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Seismic stacking pattern of the Faro-Albufeira contourite system (Gulf of Cadiz): a Quaternary record of paleoceanographic and tectonic influences

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Abstract

A Quaternary stratigraphic stacking pattern on the Faro-Albufeira drift system has been determined by analysing a dense network of high-resolution single-channel seismic reflection profiles. In the northern sector of the system an upslope migrating depositional sequence (elongate separated mounded drift) parallel to the margin has been observed associated with a flanking boundary channel (Alvarez Cabral moat) that depicts the zone of Mediterranean Outflow Water (MOW) acceleration and/or focussing. A consequent erosion along the right hand border and deposition on the left hand flank is produced in this sector. The sheeted aggrading drift is the basinward prolongation of the elongate separated mounded drift, and developed where the MOW is more widely spread out. The overall sheeted contourite system is separated into two sectors due to the Diego Cao deep. This is a recent erosional deep that has steep erosional walls cut into Quaternary sediments. Two major high-order depositional sequences have been recognised in the Quaternary sedimentary record, Q-I and Q-II, composed of eight minor high-order depositional sequences (from A to H). The same trend in every major and minor depositional sequence is observed, especially in the elongate mounded drift within Q-II formed of: A) Transparent units at the base; B) Smooth, parallel reflectors of moderate-high amplitude units in the upper part; and C) An erosional continuous surface of high amplitude on the top of reflective units. This cyclicity in the acoustic response most likely represents cyclic lithological changes showing coarsening- upward sequences. A total of ten minor units has been distinguished within Q-II where the more representative facies in volume are always the more reflective and are prograding upslope with respect to the transparent ones. There is an important change in the overall architectural stacking of the mounded contourite deposits from a more aggrading depositional sequence (Q-I) to a clear progradational body (Q-II). We suggest that Q-I and Q-II constitute high-order depositional sequences related to a 3rd-order cycle at 800 ky separated by the most prominent sea-level fall at the Mid Pleistocene Revolution (MPR), 900–920 ky ago. In more detail the major high-order depositional sequences (from A to H) can be associated with asymmetric 4th-order climatic and sea-level cycles. In the middle slope, the contourite system has a syn-tectonic development with diapiric intrusions and the Guadalquivir Bank uplift. This syn-tectonic evolution affected the overall southern sheeted drift from the A to F depositional sequences, but G and H are not affected. These last two depositional sequences are less affected by these structures with an aggrading stacking pattern that overlaps the older depositional sequences of the Guadalquivir Bank uplift and diapiric intrusions.

Introduction

In this paper we describe the seismic characteristics, sequence stratigraphy and stacking pattern of the Faro-Albufeira contourite system, which is located on the middle continental slope south of the Iberian peninsula (Figure 1). The system includes asymmetric elongate separated mounded and sheeted drifts that have accumulated in association with active diapirs and the uplift of the Guadalquivir Bank. Following the nomenclature of Faugères et al. (1999), the mounded portion that forms the northern part of the system is characterised by a progradational seismic stacking pattern and is classified as a separated elongate mounded drift. The drifts of the Faro Planalto together with the neighbouring Bartolomeu Dias Planalto that display a simple aggrading stacking pattern are classified as broad sheeted drifts. The 'Fosses' are interpreted

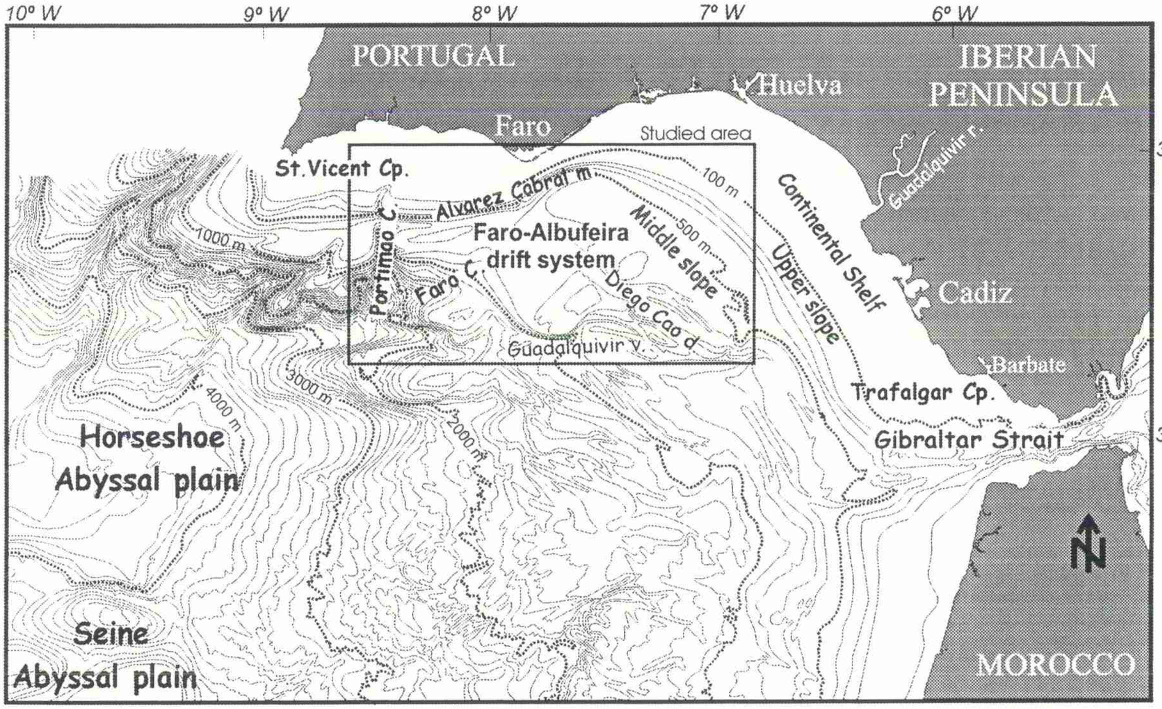

Figure 1. Location of the Faro-Albufeira contourite system in the Gulf of Cadiz. (Bathymetry from Heezen and Johnson, 1969).

as moats strongly influenced by bottom-current erosion. Widespread erosional surfaces and sub-bottom unconformities are also evident within the drift-system sequence. We focus in particular on the Quaternary stacking pattern and the relationship between the major erosional discontinuities and the major eustatic events and their correlation with the most important changes in climate and paleoceanography.

Vanney and Mougenot (1981) and Mougenot (1989) were the first authors to recognise the influence of Mediterranean Outflow Water (MOW) on Pliocene-Quaternary age contourite drift construction along this margin. They distinguished a series of relatively small drifts, 40–50 km long, 10–20 km width and 300 m thick (*rides* and marginal plateaus or *Planaltos*) lying between 600 and 800 m contours south of Iberian Peninsula, and surrounded by narrow elongated depressions (*Fosses* or deeps). In the Faro drift they identified 6 depositional sequences since Late Cretaceous bounded by main discontinuities. The basal discontinuity marks the beginning of a new hydrodynamic regimen resulting from the influence of the Mediterranean undercurrent. The most recent discontinuity identified by these authors was produced during the Pliocene (about 3 Ma) and the overlying depositional unit is characterised by the most prograding configuration in the Faro drift towards the north.

The general sedimentation of the continental margin, therefore, is characterised by widespread erosional surfaces and sub-bottom unconformities (Faugères et al., 1985; Mougenot, 1989; Nelson et al., 1993; Terrinha, 1998; Maldonado et al., 1999; Hernández-Molina et al., in press, amongst others). These authors have identified several erosional surfaces within the drifts since the Messinian stage that are believed to be due to changes in the activity of the undercurrent. Recently, in the Strait of Gibraltar, three important erosional phases were observed within the sedimentary record (Esteras et al., 2000). The oldest erosional stage was contemporaneous with the opening of the Strait of Gibraltar during the lower Pliocene, a middle erosional phase occurred during the upper Pliocene, and the youngest erosional phase is found during the Quaternary.

More detailed studies in the early 1980s and 1990s were also carried out especially in the upper depositional units (upper Quaternary) of the Faro Drift (Gonthier et al., 1984; Faugères et al., 1985, 1993; Stow et al., 1986; Nelson et al., 1993, 1999; amongst others).

Detailed seismic and sedimentological analyses have been carried out on Holocene and later Pleistocene sediments. The Faro drift is composed of silt to fine sand deposits interbedded with clay. This facies cyclicity can be interpreted in terms of cyclic variation in activity of the undercurrent as well as variation in sediment supply. The sandy contourites are believed to result from a stronger current activity. Sierro et al. (1999) proposed that these sandy layers could be condensed layers, that originated during episodes of relative sea-level rise. The terrigenous input decreased as it began to be trapped on land and there is more efficient winnowing of the sediment. More recent studies using single-channel and multichannel seismic reflection profiles have outlined more detailed ideas about the Faro drift, principal stratigraphic events, sequential stratigraphy, construction and evolution (Llave et al., 2000; Vázquez et al., 2000; Barnolas et al., 2000; Stow et al., in press).

Much progress has been made in recent years on Quaternary chronostratigraphy and in linking this with the marine oxygen-isotope stratigraphic record. Three major changes in climate which correspond to the most prominent sea-level falls can be identified in the Messinian at 5.2–5.5 Ma, in the Upper Pliocene at 2.4 Ma, and in the Mid Pleistocene at 900–920 ky (Shackleton, 1987; Thunell et al., 1991; Zazo, 1999). The Quaternary period has been characterised by glacial/interglacial variations dominated by 41 ky obliquity cycles prior to about 900–920 ky BP (Upper Pliocene-Middle Pleistocene), and by 100 ky eccentricity cycles during the Bruhnes chron after 900–920 ky (Isotopic Index-ID-22/23). Cycles of 20 ky were also evident during this latter period, but the 40 ky cycles were depressed. This important change in the climatic trend is known as the 'Mid Pleistocene Revolution (MPR)' (Shackleton and Opdyke, 1973; Shackleton et al., 1990; Berger and Wefer, 1992; Berger et al., 1994; Muldelsee and Stattegger, 1997; Howard, 1997; Paillard, 1998; Loutre and Berger, 1999). Since the 900–920 ky change implies a shift to longer-period glacial/interglacial cycles, there is a decrease in frequency in addition to the increase in the cycle amplitude. This intensification of glacial episodes marked the beginning of the so called 'Glacial Pleistocene' (Thunell et al., 1991). Moreover, the sea-level fluctuations after the MPR were characterised by marked asymmetry (Hernández-Molina et al., in press). After the MPR, the period of 420 to 360 ky (ID 11/12) underwent the most severe climatic conditions of the last half-million years.

Geological framework and oceanographic setting

Geological framework

The Cadiz margin is a tectonically deformed area at present, related to convergence between the Eurasian and African plates. From the Oligocene to the present, the Gulf of Cadiz has been located over the African-Eurasian plate boundary in the Atlantic realm (Srivastava et al., 1990). It originally developed as a rifted margin during the Central Atlantic opening between the plates of Northern America, Eurasia and Africa (Maldonado et al., 1999). The area has also been greatly influenced by closing and opening of the Strait of Gibraltar, which has acted as the major gateway between the Atlantic Ocean and the marginal, semi-enclosed Mediterranean Sea (Nelson et al., 1999).

The evolution of the Gulf of Cadiz is marked by four successive phases (Maldonado et al., 1999): (1) The development of a passive margin of Mesozoic age, related to the opening of the Central and Northern Atlantic. (2) The occurrence of a compressional regime during the Late Eocene to Early Miocene, related to closure of the Tethys Alpine Sea. (3) Foredeep evolution during the Miocene, associated with formation of the Betic-Rif orogen and opening of the Western Mediterranean basin. (4) The onset of oblique convergence, during the Late Messinian and Pliocene, that caused the gravitational acceleration of the dismantling of the collisional front. This was resolved by an extensional collapse and progressive emplacement of an olistostromic body in the eastern Gulf of Cadiz, giving rise to high rates of basin subsidence and strong diapiric activity (Flynch et al., 1996; Somoza and Maestro, 1997; Somoza et al., 1999). During this last period, the connection between the Atlantic and the Mediterranean through the Strait of Gibraltar opened, leading to the end of the Messinian salinity crisis in the Mediterranean region (Campillo et al., 1992; Maldonado and Comas, 1992; Nelson et al., 1993; Esteras et al., 2000). Consequently deposits of the margin have recorded a complex growth pattern influenced by global sea level factors and by local tectonic evolution.

Physiography setting

The Gulf of Cadiz is a large concave embayment lying along the eastern margin of the central North Atlantic (Figure 1). The western sector is characterised by an abrupt margin, scoured by submarine canyons (e.g., Portimao canyon) (Barnolas et al., 2000; Vázquez et al., 2000). The eastern sector is a progradational margin without submarine canyons. Towards the south, up to the Gibraltar Strait, the margin is steep and cut by submarine canyons. This part of the margin is characterized by the existence of a wide platform area and submarine valleys or moats parallel to the margin that interact with downslope-oriented submarine canyons.

In general, there is a smooth and progradational shelf break at about 120 m depth, but south of Saint Vicent Cape the shelf break is abrupt (Lobo, 1995). The continental slope of the Gulf of Cadiz shows an irregular relief and a smooth transition to the continental rise, except in the southern margin between Trafalgar Cape and the Strait of Gibraltar (Maldonado and Nelson, 1988). The slope can be divided into three domains based on the slope gradient and morphologic features (Roberts, 1970; Malod and Mougenot, 1979; Baraza and Nelson, 1992; Nelson et al., 1993) (Figure 1): A) *Upper slope*, between 120–400 m depth, 19 km wide (locally > 20 km) and a slope gradient between 1 and 3° (Figure 1). B) *Middle slope* between 400–800 m depth, showing a broad platform or terrace. This terrace region is 40 km wide, has a very low gradient between 0.5 and 1°, and several distinct sectors (Figure 1):

- *The Strait of Gibraltar to Cadiz sector*, characterised by a smooth platform with scoured submarines valleys parallel to the slope.
- *The Cadiz to Guadalquivir River sector*, with NE–SW oriented morphological ridges, submarine canyons and submarine valleys (Guadalquivir and Cadiz Valleys).
- *The Guadalquivir River to Faro sector*, has a smooth terrace scoured by submarine valleys parallel to the slope (Alvarez Cabral and Diego Cao).
- *The Faro to Saint Vicent Cape sector* characterised by a narrow terrace cut by NE–SW oriented submarine canyons (Faro and Portimao).

C) *Lower slope*, between 800–4,000 m depth, showing an undulating morphology resulting from slope instability. Below 4,000 m depth, the slope merges with the Seine and Horseshoe Abyssal plains.

Oceanographic setting

The circulation pattern of the present Gulf of Cadiz is characterised by strong oceanographic dynamics controlled by the exchange of water masses through the Strait of Gibraltar (Figure 2). This exchange consists of near-bottom Mediterranean Outflow Water (MOW) into the Atlantic Ocean and an influx of Atlantic Inflow Water (AI) at the surface into the Mediterranean. MOW is typified by highly saline (>36.4‰) and warm waters (>13°), whereas AI is a turbulent, less saline cool-water mass (Ambar and Howe, 1979, amongst others). The MOW includes two different water masses that join in the Strait of Gibraltar (Figure 2): Mediterranean Intermediate Water (MIW) and Mediterranean Deep Water (MDW). These combined water masses pass through the Strait of Gibraltar as the MOW, constrained at a minimum water depth of 200 m below AI, and reach a peak velocity of approximately 300 cm/s (Lacombe and Tchernia, 1972; Wust, 1961; Millot, 1987; Parrilla and Kinder, 1987; Perkins et al., 1990).

After passing through the Strait of Gibraltar, the MOW decreases in velocity to 180 cm/s and veers northwards in the Gulf of Cadiz, constituting a strong contour current moving at a water depth of 700–1,500 m around the Iberian slope. There it further divide into several branches due to the influence of deep submarine canyons and valleys (Figure 2) (Madelain, 1970; Caralp, 1988; Ochoa and Bray, 1990; Nelson et al., 1993, 1999; Beringer and Price, 1999). The interaction of the MOW with the slope generates a series of contourite bodies controlled by the northwestward decrease in velocity (Gonthier et al., 1984; Nelson et al., 1993, 1999). In the Gulf of Cadiz, Atlantic Surficial Water (ASW), at a depth of 0–100 m, and North Atlantic Superficial Water (NASW), at 100–700 m, move towards the SE and control present-day sedimentary dynamics at these shallower water depths (Figure 2) (Gascard and Richez, 1984; Ochoa and Bray, 1990; Caralp, 1988, 1992). The Deep Northatlantic Water (DNAW) flows at a depth of more than 1,500 m with a temperature of 3–8 °C, a salinity of 34.95–35.2‰ and an elevated oxygen content of 5.3–5.5 ml/1 (Caralp, 1988, 1992). This is generated in the Greenland-Norway Sea region and flows towards the South through North Atlantic gateways (Caralp, 1988, 1992).

Paleoceanography

Precise reconstruction of the evolving paleocirculation pattern during the period of drift growth is not presently possible, due to the lack of data. In general terms, it can be assumed that the present-day circulation pattern started to develop after the opening of the Strait of Gibraltar during the Messinian (Nelson et al., 1993), and that the Strait of Gibraltar has

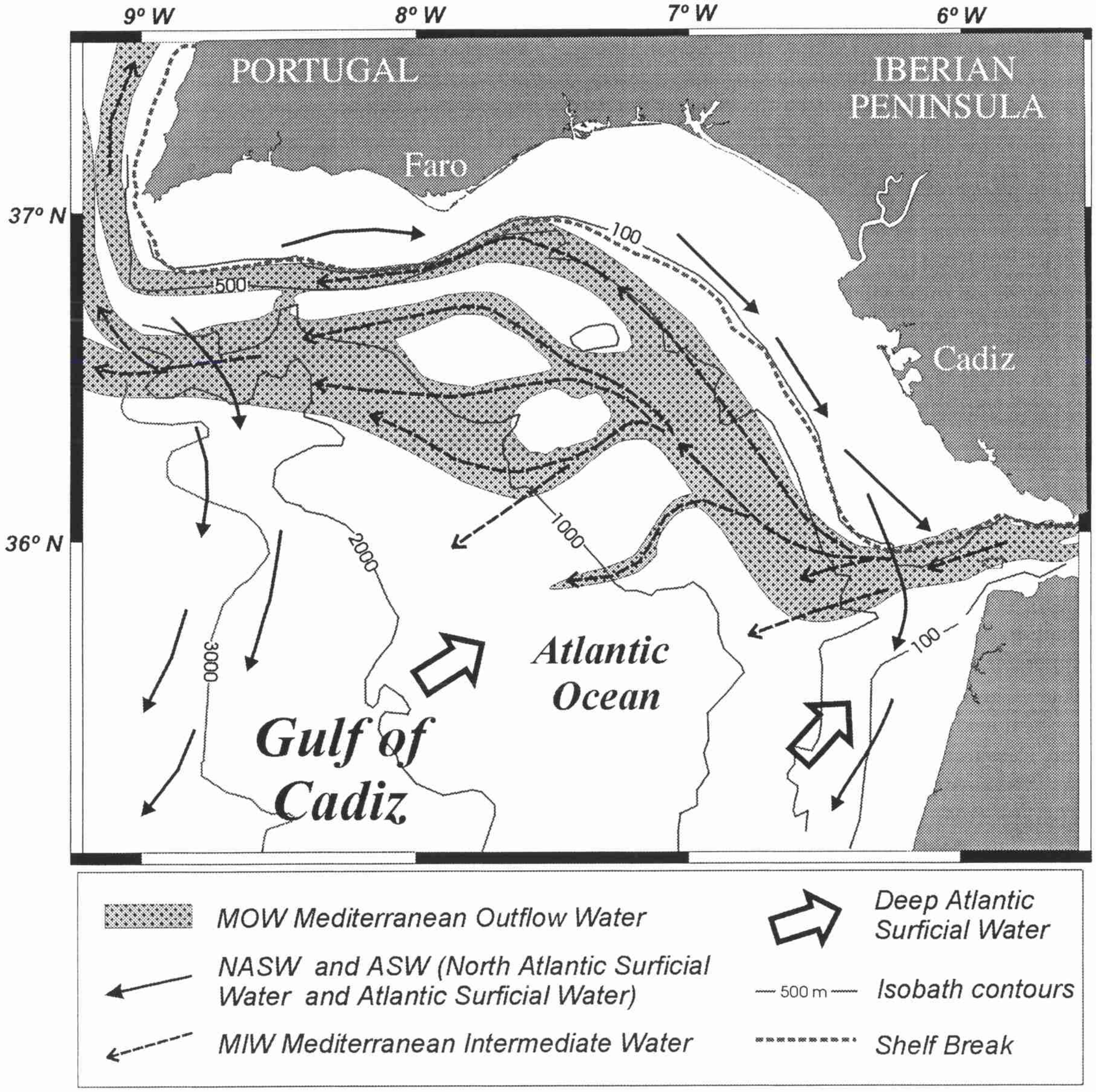

Figure 2. General circulation patterns of water masses in the Gulf of Cadiz (modified from Hernández-Molina, 1993).

controlled the dynamics of water mass exchange over time, modulating that exchange between the Gulf of Cadiz and Alboran Sea. The effective cross-section at the Strait of Gibraltar was significantly reduced during lowstands and the Mediterranean undercurrent outflow underwent major fluctuations (Nelson et al., 1993, 1999). However, a marked 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-Haas, 1973; Grousset et al., 1988; Vergnaud-Grazzini et al., 1989; Caralp, 1988, 1992; Nelson et al., 1993).

The MOW circulation and sea-level variations from the last glacial stage to the present are better known. During the last glacial stage (20,000–18,000 y BP) there was an important vertical exchange between water masses (Caralp, 1988, 1992). Nevertheless, the pattern of exchange through the Gibraltar Strait was similar to the present with a weak MOW flow to the west (Grousset et al., 1988; Caralp, 1988, 1992; Vernaud-Grazzini et al., 1989). During the deglaciation stage (15,000–13,000 y BP) the flow of MOW increased in intensity. Between 13,000–11,000 y BP (Younger Dryas stage), MOW flow decreased. Further marked intensification of MOW flow toward the west took place between 11,000–10,000 y BP, but during the Lower Holocene (10,000–7,000 y BP) the circulation again reduced and a quasi-permanent thermocline was established. Finally, in the Upper Holocene (since 7,000 y BP), an increase in flow of MOW was observed to its present level (Abrantes, 1988; Caralp, 1988, 1992; Vernaud-Grazzini et al., 1989).

Methodology

Data base

This work is based primarily on the analyses and interpretation of a broad database including (Figure 3): (1) bathymetric and geomorphological data; (2) seismic data of high-resolution (Sparker 3000, 4000 and 7500 J) obtained during several cruises supported by Spanish Research Council projects during the last 5 years. These data were collected onboard the B/O *Francisco de Paula Navarro* and the B/O *Cornide de Saavedra* during the oceanographic research cruises FADO 9711, ANASTASYA 9909 and ANASTASYA 2000/09. The seismic emission frequency used was between 100 and 1,500 Hz, giving an average vertical resolution of 1.5 m. The emission shot interval was every 3 sec giving a horizontal resolution of about 7 m. A differential GPS navigation system was used.

Interpretation

The seismic data were interpreted in two main stages (A and B) divided into several steps: A.1. Identification of depositional sequences of the Quaternary sedimentary record by seismic and sequential stratigraphy analyses. A.2. The medium-high-resolution seismic profiles (2 s, 1 s and 0.5 s two-way travel time scale) were used for studying the high-resolution sedimentary record. A.3. A general and theoretical age background at a large time scale was constructed from previous studies and oil company borehole data (Mougenot, 1989; Terrinha, 1998). B.1. The Quaternary chronostratigraphy has been closely linked to the global oxygen-isotope stratigraphy, which provides approximate ages for the interglacial/glacial stages, and has been used as an approximate estimator of eustatic changes (Shackleton, 1987; Thunell et al., 1991; Zazo, 1999). B.2. A theoretical correlation between depositional sequences and discontinuity ages and the Quaternary isotopic stratigraphy, has been made by considering relative sea level and regional paleoceanographic changes. B.3. The main major erosional surfaces of the Quaternary sedimentary record have been interpreted as being caused by the main sea-level falls during the Quaternary. B.4. The cyclic trend observed in the contourite drift stacking pattern has been used to identify major depositional sequences. B.5. The minor erosional surfaces of the Quaternary sedimentary record have been linked to minor sea-level falls during the Quaternary. B.6. The cyclic trend observed in the main depositional sequences has permitted identification of minor depositional sequences.

Seismic analyses of the Faro-Albufeira contourite system

Morphological elements of the contourite system

The Faro-Albufeira contourite system is composed of five morphological elements which are, from the upper slope to the middle slope: I.-Erosional surface on the upper slope; II.-Alvarez Cabral moat; III.-elongate separated mounded drift; IV.-Sheeted drift and V.-Erosional features over the drift (Figure 4).

I.- *Erosional surface of the upper slope*. There is a steep erosional escarpment on the upper slope south of Faro and along the northern flank of the Alvarez Cabral moat (Figures 4 and 5.I). This has a variable extent, becoming steadily wider towards the west.

II.- *Alvarez Cabral moat*. The Alvarez Cabral moat is believed to have formed largely as the result of strong, erosional bottom currents that develop where MOW is constrained against the continental slope. It is up to 90 km long and about 5 km wide (Figures 4, 5 and 6). In the far SE, the moat is imperceptible, then gradually deepens to around 500 m south of Faro, and as much as 800 where it joins Portimao Canyon in the W. It deepens along a slightly curved trend from ENE–WSW (Díaz-del-Río et al., 1998; García et al., 2000).

III.- *Elongate mounded drift*. This part of the contourite accumulation is distinctly mounded, with an asymmetrical cross section and elongate form, separated from the margin by the Alvarez Cabral moat (Figure 4). It is 80 km in length, deepening and narrowing from a crestal water depth of about 500 m and

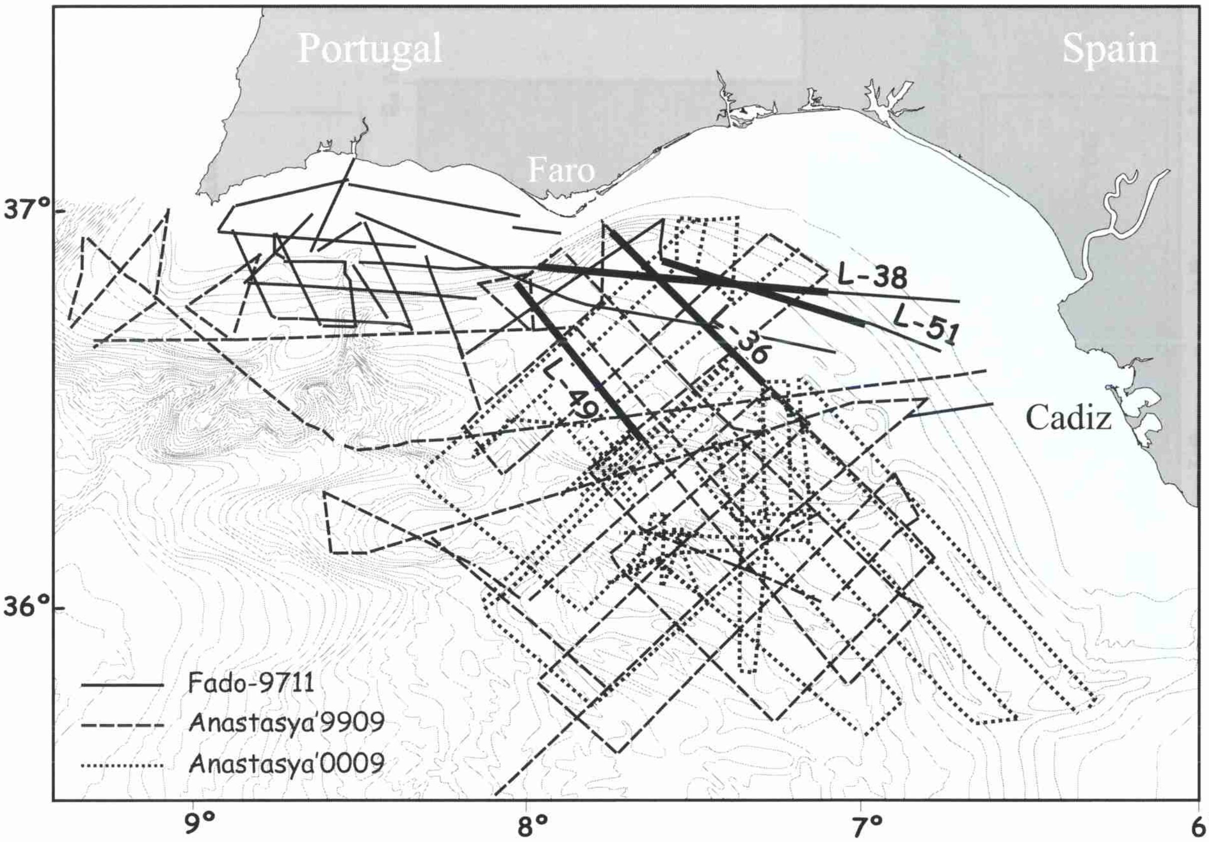

Figure 3. Location map of geophysical reflection profiles: 1.- Sparker (FADO-9711); 2. Sparker (ANASTASYA-9909), 3.- Sparker (ANASTASYA-2000). Thick lines show the location of seismic profiles illustrated in figures 6, 7, 9 and 10.

8 km width (Faro sector) to 675 m and 4 km width in the west. It has a maximum relief above the sheeted drift to the south of about 150 m decreasing towards the NE, but a much greater relief into the Alvarez Cabral moat to the north. It shows an elongation parallel to the margin, in a generally E–W direction, with a maximum thickness of 600 ms (*) (Figure 7), an average thickness of 500 ms, and a NW direction of progradation towards the upper slope (Figures 5 and 6).

IV.- *Sheeted drift.* Towards the middle slope of the Gulf of Cadiz basin, the mounded drift merges with a broad area of sheeted contourite drift that has been dissected into three distinct parts by canyon-channel-moat systems. Although these sheeted drifts form the same drift system as the basinward prolongation of the Faro-Albufeira elongate mounded drift, they are named separately as Faro-Cadiz, Bartolomeu Dias, and Albufeira sheeted drifts (Figure 4,) following the nomenclature of Vanney and Mougenot (1981) and Mougenot (1989).

A) The Faro-Cadiz sheeted sector is the basinward prolongation of Faro-Albufeira mounded drift at around 600 m water depth. It is 20 km wide and 30 km long and its westward extent is limited by the Diego Cao deep, to the E by the upper slope and to the SE and S by the Guadalquivir ridge-channel system (Figure 4). The sediment accumulation is about 350 ms thick in average (a maximum of 500 ms) (Figure 7), decreasing slightly in thickness due to the development of diapirs in the South. Some of these diapiric structures affect the whole sedimentary succession and outcrop on the sea-floor, whereas others affect only the oldest units (Figures 5, 6 and 8). Diapir-related faulting is quite common, in some cases affecting even the most recent units.

B) The Bartolomeu Dias sheeted sector is the basinward prolongation of the Faro mounded drift around 750 m water depth. It is 30 km wide, 45 km long and

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*Thickness are mainly given as milliseconds (ms) two-way-travel-time (TWT).

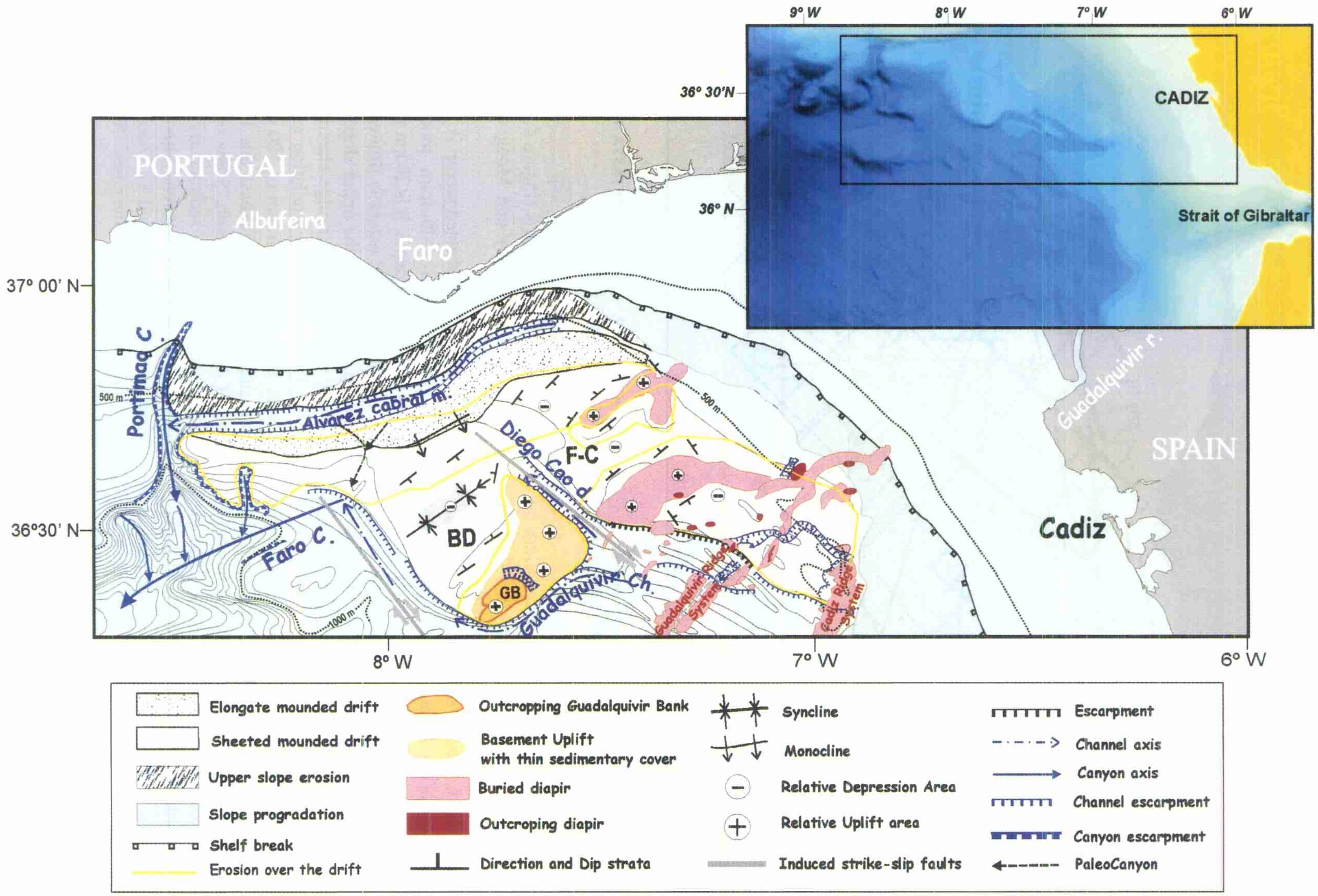

Figure 4. Morphosedimentary sketch of the Faro-Albufeira contourite system. Note: A: Albufeira sheeted drift; BD: Bartolomeu Dias sheeted drift; F-C: Faro-Cadiz sheeted drift.

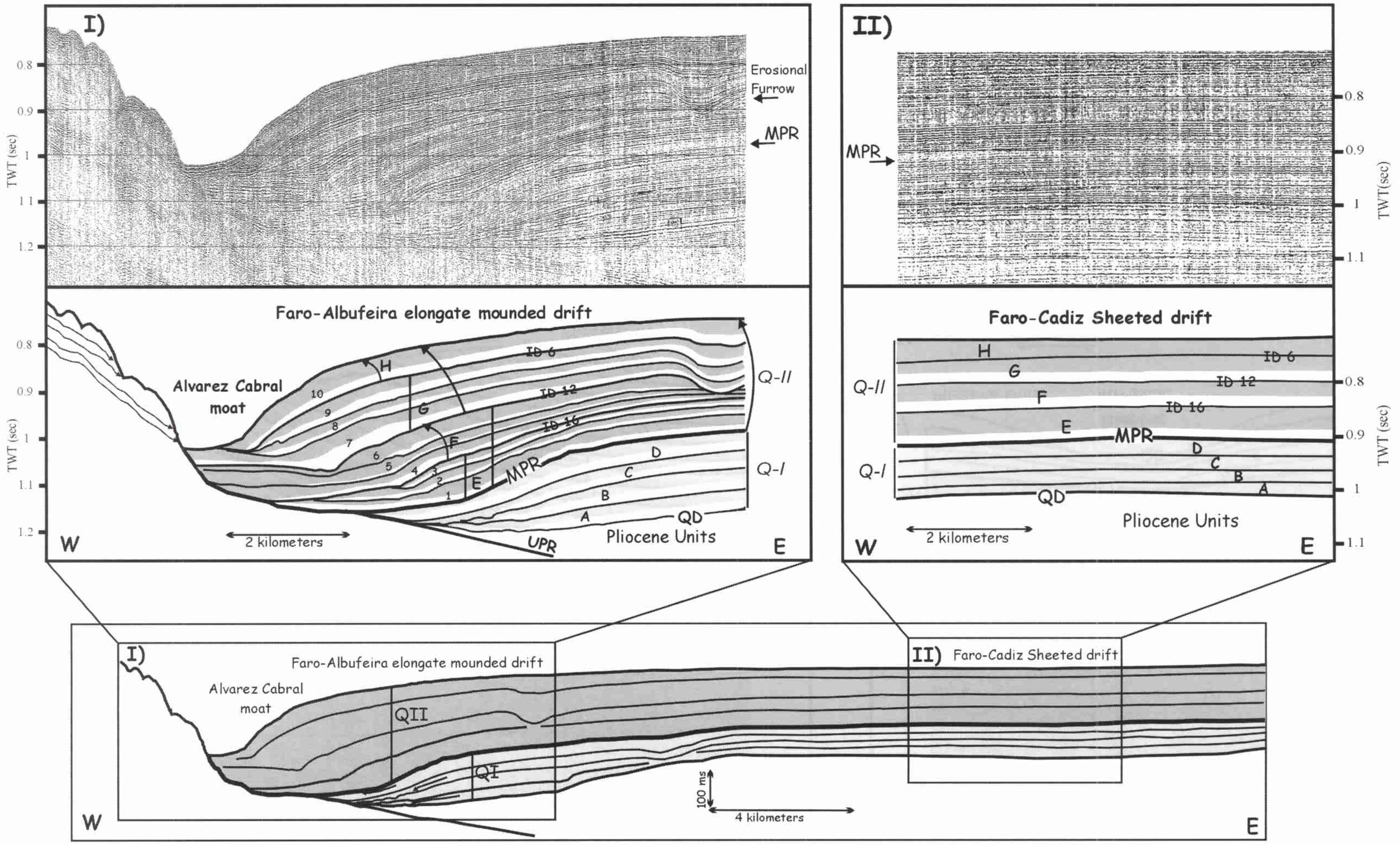

Figure 5. Sparker seismic profile and line drawing through part of the Faro-Albufeira drift, FADO'9711-38. I) Progradational stacking pattern in the Faro-Cadiz elongate separated mounded drift. II) Aggrading stacking pattern in the Faro-Cadiz sheeted drift. In grey is shown the reflective seismic facies and in white the transparent seismic facies. See Figure 4 for location.

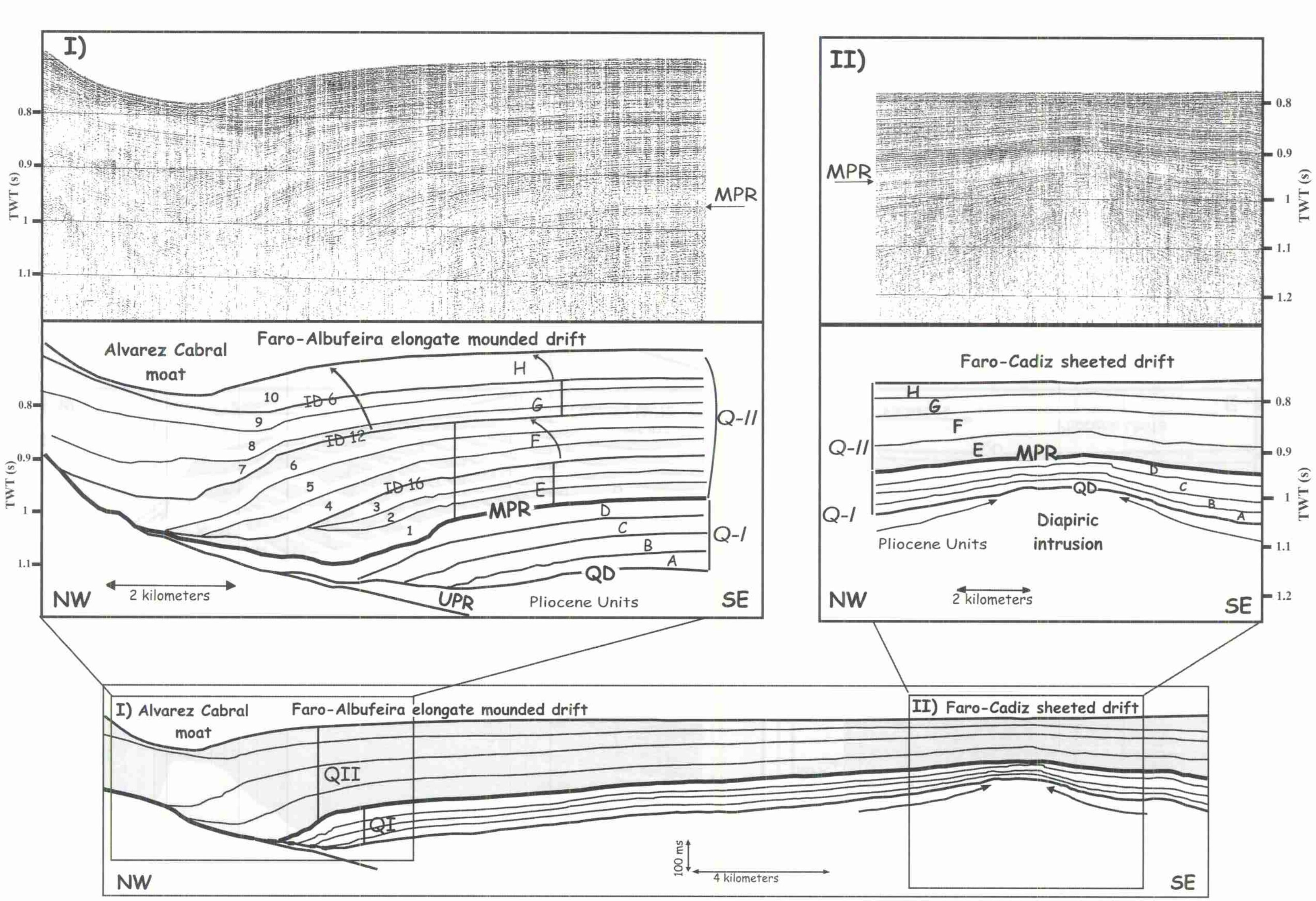

Figure 6. Sparker seismic profile and line drawing through part of the Faro-Albufeira drift, FADO'9711-51. I) Progradational stacking pattern in the Faro-Cadiz elongate separated mounded drift. II) Aggrading stacking pattern in the Faro-Cadiz sheeted drift above the diapiric intrusion. In grey is shown the reflective seismic facies and in white the transparent seismic facies. See Figure 4 for location.

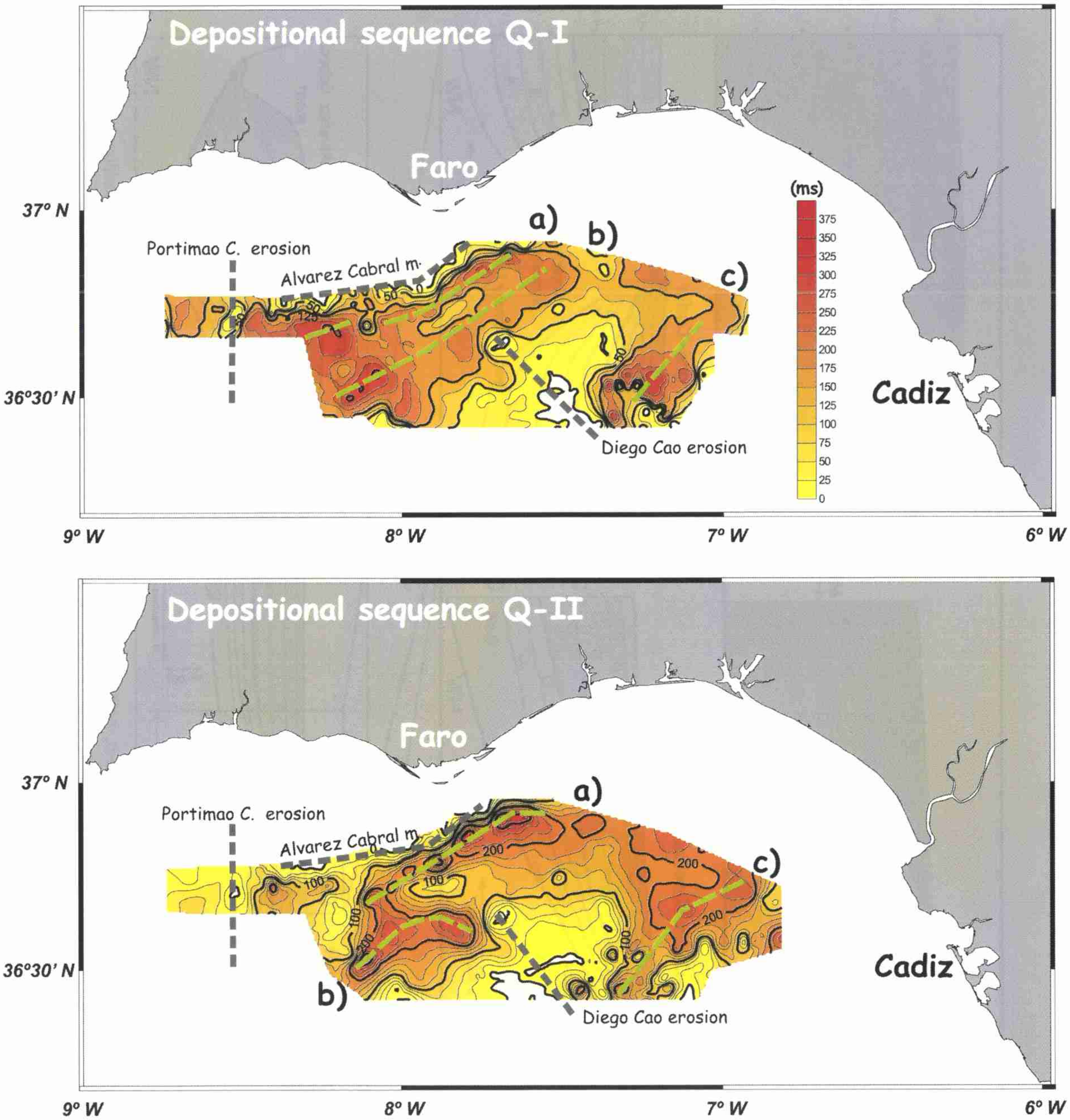

Figure 7. Isopach maps in milliseconds of Q-I and Q-II. The distribution of the main depocentres is shown in location a, b and c with dashed green lines highlighting the NE to SW orientation. The dashed grey lines highlight regions of lesser thickness and/or erosion.

its westward extension is limited by the Faro Canyon, to the south by the Guadalquivir Channel System and to the east by the Diego Cao deep (Figure 4). The sediment accumulation is about 500 ms thick in average and up to a maximum of 625 ms (Figure 7), forming a basin-fill type geometry due to the presence of the Guadalquivir Bank to the South (Figure 9).

C) The Albufeira sheeted sector is the basinward prolongation of the Albufeira mounded drift at around 850 m depth. Its westward extent is limited by the Portimao Canyon, and to the east and south by the Faro Canyon (Figure 4). It is 24 km long, 10 km wide, and it has a uniform sediment thickness up to 300 ms (Figure 7).

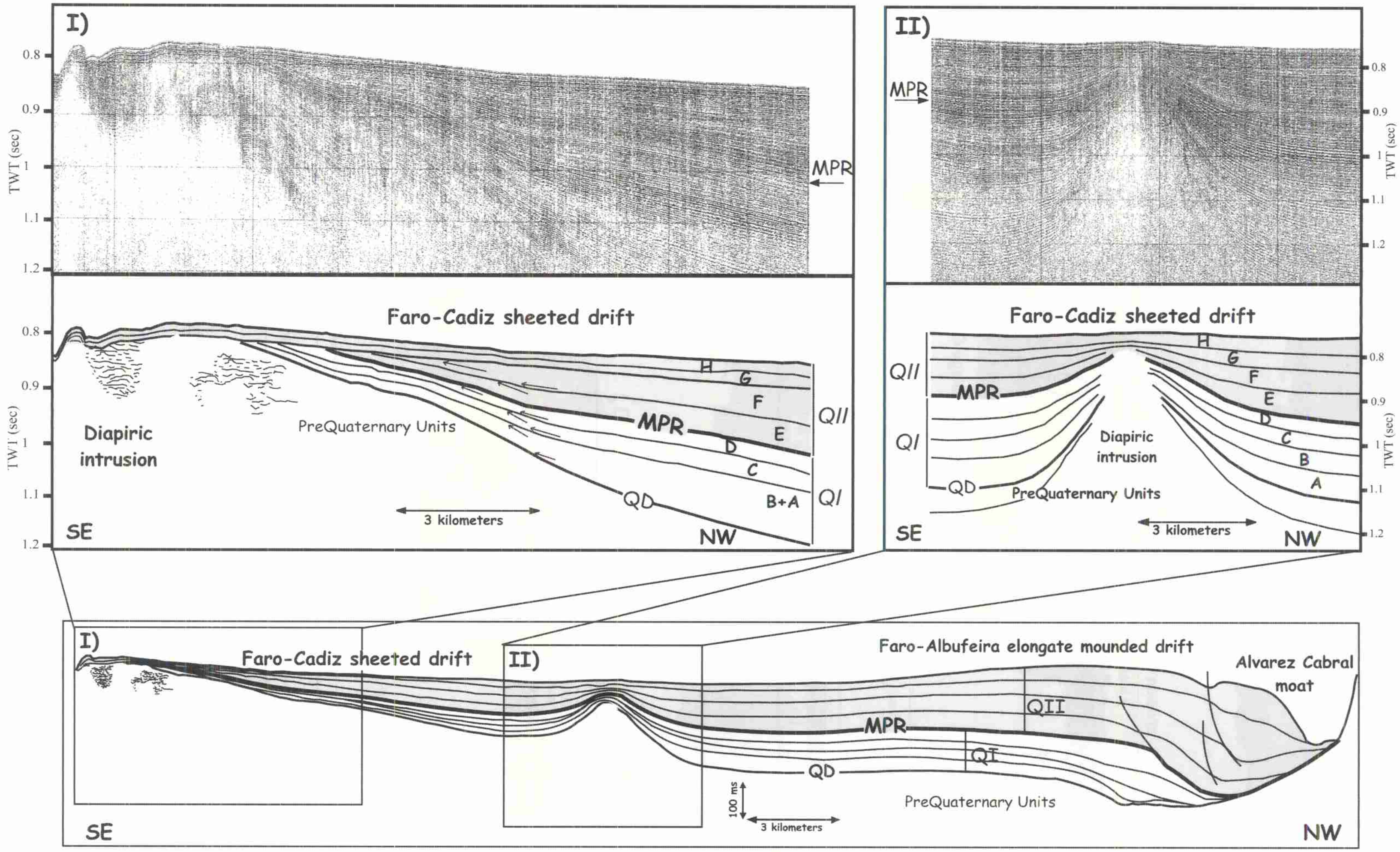

Figure 8. Sparker seismic profile and line drawing through part of the Faro-Albufeira drift, ANASTASYA'99-36. I) Stacking pattern composed of syn-tectonic depositional sequences in the Faro-Cadiz sheeted drift. Note that G and H have an aggrading stacking pattern. II) Effect of buried diapiric structure on the stacking pattern of the Faro-Cadiz sheeted drift. See Figure 4 for location.

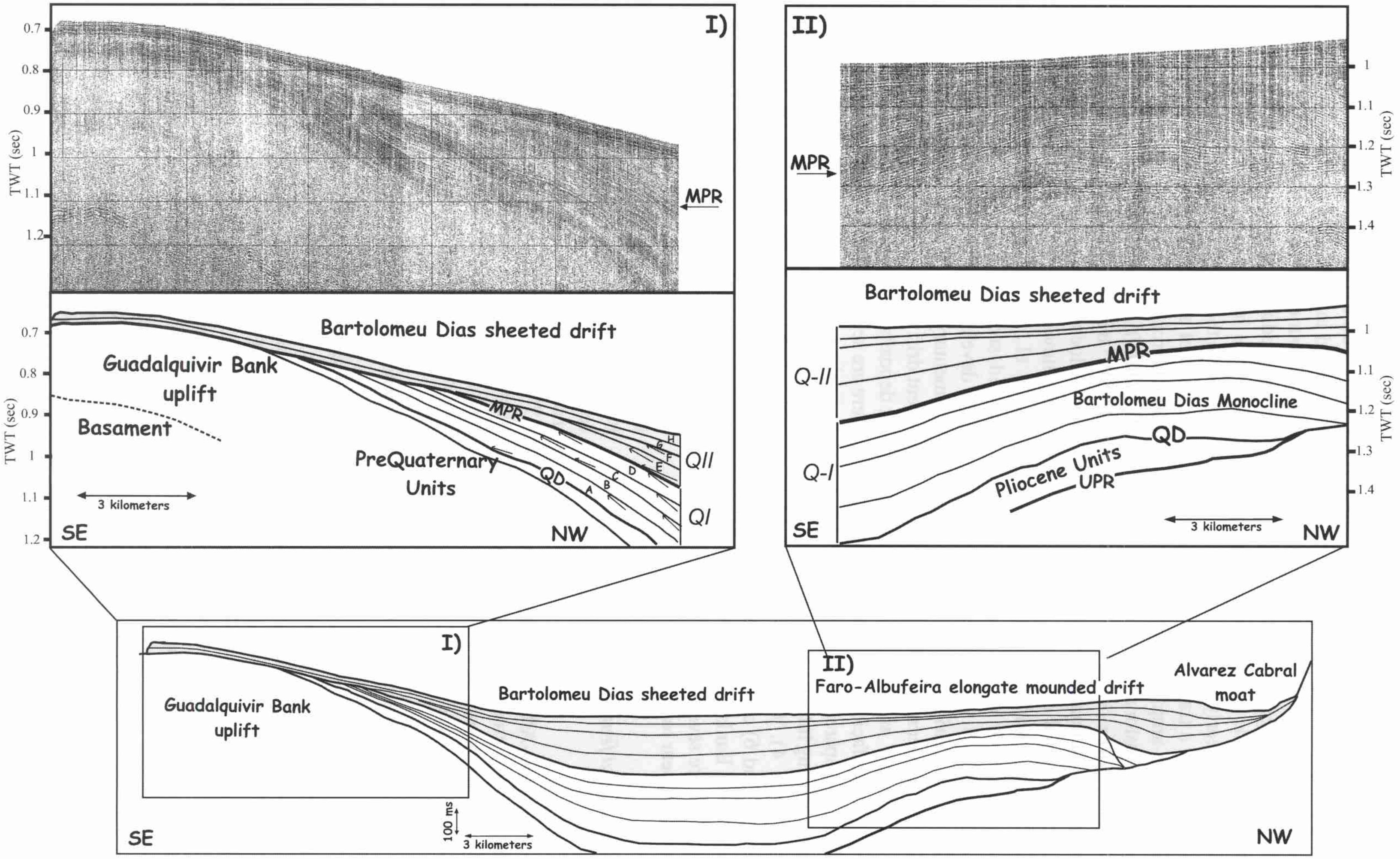

Figure 9. Sparker seismic profile and line drawing through part of the Bartolomeu Dias sheeted drift and Faro-Albufeira mounded drift, ANAS'99-49. I) Stacking pattern affected by the Guadalquivir Bank uplift. II) Monocline structure in the northern sector of Bartolomeu Dias sheeted drift. See Figure 4 for location.

Each of these sheeted drifts is characterised by an alternation of seismic facies from medium amplitude, parallel and laterally continuous reflectors, to a semi-transparent discontinuous reflector pattern. They show vertical stacking or aggrading seismic units. The mounded drifts also show the same cyclic arrangement of seismic facies, more clearly than the sheeted drifts. The mounded drifts show a transparent seismic facies passing upward into high-amplitude parallel reflectors typically topped by an erosional discontinuity.

V.- *Erosional features over the drift.* There are several horizontal and low-inclination reflectors truncated at the seafloor or by internal erosional discontinuities (Figure 4). The older erosional surfaces are widespread discontinuities both at the base and within the drift, extending across the whole drift system. Typically surfaces are marked by continuous high-amplitude reflectors between two distinct seismic facies. Usually they occur as an erosional surface at the top of the reflective facies units, separating them from the overlying transparent units. The present day seafloor surface is eroding into the youngest contourite unit in places (Figure 4), for example, within the channels (Figures 5 and 6) and near the uplift of diapirs and Guadalquivir Bank (Figures 8 and 9). In the mounded drifts there are several buried paleochannels (Figure 5.I), which appear to prograde northward.

Erosional and structural features control the contourite system

Development of the Faro-Albufeira contourite system has been affected by two erosional and two structural features: I.- Portimao canyon; II.- Diego Cao deep; III.- Local diapiric structures and IV.- Guadalquivir Bank uplift.

I.- *Portimao submarine canyon.* This canyon cuts across the southern Portuguese continental margin from the shelf to the deep basin. Its head region lies near the shelf-break at a depth of 110 m and it intersects the contourite drift at intermediate depths of 700–1,000 m (Figure 4). The orientation of the canyon in the upper reaches is NNE–SSW, showing an asymmetrical cross section. On the middle slope the orientation becomes to N–S, and the section is symmetrical. The canyon has a V-shaped incision in the Portuguese margin, a maximum depth of 1,100 m, and steep erosional walls (Vázquez et al., 2000; Barnolas et al., 2000).

II.- *Diego Cao deep.* The Diego Cao deep is an erosional channel that has been cut recently into the sheeted drift system and now separates the Faro-Cadiz from the Bartolomeu Dias sheeted drift (Figure 4). It is oriented in a NW–SE direction, with its maximum depth (around 800 m) and steep erosional walls in the SE and gradual diminution to the NW. It is 45 km long, 4 km wide in the SE and some 12 km wide before it dies out in the NW. Its appears to have developed along the crest of a series of salt diapirs (Díaz-del-Río et al., 2000; García et al., 2000)

III.- *Diapiric structures.* These typically occur along NE–SW trends and include both Triassic evaporites (Allochthonous Guadalquivir Unit) and Miocene marly limestone units (Olistostrome front) (Maldonado et al., 1999). They affect only the Faro-Cadiz sheeted sector (Figure 4), where the geometry of drift development clearly shows that they are syn-sedimentary with drift growth (Figure 8). The most recent drift units are found overlying some of the oldest deposits on the diapiric structures. In the SE sector there are several diapiric outcrops which constitute the Guadalquivir ridge system (Figure 4).

IV.- *Guadalquivir Bank.* This is made up of Paleozoic and Mesozoic rocks of the Iberian margin and has played an important part in affecting the hydrodynamic system and accommodation space for the Pliocene-Quaternary sedimentation (Figure 4). It is orientated broadly NE–SW and its uplift has produced an overall synclinal geometry in the region of the Bartolomeu Dias sheeted drift (Figure 9). In the northern sector, the basin is characterised by a south-verging monoclinal fold. In the south, there is a ramp with a 1.7° slope towards the north. The filling of the sedimentary units is expressed as angular syn-tectonic unconfomities at the basin margins and conformities toward the basin centre.

Seismic stratigraphy

Our seismic profiles penetrate up to 700 ms below the sea-floor in the drift deposit. The Faro-Albufeira elongate mounded drift reaches a maximum thickness of 600 ms (Figure 7). It displays a dominantly layered internal acoustic reflection pattern with significant upslope accretion. It is characterised by a progradational sigmoidal to oblique landward configuration prograding upslope. Individual reflections display either onlapping or downlapping terminations onto the several unconformity surfaces towards the north (Figures 5.I and 6.I). The Faro-Albufeira sheeted drift has an average thickness of 425 ms TWT that reaches a maximum of 625 ms TWT in the basin-fill type geometry of the

Bartolomeu Dias sheeted sector (Figure 7) and displays an aggradational stacking pattern (Figures 5.II, 6.II and 8.II).

The lower discontinuity described only in that seismic profiles close to the mounded drift but not followed in the overall seismic data, has been called UPR. It is a highly reflective and erosional surface at about 2 seconds depth. The base of the drift is a discontinuity represented by a reflective and erosional surface well observed in those seismic profiles through the mounded drift. This is the Quaternary Discontinuity (QD) (Figures 5 and 6). The main discontinuity observed in the seismic profiles (MPR) is a highly reflective and erosional surface that separates prograding stacking pattern deposits from aggrading ones. This feature can be observed in the seismic profiles of the mounded drift (Figures 5 and 6). Prograding deposits observed in the mounded drift (Figures 5 and 6) are internally characterised by a sequence of minor depositional sequences showing a progradational stacking pattern bounded by minor erosional discontinuities.

Two main depositional sequences within the Faro-Albufeira contourite system can be identified (Figures 5 and 6): Q-I and Q-II. These two sequences are separated by a marked continuous reflector of strong amplitude (MPR) underlined by a change in seismic facies. The Q-I depositional sequence is bounded by a basal erosional surface, QD, and by a highly reflective and erosional surface at the top, the MPR discontinuity (Figures 5.I and 6.I). It shows a general progradational stacking pattern in the elongate mounded drift (Figure 5.I and 6.I) that tends to become aggradational in the sheeted drift (Figure 5.II). The seismic facies is one of parallel-laminated, laterally continuous reflectors, that are uniformly distributed across the drift system (Figure 7) and it is seen to be affected by the diapiric structures in the south (Figure 6.II). The depositional sequence is syn-tectonic with the uplift of these diapiric structures so that onlap and offlap reflector terminations can be observed in each unit (Figure 8.I). Where the diapiric extrusion is buried the sediment thickness is slightly affected (Figure 8.II). There is a decrease in the thickness in the southern sector of this sheeted drift deposit due to the Guadalquivir Bank so that onlap and offlap reflector terminations can be observed in each unit (Figure 9.I). There is less or no sedimentation between Faro-Cadiz and Bartolomeu Dias sheeted drift (Figure 7). The Albufeira sheeted drift has a constant thickness of about 150 ms and it displays a flatter geometry with an aggrading stacking pattern. Three depocentres are evident with some NE–SW preferred orientation discernible (Figure 7). (a) In the Faro-Albufeira mounded drift Q-I reaches a maximum thickness of 200 ms; (b) The northern part of the sheeted drift exhibits an orientation nearly parallel to the depocentre located in the mounded drift and specially in the Bartolomeu Dias sector there is a second depocentre about 300 ms of thickness; (c) In the southwestern part of the Faro-Cadiz sheeted drift sector the maximum thickness is of 250 ms.

Within the mounded drift the transparent acoustic facies evolve upwards to high-reflectivity facies ending in an erosional surface. The transparent depositional facies are seen to prograde to a certain extent. The highly reflective depositional facies show even more marked upslope progradation above the transparent layers, and have a sigmoid wedge-shaped geometry. The Q-I depositional sequence is made up of the superposition of four minor depositional units: A, B, C, D (from oldest to youngest). The general geometry of these units is lenticular and they are bounded by erosional and reflective surfaces that are considered to be the main discontinuities named from oldest to youngest: QD, ID46, ID40, ID32 and MPR. The lower part of Q-I shows an aggradational stacking pattern (A and B), but the upper parts (C and D) show a progradational stacking pattern in the moat (Figures 5.I and 6.I). Laterally, in the sheeted drift, these depositional sequences are characterised by an aggrading stacking pattern (Figure 5.II). In general, each minor depositional sequence shows the same seismic facies and distribution pattern as the major depositional sequences Q-I.

The *Q-II depositional sequence* is bounded at the base by the MPR discontinuity and at the top by the actual sea floor (Figures 5 and 6). In the Faro-Albufeira elongate mounded drift it shows a general sigmoidal to oblique configuration prograding upslope above the Q-I depositional sequence (Figures 5.I and 6.I). In the sheeted drift, it tends to become aggradational (Figure 5.II). This depositional sequence has a regular distribution in the studied area showing variations in thickness in some sectors due to the effect of the diapiric structures and Guadalquivir Bank uplift. There is an overall synclinal geometry filled by Q-II units (Figure 9.I). In this sector, the geometry of the oldest units is affected by the folding mechanisms caused by uplift of the Guadalquivir Bank in the south (Figure 9.I). Both onlap and offlap reflector terminations are present in the oldest units (E and F), whereas the most recent units (G and H) overlap all the sedimentary units with an aggrading seismic facies pattern, except where the Guadalquivir Bank outcrops and no sedimentation occurs (Figures 4 and 9.I). The Albufeira sheeted drift has an average Q-II thickness of about 150 ms (Figure 7) that exhibits a general flat geometry and an aggrading stacking pattern. The main depocentres are aligned in three sectors (Figure 7): (a) In the Faro-Cadiz elongate mounded drift the maximum thickness of the Q-II depositional sequence is about 375 ms in a NE–SW orientation; (b) In the middle of the Bartolomeu Dias sheeted drift the maximum thickness is 325 ms in an E–W orientation; (c) In the southern part of Faro-Cadiz sheeted drift, the maximum thickness is about 250 ms in a NE–SW orientation. The erosional Diego Cao deep moat separates the depocentres ‘b’ and ‘c’ described above.

The QII depositional sequence comprises the superposition of four minor depositional sequences, each with a lenticular geometry (from E to H) bounded by reflective and erosional discontinuities. These discontinuities are, from oldest to youngest: MPR, ID16, ID12, ID6 and the actual sea floor (Figures 5 and 6). The discontinuity that separates the units F and G (ID12) shows an erosional paleochannel (Figure 5.I). The seismic facies of each minor depositional sequence shows a progradational stacking on the mounded drift (Figures 5.I and 6.I) and laterally aggrading reflective seismic facies (Figure 5.II). Within the mounded drifts, Q-II has a more accentuated prograding stacking pattern than Q-I. The lower part of Q-II shows a more aggradational stacking pattern (E and F), but the upper parts (G and H) show a more progradational stacking pattern (Figures 5.I and 6.I). Within the mounded drift, each minor and major depositional sequence shows a lower more transparent acoustic facies that passes up into a highly reflective facies ending in an erosional surface. The highly reflective units are prograding upslope above the transparent units, showing a sigmoidal wedge-morphology (Figures 5.I and 6.I). Ten minor units can be identified with a generally thicker development of the reflective than transparent seismic facies (Figures 5.I and 6.I). Each minor depositional sequence and unit shows the same geometry as that of the major Q-II depositional sequence, with variations in thickness (Figure 7) due to local diapirism (Figures 6.II and 8) and the Guadalquivir Bank uplift (Figure 9.I). The older depositional sequences, E and F, are syn-tectonic with diapiric intrusions and Guadalquivir Bank uplift. They are characterised by onlap and offlap reflector terminations whereas the most recent depositional sequences, G and H, are seen to overlie the older diapirs and Guadalquivir Bank structures with an aggrading stacking pattern (Figures 8.I, 8.II and 9.I).

Discussion

Depositional system

The Faro-Albufeira Quaternary contourite system is formed by the influence of the MOW and its interaction with both Coriolis force and the slope morphology. The MOW at the exit of the Strait of Gibraltar flows towards the NW parallel to the continental margin. This undercurrent separates into several branches (Figure 2). The upper branch follows the Iberian upper slope northwestward interacting with the concave shape of the southern Iberian margin and beginning to erode the slope to the SE of Faro. In this region, the MOW becomes channelled and forms the slightly sinuous Alvarez Cabral moat. Because of the Coriolis force causes the MOW current to veer to the right the flow tends to erode the right flank of the moat and to construct an elongate separated mounded drift (about 500 ms of average thickness) on the left side where the current velocity slackens. The migration of the mounded drift is dependent on the location of the axial Alvarez Cabral flow pathway. As the drift has migrated against and along the northern slope there has been a progressive increase in relief of the moat, coupled with its upslope migration and some erosion of the continental slope (Figures 4 and 5.I). The material eroded probably feeds into the Portimao canyon to the west of the system.

The basinward prolongation of the mounded drift is a dissected sheeted drift system occupying a large part of the basin floor. There is no significant migration over the area swept by the expanded MOW, so that depositional units have an aggradational stacking pattern and a regular thickness (about 425 ms TWT) except in the areas where diapiric intrusions and the Guadalquivir Bank uplift are present. This sheeted drift is divided in two sectors, Faro-Cadiz and Bartolomeu Dias, limited by the Diego Cao deep. This channel represents a pathway through which flows a deeper second branch of the MOW. Diego Cao deep is a very recent and erosional deep, with a NW–SE orientation that has excavated through the whole Quaternary section of the sheeted drift. Its location is most probably related to a tectonic structure.

Sequence stratigraphy and chronostratigraphy

A proposed correlation is made between the main discontinuities and depositional sequences identified within the Faro-Albufeira drift system, the principal discontinuities in the Quaternary isotopic Stratigraphy based on ODP site 806, and the relative sea level and regional paleoceanographic changes. The lower discontinuity described, UPR, although not everywhere present in the high-resolution seismic data, is interpreted to correlate with an important sea level fall (2.4 Ma), which is the next most important discontinuity after the Messinian (Figure 10). The middle discontinuity observed that is the base of the contourite deposits studied, QD, represents an erosional and reflective surface. Another clear discontinuity that is present in all the high-resolution seismic profiles examined is the MPR. In the seismic profiles there is a marked change in stratigraphic architecture in the whole elongate mounded drift deposits at the MPR, from a more aggradational pattern (Q-I) to a clearly progradational one (Q-II) (Figures 5 and 6).

Assuming that the MPR discontinuity is about 900–920 ky of age, then the sediment accumulation rate is about 20 cm/ky (Q-I) to 33 cm/ky (Q-II). Therefore, more displacement of the MOW upslope during the QII than during QI can be derived from observation of the seismic data. In the sheeted drift the sediment accumulation rates are very similar, about 25 cm/ky, except in Bartolomeu Dias which is characterised by generally higher rates of about 25 cm/ky in QI and more than 35 cm/ky in QII. In the Albufeira sheeted drift there is an average accumulation rate of 15 cm/ky in both QI and QII. This noticeable change at the MPR erosional surface in the mounded drift is interpreted as the result of the significant sea level fall at 900–920 ky (Figure 10) (Lowrie, 1986; Haq et al., 1987; Hernández-Molina et al., 1998). The lowered sea level is related to an important change in the climatic trend, driven by a shift to longer-period glacial/interglacial cycles and an increase in the cycle amplitude since ID 22. The marked change in stratigraphic architecture at this boundary is correlated with the influence of asymmetric 4th-order sea-level cycles of 41 ky (obliquity cycles) before the MPR, and the influence of asymmetric 4th-order sea-level cycles of 100–120 ky (eccentricity cycles) after the MPR. This architecture is apparently related to the abrupt increase in amplitude (to 100–120vm) of sea-level variations during the last 900–920 ky, after the MPR (Lowrie, 1986; Haq et al., 1987). The MPR, which separates the two major depositional sequences (Q-I and Q-II), is believed to be related to 3rd-order Quaternary units of about 800 ky.

Within these major depositional sequences eight minor depositional sequences are observed (from A to H) that could be associated with asymmetric 4th-order cycles of approximately 200 ky bounded by minor erosional discontinuities, which are associated with sea-level falls produced by the most prominent Quaternary events (Figure 10). These minor depositional sequences show a prograding stacking pattern, especially from E to H.

The same general trend is observed in each major and minor depositional sequence, especially in the mounded drift, which is characterised by transparent facies at the bottom, a thick reflective facies at the top and an upper erosional surface. This cyclic pattern in the acoustic response may be correlated with repetitive lithological changes in the contourite deposit, alternating from fine-grained deposits to coarse-grained deposits, in coarsening upward sequences.

This trend is also observed in the stacking pattern on the continental shelves of the southern Iberian Peninsula and related to asymmetric 4th-order sea-level cycles of 200 ky (Hernández-Molina et al., in press). In more detail, the Q-II depositional sequence of the elongate separated mounded Faro-Albufeira drift is composed of 10 sequences with the same cyclic trend believed to be related to approximately 100 ky sea-level cycles (Hernández-Molina et al., in press).

Tectonic control on deposition of the Quaternary units

Structures of probable Mesozoic age and the evolution of diapiric structures also modulated the sedimentary evolution of the Faro-Albufeira contourite system. Two sectors can be established depending on the deformational process influenced by diapirs or faults: Faro-Cadiz and Bartolomeu Dias sheeted drift sectors.

Faro-Cadiz sheeted sector.

The deformation observed in Faro-Cadiz sheeted sector is basically influenced by diapirism and faults. The diapiric structures are oriented NE–SW, and in some southern areas it is possible to recognise several outcrops of diapiric ridges (Figure 4). The sediments of the northern border of this sector that are deposited during diapiric doming growth, are characterised by (Figure 8): (1) thinning toward the axis of the diapiric uplift; and (2)only minor thickening into relatively distant peripheral sinks. The diapiric in-

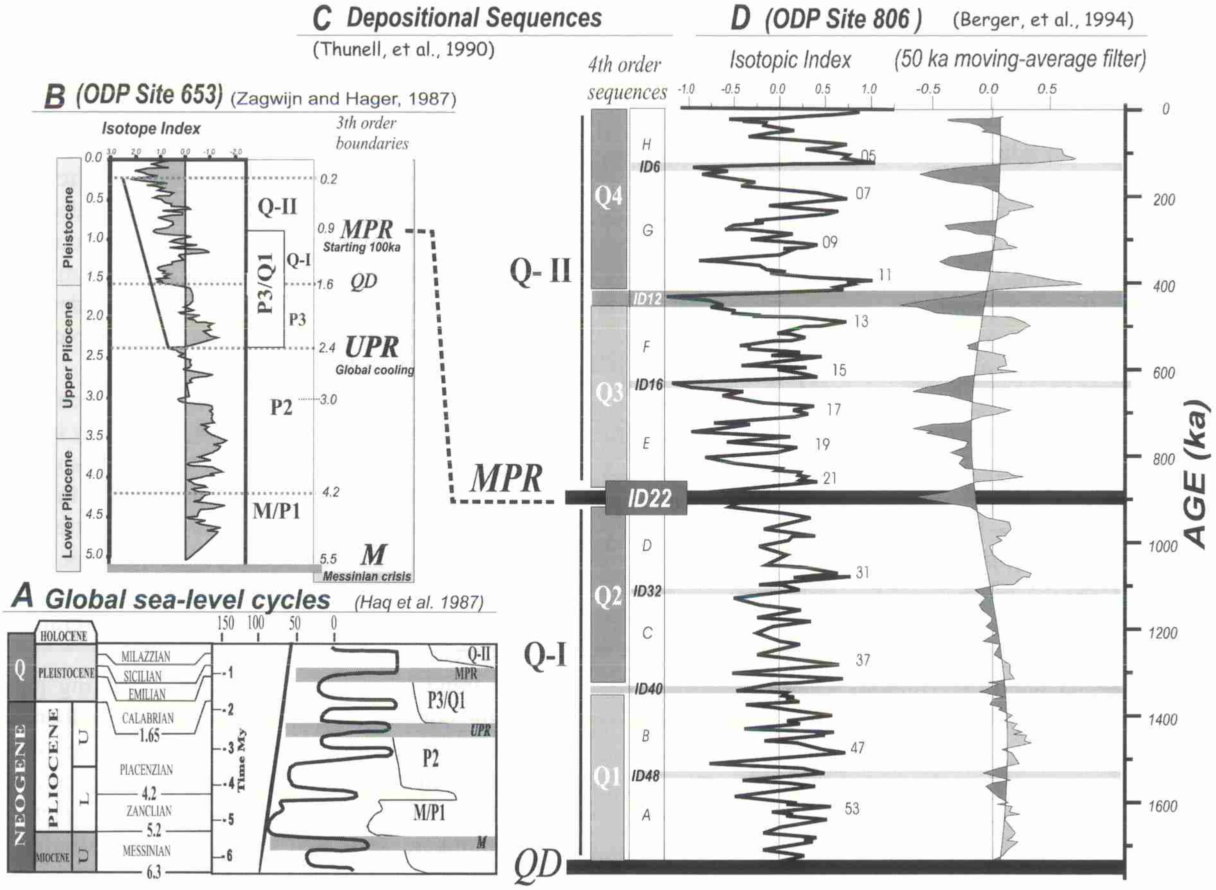

Figure 10. Chronostratigraphic interpretation of the depositional sequences in the Faro-Albufeira drift and their relationship with global sea-level cycles and Quaternary isotopic stages (modified from Hernández-Molina et al, in press).

trusions affect nearly all the Quaternary depositional sequences Q-I and Q-II. The depositional units A to F are syn-tectonic with the intrusion of diapiric structures showing onlapping and offlapping configuration. The depositional sequence QII (from E to H) is not so affected especially the units G and H that are less affected by diapiric intrusions and overlap all earlier units with an aggrading stacking pattern.

Bartolomeu Dias sheeted drift sector.

The present geometry of the sedimentary units in the Bartolomeu Dias sheeted sector shows coeval development with the folding mechanism. This mechanism is associated with the uplift of Guadalquivir Bank and the reactivation of ancient faults (Figure 4). This mid-slope area in the northern Gulf of Cadiz has an overall synclinal geometry, resulting from the active subsidence during the Quaternary which is expressed as angular syn-tectonic unconformities at the basin margins and conformities toward the basin centre (Figure 9). The syncline has a maximum thickness of 625 ms of preserved Quaternary sediments deposited. The maximum changes in thickness occur in units from A to F. This indicates the maximum deformation period occurred between A and F. The change in dip and thickness within the growth wedge affects all the sedimentary units apart from the highest Quaternary units (G and H). These younger depositional sequences overlap the older Quaternary ones and also the Guadalquivir Bank in the southern part of the Bartolomeu Dias sheeted deposits which indicates that they are less affected by to the uplift (Figure 9.I and 4).

This overlapping of G and H with an aggrading stacking pattern is a general stratigraphic feature at a major scale in the middle slope of the Gulf of Cadiz. The beds also have a gentle inclination and indicate that Guadalquivir Bank uplift has continued until recent times. The northern border is defined by a NE–SW trending monocline that can be followed for 20 km along strike (Figure 9.II and 4). Changes in thickness within the Quaternary deposits between the Albufeira, Bartolomeu Dias and Faro-Cadiz sheeted sectors appear to be correlated with older faults reactivated during the late Miocene to present convergent regime (Mougenot, 1988; Kullberg et al., 1992; Terrinha, 1998). Furthermore the existence of Mesozoic faults can be inferred from the geometry of pre-Quaternary strata.

It is significant that the stratigraphic architectural changed from F to G in the area where diapirs and Guadalquivir Bank uplift are present. From A to F the depositional sequences are syn-tectonic with these structures, whereas G and H are less affected by, thus G and H record this tectonic change in the central slope area of the Gulf of Cadiz. Because these more recent depositional sequences show the change in deformation history, and because of the presence of paleochannels at the base of G, we suggest that there was an important morphostructural and hydrodynamic change after the discontinuity at the base of G. The recent origin of Diego Cao deep also fits stratigraphically into this time frame.

Conclusions

The interpretation of the Faro-Albufeira drift system throughout the Quaternary is based on high-resolution seismic data. The Faro-Albufeira middle-slope contourite system is an upslope migrating depositional sequence developed parallel to the margin and associated with a flanking boundary channel (Alvarez Cabral moat) that marks the zone of MOW shear against the Faro margin area. Consequently, erosion is produced along the right border of the channel and deposition on the left flank, which forms a large elongate separated mounded drift with an average thickness of 500 ms TWT. The basinward prolongation of the elongate mounded drift is the sheeted aggrading drift, with an average thickness of 425 ms TWT, where the MOW is dispersed southwestward. These different types of contourite deposits depend on their respective closeness or distance from the moat. The Diego Cao deep separates the overall sheeted contourite system into two regions. This moat is eroding recent Quaternary sediments and cutting a steep northern wall.

The overall contourite sedimentation has been influenced by both climatic and tectonic changes. The MPR is the most important erosional reflective surface in the Quaternary deposits that are observed in every high-resolution seismic profile studied from the area. This stratigraphic discontinuity appears to be correlated with an important change in the climatic trend known as the ‘Mid Pleistocene Revolution’, which occurred 900–920 ky ago. This represents a shift to longer-period glacial/interglacial cycles and an increase in the cycle amplitude since ID 22. The discontinuity forms the boundary between of asymmetric 4th-order sea-level cycles of 41 ky (obliquity cycles) before the MPR, and the subsequent onset of the 100 ky eccentricity orbital cycles.

This discontinuity separates two 3rd-order Quaternary units of about 800 ky (Q-I and Q-II) which, in the elongate separated mounded drift, is also marked by a change in stratigraphic architecture. There is a separation between a more aggrading contourite body (Q-I) and a thicker and more prograding one (Q-II). Q-I and Q-II depositional sequences each comprises four minor depositional sequences termed: A, B, C, D and E, F, G, H, respectively. These constitute asymmetric 4th-order sequences of 200 ky, separated by erosional discontinuities, which are associated with sea-level falls produced by the most prominent Quaternary events. In the elongate separated mounded drift, the depositional sequences from E to H are composed of 10 minor depositional sequences with the same cyclic trend that can be related to the Quaternary eccentricity cycles of 100 ky.

In the southern sector of the contourite sheeted system, the general geometry of the deposits has been affected by the emplacement of diapiric structures and the Guadalquivir Bank uplift. Deposition was mainly syn-tectonic with the deformation related to these structures except for the two most recent depositional sequences, G and H, which are les affected. These units show an aggrading stacking pattern that overlaps the older units of the Guadalquivir Bank uplift and diapiric intrusions.

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