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Quaternary stratigraphic stacking patterns on the continental shelves of the southern Iberian Peninsula: their relationship with global climate and palaeoceanographic changes

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Abstract

A Quaternary stratigraphic stacking pattern on the continental shelves of the southern Iberian Peninsula has been determined by analysing and comparing a dense network of low-, medium-, high- and very high-resolution mono-channel and multi-channel reflection seismic lines and well-log data. Four major low-resolution depositional sequences related to a 3rd-order cycle at 1.4–1.6 Ma have been recognised in the Pliocene–Quaternary sedimentary record (M/P1, P2, P3/Q-I and Q-II). They are separated by four discontinuities corresponding to the most drastic changes in climate and palaeoceanography affecting the Atlantic and Mediterranean linkage, and especially to the most prominent sea-level falls in the Messinian (M) at 5.5 Ma, in the Lower Pliocene at 4.2 Ma in the Upper Pliocene at 2.4 Ma and in the Mid-Pleistocene at 900–920 ka (MPR). These major sequences were built up by asymmetrical sea-level cycles. The regressive and lowstand system tracts are the best-developed deposits, controlling the main progradation of the shelf basinwards as well. The Quaternary shelf stratigraphy can be divided into asymmetric 3rd-order sequences of 800 ka (Q-I and Q-II), and into 4th-order asymmetric sequences of approximately 400 ka (Q1–Q4), 200 ka (A–H) and 100 ka. On low-, medium- and high-resolution seismics, the overall architectural stacking of the shelf shows a change after the MPR discontinuity, characterised by well-differentiated sequences of shelf-break wedges with progradational sigmoid configurations, assumed to be related to approximately 100 ka sea-level cycles. This change in the configuration of the shelf wedges during the Quaternary is attributed to the onset of the 100 ka eccentricity orbital cycles, which abruptly increased the amplitude of sea-level variations (100–120 m) during the last 900–920 ka. © 2002 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

Detailed studies of the Quaternary stratigraphy of continental shelves are frequently carried out using high-resolution, low-penetration seismic reflection profiles and short cores, which make it possible to analyse sedimentary facies and date them accurately. These studies have led to important advances in our knowledge about the influence of sea level and climate on stratigraphic changes, especially during the Late Pleistocene–Holocene, since this methodology cannot provide information about older sediments. A global Quaternary continental shelf chronostratigraphy has, therefore, yet to be defined. The reasons for this include methodological limitations, a loss in the resolution of the stratigraphic record before the Late Pleistocene, and a focus until now on the interpretation of the pre-Quaternary sedimentary record of slope and deep-basin realms. In order to increase our data on the Quaternary stratigraphic record of continental shelves, it seems necessary to use a broader method, operating at different temporal scales. In the present paper, we have analysed the Quaternary stratigraphic stacking pattern of the shelves off the southern Iberian Peninsula (Fig. 1), focusing on the following points: (1) the relationship between Quaternary stratigraphy and the oxygen-isotope stratigraphy and major eustatic events; (2) a stratigraphic characterisation of the Quaternary boundary (QB); (3) the timing and mechanism of the morphological development of the continental shelves;

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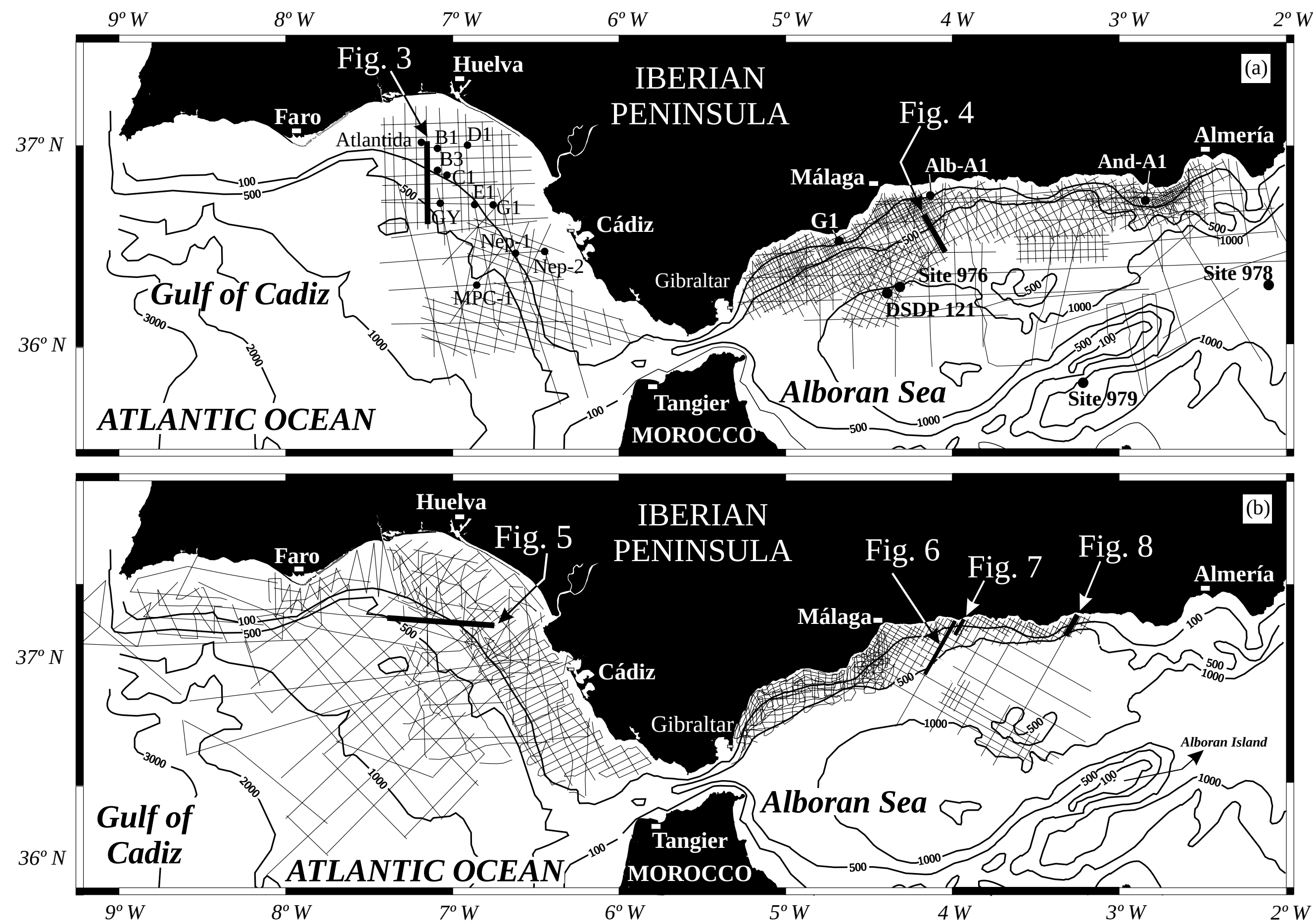


Fig. 1. General sketch of the Iberian continental shelves of the Gulf of Cadiz and the Alboran Sea. (a) MCS profile network. Location of the cores is given. (b) Middle-, high- and very high-resolution seismic profile network. Depth in metres.

and (4) the role played by climatic/eustatic variations controlling the structuring of the shelves.

The Pliocene–Quaternary chronostratigraphy has been closely linked to the oxygen-isotope stratigraphy, which provides approximate ages for the interglacial/glacial stages, and has been used as an approximate estimator of eustatic changes (Martison et al., 1987; Shackleton, 1987; Thunell et al., 1991; Zazo, 1999). During the last 5 Ma, there have been significant changes in global climatic systems and palaeoceanographic and sea-level conditions (Thunell et al., 1991; Droxler et al., 1999). In our latitudes (36–37°N), marine isotope stages (MIS) and continental data record a climatic trend, from relatively warm global climates during the early Pliocene to the generally cooler climates during the Pliocene–Pleistocene (Thunell et al., 1991; Poore and Sloan, 1996). The Lower Pliocene (5–3.5 Ma) was dominated by warm subtropical–tropical climates, and the variability in global climatic systems was apparently controlled by high-amplitude precessional climatic fluctuations of about 20 ka, modulated by low-frequency eccentricity cycles of about 400 ka (Thunell et al., 1991; Clemens and Tiedemann, 1997). In terms of sea-level changes, at the end of the Messinian (Latest Miocene), a marked fall in sea level took place at 5.5 Ma. During the Lower Pliocene the sea level rose until 4.2 Ma, when another global sea-level fall occurred, started a new eustatic rise (Haq et al., 1987; Alonso and Maldonado, 1992). Later, a drastic change in global climatic systems occurred during the Late Pliocene, from 3.5 to 1.6 Ma, related to the onset of the periodic growth and decay of large continental ice sheets in the Northern Hemisphere. The cooling associated with this climatic change began at 3 Ma (Shackleton and Opdyke, 1977; Keigwin, 1986), but more dramatic global cooling took place later at 2.4 Ma (Shackleton et al., 1984; Raymo et al., 1989). This profound change in the global climate had a major impact on the local climatic, sea-level and hydrodynamic conditions of the Mediterranean region, triggering a major drop in sea level (Lowrie, 1986; Haq et al., 1987).

The Pliocene/QB was established by the International Commission on Stratigraphy (ICS) and the International Geological Congress (IGC), first at 1.6 Ma in

1948 and later at 1.8 Ma in 1984; however, the estimated dating of this boundary remains controversial (Morrison and Kukla, 1998). The QB is not sufficiently well marked by globally recognisable stratigraphic criteria to become a practical worldwide boundary. Many geologists consider the QB to be determined by the first major continental glaciation in the Northern Hemisphere (Beard et al., 1982), although this event occurred at 2.4 Ma. As a result, the INQUA resolved, in 1995, to fix the QB at between 2.4 and 2.5 Ma (MIS 100/101) as a true global climato-stratigraphic boundary (Morrison and Kukla, 1998).

The Quaternary has been characterised by highly significant climatic changes. Glacial/interglacial variations during the last 2.4 Ma, until 900/920 ka (Upper Pliocene–Mid-Pleistocene), were dominated by 41 ka obliquity cycles, but 100 ka eccentricity cycles became dominant during the Brunhes chron after 900/920 ka (MIS 22/23). This important change in the climatic trend within the Quaternary in known as the 'Mid-Pleistocene Revolution' (MPR) (Shackleton and Opdyke, 1973; Shackleton et al., 1990; Berger and Wefer, 1992; Berger et al., 1994; Howard, 1997; Mudelsee and Stattegger, 1997; Paillard, 1998; Loutre and Berger, 1999). Coinciding with this change to longer glacial/ interglacial cycles, an increase in the amplitude of these cycles has also been determined, with this intensification of glacial episodes marking the beginning of the so-called 'Glacial Pleistocene' (Thunell et al., 1991). In addition, a major sea-level drop has also been recorded during the MPR (Lowrie, 1986; Haq et al., 1987). From the MPR to the present, climatic and glacio-eustatic fluctuations have been determined mainly by cycles of approximately 100 and 20 ka. Obliquity cycles of approximately 40 ka seem to have played a minor role during this interval. Thus, before the MPR, sea-level fluctuations had smaller amplitudes (around 50 m) and a lower frequency, but after the MPR, sea-level fluctuations ranged up to 120–150 m (Lowrie, 1986) and were also characterised by marked asymmetry (Hernández-Molina et al., 2000). This global change in the climate trend during the Mid-Pleistocene has been reported in the Mediterranean region by Pierre et al. (1999) and Grafenstein et al. (1999). After the MPR, the period of 420–360 ka (MIS 11/12) underwent the most severe cooling and warming conditions of the last half-million years. MIS 11 was the longest and warmest interglacial interval, and the sea-level highstand was about +20 m above the present (Howard, 1997; Hearty et al., 1999). During the interglacial MIS 9 and MIS substage 5e, sea level was similar to the present (MIS 1), but during the interglacials MIS 19, 15, 13 and 7, the sea level did not reach its present position (Zazo, 1999).

The climatic, sea-level and stratigraphic changes throughout the Late Pleistocene–Holocene are well known (Shackleton and Opdyke, 1973; Shackleton, 1987). Climatic changes were controlled by the last 100 ka cycle, but were modulated by the 22–23 ka precession cycles (MIS substages, 5d to 2). In addition, during the last 80 ka of this period, very high-frequency climate and sea-level changes related to the Heinrich events (10–15 ka), *P* cycles (4.5 ka). Dansgaard–Oeschger oscillations, and *h* pulses (2300–970 yr) and *c* cycles (700–500 yr) appear to have been important, as inferred by their deep-sea-core signatures (Heinrich, 1988; Bond et al., 1993; Dansgaard et al., 1993; Bond and Lotti, 1995; Mayewski et al., 1996). These cycles are also recognised by the sedimentary cyclicity in shelf, deltaic and coastal deposits during the Late Pleistocene and Holocene (e.g. Fairbridge, 1987, 1997; Swift et al., 1991; Hernández-Molina et al., 1994, 1996, 2000; Zazo et al., 1994, 1996; Lowrie and Hamiter, 1995; Somoza et al., 1997, 1998).

2. Geological framework and oceanographic setting

The present study was carried out on the Iberian continental shelves of the Gulf of Cadiz and the Alboran Sea, bounded to the north by the Iberian Peninsula and to the south by Africa and connected through the Straits of Gibraltar (Fig. 1). These two areas display different physiographic and sedimentary signatures. The Gulf of Cadiz has a wide, smooth shelf and slope and a high sediment supply. In contrast, the northern shelf of the Alboran Sea is very narrow with a low sediment supply, but has a very steep shelf and slope gradient.

2.1. Geological framework

The Gulf of Cadiz, located in the eastern sector of the central North Atlantic, is concave in shape, with a NW–SE orientation (Roberts, 1970; Malod, 1982). The physiographic profile of the margin includes a wide shelf (30–40 km) with a sea-floor slope of 0.2–0.32°, a shelf-break located at a water depth of between 140 and 120 m, and a smooth continental slope, with sea-floor gradients of 1.5° in the upper part and 0.5–1° in the middle and lower parts (Baraza et al., 1999). On the eastern side of the Straits of Gibraltar lies the Alboran Sea basin, at the western edge of the Mediterranean Sea (Fig. 1). It is arc-shaped, and characterised generally by a complex physiography related to its tectonic history. The Spanish margin has a very narrow, steep shelf (5–10 km) up to the shelf-break at 110–120 m water depth, which establishes the boundary, with a shelf gradient of 0.5–0.7° and a slope of 2.3° (Ercilla et al., 1992; Hernández-Molina, 1993; Hernández-Molina et al., 1994).

The study area is located in the transitional zone between the Gloria transform zone, which is the African–Eurasian plate boundary in the Atlantic realm, and the westernmost part of the Alpine–Mediterranean orogenic belt, represented by the Gibraltar Arc, the western front of the Betic-Rif collisional orogen (Fig. 1). Kinematic studies of the African and Eurasian plates (Dewey et al., 1989; Olivet, 1996) show that the area was situated in a north to south convergence setting from the Late Cretaceous to the Late Miocene (Tortonian). From the Late Miocene to the present, the convergence between Africa and Eurasia changed to a transpressive northwest–southeast regime (Argus et al., 1989). The evolution of the Gulf of Cadiz is marked by three successive phases (Maldonado et al., 1999): (1) the development of a passive margin of Mesozoic age, related to the opening of the North Atlantic; (2) the occurrence of a compressional regime during the Late Eocene to Early Miocene, related to the closure of the Tethys Alpine Sea; and (3) the Miocene foredeep evolution, associated with the formation of the Betic-Rif orogen and the opening of the Western Mediterranean basin. This stage was characterised by the collision of the Betic-Rif accretionary front with the passive margins of the Iberian Peninsula and Africa, which involved the emplacement of a large olistostromic body on the Gulf of Cadiz margin during the Middle Miocene. Since the Late Tortonian, the onset of oblique convergence caused the gravitational acceleration of the dismantling of the collisional front, resolved by an extensional collapse and the progressive emplacement of the olistostromic body in the eastern Gulf of Cadiz (Maldonado et al., 1999). At the end of the Lower Pliocene, subsidence decreased, and the margin evolved to more stable conditions during the Upper Pliocene and Quaternary (Maldonado et al., 1999).

The Alboran Sea basin originated during the Miocene, due to two successive episodes of rifting (Comas et al., 1992). Its formation and later evolution are closely related to the development of the Betic-Rif orogen and to the oceanic spreading of the Western Mediterranean basin. The structures affecting the Upper Miocene to Quaternary units have been interpreted as oblique strike-slip faults (Woodside and Maldonado, 1992). Very recent studies reveal a significant change in the subsidence pattern trend at 2.5 Ma (Late Pliocene), from uplifting to rapid subsidence due to a contractive reorganisation of the basin. However, at 1.7 Ma the margin probably became more stable, remaining so during the Quaternary (Comas et al., 1999; Rodriguez-Fernandez et al., 1999). The Neogene–Quaternary infilling of the Alboran Sea basin was deposited over a faulted basement called the Alboran Domain (Comas et al., 1999).

There are a number of studies in the literature focusing on Pliocene–Quaternary sedimentary architecture in the Gulf of Cadiz (Mougenot, 1988; Nelson et al., 1993; Riaza and Martinez del Olmo, 1996; Maldonado et al., 1999) and in the Alboran Sea (Alonso and Maldonado, 1992; Campillo et al., 1992; Ercilla et al., 1992; Jurado and Comas, 1992; Estrada et al., 1997; Comas et al., 1992, 1999; Alonso et al., 1999). The Late Pleistocene–Holocene stratigraphy has been characterised by different authors (Hernández-Molina et al., 1994, 1996, 2000; Somoza et al., 1997; Lobo et al., 1999; Rodero et al., 1999). The Pliocene to Pleistocene in the Gulf of Cadiz is characterised by progradation of a siliciclastic coastal wedge from the fluvial systems that developed in the ancient Guadalquivir foreland basin and, simultaneously, by progradation of a mid-slope contourite drift from the Guadalquivir margin to the Algarve margin due to the influence of Mediterranean outflow water (MOW). In the Alboran Sea, the Pliocene–Pleistocene is marked by (a) the opening of the Straits of Gibraltar during the Messinian, (b) the tilting of continental margins to the inner part of the basin, (c) the subsiding pulse in the Upper Pliocene and (d) the amplification of sea-level fluctuations through the Straits. In both areas, the Lower Pliocene sedimentary record reveals major aggradational depositional units, which are mainly composed of deep-marine hemipelagic and pelagic clays. The Late Pliocene sedimentary record is represented by a seismic unit with parallel and discontinuous reflectors related to a falling sea-level, characterised by sands with a suite of erosional events, high-energy channelised turbidites, bottom currents, debris flows and hemipelagic settling processes recorded in the Alboran Sea, and sand and clay contourites and hemipelagic clays in the Gulf of Cadiz. During the Quaternary, the sedimentary sequences were controlled by fluctuating sea level, and formation of shelf-margin deltas and slope wedges took place during regressive and lowstand intervals (Somoza et al., 1997; Rodero et al., 1999; Hernández-Molina et al., 2000).

2.2. Oceanographic setting

Circulation patterns of the present-day Gulf of Cadiz and Alboran Sea are characterised by very strong oceanographic dynamics controlled by the exchange of water masses through the Straits of Gibraltar (Fig. 2). This exchange is determined by the MOW near the bottom and Atlantic inflow (AI) water at the surface. MOW is typified by highly saline and warm waters, whereas AI is a turbulent, less saline cool-water mass. The Straits of Gibraltar have controlled the water masses dynamics over time, modulating the horizontal water changes and amplifying Quaternary high-frequency sea-level changes.

MOW comprises of two different water masses that join in the Straits of Gibraltar (Fig. 2): Mediterranean intermediate water (MIW) and Mediterranean deep water (MDW). MIW travels from the Western Mediterranean basin towards the Straits of Gibraltar through the Alboran Sea, and from its bifurcation near Alboran

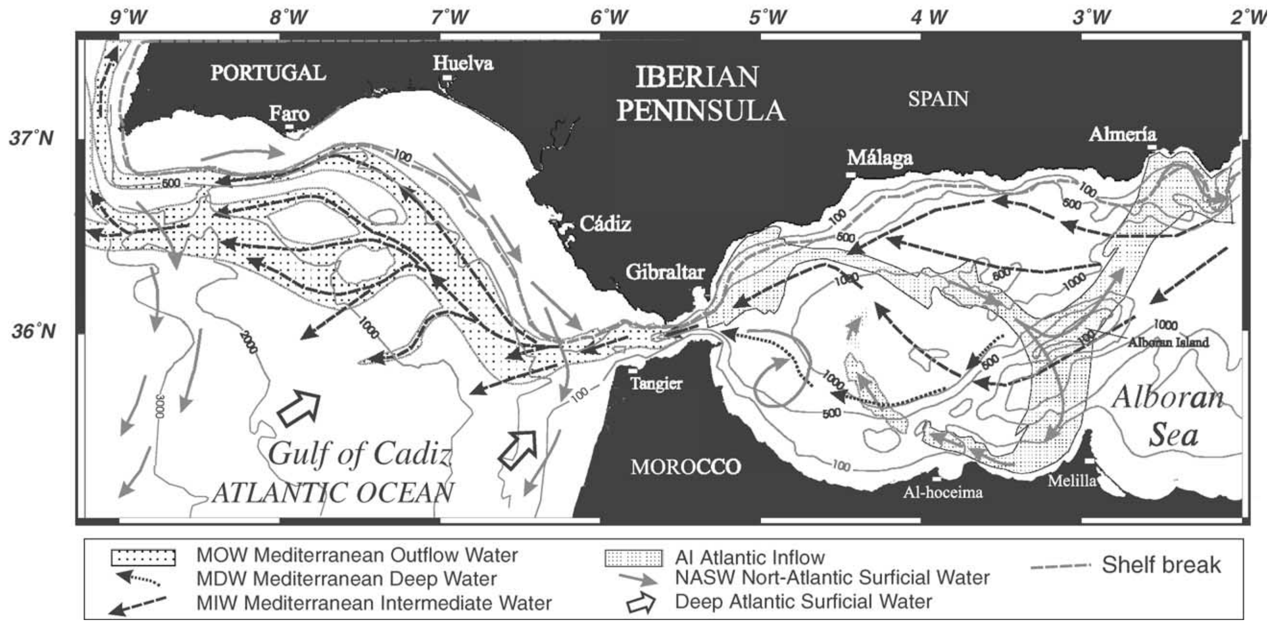


Fig. 2. General circulation patterns of water masses in the Gulf of Cadiz and the Alboran Sea (modified from Hernández-Molina, 1993). Depth in metres.

Island it flows around the base of the Spanish continental margin with a variable velocity of about 5–10 cm/s. MDW moves with a velocity of about 2 cm/s around the base of the African slope before coming up towards the sill of the Straits of Gibraltar (Wüst, 1961; Lacombe and Tchernia, 1972; Millot, 1987; Parrilla and Kinder, 1987; Perkins et al., 1990). MOW goes through the Straits of Gibraltar at a water depth of 200 m below AI, with a peak velocity of approximately 200 cm/s. After passing through the Straits of Gibraltar, MOW turns northwards in the Gulf of Cadiz, constituting a strong contour current moving at a water depth of 300–1500 m around the Spanish slope (Fig. 2), where it divides into several branches lower down due to the influence of several deep submarine canyons and valleys (Madelain, 1970; Caralp, 1988; Ochoa and Bray, 1990; Nelson et al., 1993, 1999; Beringer and Price, 1999). The interaction of MOW with the slope generates a series of contouritic sedimentary bodies and channels controlled by the westward and northward decrease in velocity (Gonthier et al., 1984; Nelson et al., 1993, 1999). In the Gulf of Cadiz (Fig. 2), Atlantic surficial water (ASW), at a depth 0–100 m, and North Atlantic surficial water (NASW), at 100–700 m, move towards the SE and control present-day sedimentary dynamics (Gascard and Richez, 1984; Caralp, 1988, 1992; Ochoa and Bray, 1990). The water masses that constitute AI enter the Alboran Sea through the Straits of Gibraltar, over MOW, with variable thickness and a velocity sometimes surpassing 1 m/s (Lacombe and Richez, 1982; Parrilla and Kinder, 1987; Garrett et al., 1990). After its entrance into the Alboran Sea, the AI constitutes a 'jet' that is deflected towards the NE, forming an anticyclonic gyre in the western Alboran Sea. This gyre moves along the Spanish margin and interacts with the sea bottom of the shelf and slope (Lanoix, 1974; Cheney and Doblar, 1982; Bucca and Kinder, 1984; Cano and García, 1991). In addition, ASW generates another anticyclonic gyre in the eastern Alboran Sea (Millot, 1987; Herburn and La Violette, 1990; Perkins et al., 1990).

This general circulation pattern started to develop after the opening of the Straits of Gibraltar during the Messinian (Nelson et al., 1993). During the Lower Pliocene, an estuarine-type water-mass exchange developed between the Atlantic and Mediterranean (inflow of Atlantic intermediate water and outflow of Mediterranean surface water), indicating a positive water balance, and therefore much more humid conditions in the Mediterranean region that at present (Thunell et al., 1991). The global cooling at 2.4 Ma triggered a shift to more arid conditions in the Mediterranean region, resulting in the establishment of a negative water balance, and, consequently, of an anti-estuarine water-mass exchange between the Mediterranean and the Atlantic similar to the present-day situation (Loubere, 1987; Thunell et al., 1991). Since 2.4 Ma, the water-mass exchange has undergone significant variations in relation to climatic and sea-level changes (Huang and Stanley, 1972; Diester-Hass, 1973; Grousset et al., 1988; Vergnaud-Grazzini et al., 1989; Caralp, 1988, 1992; Nelson et al., 1993).

3. Methodology

3.1. Database

In the present study, we have used a broad database comprising (Fig. 1a and b): (1) bathymetric and geomorphological data; (2) seismic data; and (3) core data from oil companies, DSDP 121, and from ODP Leg 161. The continental shelves of the southern Iberian Peninsula have been explored by oil companies, thus providing a dense network of multi-channel seismic (MCS) profiles in the Gulf of Cadiz (Delaplanche et al., 1982; Martínez del Olmo et al., 1984; Riaza and Martínez del Olmo, 1996) and in the Alboran Sea (Comas et al., 1992, 1999; Vázquez et al., 1995; Vegas et al., 1997). We used low-resolution MCS profiles form oil companies (at 4–6 s two way travel time (TWTT) record length) for the study of the Pliocene–quaternary sedimentary record (Fig. 1a). Since 1989, medium-, high- and very high-resolution seismic profiles have been obtained during several cruises supported by Spanish research council projects (Fig. 1b). The medium-resolution seismic profiles of Sparker (3000, 4000 and 7500 J) and Airgun recordings at 2, 1 and 0.5 s TWTT have been used for the study of the Pleistocene sedimentary record. High-resolution seismic lines employing Geopulse (300 J) and Uniboom sources recording up to 250 ms TWTT, and very high-resolution seismic profiles using a 3.5 kHz mud penetrator source up to 100 ms TWTT, have been used for the study of the Late Pleistocene–Holocene record (Fig. 1b).

The correlation of 8 well-logs drilled on the shelf of the Gulf of Cadiz (Maldonado et al., 1999) and 9 well-logs obtained on the slope and shelf of the Alboran Sea (Comas et al., 1999; Zahn et al., 1999) with MCS, Airgun and Sparker seismic lines have made it possible to establish the thickness, lithology, sedimentary facies, and age of the seismo-depositional units.

3.2. Interpretation

The seismic data were interpreted in four steps: (1) seismic units on the shelf and upper slope were identified by studying seismic facies; (2) sequence stratigraphic analysis was conducted; (3) a detailed correlation between seismic profiles and cores enabled us to identify the following stratigraphic boundaries: the Messinian discontinuity, the Lower and Upper Pliocene, the Pliocene–Pleistocene, and the Lower and Middle Pleistocene; and (4) the correlation between seismic units and discontinuity ages and the Pliocene–Quaternary isotopic stratigraphy, by considering relative sea level and regional palaeoceanographic changes.

In order to clarify the terminology we have used in the present paper related to the depositional sequences (DS), it is important to keep in mind that Pliocene–Quaternary stratigraphic analysis has been carried out by determining DS at different scales. Table 1 is important to clarify the terms and scales of the DS. During the MCS surveys, two types of low-resolution depositional sequences (LDS) were determined: *major LDS* and *minor LDS*. In the medium-resolution seismic profiles, three types of medium-resolution depositional sequences (MDS) have been recognised: *major MDS*, *middle MDS* and *minor MDS*. Moreover, the high-resolution and very high-resolution seismic profiles characteristically have high- and very high-resolution depositional sequences. In the sequence stratigraphic analysis, we consider the lowstand system tracts (LST), the transgressive system tract (TST) and the highstand system tract (HST), but we have also incorporated the regressive system tract (RST), because it is particularly relevant in the Quaternary record (Hernández-Molina et al., 2000). The RST + LST and TST + HST are considered jointly in our analysis, since the boundary between them is difficult to establish. We interpreted the RST + LST as a reflective progradational sedimentary body with a sigmoidal-to-oblique internal configuration and an external wedge shape. The TST + HST is interpreted as an aggradational sedimentary body with parallel and weak internal configuration with laminar or lensoidal external shapes.

4. Seismic stratigraphy analysis

Stratigraphic structuring has been recognised by means of seismic analysis of MCS, medium- and high-resolution seismic profiles (Table 1).

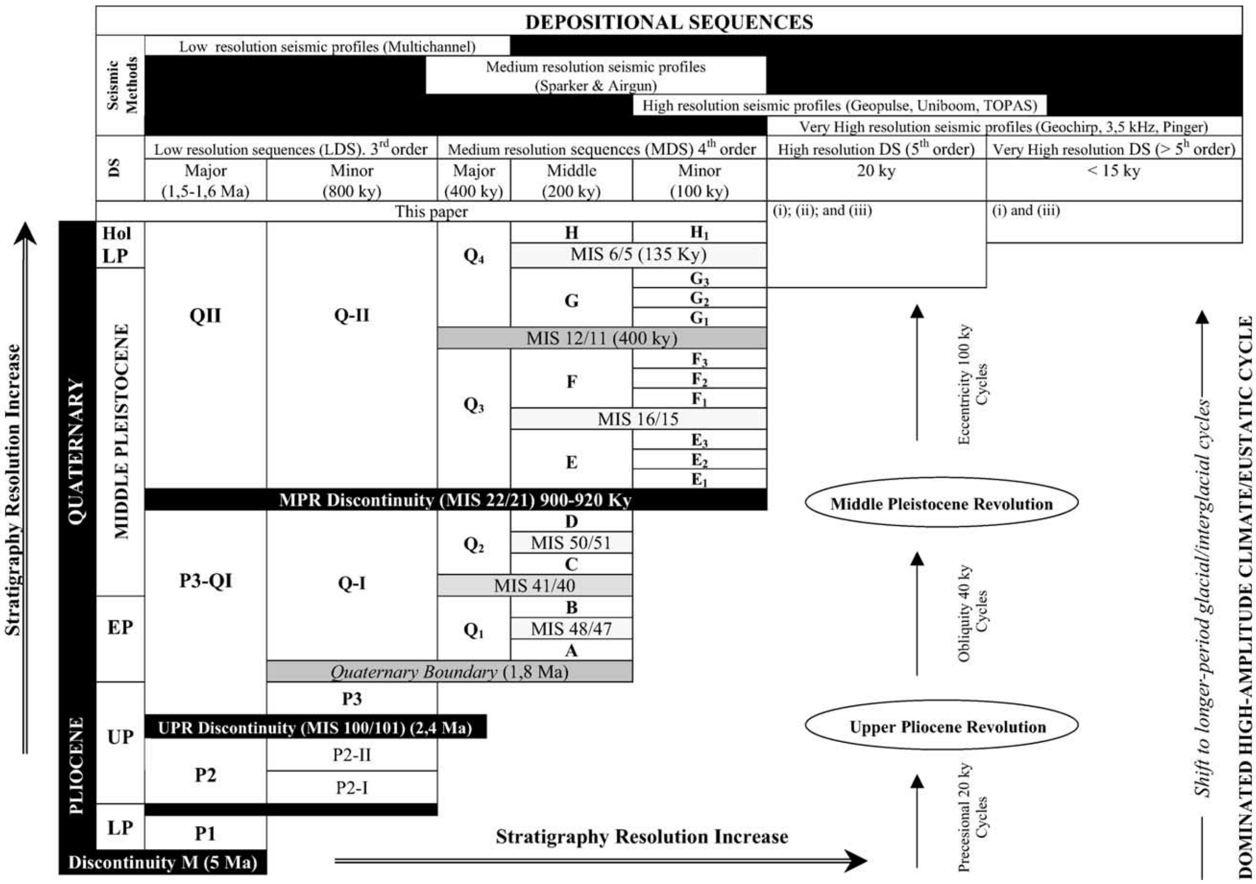
4.1. Pliocene–Quaternary LDS

4.1.1. Major low-resolution depositional sequences

Four major LDS have been recognised in the Pliocene–Quaternary sedimentary record through the analysis of MCS profiles: M/P1, P2, P3/Q-I and Q-II (Table 1; Figs. 3–5). They are bounded by four notable discontinuities related to the most relevant sea-level falls: the Late Messinian discontinuity (M), Lower Pliocene discontinuity (LPR) the Upper Pliocene regional discontinuity (UPR) and the Mid-Pleistocene regional discontinuity (MPR). Each of these major LDS comprises two pairs of deposits: the TST + HST and the RST + LST. All of these major LDS are asymmetrical, because the RST + LST represent approximately 60% of the thickness of each sequence. LDS P3/Q-I and Q-II show greater stratigraphic resolution in the MCS lines (Figs. 6–8).

Seismic and core correlation determined an estimated Late Messinian to Lower Pliocene age for the major LDS M/P1 bounded by the LPR at its top, and the upper Lower Pliocene and Upper Pliocene for the major

Table 1
Chronostratigraphy of the different orders of DS for the Pliocene, and especially for the Quaternary: (i) Hernández-Molina et al., 1994; (ii) Somoza et al., 1997; (iii) Hernández-Molina et al., 2000



LDS P2 (Figs. 3–5). The upper boundary of the major LDS P2 is UPR, which is the most prominent discontinuity after M. It is a high-amplitude erosional regional discontinuity throughout the shelf, slope and basin domains in the Gulf of Cadiz and Alboran Sea (Table 1). The major LDS P3/Q-I correlates with the Late Pliocene (P3) and the Pleistocene (Q-I). The upper boundary of this major LDS is another high-amplitude regional discontinuity previously defined as the MPR by Hernández-Molina et al. (1998). This stratigraphic surface is the most evident regional discontinuity in the Quaternary record on the continental margins and basins of the Gulf of Cadiz and Alboran Sea. It has been recognised by MCS and medium-resolution seismics. The major LDS Q-II correlates with the Mid-Pleistocene–Holocene, and the upper boundary is the present-day sea bottom (Table 1; Figs. 3–5).

The major LDS conditioned the build-up of the continental margins. The first evidence of the existence of a physiographic profile similar to the present-day shelf profile lies within the M/P1 (Fig. 3), conditioned by the development of RST + LST during the Lower Pliocene. However, the stacking patterns of the major LDS are slightly different in each area. These sequences in the Gulf of Cadiz determined the build-up of the shelf and upper slope and show an aggradational stacking pattern for the Lower Pliocene, but a distinctive progradational stacking pattern from the Late Pliocene to the present (P2, P3/Q-I and Q-II). The thickness of each LDS is about 500–550 ms, and the thickness of each pair of deposits is also relatively homogeneous. The TST + HST ensembles inside each LDS are approximately 230–250 ms thick, and the RST + LST are about 300–350 ms. However, the RST + LST of the last major LDS (Q-II) is incomplete, and it is thinner than the previous one, approximately 250 ms (Fig. 3).

The major LDS in the Alboran Sea conditioned the build-up of the upper and middle slope, and they are arranged in a slightly different stacking pattern (Figs. 4 and 5). M/P1, P2, and the lower part of P3/Q-I (Pliocene to Lower Pleistocene) show an aggradational stacking pattern, but the upper parts of P3/Q-I and Q-II (Lower Pleistocene to present) show an progradational stacking

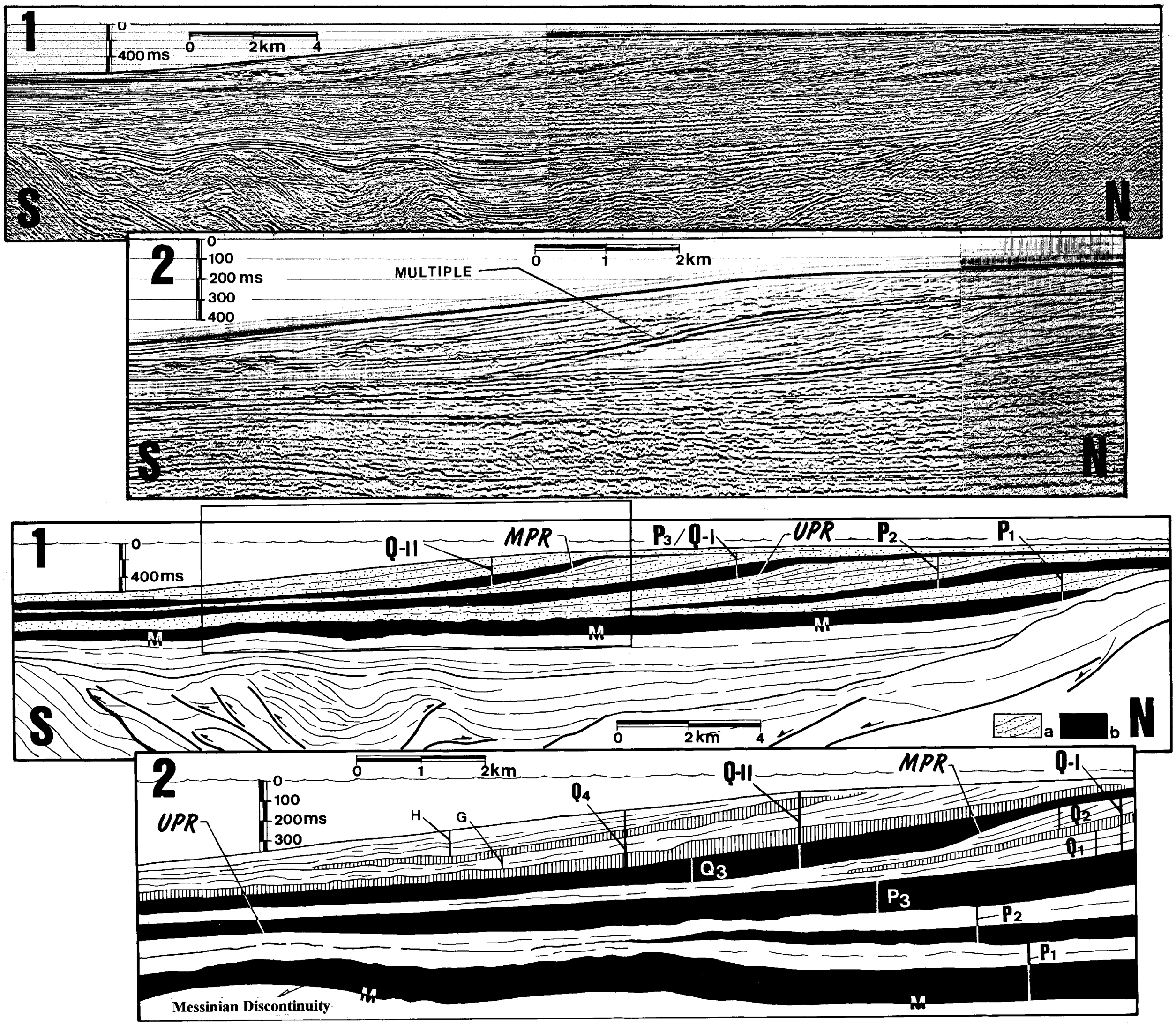


Fig. 3. Uninterpreted and interpreted medium-resolution seismic profile of low resolution (Multi-channel at 4 s TWTT record length) on two different scales of the Gulf of Cadiz shelf. Note the stratigraphic position of the UPR and MPR discontinuities and the major LDS (M/P1, P2, P3/Q-I and Q-II) stacking pattern. Aggradational unit between B–C, F–G and G–H is noted. (a)RST + LST, and (b)TST + HST. M = Messinian discontinuity. See Fig. 1a for location.

pattern. The thickness of each LDS is approximately 250–300 ms, and the thickness of each deposit is relatively homogeneous. The TST + HST is around 50–70 ms, and the RST + LST is around 200–240 ms. However, the RST + LST of the last major LDS is around 170 ms thick (Fig. 4).

4.1.2. Minor low-resolution depositional sequences

Five minor LDS have been determined in the MCS profiles: P2-I, P2-II, P3, Q-I and Q-II (Table 1). In the Alboran Sea, the LDS P2 comprises two minor LDS, P2-I and P2-II, but these sequences were not discerned in the Gulf of Cadiz.

The major LDS P3/Q-I comprises two minor LDS, P3 (upper part of the Late Pliocene) and Q-I (Early and Mid-Pleistocene). The boundary between these top LDS represents a downlap surface but not an erosional, high-amplitude regional discontinuity, such as the UPR or MPR discontinuities (Figs. 6–8). In the Gulf of Cadiz, the thickness of P3 and Q-I are approximately 230 and 300–400 ms, respectively. In the Alboran Sea, P3 and Q-I are approximately 100 and 250 ms thick, respectively.

4.2. Medium-resolution depositional sequences

4.2.1. Major medium-resolution depositional sequences

The Quaternary shelf stratigraphy was resolved using low- and medium-resolution seismics. It is characterised by four major MDS, termed Q1–Q4 (Table 1; Figs. 5–7). The major MDS Q2 is separated from the major MDS Q3 by the MPR discontinuity.

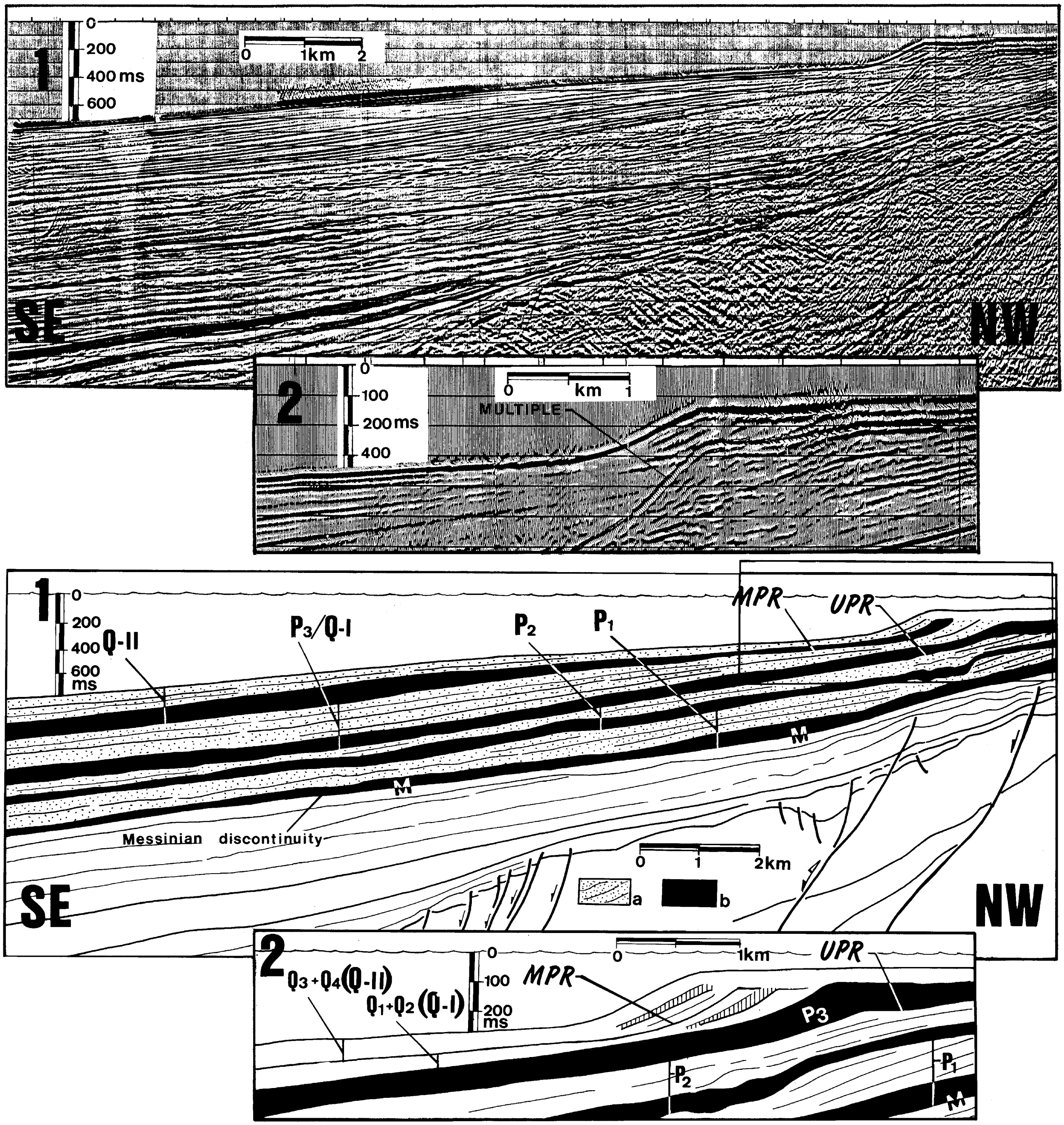


Fig. 4. Uninterpreted and interpreted low-resolution seismic profile (Multi-channel at 5 s TWTT record length) on two different scales of the Alboran Sea shelf. Note the stratigraphic position of the UPR and MPR discontinuities and the major LDS (M/P1, P2, P3/Q-I and Q-II) stacking pattern. (a) RST + LST, and (b) TST + HST. M = Messinian discontinuity. See Fig. 1a for location.

Each of these major MDS comprises two pairs of deposits: a TST + HST and a RST + LST. All of these sequences are more clearly asymmetrical than the LDS, since the RST + LST represents approximately 65–80% of the thickness of each sequence.

The major DS Q1, Q2, and Q4 show a progradational stacking pattern seawards, but Q3 has an aggradational stacking pattern. Therefore, Q2 progrades seawards away from Q1, and Q4 progrades seawards with respect to Q3 (Figs. 5–7). The thickness of each major MDS is approximately 150–170 ms in the Gulf of Cadiz, and the TST + HST within each sequence is approximately 60–70 ms, while the RST + LST is 100–150 ms. In the Alboran Sea, the thickness of each major MDS is about 120–130 ms, but the thickness of each pair of deposits is relatively homogeneous: the TST + HST is approximately 40 ms and the RST + LST is 70–100 ms.

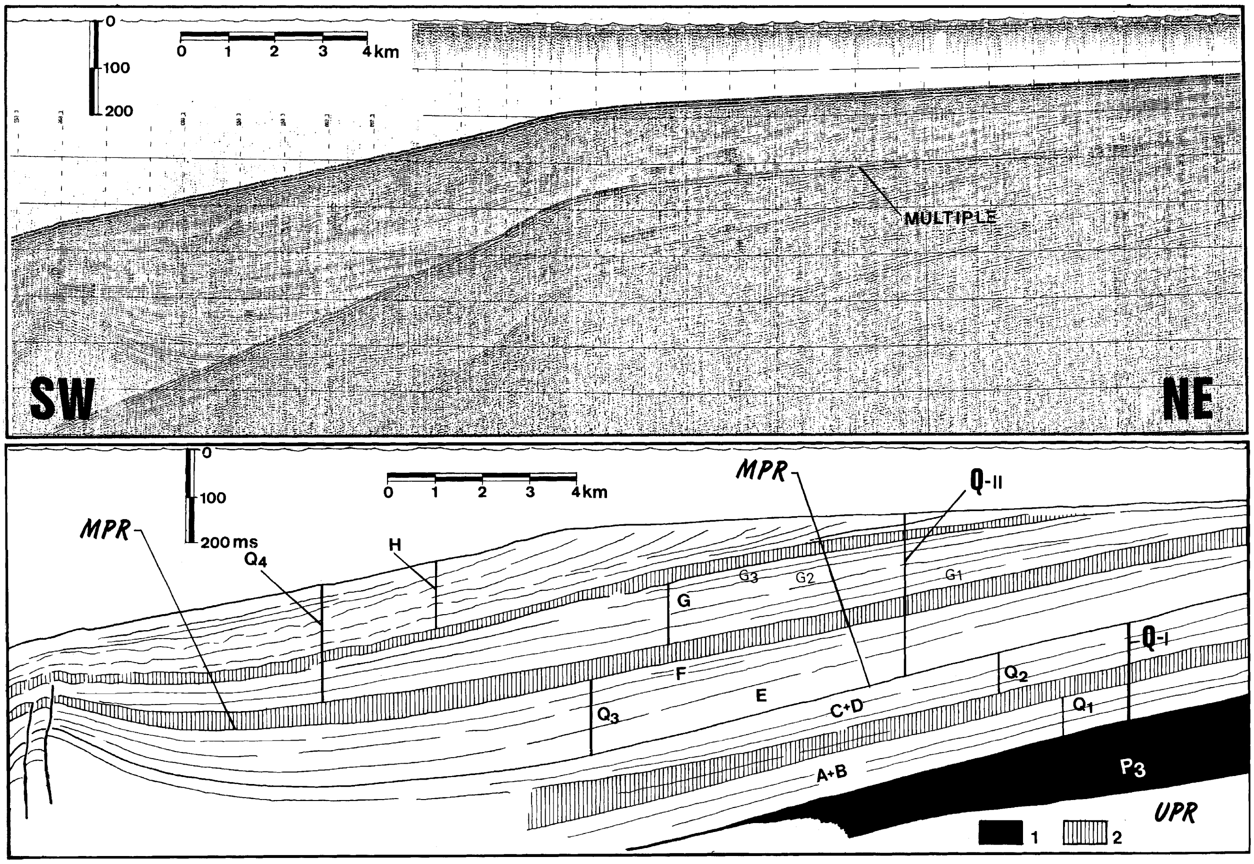


Fig. 5. Uninterpreted and interpreted medium-resolution seismic profile (Sparker, 4000 J.) of the Gulf of Cadiz shelf. Seismic units are differentiated. Note the stratigraphic position of the UPR and MPR discontinuities and the Quaternary stratigraphic stacking pattern. (1) 3rd-order aggradational unit; (2) 4th-order aggradational units. Aggradational unit between F–G and G–H is indicated. M = Messinian discontinuity. See Fig. 1b for location.

4.2.2. Middle medium-resolution depositional sequences

Medium-resolution seismics suggest that Q1 and Q2 are composed of four middle MDS (A–D), and that Q3 and Q4 comprise another four (E–H) (Table 1). The stacking pattern of the middle MDS is quite different before and after reflector MPR (Table 1; Figs. 6 and 7). Therefore, each middle MDS (A–D) consists of very thin sequences, whose internal structure is not evident. In the Gulf of Cadiz, the thickness of every middle MDS is approximately 25–30 ms for A, 25 m for B, 30–35 ms for C, and 50–60 ms for D. In the Alboran Sea, the thickness of the middle MDS is about 20 ms for A, 20 ms for B, 15–20 ms for C, and 20 ms for D. In both the Gulf of Cadiz and the Alboran Sea, a well-developed aggradational unit is determined between B and C (Figs. 5–7).

The stratigraphic architecture of the middle MDS after the MPR (E–H) controlled the build-up of the shelf and upper slope (Table 1; Figs. 6 and 7), which have the best resolution of the sedimentary record. The stratigraphic resolution increases from E to the most modern one, H, with G and H having the best resolution (Figs. 5–7). The sequences E–H are asymmetric, because they are mainly composed of a succession of RST + LST, which dominate the shelf margin (Table 1). They are thicker than the sequences before the MPR. In the Gulf of Cadiz, the thickness of every middle MDS is approximately 100 ms for E, 70–80 ms for F, 150 ms for G, and 130–150 ms for H, with two well-developed aggradational units between F–G and G–H. In the Alboran Sea, the thickness of each middle MDS is approximately 50–80 ms for E, 35–80 ms for F, 50 ms for G, and 45–100 ms for H. It has only been possible to determine the aggradational unit between G and H (Figs. 5–7).

4.2.3. Minor medium-resolution depositional sequences

The middle MDS after the MPR are internally composed of 10 asymmetrical DS that repeat and amplify considerably. Every middle MDS E, F, G consists of three minor MDS (E1–E3; F1–F3; G1–G3), and H comprises only one minor MDS (H1). A higher-resolution study of each sequence is impossible due to the poor stratigraphic resolution of the middle seismic profiles, but each of these minor MDS are asymmetric and mainly comprise RST + LST, which represent shelf-margin deltas and slope wedges (Table 1; Figs. 5–7).

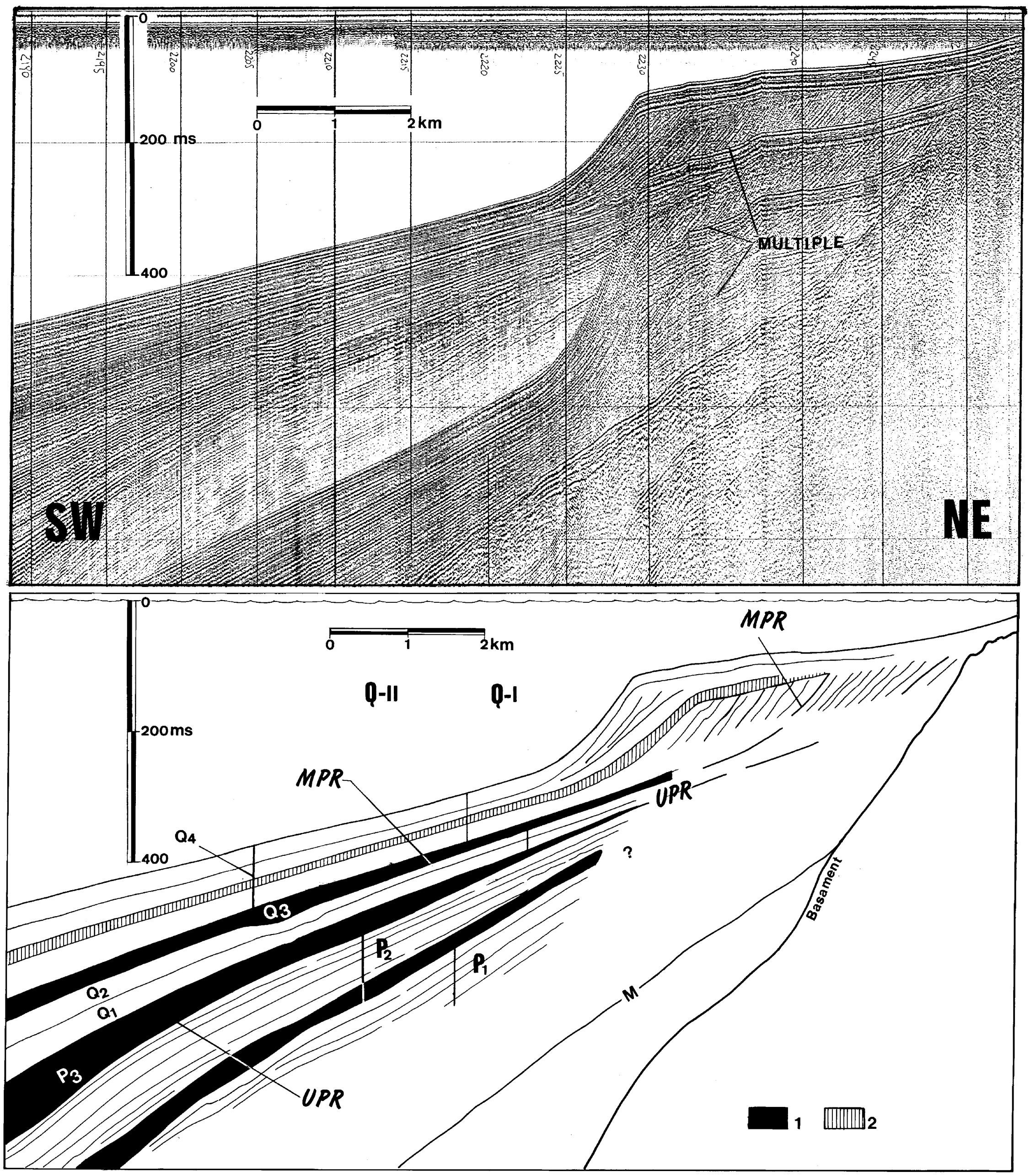


Fig. 6. Uninterpreted and interpreted medium-resolution seismic profile (Sparker, 7500 J.) of the Alboran Sea shelf. Seismic units are differentiated. Note the stratigraphic position of the UPR and MPR discontinuities and the Quaternary stratigraphic stacking pattern. (1) 3rd-order aggradational unit; (2) 4th-order aggradational units. See Fig. 1b for location.

4.3. High- and very high-resolution depositional sequences

The last minor MDS (H1) presents the highest stratigraphic resolution in the medium-resolution seismics. High and very high depositional sequences have been recognised by high- and very high-resolution seismic profiles made with Geopulse, Uniboom and 3.5 kHz sources (Figs. 6 and 7). See Somoza et al. (1997) and Hernández-Molina et al. (2000) for descriptions of the sequence stratigraphy.

5. Quaternary stratigraphy: a complex stacking pattern controlled by climatic changes and modulated by tectonics

5.1. Chronologic framework of the sequences

Seismic and sequence stratigraphy analyses have been correlated with the sedimentary facies and age of the units using the core data, with the main aim being to correlate the significant discontinuities with the Plio-cene–Quaternary isotopic stratigraphy, relative sea level and regional palaeoceanographic changes. On the basis

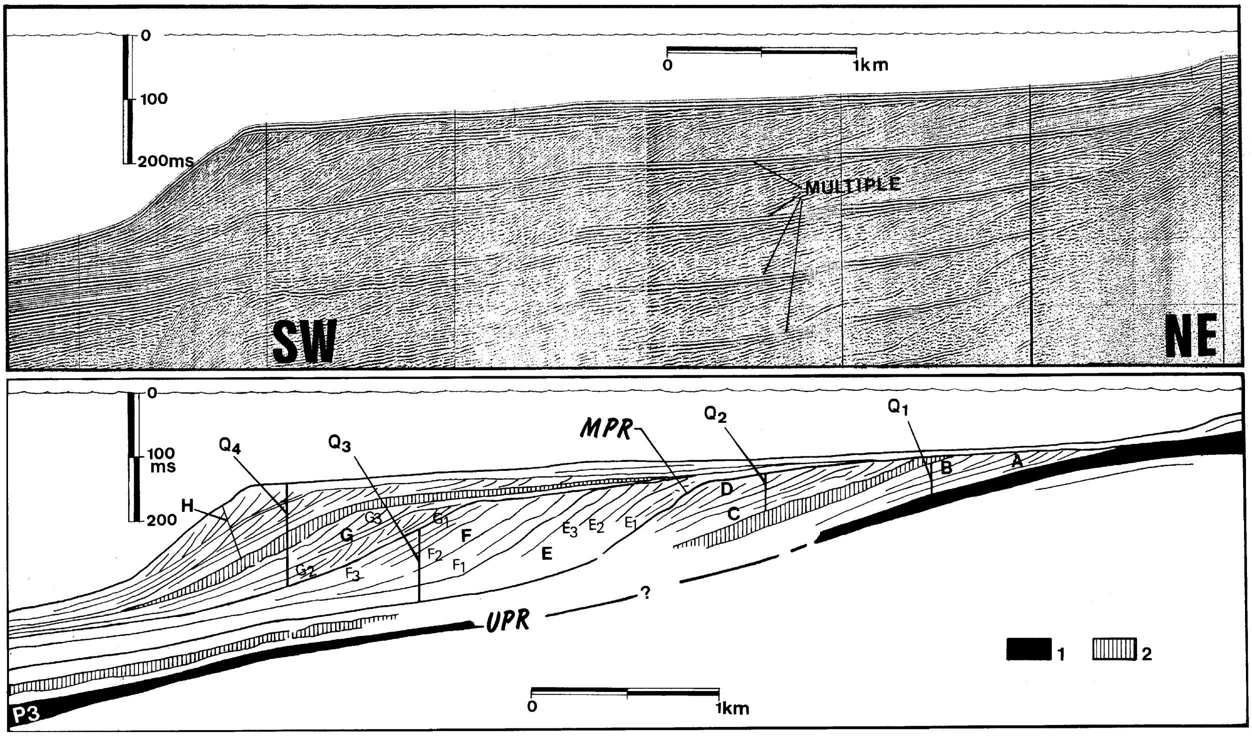


Fig. 7. Uninterpreted and interpreted medium-resolution seismic profile (Sparker, 3000 J.) of the Alboran Sea shelf. Seismic units are differentiated. Note the stratigraphic position of the UPR and MPR discontinuities and the Quaternary stratigraphic stacking pattern. (1) 3rd-order aggradational unit; (2) 4th-order aggradational units. Aggradational unit between B–C and G–H is indicated. See Fig. 1b for location.

of that correlation, we present a general Quaternary chronostratigraphy (Fig. 9). We have observed a 'Russian doll' or 'fractal' structure, in which low-resolution sequences are composed internally of medium-resolution sequences, which also comprise high- and very high-resolution sequences. In this stacking pattern it is absolutely essential to know the scale we are working with and the resolution of the method.

The Pliocene–Quaternary major LDS M/P1, P2, P3/Q-I and Q-II are related to 3rd-order cycles of about 1.4–1.6 Ma in duration and are bounded by the most prominent discontinuities related to the most significant relative sea-level falls (Fig. 9a–c). The UPR and MPR are the most important discontinuities of the Pliocene–Quaternary sedimentary record (Fig. 9a–c). Both discontinuities have a very important stratigraphic signature in the continental margin and basin. The UPR discontinuity is correlated (Fig. 9a–c) with the major sea-level fall recorded at 2.4 Ma between MIS 101/100 (Lowrie, 1986; Haq et al., 1987; Morrison and Kukla, 1998), which was coeval with global cooling (Shackleton et al., 1984; Raymo et al., 1989) and with an important change in climatic cyclicity (Upper Pliocene Revolution). The UPR is correlated with a stratigraphic discontinuity reported by Maldonado et al. (1999) in the Gulf of Cadiz, by Alonso et al. (1999), Campillo et al. (1992), Comas et al. (1999) and Fernández-Puga et al. (2000) in the Alboran Sea, by Torres et al. (1995) and Droz (1983) in the Gulf of Lyon, and by Vitale (1998) in the Pliocene outcroppings of Sicily. Furthermore, this discontinuity is related to the establishment of the present-day regional hydrodynamics in the region of the Straits of Gibraltar (Loubere, 1987; Thunell et al., 1991) and with important uplifting of the mountain belts in the Northern Hemisphere (Bell and Walker, 1992).

The MPR discontinuity is correlated with the major sea-level fall recorded in the Mid-Pleistocene at 900–920 ka (Lowrie, 1986; Haq et al., 1987; Hernández-Molina et al., 1998) and with an important change in the climatic trend known as the 'Mid-Pleistocene Revolution', which is a new cooling pulse, driven by a shift to longer-period glacial/interglacial cycles and an increase in the cycle amplitude since MIS 22/21 (about 900–920 ka).

The major LDS M/P1 and P2 are correlated with the transparent seismic unit of Pliocene age in the Mediterranean and North Atlantic, and the minor LDS P3 after the UPR is correlated with the sandy seismic unit form the Late Pliocene (Droz, 1983; Campillo et al., 1992; Nelson et al., 1993; Torres et al., 1995; Riaza and Martinez del Olmo, 1996; Alonso et al., 1999; Comas et al., 1999; Maldonado et al., 1999).

The minor LDS P2-I, P2-II, P3 and Q-I are asymmetric sequences related to 3rd-order cycles of about 800 ka. The sequence boundary between the minor LDS P2-I and P2-II (Fig. 9b and c) was

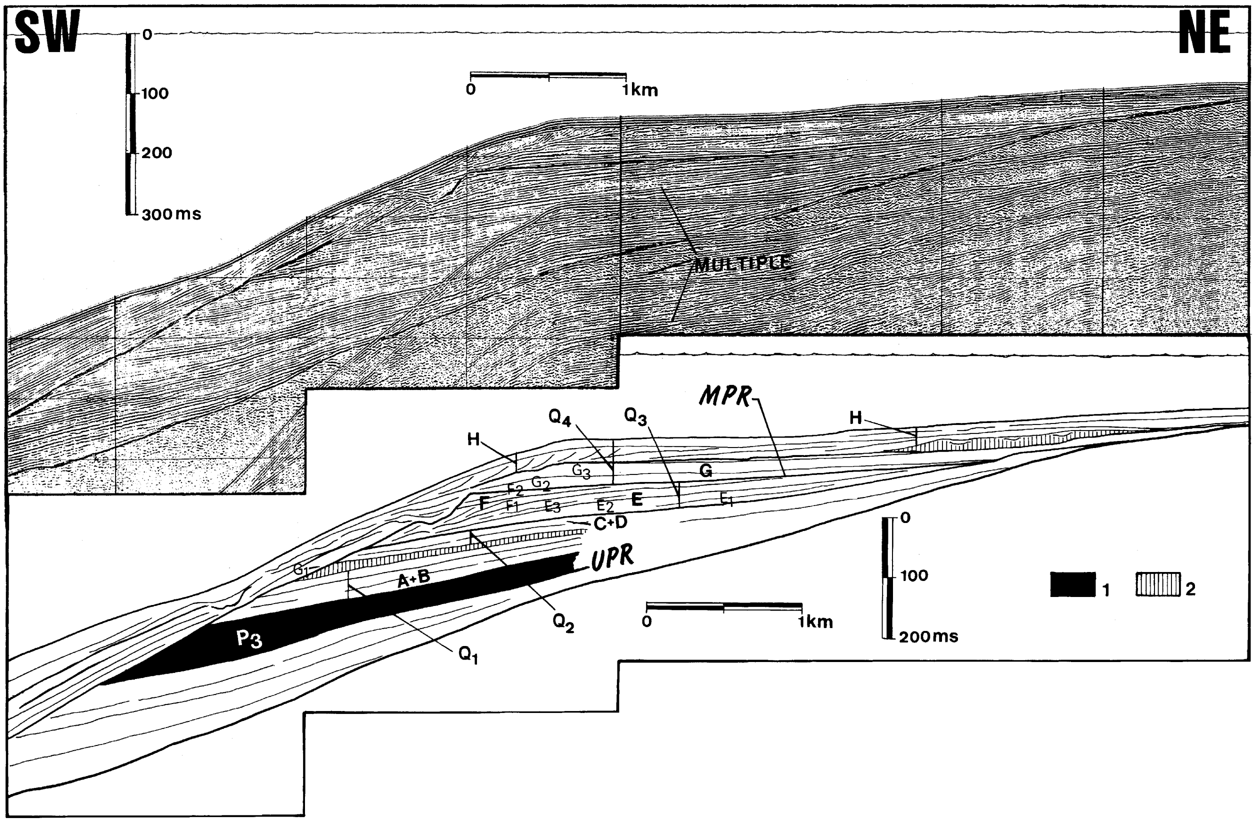


Fig. 8. Uninterpreted and interpreted medium-resolution seismic profile (Sparker, 3000 J.) of the Alboran Sea shelf. Seismic units are differentiated. Note the stratigraphic position of the UPR and MPR discontinuities and the Quaternary stratigraphic stacking pattern. (1) 3rd-order aggradational unit; (2) 4th-order aggradational units. Aggradational unit between B–C and G–H is indicated. See Fig. 1b for location.

originated by the sea-level fall and cooling event at 3 Ma (Shackleton and Opdyke, 1977; Keigwin, 1986). Both minor LDS are equivalent with the sequences presented by Fernández-Puga et al. (2000). The minor LDS Q-II have an estimated age covering the Mid-Pleistocene to the Holocene (Table 1; Fig. 9c and d).

The Quaternary stratigraphic record comprises two 3rd-order minor LDS of about 800 ka (Q-I and Q-II), separated by the MPR reflector (Table 1; Fig. 9c and d). These sequences are composed of major MDS of about 400 ka (Q1–Q4) separated form each other by erosional discontinuities, which we associate with sea-level falls produced by the most prominent Quaternary cooling events (Fig. 9a, c and e). The discontinuity between Q1 and Q2 has been correlated with the MIS 41/42. The top of the Q2 comprises the reflector MPR (MIS 22/21), and the discontinuity between Q3 and Q4 is probably located at MIS 12/11.

The noticeable stratigraphic change in thickness after the MPR has been correlated with the influence of asymmetric 4th-order sea-level cycles of 100–120 ka. The aggradational units between B and C, F and G, and G and H are related to the most prominent transgressive and highstand intervals since the Mid-Pleistocene. The aggradational unit between B and C could be related to the transgressive and highstand interval of the MIS 40/41 (Fig. 9a, c and e). The aggradational units between F and G could be related to the transgressive and highstand interval of the MIS 12/11, and the aggradational unit between G and H might be related to the transgressive and highstand interval of the MIS 6/5. Ten asymmetrical minor MDS (E1–H1) inside the middle MDS E, F, and G may be associated with 4th-order sea-level cycles of 100–120 ka (Fig. 9e).

Somoza et al. (1997) and Hernández-Molina et al. (2000) have studied the overall Late Pleistocene–Holocene shelf stratigraphic architecture of the last 4th-order DS of 100–120 ka (H). This sequence constitutes a type 1 DS and consists of a RST, LST, TST and HST. The RST and LST are volumetrically the most important system tracts. This depositional sequence comprises the highest depositional sequence (Table 1), generated by 5th-order asymmetric relative sea-level changes (22–23 ka) and mainly composed of RST and LST. TST and HST did not develop on the shelf during the 5th-order cycles. In addition, Hernández-Molina et al. (1994, 1996, 2000) have determined that the 5th-order sea-level fall was itself, for the last

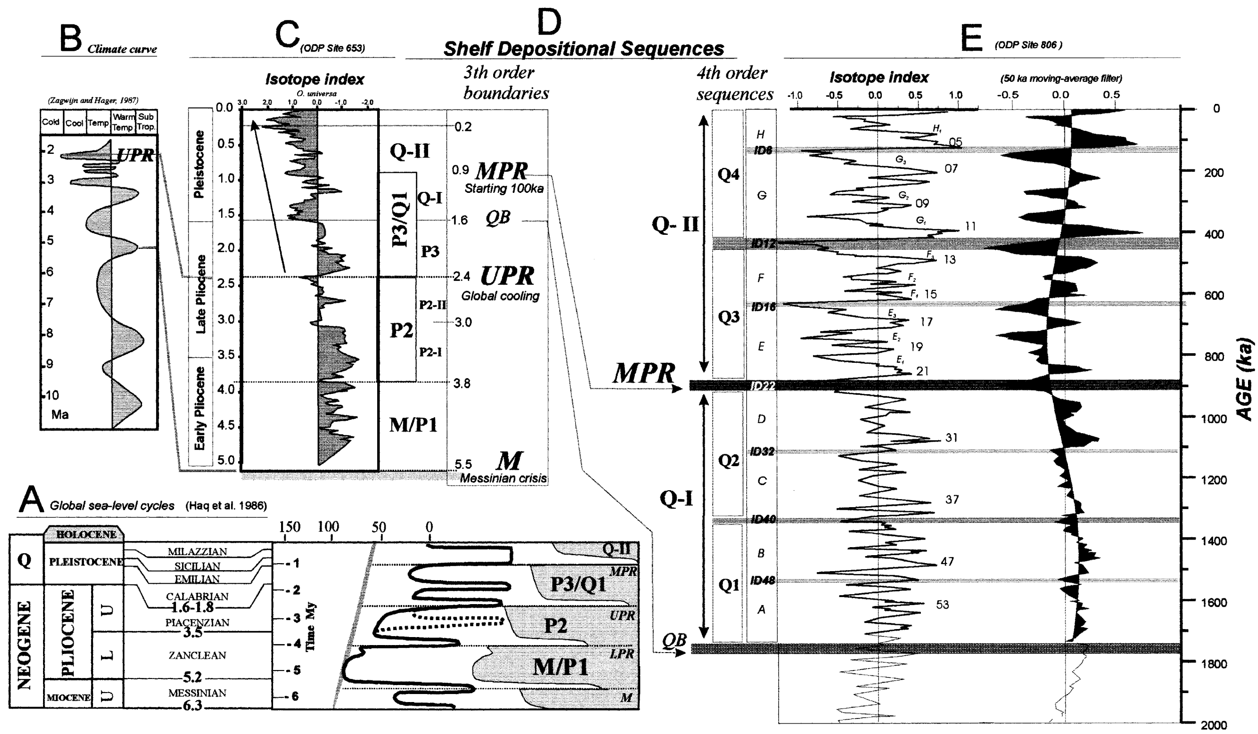


Fig. 9. Chronostratigraphic sketch with the depositional sequences of the shelf and their relationships with global sea-level cycles and Quaternary isotopic stages. Note the stratigraphic position of the UPR and MPR discontinuities. (a) Global seal-level cycles (Haq et al., 1987); (b) Pliocene climate curve (Zagwijn and Hager, 1987); (b) Pliocene–Quaternary Isotope index from ODP Site 653 (Thunell et al., 1990); (d) Shelf DS of 3rd, 4th and 5th order; (e) Quaternary Isotope index from ODP Site 806 (Berger et al., 1994).

80 ka BP, punctuated by minor cycles, generating very high-frequency DS (Table 1) related to higher-frequency asymmetric relative sea-level cycles operating on different time scales: Heinrich events (10–15 ka), *P*-cycles (4000–4500 yr), Dansgaard–Oeschger fluctuations and *h*-cycles (2300–970 yr), and *c*-cycles (500–50 yr). These higher-frequency sea-level cycles produced very high-order asymmetric sequences, of 6th, 7th, 8th and 9th order, in which the RST + LST are the most common deposits.

5.2. Stratigraphic considerations

The major LDS M/P1, P2, P3/Q-I and Q-II primarily conditioned the build-up of the shelf in the Gulf of Cadiz, and of the upper and middle slope in the Alboran Sea, due to the different characteristics of the margins. The progradational shelf of the Gulf of Cadiz is related to a high sediment supply and a gentle shelf and slope progradational profile. However, in the Alboran Sea, the progradation of the slope and the existence of a very narrow shelf is due mainly to the very steep gradient of the margin and to the very slow sediment supply. Subsidence controlled the stacking pattern of the major LDS M/P1, P2, P3/Q-I and Q-II. The change in the stacking pattern determined in the shelf of the Gulf of Cadiz, form aggradational in the Lower Pliocene to clearly progradational during the Late Pliocene to the present (P2, P3/Q-I and Q-II), is attributed to the decreasing subsidence of the margin that occurred at the end of the Early Pliocene and led to a more stable margin during the Upper Pliocene–Quaternary (Maldonado et al., 1999). The stacking pattern in the Alboran Sea also underwent an alteration in the shelf, from aggradational (M/P1, P2, and the lower part of P3/Q-I) during the Pliocene to Lower Pleistocene, to a plainly progradational stacking pattern from the Lower Pleistocene to the present (upper part of P3/Q-I and Q-II). This major change must be related to the significant variation in the subsidence trend at 2.5 Ma (Late Pliocene), to a relatively more stable margin during the Quaternary since 1.7 Ma (Comas et al., 1999; Rodriguez-Fernandez et al., 1999).

The data obtained also permitted comparison of the volumetric significance of the amount of progradation of the RST and LST to those of other system tracts. Our data illustrate that 3rd-order sequences (LDS) are asymmetrical, but the 4th-, 5th- and >5th-order depositional sequences are also asymmetrical sequences, in which the TST + HST are less volumetrically significant and tend not to be associated with major basinward shelf progradation when compared with the RST + LST. The RST + LST are the best-developed deposits of each cycle. In terms of volume and basinward progradation of the shelf margin, the RST + LST deposited during falling sea-level and lowstand sea-level positions dominate the Pliocene, Pleistocene and Late Pleistocene–Holocene stratigraphy. The stratigraphic architecture of the sequences has previously been determined for the Late Pleistocene (Hernández-Molina et al., 2000), but based on the present work it could be extended to the entire Pliocene–Quaternary sedimentary record at different temporal scales. The greater importance of the RST + LST in comparison to the poorly developed TST + HST reflects the effect of the asymmetric glacio-eustatic sea-level cycles, which are characterised by rapid rises and long gradual falls, separated by short high- and lowstand conditions. In both study areas, the first deposits showing a shelf profile equivalent to the present shelf from a morphological point of view can be determined in the RST + LST of the M/P1 DS, at the end of the Lower Pliocene. In addition, it should be noted that all of the morphological shelves determined since the Early Pliocene are, in fact, relict shelves and represent the relict depositional equilibrium profile related to the lowest position of the sea level in each cycle.

The boundary between the minor LDS P3 and Q-I is most likely the QB, but this surface does not have the same stratigraphic signature as the erosional regional discontinuities UPR and MPR (Figs. 6–8). Therefore, we believe that this boundary does not represent a significant 3rd-order stratigraphic boundary, but it does support the older age for the QB at 2.4 Ma proposed by Morrison and Kukla (1998) as a true stratigraphic boundary.

The Quaternary progradational stacking pattern shown by the major MDS Q1 and Q2 can be explained if Q2 developed in the regressive and lowstand position of the 3rd-order cycle (800 ka) before the MPR (Fig. 9e). The aggradational stacking pattern of Q3 is attributed to its generation during the transgressive interval of that 3rd-order cycle (Q-II) between the MIS 22 and 12 (Fig. 9e) rather than the transgressive trend of the 3rd-order cycle of 1.5–1.6 Ma. The progradational stacking pattern of Q4 with respect to Q3 could be due to the fact that Q4 was generated during the regressive and lowstand positions of the 3rd-order cycle (800 ka) (Fig. 9e).

The middle MDS (A–H) are related to asymmetric 4th-order sea-level cycles of 200 ka. The internal stacking pattern of A–D is most probably dominated by the 41 ka obliquity cycles, which generated sea-level fluctuations of small amplitude (approximately 50 m), developing sequences 20–50 m thick. After the MPR, the middle MDS (E–H) reflects the influence of asymmetric 4th-order sea-level cycles of 100–120 ka, and the influence of the climatic/eustatic fluctuations generated by eccentricity cycles that repeat and amplify considerably during the last 920 ka. These cycles seem to have played a dominant role in determining the structuring of the continental shelves from the Mid-Pleistocene to the present, generating sequences approximately 70–150 m thick. The MPR represents an erosional discontinuity throughout the margin during the sea-level fall and on the slope and in the deep basin due to palaeoceanographic change, which could indicate an important stratigraphic break. The absence of an aggradational unit between F and G in the Alboran Sea shelf (Figs. 6–8) could be explained by the following possibilities: (1) the existence of uplifting, compensating for the effect of the eustatic sea-level rise and highstand coeval with the MIS 12/11 (Fig. 8); (2) increased erosion after MIS 12/11 throughout the margin and basin due to the sea-level fall, whose effect was increased by the uplift tectonics of the margin and palaeoceanographic changes in the deep basin (Fig. 8); or (3) both possibilities.

The stratigraphic resolution increases from the Lower Pliocene to the Late Pleistocene–Holocene, which is evidence for the major LDS to minor MDS. This increase in the resolution can be explained by the climatic/eustatic fluctuations, which increase from 20 ka (5–2.4 Ma), to approximately 40 ka (2.4 to 900–920 ka) and then to approximately 100 ka (during the last 900–920 ka).

6. Conclusions

Based on the seismic and sequence stratigraphic analysis from the Pliocene–Quaternary of the southern Iberian shelves, the following main conclusions have been drawn:

1. Four major low-resolution depositional sequences (major LDS) have been recognised by MCS profiles in the Pliocene–Quaternary sedimentary record (M/P1, P2, P3/Q-I and Q-II) related to 3rd-order cycles of about 1.4–1.6 Ma duration. They are separated by four discontinuities associated with the most prominent sea-level falls: in the Late Messinian discontinuity (M) at 5.5 Ma; in the Lower Pliocene at 4.2 Ma (LPR); in the Upper Pliocene at 2.4 Ma (UPR); and approximately 900–920 ka in the Mid–Pleistocene (MPR).
2. These four major LDS are asymmetrical, with the regressive and lowstand system tracts being the best-developed deposits of each sequence, and control the major basinward progradation of the shelf in the Gulf of Cadiz and the slope in the Alboran Sea.
3. The Quaternary Boundary is not a prominent enough discontinuity to be a practical 3rd-order regional boundary without the same stratigraphic signature as the UPR or MPR discontinuities.

4. The Quaternary stratigraphic stacking pattern could be divided into two minor resolution depositional sequences (minor LDS) of 3rd order, of approximately 800 ka (Q-I and Q-II) and separated by the MPR. These sequences are divided into four major medium-resolution depositional sequences (major MDS) of 4th order, of approximately 400 Ka (Q1–Q4), bounding each other via erosional discontinuities that we have correlated with sea-level falls produced by the most prominent cooling events. Q1 and Q2 are composed of four middle MDS (A–D), and Q3 and Q4 by another four (E–H). Each of these asymmetric sequences is related to an asymmetric 4th-order cycle about 200 ka in duration.
5. A stratigraphic change has been determined after the MPR discontinuity. The sequences E–H are internally composed of 10 asymmetrical minor MDS, related to the influence of asymmetric 4th-order sea-level cycles of 100–120 ka. The influence of the climatic/eustatic fluctuations generated by eccentricity cycles that have repeated and amplified considerably during the last 900–920 ka seem to have played a dominant role in determining the structuring of the continental shelf from the Mid-Pleistocene to the present.
6. A shelf equivalent to the present shelf from a morphological point of view can be determined since the end of the Lower Pliocene, and all of the morphological shelves recognised since then represent relict depositional equilibrium profiles related to the lowest sea level.
7. Stratigrapic resolution increases from the Lower Pliocene to the Late Pleistocene–Holocene. This change in the resolution can be observed with the same method at different scales, and can be explained by climatic/eustatic fluctuations increasing from the Lower Pliocene (20 ka cycles) to the Mid-Pleistocene (100–120 ka cycles).

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