

Contourite erosive features caused by the Mediterranean Outflow Water in the Gulf of Cadiz: Quaternary tectonic and oceanographic implications

M. García^{a,*}, F.J. Hernández-Molina^b, E. Llave^c, D.A.V. Stow^d, R. León^c, M.C. Fernández-Puga^e, V. Diaz del Río^e, L. Somoza^c

^a Instituto de Ciencias del Mar, CSIC, Paseo Marítimo de la Barceloneta 37-49, 08003 Barcelona, Spain

^b Facultad de Ciencias del Mar, Universidad de Vigo, 36200 Vigo, Spain

^c Instituto Geológico y Minero de España, Ríos Rosas, 23, 28003 Madrid, Spain

^d ECOSSE, Institute of Petroleum Engineering, Heriot Watt University, Edinburgh, UK

^e Instituto Español de Oceanografía, C/ Puerto Pesquero s/n, 29640 Fuengirola, Spain

ARTICLE INFO

Article history:

Received 27 February 2008

Received in revised form 18 October 2008

Accepted 21 October 2008

Keywords:

erosive features
Mediterranean Outflow Water
Gulf of Cadiz
continental slope
contourites
neotectonics
Quaternary

ABSTRACT

Contourite depositional systems have been the focus of much recent research, but still relatively little is known about contourite erosive features and their associated processes. Based on multibeam bathymetry, side-scan imagery and different resolution seismic records, a detailed description and classification of the major erosive submarine valley features of the Contourite Depositional System of the Gulf of Cadiz middle slope is presented for the first time. Four types of erosive features have been differentiated, including *contourite moats*, *contourite channels*, *marginal valleys* and *large isolated furrows*, and interpreted in terms of their tectonic and oceanographic implications during the Quaternary. The study of the distribution and characteristics of erosive features is essential to better understand the present and past interaction of the Mediterranean Outflow Water (MOW) with the middle slope seafloor, and allows us to propose a new and more precise scheme for the MOW circulation patterns. This scheme includes a main along-slope circulation responsible for the excavation of the contourite moat and channels, and a secondary down-slope circulation responsible for the erosion of marginal valleys and isolated furrows. Three evolutionary stages have been observed in the development of the erosive system during the Quaternary, that can be related to changes in the distribution and splitting of the MOW as a consequence of the segmentation of the NE–SW diapiric ridges by neotectonic effects: 1) *Early Pleistocene to Mid-Pleistocene*: linear diapiric ridges; 2) *Mid-Pleistocene to Late Pleistocene*: diapiric reactivation and 3) *Late Pleistocene to Holocene*: main recent phase of diapiric ridges segmentation and rotation. This study provides important regional clues for establishing the evolution of the erosive features in relation with neotectonic effects, and represents a good example of the potential of erosive features as evidences for the reconstruction of the paleoceanography and recent tectonic changes.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

The impact of contour currents on continental margins has received the attention of many studies that have focused on the morphology, seismic and sedimentary products and associated processes (Faugères et al., 1999; Stow et al., 2002; Rebesco, 2005; Viana and Rebesco, 2007). Contour currents may form in a wide variety of oceanographic contexts and are responsible for the generation of contourite deposits of variable dimensions in a range of geological settings (Stow et al., 1986; Ercilla et al., 1998; Gao et al., 1998; Faugères et al., 1999; Stow et al., 2002; Viana, 2001; Maldonado et al., 2003, 2005; Rebesco, 2005; Mulder et al., 2006;

Rebesco and Camerlenghi, in press; Stow et al., in press-a,c, among others).

Although there are several recent classifications of contourite deposits (McCave and Tucholke, 1986; Faugères et al., 1999; Rebesco and Stow, 2001; Stow et al., 2002; Rebesco, 2005), the variety of erosive features that develop in relation to the activity of contour currents are still the “ugly duckling” of contourite studies. Knowledge of the distribution and evolution of these features is essential for understanding the oceanographic circulation regarding the direction, velocity of the current, secondary flows, filaments, local turbulence and other local hydrodynamic features. This work characterizes, in particular, the erosive submarine valley features generated by the Mediterranean Outflow Water (MOW) on the Gulf of Cadiz middle slope (Fig. 1) with three aims: a) identification of sedimentary processes associated with the erosive features; b) establishment of a detailed present-day

* Corresponding author. Ifremer, Centre de Brest Z.I. Pointe du Diable B.P. 70 Plouzané, France. Tel.: +33 0298224237; fax: +33 0298224549.

E-mail address: mgarcia@icm.csic.es (M. García).

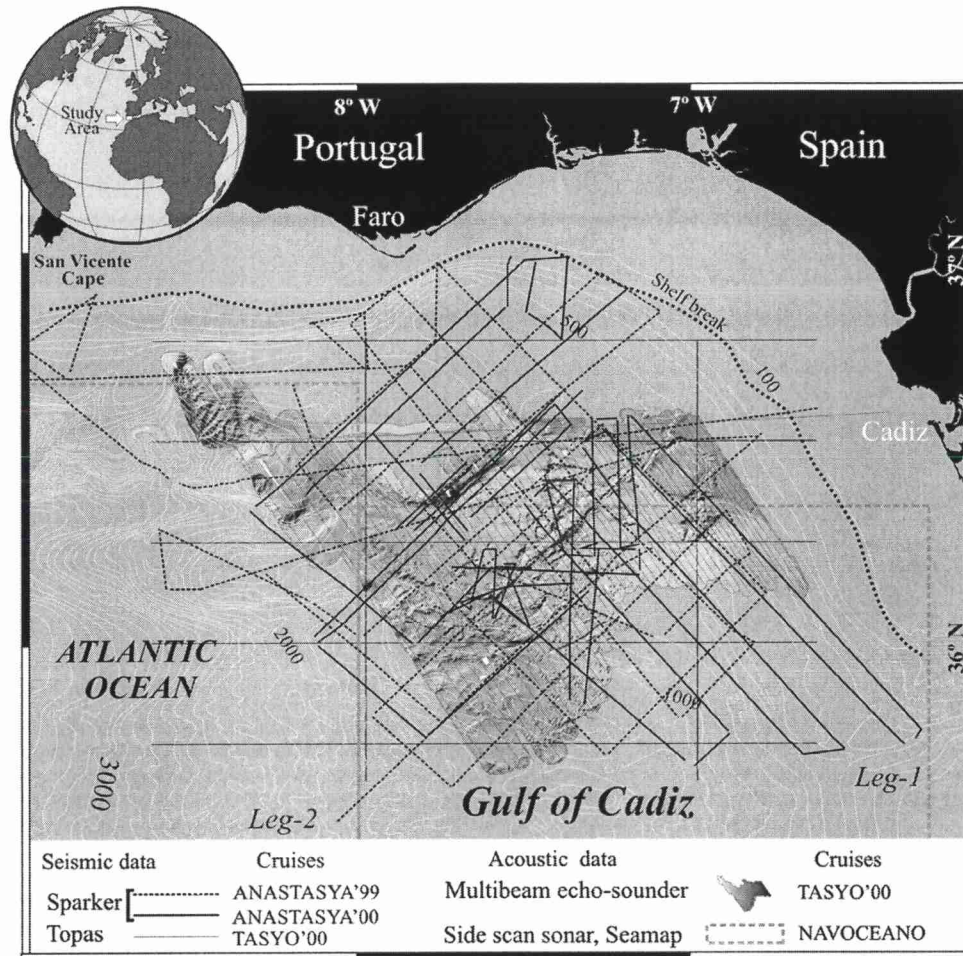


Fig. 1. Study area and datasets studied in this work, including mono-channel reflection seismic data (Sparker and TOPAS), multibeam echo-sounder mosaic and side-scan sonar imagery.

circulation model of the MOW cores and branches; and c) interpretation of the Quaternary tectonic and oceanographic evolution responsible for the generation of the erosive features.

2. Methodology

The present study is based on an extensive database of bathymetric and seismic reflection profiles (Fig. 1). Regional bathymetric maps by Heezen and Johnson (1969) and Serrano et al. (2005) were used for the regional morphological study. High-resolution swath bathymetry and backscatter data were obtained with the Simrad EM12S-120 multibeam echo-sounder system and the Seamap Side Scan Sonar system operated by the NRL and Naval Oceanographic Office (NAV-OCEANO). Seismic reflection profiles were obtained with a Sparker system. The seismic emission frequency was between 100 and 1500 Hz, giving an average vertical resolution of 1.5 m. Global Positioning System (GPS) and GPS-Differential systems were used for the data positioning.

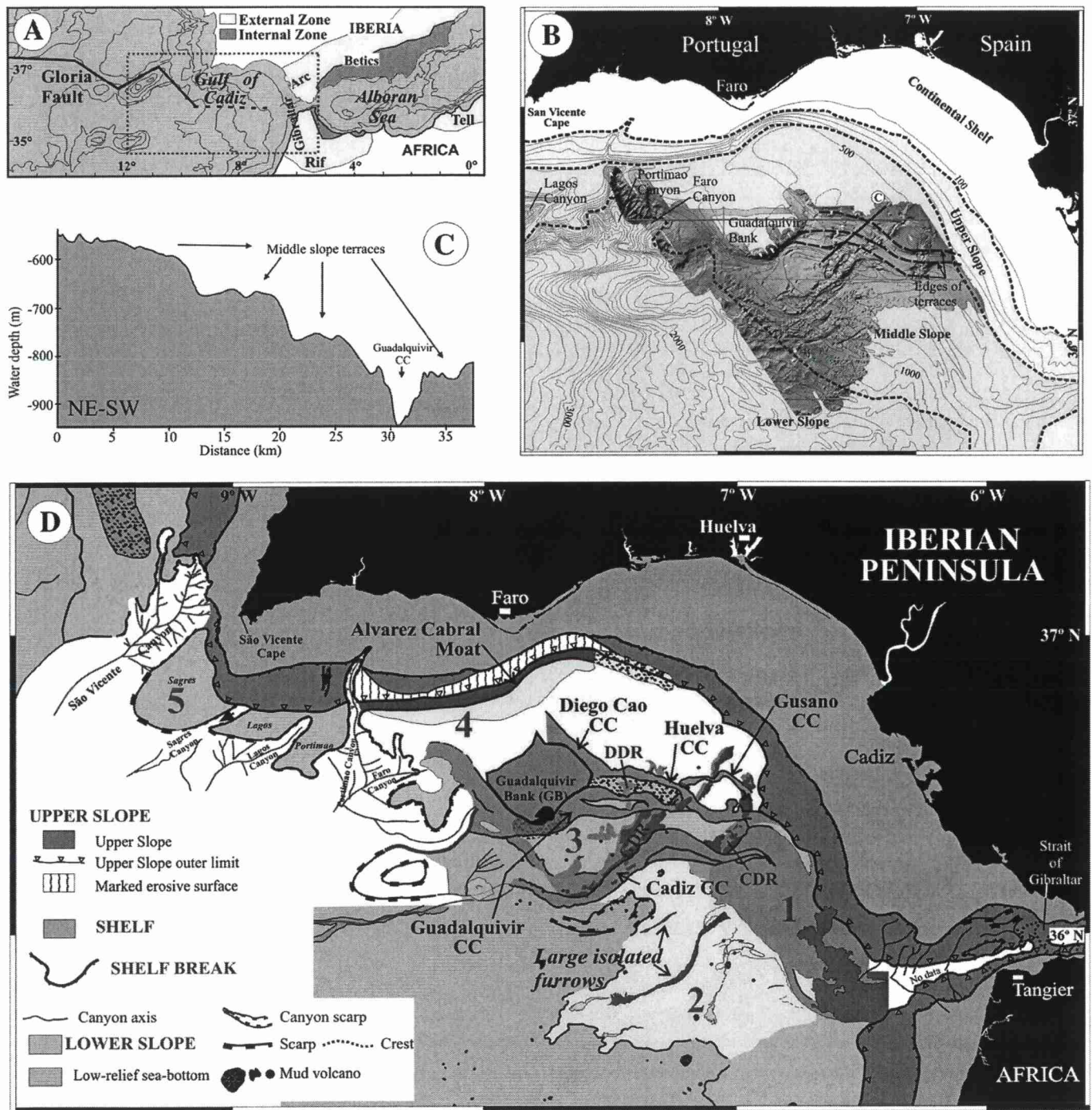
3. Geological and oceanographic setting

The Gulf of Cadiz is located at the SW margin of the Iberian Peninsula (Fig. 2A). Since the late Miocene, different tectonic regimes have affected this area, from compressive to transtensional regimes. The emplacement of a giant "olistostrome" (the Cadiz Allochthonous Unit or Cadiz Nappe) during the Tortonian induced very high rates of basin subsidence and strong diapiric activity (Maldonado and Nelson, 1999; Maldonado et al., 1999; Somoza et al., 1999; Medialdea et al., 2004). The olistostrome has

been alternatively defined as an actively deforming accretionary wedge originated by the ongoing W-SW shortening in a scenario of active subduction in a compressive tectonic regime (Gutscher et al., 2002). Salt-and shale-tectonics resulting from extensional events from Late Tortonian to Late Messinian and from Early Pliocene to Late Pliocene affected the olistostrome and induced large-scale mass wasting events (Maestro et al., 2003). Neotectonic reactivation in the Gulf of Cadiz is indicated by the occurrence of mud volcanoes, diapiric ridges and fault reactivation (Maestro et al., 1998; Díaz del Río et al., 2003; Lobo et al., 2003; Maestro et al., 2003; Somoza et al., 2003; Fernández-Puga, 2004; Fernández-Puga et al., 2007; Llave et al., 2007a,b).

The continental slope of the Gulf of Cadiz is composed of three domains: *upper*, *middle* and *lower* slope (Fig. 2B) based on the gradient and morphological features (Heezen and Johnson, 1969; Maldonado and Nelson, 1999; Hernández-Molina and Lobo, 2005). The *upper slope* occurs from 120–140 to 500 m water depth. The *middle slope* occurs at depths of about 500–1200 m, with a maximum width of 100 km and low gradients of 0.5–1°. The *lower slope* is 50–200 km wide and connects with the abyssal plains at 4300–4800 m water depth.

A Contourite Depositional System (CDS) has been characterized within the Gulf of Cadiz middle slope region (Llave et al., 2001; Hernández-Molina et al., 2003, 2006; Llave et al., 2006) and is composed of five morphosedimentary sectors (Fig. 2D): *proximal scour and sand ribbons*; *overflow sedimentary lobe*; *channels and ridges*; *contourite drifts and submarine canyons* sectors. Amongst several different types of erosive features, those designated as submarine valleys include *contourite channels*, *large isolated furrows*, *marginal valleys* and *moats*



CONTOURITE DEPOSICIONAL SYSTEM

1) Proximal scour & ribbons sector

- Abrasive surface with erosive scour alignments, sand dunes & sand ribbon fields
- Rock outcrops

2) Overflow sedimentary lobe sector

- Sedimentary lobe with bedforms, slides & erosive scours
- Large isolated furrows
- Mud & sand sedimentary lobes

3) Channels and ridges sector

- Contourrite Channels
- Channel scarp
- Diapiric ridge: a) Outcropping diapir b) Subsurface diapir
- Buried mounded Drift
- Deformed sheeted Drift
- Buried mounded Drift at S of Guadalquivir Bank

4) Contourrite depositional sector

- Mounded elongated & separated Drift
- Plastered Drift
- Sheeted Drift
- Contourrite Moat

5) Submarine canyons sector

- Middle Slope with Sheeted Drifts and occasionally Detached & Separated Drifts
- Confined, Separated & Plastered Drifts

Fig. 2. Regional sketch of the study area. A) Localisation within the structural frame; B) Physiography, including the continental shelf, upper, lower and middle slope. Dashed lines show the limits of the middle slope terraces; C) Topographic profile along the middle slope terraces (see location of the profile in C); D) Map of the Gulf of Cadiz showing the morphosedimentary sectors of the Contourrite Depositional System and the location of the main structural and erosive features. CC: Contourrite Channel. CDR: Cadiz Diapiric Ridge. GDR: Guadalquivir Diapiric Ridge. DDR: Doñana Diapiric Ridge.

(García, 2002; Hernández-Molina et al., 2003, 2006). The major physiographic structures are the basement outcrop that forms the Guadalquivir Bank and the Doñana, Guadalquivir and Cadiz diapiric ridges that form NE–SW-oriented linear and segmented structures. These either outcrop at 300–1100 m water depth (Fernández-Puga, 2004; Medialdea et al., 2004; Hernández-Molina et al., 2006; Fernández-Puga et al., 2007) or form buried structures that lead to an undulating deformational topography (Fig. 2). The Gulf of Cadiz CDS developed after the opening of the Straits of Gibraltar at the end of the Messinian and its evolution has been controlled by the exchange of water masses through this strait (Kenyon and Belderson, 1973; Gardner and Kidd, 1983; Nelson et al., 1993; Baraza et al., 1999; Nelson et al., 1999). From the Pleistocene, when the orbital parameters of precession, obliquity and eccentricity controlled the periodicities of glacial-interglacial cycles (Paillard, 1998), the Gulf of Cadiz deposition was affected by climatic cycles (Llave, 2003; Voelker et al., 2006; Llave et al., 2006, 2007a,b; Toucanne et al., 2007).

The Gulf of Cadiz present-day oceanographic circulation is controlled by the superficial flow of Atlantic Inflow Water (AIW) towards the Mediterranean Sea and the deeper water flow of Mediterranean Outflow

Water (MOW) towards the Atlantic Ocean (Lacombe and Lizeray, 1959; Ochoa and Bray, 1991; Nelson et al., 1999) (Fig. 3). MOW represents an independent strong contour current, moving from the SE to the NW along the middle slope between 500 and 1200 m water depth above the North Atlantic Deep Water (NADW) (Lacombe and Lizeray, 1959; Zenk, 1975; Thorpe, 1976; Ochoa and Bray, 1991; Ambar et al., 1999; Serra et al., 2005). The MOW enters the Gulf of Cadiz at depths of 250–300 m with a western trend and velocities of up to 250 cm/s (Ambar and Howe, 1979; Mulder et al., 2003). The Coriolis effect produces a deviation of the flow towards the northwest where the flow is split into an Upper Core (MU) and Lower Core (ML) (Madelain, 1970; Zenk, 1975; Grundlingh, 1981; Borenäs et al., 2002; Serra et al., 2005) by the effects of the bottom friction and seafloor topography (Borenäs et al., 2002; Serra et al., 2005) (Fig. 3). MU flows slope-parallel at depths of 500–800 m (Figs. 2 and 3). At the Algarve margin part of its flow is captured by the Portimao Canyon (Marchès et al., 2007). ML has a general NW trend and concentrates the major part of the flow west of 7° W (Madelain, 1970). At 7° W a filament is detached from the southern part of the ML with a SW direction. At 7° 20' W ML is divided in three distinct branches with a general NW direction: the *Southern Branch* (SB), the *Principal Branch* (PB) and the *Intermediate*

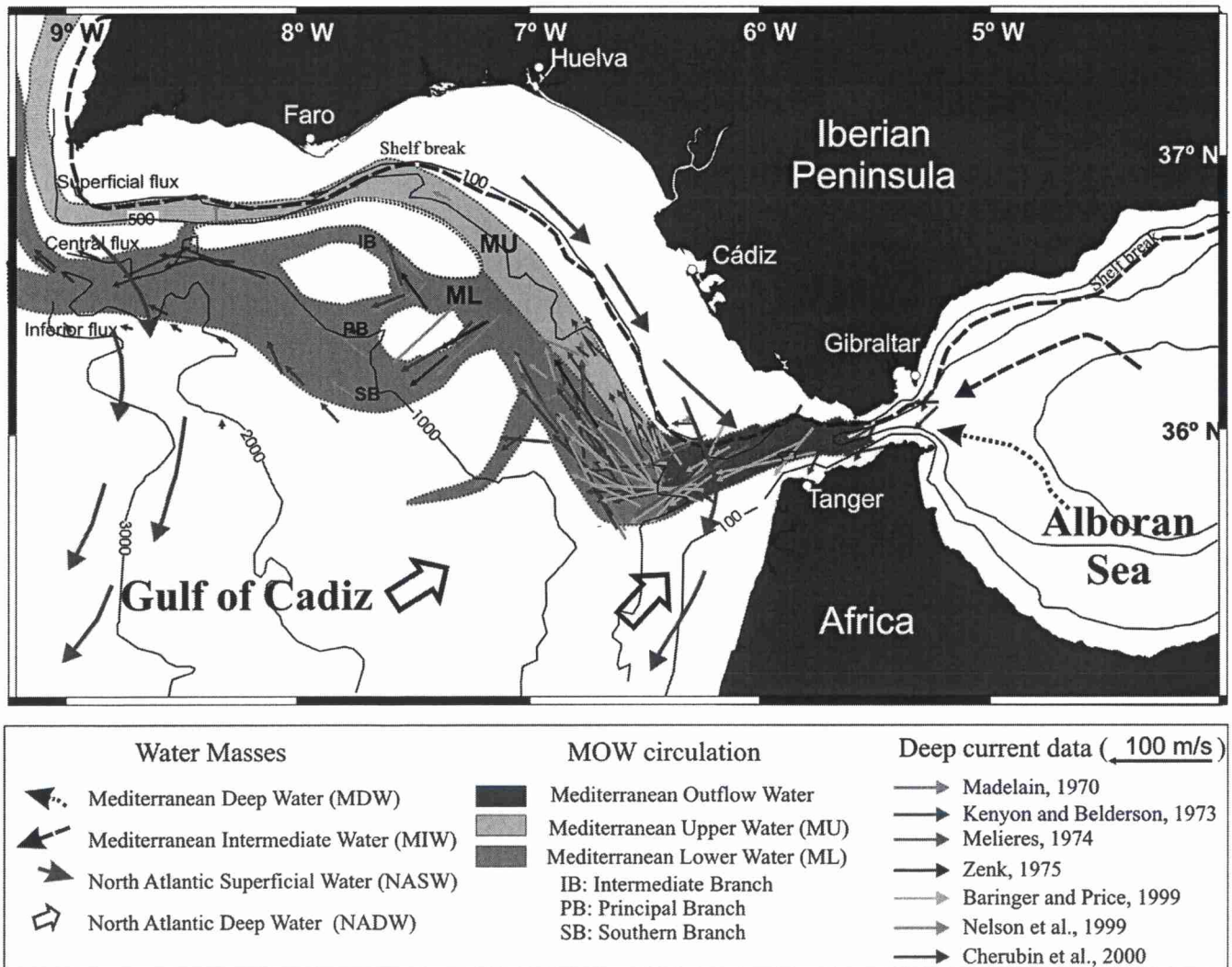


Fig. 3. Overview of the oceanographic patterns in the Gulf of Cadiz area, showing the circulation pattern of the cores and branches in which the MOW is split: the Mediterranean Upper Core (MU) and the Mediterranean Lower Core (ML), which is divided into the Southern Branch (SB), the Principal Branch (PB) and the Intermediate Branch (IB). Arrows represent values of deep current velocity and direction obtained from the bibliography.

Table 1
Morphologic parameters of the erosive features described in this study, including the contourite moat, the contourite channels, the marginal valleys and the furrows

EROSIVE FEATURE		Length (km)	Width (km)	Direction	Axial Gradient (°)	E extreme Axial Depth (m)	W extreme Axial Depth (m)	Incision Depth (m)
Moat	Alvarez Cabral	80	3.5–11	ENE–WSW	0.28	500	900	> 100
Contourite Channels	Cádiz	110	3.2–8	E–W; NE–SW	0.4	720	1500	20–120
	Guadalquivir	90	1–12	E–W; ESE–WNW	0.37	600	1200	10–130
	Huelva	58	1.8–5.5	SE–NW; E–W	0.15	560	710	20–290
	Diego Cao	30	4.8–14	SE–NW		780	–900	130–305
	Gusano	39	1.5–3	SE–NW; NE–SW	0.4	490	765	10–180
Marginal Valleys		3.3–28.4	0.4–5	N–S to NE–SW	0.06–3.29	605–1012	610–1120	5–260
Furrows	Furrow I	15.7	0.8–2.3	NE–SW	0.75	915	1115	25–160
	Gil Eanes	55	0.8–1.7	NE–SW; NNE–SSW; ENE–WSW	0.23	–1000	1225	50–90

Branch (IB). They re-join at about 8° 20' W and leave the Gulf of Cadiz towards the west Iberian margin and central north-Atlantic (Fig. 3).

4. Morphological characterization of the erosive features of the Gulf of Cadiz middle slope

The Gulf of Cadiz middle slope is a complex area formed by four relatively flat terraces with gradients of less than 0.5°, at average depths of 500, 675, 750 and 850 m (Fig. 2C) and bounded by relatively steep steps with gradients of 1.5–3°. The Guadalquivir Bank, the Doñana, Guadalquivir and Cadiz diapiric ridges and numerous isolated diapiric highs are the most prominent highs on the Gulf of Cadiz middle slope (Fig. 2). In this scenario, a complex pattern of erosive features occurs, composed of four types of submarine valleys: *contourite moats*, *contourite channels*, *marginal valleys* and *large isolated furrows* (García, 2002; Hernández-Molina et al.,

2003, 2006). Table 1 summarizes the morphologic parameters of these different erosive features, which are described in detail in the next sections.

4.1. Contourite moat

The *Alvarez Cabral Moat* (Alvarez Cabral CM) is the only erosive feature defined as a contourite moat in the Gulf of Cadiz (Fig. 2D), since it is associated with the Faro–Cadiz and Albufeira elongated mounded and separated drift (Gonthier et al., 1984; Llave et al., 2001; García, 2002; Stow et al., 2002; Hernández-Molina et al., 2003, 2006; Marchès et al., 2007). It is excavated at the base of the upper slope of the Algarve margin and has a WSW trend, parallel to the slope (Fig. 4A). It is 80 km long and 3.5 to 11 km wide, being narrower at the central part, and has incision depths up to 100 m (Fig. 4B and C). Transverse profiles are markedly asymmetrical, with gradients up to 5.7° in the northern flank where

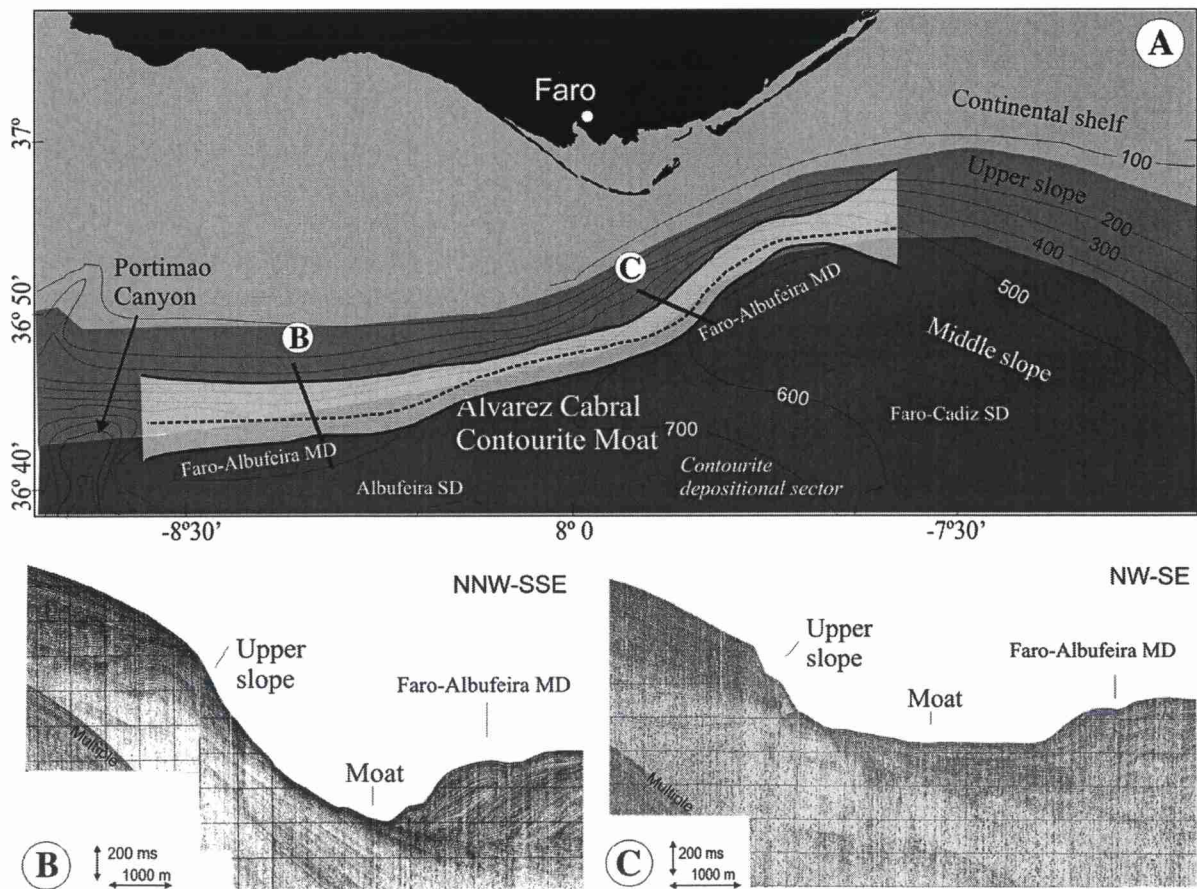


Fig. 4. Characterization of the Alvarez Cabral Contourite Moat. A) Localisation of the moat, at the foot of the upper slope of the Algarve margin. The dashed line shows the axis of the moat; B, C) Transversal V- and U-shaped seismic profiles showing the asymmetry of the moat, with a steep upper slope forming the northern flank, and the Faro–Albufeira Mounded Drift (MD) that forms the southern flank.

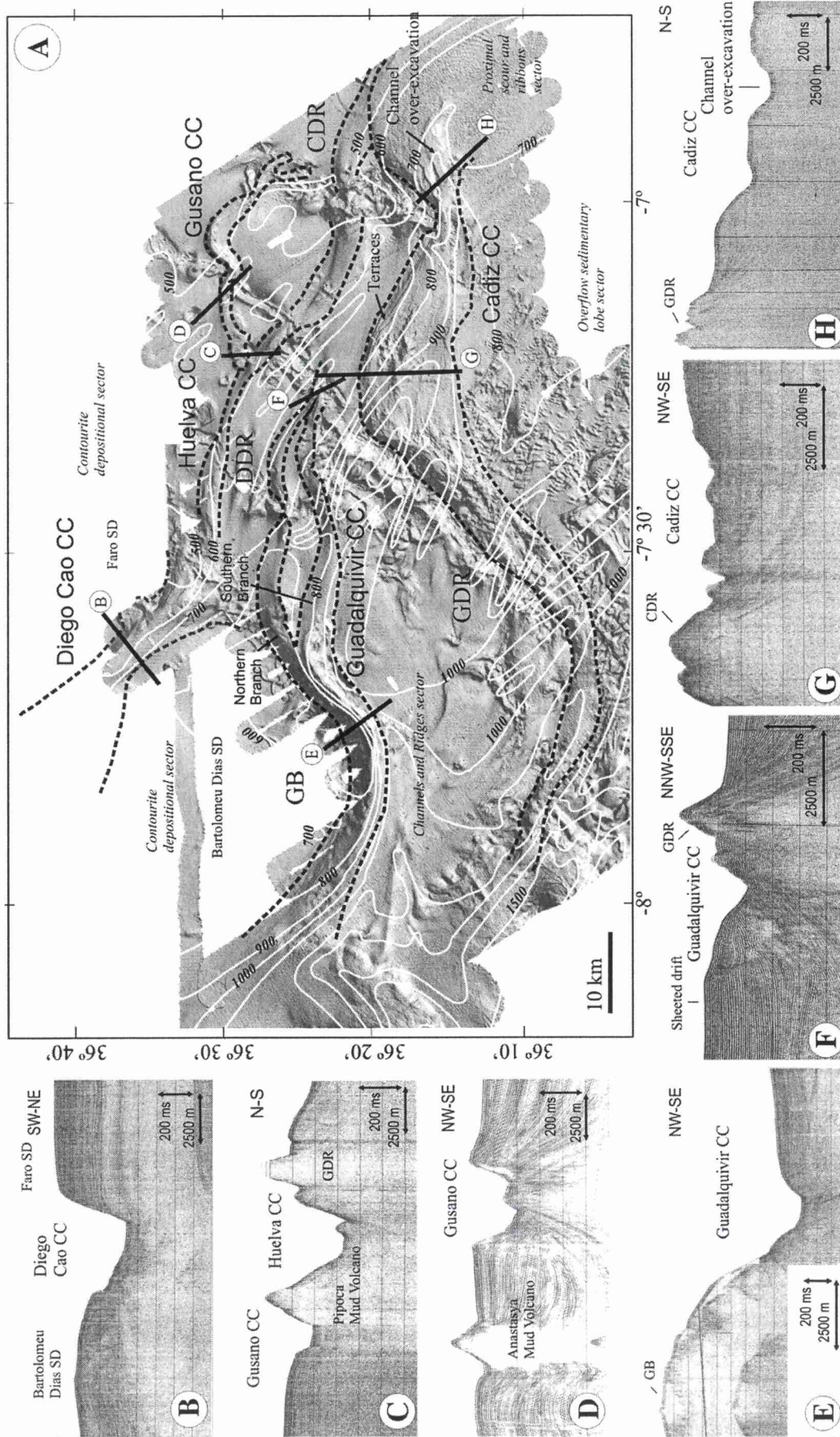


Fig. 5. Characterization of the Contourrite Channels. A) Shaded relief image showing the bathymetry of the Gulf of Cadiz middle slope and the location of the main Contourrite Channels (CC). B to H) Transversal seismic profiles showing the U- and V-shaped, symmetric or asymmetric profiles of the Diego Cao (B), the Gusano (C), the Huelva (C, D) the Guadalquivir (E, F) and the Cadiz (G, H) channels. Legend: GB: Guadalquivir Bank. CDR: Cadiz Diapiric Ridge. GDR: Guadalquivir Diapiric Ridge. DDR: Doñana Diapiric Ridge. SD: Sheeted Drift. The Cadiz Channel shows a marked over-excavation in its axis (H).

seismic profiles show truncated reflectors, and a gentler southern side with maximum slopes of 2.8° characterized by stratified subparallel reflections with a northward progradation (Fig. 4B and C).

4.2. Contourite channels (CC)

Five contourite channels stand out as the main erosive features in the central area of the Gulf of Cadiz middle slope. They occur in the Channels

and Ridges Sector, at the southern flank of the diapiric ridges and the Guadalquivir Bank (Fig. 2D). From north to south, the main contourite channels are denominated *Diego Cao*, *Huelva*, *Gusano*, *Guadalquivir* and *Cadiz Contourite Channels*, but other small channels can be found in the southern and western parts of the study area. Despite their differences in dimensions, all these channels have as a common characteristic a gently sinuous trend (Figs. 2D and 5) where two types of sectors can be differentiated (Fig. 5). The *downslope-trending sectors*

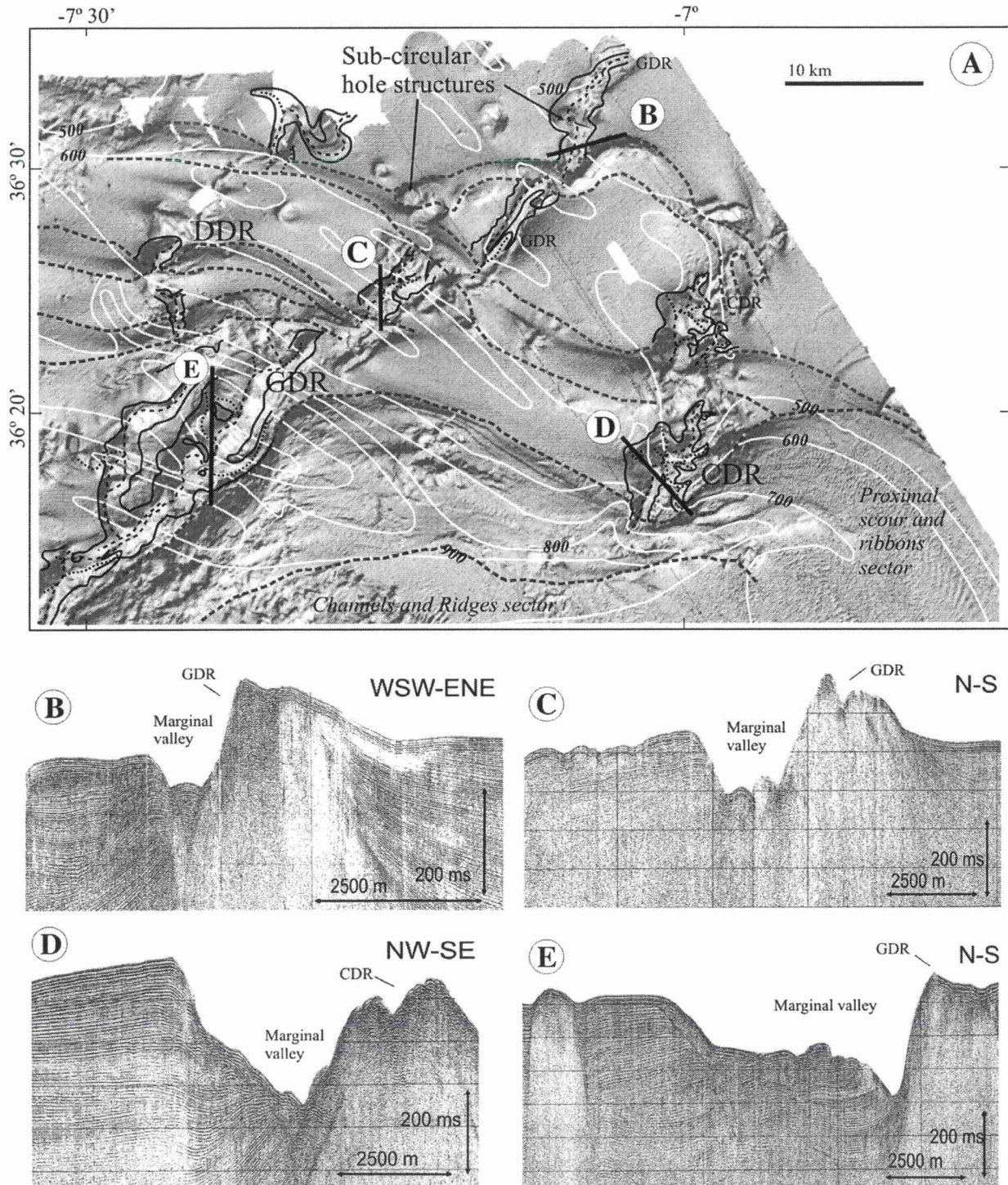


Fig. 6. Characterization of the Marginal Valleys. A) Shaded relief image showing the location of the main valleys at the NW flank of the diapiric ridges. B) to E) Transversal seismic profiles across the valleys. Legend: CDR: Cadiz Diapiric Ridge. GDR: Guadalquivir Diapiric Ridge. DDR: Doñana Diapiric Ridge. Note the presence of sub-circular hole structures along the course of the valleys (A).

run parallel to the diapiric ridges and structural features at their SE flank. Channels are narrow (less than 1 km wide) and reach maximum vertical incision depths (290 m) with markedly asymmetrical transverse profiles. The northern flanks are coincident with the southern flank of ridges and are characterized by an opaque acoustic response in seismic profiles. The southern flanks are much smoother and generally correspond to contourite deposits that show the presence of truncated reflectors on the flanks and in the channel bottom. In contrast, the *alongslope-trending sectors* cross the contourite deposits. Transverse profiles are smoother and symmetrical presenting the maximum values of width, up to 12 km, and seismic profiles show truncated reflectors on both flanks and on the channel bottom (Fig. 5). The western terminations of all contourite channels occur at similar depths, ranging from 1000 to 1500 m.

The Diego Cao CC corresponds with the Channel-4 identified by Kenyon and Belderson (1973) and was referred to as a moat by Faugères et al. (1985). It separates the Faro and the Bartolomeu Dias sheeted drifts at the northern part of the Channels and Ridges sector (Figs. 2D, 5A and B). This channel is about 30 km long and is funnel-shaped, with a general increase in width from the narrow central part (about 4.8 km) to the NW (more than 30 km). The Diego Cao CC has incisions depths of up to 300 m in the SE area and irregularly asymmetrical U-shaped profiles (Fig. 5B). Toward the northwest, incision depths reach 250 m, and transverse profiles are asymmetrical with steeper terraced eastern flanks. The axis has gradients of 1.7° in the SE area, but northwards the channel bottom is relatively flat at 860–900 m.

The Huelva CC is located at the NE part of the Gulf of Cadiz middle slope and has a general ESE–WNW direction (Figs. 2D and 5A). It crosses, from E to W, the Cadiz and Guadalquivir diapiric ridges and the southern limit of the Faro–Cadiz sheeted contourite drift. It is 58 km long and has widths that range from 1.8 km in the diapiric areas to 5.5 km in the areas crossing contourite deposits. Huelva CC has depths of up to 290 m (Fig. 5C). The axial gradient has an average value of 0.15° .

The Gusano CC is located at the NE part of the Gulf of Cadiz middle slope. It crosses the Cadiz and Guadalquivir diapiric ridges and opens into the Huelva CC (Fig. 2D and 5A). It is markedly sinuous, with prominent bends around the diapiric ridges. This channel is 39 km long, 1.5–5 km wide and up to 180 m deep (Fig. 5C and D). The axial gradient is irregular with an average value of 0.4° .

The Guadalquivir CC is located between the Guadalquivir DR and the Guadalquivir Bank (Fig. 2D and 5A). It corresponds with the Channel-3 identified by Kenyon and Belderson (1973). This channel has two almost parallel E–W oriented branches that merge near the Guadalquivir Bank: the southern and northern branches of the Guadalquivir CC (Fig. 5A). After merging, the unique channel is parallel to the Guadalquivir Bank. Widths range from 1 to 12 km, with the minimum values in the distal reaches. Vertical incision depths reach 130 m and transverse profiles are asymmetrical, U- or V-shaped, with generally steeper northern flanks (Fig. 5E). The average axial gradient is 0.37° for the northern branch and 0.44° for the southern branch.

Cadiz CC is the largest contourite channel on the Gulf of Cadiz middle slope, corresponding with Channel-2 identified by Kenyon and Belderson (1973). It has a SE–NW direction in the areas close to the ridges and a SW–NE direction where it crosses contourite deposits (Figs. 2C, D and 5A). It is 110 km long and 2.4 to 8 km wide with depths reaching 120 m (Fig. 5G and H). The sector between diapiric ridges presents some morphological peculiarities, including the occurrence of two terraces on the northern flank at depths between 750 and 850 m, and a 20–80 m deep over-excavation at the southern side of a relief that outcrops on the channel floor (Fig. 5A and H). This channel has an average axial gradient of 0.4° .

4.3. Marginal Valleys

Marginal Valleys are distinctive erosive features identified along the NW sides of the diapiric ridges and isolated diapirs in the Channels and Ridges sector (Figs. 2D and 6A). They have a predominant NE–SW trend, although their courses are very irregular and locally sinuous. Marginal Valleys associated with diapiric ridges are long (up to 28.4 km) and reach widths of up to 5 km, while those around small or isolated diapirs are shorter and narrower. Incision depths reach values of more than 250 m. The valley axes are very irregular, following the uneven pattern marked by the diapiric reliefs, and many valleys are formed by numerous secondary axes. Transverse profiles vary in their symmetry and can be U- or V-shaped (Fig. 6B–E). Locally, circular and sub-circular negative reliefs form along the axis of the valleys, especially at the NW side of the maximum reliefs of the diapiric ridges (Fig. 6B). Seismic profiles show an opaque acoustic response in the southern flanks, which correspond with

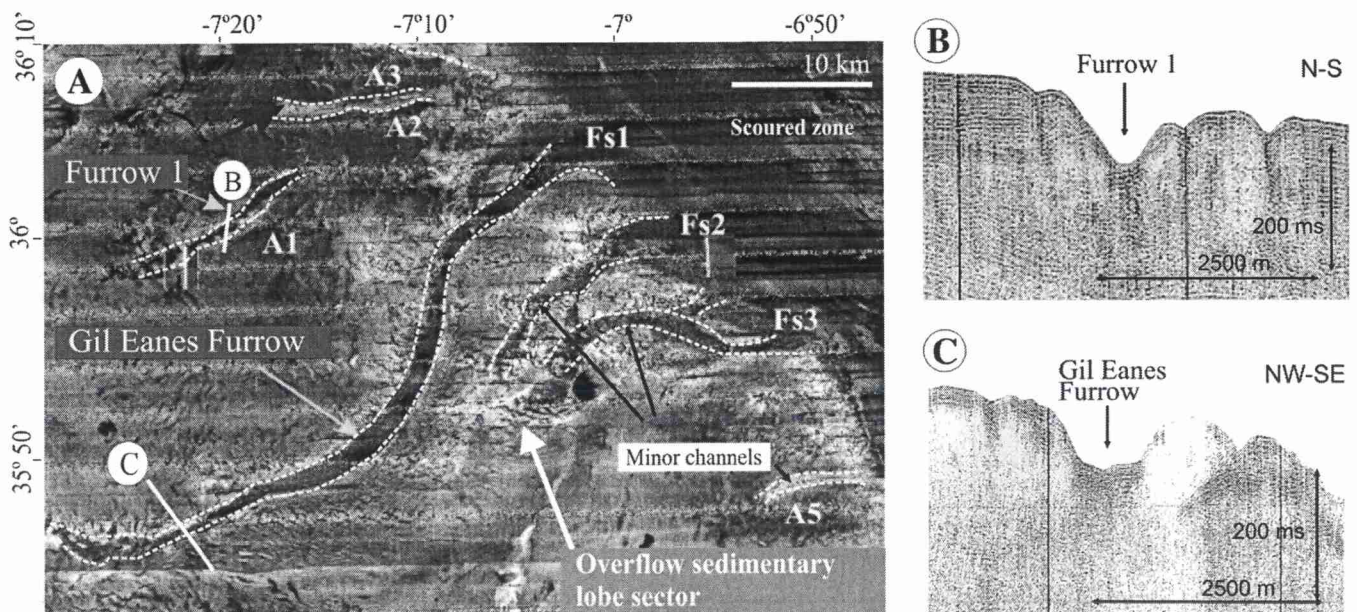


Fig. 7. Characterization of the Furrows. A) Seemap side-scan sonar image showing the location and trend of Furrow I, Gil Eanes Furrow and the small furrows on the overflow sedimentary lobe sector at the south-eastern part of the study area. Modified from Hernández-Molina et al. (2006). B) and C) Transversal seismic profiles across the Marginal Valleys.

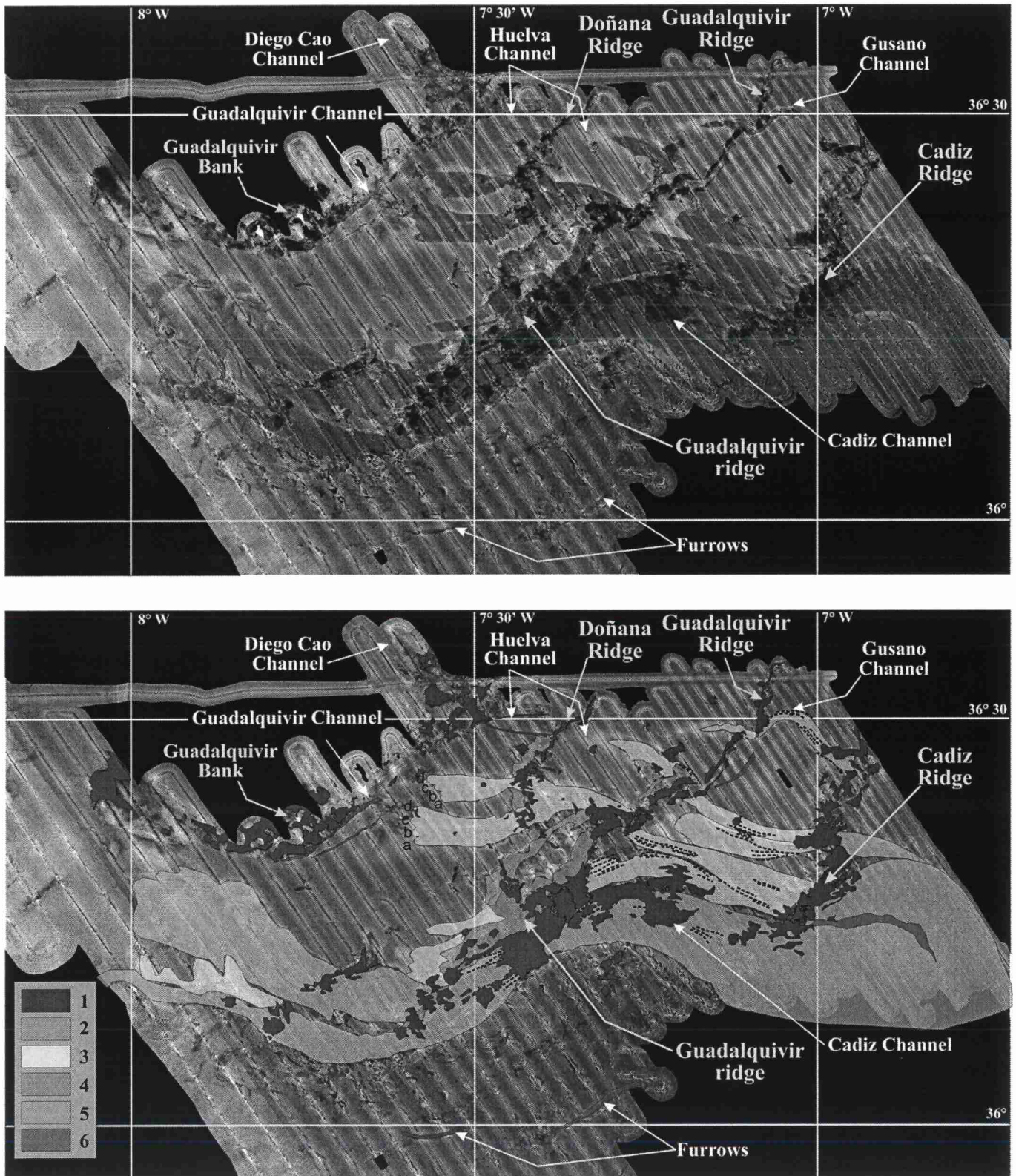


Fig. 8. Backscatter analysis. A) Backscatter image. B) Interpretation of the backscatter signal. Six types of signals have been identified: 1. Irregular patches of very high reflectivity; 2. Wide homogeneous surfaces with high reflectivity; 3. Elongated lobate patches of medium-high reflectivity surrounded by a diffuse band of very low reflectivity; 4. An elongated fan-shaped patch of medium-low reflectivity with a halo of very low; 5. Irregular backscatter signal, with medium to high reflectivity; 6. Elongated narrow strips of medium-high reflectivity.

the diapiric ridges and truncated layered reflections in the contourite deposits on the northern flanks (Fig. 6B–E).

4.4. Large isolated furrows

Large isolated furrows are identified in the southern part of the study area, in the Overflow-Sedimentary-lobe Sector (Fig. 2D). Most of the furrows have been identified on the basis of their backscattering response (Fig. 7A). Recent studies have interpreted these large-scale furrows as erosive features related to the action of the MOW and affected by gravity processes (Habgood et al., 2003; Mulder et al., 2003; Hanquiez et al., 2007).

Furrow 1 coincides with furrow A1 of Habgood et al. (2003). It is 15.7 km long and 0.8–1.5 km wide (Fig. 7A). It has a NE–SW trend and is very homogeneous along its course. Incision depths reach 160 m and the transverse profiles are symmetrical, U- or V-shaped (Fig. 7B). *Gil Eanes Furrow* was described by Kenyon and Belderson (1973) and Hanquiez et al. (2007) and coincides with furrow Fs1 of Habgood et al. (2003) (Fig. 7A). This furrow has widths of 0.8–1.7 km and a sinuous trend, with broad changes in direction from NE–SW to NNE–SSW and ENE–WSW. Vertical incision depth reaches 90 m and transverse profiles are symmetrical, with irregular flanks and flat bottoms (Fig. 7C). Some smaller furrows with linear trends, lengths of up to 15 km and widths of up to 2 km are also recognised in the Overflow-Sedimentary-lobe Sector (Fig. 7A). Their directions show a northwards change from NE–SW to SE–NW. These furrows coincide with the “minor channels” (Fs2, Fs3, A2, A3, A5 in Fig. 7A) described by Habgood et al. (2003) and Hanquiez et al. (2007). Erosive furrows located at the southernmost part of the study area, including *Gil Eanes furrow*, are morphologically connected to the Scour and Sand-Ribbons Sector, while those located to the north seem to start and end abruptly on the Overflow-Sedimentary-lobe Sector (Fig. 7A).

5. Backscatter interpretation

The central sector of the middle slope shows a marked contrast of backscatter signal between the depositional, erosive, and structural features (Fig. 8A). In general, contourite deposits have a very homogeneous backscatter with a average value of about –20 dB (Fig. 8A). Six types of backscatter signal may be differentiated in the area where erosive features occur (Fig. 8B):

- 1) The structural features are characterized by irregular patches of very high reflectivity (–8 to –15 dB), with lengths of few kilometres (Fig. 8). These patches represent the Guadalquivir Bank outcrop, the diapiric ridges and the isolated diapiric highs. The alignment of patches indicates that the diapiric ridges are not really continuous but comprise a series of short segments, each 10–20 km in length.
- 2) Most of the Cadiz CC and the proximal parts of the Huelva and Gusano CCs show wide homogeneous surfaces with high reflectivity (–12 to –17 dB).
- 3) The middle course of the Cadiz (the northern part), Guadalquivir, Huelva and Gusano CC between the Cadiz diapiric ridge and the Guadalquivir Bank are mostly characterized by elongated lobate patches, oriented W to WNW, of medium-high reflectivity (–20 to –24 dB), surrounded by a diffuse band of very low reflectivity (–27 to –31 dB). The largest patches are 5–10 km long and 2–5 km wide and generally coincide with the location of contourite channels at the W side of the diapiric ridges, but covering a wider extension towards the S. Smaller patches are identified at the western side of the distal area of the Guadalquivir DR. In some cases, multiple lobes can be identified at the western end of the elongated patches. In particular the Guadalquivir CC northern and southern branches have four lobes between Doñana DR (a–d in Fig. 8B) and the Guadalquivir Bank and the Huelva CC has two partially superposed lobes between the Cadiz and Guadalquivir DR (Fig. 8B).

- 4) An elongated fan-shaped patch, oriented NW, of medium–low reflectivity (–23 to –27 dB), with a halo of very low reflectivity (–27 to –31 dB). This patch, 30 km long and up to 10 km wide, corresponds to the drift located between the distal end of the Guadalquivir DR and the Guadalquivir Bank. The distal NW end has an irregular shape with bands of higher and lower reflectivity.
- 5) The area covered by the marginal valleys west of the Guadalquivir (southern part) and Doñana diapiric ridges is characterized by a irregular backscatter signal, with amplitudes ranging from –27 to –15 dB.
- 6) Elongated narrow strips of medium-high reflectivity (–20 to –24 dB), up to 10 km long and few kilometres wide coincide with the locations of erosive furrows and low-relief incisions of the Huelva, Guadalquivir and Cadiz CC. They have directions that vary from WSW to NNW.

6. Discussion

The study of the morphological character of erosive features, their distribution and the backscatter signal in the study area allows an interpretation of the processes involved in the genesis and development of these features.

6.1. Genesis of erosive features

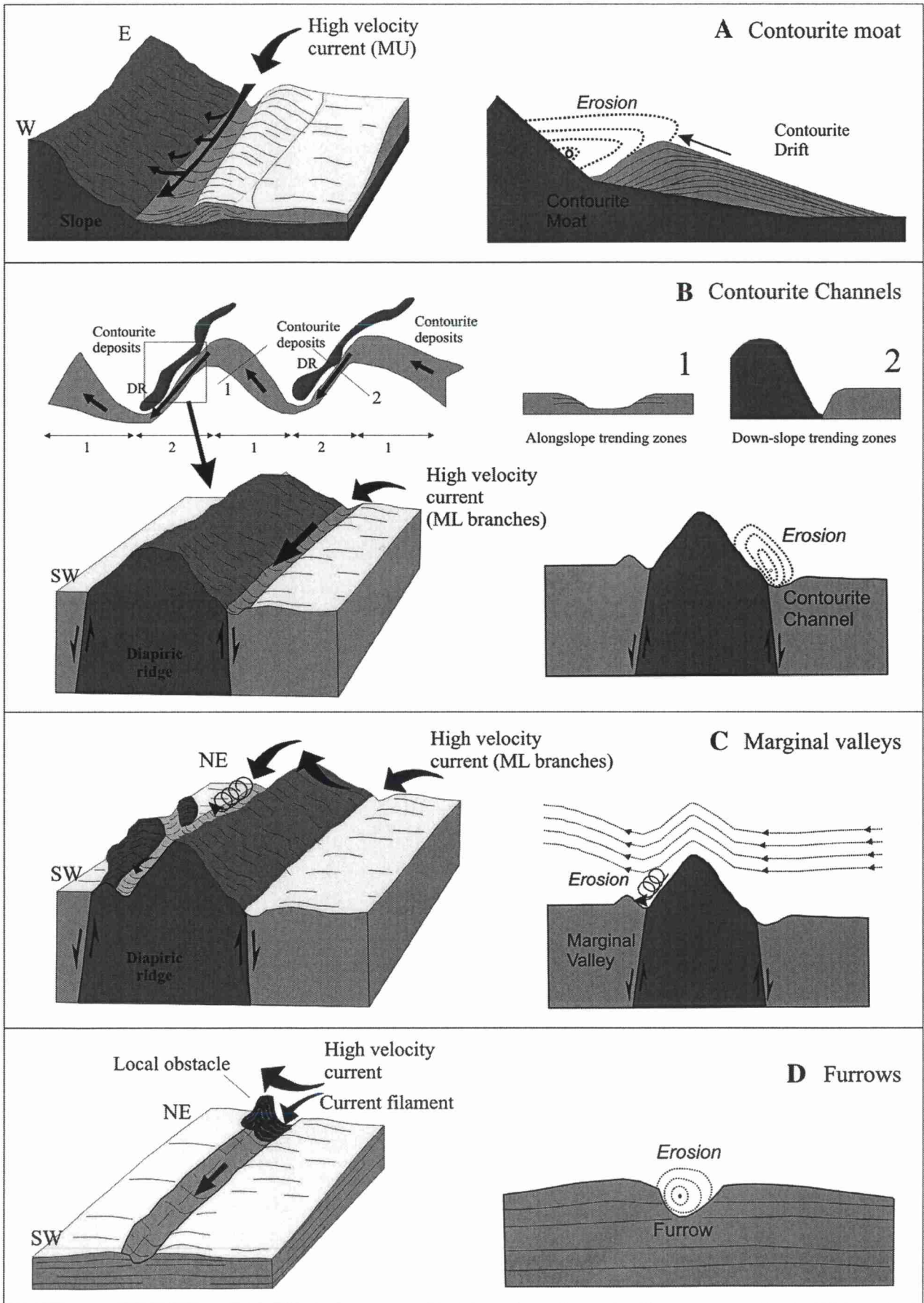
6.1.1. Contourite moats

The Alvarez Cabral Contourite Moat originated by localised erosion beneath the core of the MOW Upper Water (MU). The flow of this current strand along the Algarve margin is accentuated by the Coriolis force and topographically constricted by the change of trend in the upper slope (Figs. 2D and 9A). The migration of the current core causes erosion along its right-hand side (at the base of the upper slope) and corresponding deposition of the Faro–Albufeira mounded drift along the left-hand southern flank, where the current velocity and erosive capacity decrease (Mougenot and Vanney, 1982; Gonthier et al., 1984; Faugères and Stow, 1993; Faugères et al., 1993, 1999; Llave et al., 2001; Stow et al., 2002; Llave et al., 2006; Hernández-Molina et al., 2006; Marchès et al., 2007). This is consistent with the information provided by the seismic lines in the area, which show truncated reflections in the northern flank and northward prograding layered reflections in the southern flank, as a result of the upslope migration of the core. Towards the west, the current decreases in velocity from values of about 95 cm/s to less than 20 cm/s (Cherubin et al., 2000) as a result of the capture of part of the flow by the Portimao Canyon (Marchès et al., 2007).

6.1.2. Contourite channels

Contourite Channels were created by erosive processes, as suggested by the presence of truncated reflections and the lack of depositional features along their course. The trend, depth and asymmetry of the contourite channels can be used to infer the direction and relative velocity of the flow. The two types of sector (alongslope -trending and downslope -trending sectors) and their correlation with oceanographic parameters allows interpretation of the processes involved in their origin (Fig. 9B). In *alongslope-trending zones* the MOW has medium to low velocities of 10–50 cm/s in a SE–NW direction (Madelain, 1970; Zenk, 1975; Nelson et al., 1999) (Fig. 3B). By contrast, in *downslope-trending zones* the MOW shows higher velocities of 50–90 cm/s in a NE–SW direction (Madelain, 1970; Kenyon and Belderson, 1973; Melières, 1974; Zenk, 1975; Nelson et al., 1999; Stow et al., in press-b) (Fig. 3B). Hanquiez et al. (2007) suggest a similar intensification of the current velocity in the downslope-trending sectors, based on estimated transport velocity values and the orientation of bedforms.

The correlation of morphological parameters and oceanographic data allows an interpretation of the interaction between the bottom current and the diapiric ridges (Fig. 10B). As a result of Coriolis force, the initial flow is directed towards the NW after exiting from the Straits of Gibraltar. When the flow reaches the diapiric ridges, the lower section of



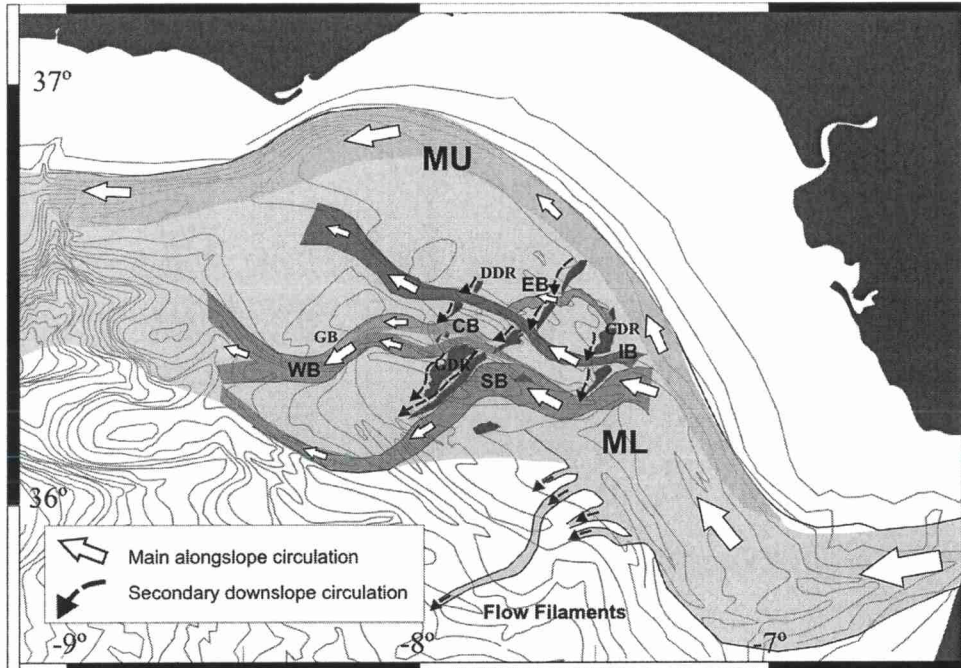


Fig. 10. Regional scheme of the circulation of the MOW on the Gulf of Cadiz middle slope, with the interplay of the alongslope and downslope circulation levels. The Mediterranean Upper Water (MU) flows parallel to the bathymetry close to the upper slope of the Gulf of Cadiz. The Mediterranean Lower Water (ML) is interpreted to be divided into five branches: Southern Branch (SB), Western Branch (WB), Central Branch (CB), Intermediate Branch (IB) and Eastern Branch (EB). Legend: GB: Guadalquivir Bank. CDR: Cadiz Diapiric Ridge. GDR: Guadalquivir Diapiric Ridge. DDR: Doñana Diapiric Ridge.

the flow is affected by the topography and suffers an increase in velocity and erosive capability while it is deflected towards the SW and is constricted by the topography. The Coriolis effect forces the trend of the flow towards the right and this would enhance the erosive capability of the flow along the NW flank of the channel, inducing migration in that direction. The flow in contourite channels is strong enough to erode both the NW and SE flanks, but no associated generation of mounded contourite drifts occurs. A similar effect of salt walls and diapirs has been interpreted to cause acceleration of deep currents on the Brazilian margin (Viana et al., 2007).

6.1.3. Marginal valleys

Marginal valleys of the Gulf of Cadiz are interpreted as the result of formation of flow instabilities by interaction of MOW with the diapiric ridges. As bottom currents approach dome-like obstacles in their path they undergo destabilization, with speed increase due to hydraulic jumps and the formation of eddies and vortices leeward of the obstacle (Guo et al., 2000; McCready and Pawlak, 2001). As a result of these flow instabilities, erosive features develop on both the lee and stoss sides of an obstacle, as well as on both lateral flanks (Davies and Laughton, 1972; Kennet, 1982; McCave and Carter, 1997). In the case of linear obstacles, the influence of topography on the large-scale ocean circulation causes the formation of jets at the opposite side of the obstacle (Marshall, 1995). Furthermore, the underwater dissolution of salt diapiric ridges by oceanographic flows has been interpreted to enhance the density of water masses and thereby accelerate the current (Nibbelink, 1999; Michaud et al., 2005; Viana et al., 2007; Stow et al., in press-a). In the Gulf of Cadiz, linear and downslope-oriented obstacles have caused flow instabilities that induced downslope-trending turbulent flows along the NW side of the diapiric ridges, which we interpret as responsible for the

erosion of marginal valleys (Fig. 9C). Marginal valleys have been interpreted as conduits for the transport of sediment from the shelf to the slope by downslope gravity currents (Hanquiez et al., 2007) but, in contrast with the Algarve continental shelf, no downslope-trending erosive features such as submarine canyons occur on the SE shelf of the Gulf of Cadiz (Lobo et al., 2000; Hernández-Molina and Lobo, 2005). This favours the interpretation of marginal valleys as the result of instabilities related to the MOW, although their implication in downslope-trending sediment transport during periods of low sea-level can not be neglected.

6.1.4. Large isolated furrows

Most furrows of all types and dimensions have an erosive character, as evidenced by the presence of truncated layered reflections along their flanks. In shallow water, the formation of fields of furrow bedforms has been related to the action of strong cross-shore bottom currents, associated in many cases with erosional sedimentary settings in the presence of rock outcrops (Cacchione et al., 1984; Murray and Thiel, 2004; Garnaud et al., 2005). In the case of the Gulf of Cadiz mid-slope region, large isolated furrows with NE–SW orientation and relatively small dimensions indicate that they are eroded by W–SW trending flows. The absence of levees on the rims of the furrows indicated in our data does not allow their interpretation as channel-levee systems related to turbidity flows. Therefore, we interpret these large isolated furrows as having been eroded by flow filaments separated from the MOW main current, such as those described by Madelain (1970) and Baringer and Price (1999) (Figs. 3B, 8 and 9D). These filaments flow in a SW direction with measured current velocities that decrease from 20 to around 10 cm/s, although furrow erosion must have occurred during periods of greater velocity. This interpretation is also consistent with the numerical results obtained by Serra et al. (2005) and the studies of Hanquiez et al. (2007).

Fig. 9. Interpretation of the processes involved in the origin and evolution of the erosive features. A) The contourite moat is originated by the erosion and deposition by the Mediterranean Upper Water (MU); B) The contourite channels show alongslope and downslope trending sectors and are related to the erosion of branches of the Mediterranean Lower Water (ML). DR: Diapiric ridge; C) The marginal valleys are eroded at the NW side of the diapiric ridges by the instabilities formed in the flow by the interaction with the seafloor topography; and (D) Furrows are the result of the erosion of current filaments with a downslope direction.

6.2. MOW circulation scheme deduced from the contourite erosive features

The distribution of erosive features, together with the data on current velocity and direction obtained from the literature and summarised in Fig. 3B, allows the proposal of a new and more detailed scheme for present-day circulation of the MOW (Fig. 10). In this scheme we consider the simultaneous occurrence of two circulation models: A *Main Alongslope Circulation*, which is involved in the origin of the contourite moat and contourite channels, and a *Secondary Downslope Circulation*, which is related to the creation of the marginal valleys and large isolated furrows.

6.2.1. Main alongslope circulation

The Main Alongslope Circulation refers to flow of the two cores into which the MOW is divided on the Gulf of Cadiz middle slope (Fig. 3). MU flows with a NW trend, parallel to the bathymetry at depths shallower than 500 m. It is deviated by Coriolis force towards the right and by topographic constriction of the upper slope. When this flow reaches the Algarve margin, where the slope direction changes from SE–NW to NE–SW, the velocity increases and MU erodes the Alvarez Cabral moat (Fig. 10). Part of the MU flow is captured at the Portimao Canyon, and the current flowing westwards of the canyon loses part of its erosive character (Marchès et al., 2007). ML is also affected by the topography of the seafloor and is divided into different branches on the middle slope, that follow defined pathways at different water depth levels, related to the middle slope terraces (Fig. 10) and to interaction with diapiric ridges.

- a) The *Southern Branch* separates from the main flow at depths of about 700 m, where the flow is affected by the southern part of the Cadiz Diapiric Ridge. It runs parallel to the ridge and turns to the NW at its distal reaches. This branch is responsible for the erosion and formation of the Cadiz channel and coincides with the Southern Branch of Melièrès (1974). The over-excavation in the Cadiz channel axis may be interpreted as the result of a recent intensification of this branch.
- b) The *Western Branch* starts at the Guadalquivir Diapiric Ridge (about 800 m water depth), crosses the contourite deposits in the central part of the study area and flows at the S side of the Guadalquivir Bank. This branch is responsible for erosion of the southern branch of the Guadalquivir CC, and would coincide with the Principal Branch of Melièrès (1974).
- c) The *Central Branch* flows along the narrow terrace at 750 m water depth and erodes the northern branch of the Guadalquivir CC. It forms at the Guadalquivir DR, crosses the Doñana DR and turns to the SW at the Guadalquivir Bank, where it merges with the Western Branch.
- d) The *Intermediate Branch* defined by Melièrès (1974), is interpreted in this paper as being separated just north of the Southern Branch, at about 500 m water depth, in a first gateway of the Cadiz Diapiric Ridge and to flow along the narrow terrace that occurs at 600–700 m water depth. This branch crosses the three diapiric ridges with a general WNW direction, eroding the Huelva CC and turns to the NW at the east of the Guadalquivir Bank, eroding the sheeted drifts and forming the Diego Cao CC.
- e) The *Eastern Branch* separates from the ML by interaction with the Cadiz Diapiric Ridge, and flows along the shallower terrace (500–600 m water depth), eroding the Gusano CC. It crosses the Cadiz and Guadalquivir Diapiric Ridges before turning to the SW and merging with the Intermediate Branch.

6.2.2. Secondary downslope circulation

The secondary downslope circulation of the MOW is mainly deduced from the occurrence of marginal valleys and furrows. Marginal valleys present a downslope direction along the leeside of the diapiric ridge and isolated diapiric mounds (Fig. 7). Where MOW interacts with the diapiric

ridges, flow instabilities are created in the flow and channelized in a downslope direction along the NW side of the obstacles (Fig. 10). The erosion of the furrows is produced by current filaments with a general SW direction separated from the main current by isolated reliefs in the southern part of the study area (Fig. 10).

6.3. Evolution of erosive features forced by neotectonics

Based on the present configuration and morphology of erosive features and diapiric reliefs, together with interpretation of the backscatter signal amplitudes, three evolutionary stages can be considered (Fig. 11A–C) and tentatively correlated with the stages established by Llave (2003) and Llave et al. (2006, 2007b) for Quaternary evolution of the CDS, based on stratigraphy of the contourite drifts. These stages are the result of changes in the distribution and splitting of the MOW by diapiric reactivation caused by an interplay between tectonics and climate/sea-level changes (Llave et al., 2007a,b). The three evolutionary stages include: a) from Early Pleistocene to Mid-Pleistocene, the Cadiz–Faro–Albufeira and Huelva–Guadalquivir mounded elongated drifts were deposited; b) from Mid-Pleistocene to Late Pleistocene, the western part of the mounded Huelva–Guadalquivir drift became inactive; and c) from Late Pleistocene to Holocene, the Huelva–Guadalquivir drift became totally inactive and erosive processes became dominant on the middle slope. The correlation of our interpretation with these stages is summarized below.

6.3.1. Early Pleistocene to Mid-Pleistocene: linear diapiric ridges

During this stage the MU excavated the Alvarez Cabral Moat at the base of the upper slope on the Algarve margin and deposited the Cadiz–Faro–Albufeira mounded elongated drift. The ML was split into two branches. A Northern Branch followed the present-day trend of the proximal part of the Huelva CC and the distal part of the Guadalquivir CM. It excavated a contourite moat with the associated development of Huelva–Guadalquivir mounded drift (Llave et al., 2006, 2007a). The Southern Branch excavated the Cadiz CC (Fig. 11A) and is interpreted to have been volumetrically greater than at present as suggested by the extension of the homogeneous surface with high reflectivity (backscatter signals 2 and 3, Fig. 8B). The western extreme of the Cadiz CC occurred at a position displaced to the north in comparison with the present-day location, as suggested by the deposition of the elongated fan-shaped lobe at the NW of the termination of the Guadalquivir DR (Fig. 11A).

6.3.2. Mid to Late Pleistocene: diapiric reactivation

During this stage, diapiric reactivation induced an increase in relief of the diapiric ridges (Figs. 9B and 11B), possibly in relation to their deformation by tectonic subsidence of the Cadiz Nappe (Maestro et al., 2003). During this stage, MU was not significantly affected. The Northern branch of the ML lost strength and only its proximal part continued acting as a contourite moat and deposited the Huelva mounded elongated drift while the Guadalquivir drift was fossilised and developed as a sheeted drift (Llave et al., 2006, 2007a,b). The Cadiz CC was active during this stage (Fig. 11B).

6.3.3. Late Pleistocene to Holocene: main phase of diapiric ridge segmentation and rotation

During this stage, an important phase of diapiric segmentation induced the opening of new gateways in the northern diapiric ridges producing the present-day complex configuration of erosive features (Fig. 11C). Segmentation of the diapiric ridges may be explained by neotectonic activity. NW–SW-trending faults have been documented in the Gulf of Cadiz by Pinheiro et al. (2003) and Medialdea et al. (2004). More recently, the activity of a group of dextral WNW–ESE-trending faults has been interpreted as responsible for the morphologic lineaments in this area (Rosas et al., in press). NW–SE-trending fault activity is coherent with the segmentation pattern of the diapiric ridges

(Fig. 11C). During this stage, paleoceanographic conditions were also controlled by global climate changes (Llave et al., 2006, 2007a,b).

Changes in the MOW circulation during this stage include the formation of new gateways for the ML through the diapiric ridges and the establishment of new branches of the ML: the Eastern, Intermediate and Western Branches, which excavated the Gusano, Huelva and Diego Cao, and the southern branch of the Guadalquivir CC, respectively (Fig. 11C). These flows were also responsible for deposition of sedimentary lobes at the western side of the ridges (backscatter signal 2, Fig. 8B). The flow of the Northern Branch of the ML was pirated by the Intermediate and Western branches, although a part of it probably joined the MU generating a greater volume core responsible for the deposition of a plastered contourite drift on the upper slope (see Fig. 2 for its location). Further details on Hernández-Molina et al., 2006; and Llave et al., 2006) and the definitive fossilization of the Huelva mounded elongated and separated drift (Llave et al., 2007a). A general NW turn of the contourite channels is suggested by the coincidence of the present-day morphology with the northern lobes of the elongated patches of high reflectivity (Fig. 8B). This turn was not continuous, but it occurred through distinct phases that caused the marked lobes in the backscatter signal and can be explained by a succession of pulses of diapiric deformation. Over-excavation of the Cadiz CC east of the Cadiz DR may have resulted from an increase in relief of the ridge, which enhanced the erosive capability of the flow. Towards its western extremity the Cadiz CC veered towards the SW, and the elongated fan-shaped lobe was abandoned (Fig. 11C). The large isolated furrows were probably created during this last stage by the formation of new isolated small-sized reliefs.

Paleoceanographic events occurring during this stage affected the location and depth of the MOW. We interpret that the flow was concentrated on the Western, Central and Southern branches during cool episodes of low sea-level (Fig. 11D), when denser water masses and deeper MOW flow occurred at deeper areas (Llave et al., 2006, 2007a,b) and the MOW velocity was relatively high (Voelker et al., 2006; Toucanne et al., 2007). In contrast, the main flow was concentrated on the Intermediate and Eastern branches of ML and on MU during the warm episodes with high sea-level (Fig. 11E), when water masses were less dense, the interaction of the flow with the seafloor was more intensive at shallower depths (Llave et al., 2006, 2007a,b) and the flow velocity was comparatively lower (Voelker et al., 2006; Toucanne et al., 2007). A similar paleoceanographic control on contour currents has been documented on the south-eastern Brazilian margin.

7. Summary and conclusions

Based on interpretation of the morphology and backscatter signal amplitudes, four major types of contourite erosive submarine valleys have been identified within the Contourite Depositional System of the Gulf of Cadiz middle slope. These are: contourite moats, contourite channels, marginal valleys and large isolated furrows. These features are interpreted as the result of interaction between MOW and seafloor topography.

The present-day configuration of erosive features allows us to propose a new and more detailed scheme for MOW circulation, which combines: a) a main alongslope circulation, involved in the development of the contourite moat and contourite channels, and b) a secondary downslope circulation, related to the creation of the marginal valleys and furrows. The Alvarez–Cabral Moat has been configured by the MOW Upper Core (MU) since the establishment of the MOW circulation, migrating upslope but without any large significant change during its history. Five major contourite channels are the result of the interaction of branches of the MOW Lower Core (ML) with the Gulf of Cadiz middle slope. Their evolution has been controlled by neotectonic activity, including two events of diapiric ridge deformation. The Guadalquivir CC evolved from a contourite moat to a contourite channel. The Diego Cao, Gusano and the proximal part of Huelva Contourite Channels were

generated very recently (presumably since the late Pleistocene). The Cadiz Contourite Channel has been active at least since the early Pleistocene, but the progressive splitting of the flow responsible for its excavation has reduced its activity until the present day. Also, the MOW circulation was controlled by late Pleistocene climatic changes. During cool stages, deeper circulation was enhanced (Western, Central and Southern branches of ML), while during warm stages the flow intensified at shallower levels (Intermediate and Eastern branches of ML and MU). Marginal Valleys are the result of a secondary circulation caused by downslope channelization of instabilities created by an interplay between the impinging MOW flow and the linear relief. The furrows are related to weak flows separated from the ML at the southern part of the study area.

This study provides important regional clues for establishing the different phases of evolution of erosive features in relation to the most recent neotectonic effects. We anticipate that analogous contourite erosive features in other deep marine environments can be similarly used as evidence for the reconstruction of oceanographic and recent tectonic changes.

Acknowledgments

This work was supported by the projects FADO (PB94-1090-C03-03), TASYO (MAR-98-0209), GADES (REN2002-04117-C03-01/02/03) and CONTOURIBER (CTM 2008-06399-C04-01/MAR). In addition, our results are related to the Special Actions: REN2002-11669-E (MVSEIS Project) and REN2002-11668 (MOUNDFOURCE Project). The contribution by M. García to this paper was supported by a FSE fellowship from the Instituto Español de Oceanografía (IEO) and a FPI fellowship from the Spanish Education Ministry in the Framework of the MARSIBAL Project (REN2001-3868-C03-03). This work has been partially carried out during a research stage of *F. J. Hernández-Molina* funded by the 'Mobility Award' from the Spanish Ministry of Education and Science at NOCS (UK) (PR2006-0275) and Marine & Geophysical Division of the Argentine Hydrographic Institute (PR2007-0138). Also, we are grateful to Patricia Bárcenas for her help with the data management.

References

- Ambar, I., Howe, M.R., 1979. Observations of the Mediterranean outflow I. Mixing in the Mediterranean outflow. *Deep-Sea Res.* 26A, 535–554.
- Ambar, I., Armi, L., Bower, A., Ferreira, T., 1999. Some aspects of time variability of the Mediterranean Water off South Portugal. *Deep-Sea Res.* 46, 1109–1136.
- Baraza, J., Ercilla, G., Nelson, C.H., 1999. Potential geologic hazards on the eastern Gulf of Cadiz slope (SW Spain). *Mar. Geol.* 155, 191–215.
- Baringer, M.O., Price, J.F., 1999. A review of the physical oceanography of the Mediterranean Outflow. *Mar. Geol.* 155, 63–82.
- Borenäs, K.M., Wåhlin, A.K., Ambar, I., Serra, N., 2002. The Mediterranean outflow splitting – a comparison between theoretical models and CANIGO data. *Deep-Sea Res.* Pt II 49, 4195–4205.
- Cacchione, D.A., Grant, W.D., Tate, G.B., 1984. Rippled scour depressions on the inner continental shelf off central California. *J. Sediment. Petrol.* 54, 1280–1291.
- Cherubin, L., Carton, X., Paillet, J., Morel, Y., Serpatte, A., 2000. Instability of the Mediterranean Water undercurrents southwest of Portugal: effects of baroclinicity and topography. *Oceanol. Acta* 23 (5), 551–573.
- Davies, T.A., Loughton, A.S., 1972. Sedimentary processes in the North Atlantic. In: Loughton, A.S., Berggren, W.A. (Eds.), *Initial Reports of the DSDP. U.S. Government Printing Office, Washington, D.C.*, pp. 905–934.
- Díaz del Río, V., Somoza, L., Martínez-Frías, J., Mata, M.P., Delgado, A., Hernández-Molina, F.J., Lunar, R., Martín-Rubí, J.A., Maestro, A., Fernández-Puga, M.C., León, R., Llave, E., Medialdea, T., Vázquez, J.T., 2003. Vast fields of hydrocarbon-derived carbonate chimneys related to the accretionary wedge/olistostrome of the Gulf of Cadiz. *Mar. Geol.* 195, 177–200.
- Ercilla, G., Baraza, J., Alonso, B., Canals, M., 1998. Recent geological processes in the Central Bransfield Basin (Western Antarctic Peninsula). In: Stoker, M.S., Evans, D., Cramps, A. (Eds.), *Geological Processes on Continental Margins: Sedimentation, Mass-Wasting and Stability. Geol. Soc. London Sp. Publ.*, vol. 129, pp. 205–216.
- Faugères, J.C., Stow, D.A.V., 1993. Bottom current controlled sedimentation: a synthesis of the contourite problem. *Sediment. Geol.* 82, 287–297.
- Faugères, J.C., Frappa, M., Gonthier, E., De Resseguier, A., Stow, D.A.V., 1985. Modelé et faciès de type contourite a la surface d'une ride sédimentaire édifiée par des courants issus de la veine d'eau méditerranéenne (ride du Faro, Golfe de Cadix). *Bull. Soc. Geol. Fr.* (1), 35–47.

- Faugères, J.C., Mézerais, M.L., Stow, D.A.V., 1993. Contourite drift types and their distribution in the North and South Atlantic Ocean Basins. *Sediment. Geol.* 82, 189–203.
- Faugères, J.C., Stow, D.A.V., Imbert, P., Viana, A.R., 1999. Seismic features diagnostic of contourite drifts. *Mar. Geol.* 162, 1–38.
- Fernández-Puga, M.C., 2004. Diapirismo y estructuras de expulsión de gases hidrocarburos en el talud continental del Golfo de Cadiz. Ph.D. Thesis. Facultad de Ciencias del Mar, University of Cadiz, unpublished.
- Fernández-Puga, M.C., Vázquez, J.T., Somoza, L., Díaz del Río, V., Medialdea, T., Mata, M.P., León, R., 2007. Gas-related morphologies and diapirism in the Gulf of Cadiz. *Geo-Mar. Lett.* 27, 213–221.
- Gao, Z.Z., Eriksson, K.A., He, Y.B., Luo, S.S., Guo, J.H., 1998. Deep-Water Traction Current Deposits — A Study of Internal Tides, Internal Waves, Contour Currents and Their Deposits. Science Press, New York, 100 pp.
- García, M., 2002. Caracterización morfológica del sistema de canales y valles submarinos del talud medio del Golfo de Cadiz (SO de la Península Ibérica): implicaciones oceanográficas. M. Sc. Thesis, University of Cadiz, unpublished.
- Gardner, J.V., Kidd, R.B., 1983. Sedimentary processes on the Iberian continental margin viewed by long-range side-scan sonar. 1: Gulf of Cadiz. *Oceanol. Acta* 6 (3), 245–254.
- Garnaud, S., Lesueur, P., Garland, T., 2005. Origin of rippled scour depressions associated with cohesive sediments in a shoreface setting (eastern Bay of Seine, France). *Geo-Mar. Lett.* 25, 34–42.
- Gonthier, E.G., Faugères, J.C., Stow, D.A.V., 1984. Contourite facies of the Faro Drift, Gulf of Cadiz. In: Stow, D.A.V., Piper, D.J. (Eds.), *Fine-Grained Sediments: Deep-Water Processes and Facies*. Geol. Soc. Sp. Publ., vol. 15, pp. 275–292. Oxford.
- Grundlingh, M., 1981. On the observation of a solitary event in the Mediterranean Outflow west of Gibraltar. *Meteor.-Forsch. Ergeb. A/B* (23), 15–46.
- Guo, Y., Davies, P.A., Cavalletti, A., Jacobs, P., 2000. Topographic and stratification effects on shelf edge flows. *Dyn. Atmos. Ocean.* 31, 73–116.
- Gutscher, M.-A., Malod, J., Rehault, J.-P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. *Geology* 30, 1071–1074.
- Habgood, E.L., Kenyon, N.H., Masson, D.G., Akhmetzhanov, A., Weaver, P.P.E., Gardner, J., Mulder, T., 2003. Deep-water sediment wave fields, bottom current sand channels and gravity flow channel-lobe systems: Gulf of Cadiz, NE Atlantic. *Sedimentology* 50, 483–510.
- Hanquiez, V., Mulder, T., Lecroart, P., Gonthier, E., Marchès, E., Voisset, M., 2007. High resolution seafloor images in the Gulf of Cadiz, Iberian margin. *Mar. Geol.* 246, 42–59.
- Heezen, B.C., Johnson, G.L., 1969. Mediterranean undercurrent and microphysiography west of Gibraltar. *Bull. Inst. Océanogr. Monaco* 67 (1382), 1–95.
- Hernández-Molina, F.J., Lobo, F.J., 2005. El margen continental del Golfo de Cadiz. In: Martín-Serrano, A., Nozal, F., Maestro, A. (Eds.), *Memoria del Mapa Geomorfológico de España 1:1.000.000: Geomorfología de la zona sumergida española*. Servicio de Publicaciones Instituto Geológico y Minero de España, Madrid.
- Hernández-Molina, F.J., Llave, E., Somoza, L., Fernández-Puga, M.C., Maestro, A., León, R., Barnolas, A., Medialdea, T., García, M., Vázquez, J.T., Díaz del Río, V., Fernández-Salas, L.M., Lobo, F., Alveirinho Dias, J.M., Rodero, J., Gardner, J., 2003. Looking for clues to paleoceanographic imprints: a diagnosis of the Gulf of Cadiz contourite depositional systems. *Geology* 31 (1), 19–22.
- Hernández-Molina, F.J., Llave, E., Stow, D.A.V., García, M., Somoza, L., Vázquez, J.T., Lobo, F.J., Maestro, A., Díaz del Río, V., León, R., Medialdea, T., Gardner, J., 2006. The contourite depositional system of the Gulf of Cadiz: a sedimentary model related to the bottom current activity of the Mediterranean outflow water and its interaction with the continental margin. *Deep-Sea Res. Pt II* 53, 1420–1463.
- Kennet, J., 1982. *Marine Geology: Paleocanographic and Sediment History of the Ocean Basin*. Prentice Hall, Englewood, NJ, 813 pp.
- Kenyon, N.H., Belderson, R.H., 1973. Bed forms of the Mediterranean undercurrent observed with side-scan sonar. *Sediment. Geol.* 9, 77–99.
- Lacombe, H., Lizeray, J.C., 1959. Sur le régime des courants dans le Détroit de Gibraltar. *C. R. Acad. Sci., Paris* 248, 2502–2504.
- Llave, E., 2003. Análisis morfosedimentario y estratigráfico de los depósitos contormíticos del Golfo de Cadiz de Implicaciones paleoceanográficas. *Serie de Geología. Instituto Geológico y Minero de España*. 294 pp.
- Llave, E., Hernández-Molina, F.J., Somoza, L., Díaz-del-Río, V., Stow, D.A.V., Maestro, A., Alveirinho Dias, J.M., 2001. Seismic stacking pattern of the Faro-Albufeira contourite system (Gulf of Cadiz): a Quaternary record of paleoceanographic and tectonic influences. *Mar. Geophys. Res.* 22 (5–6), 475–496.
- Llave, E., Schönfeld, J., Hernandez-Molina, F.J., Mulder, T., Somoza, L., Díaz del Río, V., Sánchez-Almazo, I., 2006. High-resolution stratigraphy of the Mediterranean outflow contourite system in the Gulf of Cadiz during the Pleistocene: the impact of Heinrich events. *Mar. Geol.* 226, 241–262.
- Llave, E., Hernández-Molina, F.J., Somoza, L., Stow, D., Díaz del Río, V., 2007a. Quaternary evolution of the Contourite Depositional System in the Gulf of Cadiz. In: Viana, A., Rebesco, M. (Eds.), *Economic and Paleocanographic Importance of Contourites*. Geol. Soc. London, Sp. Publ., vol. 276, pp. 49–79.
- Llave, E., Hernández-Molina, F.J., Stow, D.A.V., Fernández-Puga, M.C., García, M., Vázquez, J.T., Maestro, A., Somoza, L., Díaz del Río, V., 2007b. Reconstructions of the Mediterranean Outflow Water during the Quaternary since the study of changes in buried mounded drift stacking pattern in the Gulf of Cadiz. *Mar. Geophys. Res.* 28, 379–394.
- Lobo, F.J., Hernández-Molina, F.J., Somoza, L., Rodero, J., Maldonado, A., Barnolas, A., 2000. Patterns of bottom current flow deduced from dune asymmetries over the Gulf of Cadiz shelf (southwest Spain). *Mar. Geol.* 164, 91–117.
- Lobo, F.J., Dias, J.M.A., González, R., Hernández-Molina, F.J., Morales, J.A., Díaz del Río, V., 2003. High-resolution seismic stratigraphy of a narrow, bedrock-controlled estuary: the Guadiana estuarine system, SW Iberia. *J. Sediment. Res.* 73 (6), 973–986.
- Madelain, F., 1970. Influence de la topographie du fond sur l'écoulement Méditerranéen entre le Détroit de Gibraltar et le Cap Saint-Vincent. *Cah. Océanogr.* 22, 43–61.
- Maestro, A., Somoza, L., Díaz del Río, V., Vázquez, J.T., Martín-Alfageme, S., Alveirinho Dias, J.M., Barnolas, A., Vegas, R., 1998. Neotectónica transpresiva en la plataforma continental Suribérica Atlántica. *Geogaceta* 24, 203–206.
- Maestro, A., Somoza, L., Medialdea, T., Talbot, C.J., Lowrie, A., Vázquez, J.T., Díaz-del-Río, V., 2003. Large-scale slope failure involving Triassic and Middle Miocene salt and shale in the Gulf of Cadiz (Atlantic Iberian Margin). *Terranova* 15, 380–391.
- Maldonado, A., Nelson, C.H., 1999. Interaction of tectonic and depositional processes that control the evolution of the Iberian Gulf of Cadiz margin. *Mar. Geol.* 155, 217–242.
- Maldonado, A., Somoza, L., Pallarés, L., 1999. The Betic orogen and the Iberian-African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic). *Mar. Geol.* 155, 9–43.
- Maldonado, A., Barnolas, A., Bohoyo, F., Galindo-Zaldívar, J., Hernández-Molina, F.J., Lobo, F., Rodríguez-Fernández, J., Somoza, L., Vázquez, J.T., 2003. Contourite deposits in the central Scotia Sea: the importance of the Antarctic Circumpolar Current and the Weddell Gyre flows. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 198, 187–221.
- Maldonado, A., Barnolas, A., Bohoyo, F., Escutia, C., Galindo-Zaldívar, J., Hernández-Molina, F.J., Jabaloy, A., Lobo, F., Nelson, C.H., Rodríguez-Fernández, J., Somoza, L., Vázquez, J.T., 2005. Miocene to recent contourite drifts development in the northern Weddell Sea (Antarctica). In: Florindo, F., Harwood, D.M., Wilson, G.S. (Eds.), *Long-Term Changes in Southern High-Latitude Ice Sheets and Climate: the Cenozoic History*. Global Planet. Change, vol. 45(1–3), pp. 99–129.
- Marchès, E., Mulder, T., Cremer, M., Bonnel, C., Hanquiez, V., Gonthier, E., Lecroart, P., 2007. Contourite drift construction influenced by capture of Mediterranean Outflow Water deep-sea current by the Portimao submarine canyon (Gulf of Cadiz, South Portugal). *Mar. Geol.* 242, 247–260.
- Marshall, D., 1995. Influence of topography on the large-scale ocean circulation. *J. Phys. Oceanogr.* 25, 1622–1635.
- McCave, I.N., Carter, L., 1997. Recent sedimentation beneath the Deep Western Boundary Current off northern New Zealand. *Deep-Sea Res. Pt I* 44 (7), 1203–1237.
- McCave, I.N., Tucholke, B.E., 1986. Deep current-controlled sedimentation in the western North Atlantic. In: Vogt, P.R., Tucholke, B.E. (Eds.), *The Geology of North America (The Western North Atlantic Region)*. Geol. Soc. Am., pp. 451–468.
- McCready, P., Pawlak, G., 2001. Stratified Flow along a Rough Slope: Separation Drag and Wave Drag. *J. Phys. Oceanogr.* 31, 2824–2839.
- Medialdea, T., Vegas, R., Somoza, L., Vázquez, J.T., Maldonado, A., Díaz-del-Río, V., Maestro, A., Córdoba, D., Fernández-Puga, M.C., 2004. Structure and evolution of the "Olistostrome" complex of the Gibraltar Arc in the Gulf of Cadiz (eastern Central Atlantic): evidence from two long seismic cross-sections. *Mar. Geol.* 209, 173–198.
- Melières, F., 1974. *Recherches sur la dynamique sédimentaire du Golfe de Cadix (Espagne)*. Ph. D. Thesis, University of Paris VI, unpublished.
- Michaud, F., Chabert, a., Collot, J.-Y., Sallarès, V., Flueh, E.R., Charvis, P., Graindorge, D., Gutscher, M.-A., Bialas, J., 2005. Fields of multi-kilometer scale sub-circular depressions in the Carnegie Ridge sedimentary blanket: effect of underwater carbonate dissolution? *Mar. Geol.* 216, 205–219.
- Mougenot, D., Vanney, J.R., 1982. Les rides de contourites Plio-Quaternaires de la pente continentale Sud-Portugaise. *Bull. Inst. Geol. Bassin Aquitaine* 31, 131–139.
- Mulder, T., Voisset, M., Lecroart, P., Le Drezen, E., Gonthier, E., Hanquiez, V., Faugères, J.C., Habgood, E., Hernandez-Molina, F.J., Estrada, F., Llave-Barranco, E., Poirier, D., Gorine, C., Fuchey, Y., Voelker, A., Freitas, P., Lobo Sanchez, F., Fernandez, L.M., Kenyon, N.H., Morel, J., 2003. The Gulf of Cadiz: an unstable giant contourite levee. *Geo-Mar. Lett.* 23, 7–18.
- Mulder, T., Lecroart, P., Hanquiez, V., Marches, E., Gonthier, E., Guedes, J.C., Thiébot, E., Jaaidi, B., Kenyon, N., Voisset, M., Perez, C., Sayago, M., Fuchey, Y., Bujan, S., 2006. The western part of the Gulf of Cadiz: contour currents and turbidity currents interactions. *Geo-Mar. Lett.* 26, 31–41.
- Murray, A.B., Thieler, E.R., 2004. A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and "rippled scour depressions". *Cont. Shelf Res.* 24, 295–315.
- Nelson, C.H., Baraza, J., Maldonado, A., 1993. Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. *Sediment. Geol.* 82, 103–131.
- Nelson, C.H., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., Barber, J.H., 1999. Influence of the Atlantic inflow and Mediterranean outflow currents on Late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. *Mar. Geol.* 155, 99–129.
- Nibbelink, K., 1999. Modeling deepwater reservoir analogs through analysis of recent sediments using coherence, seismic amplitude, and bathymetry data, Sigsbee escarpment, Green Canyon, Gulf of Mexico. *Lead. Edge* 18, 550–561.
- Ochoa, J., Bray, N.A., 1991. Water mass exchange in the Gulf of Cadiz. *Deep-Sea Res.* 38 (1), 465–503.
- Paillard, D., 1998. The timing of Pleistocene glaciations from a simple multiple-state climate model. *Nature* 391, 378–381.
- Pinheiro, L.M., Ivanov, M.K., Sautkin, A., Akhmanov, G., Magalhaes, V.H., Volkonskaya, A., Monteiro, J.H., Somoza, L., Gardner, J., Hamouni, N., Cunha, M.R., 2003. Mud volcanism in the Gulf of Cadiz: results from the TTR-10 cruise. *Mar. Geol.* 195, 131–151.
- Rebesco, M., 2005. Contourites. In: Richard, C., Selley, R.C., Cocks, L.R.M., Plimer, I.R. (Eds.), *Encyclopedia of Geology*, vol. 4. Elsevier, London, pp. 513–527.
- Rebesco, M., Stow, D.A.V., 2001. Seismic expression of contourites and related deposits: a preface. *Mar. Geophys. Res.* 22, 303–308.
- Rebesco, M., Camerlenghi, A. Contourites. *Developments in Sedimentology*. Elsevier, in press.
- Rosas, F.M., Duarte, J.C., Terrinha, P., Valadares, V., Matias, L., in press. Morphotectonic characterization of major bathymetric lineaments in Gulf of Cadiz (Africa-Iberia

- plate boundary): Insights from analogue modelling experiments. *Mar. Geol.* doi:10.1016/j.margeo.2008.08.002.
- Serra, N., Ambar, I., Käse, R.H., 2005. Observations and numerical modelling of the Mediterranean outflow splitting and eddy generation. *Deep-Sea Res. Pt II* 52, 383–408.
- Serrano, A., Maestro, A., Nozal, F. (Coord.), 2005. Memoria del mapa Geomorfológico de España a escala 1:1000.000: Geomorfología de la zona submarina española. Servicio de Publicaciones del Instituto Geológico y Minero de España, Madrid.
- Somoza, L., Lowrie, A., Maestro, A., Fernández-Puga, M.C., Vázquez, J.T., Roque, C., Díaz del Río, V., Torrescusa, S., 1999. Gravity spreading and sliding of mobile shales and salt sheets along the slope of the Gulf of Cadiz (Atlantic Iberian Margin). Meeting Association of European Geological Societies.
- Somoza, L., Díaz-del-Río, V., León, R., Ivanov, M., Fernández-Puga, M.C., Gardner, J.M., Hernández-Molina, F.J., Pinheiro, L.M., Rodero, J., Lobato, A., Maestro, A., Vázquez, J.T., Medialdea, T., Fernández-Salas, L.M., 2003. Seabed morphology and hydrocarbon seepage in the Gulf of Cadiz mud volcano area: acoustic imagery, multibeam and ultra-high resolution seismic data. *Mar. Geol.* 195, 153–176.
- Stow, D.A.V., Faugères, J.C., Gonthier, E., 1986. Facies distribution and textural variations in Faro Drift contourites: velocity fluctuation and drift growth. *Mar. Geol.* 72, 71–100.
- Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugères, J.C., Viana, A.R., 2002. Deep-water contourite systems: modern drifts and ancient series seismic and sedimentary characteristics. *Geological Society of London Memoir*, p. 22.
- Stow, D.A.V., Hunter, S., Wilkinson, D., Hernández-Molina, F.J., in press-a. The nature of contourite deposition. In: Rebesco, M., Camerlenghi, A. (Eds.), *Contourites. Developments in Sedimentology*. Elsevier, 143–156.
- Stow, D.A.V., Díaz del Río, V., Hernández-Molina, F.J., Llave, E., García, M., Somoza, L., Maestro, A., Rolf, J., Bruno, M., in press-b. The Cadiz Contourite Channel: photographic evidence for active bottom currents and deep tidal influence. *Mar. Geol.*
- Stow, D.A.V., Díaz del Río, V., Hernández-Molina, F.J., Llave, E., Sayago, M., Branson, A., in press-c. Bedform-velocity matrix: the estimation of bottom current velocity from bedform observations. *Geology*.
- Thorpe, S.A., 1976. Variability of the Mediterranean undercurrent in the Gulf of Cadiz. *Deep-Sea Res. Pt. A* 23, 711–727.
- Toucanne, S., Mulder, T., Schönfeld, J., Hanquiez, V., Gonthier, E., Duprat, J., Cremer, M., Zaragosi, S., 2007. Contourites of the Gulf of Cadiz: a high-resolution record of the paleocirculation of the Mediterranean outflow water during the last 50.000 years. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 246, 354–366.
- Viana, A.R., 2001. Seismic expression of shallow- to deep-water contourites along the south-eastern Brazilian margin. *Mar. Geophys. Res.* 22, 509–521.
- Viana, A.R., Rebesco, M., 2007. Economic and Paleooceanographic significance of contourites. *Geol. Soc. London Sp. Publ.* 276, 350.
- Viana, A.R., Almeida Jr., W., Nunes, M.C.V., Bulhõe, E.M., 2007. The economic importance of contourites. In: Viana, A., Rebesco, M. (Eds.), *Economic and paleooceanographic significance of contourite deposits*. Geological Society of London Special Publication, vol. 276, pp. 1–23.
- Voelker, A., Lebreiro, S., Schönfeld, J., Cacho, I., Exlenkenser, H., Abrantes, F., 2006. Mediterranean outflow strengthenings during Northern Hemisphere coolings: a salt sources for the glacial Atlantic? *Earth and Planetary Science Letters* 245, 39–55.
- Zenk, W., 1975. On the origin of the intermediate double-maxima in T/S profiles from the North Atlantic. *Meteor-Forsch. Ergeb. A* (16), 35–43.