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Pliocene–Quaternary contourites along the northern Gulf of Cadiz margin: sedimentary stacking pattern and regional distribution

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Abstract This study reports novel findings on the Pliocene–Quaternary history of the northern Gulf of Cadiz margin and the spatiotemporal evolution of the associated contourite depositional system. Four major seismic units (P1, P2, QI and QII) were identified in the Pliocene–Quaternary sedimentary record based on multichannel seismic profiles. These are bounded by five major discontinuities which, from older to younger, are the M (Messinian), LPR (lower Pliocene revolution), BQD (base Quaternary discontinuity), MPR (mid-Pleistocene revolution) and the actual seafloor. Unit P1 represents pre-contourite hemipelagic/pelagic deposition along the northern Gulf of Cadiz margin. Unit P2 reflects a significant change in margin sedimentation when contourite deposition started after the Early Pliocene. Mounded elongated and separated drifts were generated during unit QI deposition, accompanied by a general upslope progradation of drifts and the migration of main depocentres towards the north and northwest during both the Pliocene and Quaternary. This progradation became particularly marked during QII deposition after the mid-Pleistocene (MPR). Based on the spatial distribution of the main contourite depocentres and their thickness, three structural zones have been identified: (1) an eastern zone, where NE–SW diapiric ridges have controlled the development of two internal sedimentary basins; (2) a central zone, which shows important direct control by the Guadalquivir Bank in the south and an E–W Miocene palaeorelief structure in the north, both of which have significantly conditioned the basin-infill geometry; and (3) a western zone, affected in the north by the Miocene palaeorelief which favours deposition in the southern part of the basin. Pliocene tectonic activity has been an important factor in controlling slope morphology and, hence, influencing Mediterranean Outflow Water pathways. Since the mid-Pleistocene (MPR), the sedimentary stacking pattern of contourite drifts has been less affected by tectonics and more directly by climatic and sea-level changes.

Introduction

After the end of the Miocene and following the opening of the Gibraltar Strait during the Zanclean, a large contourite depositional system (CDS) developed along the northern

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Gulf of Cadiz continental margin, mainly as result of alongslope processes (i.e. bottom or contour currents) focussed in the upper and middle slope sector (e.g. Kenyon and Belderson 1973; Gonthier et al. 1984; Faugères et al. 1985, 1999; Stow et al. 1986; Hernández-Molina et al. 2003, 2006, 2010; Hanquiez 2006; Roque 2007; Llave et al. 2007; Marchès et al. 2007; Hernández-Molina 2009; Fig. 1). This CDS comprises both depositional and erosional features distributed in five morphosedimentary sectors along the margin (numbered 1 to 5 in Fig. 2; Llave 2003; Hernández-Molina et al. 2003; Llave et al. 2007; García et al. 2009).

The distribution of features in the CDS and the differentiation of morphosedimentary sectors can be related to a complex combination of factors involving (1) deceleration of the warm and saline intermediate water mass (Mediterranean Outflow Water, MOW) flowing out of the Mediterranean Sea westwards through the Strait of Gibraltar, at 500–1,400 m water depths (Fig. 1), (2) MOW interaction with bathymetric irregularities, (3) effects of the Coriolis force and (4) neotectonic activity (Hernández-Molina et al. 2003, 2006; Llave et al. 2007). Only in sectors 2 (west of the Gibraltar gateway) and 5 (close to Cape San Vincent; see Hernández-Molina et al. 2003) is there evidence of interaction between downslope gravity processes and contour currents in the development of slope sedimentary architecture. Sector 2 comprises several slope-centred channels currently used by contour currents, but with small terminal lobes which suggest the occurrence of periodic gravity flows (Habgood et al. 2003; Hanquiez 2006; Mulder et al. 2006; Hanquiez et al. 2010). Sector 5 comprises a slope dissected by several canyons formed by downslope processes, but large accumulations of gravity deposits have not been found at the downslope ends of these canyons (Mulder et al. 2006; Marchès et al. 2007).

Because they are commonly associated with high sedimentation rates, contourite deposits represent key records for palaeoenvironmental and palaeoceanographic reconstructions (e.g. Stow et al. 2002a; Llave et al. 2006; Voelker et al. 2006; Marchès et al. 2007; Toucanne et al. 2007). This is true also for the Faro-Albufeira mounded elongated and separated drift along the Algarve margin, one of the most extensive and complex drifts of the CDS in the northern Gulf of Cadiz (Hernández-Molina et al. 2003). The Pliocene–Quaternary sedimentary record of the gulf

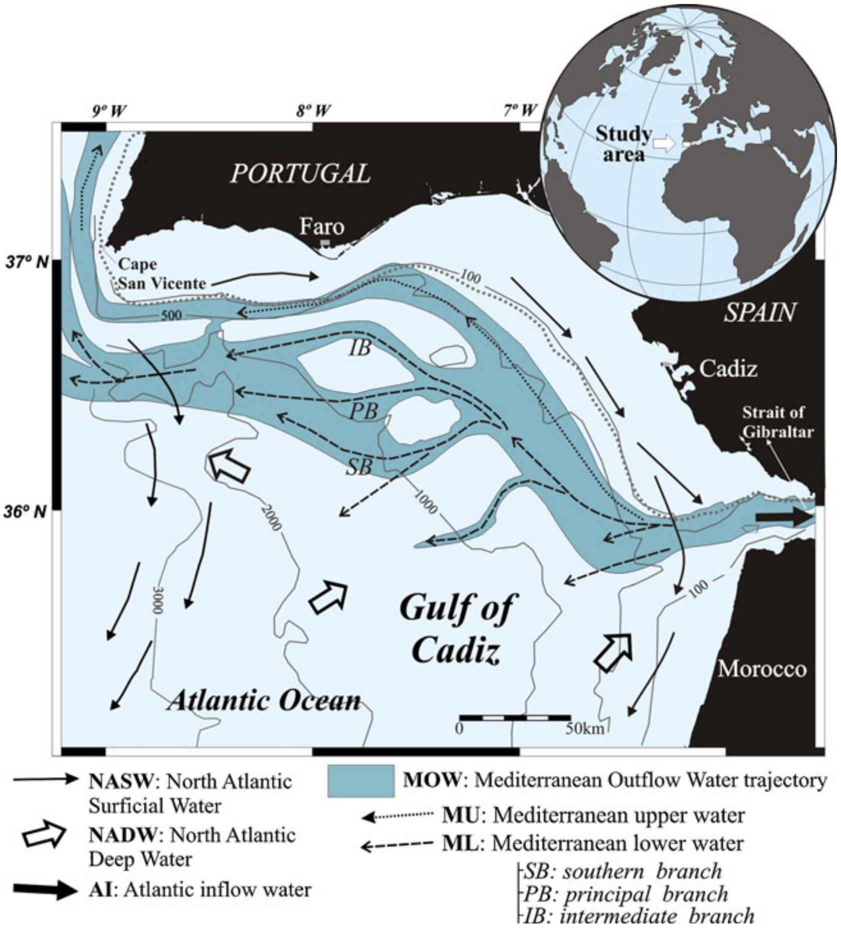

Fig. 1 Locality map with main water-mass circulation along the northern Gulf of Cadiz margin (modified from Hernández-Molina et al. 2006)

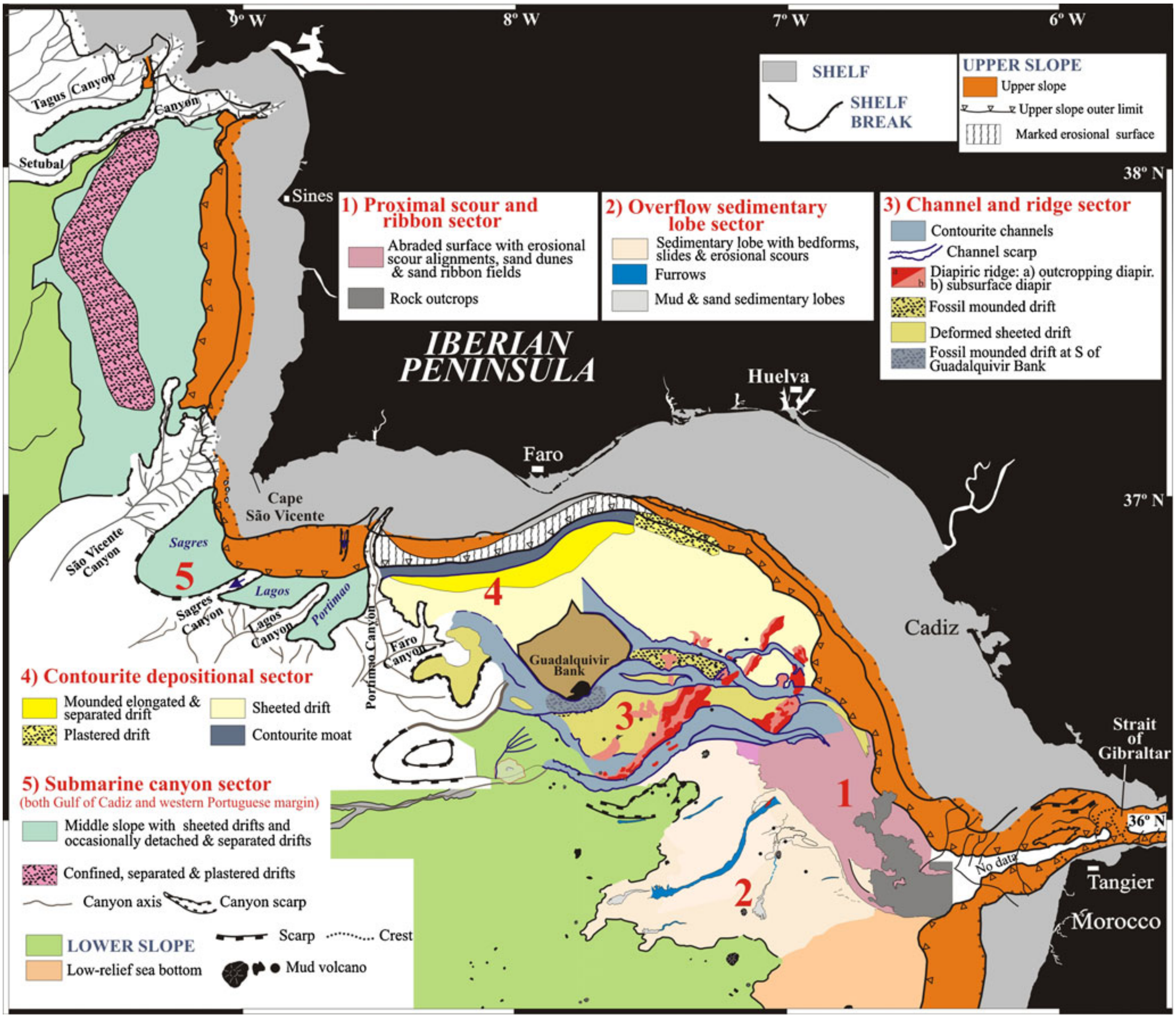

Fig. 2 Regional map (simplified) of the contourite depositional system on the middle slope of the Gulf of Cadiz and West Iberian margin (based on Llave 2003; Hernández-Molina et al. 2003, 2006 and adapted from Stow et al. 2011)

has four main depositional sequences, associated with important MOW palaeoceanographic changes (Llave et al. 2001, 2007; Hernández-Molina et al. 2002, 2006; Stow et al. 2002b; Llave 2003). These sequences are bounded (from bottom to top) by the M (Messinian), LPR (lower Pliocene revolution), UPR (upper Pliocene revolution) and MPR (mid-Pleistocene revolution) regional discontinuities. Note that, following reassignment of the duration of the Quaternary by the International Commission on Stratigraphy (Mascarelli 2009), Hernández-Molina (2009) re-designated the UPR as the BQD, base Quaternary discontinuity. These Gulf of Cadiz data have been tentatively correlated with corresponding information from the Strait of Gibraltar (Esteras et al. 2000), where four depositional phases/sequences are also differentiated and bounded by erosional stages. In this strait, the lowermost unit comprises chaotic clayey breccias, interpreted by Esteras et al. (2000) as debrites related to tectonic and slope instabilities during the opening of the gateway. This is overlain by a highly erosional boundary, which could represent the onset of MOW circulation, and then by a sequence of bioclastic sand and gravel deposits (megadunes) which could have developed under the influence of a strong MOW circulation pattern similar to that of today.

This paper presents novel findings on the overall sedimentary record of the Pliocene–Quaternary history of the northern Gulf of Cadiz margin, based on newly available seismic data. This record is interpreted in terms of existing knowledge on MOW water mass dynamics along this margin (sectors 3 and 4 of the CDS shown in Fig. 2) since the opening of the Gibraltar gateway, as well as tectonic and/or environmental changes.

Geological and oceanographic setting

The Gulf of Cadiz is located along the south-western margin of the Iberian Peninsula at the eastern end of the Azores-Gibraltar Zone, a diffuse plate boundary between Eurasia and Africa where NW-SE-trending plate convergence is occurring at a rate of about 4 mm/year (Argus et al. 1989; Olivet 1996). Crustal deformation, fault reactivation and diapirism related to this NW convergence have controlled the tectono-stratigraphic evolution of this part of the Iberian Peninsula (Malod and Mauffret 1990; Srivastava et al. 1990; Maldonado et al. 1999; Alves et al. 2003; Medialdea et al. 2004; Lopes et al. 2006; Zitellini et al. 2009). At the end of the Messinian, the complete isolation of the Mediterranean Sea ended (Ryan et al. 1973; Hsü et al. 1978; Duggen et al. 2003) when a transtensional regime induced the reopening of the connection between the Atlantic and the Mediterranean through the Strait of Gibraltar (Maldonado et al. 1999; García-Castellanos et al. 2009). In an oceanic context this strait is generally known as the Gibraltar gateway, through which warm saline MOW exits into the Atlantic Ocean.

Since the latest Miocene, an oblique compressional regime has developed simultaneously with the extensional collapse of the Betic-Rif orogenic front, by westward emplacement of a giant chaotic body known as the Cadiz allochthonous unit (CAU), and by very high rates of basin subsidence coupled with strong diapiric activity (Maldonado et al. 1999; Medialdea et al. 2004). During the Pliocene and Quaternary, the effects of glacio-eustatic variations have partly overprinted structural effects on the margin, resulting in erosion, sedimentary progradation and the incision of major submarine canyons. By the end of the Early Pliocene, subsidence decreased and the margin evolved towards its more stable, present-day condition (Mougenot 1988; Maldonado et al. 1999; Alves et al. 2003; Maestro et al. 2003; Terrinha et al. 2003; Medialdea et al. 2004). Some neotectonic reactivation is also evident, as indicated by the occurrence of mud volcanoes and diapiric ridges (Díaz-del-Río et al. 2003; Somoza et al. 2003; Fernández-Puga 2004; Fernández-Puga et al. 2007), and fault reactivation (Maestro et al. 1998; Lobo et al. 2003; Zitellini et al. 2009). Indeed, tectonics has been a key long-term factor affecting seafloor morphology in the region, in turn exerting strong control on MOW pathways and, ultimately, on the architecture of the CDS.

The present-day regional circulation pattern is dominated by the exchange of water masses through the Strait of Gibraltar (Fig. 1), driven by highly saline and warm MOW near the bottom and turbulent, less saline and cooler Atlantic inflow water at the surface. The MOW forms a strong bottom current flowing towards the west and northwest above North Atlantic Deep Water (Madelain 1970; Mélières 1974; Thorpe 1975; Zenk 1975; Ambar and Howe 1979). After exiting through the Strait of Gibraltar, the MOW forms a narrow turbulent flux approx. 150–200 m wide and attaining velocities in excess of 250 cm/s (Ambar and Howe 1979). It spreads westwards into the Gulf of Cadiz, descending the slope in two main cores: the Mediterranean upper water, between 500 and 800 m water depth, and the Mediterranean lower water between 800 and 1,200 m water depth. This lower core then subdivides into three distinct branches, eventually losing contact with the seafloor at ca. 1,400 m water depth (Madelain 1970; Zenk 1975; Ambar and Howe 1979; Gardner and Kidd 1983; Zenk and Armi 1990; Ochoa and Bray 1991; Baringer 1993; Bower et al. 1997; Johnson and Stevens 2000; Borenäs et al. 2002).

After exiting the Gulf of Cadiz, the MOW splits up into three principal branches (Fig. 1): a main one flowing to the north, a smaller one to the west and another small one to the south which reaches the Canary Islands, from where it veers towards the west (Iorga and Lozier 1999; Slater 2003). The northern branch flows along the middle slope of the Portuguese margin, extending into the Bay of Biscay and reaching the Porcupine Bank from where it partly continues to the north along the Rockall Trough as far as the Norwegian Sea. MOW interaction with different sectors of the middle slope of the Atlantic Iberian margin has generated a series of CDSs along the Portuguese margin (Alves et al. 2003), the Galicia Bank (Ercilla et al. 2006), the Cantabrian margin, and the Le Danois Bank or “Cachucho” (Van Rooij et al. 2010). This influence of MOW can be extended as far north as the Irish margin where a CDS occurs along the middle slope off the Porcupine Bank (Van Rooij et al. 2003; Øvrebø et al. 2006).

Database and methodology

This study focuses on the interpretation of selected seismic lines from a broad database acquired by TGS-NOPEC Geophysical Company L.P. and a compilation of records from REPSOL-YPF. In all, a set of 58 lines (total of 5,820 km) of two-dimensional (2D) multi-client reflection seismic data was acquired by TGS in 2001 in the Algarve basin, and 21 lines during several surveys by REPSOL in the past 20 years in the Gulf of Cadiz. The total coverage of the full 2D seismic dataset is 12,500 km^2, extending from the shelf to the basinal part of the gulf (Fig. 3).

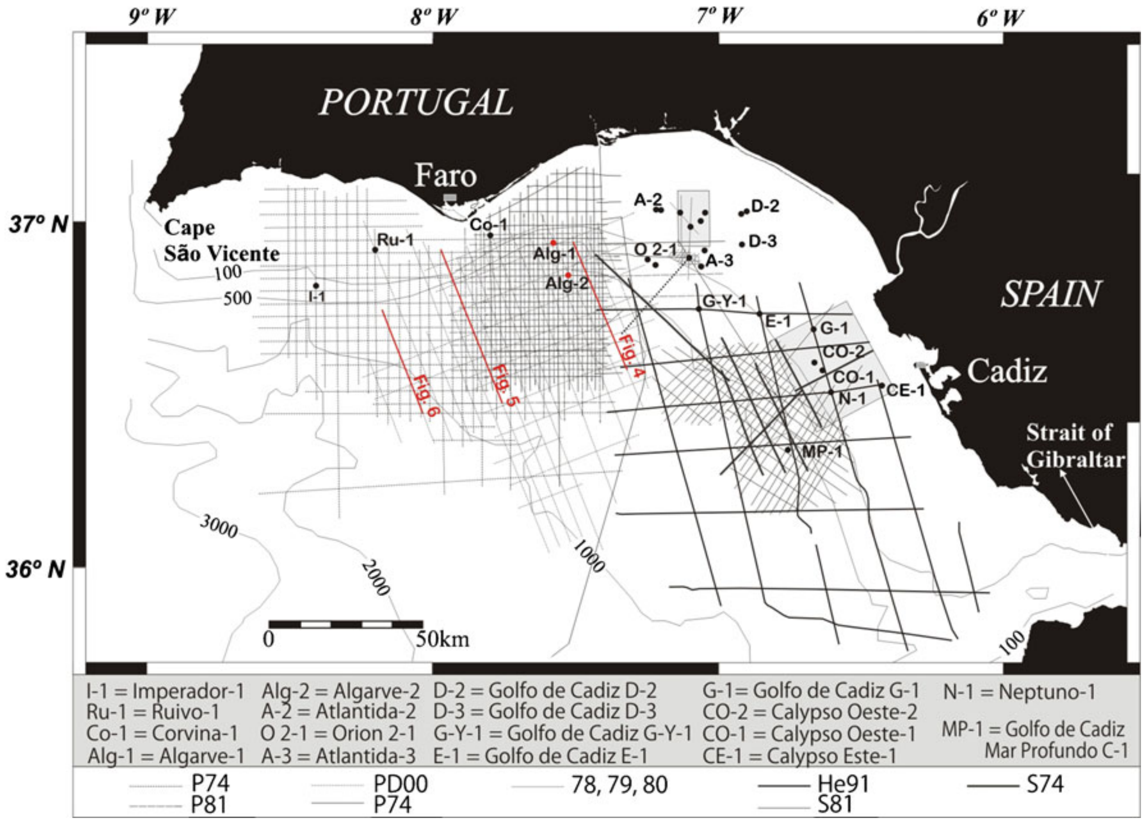

Fig. 3 Locations of oil company multichannel seismic records and borehole dataset

The TGS seismic surveys were conducted with a 6,000 m streamer; line spacing was about 8×4 km in a NNW–SSE and ENE–WSW direction, with a shotpoint interval of 25 and 30 m respectively. Recording length was 12,000 ms two-way travel time (TWT) with a sampling rate of 2 ms, later re-sampled during processing at 4 ms. The dominant frequency of the seismic data varies with depth but is approx. 30 Hz at the level of interest. Vertical (λ/4) and lateral (λ) resolutions are estimated to be 17 and 67 m respectively, assuming an average velocity of 2,000 m/s for the Neogene section. This velocity has been also used for all time-to-depth conversions. The overall seismic grid has a spacing of 2×2 km in the Algarve basin and 4×4 km in the eastern Gulf of Cadiz.

Well data were provided by DGGE (Direcção Geral de Geologia e Energia-PORTUGAL) through the DPEP (Divisão para a Pesquisa e Exploração de Petróleo) library, and consist of drilling reports, well log geological evaluations, checkshots and regional exploration reports from several oil companies. Data from wells in the eastern Gulf of Cadiz were taken from Lanaja et al. (1987). Well-to-seismic tie was performed using checkshot and sonic log data from ten wells, enabling suitable calibration and dating of interpreted horizons.

All available data were loaded into a Kingdom Suite project, the project datum being at mean sea level (0 m). Mapping is based on the UTM29 (Universal Transverse Mercator) projection coordinate system, the datum ellipsoid being WGS84. The well data and associated depths have all been referenced to true vertical depth sub-sea (TVDSS), corrected for Kelly Bushing (KB) elevation and drilling deviations. Throughout this paper, seismic sections and maps are displayed in TWT (ms). Depths and thickness are expressed in meters where time–depth conversion was conducted.

Seismic and sequence stratigraphic analyses are based on the criteria of Faugères et al. (1999) and Nielsen et al. (2008) for identification of sediment drift features. The extended Late Pliocene–Quaternary sedimentary record was correlated with that developed in earlier studies (Llave et al. 2001, 2006, 2007; Hernández-Molina et al. 2002, 2006; Stow et al. 2002b; Llave 2003). Isopach maps were generated using Surfer 8 software, with a kriging gridding method and a grid spacing of approx. 1,500×1,500 m.

Based on biostratigraphic data from boreholes along the Algarve margin (Algarve 1 and especially Algarve 2; Fig. 3), as well as on reinterpretations by Ledesma (2000) and intercorrelations with the northern Gulf of Cadiz margin made by REPSOL (Hugo Matias, unpublished data), an improved constraint of the timing of principal discontinuities was possible.

Results

Seismic stratigraphy

The stratigraphic boundaries M, LPR, BQD, MPR and the seafloor define four main seismic units—from bottom to top: P1, P2, QI and QII—within the Pliocene–Quaternary sedimentary record along the northern Gulf of Cadiz margin (Figs. 4, 5 and 6). The boundaries of these units are associated with high-amplitude reflectors which represent regional discontinuities and are coeval with strong changes in the stratigraphic stacking pattern of the slope.

The M discontinuity (Late Miocene), at the base of the Pliocene–Quaternary sedimentary record, marks the most prominent change in the stacking pattern and clearly truncates the underlying reflectors. The LPR (Early Pliocene) constitutes the next most prominent discontinuity, locally represented as a truncation surface which marks the lowermost upslope-prograding reflector terminations. The BQD represents the uppermost development of these terminations and the initiation of the huge mounded Faro-Albufeira drift. The MPR (mid-Pleistocene), above which the thickness of deposits increases and the mounded morphology is enhanced along the northern Gulf of Cadiz margin, is the most evident regional discontinuity within the Quaternary record of the gulf (Figs. 4, 5 and 6).

Seismic unit P1

Unit P1 is bounded by the M and LPR discontinuities and is characterised internally by low-amplitude seismic reflectors showing some downslope progradation. Locally, this unit is slightly deformed and exhibits gentle anticline/syncline structures (Figs. 4, 5 and 6).

In general, unit P1 shows a relatively uniform thickness, varying between 100 and 150 ms (TWT). There are two very subtle depocentres of about 150–200 ms thickness (I and II in Fig. 7a) in the northwest and southeast of the study area, trending ENE and NE respectively.

Seismic unit P2

Seismic unit P2 is bounded by the LPR and BQD discontinuities. It is characterised by well-stratified reflectors with high lateral continuity. The configuration and geometry of this seismic facies varies laterally; an upslope-prograding pattern with a mounded shape in the north indicates the beginning of a gentle elongated and separated drift. Parallel to sub-parallel reflectors and a generally sub-tabular geometry are observed over the rest of the margin, indicative of sheeted drifts. The lateral continuity and configuration of these deposits are affected by local deformation associated with:

1. diapirism towards the east, which results in an onlap/offlap configuration of the reflectors and a thinning of the unit towards the diapirs (Fig. 4);
2. the Guadalquivir Bank and Miocene palaeorelief structures in the central zone; parallel to sub-parallel seismic reflectors onlap onto these structures (Fig. 5);
3. the Miocene palaeorelief in the western zone, against which the P2 unit onlaps with deposits showing an upslope-prograding sedimentation pattern (Fig. 6).

The thickness of unit P2 is also affected by this structural configuration, resulting in lateral variation along the margin and the formation of four main depocentres numbered I to

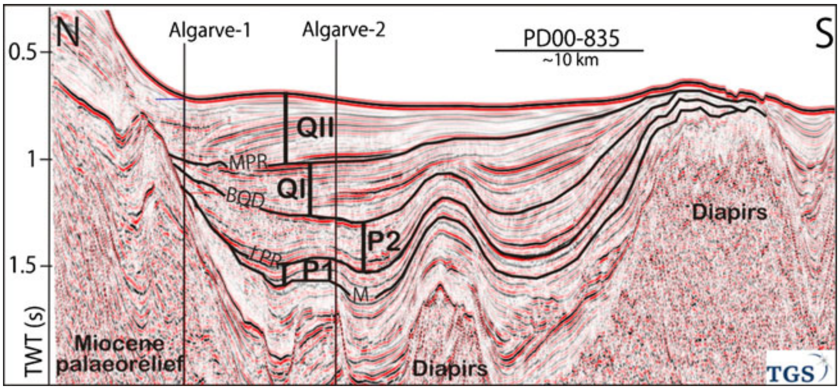

Fig. 4 Multichannel seismic reflection profile from the eastern zone of the study area (data courtesy of TGS-NOPEC Geophysical Company ASA; see location in Fig. 3), showing four major low-resolution depositional sequences in the Pliocene–Quaternary sedimentary record, separated by four discontinuities: M (late Messinian), LPR (Early Pliocene), UPR (Late Pliocene) and MPR (mid-Pleistocene). The LPR erosional discontinuity represents the onset of drift formation

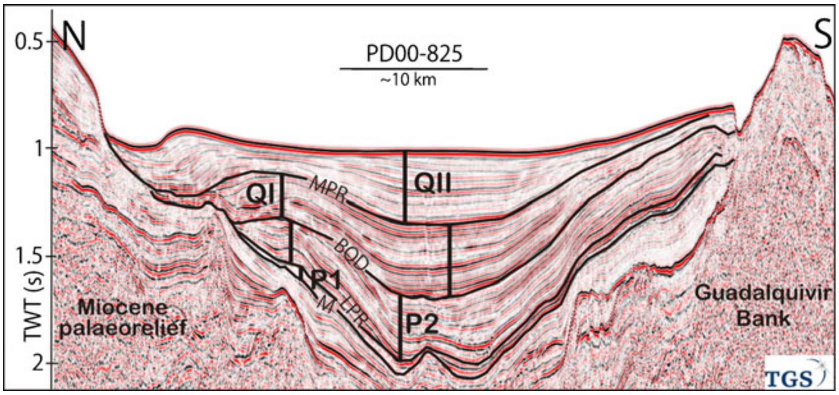

Fig. 5 Multichannel seismic reflection profile from the central zone of the study area (data courtesy of TGS-NOPEC Geophysical Company ASA; see location in Fig. 3; for more information, see Fig. 4)

IV in Fig. 7b. Depocentres I and II are about 350 ms thick (TWT) and located in the eastern zone. They have a NE trend and are separated by areas of lesser thickness (50–100 ms). Depocentres III and IV (400 ms) are in the central zone of the study area, showing NE and WNW trends respectively. These depocentres are bounded to the south and north by zones of low (50 ms) or zero thickness close to the Guadalquivir Bank and south of the Alvarez Cabral moat (Fig. 7b).

Seismic unit QI

Seismic unit QI is bounded by the BQD and MPR discontinuities. In part, it shows a pronounced oblique upslope-prograding stacking pattern which characterises a mounded elongated and separated drift where other minor erosional discontinuities are observed. Laterally, this mounded geometry evolves into an aggradational pattern characteristic of a large sheeted drift. The deformation pattern noted above for unit P2 is also evident in unit Q1, involving:

1. diapirism towards the east, with evidence of onlap/offlap reflector terminations, thinning of the units towards the diapir zone, and local small thickening in the distant peripheral sinks (Fig. 4);
2. the Guadalquivir Bank and Miocene palaeorelief structure in the central zone, where unit QI onlaps onto the bank with parallel to sub-parallel seismic reflectors, and shows a prograding onlap stacking pattern towards the Miocene palaeorelief structure in the north (Fig. 5);
3. the Miocene palaeorelief in the western zone, where reflectors onlap onto this structure with upslope-prograding sedimentation (Fig. 6).

The isopach map shows five main depocentres numbered I to V in Fig. 7c. Depocentres I and II are each about 300 ms thick (TWT) and located to the east, with a NE trend and separated by zones of lower thickness (50 ms) with similar orientation. Towards the centre of the study area, depocentres III (300 ms) and IV (400 ms) have W and NNE trends respectively and are bounded by zones of lower thickness (50 ms) close to the Guadalquivir Bank; thickness is essentially zero near the Alvarez Cabral moat. The western zone is characterised by the NNE-trending, relatively thick depocentre V (about 500 ms).

Seismic unit QII

Unit QII is bounded by the MPR and the seafloor. It has a sigmoidal to oblique reflector configuration which suggests upslope progradation in the northern area, and parallel to sub-parallel reflectors with an aggrading pattern in the vicinity of sheeted drifts towards the south. Several minor

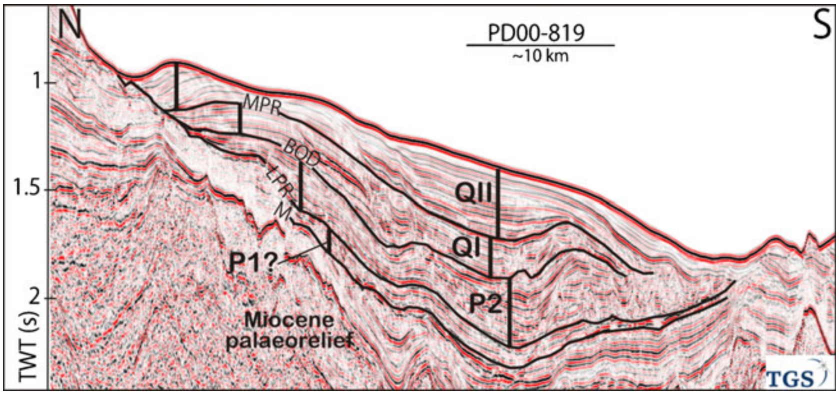

Fig. 6 Multichannel seismic reflection profile from the western zone of the study area (data courtesy of TGS-NOPEC Geophysical Company ASA; see location in Fig. 3; for more information, see Fig. 4)

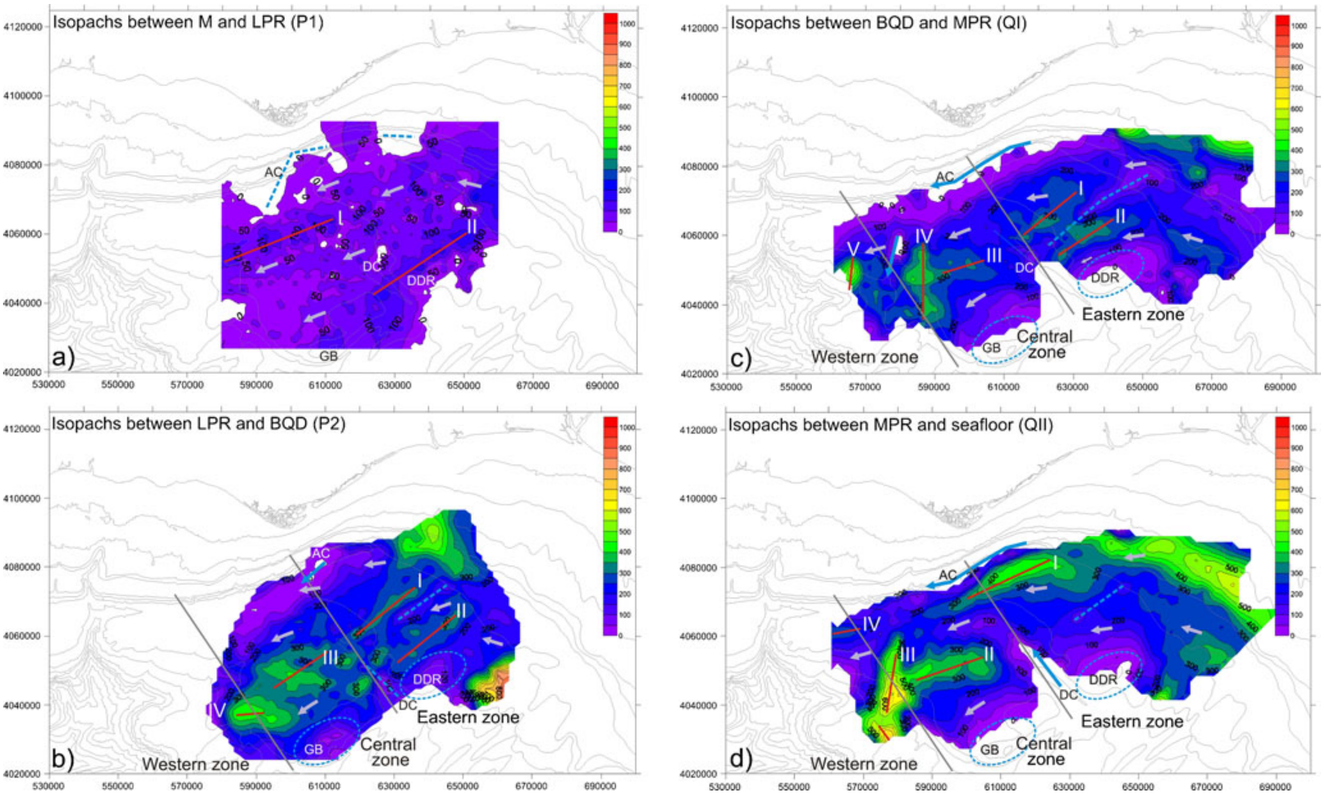

Fig. 7 Isopach maps of **a** unit P1, **b** unit P2, **c** unit QI and **d** unit QII, with the main structural domains and possible MOW circulation patterns. *Blue dashed lines* Scarce sedimentation, *red lines* main depocentres I to V, *blue arrows* MOW erosion by turbulent flow, *lilac arrows* tabular conditions in MOW circulation pattern; *AC* Alvarez Cabral moat, *DC* Diego Cao Channel, *DDR* Doñana diapiric ridge, *GB* Guadalquivir Bank

erosional discontinuities are also observed (Figs. 4, 5 and 6). The deposits of this unit exhibit onlap reflector terminations to the main geological structures, especially in the upper part of the unit, and mass-wasting facies towards the Alvarez Cabral moat (Fig. 4).

The main depocentre (about 500 ms TWT) is in the northern part of the study area and has an ENE trend, parallel to the Alvarez Cabral moat (I in Fig. 7d). In the central zone, depocentre II is about 400 ms thick and trends W, whereas depocentre III is 600 ms thick and trends NNE. Towards the west, a W-oriented and 250-ms-thick depocentre is observed (IV in Fig. 7d). Areas of low (50–100 ms) or zero thickness are found in the present-day Alvarez Cabral moat to the north, and the Doñana diapiric ridge, Diego Cao Channel and Guadalquivir Bank to the south.

Age constraints

The M discontinuity has been dated at 5.4–5.6 Ma and therefore emplaced in the Messinian, Late Miocene. The LPR represents an intra-Early Pliocene discontinuity for which, based on stratigraphic position, an age of about 4.0–4.2 Ma is here inferred. The other two major discontinuities, BQD and MPR, are less confidently dated because most boreholes have not recovered the have not provided good age control. The BQD corresponds to an intra-Late Pliocene discontinuity interpreted in earlier studies as the UPR; however, the base of the Quaternary has recently been reassigned an age of ~2.6 Ma by the International Commission on Stratigraphy (cf. Introduction). Moreover, information from well E-1 enabled Llave et al. (2007) to assign the MPR discontinuity an age of approx. 900 ka (mid-Pleistocene).

Discussion and conclusions

The integration of seismic stratigraphy and tectonic structures in the present study has facilitated better documentation of the Pliocene–Quaternary sedimentary evolution of the northern Gulf of Cadiz continental margin. Four major depositional sequences (P1, P2, QI and QII) each spanning a time period of approx. 1 to 2 million years have been identified and can be associated with three distinct evolutionary phases: a pre-contourite phase (unit P1, ca. 5.4–5.6 to 4.0–4.2 Ma), an early contourite phase (unit P2, 4.0–4.2 to 2.6–2.4 Ma) and a late contourite phase (units QI and QII, 2.6–2.4 Ma to the present). This evolution can be interpreted in terms of the interplay between sea-level changes, variations in MOW circulation and periods of tectonic deformation (Fig. 8).

Pre-contourite phase

Although the timing of the Gibraltar gateway opening at the Zanclean, end of the Miocene (5.3 Ma) is in little doubt (Berggren and Hollister 1974; Mulder and Parry 1977; Maldonado et al. 1999; Blanc 2002; García-Castellanos et al. 2009), the precise onset of MOW influx into the Atlantic is still uncertain. In the present study, unit P1 is interpreted as representing a pre-contourite phase prior to any or significant MOW influx. The northern Gulf of Cadiz margin is characterised by a mainly tabular sedimentation geometry up to 150 ms thick (TWT), relatively uniform draping of seafloor irregularities and some seaward progradation of reflectors (Fig. 7a). Most likely, these sediments are predominantly of hemipelagic and pelagic origin. Hemipelagic processes involve a slow seaward diffusion of material coupled with vertical settling (Stow and Tabrez 1998) and, therefore, would explain the slight seaward progradation of reflectors observed.

Early contourite phase

The LPR discontinuity represents the first significant change in northern Gulf of Cadiz margin sedimentation, interpreted as marking the onset of contourite deposition with sheeted drift deposits onlapping upslope (P2 depositional sequence). Based on available borehole data, the LPR discontinuity is intra-Early Pliocene in age and tentatively placed at ca. 4.0–4.2 Ma. Although this correlates with an important global sea-level fall (Haq et al. 1987; Alonso and Maldonado 1992), it would also represent a time of tectonic adjustment in the Gibraltar gateway, such that active MOW outflow began. Further work, including better chronological constraints, is needed to confirm this hypothesis (Fig. 8).

In the eastern zone, two main NE-SW-trending diapiric structures appear to control the location and geometry of sheeted drifts at an early stage of CDS development within the northern Gulf of Cadiz margin. This is particularly true in the Late Pliocene, when syn-sedimentary diapiric intrusion became more active. The lateral extension of the sedimentary units into the central zone is controlled by the Miocene palaeorelief (Terrinha 1998; Lopes et al. 2006) to the north and by the Guadalquivir Bank to the south (Figs. 7 and 8). This mid-slope area in the northern Gulf of Cadiz has an overall synclinal geometry, resulting from locally active subsidence during the Pliocene and at the beginning of the Quaternary, expressed as angular syn-sedimentary unconformities at the basin margins and conformities towards the basin centre. The change in thickness within the growth wedge affects the depositional sequence P2 in particular (Figs. 4, 5, 6 and 7).

It is evident that an energetic MOW dominated during P2 deposition, affected by the CAU coupled with subsidence and diapiric activity (Maldonado et al. 1999; Nelson et al. 1999; Medialdea et al. 2004). Both tectonically

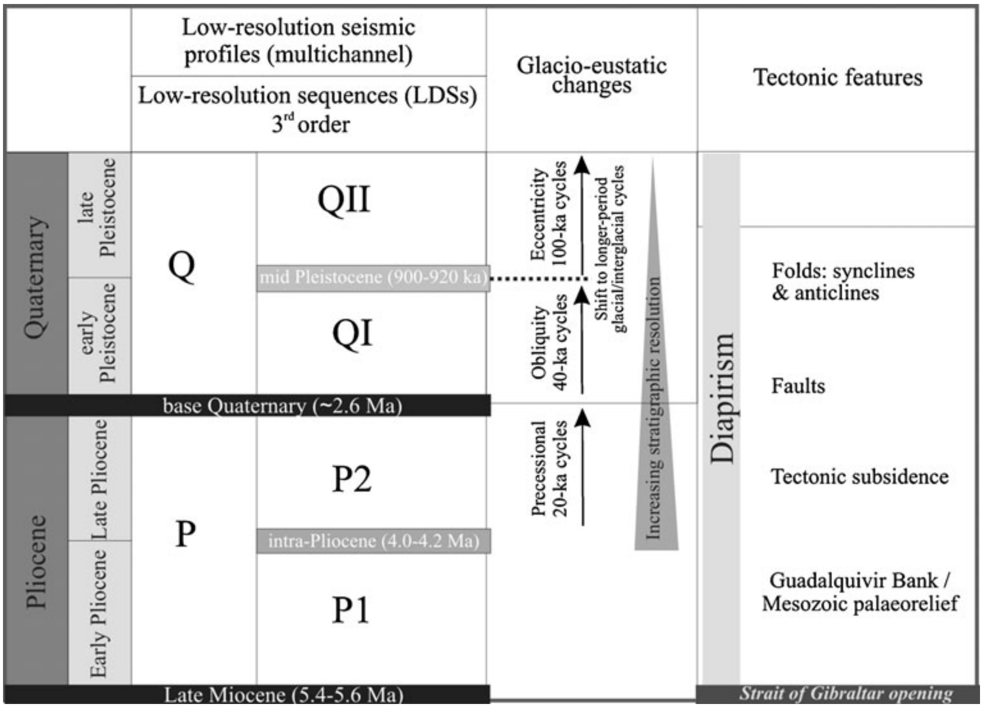

Fig. 8 Tectonic and glacio-eustatic control on depositional sequences of the middle slope of the northern Gulf of Cadiz margin

controlled margin morphology and progressive climatic change then contributed to flow intensification and the development of new flow pathways across the northern Gulf of Cadiz margin (Fig. 8).

Late contourite phase

The BQD discontinuity at ca. 2.6 Ma marks another change in margin evolution, representing the base of further evolution of contourite deposition and the marked growth of the Faro-Albufeira mounded, elongated and separated middle-slope drift parallel to the margin. A general upslope progradation of contourite drifts is observed, with the main depocentres migrating towards the north and northwest during the Quaternary (Fig. 7c). This is associated with a flanking boundary channel (Alvarez Cabral moat) to which a narrow flow of MOW would be constrained. Its turbulent nature would be enhanced by shear against the Faro margin due to Coriolis deflection. Thus, pronounced erosion would occur along the right flank of the channel and deposition over the mounded drift on the left flank. Upslope migration would result from the progressive increase in relief of the drift, associated with deflection of the Alvarez Cabral flow pathway in response to the changing seafloor morphology (Llave et al. 2001; Roque 2007). By the end of the Early Pliocene, regional subsidence decreased and the margin evolved towards its present-day, more stable condition (Maldonado et al. 1999; Maestro et al. 2003; Medialdea et al. 2004); nevertheless, neotectonic processes related to halokinesis and local fault movements have played a key long-term role in controlling the architecture of the CDS (Fig. 8). This appears to have affected unit QI in particular. Depositional sequence QII is less affected, especially the upper part of the sequence which overlaps or onlaps onto all earlier units and tectonic structures with an aggrading stacking pattern (Figs. 4, 5 and 6).

These interpretations concur with earlier work (Loubere 1987; Thunell et al. 1991) reporting that, following BQD formation at the beginning of the Quaternary (2.6–2.4 Ma), the Recent hydrodynamic pattern of MOW was completely established. This was contemporary with further global cooling which initiated full glacial–interglacial cyclicity characteristic of the Pleistocene (Thunell et al. 1991), although the direct cause–effect link between climate and MOW is not yet fully understood. Certainly, the influence of environmental changes on MOW dynamics and the latter's impact on marine sedimentation are at least partially known since BQD formation (Grousset et al. 1988; Vergnaud-Grazzini et al. 1989; Nelson et al. 1993; Cacho et al. 2000; Llave et al. 2006; Voelker et al. 2006).

During the Quaternary contourite evolution, the last major change in the depositional stacking pattern is observed after the development of the MPR discontinuity. This has been correlated by Llave et al. (2001, 2007) with an important change in climate known as the mid-Pleistocene revolution and dated at approx. 900–920 ka. Since that time, the sedimentary record has been substantially less affected by tectonic deformation and more directly by environmental (climate and sea-level) changes (Fig. 8). During development of the QII depositional

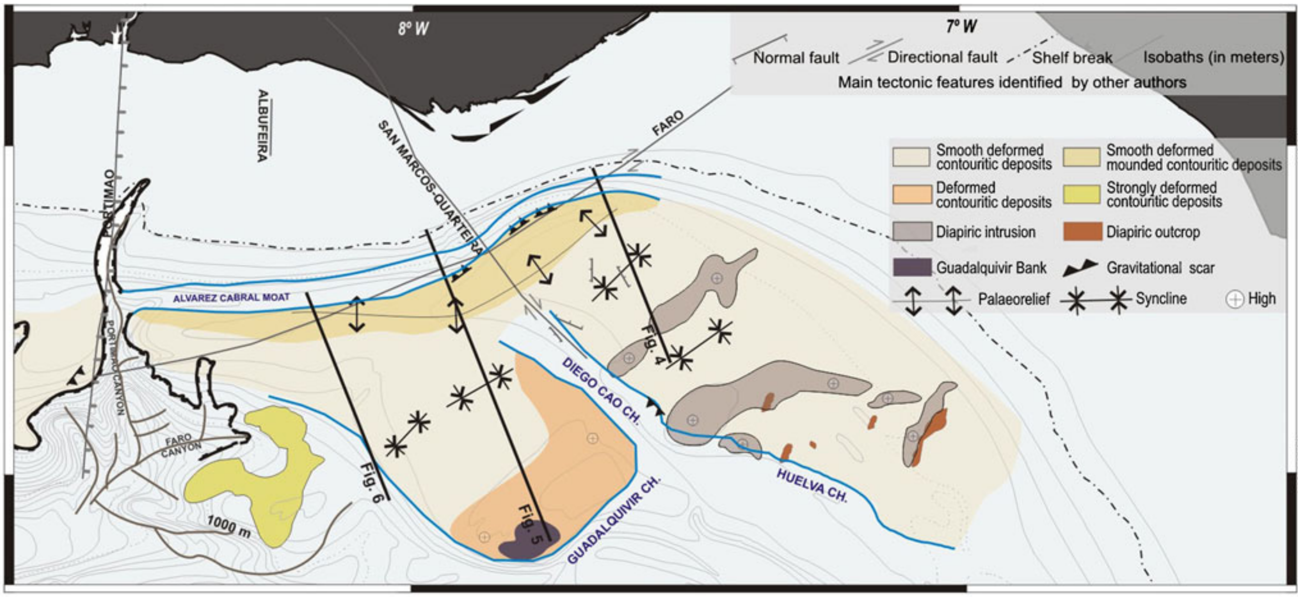

Fig. 9 Morphostructural sketch of main tectonic features influencing the initiation of the contourite depositional system and its subsequent development (adapted from Llave et al. 2001, and updated from Mougenot 1988; Maldonado et al. 1999; Lopes et al. 2006)

sequence, a general increase in sedimentation rate is inferred which would explain the development of prominent mounded, elongated and separated drifts with an average thickness of about 500 ms (TWT), particularly evident in the northern part of the Gulf of Cadiz. This increase in sediment supply would be conditioned also by MOW intensification, associated with a more erosive capacity along its pathway and where it is channelised on the upper continental slope margin. Depending on the location of the axial Alvarez Cabral flow pathway, the migration of these drifts to the north or west would be a consequence of the progressive increase in relief of the moat and drifts, combined with a more vigorous MOW circulation; these three main factors would have induced slides and mass movement sedimentation in the Alvarez Cabral southern sector. This is coincident with the shift to longer-period glacial/interglacial cycles and an increase in cycle amplitude since the mid-Pleistocene revolution (Fig. 8). Indeed, the Diego Cao Channel separates the overall sheeted contourite system into two regions, and is eroding Recent sediments (Hernández-Molina et al. 2006; Llave et al. 2007; García et al. 2009) and cutting a steep northern wall.

Structural control on sediment distribution

On the basis of the deformation observed along the northern Gulf of Cadiz margin, three structural zones were distinguished as steering CDS evolution, i.e. the eastern, central and western zones. The *eastern zone* is characterised by a Miocene palaeorelief in the north where the mounded, elongated and separated drift has developed since the Early Pliocene, including units P2, QI and QII. Basinwards of this, the development of sheeted drifts has been influenced by two main NE–SW diapiric structural trends since the beginning of CDS development. Diapiric growth was important from the Late Pliocene until the late Quaternary—units P2 and QI (Figs. 7 and 9)—and decreased during the deposition of units P1 and QII, especially for the upper part of QII which overlaps all earlier units with an aggrading stacking pattern.

The lateral extension of sedimentary units in the *central zone* is controlled by the Miocene palaeorelief to the north and by the Guadalquivir Bank to the south. This mid-slope area in the northern Gulf of Cadiz has an overall synclinal geometry resulting from local active subsidence during the deposition of unit P2 and most of unit QII, expressed as angular syn-sedimentary unconformities at the basin margins and conformities towards the basin centre (Figs. 7 and 9). Thickness variation within developing depocentres was noted for all sedimentary units, excepting for the upper part of QII. These younger sediments overlap older Quaternary sediments, suggesting that they are less affected by subsidence processes. In the *western zone*, P1 to QII units onlap onto the Miocene palaeorelief.

Although this seismic stratigraphic analysis is considered to have good regional validity for the northern Gulf of Cadiz, further in-depth work is required particularly in terms of more scientific borehole data and detailed chronology.

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