and 5th-order cycles (Einsele et al. 1991; Mitchum and Van Wagoner, 1991; Hailwood and Kidd 1993), and the well-dated sea-level fluctuations (U/Th and amino acid methods) on emerged deposits that represent the highstand systems tracts during the Late Pleistocene–Holocene times (Hillaire-Marcel et al. 1986; Somoza et al. 1987, 1991).

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Data set

The single-channel seismic source was a Geopulse (300 J) carrying out a grid of narrow-spaced profiles (800 km) over the continental shelf of the Cádiz Gulf (Fig. 1) during the Golca '93 and '94 cruises on the Spanish Oceanographic Institute vessel *Oden de Buen*. The very high vertical resolution of this system (0.5–1 m) allows the definition of the geometrical features of sedimentary bodies. Lithological information was obtained from 32 vibrocores (4–5 m penetration) collected from the main sedimentary bodies. Definition of the seismic units was based on the interpretation of all seismic lines, which allowed for the establishment of the three-dimensional geometry of the sedimentary bodies. The seismic lines presented on this paper (Figs. 2 and 3) are representative

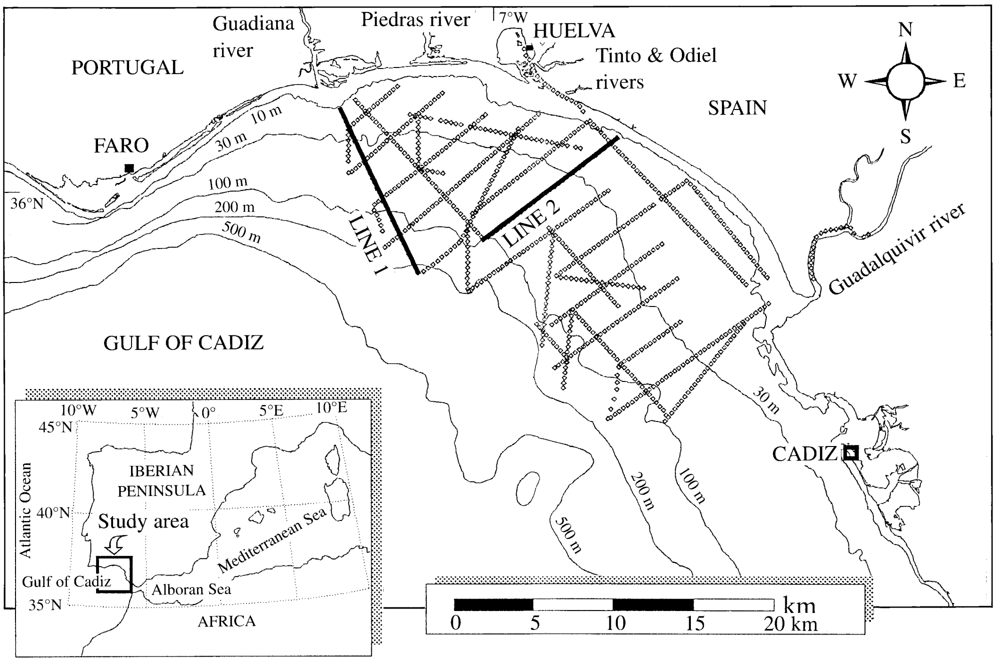


Fig. 1 Location map showing the location of high-resolution seismic lines along the Gulf of Cádiz continental margin (SW Spain). In bold: seismic lines presented in this paper

of the geometry of the stratal architecture of areas with different subsidence and sediment rates depending on local factors. The length of these seismic lines has permitted the reconstruction of the sequences in detail with great lateral continuity.

High-resolution seismic and sequence stratigraphy analysis

The seismic–stratigraphic analysis defined 14 seismic units (Figs. 2–4). These units are arranged into two major depositional sequences (I and II) comprising minor depositional subsequences.

Depositional sequence I

This type-1 depositional sequence (sensu Posamentier et al. 1988; Vail et al. 1991) is composed of seismic units 1–5 (Fig. 2 and 3), which shows an aggradational growth. This sequence can be divided into two minor depositional subsequences:

Subsequence I_1

This is interpreted as a type-2 depositional sequence formed by forced regressive deposit (seismic unit 1a), a lowstand deposit (seismic unit 1b), a transgressive surface (discontinuity between seismic units 1 and 2), and a shelf margin deposit (seismic unit 2).

Subsequence I_2

A type-1 depositional sequence is formed by a forced regressive deposit (seismic unit 3a), a lowstand deposit (seismic unit 3b), a transgressive deposit (seismic unit 4), and a highstand deposit (seismic unit 5). The presence of paleochannels indicates active fluvial incision during the lowstand sea-level stage.

Depositional sequence II

It is a type-1 depositional sequence consisting of regressive units (seismic units 6–10), a lowstand unit (seismic unit 11), a transgressive unit (12), a highstand unit (13), and a slope aggradational deposits (seismic unit 14). Sequence II can be divided into four minor depositional subsequences (Figs. 2–4):

Subsequence II_1

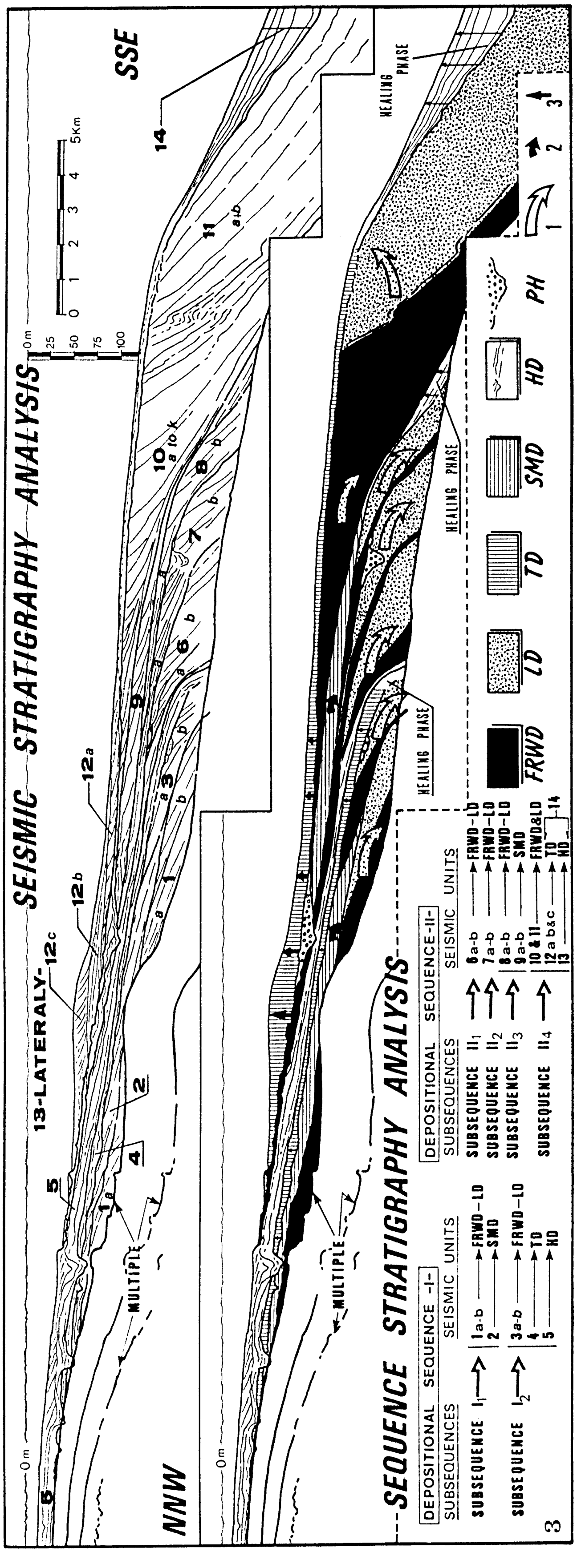
This type-2 depositional sequence is characterized by shelf-margin wedge deposits internally structured by a regressive deposit (seismic unit 6a) and a lowstand deposit (seismic unit 6b). The upper boundary of this subsequence represents a strong erosional surface.

Subsequence II_2

This type-1 depositional sequence is composed of seismic unit 7 and also represents a shelf-margin wedge deposit

Fig. 2 Synthesis of the seismic stratigraphy analysis (seismic units, type of reflection configuration, terminations, shape, and margin position) and sequence stratigraphy analysis as they correspond to the seismic profiles (Figs. 3 and 4): B: type of reflection termination with respect to its bottom; T: type of reflection termination with respect to its top. Asterisk: the paleochannel incision infill is positioned. For further details, see text

SEQUENCE STRATIGRAPHY ANALYSIS			SEISMIC STRATIGRAPHY ANALYSIS					
			SEISMIC UNIT	SUBUNIT	TYPE OF REFLECTION TERMINATIONS	REFLECTION PATTERN CONFIGURATION	GEOMETRICAL SHAPE	MARGIN POSITION
DEPOSITIONAL SEQUENCE -II-	II$_4$		14		T:Concordance.Present bottom of the sea floor on the slope B:Onlap	Progradational-divergent	Wedge	Slope
		HD	13	b	T:Concordance.Present bottom of the sea floor on the shelf B:Onlap	Sigmoidal to oblique progradational and aggradational	Wedge	Littoral and shelf
				a	T:Concordance. B:Onlap	Sigmoidal to parallel progradational and aggradational	Wedge	Littoral and inner shelf
		TD	12	c	T:Erosional truncation landward & Toplap seaward B:Downlap	Oblique to parallel progradational	Lobular to bank	Shelf
				b	T:Concordance landward to toplap latteraly seaward B:Onlap	Weak with aggradational and parallel	Lens	
				a	T:Erosional truncation landward & Toplap seaward B:Downlap	Oblique to parallel progradational	Lobular to bank	
		LD	11	b	T:Erosional truncation landward & Toplap seaward B:Downlap	Oblique progradational and aggradational	Wedge	Shelf edge
				a	T:Erosional truncation landward & Toplap seaward B:Downlap	Sigmoidal to oblique progradational and aggradational	wedge	
		FRWD	10	a to k a c e g i k	T:Erosional truncation landward & Toplap seaward B:Downlap	oblique progradational	Wedge	Outer & Shelf edge
				b d f h j	T:Erosional truncation landward, concordance & Toplap seaward B: Coastal onlap & distal Downlap	Sigmoidal-oblique aggradational and progradational	Wedge	
	II$_3$	SMD	9	b	T:Erosional truncation landward & Toplap seaward B:Downlap	Oblique progradacional	Lens	Outer & middle shelf
				a	T:Erosional truncation landward & Toplap seaward B:Downlap	Shingled to parallel progradational	Lobular to lens	
		LD	8	b	T:Erosional truncation landward & Toplap seaward B:Downlap	Oblique progradational	Wedge	Shelf edge
		FRW		a	T:Erosional truncation landward & Toplap seaward B:Downlap	Sigmoidal progradational	Wedge	Outer & shelf edge
	II$_2$	LD	7	b	T:Erosional truncation landward & Toplap seaward B:Downlap	Oblique progradational	Wedge	Shelf edge
		FRW		a	T:Erosional Truncation landward & Toplap seaward B:Downlap	Sigmoidal progradational	Wedge	Outer & shelf edge
	II$_1$	LD	6	b	T:Erosional Truncation landward & Toplap seaward B:Downlap	Weak oblique progradational	Wedge	Shelf edge
		FRW		a	T:Erosional truncation landward & Toplap seaward B:Downlap	Weak sigmoidal-oblique progradational	Wedge	Outer & shelf edge
DEPOSITIONAL SEQUENCE -I-	I$_2$	HD	5		T:Concordance landward to toplap latteraly seaward B:Onlap	Sigmoidal progradational	Wedge	Inner & outer shelf
		TD	4		T:Concordance B:Onlap	Weak aggradational to sigmoidal progradational	Sheet	Shelf
		LD	3	b	T:Erosional truncation landward & Toplap seaward B:Downlap	Weak oblique progradational	Wedge	Shelf edge
		FRW		a	T:Erosional truncation landward & Toplap seaward B:Downlap	Weak sigmoidal-oblique progradational	Wedge	Outer & shelf edge
	I$_1$	SMD	2		T:Erosional truncation landward & Toplap seaward B:Downlap	Weak oblique and/or parallel progradational	Lobular to lens	Shelf
		LD	1	b	T:Erosional truncation landward & Toplap seaward B:Downlap	Weak oblique progradational	Wedge	Shelf edge
		FRW		a	T:Erosional truncation landward & Toplap seaward B:Downlap	Weak sigmoidal-oblique progradational	Wedge	Outer & shelf edge



related to a forced regressive stage of the sea level (seismic unit 7a) and a lowstand sea-level stage (seismic unit 7b). Its upper boundary is an erosional unconformity. The presence of paleochannels incising the shelf indicates active fluvial incision during the lowstand sea-level stage.

Subsequence II_3

This type-2 depositional sequence is composed of a forced regressive deposit (seismic unit 8a), a lowstand deposit (seismic unit 8b), a transgressive surface defined by a strong erosive seismic reflector, which separates seismic units 8 and 9, and a shelf margin deposit (seismic unit 9).

Subsequence II_4

This type-1 depositional sequence is formed by a regressive deposit (seismic unit 10) in the middle and outer shelf, a lowstand deposit (seismic unit 11) in the upper slope, a transgressive deposit (seismic unit 12), and a highstand deposit (seismic unit 13). Development of unit 10a is interpreted to have built up during the lowstand and highstand intervals. The presence of paleochannels seems to indicate active fluvial incision during the lowstand sea-level stage.

Continental shelf architecture: relative sea-level cycles

The two major depositional sequences (I, II), which correspond to asymmetrical type-1 depositional sequences, are assumed to be caused by the main asymmetrical glacioeustatic sea-level changes during the Late Quaternary. These high-order (fourth, 100–200 ka) sea-level fluctuations govern the main sedimentary cycles of the stratal architecture on the continental shelf. These sequences are made up of minor high-frequency asymmetrical depositional subsequences (I_1, I_2, II_1, II_2, II_3, and II_4) defining the influence of higher frequency asymmetric sea-level cycles superimposed to those of the 4th order. The location and development of higher-order (5th) sequences through time seems to be controlled by their interaction with the 4th-order eustatic cycles, which were dominant during the Quaternary (Fig. 4). The stratal architecture of the continental shelf takes place as a result of the modulation of eustatic cycles of different frequencies. The geometrical configuration of the sedimentary sequences is highly

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Fig. 3 High-resolution seismic reflection profile 1 showing seismic units and depositional sequences. FRWD: forced regressive wedge deposits: LD: lowstand deposits: TD: transgressive deposits: SMD: shelf margin deposits, HD: higstand deposits; PH: paleochannel incised infill. 1. major progradation; 2. minor progradation and aggradation; 3. aggradation. For location see Fig. 1

dependent on the influence of each eustatic sea-level cycle order. Thus, the 4th-order depositional sequences are composed of a forced regressive wedge systems tract (FRWST) (sensu Posamentier et al. 1992; Hunt et al. 1995), a lowstand systems tract (LST), a transgressive systems tract (TST), and a highstand systems tract (HST). The 5th-order depositional sequences are mainly composed of FRWSTs and LSTs. The TST and HST were not developed on the shelf during the 5th-order depositional sequences. However, a shelf-margin system tract can be recognized on the middle shelf as a response to the maximum position of the sea level of the lowest cycle of the 5th order.

It has been observed that the transgressive and highstand system tracts are preserved only during the transgressive phases of the major 4th-order cycles, whereas lowstand and shelf-margin deposits are mainly developed during the regressive and lowstand sea-level phases of the minor 5th-order cycles (Figs. 3–5). The major stages of progradation of the continental margin take place during the phases of gradual falls or low stands of sea level influenced by high-frequency order cycles. In contrast, transgressive and highstand deposits of these cycles are not preserved over the continental shelf because they were located above the present sea level.

At present, the absence of absolute datating requires a speculative correlation between the described depositional sequences with nearby Mediterranean and Atlantic areas having well-dated subaerially exposed marine emerged deposits. Three high stands of the sea levels have been described from the Spanish coast, dated by means of the U/Th method, on emerged coastal deposits during the last interglacial (Goy et al. 1993; Zazo et al. 1993): T-II (140–120 ka BP, isotopic stage 5e), T-III (105–100 ka BP, isotopic stage 5c), and T-IV (80–70 ka BP, isotopic stage 5c). Deposits from another relative sea-level high stand have been recognized at 55–50 ka, mainly from tectonically active coasts (Bloom et al. 1974; Somoza et al. 1987). The periodicity of these sea-level fluctuations is closely connected with the 22- to 23-ka Milankovitch cycle (Ruddiman and McIntyre 1981).

To establish a chronologic framework (Fig. 5), we assume that (1) depositional sequence II is part of the last 4th-order eustatic cycle that comprises the time span from the last interglacial (isotopic stage 5e) to the Present, and (2) that the lowstand deposits that are correlated to each highstand of the last interglacial referred to above are

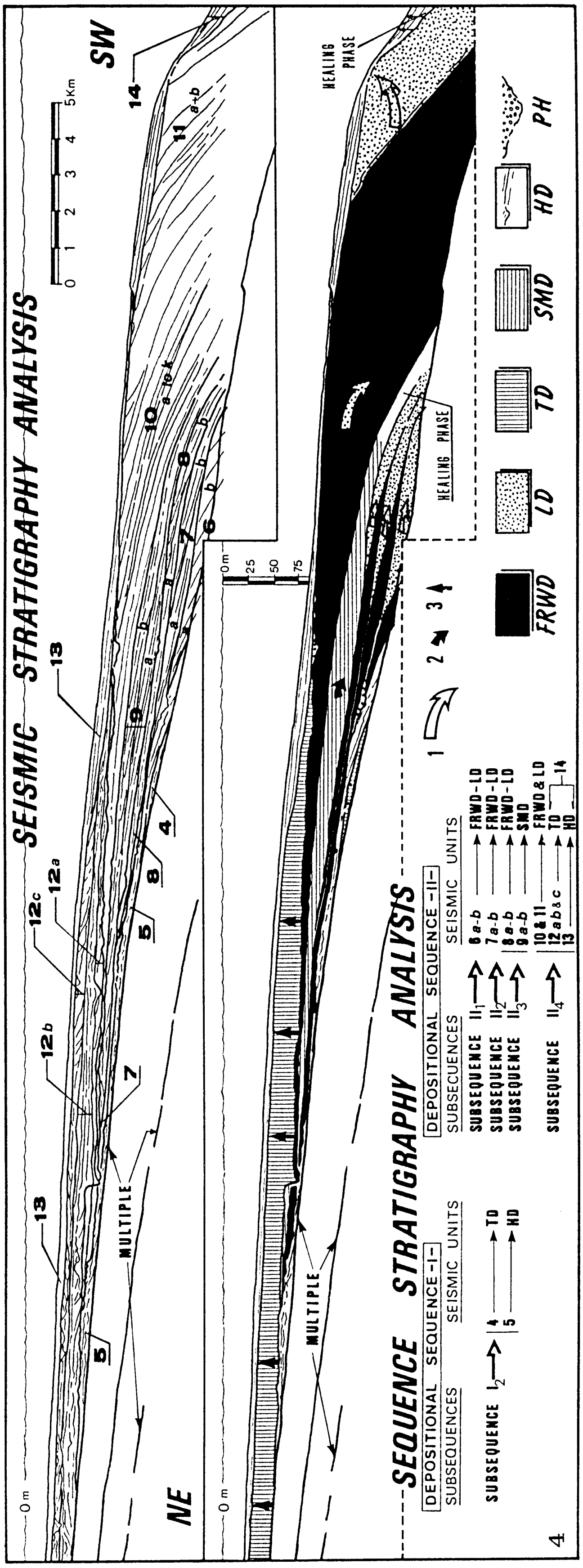

Fig. 4 High-resolution seismic reflection profile 2 showing seismic units and depositional sequences. This area underwent more subsidence than the area of seismic profile 1, making it possible to determine depositional sequence II with more detail. FRWD: forced regressive wedge deposits; LD: lowstand deposits; TD: transgressive deposits; SMD: shelf margin deposits, HD: higstand deposits; Ph: paleochannel incised infill. 1. major progradation; 2. minor progradation and aggradation; 3. aggradation. For location see Fig. 1

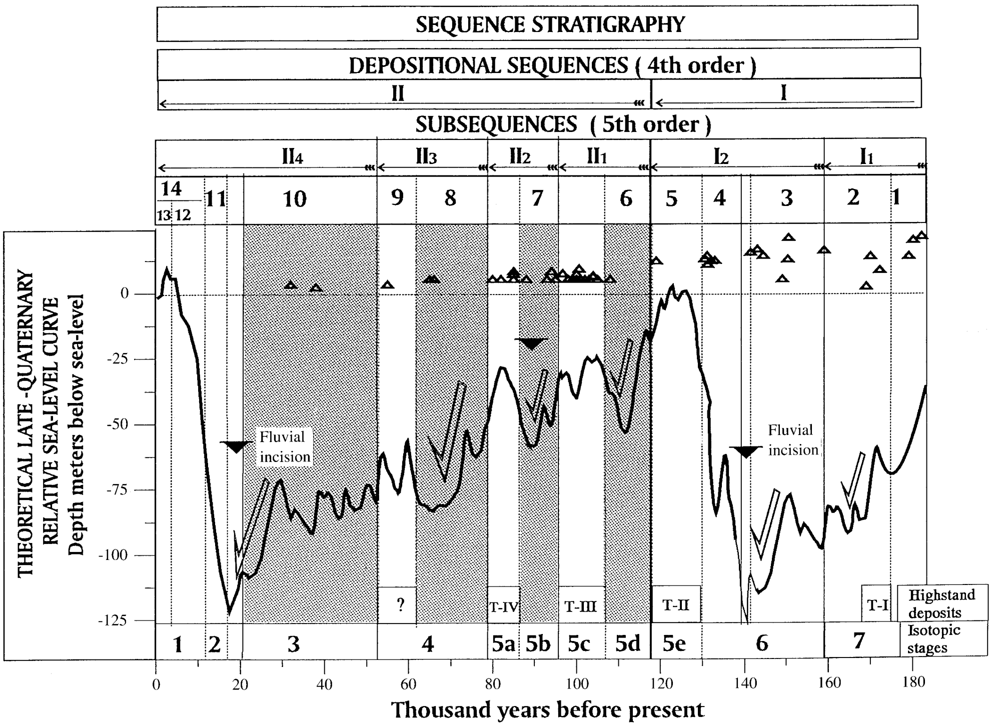

Fig. 5 Theoretical chronological scheme showing the proposed correlation between seismic units 1 and 14, depositional sequences I and II, and highstand of sea level on emerged deposits on Spain, Th/U dated for the Late Pleistocene–Holocene. Relative sea-level curves computed applying ranges from 0.3 m ka^{-1} uplift to 0.3 m ka^{-1} subsidence rates to a eustatic reference curve for the Late Pleistocene times. The rates are considered as linearly time-dependent. The uplift rates are based on those defined for the highstand deposit on the coast of Spain (Betic Domain) (Zazo et al. 1993). Relative sea-level curves with subsidence rates show position of lowstand sea levels between 75 and 100 m

located on the continental shelf and form 5th-order cycles. Therefore, we assume that the subsequences II$_1$, II$_2$, and II$_3$ were formed during the eustatic cycles between the highstand peaks of the last interglacial. Regressive and lowstand deposition of each subsequence represented by the seismic units 6, 7, and 8 took place after each high stand, i.e. 140–120, 105–100, and 70–80 ka (Fig. 5). Shelf-margin deposits of seismic unit 9 can be correlated with the beginning of the isotopic stage 3 (Fig. 5). For the last subsequence of the 5th-order cycle (II$_4$ subsequence), the regressive deposits (seismic unit 10) and the lowstand deposits (seismic unit 11) would be formed during the last interval of the sea-level regressive and lowstand stage (40–14 ka), the transgressive deposits (seismic unit 12) during the Flandrian transgression (14–6.5 ka), and the highstand deposits (seismic unit 13) from the Holocene higher sea level to the Present (6.5 ka to present) (Boy et al. 1989; Chiocci 1994; Hernández-Molina et al. 1994).

Depositional sequence I correlates with the time span of 220–140 ka, corresponding to a 4th-order of a Late Pleistocene eustatic cycle (Fig. 5). The depositional subsequences I$_1$ and I$_2$ would define the influence of the 5th-order eustatic cycles, very similar to the II$_3$ and II$_4$ subsequences. The regressive (seismic unit 3a), lowstand (unit 3b), transgressive (seismic unit 4), and highstand (seismic unit 5) deposits of subsequence I$_2$ would be formed during the eustatic hemicycle that gave rise to the maximum sea level corresponding to isotopic stage 5e (120–140 ka). Thus, subsequence I$_1$ should be correlated to the previous 5th-order eustatic cycle, probably related to a questioned relative sea-level highstand at 180–170 ka (T-1, isotopic stage 7) (Hillaire-Marcel et al. 1986).

Conclusions

The results and interpretations described above lead us to the following conclusions:

1. The 14 seismic units that make up the Late Pleistocene–Holocene continental margin are grouped into two major type-1 asymmetrical depositional sequences containing stacked minor depositional subsequences: (a) depositional sequence I, formed by two asymmetrical minor subsequences (I$_1$ of type-2 and I$_2$ of type-1); and (b) depositional sequence II comprising four minor depositional subsequences (II$_1$ of type-2, II$_2$ of type-I, II$_3$ of type-2, and II$_4$ of type-1).

2. The two major asymmetrical depositional sequences are related to asymmetric 4th-order eustatic cycles (100–120 ka), which determine the main trend of sea-level fluctuations during Late Pleistocene–Holocene times. The 4th-order depositional sequences are structured by minor asymmetrical depositional subsequences caused by 5th-order asymmetrical sea-level changes, which are superimposed on and punctuated the longer regressive trends of 4th-order cycles. The 5th-order depositional sequences are mainly composed of forced regressive wedge system tracts

and lowstand system tracts. They caused the main progradation of the margin, so they consequently build up the main margin structure. The transgressive system tract and highstand system tract deposits were not developed on the shelf during the 5th-order depositional sequences.

3. The application of sequence stratigraphic concepts to high-resolution seismic reflection profiles shows that the building up of the continental margin took place as a consequence of the modulation of different frequency eustatic cycles. In 5th-order depositional sequences, lowstand deposits are volumetrically predominant. They caused the main progradation of the margin in such a way that they form the margin structure almost entirely. In contrast, in 4th-order depositional sequences, highstand and transgressive deposits are well recorded.

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