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Quaternary evolution of the contourite depositional system in the Gulf of Cadiz

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Abstract: This paper provides for the first time a detailed vertical and spatial representation of Quaternary evolution of the contourite depositional system (CDS) in the Gulf of Cadiz, based on the results of careful morphological, structural and stratigraphic analyses using high-resolution seismic reflection profiles as well as oil company borehole data, and piston and gravity cores. Different drifts observed on the stratigraphic architecture allow us to propose a regional Quaternary evolution for the whole system, in which three major stages can be identified. (1) In the Early Pleistocene to Mid-Pleistocene, the CDS was mainly dominated by depositional processes, where the upper and lower cores of the Mediterranean Outflow Water (MOW) generated the mounded elongated Cadiz–Faro–Albufeira drift in the transition between the middle and upper slope, and the equivalent Huelva–Guadalquivir drift on the middle slope. During this stage the main erosive features were established close to the Strait of Gibraltar. (2) In the Mid-Pleistocene to Late Pleistocene, two important changes in the CDS took place. One occurred at the transition between the middle and upper slope, related to a change in the upper branch of the MOW, when a mixed drift began to develop, burying the eastern part of the Cadiz–Faro–Albufeira mounded elongated and separated drift. The second change is observed on the central area of the middle slope, related to the lower branch of the MOW, where a large contourite channel (the Guadalquivir channel) progressively eroded the western part of the mounded Huelva–Guadalquivir drift. Laterally an extensive sheeted drift buried the previous mounded deposits. (3) In the Late Pleistocene to Holocene, in the northern area of the CDS, a plastered drift started to be developed in the transitional zone between the upper and middle slope. On the middle slope, the mounded elongated Huelva–Guadalquivir drift was not developed and more erosive processes became dominant as the lower core of the MOW intensified. In the sector close to the Straits of Gibraltar, a field of broad seabed forms was generated. These three evolutionary stages have been controlled by tectonics, including recent diapiric movement, Guadalquivir Bank uplift, and reactivation along several fault systems and anticline–syncline structures. Tectonics has been a key factor in the sea-floor morphological changes, which has caused new pathways for the core and branches of the MOW, and consequently has produced the contourite stratigraphic and architectural changes. Superimposed on these tectonic changes, both climatic and eustatic changes during the Quaternary (but especially from the Mid-Pleistocene) have controlled the development of vertical contourite stratigraphy. The general conclusion of this study is that the contourite depositional system of the Gulf of Cadiz has changed from a dominantly depositional system to a dominantly erosive one during the Quaternary.

It is possible to deduce, from the characteristics of contourite deposits (their morphology, internal seismic facies and position in the oceanic basin), the pathway of the water mass that was responsible for their development. This is particularly relevant when buried contourite drifts are found in the sedimentary record of a basin, because it then becomes possible to reconstruct the original palaeoceanographic conditions (Hernández-Molina *et al.* 2006). In addition, the stratigraphic architecture of contourite deposits provides essential indicators for determining the evolution of marine environments and palaeoceanographic conditions of the water masses with time. Long-term records may provide information about the distribution and timing of large-scale sedimentary changes related to bottom-current circulation changes (or other factors that control those changes, such as

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tectonics), as expressed by unconformities and changing styles of deposition.

The contourite depositional system (CDS) along the northern margin of the Gulf of Cadiz has been defined and characterized very recently as a unique system that results from Mediterranean Outflow Water (MOW) interaction with the sea floor (Fig. 1) (Hernández-Molina *et al.* 2003; Llave 2003). There have been numerous studies focused on the influence of the MOW on the sedimentary stacking pattern of some specific parts of the CDS (e.g. Madelain 1970; Kenyon & Belderson 1973; Mélières 1974; Gonthier *et al.* 1984; Faugères *et al.* 1985; Stow *et al.* 1986, 2002; Nelson *et al.* 1993, 1999; Llave *et al.* 2001, 2004*a*, 2006; García 2002; Stow *et al.* 2002; Habgood *et al.* 2003; Mulder *et al.* 2003). Special attention has been paid to the establishment of depositional facies models (Stow 1979, 1982; Faugères *et al.* 1984, 1993, 1999; Gonthier *et al.* 1984) and their mechanism of formation (Stow & Faugères 1993, 1998; Stow *et al.* 1996; Shanmugam 2000; Stow & Mayall 2000) to achieve the possibility of reconstructing the depositional history of drift development, of demonstrating the changing seismic character of contourites and geometry of the drifts, and of placing specific phases of deposition within a palaeocirculation framework. A cyclic pattern of deposition and erosion as a consequence of changes in the intensity of MOW through time has been recognized (Nelson *et al.* 1993). Cyclicity has also been described from the CDS seismic and sediment facies, which are interpreted as resulting from fluctuations in grain size as a consequence of varying MOW intensity, which in turn can be related to palaeoclimatic changes (Llave *et al.* 2001; Stow *et al.* 2002; Llave 2003).

In spite of this large volume of previous work, there has been no overall synthesis dealing with the evolution of the CDS as a whole. The main goal of this paper, therefore, is to present for the first time an attempt at reconstruction of the Quaternary evolution of the CDS in the Gulf of Cadiz, through an integration of tectonic, stratigraphic and palaeoceanographic changes. We find six major types of contourite drift deposits within the CDS and emphasize differences in the stratigraphic stacking patterns, and we then elucidate their evolution within a general tectonostratigraphic framework. Emphasis is placed on the varied depositional and erosive features of Quaternary contourite deposits, as identified from regional seismic data, and how these relate to changes in basin geometry and palaeocirculation.

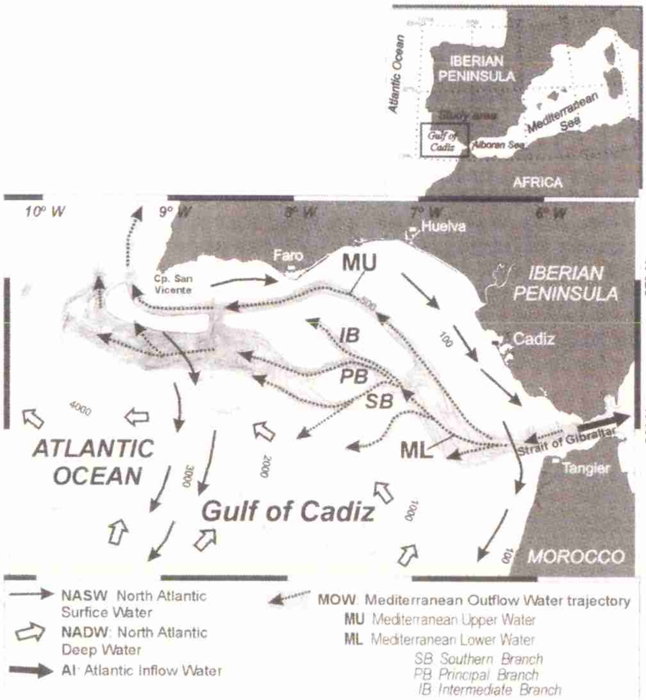


Fig. 1. Location of the Gulf of Cadiz in a regional bathymetric map (Heezen & Johnson 1969) indicating the general circulation patterns of MOW. (Modified from Hernández-Molina *et al.* 2003.)

Gulf of Cadiz: geological and oceanographic setting

Geological framework

The southwestern margin of the Iberian Peninsula, at the eastern end of the Azores–Gibraltar zone, is the location of the diffuse plate boundary between Europe and Africa. Distinct periods of crustal deformation, fault reactivation and halokinesis related to the movement between Eurasia and Africa (Malod & Mauffret 1990; Srivastava *et al.* 1990; Maldonado *et al.* 1999; Gutscher *et al.* 2002; Alves *et al.* 2003; Gutscher 2004; Medialdea *et al.* 2004) are known to have controlled the tectonostratigraphic evolution of this part of the Iberian Peninsula. The tectonic structure of this area (Fig. 2) is a consequence of the distinct phases of rifting from the Late Triassic to the Early Cretaceous (Murillas *et al.* 1990; Pinheiro *et al.* 1996; Wilson *et al.* 1996; Borges *et al.* 2001) and its later deformation during the Cenozoic, especially in the Miocene (Ribeiro *et al.* 1990; Alves *et al.* 2003). Since the late Miocene, the NW–SE compressional regime has developed simultaneously with the extensional collapse of the Betic–Rif orogenic front, by westward emplacement of a giant 'olistostrome', the Cadiz Allochthonous Unit, and by very high rates of basin subsidence coupled with strong diapiric activity (Perconig 1960–1962; Torelli *et al.* 1997; Flinch & Vail 1998; Maldonado *et al.* 1999; Gracia *et al.* 2003; Medialdea *et al.* 2004). By the end of the Early Pliocene the connection between the Atlantic and the Mediterranean through the Strait of Gibraltar opened, leading, after the end of the Messinian salinity crisis, to the establishment of the circulation pattern as it is known nowadays (Thunell *et al.* 1991; Nelson *et al.* 1993). The margin evolved towards more stable conditions during the Late Pliocene–Quaternary (Maldonado *et al.* 1999; Somoza *et al.* 1999; Maestro *et al.* 2003; Fernández-Puga 2004; Medialdea *et al.* 2004). Some neotectonic reactivation is also evident, as expressed by the occurrence of mud volcanoes and diapiric ridges (Díaz del Río *et al.* 2003; Llave 2003; Somoza *et al.* 2003;

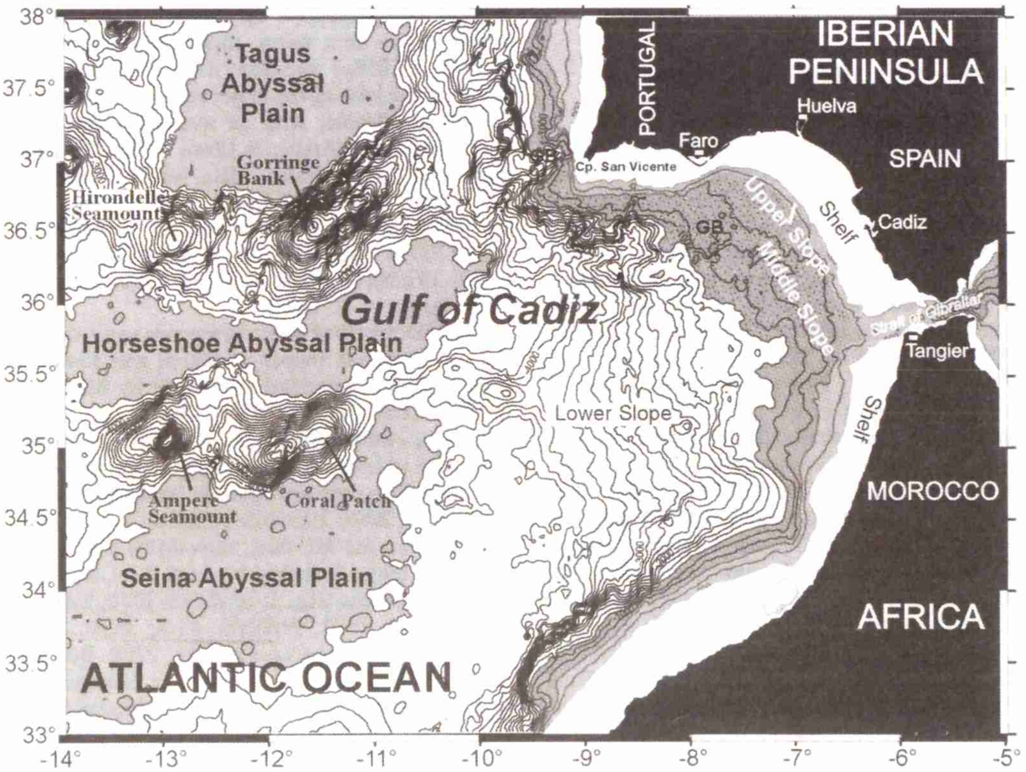


Fig. 2. Regional bathymetric map (in metres, from satellite data of Smith & Sandwell 1997) of the continental margin of the Gulf of Cadiz (modified from Hernández-Molina *et al.* 2006). The contourite depositional system (CDS) of the Gulf of Cadiz is shown by the dotted area.

Fernández-Puga 2004), and fault reactivation (Maestro *et al.* 1998; Lobo *et al.* 2003).

Sea-bed topography

The major part of the Gulf of Cadiz comprises a giant outward bulge sloping to the west, with irregular surface relief (Fig. 2). Based on the slope gradient and morphological features, the principal physiographic features of this broad slope are (Malod & Mougenot 1979; Baraza & Nelson 1992; Nelson *et al.* 1993): a shelf-break located between 100 and 140 m depth; a steeper (2–3°) upper slope between 150 and 400 m depth and 19 km wide; two gently dipping (>1°) wide terraces located at water depths of 500–750 and 800–1200 m on the middle slope, crossed by channels and ridges that trend NE; a smooth lower slope (0.5–1°), between 800 and 4000 m depth; and the abyssal plains, at water depths greater than 4300 m, separated by submarine banks (or seamounts) trending ENE. For the most part, this continental slope lacks submarine canyons, except in the western area of the Algarve margin and close to the Strait of Gibraltar (Hernández-Molina *et al.* 2006).

Oceanographic setting

The oceanographic setting in the Gulf of Cadiz is characterized by intense hydrographic dynamics controlled by the exchange of water masses through the Strait of Gibraltar. This is determined by the overflow at a depth of 40–200 m of dense, highly saline and warm Mediterranean Outflow Water (MOW) near the bottom, and the turbulent, less saline, cool-water mass of Atlantic Inflow Water (AI) on the surface (Fig. 1; e.g. Madelain 1970; Mélières 1974; Zenk 1975; Ambar *et al.* 1976; Ambar & Howe 1979; Baringer & Price 1999; Nelson *et al.* 1999). Because of its higher density compared with the ambient Atlantic waters, the Mediterranean overflow forms a turbulent flux ranging from 150 to 200 m wide, which moves along a straight channel in a WSW direction at a speed of more than 200 cm s^{-1} (Ambar & Howe 1979). It then progressively sinks northwestwards, descending from the 300 m deep strait down the continental slope of the eastern Gulf of Cadiz (e.g. Madelain 1970; Mélières 1974; Thorpe 1975; Zenk 1975; Gardner & Kidd 1983; Ochoa & Bray 1991; Baringer & Price 1999; Nelson *et al.* 1999).

Above the MOW, the water masses in the Gulf of Cadiz comprise the North Atlantic Surface Water (NASW), which flows at the surface to a water depth around 100 m, and the North Atlantic Central Water (NACW), which flows between 100 and 700 m depth. Parts of these water masses together constitute the Atlantic Inflow (AI) towards the Alboran Sea through the Strait of Gibraltar, characterized by high temperatures and moderate salinities (12–16 °C, 34.7–36.25‰).

In the Gulf of Cadiz, part of the deep, warm and more saline MOW joins the NADW. This mixture flows very slowly southwards along the western part of the Atlantic Ocean (Zenk 1975; Knauss 1978). The NADW component is characterized by low temperatures (3–8°) and 34.95–35.2‰ salinity (Caralp 1988, 1992), flowing southwards from its source in the Greenland–Norwegian Sea region (e.g. Reid 1994).

MOW itself is composed mainly (90%) of Levantine Intermediate Water (LIW) and, to a much lesser extent, of Western Mediterranean Deep Water (WMDW) (Bryden & Stommel 1984), and is characterized as warm and saline (13 °C, 36.5‰) with an oxygen content of 4‰ (Madelain 1970; Ambar & Howe 1979). As it moves westwards, MOW shows a decrease in temperature, salinity and velocity. It is influenced by both Coriolis force and topography, being divided into two main cores (Fig. 1): (1) Mediterranean Upper Water (MU), which corresponds to the small shallow core described by Ambar *et al.* (1999), which moves as a warm, moderately saline flux (3.7 °C, 37.07‰) between depths of 400 and 600 m at the base of the upper slope as far west as Cape San Vicente, with an average velocity of about 46 cm s^{-1} (Ambar & Howe 1979); (2) Mediterranean Lower Water (ML), which constitutes the more saline (37.42‰), lower core and the MOW's principal nucleus, at a depth of 600–1200 m and with an average velocity of *c.* 20–30 cm s^{-1} (Zenk & Armi 1990; Baringer 1993; Bower *et al.* 1997).

The ML described here corresponds to the sum of the two branches (upper at 800 m and lower at 1200 m depth) described previously by Madelain (1970), Zenk (1970, 1975), Ambar & Howe (1979) and Ambar (1983). The study area is characterized by an irregular slope morphology, as shown by bathymetry data and acoustic imagery (Mulder *et al.* 2002, 2003; Hernández-Molina *et al.* 2003), which diverts the ML flow, such that it subdivides into three minor branches between the Cadiz and Huelva meridians (Fig. 1; Madelain 1970; Kenyon & Belderson 1973; Mélières 1974; Zenk 1975; Ambar 1983; Nelson *et al.* 1993, 1999; Borenäs *et al.* 2002). These include: (1) the Intermediate Branch (IB), which moves northwestwards through the Diego Cao channel; (2) the Principal Branch (PB), which is believed to transport, at present, the MOW's major flow (Madelain 1970), through the Guadalquivir channel south of the Guadalquivir Bank, which modifies the flux toward the SE; (3) the Southern Branch (SB), which follows a steep valley towards the SW through the Cadiz channel (Fig. 1).

As far west as 8°W, the MOW constitutes a bottom layer along the base of the upper slope and middle slope, but further west the MOW density range reaches a neutral buoyancy that characterizes an intermediate oceanic level (Madelain 1970; Gardner & Kidd 1983; Ochoa & Bray 1991; Ambar *et al.* 2002). It thereby loses contact with the sea floor at 1000 m depth in the eastern sector and at 1400 m depth in the western sector (Gardner & Kidd 1983; Baringer & Price 1999).

Palaeoceanography

The palaeocirculation of the MOW, from the last maximum glacial stage to the present, has been studied in detail based on benthic and planktonic Foraminifera, and sedimentological, mineralogical and geochemical analyses. However, there is still considerable controversy on definition of the age of the warmer and colder periods, on limits in the time scale and on sample resolution to study the variation of flow (and the effect on the precision of faunal data). It is generally agreed that during the last glacial stage (20–18 ka BP) there was significant vertical exchange between water masses (Caralp 1988, 1992). The direction of exchange through the Gibraltar gateway was similar to the present one, with MOW flow to the west (Caralp 1988, 1992; Grousset *et al.* 1988; Vernaud-Grazzini *et al.* 1989), but the relative intensity of flow is disputed.

Some researchers (Faugères *et al.* 1984, 1985; Stow *et al.* 1986; Nelson *et al.* 1993; Sierro *et al.* 1999; Pailler & Bard 2002) have suggested that during the first and second stages of the last deglaciation (15–13 ka BP), and especially during the Bolling Allerod (14–11 ka BP), there was a marked increase in MOW intensity, and a decrease in the MOW flow between 11 and 10 ka BP (the Younger Dryas stage). During the Early Holocene (10–7 ka BP), the intensity was once again somewhat reduced and a quasi-permanent thermocline was established. Finally, an increase in flow of MOW took place to its present level during the Late Holocene (since 7 ka BP). Other workers have considered that MOW intensification did not occur during the deglaciation stages, but was most marked during the cooler episodes (Caralp 1988, 1992; Vernaud-Grazzini *et al.* 1989; Cacho *et al.* 2000; Schönfeld & Zahn 2000). Recent studies have supported this view and suggested that the MOW played a stronger role during cold intervals and Heinrich events in deeper waters than during warmer intervals (Cacho *et al.* 2000; Llave *et al.* 2004*a*, 2006). During these cool stages, a smaller and denser MOW was developed and mixed vigorously with North Atlantic waters (Baringer & Price 1999). However, this view is still controversial, as the MOW volume would have decreased with the reduced cross-section of Gibraltar Strait during the glacial sea-level lowstands (Gardner & Kidd 1983; Bryden & Stommel 1984; Zahn 1997; Matthiesen & Haines 1998), thereby diminishing the exchange between the Mediterranean Sea and the Atlantic Ocean (Bethoux 1984; Bryden & Stommel 1984; Duplessy *et al.* 1988). On the other hand, owing to this diminished exchange coupled with lowered temperatures (Paterne *et al.* 1986; Rohling *et al.* 1998; Ambar *et al.* 1999) and a drier Mediterranean, the MOW formed during these cool conditions would have had a significantly higher salinity and hence greater density (Zahn *et al.* 1987; Thunell & Williams 1989; Schönfeld 1997; Zahn 1997; Cacho *et al.* 2000; Ambar *et al.* 2002). This would have led to an intense and deeper MOW (Thomson *et al.* 1999; Schönfeld & Zahn 2000; Rogerson 2002), creating a stronger interaction with the sea floor at greater depths, and hence facilitating the transport and deposition of coarser material, and so also leading to higher sand contents in contourites (Llave *et al.* 2004*a*, 2006).

Dataset and methods

This study uses a broad database comprising both seismic and sediment data. Seismic data have been obtained during several cruises supported by Spanish Research Council projects under a Hispano-Portuguese collaboration during the last 7 years including high-resolution (sparker 3000, 4000 and 7500 J, airgun) and very high-resolution seismic data (3.75 kHz and TOPAS). Further details on the seismic network have been given by Hernández-Molina *et al.* (2003). The seismic data were collected on board R.V. *Francisco de Paula Navarro*, R.V. *Cornide de Saavedra* and R.V. *Hesperides* during the oceanographic research cruises FADO 97/11, ANASTASYA 99/09, TASYO 2000, ANASTASYA 00/09 and ANASTASYA 01/09. The seismic emission frequency used was between 100 and 1500 Hz, giving an average vertical resolution of 1.5 m. The emission shot interval was 3 s, giving a horizontal resolution of about 7 m. A differential global positioning system (GPS) navigation system was used. Borehole data from the north Cadiz margin have been made available by Portuguese and Spanish oil companies (Fig. 3). Several Calypso piston cores, up to 20 m long, were recovered during the IMAGES V cruise on board R.V. *Marion Dufresne*, and a number of shorter gravity cores (<3 m long) were

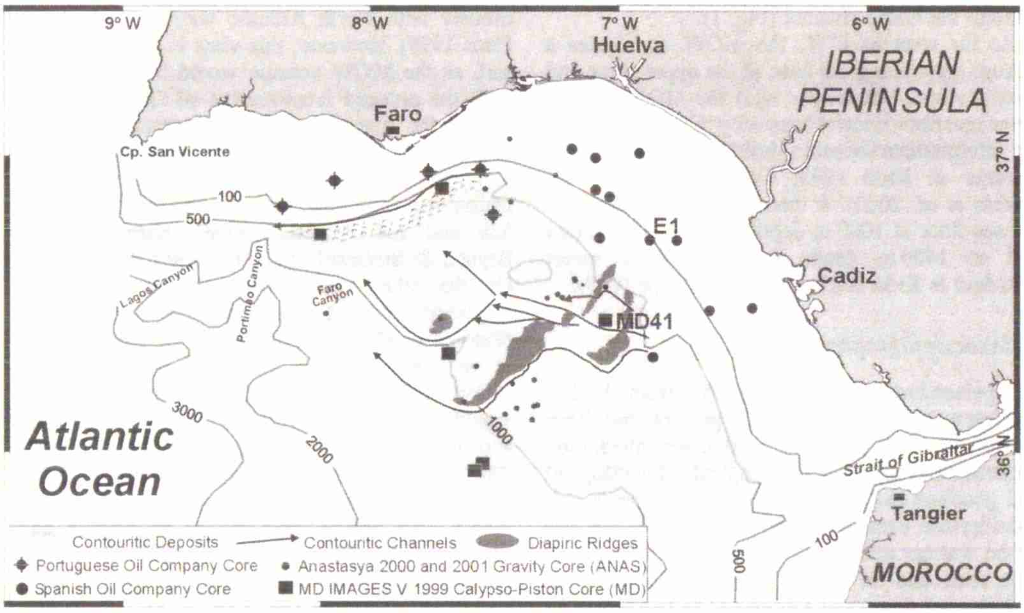


Fig. 3. Location of cores within the main sedimentary features of the contourite depositional system. The labels correspond to the dated examples shown in Figures 6 and 10 (E1 and MD41). The bathymetry is in metres.

obtained during ANASTASYA 2000 and 2001 cruises on board R.V. *Cornide Saavedra* (Fig. 3). All cores are from water depths between 500 and 1300 m.

For this study, the distribution, seismic stratigraphy and sedimentary stacking of the depositional contourite features are considered. Regional mapping of the distribution and boundaries of the seismic units was carried out, but only in the central, north and west sector of the middle slope of the Gulf of Cadiz. In the sector close to the Strait of Gibraltar it was not possible because of the presence of many recent tectonic features (mainly the diapiric ridges), which make it difficult to correlate the regional stratigraphy with the same degree of detail. Major results have been published where a more detailed explanation of the seismic stratigraphy of the contourite deposits along the middle slope has been given (see Llave *et al.* 2001, 2006; Hernández-Molina *et al.* 2002, 2006; Stow *et al.* 2002; Llave 2003). However, in this paper we focus on certain features such as the following.

(1) The development of a general chronostratigraphy of the depositional sequences for the Quaternary sedimentary record. For this we have used the following information. (a) Correlation of the dense network of low-resolution to very high-resolution single-channel and multi-channel seismic reflection lines with the results of core and borehole data from various surveys. We used cores and borehole data obtained by oil company drilling (Fig. 3) to establish the chronological framework for the Pliocene and Quaternary, and Calypso giant piston and standard gravity cores were used for the Late Pleistocene and Holocene chronostratigraphy (Llave *et al.* 2001, 2004*a*, *b*, 2006; Llave 2003). (b) Correlation of our sequences and units with the stratigraphic seismic results obtained previously by other workers on the continental margin made at different scales: (i) Mesozoic and Cenozoic sedimentary record (Baldy *et al.* 1977; Malod 1982; Mougenot & Vanney 1982; Mougenot 1988; Riaza & Martínez del Olmo 1996; Tortella *et al.* 1996; Maldonado *et al.* 1999; Terrinha *et al.* 2002; Fernández-Puga 2004; Medialdea *et al.* 2004); (ii) Pliocene and Quaternary (Rodero 1999; Rodero *et al.* 1999; Hernández-Molina *et al.* 2002); (iii) Quaternary (Llave *et al.* 2001, 2004*a*; Llave 2003); (iv) Late Pleistocene–Holocene (Hernández-Molina *et al.* 1994, 2000; Lebreiro 1995; Lobo 1995, 2000; Lebreiro *et al.* 1997; Somoza *et al.* 1997; Lobo *et al.* 2001, 2002, 2005*a*; Llave *et al.* 2004*b*, 2006); (v) Late Holocene (Lobo *et al.* 2003, 2005*b*; Llave *et al.* 2004*b*).

(2) The development of a detailed chronostratigraphy for the Upper Quaternary sedimentary record based on correlation of two Calypso piston cores (isotope-dated) with very high-resolution seismic profiles, using a sound velocity in sediments of 1600 m s^{-1} (Llave *et al.* 2004*b*).

(3) A sequence stratigraphic analysis of the Quaternary and Late Pleistocene–Holocene contourite deposits.

(4) The interpretation of climatic changes in relation to palaeoceanographic evidence in the CDS.

(5) The consideration of the tectonic influence on palaeoceanography and the evolution of contourite depositional architecture.

The contourite depositional system: present-day morphosedimentary features

Five morphosedimentary sectors within the CDS in the middle slope of the Gulf of Cadiz have been distinguished by Hernández-Molina *et al.* (2003) and Llave (2003): (1) proximal scour and sand ribbons sector; (2) overflow–sedimentary lobe sector; (3) channels and ridges sector; (4) active contourite depositional sector; (5) submarine canyons sector (Fig. 4).

Sector 1: proximal scour and sand ribbons sector

This is characterized by a smooth platform located alongslope in the SE zone close to the Strait of Gibraltar, between 500 and 800 m water depth. It is an extensive area dominated by an abrasion surface and several erosive scour features oriented NE–SW, with a smooth 'V' shaped expression and truncated reflectors in the seismic profiles. There are also some depositional features, including a SE–NW oriented sequence of bedforms, comprising ripple marks, sand ribbons and sand waves (first described by Kenyon & Belderson 1973) showing regular and symmetrical morphologies and high acoustic reflectivity.

Sector 2: overflow–sedimentary lobe sector

This is adjacent to and seawards of Sector 1, between 800 and 1600 m water depth, and has a fan shape 65 km long and 60 km wide. It constitutes a large sedimentary lobe with surface bed-forms, including small sandy and muddy lobate bodies and wave-fields, which in the seismic profiles show asymmetrical morphologies, smooth topographies and medium to low reflectivity. Erosive features are also important, including several large furrows with a NE–SW orientation, which display gravitational features

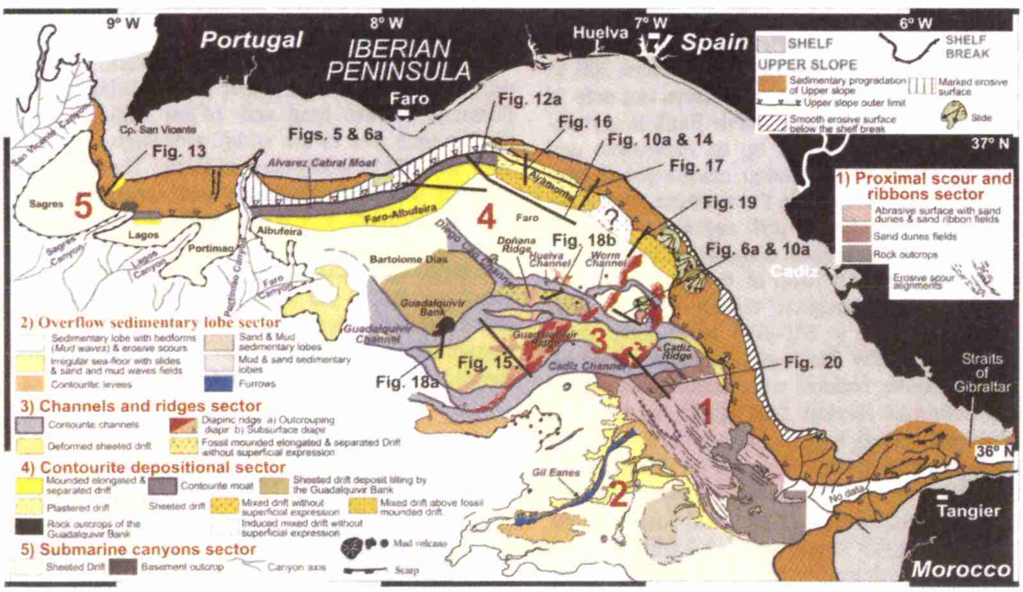


Fig. 4. Morphosedimentary map of the contourite depositional system on the middle slope of the Gulf of Cadiz with the location of the seismic examples (sparker seismic profiles). Morphosedimentary sectors: (1) proximal scour and sand ribbons sector; (2) overflow sedimentary lobe sector; (3) channels and ridges sector; (4) contourite depositional sector; (5) submarine canyon sector. (Modified from Hernández-Molina *et al.* 2003.)

on their margins. Although Hernández-Molina *et al.* (2003) interpreted this sector as an overflow–sedimentary lobe, and Mulder *et al.* (2003) as an unstable giant contourite levee, these hypotheses are not contradictory, as we can see gravitational features, and these are by numerous sea-floor emissions of hydrocarbon-enriched fluids, many fields of mud volcanoes, hydrocarbon seepage and hydrocarbon-derived carbonate chimneys (Somoza *et al.* 2002, 2003; Díaz del Río *et al.* 2003).

Sector 3: channels and ridges sector

This is located in the central area of the middle slope, between 800 and 1600 m water depth. It is dominated by the presence of significant erosive and tectonic elements. Five main contouritic channels known as the Cadiz, Guadalquivir, Huelva, Diego Cao and Gusano channels represent the main erosive features. These channels are asymmetrical, with lengths of 10 km to over 100 km, widths of 1.5–10 km, and depths of *c.* 10–350 m, generally presenting a deeper and more abrupt northern flank. They are 'S'-shaped, with alongslope zones oriented NW–SE, which change to downslope zones oriented NE–SW as a result of interaction between the bottom current pathway and the irregular slope morphology. These irregularities in the sea floor are marked by the occurrence of some structural relief features: the Guadalquivir, Cadiz and Doñana diapiric ridges and the Guadalquivir Bank uplift. The Guadalquivir and Cadiz diapiric ridges are NE–SW-oriented elongate outcropping ridges, from 300 to 1100 m depth. The Doñana ridge crops out only in restricted areas. The Guadalquivir Bank is a structural basement high made up of Palaeozoic and Mesozoic rocks of the Iberian margin (Medialdea *et al.* 2004). It is located in the southern part of the Bartolomeu Dias sheeted drift and has a NE–SW orientation. The principal contourite channels are located along the SE flank of the diapiric ridges; however, several marginal valleys with irregular morphologies and a NE–SW trend have been detected on the NW flanks of the diapiric ridge. All of these erosive features were established over a broad deformed sheeted drift, which is the main depositional morphology in this sector. Some mass movement elements are observed on the flanks of the diapiric structures and on the margins of the contourite channels. Finally, several mud volcanoes can be observed in this sector associated with sea-floor emissions of hydrocarbon-enriched fluids (Somoza *et al.* 2002, 2003).

Sector 4: active contourite depositional sector

This is developed in the central and NW areas of the middle slope. It is characterized by the dominance of depositional features represented by the following. (1) The mounded elongated and separated Faro–Albufeira drift, located at 500 m depth on the South Portuguese margin. (2) A sheeted drift complex, forming the basinward prolongation of the mounded drift and characterized by a planar and horizontal morphology. Three main sheeted drift segments have been differentiated: the Faro–Cadiz, at a water depth of 600 m, which is 20 km wide and 30 km long; the Bartolomeu Dias, at 750 m depth, which is 30 km wide and 45 km long; and the Albufeira, at 850 m depth, which is 10 km wide and 24 km long. (3) A plastered drift, located to the east of the mounded drift, between 300 and 600 m depth, about 35 km long and 12 km wide. The smooth contourite terrace is scoured by an important erosive contouritic channel parallel to the slope named the Alvarez Cabral Moat, which is 80 km long and 4–11 km wide, with a 'U'-shaped cross-section. There are also gravitational features defined on the mounded drift and Faro–Cadiz sheeted drift.

Section 5: submarine canyons sector

This sector is located in the western area of the middle slope and is characterized by the occurrence of a number of channels cutting across the slope from NE to SW, including the Portimao, Lagos, Sagres and San Vicente submarine canyons, with steep margins and erosive surfaces. These erosive features cut through and delineate several sheeted drifts at around 1000 m water depth, including the Portimao (16 km long and 14 km wide), Lagos (24 km long and 12 km wide), and Sagres (26 km long and 30 km wide) sheeted drifts. There is also a small mounded elongated and separated drift (the Lagos drift) at a water depth of 950 m. It is 8 km long, 6 km wide, and has 75 m relief. It is developed along the left margin of a small erosive moat, parallel to the south coast of San Vicente, and is about 8 km long and 4 km wide. Some mass-wasting elements are observed on the sheeted drifts near the canyons.

Seismic stratigraphic and chronostratigraphic framework

Within the Quaternary sedimentary record of the contourite deposits, two main depositional sequences have been identified regionally: Q-I and Q-II. These two sequences are separated by a marked continuous reflector of high reflectivity that shows distinct erosion in parts (Fig. 5); this is defined as the MPR discontinuity. This discontinuity marks a change in seismic facies, separating deposits with a more aggrading pattern (Q-I) from those above with a more progradational

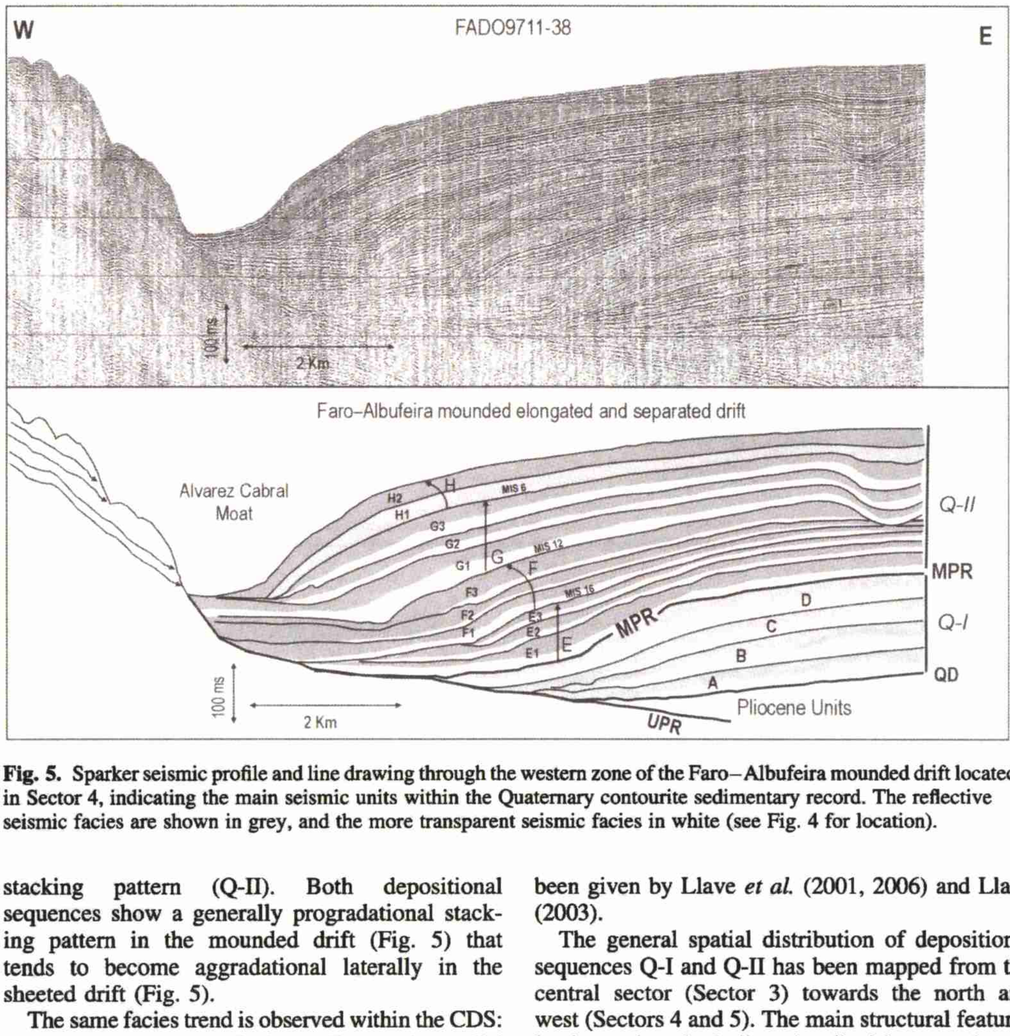


Fig. 5. Sparker seismic profile and line drawing through the western zone of the Faro–Albufeira mounded drift located in Sector 4, indicating the main seismic units within the Quaternary contourite sedimentary record. The reflective seismic facies are shown in grey, and the more transparent seismic facies in white (see Fig. 4 for location).

stacking pattern (Q-II). Both depositional sequences show a generally progradational stacking pattern in the mounded drift (Fig. 5) that tends to become aggradational laterally in the sheeted drift (Fig. 5).

The same facies trend is observed within the CDS: (1) a transparent zone at the base; (2) smooth, parallel reflectors of moderate to high amplitude in the upper part; (3) a high-amplitude erosive continuous surface at the top (Fig. 5). This cyclicity has helped to differentiate the superimposition of four minor depositional units in Q-I and Q-II (from A to D and from E to H) bounded by minor erosive and reflective surfaces, which are interpreted as discontinuities (Fig. 5). A further cyclic repetition of seismic facies is seen in Q-II, allowing the differentiation of minor seismic units (E_1, E_2, E_3, F_1, F_2, F_3, G_1, G_2, G_3, H_1 and H_2). The uppermost sequence, H is composed of four minor units: *a*, *b*, *c* and *d*, bounded by minor discontinuity surfaces. These minor units show vertical and gradual changes from transparent facies at the bottom to reflective facies near the top, which has allowed the differentiation of 10 subunits: a_1, a_2 and a_3; b_1, b_2, b_3 and b_4; *c*; d_1 and d_2 (Fig. 6a and b). The detailed description of these units is beyond the scope of the present paper, and further details have been given by Llave *et al.* (2001, 2006) and Llave (2003).

The general spatial distribution of depositional sequences Q-I and Q-II has been mapped from the central sector (Sector 3) towards the north and west (Sectors 4 and 5). The main structural features in the region, including the diapiric mounds and ridges and the Guadalquivir Bank uplift, have had a marked effect on the distribution of these depositional sequences. The most important depocentres in depositional sequence Q-I are located in the following areas (Fig. 7a): (1) the Faro–Albufeira drift, where the maximum thickness is about 200 ms; (2) south of the Faro–Cadiz sheeted drift, with a maximum thickness of 250 ms; (3) the central part of the Bartolomeu Dias sheeted drift, where a depocentre up to 300 ms (two-way travel time; twtt) thick is observed. The main depocentres of depositional sequence Q-II are located in similar areas and with similar orientations to those of sequence Q-I, as follows (Fig. 7b): (1) the Faro–Albufeira drift, where the maximum thickness is about 375 ms; (2) south of the Faro–Cadiz sheeted drift, up to 250 ms (twtt) thick; (3) the central part of the Bartolomeu Dias sheeted drift, where the depocentre is up to 300 ms (twtt) thick.

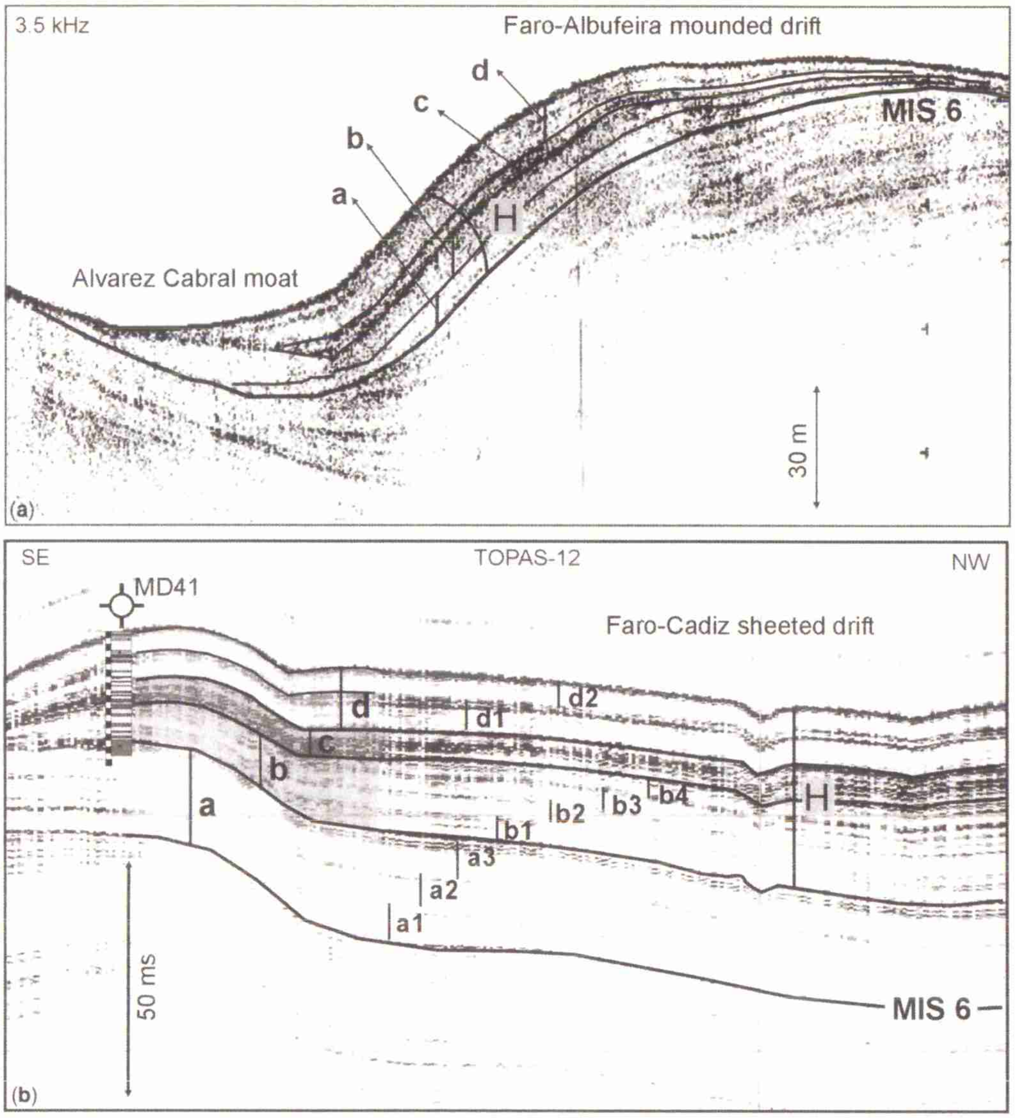


Fig. 6. (**a**) A 3.75 kHz seismic profile and line drawing through the mounded Faro–Albufeira drift indicating the main Late Pleistocene seismic units; (**b**) Topas seismic profile and line drawing through the Faro–Cadiz sheeted drift indicating the main seismic units within the main Late Pleistocene seismic units (modified from Llave *et al.* 2006) (see Fig. 4 for location).

A regional Quaternary chronostratigraphic framework is shown in Figure 8, where it can be determined that depositional sequences Q-I and Q-II are Quaternary in age, and the main discontinuities QD, MPR and MIS12 are dated at around 1.8 Ma, 900 ka and 400 ka, respectively (Llave 2003; Llave *et al.* 2004*a*, *b*, 2006), corresponding in age to the base of the Quaternary, the mid-Pleistocene and the late part of the mid-Pleistocene, respectively (Fig. 10a). In more detail, the youngest depositional sequence (H) is Late Pleistocene–Holocene in age (Fig. 10a). The oldest seismic unit *a* within sequence H was deposited between MIS 6 (135 ka) and Heinrich event H6 (57 ka), seismic unit *b* was deposited between H6 (57 ka) and H3 (32 ka), seismic unit *c* between H3 (32 ka) and H2 (24 ka), and the youngest seismic unit *d* was deposited between H2 (24 ka) and the present (Llave 2003; Llave *et al.* 2004*a*, *b*, 2006).

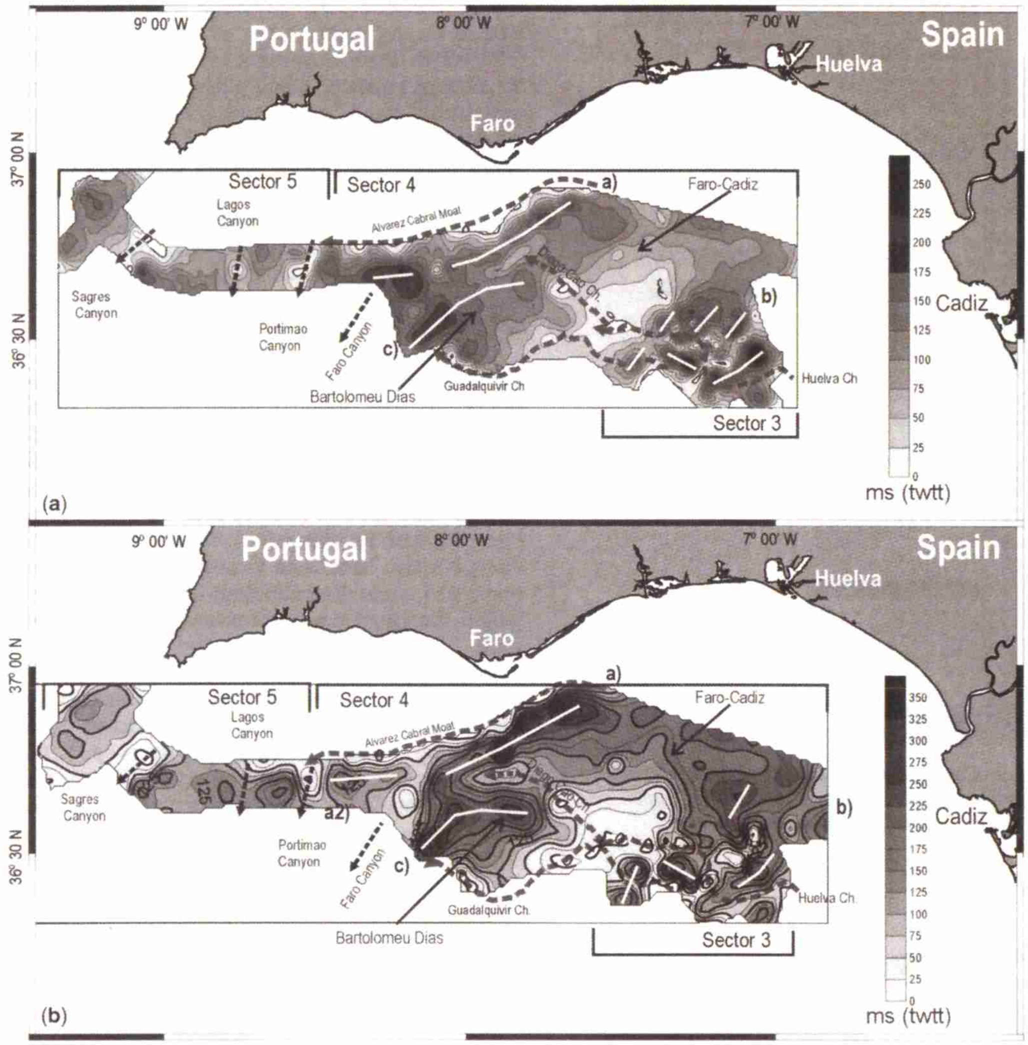


Fig. 7. Distribution and main depocentres of seismic units Q-I (**a**) and Q-II (**b**). The main depocentres are shown by white lines and lower-case letters.

Stratigraphic architecture of the major drift deposits

Within the CDS, significant differences in the Quaternary stratigraphic stacking pattern of the same major and minor depositional sequences are identified in the active and fossil (buried) drifts. Defining these changes is essential to understanding the evolution of the depositional system and for identifying major palaeoceanographic events.

Six contourite drifts have been identified (Fig. 11). Four of them follow the nomenclature of Faugères *et al.* (1999): (1) mounded elongated and separated; (2) sheeted; (3) plastered; and (4) wave fields, on the present sea floor. The other two are (5) fossil mounded drifts and (6) mixed drifts, so named because they are composed of inactive mounded drifts.

Active drifts

Mounded elongated and separated drifts. These drifts are located in Sectors 4 and 5 of the CDS. Three mounded elongated and separated drifts (hereinafter referred to as mounded drifts) are identified: the Faro–Albufeira, Lagos and Sagres drifts.

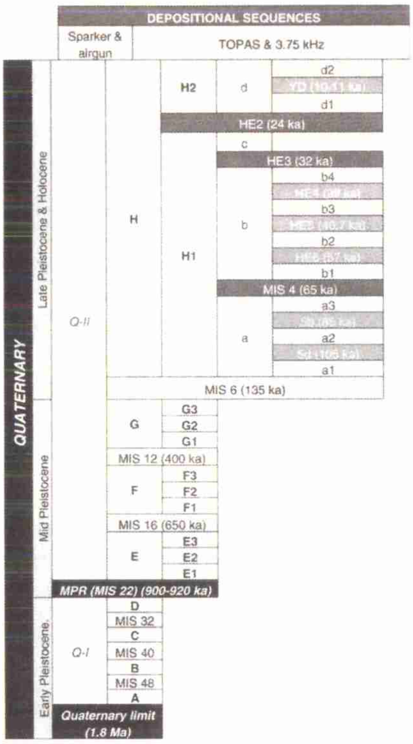


Fig. 8. Chronostratigraphic table of the Quaternary depositional sequences described from different resolution seismic profiles analyses.

The mounded Faro–Albufeira drift (Fig. 4) is located on the middle slope of Sector 4 at about 500–600 m depth. Two zones can be differentiated: an eastern proximal zone where the drift has a general SW trend, and a more distal western zone where the drift has a westward trend. These two zones follow the curved margin morphology, so that the drift is parallel to the upper slope, but separated from it by the Alvarez Cabral moat. The drift displays an asymmetrical mound shape with a steep, slump-prone northern flank and a gentler, smooth southern flank. It is around 80 km long, 12–20 km wide and about 75–100 m high.

Llave *et al.* (2001) considered that the Faro–Albufeira mounded drift is part of a system composed of five morphological elements; these are, from the upper slope to the middle slope: erosive surface on the upper slope; Alvarez Cabral moat; mounded elongated and separated drift; sheeted drift; erosive features over the drift. These elements can be recognized on the present sea floor, but also have been identified in each of the major and minor discontinuities defined previously within the Quaternary sedimentary record of the drift.

Major (Q-I and Q-II) and minor (A–H) depositional sequences described previously are vertically and spatially related, forming a 600 ms (twtt) thick Quaternary contourite deposit (Figs 4 and 5). Sequences exhibit a layered reflection pattern, the reflectors ranging from parallel and continuous to divergent or convergent, resulting in non-uniform thickness of the component layers with an evident

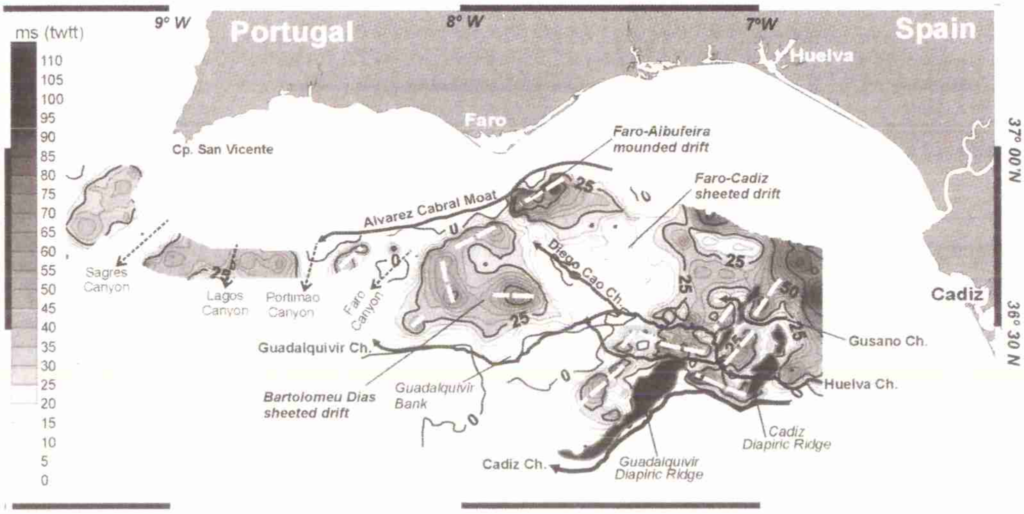


Fig. 9. Distribution and main depocentres of seismic unit H. The main depocentres are shown by white lines and lower-case letters.

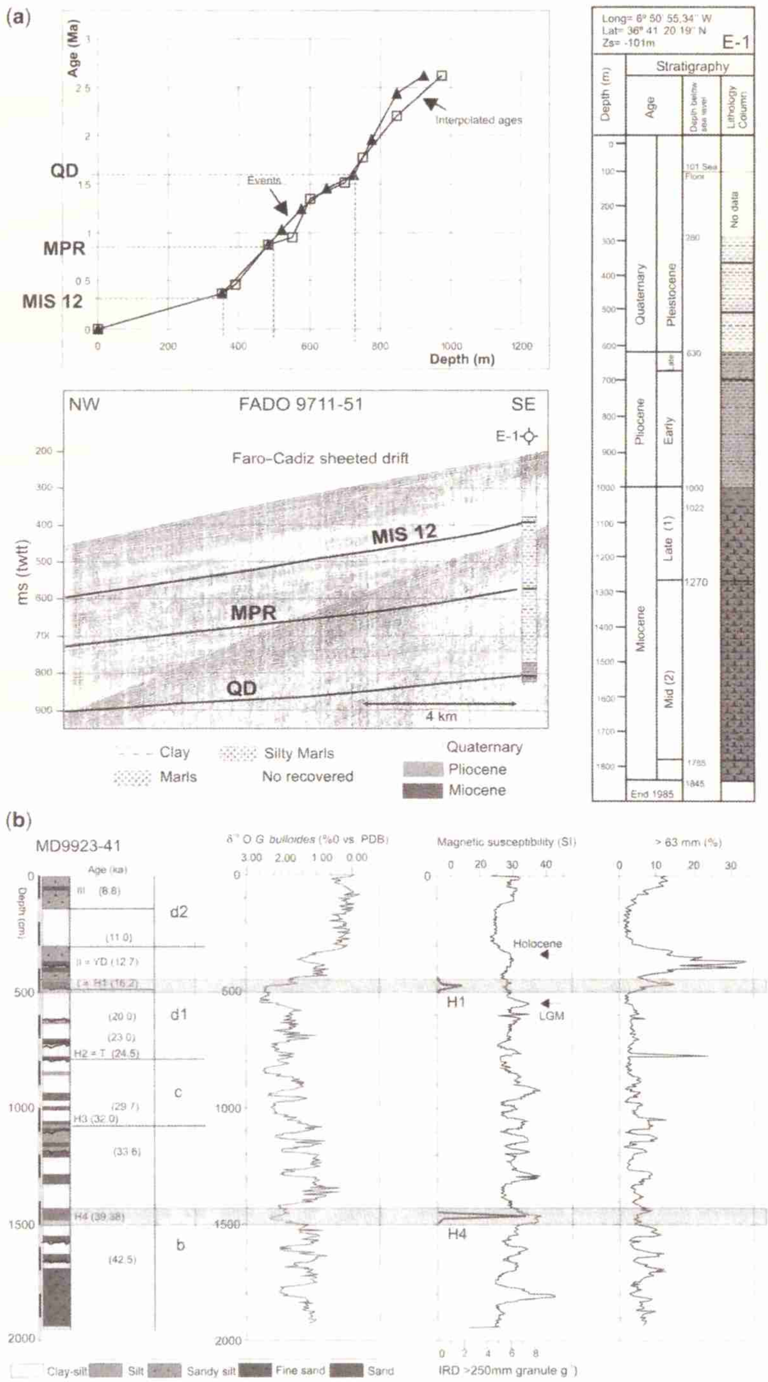


Fig. 10. (**a**) Example of the correlation between borehole E1 (see Fig. 3 for location) and a sparker seismic profile. The chronology of the discontinuities is based on calcareous nannofossil analyses, with three events that correspond to QD, MPR and MIS 12 (for detail see Llave *et al.* 2004*b*). (**b**) Example of the correlation between TOPAS seismic profile and Calypso piston core MD-41 (see Fig. 3 for location) and its $\delta^{18}O$, magnetic susceptibility and grain-size curves (after Mulder *et al.* 2002; Llave *et al.* 2006).

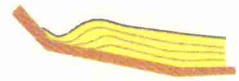
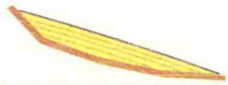
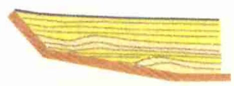
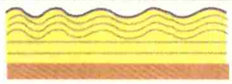
TYPES OF CONTOURITES					
	Deposits	Location		Stacking pattern	Sketch
ACTIVE DRIFTS	Elongate mounded & separated	Distal part of upper slope-Middle	Faro–Albufeira	Vertical and lateral prograding stacking pattern with downlap terminations	
		Upper slope	Sagres		
	Plastered	Upper slope	Ayamonte	Parallel stacking pattern with onlap terminations	
	Sheeted drift	Middle slope	- Faro-Cadiz - Bartolomeu Dias - Albufeira - Portimao - Lagos - Sagres	Vertical parallel or subparallel stacking pattern	
FOSSIL DRIFTS	Elongate mounded & separated	East of Faro–Albufeira active mounded drift	Cadiz	General prograding stacking pattern and change to aggrading stacking pattern in recent units	
		South of Guadalquivir Bank	Guadalquivir		
		Between Huelva and Guadalquivir channels	Huelva		
MIXED DRIFT		Middle slope	Ayamonte	Alternating aggrading stacking pattern units connected with the upper slope and prograding stacking pattern units separated from the upper slope	
BED FORMS		Middle slope: Sectors 1 and 2	Sectors 1 and 2 sedimentation	Bedforms in Unit H fossilizing the sheeted drift	

Fig. 11. Summary of the different types of contourite drifts described in the middle slope of the Gulf of Cadiz.

overall upslope direction of lateral sediment accretion. The most important change in the stacking pattern of the Faro–Albufeira mounded drift is associated with the MPR discontinuity, marking the change from an oblique progradational pattern to a more sigmoid progradational pattern (Figs 5 and 12a). This more progradational stacking pattern is observed in the western zone of the Faro–Albufeira drift, where depositional sequences are downlapping against the upper boundary of the lower sequences (Fig. 5), whereas in the eastern zone a change is observed from a sigmoid progradational configuration of the oldest sequences ($A–G_1$) (for the nomenclature see Llave *et al.* 2001; Llave 2003) to a more aggradational stacking pattern of the two youngest sequences ($G_2–H$) (Fig. 12a). Nevertheless, in the western zone a coeval change in the stacking pattern can be determined. Regarding the changes observed after MPR, depocentre locations of the minor sequences A–D display a NE migration, and a similar migration of depocentres has been determined for each of the sequences E–H (Fig. 12b). Nevertheless, a clear depocentre migration towards the SW is identified by comparing sequences D–E, in relation to the MPR discontinuity (Fig. 12b).

The mounded Lagos drift is located on the middle slope of Sector 5 with an east–west trend at around 950 m water depth, parallel to the upper slope, and separated from it by the Lagos moat (Fig. 4). It has an asymmetrical mound shape, and is around 8 km long, 6 km wide and about 75 m high. The Quaternary deposits reach about 240 ms (twtt) thick. Sequences display a similar stratigraphic stacking pattern to that of the Faro–Albufeira mounded drift in the western zone.

The mounded Sagres drift is located on the upper slope of Sector 5 south of Cape San Vicente, close to the shelf break between 300 and 500 m depth (Fig. 4). It has an asymmetrical shape, and is about 3 km long and 50 m high. The present sea floor represents a significant erosive surface, more prominent than any equivalent surface within the sedimentary record (Fig. 13). Sequences have a progradational stacking pattern towards the shelf break through the upper slope. They display a sigmoid to oblique–parallel configuration along with a significant discontinuity at the base.

Sheeted drifts. Within the CDS, seven major sheeted drifts have been recognized (Fig. 4), which occupy a large part of the basin floor of the

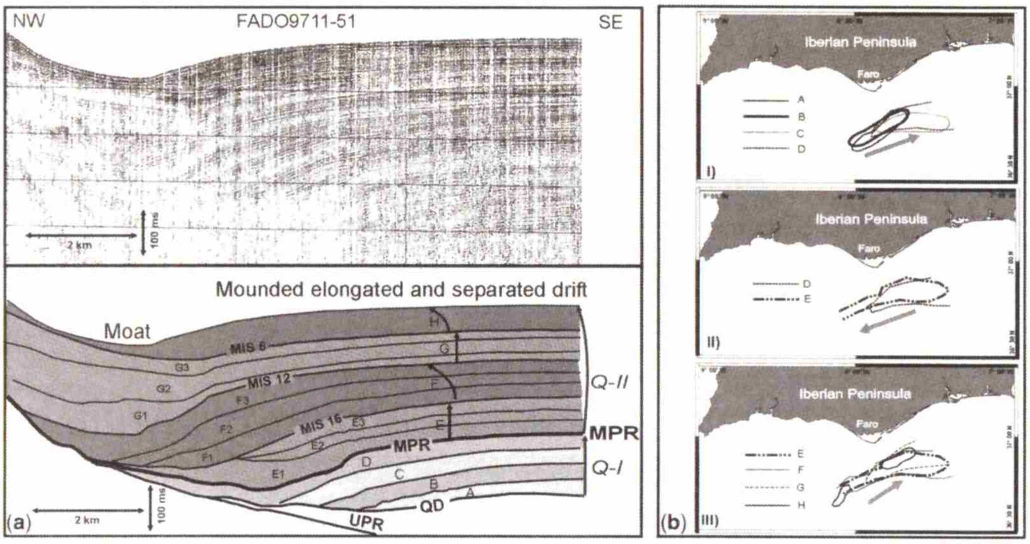


Fig. 12. (**a**) Sparker seismic profile and line drawing through the eastern zone of the Faro–Albufeira mounded drift located in Sector 4, indicating the main seismic units within the Quaternary contourite sedimentary record. The change related to the MPR discontinuity should be noted. Also, a change from a sigmoid progradational configuration of the oldest sequences (A–G) to a more progradational stacking pattern of the two youngest sequences (G and H) can be identified (see Fig. 4 for location). (**b**) Sketches of the changes observed in the western zone of the Faro–Albufeira mounded drift depositional sequences depocentres.

middle slope. They are located in Sector 4 (Faro–Cadiz; Bartolomeu Dias and Albufeira drifts, which form the basinward prolongation of the Albufeira–Faro mounded drift) and Sector 5 (Portimao, Lagos and Sagres drifts). In Sector 3, contourite deposits are mainly sheeted drifts but are widely deformed by diapirirism activity. Sheeted drifts are around 400 ms (twtt) thick on average in Sector 4, around 300 ms (twtt) on average in Sector 5, and up to 600 ms (twtt) in the deformed sheeted drifts of Sector 3. The *Faro–Cadiz drift* is the largest sheeted drift, with a maximum thickness up to

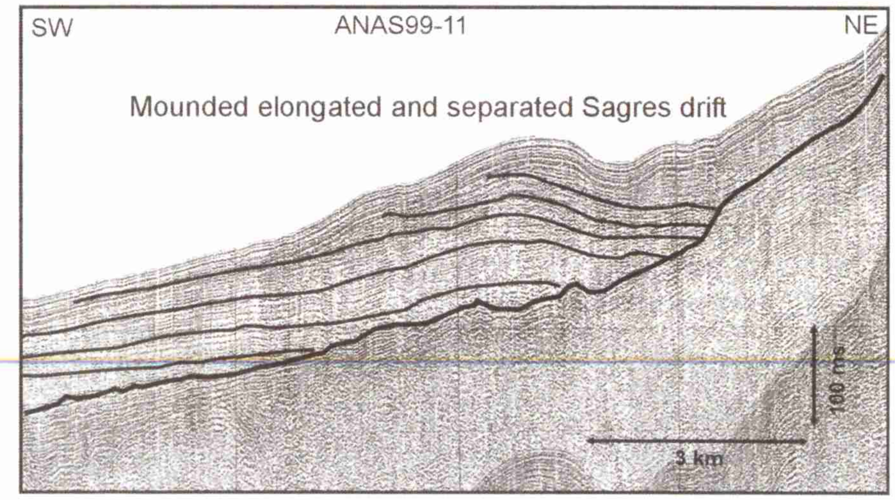


Fig. 13. Sparker seismic profile of the mounded Sagres drift located in Sector 5, which displays a sigmoid to oblique–parallel configuration along a discontinuity at its base (see Fig. 4 for location).

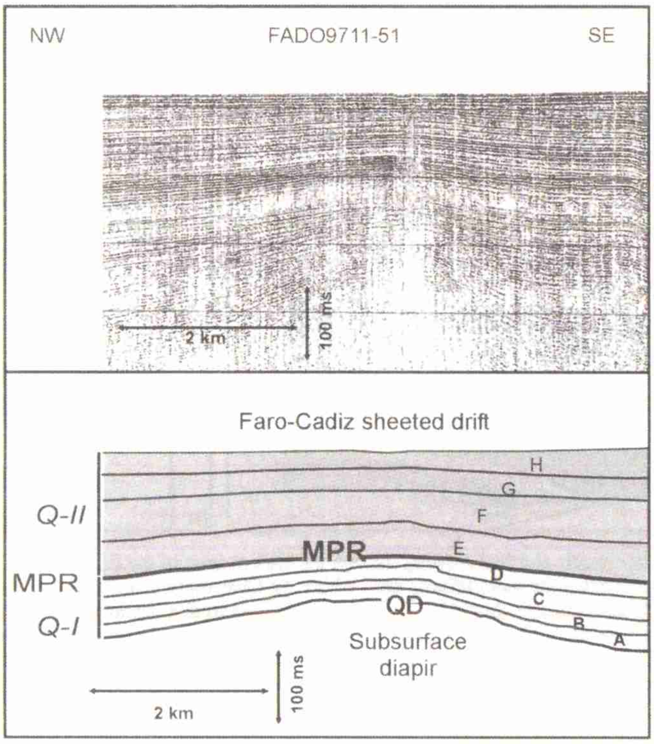


Fig. 14. Sparker seismic profile and line drawing through part of the Faro–Cadiz sheeted drift indicating the main seismic units within the Quaternary contourite sedimentary record. The stratigraphic stacking pattern of the sequences that form the sheeted drifts is mainly aggradational (see Fig. 4 for location).

500 ms and a width of several tens of kilometres. Its lateral extent is controlled by the upper slope to the east, several channels and diapiric ridges to the south, and the Diego Cao channel to the west (Fig. 4). The stratigraphic stacking pattern of the sequences that make up the sheeted drifts is mainly aggradational (Fig. 5b), with stratified, parallel (or subparallel) seismic facies, showing high lateral continuity (Fig. 14). Additionally, in Sector 3, the sequences are affected by low-frequency and low-amplitude anticline–syncline structures (Fig. 15).

Plastered drift. The plastered drift is located between the middle slope and the distal part of the upper slope, between 300 and 600 m water depth (Fig. 4), and develops eastward from the Faro–Albufeira mounded drift. It has a convex shape on the upper slope changing to concave on the middle slope. It is 35 km long and 12 km wide, with a thickness around 100 ms (twtt), forming depositional sequence H, and shows an aggradational stacking pattern and lens shape (Fig. 16). One intriguing feature of this drift is that it started

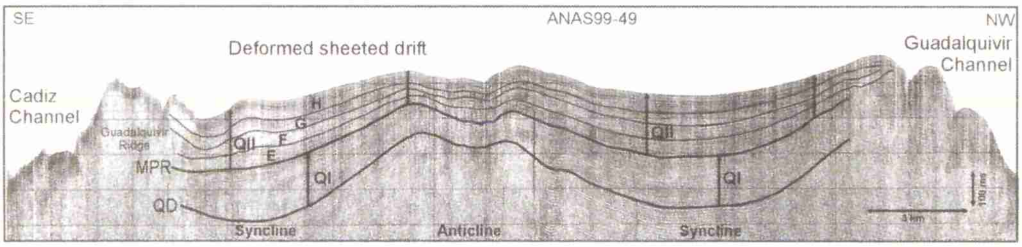


Fig. 15. Sparker seismic profile and line drawing through part of the deformed sheeted drift located in Sector 3 affected by low-frequency, low-amplitude anticline–syncline structures (see Fig. 4 for location).

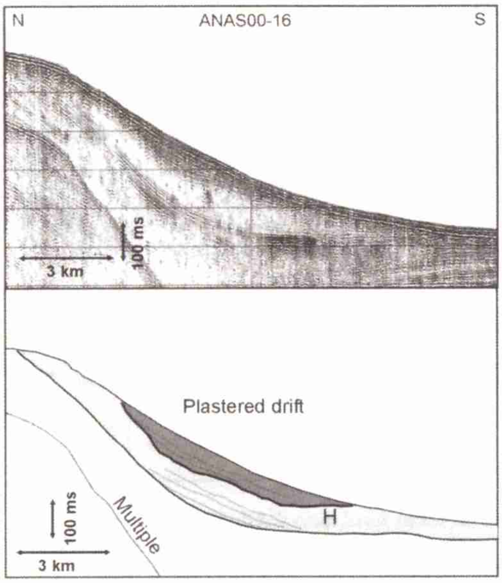


Fig. 16. Sparker seismic profile and line drawing through part of the plastered drift and the Ayamonte mixed drift located in Sector 4 (see Fig. 4 for location).

to be progressively developed some time within the deposition between depositional sequences G and H. This change in the stacking pattern of the upper slope could be coeval with the change in sedimentary architecture identified on the mounded Faro–Albufeira drift. On the other hand, within depositional sequence H a remarkable erosive surface is identified. Above this surface, the reflector configuration of the youngest deposits is one of onlap and downlap (Fig. 16).

Non-active mounded or fossil mounded drifts

In Sector 3 and part of Sector 4 of the middle slope, the main Late Quaternary deposits are sheeted drifts, deformed by local tectonics in Sector 3 and the alternation of mounded or sheeted drifts in Sector 4. However, beneath these deposits, three main mounded elongated and separated drifts have been identified, referred to here as fossil mounded drifts. The criterion for use of this nomenclature is based on the cessation of the mounded drift developing and their burial by a different contourite architectural style, generally sheeted drifts (Hernández-Molina *et al.* 2003; Llave *et al.* 2003*a*, *b*, 2006).

These fossil mounded deposits are: (1) the Cadiz fossil mounded drift (CFD); (2) the Guadalquivir fossil mounded drift (GFD); (3) the Huelva fossil mounded drift (HFD).

The Cadiz fossil mounded drift (CFD) is located in the NE zone of Sector 4, between 500 and 600 m depth, in the transition between the upper and middle slopes. It is 35 km long and 12–20 km wide. The CFD is composed only of sequence Q-I, and the stratigraphic stacking pattern of its minor sequences (A–D) displays a progradational configuration towards the upper slope (Fig. 17). Discontinuities bounding these minor sequences are locally depressed at the transition between the middle slope and the upper slope, which represents a system of fossilized moats laterally connected towards the west with the Alvarez Cabral moat (Fig. 17). These moats have no morphological expression on the present sea floor because they are completely filled and buried by sequence Q-II. Consequently, this mounded drift is an abandoned eastern part of the Faro–Albufeira mounded drift, which ended its development as a mounded elongated from and separated after the MPR discontinuity (Fig. 17).

The Guadalquivir fossil mounded drift (GFD) and the Huelva fossil mounded drift (HFD) are located in the central sector of the middle slope. They are characterized by depositional sequences with a progradational sigmoidal-to-oblique landward configuration prograding over a palaeoslope (Fig. 18a). Fossil mounded drifts are separated by a fossil moat from their palaeoslope, which will hereinafter be designated as the Guadalquivir fossil moat. The stratigraphic stacking pattern of the depositional sequences is different in both the GFD and HFD, showing a differential time interval for their activity as mounded elongated and separated drift, especially during the deposition of Q-II.

The Guadalquivir fossil mounded drift (GFD), is located south of the Guadalquivir Bank, at a depth of 1100 m. It is 15 km long and 6 km wide. In the GFD, despite strong erosion caused by the present Guadalquivir channel activity in this area, it can be observed that the fossil mounded drift deposits, *c.* 300 ms (twtt) thick, exhibit a prograding upslope stacking pattern (Q-I) (Fig. 18a). This depositional sequence has been buried and fossilized by a depositional sequence (Q-II) with an aggrading stratified stacking pattern, *c.* 175 ms (twtt) thick (Fig. 18a). Therefore, the MPR discontinuity constitutes in this sector an important erosive truncated surface, which separates the prominent northeasterly prograding body (Q-I) from a more aggrading one (Q-II) (Fig. 18a).

The Huelva fossil mounded drift (HFD) is located on the southern margin of the present-day Huelva Channel, at a depth of 650 m (Fig. 4). It is 32 km long and 6 km wide (Fig. 4). The HFD is characterized by a prominent northeasterly progradation of the internal reflectors, whereas the main axis of the body trends northwestwards. It is more than 400 ms (twtt) thick and comprises several

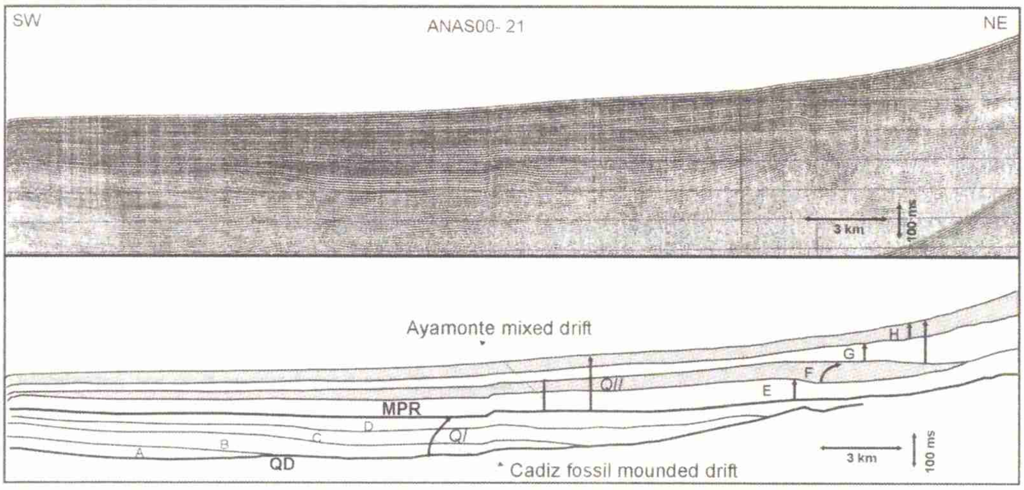


Fig. 17. Sparker seismic profile and line drawing through part of the Cadiz fossil mounded drift buried by the Ayamonte mixed drift located in Sector 4. It should be noted that the discontinuities bounded by the minor sequences of Q-I (A–D). Form depressions in the transition between the middle slope and the upper slope, which represent fossilized moats laterally connected towards the west with the Alvarez Cabral moat. Within Q-II, an aggradational stacking pattern is observed in E, and in connection with the upper slope units, followed by a mounded drift (F), and then by aggrading units connected with the upper slope depositional system (G and H) (see Fig. 4 for location).

sequences (A–H). This drift is buried by the most recent seismic unit (H), showing an aggrading stacking pattern, characterized by stratified, subparallel, high- and low-amplitude reflectors, 50–70 ms (twtt) thick (Fig. 18b). Consequently, the change in the depositional style of the mounded drift is related to the base of the seismic unit H (Fig. 18b).

The basinward prolongation of the three fossil mounded drifts (CFD, GFD and HFD) has an aggrading stacking pattern with alternating transparent and reflective units, constituting a sheeted–deformed contourite drift in Sector 3 and sheeted contourite drift in Sector 4.

Mixed drift

The mixed drift is located in the northeastern and eastern zone of Sector 4 (Fig. 4), and was developed during sequence Q-II above the Cadiz fossil mounded drift described above. It comprises an alternation of sequences with sheeted drift seismic facies characteristics and sequences with mounded and separated drift characteristics (Figs 17 and 19). This drift, named the Ayamonte mixed drift, has no morphological expression on the present sea floor, but is around 200 ms (twtt) thick within the Quaternary deposits (Q-II) (Figs 17 and 19).

The stratigraphic stacking pattern of the mixed drift is complex and two zones have been determined. In the northeastern zone the stratigraphic stacking pattern displays an alternation of sheeted and mounded deposits for sequences E and F, but a general aggrading stacking pattern for sequences G and H (Fig. 17). Sequences with sheeted drift facies are connected with the sequences of the upper slope but mounded drift facies at the top are disconnected from the upper slope (Fig. 17). The main change in the depositional style is related to the base of sequence G. Discontinuities bounding sequences E and F have depressions at the transition between the middle slope and the upper slope, which represent fossilized moats laterally connected towards the west with the Alvarez Cabral moat. These moats have no morphological expression on the present sea floor (Figs 4 and 17). In the southeastern zone, across the diapiric ridges, a different stratigraphic stacking pattern is evident. An alternation in the seismic facies has been identified within sequences EH. Transparent and massive facies in the lower part of the sequence have sheeted facies, but the reflective upper part of the sequence is characterized by a mounded and progradational seismic facies, which is visible in the youngest sequence (H; Fig. 19). At the top of the mounded and reflective facies an erosive surface is developed as the present sea floor in this area (Fig. 19).

Sediment wave fields

Sedimentary wave fields are widespread on the present sea floor in Sector 2, and especially in

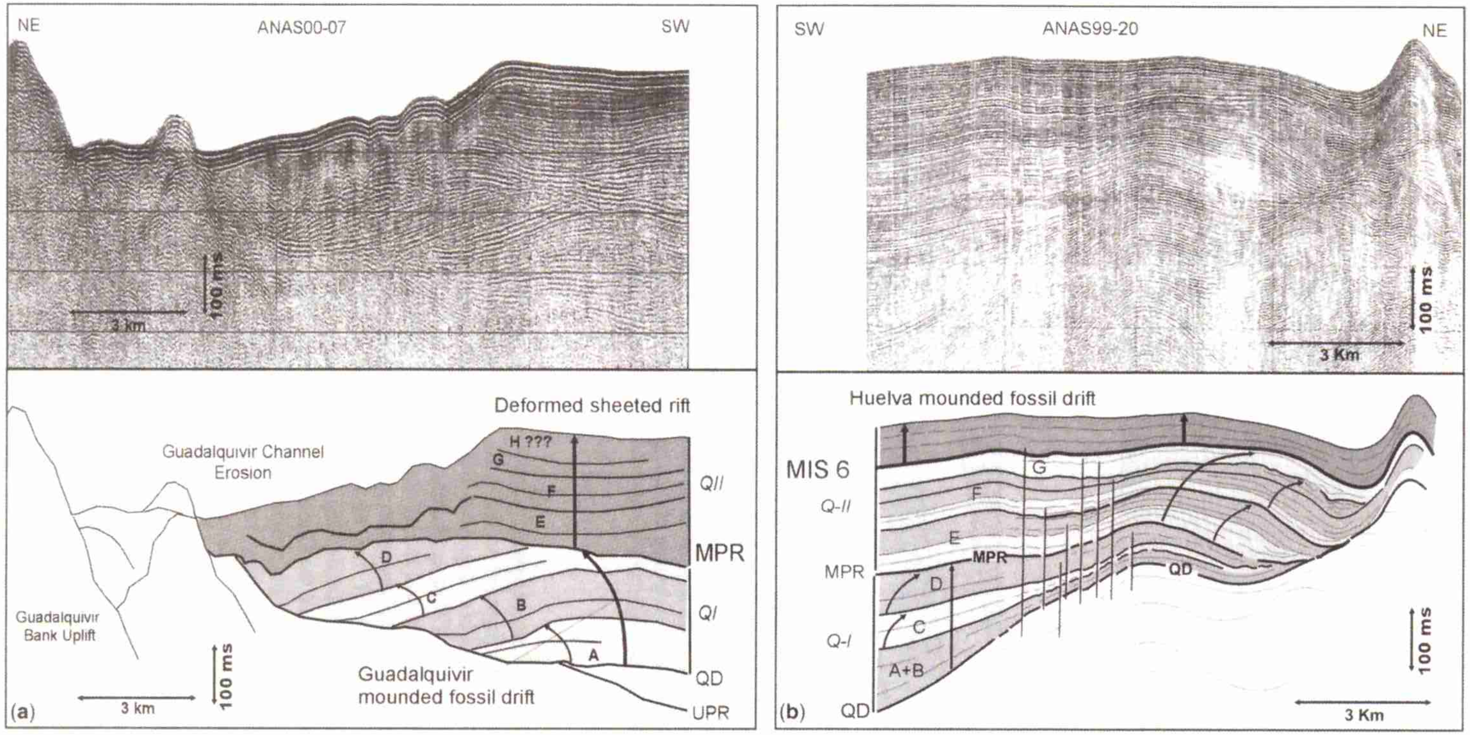


Fig. 18. (**a**) Sparker seismic profile and line drawing through part of the Guadalquivir fossil mounded drift. This drift is fossilized by the most recent aggradational seismic unit (H) (see Fig. 4 for location). (**b**) Sparker seismic profile and line drawing through part of the Huelva fossil mounded drift. The MPR discontinuity constitutes in this sector an important erosive truncated surface, which separates the prominent northeastwards prograding body (Q-I) from a more aggrading one (Q-II).

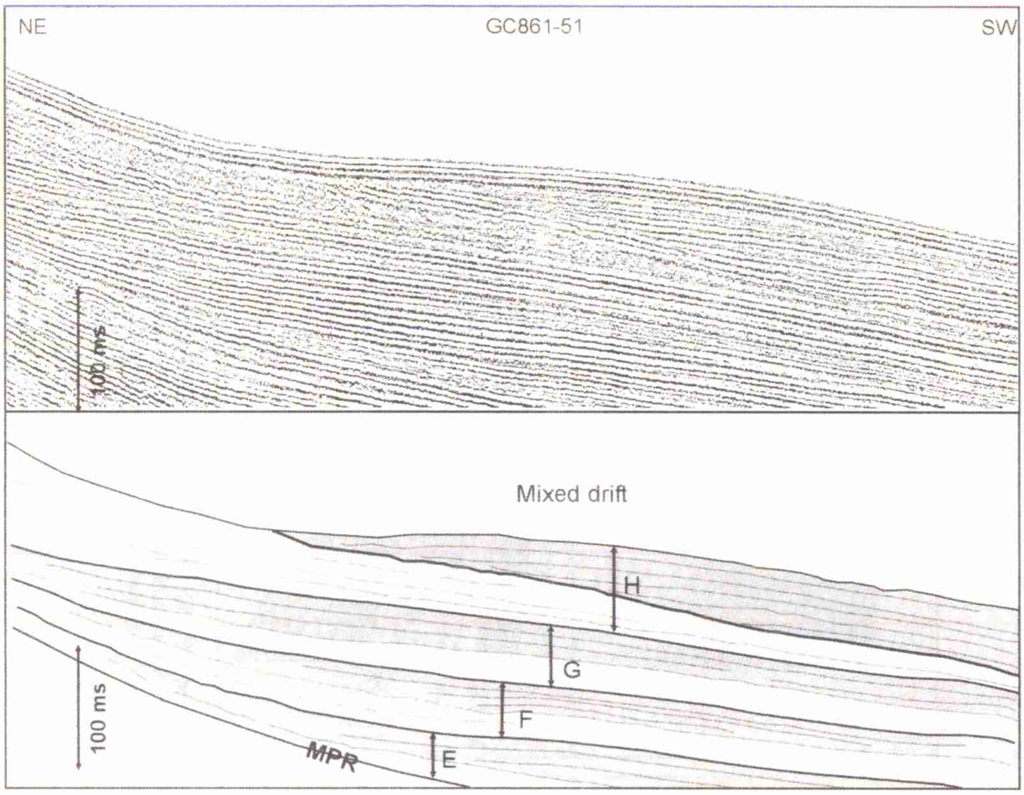


Fig. 19. Airgun seismic profile and line drawing through part of theAyamonte mixed drift located in the western zone of Sector 4. An alternation in the seismic facies has been identified within sequences E–H (see text for further details). It should be noted that the base of each depositional sequence is connected with the sedimentation of the upper slope; however, the top of the units is separated from the upper slope by erosive surfaces (see Fig. 4 for location).

Sector 1 of the CDS (Fig. 4). They represent secondary sedimentary features superimposed on the most recent sequence (H). This sequence displays a low-angle progradation towards the NW to aggradational configuration with high-amplitude and lateral continuity reflectors. Sedimentary wave fields have undulating seismic facies composed of bedforms of various wavelengths and low amplitude (Fig. 20). The stratigraphic stacking pattern of the Quaternary deposits of Sector 1 shows that the sedimentary wave field occurs only in the youngest sequence H. Older sequences (G, F, etc.) display sheeted contourite facies with less acoustic response and without the undulating wave facies (Fig. 20).

Major morphostructural features

The development and distribution of contourite deposits have been strongly influenced by the major morphostructural features in the Gulf of Cadiz, including the movement of diapirs, leading to both outcropping and buried diapiric ridges, the uplift of the Guadalquivir Bank, the displacement along several fault systems, and the evolution of anticline–syncline structures (Figs 4 and 21).

The areas where the deposits are more clearly deformed by recent tectonics are Sector 3 and the southern zone of Sector 4. The main structures that affect the contourite deposits in these sectors are (Figs 4 and 21): (1) the Cadiz and Guadalquivir diapiric ridges (GDR and CDR); (2) the Doñana buried diapiric ridge (DBDR); (3) the Guadalquivir Bank (GB). Diapiric ridges (GDR, CDR and DBDR) constitute elongated structures oriented NE–SW to NNE–SSW (Figs 4 and 21), which have undergone several episodes of activity from the Middle Miocene to the present (Maldonado *et al.* 1999; Maestro *et al.* 2003; Fernández-Puga 2004; Llave *et al.* 2006). In general, it has been

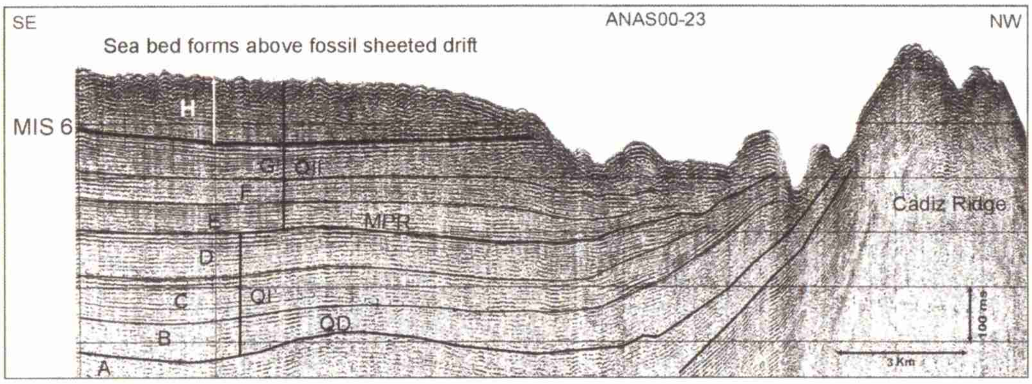


Fig. 20. Stratigraphic stacking pattern of the Quaternary deposits of Sector 1, showing that the sedimentary wave facies and seismic facies of sequence H are not identified in the oldest sequences, which display sheeted contourite facies with less acoustic response and without undulated facies (see Fig. 4 for location).

observed that the contourite sequences are synsedimentary with the emplacement of these tectonic structures during the Quaternary, especially observed within the depositional sequences A–G (Fig. 21b), the most recent sedimentation (depositional sequence H) being post-sedimentary (Fig. 21c). Several isolated diapiric outcrops and buried diapirs affect contourite sedimentation locally (Díaz del Río *et al.* 2003; Somoza *et al.* 2003). The contourite seismic units deposited during diapiric dome growths are characterized by thinning toward the axis of the diapiric uplift and only minor thickening into relatively distant peripheral sinks (Fig. 21b). These structures have determined not only the deformation of the sheeted drift and their extension in Sector 3, but have also conditioned the irregularities of the sea floor and the location of the Guadalquivir and Cadiz channels. The Guadalquivir Bank represents a structural high made up of Palaeozoic and Mesozoic basement rocks of the Iberian margin (Fernández-Puga 2004; Medialdea *et al.* 2004). This structure, located in the southern part of the Bartolomeu Dias sheeted drift (Figs 4 and 21), has played an important role in this area, affecting the hydrodynamic system and the accommodation space for Pliocene–Quaternary sedimentation, as we will see in the Quaternary evolution of the CDS. Its uplift from Pliocene to recent times (Maestro *et al.* 2003; Fernández-Puga 2004; Llave *et al.* 2006) has produced changes in the depositional geometry. Several discontinuities within the Bartolomeu Dias contourite sheeted drift have developed, as well as the generation of a monocline in the northern Bartolomeu Dias zone affecting especially the Q-I unit (Fig. 21d and e). The contourite sedimentation and MOW pathways have been conditioned not only by these morphostructural features, but also by the submarine canyons' trajectories (Fig. 21a and f).

Quaternary evolution of the contourite depositional system: a discussion

The contourite depositional system (CDS) of the Gulf of Cadiz began its development after the opening of the Strait of Gibraltar at the end of the Messinian (e.g. Madelain 1970; Mélières 1974; Gonthier *et al.* 1984; Faugères *et al.* 1985; Nelson *et al.* 1993, 1999; Llave *et al.* 2001, 2004*a*, 2006; García 2002; Mulder *et al.* 2002, 2003; Stow *et al.* 2002; Habgood *et al.* 2003; Hernández-Molina *et al.* 2003, 2006; Llave 2003). Since then, it has been influenced principally by tectonics, global climate and sea-level changes. The influence of global climate and sea-level changes is observed in the cyclic nature of the depositional sequences, not only the seismic facies but also the distribution of depocentres, especially observed in the northern part of the CDS, in the Faro–Albufeira mounded elongated and separated drift (Llave *et al.* 2001; Llave 2003). Based on the stratigraphic stacking patterns identified in the six types of contourite drifts described, three main stages have been recognized in the evolution of the CDS influenced by tectonics (Fig. 22): (1) Early Pleistocene to Mid-Pleistocene; (2) Mid-Pleistocene to Late Pleistocene; and (3) Late Pleistocene to Holocene.

Early Pleistocene to Mid-Pleistocene CDS: depositional stage (from QD to MIS 22)

The regional paleogeography during this first evolutionary stage of the Quaternary, which covers the time interval of sequence Q-I (depositional

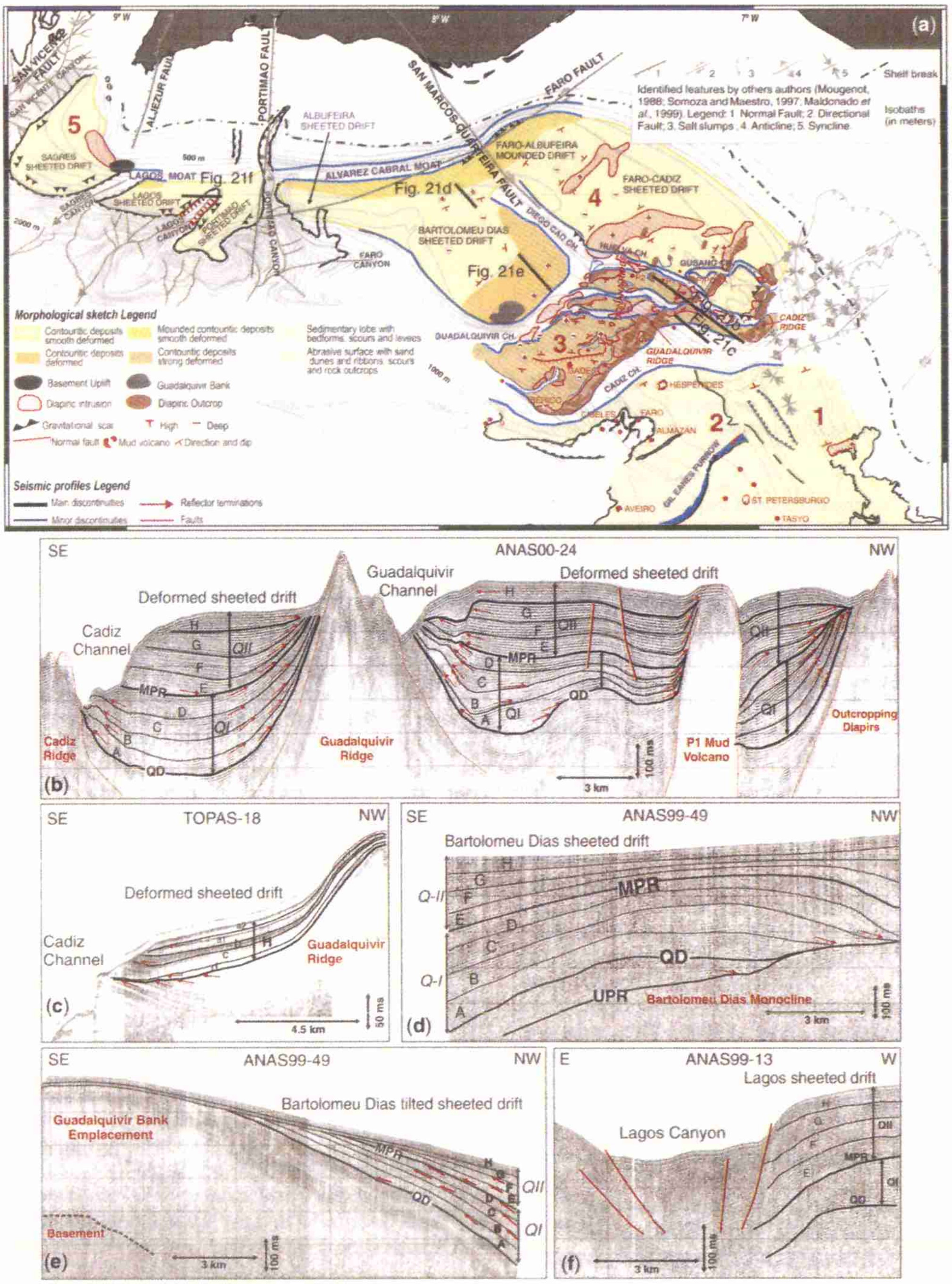


Fig. 21. Morphostructural sketch of the main geological features that affect the contourite depositional system on the middle slope of the Gulf of Cadiz, with some examples of these structural characteristics shown on sparker seismic profiles.

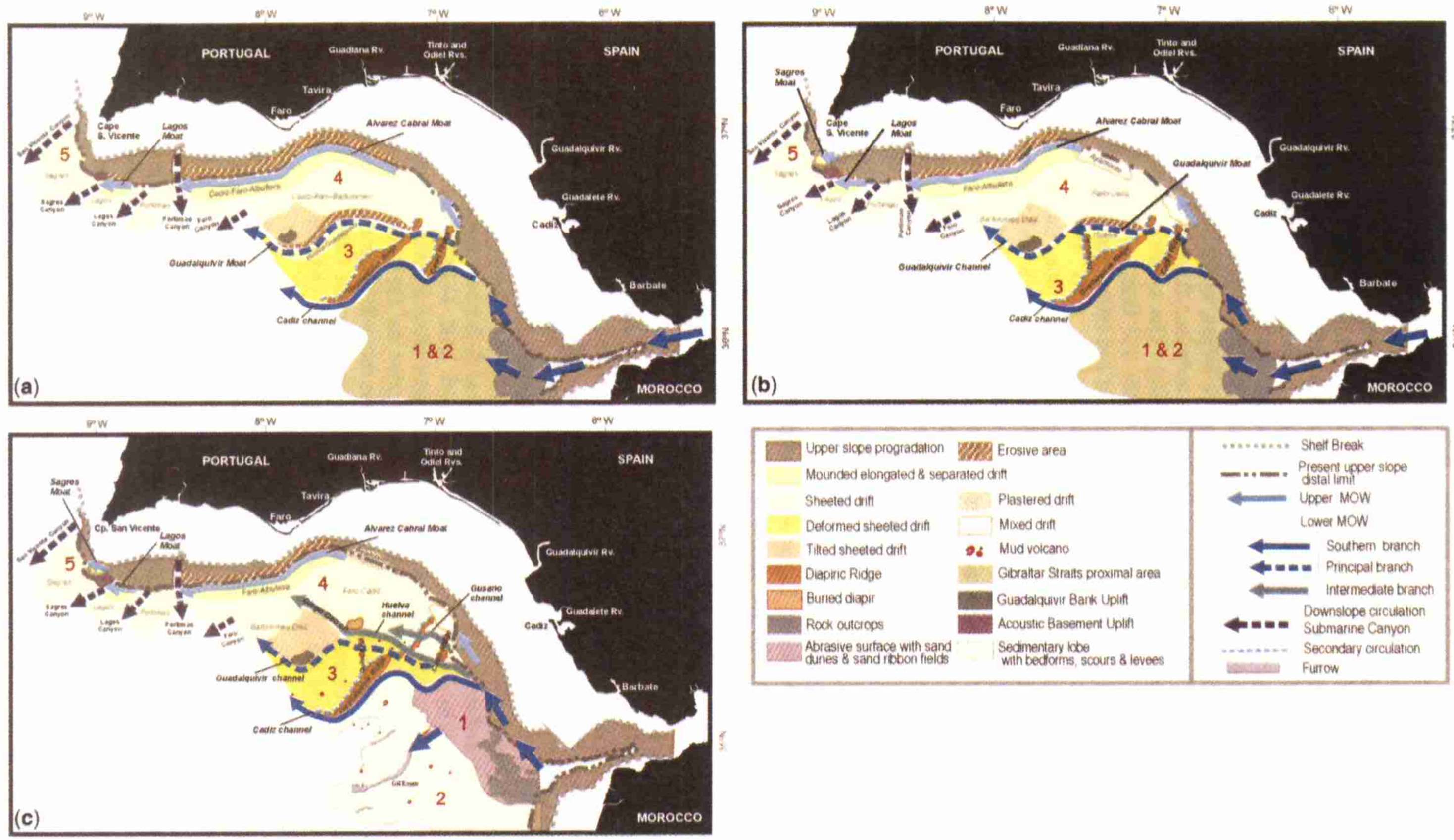


Fig. 22. Interpretative sketch of palaeogeography and palaeoceanography with a reconstruction of the evolution of the contourite depositional system during: **(a)** the Early to Mid-Pleistocene, when the depositional sequences A–D developed; **(b)** the Mid- to Late Pleistocene, when depositional sequences E–G developed; **(c)** the Late Pleistocene and Holocene, when depositional sequence H developed. (See text for details.)

sequences A–D), is shown in Figure 22a. Sectors 1 and 2 of the CDS were characterized by the development of broad sheeted drifts bounded by extensive abrasion surfaces. In the northern part of Sector 3, the wide mounded elongated and separated Huelva–Guadalquivir drift (Fig. 18) was developed along the southern side of the Guadalquivir moat (Fig. 22a). The basinward prolongation of this mounded drift is composed of a large sheeted drift (Fig. 22a), whereas in the southern part of Sector 3, the Cadiz Channel was active between the Cadiz and Guadalquivir diapiric ridges as a large contourite channel (Fig. 22a).

During this period, the Alvarez Cabral moat and the mounded elongated and separated Cadiz–Faro–Albufeira drift were already active in the northern part of Sector 4 (Figs 12 and 17), being located close to the diapiric structures of Sector 3 and extending as far west as Portimao Canyon. As can be observed, the eastern lateral extension with respect to the present Faro–Albufeira mounded drift is consequently greater (Fig. 4), this being zthe reason why it has been named the Cadiz–Faro–Albufeira drift (Fig. 22a). The basinward prolongation of this mounded drift was represented by broad sheeted drifts (the Faro–Cadiz–Bartolomeu Dias and Albufeira drifts). In Sector 5, the main contourite sheeted drifts (the Portimao, Lagos and Sagres drifts) were deposited. Only the mounded elongated and separated Lagos drift was already active in the northern part of the Lagos shelf (Fig. 22a).

Based on the aforementioned regional palaeogeographical reconstruction, the regional MOW palaeoceanographic conditions are considered during this time. From Early Pleistocene to Mid-Pleistocene times, contourite depositional processes dominated in Sectors 2–5. Erosive processes were dominant in Sector 1 close to the Strait of Gibraltar, giving rise to the rough surface.

Sheeted drifts identified in Sectors 1 and 2 are indicative of a tabular behaviour of the MOW (Fig. 22a). Following this, three main branches of the MOW can be defined. One branch can be related to the Mediterranean Upper Core (MU) of the MOW, and the other two to the Mediterranean Lower Core (ML).

The MU flowed along the base of the upper slope. This core became turbulent after the diapiric structures located in the northern part of Sector 3, favouring enhancement of the MU and development of the Alvarez Cabral moat (Fig. 22a). This moat extended to the west as far as Portimao Canyon and along the MU trajectory, and the flow generated both erosion in the northern margin (upper slope) and the mounded Cadiz–Faro–Albufeira drift in the south (Fig. 22a). Westward from the Portimao Canyon, the MU evolved into a more tabular flow (Fig. 22a), once more becoming locally turbulent close to the Sagres Canyon as a result of its interaction with local topography. This led to the development of the short Lagos moat and the mounded elongated and separated Lagos drift (Fig. 22a).

The ML flowed along the middle slope and its interaction with the Cadiz and Guadalquivir diapiric ridges produced two branches (Fig. 22a), the southern and northern branches. The southern branch interacted with the Cadiz diapiric and Guadalquivir ridges, where it was intensified and generated a turbulent flow through the Cadiz channel (Fig. 22a). The northern branch flowed through the Cadiz and Guadalquivir ridges and became a turbulent and intensified flow, which generated the Guadalquivir moat (Fig. 22a). The northern branch through this moat formed an erosive surface to the north and developed the Huelva–Guadalquivir mounded drift to the south (Fig. 22a). A wide sheeted drift constituted the basinward prolongation of these mounded drifts, where the ML became tabular (Fig. 22a). The circulation of the ML through the north of the diapiric structures also generated marginal valleys that eroded the adjacent sheeted drifts (Fig. 22a).

Mid-Pleistocene to Late Pleistocene CDS: transitional stage (from MIS 22 to MIS 6)

Most of sequence Q-II (depositional sequences E–G) was deposited during this second major evolutionary stage. The characteristics of Sectors 1 and 2 were nearly the same as for the first stage, and the most important change produced in the stacking pattern of the contourite deposits occurred in Sector 3. The westernmost part of the Guadalquivir–Huelva mounded elongated and separated drift located south of the Guadalquivir Bank, in the area of Sector 3, became inactive (fossil Guadalquivir mounded drift, FGD) (Figs 18 and 22b). In its place, extensive sheeted drift sequences were generated after the MPR discontinuity, fossilizing the previous mounded deposits. It can also be observed in this zone that the Guadalquivir moat passes into the Guadalquivir channel (Fig. 22b). On the other hand, the eastern part of this Guadalquivir–Huelva mounded drift (from now on named the Huelva mounded drift), between the Guadalquivir diapiric ridge on the right and the Doñana diapiric ridge on the left, was still active (Figs 18 and 22b).

Another change observed during this period took place in the eastern and northern parts of Sector 4, where the Ayamonte mixed drift developed (Figs 16, 17, 19 and 22b), fossilizing part of the Faro–Cadiz sheeted drift and the eastern part of the Cadiz–Faro–Albufeira mounded drift (this part is named the fossil Cadiz mounded drift, FCD). Therefore it can be observed that the active mounded drift deposits during this stage migrated northward, as did the Alvarez Cabral moat, being located at almost the same place as at present (Figs 4 and 22b). However, the palaeogeographical situation of the rest of Sectors 4 and 5, from the Mid-Pleistocene to the Late Pleistocene, was similar to that of the previous stage.

Changes in the architecture style of the contourite deposits and the evolution between the first and the second stages are probably related to tectonic activity in the Guadalquivir Bank and diapiric ridge area (Figs 21 and 22b). Diapiric ridge movements and Guadalquivir Bank uplift were most probably related to the compressive regime that took place at 740–450 and 295–225 ka as described by Rodero (1999) and Rodero *et al.* (1999).

Based on the regional palaeogeographical reconstruction for this second stage, the MOW palaeoceanographic conditions can be considered. From Mid- to Late Pleistocene, contourite depositional processes were dominant in Sectors 2–5. Erosive processes were more dominant in Sector 1, close to the Straits of Gibraltar (Fig. 22b).

New local oceanographic conditions in the Upper and Lower Cores (MU and ML) of the MOW were established.

The focus of the MU fluctuated northwards during this stage after passing the diapiric ridge in the areas where the Ayamonte mixed drifts are developed. In the westernmost part of these mixed drifts, the MU was sufficiently enhanced to excavate the Alvarez Cabral moat (Fig. 22b). The flow of this MU through the moat extends to the west as far as Portimao Canyon as a turbulent regime that generated erosion along the northern margin of the moat and the mounded Faro–Albufeira drift growth along the southern flank (Fig. 22b). This MU evolved into a tabular flow towards the west of Portimao Canyon, in Sector 5, but became turbulent again following interaction with local irregularities of the middle slope, generating the short Lagos moat and the mounded elongated and separated Lagos drift (Fig. 22b).

During this second stage, the ML circulated along the middle slope and was also divided into two branches (southern and northern). The southern branch flowed through the Cadiz contourite channel as in the first evolutionary stage. On the other hand, the northern branch showed more turbulent behaviour after crossing the diapiric ridges and was focused along the Guadalquivir moat, which developed an erosive surface to the north and the Huelva mounded drift to the south (Fig. 22b). Laterally, the Guadalquivir moat continues to the Guadalquivir channel; mounded deposits did not develop, but the deposits changed laterally into a sheeted drift (Fig. 22b). This change in the type of the contourite development is puzzling. We hypothesize that: (1) along the Guadalquivir channel, the condition of the northern branch of the ML could have been too energetic because of its interaction with the Guadalquivir Bank, so erosive processes dominated along the southern boundary of that bank (Fig. 22b); (2) the mounded drift was developed after the MPR but because the high intensity of the MOW it was later eroded; (3) the Guadalquivir Bank Uplift of ancient highly consolidated material provided insufficient material to allow construction of a mounded drift on the opposite flank. Clearly, this situation was different from that of the first stage. On the other hand, in the central area of Sector 3, the tabular ML favoured development of a broad sheeted drift (Fig. 22b).

Late Pleistocene to Holocene CDS: the present configuration (from MIS 6 to present)

During this last evolutionary stage, the upper part of sequence Q-II was deposited (depositional sequence H). Most of the present contourite features were developed during this stage; in particular, most of the erosive characters observed in Sector 3 (Fig. 22c).

In Sector 1, more erosive features began to be developed, as an abrasion surface with erosive scours alignment and furrows. Numerous sedimentary waves were also developed, not only in Sector 1 but also in Sector 2. This change in the system is determined by the high acoustic response of depositional sequence H in comparison with the previous sequences (Fig. 20).

In Sector 3, new contourite channels were formed, including the Gusano and Huelva channels and other minor branches related to the Guadalquivir channel (Fig. 22c). In the northern part of Sector 3, the previous mounded elongated and separated Huelva drift disappeared completely (fossil Huelva mounded drift, FHD), being buried by the youngest sheeted drift and eroded by the Huelva contourite channel (Fig. 22c). This change in the depositional style of the margin took place just before depositional sequence H (Figs 18 and 21).

Another change during this third stage is observed on the Ayamonte mixed drift, in the eastern and northern parts of Sector 4. Drift deposits again migrated northward with an aggradational stacking pattern (Fig. 17). Laterally to the NW, a plastered drift started to develop in the transition zone between the upper and middle slopes (Fig. 16), located to the east of the Faro–Albufeira mounded drift and Alvarez Cabral moat, which reached its present location (Fig. 22c). The palaeogeographical situation of Sector 5 during this stage was similar to that of the previous one.

These changes from the second to the third evolutionary stages can be related to coeval tectonic movements in the Strait of Gibraltar described by Zazo *et al.* (1999), and in the reactivation of the diapiric ridges and isolated diapiric bodies of Sector 3 (Pérez-Fernández 1997; Llave *et al.* 2006). Our hypothesis is that recent tectonic activity conditioned a new sea-bottom morphology, especially regarding the Guadalquivir and Cadiz diapiric ridge configuration on the sea floor (Fig. 22c), and this controlled new flow pathways, with the strongest flowing branches of the MOW over the middle slope. Consequently, a general circulation of the MOW similar to the present one was established during this stage.

Immediately outside the Strait of Gibraltar, the MOW generated erosive features in those areas close to the Strait and, where the velocity decreased, numerous depositional bedforms and sedimentary lobes were developed (Fig. 22c).

The Mediterranean Upper Branch (MU) flowed along the transition between the middle and upper slopes. Tectonic changes in the diapiric ridges (Pérez-Fernández 1997) helped condition the lateral migration of the MU towards the north, in shallower areas than during the second stage, and with a more tabular flow character. New circulation of the MU along the upper slope generated the plastered drift. The main change in the morphology of the Algarve margin from a NW to a SW bathymetric trend was important enough to generate the MU path again in the transition between the upper and middle slopes as far west as the Portimao canyon. Therefore, in the northern part of Sector 4, the MU was enhanced and excavated the *Alvarez Cabral moat*, developing an erosive surface to the north and the *mounded Faro–Albufeira drift* to the south (Fig. 22c). When the MU passed the Portimao Canyon it evolved into a tabular flow in Sector 5, although it became turbulent locally over the Lagos shelf, leading to development of the *Lagos moat* and the *mounded elongated and separated Lagos drift* (Fig. 22c).

The Mediterranean Lower Branch (ML) had a complex interaction with the sea-floor topography generated by the diapiric ridges, which led to progressive erosion through several contourite channels. The three main branches identified at present (Southern, Principal and Intermediate branches) were active during this third stage (Fig. 22c). Part of the ML flow (the Southern branch) was deflected by the linear NE–SW-trending Cadiz and Guadalquivir diapiric ridges, and focused through the Cadiz channel. The other two branches of the ML followed and sculpted different channels: the Principal branch followed the main Guadalquivir channel; the Intermediate branch first followed the Huelva channel and then linked up with the Diego Cao channel. A fourth minor, unnamed branch probably followed the Gusano channel before joining the Huelva channel (Fig. 22c).

Conclusions

According to stratigraphic stacking pattern studies of the CDS, four major contourite drift types have been identified: mounded elongated and separated drifts; sheeted drifts; plastered drifts; deformed sheeted drifts. All these drifts have a morphological expression on the present sea bottom. In this study, we recognize a further two buried drift types, mixed drifts and fossil mounded drifts, which occur in the Quaternary sedimentary record buried by other younger non-mounded elongated and separated deposits.

The nature and changes in the CDS facies have been correlated with climatic cycles during the Quaternary, especially those from the Mid-Pleistocene. Nevertheless, superimposed on these climatic changes, tectonics during the Quaternary has determined, in the short term, the local thickness, geometry and development of different types of contourite drifts owing to its contribution to new oceanographic conditions. Tectonics has represented a key long-term factor in sea-floor morphology changes, which has controlled at every stage new pathways in the cores and branches of the MOW. Consequently, the behaviour of these cores and branches controlled the contourite stratigraphic architecture. The understanding of this stratigraphic architecture has helped us to recognize three main stages during the evolution of the CDS affected by tectonics. (1) In the Early Pleistocene to Mid-Pleistocene, the CDS was mainly dominated by depositional processes, where the Upper and Lower cores of the Mediterranean Outflow Water (MOW) generated the Cadiz–Faro–Albufeira mounded elongated and separated drift in the transition between the middle and upper slope, and the equivalent Huelva–Guadalquivir drift on the middle slope. During this stage the main erosive features were established close to the Strait of Gibraltar. (2) In the Mid-Pleistocene to Late Pleistocene, two important changes in the CDS took place. One occurred in the transition between the middle and upper slope, related to a change in the upper branch of the MOW, where a mixed drift began to develop, burying the eastern part of the Cadiz–Faro–Albufeira mounded elongated and separated drift. The second change is observed on the central area of the middle slope, related to the lower branch of the MOW, where a large contourite channel (the Guadalquivir channel) progressively eroded the western part of the mounded Huelva–Guadalquivir drift. Laterally an extensive sheeted drift buried the previous mounded deposits. (3) In the Late Pleistocene to Holocene, in the northern area of the CDS, a plastered drift started to be developed in the transitional zone between the upper and middle slope, close to the eastern part of Faro–Albufeira mounded drift. On the middle slope, the mounded elongated Huelva–Guadalquivir drift was not developed and more erosive processes became dominant as the lower core of the MOW intensified. In the sector close to the Straits of Gibraltar, broad sea-bed forms were generated.

These evolutionary stages were most probably a function of synsedimentary tectonic activity, including diapiric ridge movement, bank uplift and compressive structures. The general conclusion of this study is that the contourite depositional system of the Gulf of Cadiz changed from a predominantly depositional system during the Early to Mid Pleistocene, to a predominantly erosive system during the Late Pleistocene.

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