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The contourite depositional system of the Gulf of Cádiz: A sedimentary model related to the bottom current activity of the Mediterranean outflow water and its interaction with the continental margin

F.J. Hernández-Molina[a,*], E. Llave[b], D.A.V. Stow[c], M. García[d], L. Somoza[b], J.T. Vázquez[e], F.J. Lobo[f], A. Maestro[b], V. Díaz del Río[g], R. León[b], T. Medialdea[b], J. Gardner[h]

[a]*Dpto.de Geosciencias Marinas, Facultad de Ciencias del Mar, Universidad de Vigo, 36200 Vigo (Pontevedra), Spain*
[b]*Instituto Geológico y Minero de España, Ríos Rosas 23, 28003 Madrid, Spain*
[c]*Southampton Oceanography Centre (SOC), Waterfront Campus, Southampton SO14 3ZH, UK*
[d]*Instituto de Ciencias del Mar, CSIC, Paseo Marítimo de la Barceloneta 37-49, 08003 Barcelona, Spain*
[e]*Facultad de Ciencias del Mar, Univ. de Cádiz, 11510 Puerto Real, Cádiz, Spain*
[f]*Instituto Andaluz de Ciencias de la Tierra, CSIC, Campus de Fuentenueva, s/n, 18002 Granada, Spain*
[g]*Instituto Español de Oceanografía, C/ Puerto Pesquero s/n, 29640 Fuengirola, Spain*
[h]*Naval Research Laboratory, Code 7420, 4555 Overlook Avenue SW, Washington, DC 20375, USA*

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Abstract

The present paper is mostly a synthesis of work conducted on the continental margin of the Gulf of Cádiz using a broad database collected by several cruises and projects supported by the Spanish Research Council and the NRL and Naval Oceanographic Office (USA), including: bathymetry, sidescan sonar imagery, seismic profiles, sediment cores, submarine photographs and physical oceanographic data. These data have enabled us to establish a detailed understanding of the morphologic development of the margin, its Pliocene and Quaternary stratigraphy, and a full characterization of the contourite depositional system (CDS) generated by the Mediterranean outflow water (MOW). The northern margin of the Gulf of Cádiz shows the following distinct features: (a) an active compressive framework where the "*Cádiz Allocthonous Unit*" provides an unstable substratum for Late Miocene, Pliocene and Quaternary sedimentation; (b) a relative lack of submarine canyons, except in the western area of the Algarve margin; (c) a very broad continental slope that lacks a marked continental rise; (d) a middle slope dominated by *along-slope* processes driven by the MOW, which has generated a complex CDS during the Pliocene and Quaternary; and (e) an irregular lower slope and abyssal plain region dominated by *down-slope* processes that is partly detached from an upper slope source region. The CDS is composed of both depositional and erosive features. The main depositional features are characterised by *sedimentary wave fields*, *sedimentary lobes*, *mixed drifts*, *plastered drifts*, *elongated mounded, and separated drifts* and *sheeted drifts*. The main erosive features are *contourite channels*, *furrows*, *marginal valleys* and *moats*. These various depositional and erosive features have a specific location along the margin, and their detailed distribution is essential to understand the present (and past) interaction of the MOW

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*Corresponding author. Tel.: +34 986 814017; fax: +34 986 812614.
E-mail address: fjhernan@uvigo.es (F.J. Hernández-Molina).

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with the middle slope. Based on this distribution, five morphosedimentary sectors have been identified within the CDS, which from east to west are: (1) proximal scour and sand ribbons; (2) overflow sedimentary lobe; (3) channels and ridges; (4) active contourite drifts; and (5) submarine canyons. The development of the CDS has been controlled in general by the Pliocene and Quaternary environmental and paleoceanographic changes and by the morphology of the margin, but in detail the development of each of these sectors is related to systematic deceleration of the MOW as it flows westwards, to the interaction with the margin bathymetry, and to the effects of Coriolis force. Our comprehensive sedimentary model for the CDS defines the Gulf of Cádiz margin as a mixed *contourite-turbidite* system with a *detached combined drift-fan* morphology. This is different from many other contourite influenced margins, where the contourite processes are dominant on the middle slope, and separated from the down-slope processes, which are characteristic on the lower slope and abyssal plains.

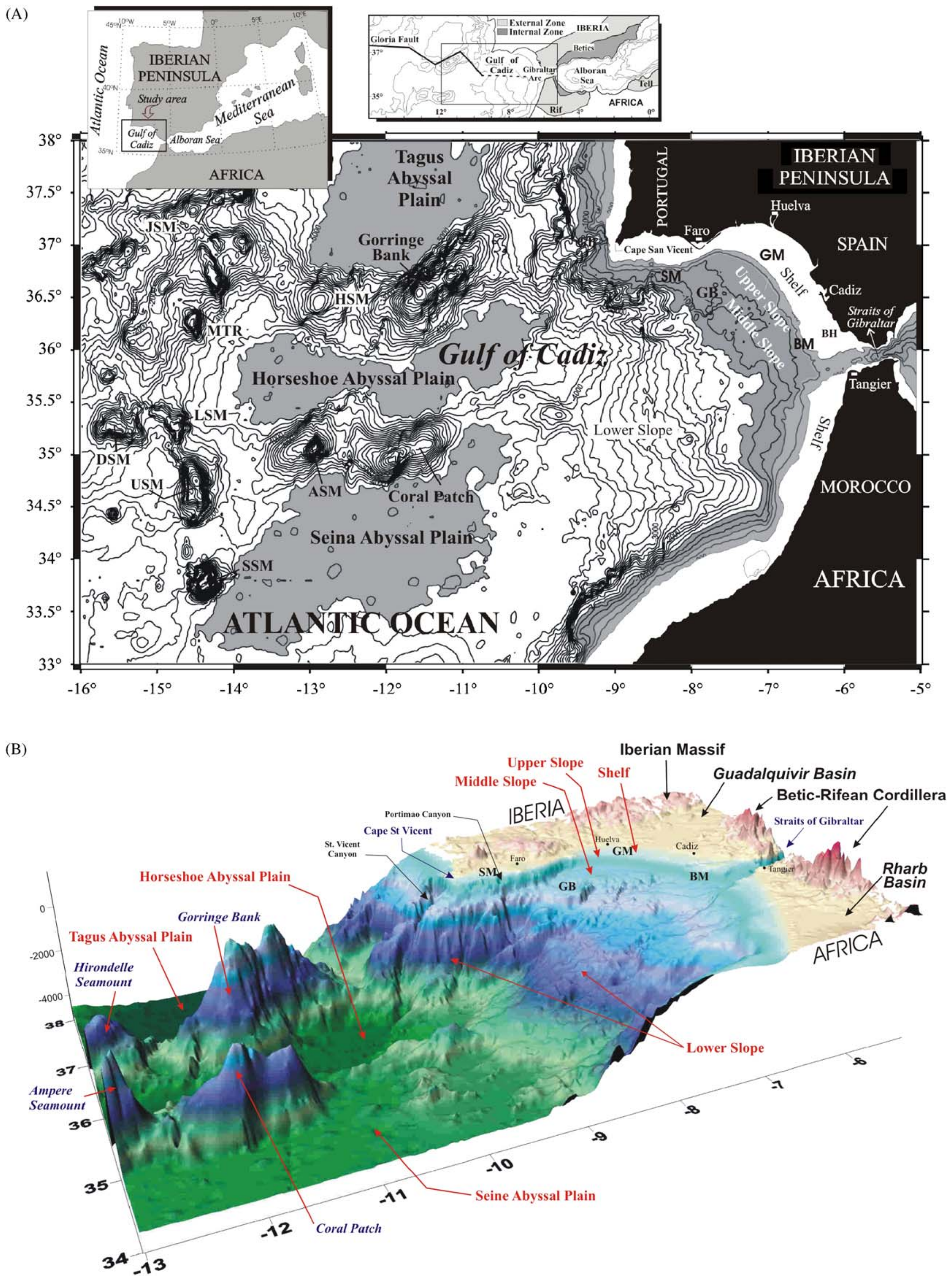
Keywords: Gulf of Cádiz; Continental margin; Morphology; Seismic stratigraphy; Sedimentary processes; Contourites

1. Introduction

Many continental margins are built up by the combined action of *down-slope* and *along-slope* sedimentary processes (Faugères et al., 1999; Weaver et al., 2000; Stow et al., 2002a). Where *down-slope* processes dominate they generate turbidite, debrite or mixed mass-gravity depositional systems (Stow, 1986, 1994; Einsele, 2000; Weaver et al., 2000). Where *along-slope* processes dominate, they generate a Contourite Depositional System (CDS) (Stow et al., 2002a; Hernández-Molina et al., 2003; Rebesco, 2005). There are many examples of continental margins built up by a combination of submarine slides, debris flows, and turbidity currents, such as the polar margins in the northern and southern Hemispheres (Larter et al., 1997; Weaver et al., 2000; Mienert and Weaver, 2003; Laberg et al., 2005) or predominantly by turbidity currents, such as many other glacially-influenced and fluvial-dominated margins (Tucholke and Mountain, 1986; Locker and Laine, 1992; Weaver et al., 2000; Benetti, 2006, among many others). In other cases, contourite deposits (*drifts*) are a common part of continental margins swept by strong bottom currents, typically in association with varied downslope deposits (Rebesco et al., 1997, 2002; Stow and Faugères, 1998; Faugères et al., 1999; Rebesco and Stow, 2001; Lu et al., 2003). Indeed, marine geological studies conducted over the past four decades have confirmed the essential role of bottom current processes in marine environments, and show that they can generate large sedimentary bodies hundreds of km long, tens of km wide, and between 200 and 2000 m thick, similar in dimensions to large-scale turbidite bodies (Stow et al., 1986, 2002b; Zhenzhong et al., 1998; Faugères et al., 1999; Maldonado et al., 2003a, 2005). Several classification systems have been proposed for contourite bodies, based mainly on morphological, sedimentological and seismic characteristics (McCave and Tucholke, 1986; Faugères and Stow, 1993; Faugères et al., 1993, 1999; Rebesco and Stow, 2001; Stow et al., 2002a; Rebesco, 2005). All drifts are related to a combination of regional oceanographic conditions and the physiographic domains in which they develop. Thus, it is possible to deduce, from their morphologic, stratigraphic and sedimentary characteristics, the temporal and spatial variations of the water mass responsible for their development.

Over a long period of geological time, continental margins are built up by sedimentary processes driven by plate tectonic evolution and environmental changes (Einsele, 2000). Both controls may result, at different periods, in continental margins sedimentation being mainly dominated by either down-slope or along-slope processes (e.g., Pickering et al., 1989, 1994; Rebesco et al., 1997, 2002; Stoker et al., 1998; Armishaw et al., 2000; Hernández-Molina et al., 2004a; Laberg et al., 2005). Over a shorter time period (e.g., Late Quaternary), environmental changes in climate, sea-level and oceanographic conditions clearly exert a major control on margin evolution, but are nevertheless modulated by local tectonic effects (Hernández-Molina et al., 2000; Weaver et al., 2000; Llave et al., 2001, 2006a–c; Øvrebø et al., 2006). Once again they condition the predominance of down-slope versus along-slope processes.

Recently, Weaver et al. (2000) and Benetti (2006) have identified the Quaternary sedimentary processes that have controlled the margin evolution in the North Atlantic Basin. Between 41°N and 33°N


(A)
Atlantic Ocean
IBERIAN PENINSULA
Study area
Gulf of Cadiz
Alboran Sea
Mediterranean Sea
AFRICA
45°N
40°N
35°N
10°W
5°W
0°
5°E
10°E
External Zone
Internal Zone
IBERIA
Gloria Fault
Betics
Gulf of Cadiz
Gibraltar Arc
Alboran Sea
Tell
Rif
AFRICA
37°
35°
12°
8°
4°
0°
Tagus Abyssal Plain
Gorringe Bank
JSM
HSM
MTR
Gulf of Cadiz
Horseshoe Abyssal Plain
LSM
DSM
USM
ASM
Coral Patch
Seina Abyssal Plain
SSM
ATLANTIC OCEAN
PORTUGAL
IBERIAN PENINSULA
Huelva
Faro
Cape San Vicent
SPAIN
GM
Shelf
Cadiz
SM
GB
Upper Slope
Middle Slope
BM
BH
Straits of Gibraltar
Tangier
Lower Slope
Shelf
MOROCCO
AFRICA
38°
37.5°
37°
36.5°
36°
35.5°
35°
34.5°
34°
33.5°
33°
-16°
-15°
-14°
-13°
-12°
-11°
-10°
-9°
-8°
-7°
-6°
-5°
(B)
Iberian Massif
Upper Slope
Shelf
Guadalquivir Basin
Middle Slope
Betic-Rifean Cordillera
IBERIA
Portimao Canyon
Cape St Vicent
St. Vicent Canyon
Straits of Gibraltar
Huelva
GM
Cadiz
Faro
SM
Tangier
GB
BM
Rharb Basin
Horseshoe Abyssal Plain
Gorringe Bank
Tagus Abyssal Plain
AFRICA
Hirondelle Seamount
Ampere Seamount
Lower Slope
Seine Abyssal Plain
Coral Patch
0
-2000
-4000
38
37
36
35
34
-13
-12
-11
-10
-9
-8
-7
-6

in the west and between 26°N and 56°N in the east Atlantic, sediment flux across the margins during glacial periods was characterised by increased supply and channelised turbidity current processes. Although the Gulf of Cádiz continental margin is located within the eastern sector of the central North Atlantic (Fig. 1A), it nevertheless shows some unique morphological, structural, sedimentary and oceanographic features, which are rather different from those proposed by Weaver et al. (2000) on the adjacent margins. The major differences appear to be due to the presence of an unstable substratum below the continental margin caused by the "*Cádiz Allocthonous Unit*" (Roberts, 1970; Maldonado et al., 1999; Medialdea et al., 2004), and to the resulting broad slope and slope terrace morphology. In this region, along-slope processes resulting from the Mediterranean Outflow Water (MOW) have dominated the middle slope since the beginning of the Pliocene, following the opening of the Straits of Gibraltar (Nelson et al., 1993, 1999; Maldonado et al., 1999; Llave et al., 2006b, d).

The Gulf of Cádiz margin is a complex domain (Fig. 1B) where many processes act together. Previous studies have focused on the link between shelf and slope in terms of sedimentary processes and stratigraphic correlation (Lobo, 2000; Hernández-Molina et al., 2000, 2002; Lobo et al., 2005a). Little work has characterised the link between the sedimentation on the middle slope and the adjacent abyssal plains (Lebreiro, 1995; Lebreiro et al., 1997), especially if compared with the neighbouring Moroccan margin, which has been closely studied in this regard (Wynn, 2000; Wynn et al., 2000a, b; Weaver et al., 2000; Mienert and Weaver, 2003). The morphology and near-surface deposits of the middle slope of the Gulf of Cádiz have been controlled by the MOW influence. Several studies have tried to characterise its variability. Heezen and Johnson (1969) identified five provinces in the Gulf of Cádiz using precision depth records and bottom photographs: rolling, smooth, rocky, current-swept, and sediment waves. Later, Kenyon and Belderson (1973) identified four main provinces using low resolution regional bathymetry and sidescan sonar images (from GLORIA and conventional systems): scour and sand ribbons, sand waves, large mud waves, and a smooth mud surface. This classification has been a standard reference during the past 35 years, with only relatively few modifications in the central area and more detailed characterisation of some parts (e.g., the ridge and valley province in the central part defined by Nelson et al., 1993, 1999; Baraza et al., 1999). Also, the contributions of Vanney and Mougenot (1981) were essential to the characterisation of the Algarve or Sudiberic Margin. Very recently, new provinces and more detailed analysis of slope morphology have become possible using modern multibeam echosounders, deep-tow sidescan sonar systems (e.g., TOBI), and ultrahigh resolution seismic reflection systems (Llave et al., 2001; García, 2002; Habgood, 2002; Hanquiez, 2002; Mulder et al., 2002, 2003, 2006; Habgood et al., 2003; Hanquiez et al., 2003; Hernández-Molina et al., 2003; Llave, 2003).

As part of this special volume on the Gulf of Cádiz region, this paper is mostly a synthesis of previous work, focusing on the development of the CDS, which have been generated by the MOW and controlled both by Pliocene and Quaternary environmental and paleoceanographic changes and by the morphology of the margin. We describe the morphology, sedimentology and stratigraphy of the margin with three main objectives: (a) to show a regional overview of the present-day characteristics of the continental margin; (b) to combine previous work and new data on the morphology and sedimentary stacking patterns of the CDS of the middle slope; and (c) to present a new comprehensive sedimentary model for the CDS, considering new aspects of genesis, sediment supply, and sequence stratigraphy. Some of the morphologic descriptions are new, including characterization of the main contourite channels and structural highs, and consideration of sedimentary processes within the contourite channels.

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Fig. 1. (A) Location of the Gulf of Cádiz and regional bathymetric map of the continental margin of the Gulf of Cádiz. Insert sketch shows major tectonic features. The different submarine domains of the margin are pointed out (Bathymetry by satellite data from Smith and Sandwell, 1997). (B) 3D regional bathymetric map made by the data of the aforementioned authors. *Legend of the physiographic reference points, in alphabetical order*: ASM = Ampere Seamount; BH = Barbate high; DSM = Dragon Seamount; GB = Guadalquivir Bank; JSM = Josephine Seamount; HSM = Hirondelle Seamount; LSM = Lion Seamount; MTR = Madeira Torre Rise; SSM = Sea Seamount; USM = Unicorn Seamount. *Legend of the morphostructural zones:* SM = Sudiberic Margin; GM = Guadalquivir Margin, BM = Betic domain Margin.

2. Methods and data base

The present study is based on a broad database collected since 1989 (Fig. 2) that has been supported by the Spanish Research Council. These data have enabled us to: (a) characterise the Pliocene and Quaternary regional seismic stratigraphy of the slope (Maldonado et al., 1999; Llave et al., 2001, 2006d; Stow et al., 2002c; Hernández-Molina et al., 2002); (b) identify the detailed sedimentary environments and processes of every morphologic sector of the present CDS on the middle slope of the Gulf of Cádiz; and (c) outline the slope evolution over time (Llave et al., 2001, 2006b; Hernández-Molina et al., 2003, 2004b; Llave, 2003).

The database used includes the following bathymetric, sidescan sonar imagery, seismic, sediment cores, submarine photographs, and oceanographic data (Fig. 2):

(a) *Bathymetric data.* Regional bathymetric maps by Heezen and Johnson (1969) and Maldonado et al. (2003b) were used as base maps on which the different morphological sectors were identified. In addition, a swath bathymetry of the middle slope was obtained using the Simrad EM12S-120 multibeam echo-sounder system. Additionally, a Simrad EK500 echo-sounder was used.

(b) *Sidescan sonar data*, using the *Seamap*, which is a variant of the University of Hawaii's MR-1 sidescan sonar system, operated by the NRL and Naval Oceanographic Office (NAVOCEANO) in 1992, provided bathymetric and backscatter imagery of the sea bottom between 6°W and 10°W and 35°10′–36°20′N.

(c) The regional network of *seismic data* analysed here is shown in Fig. 2, including low-resolution reflection Multichannel seismic (MCS) reflection profiles from oil companies (mainly from CAMPSA and REPSOL-YPF), medium-resolution seismic profiles from Sparker and Airgun systems, high-resolution seismic profiles taken with Geopulse and Uniboom systems; very high-resolution seismic profiles using a 3.5-kHz system, and ultra-high resolution seismic profiles using a topographic parametric sounder (TOPAS).

(d) Results of *core and borehole data* from different surveys also have been incorporated into the study (Fig. 2). Correlation of seismic units and discontinuities with these cores was essential in order to analyse the timing of the processes responsible for the development of

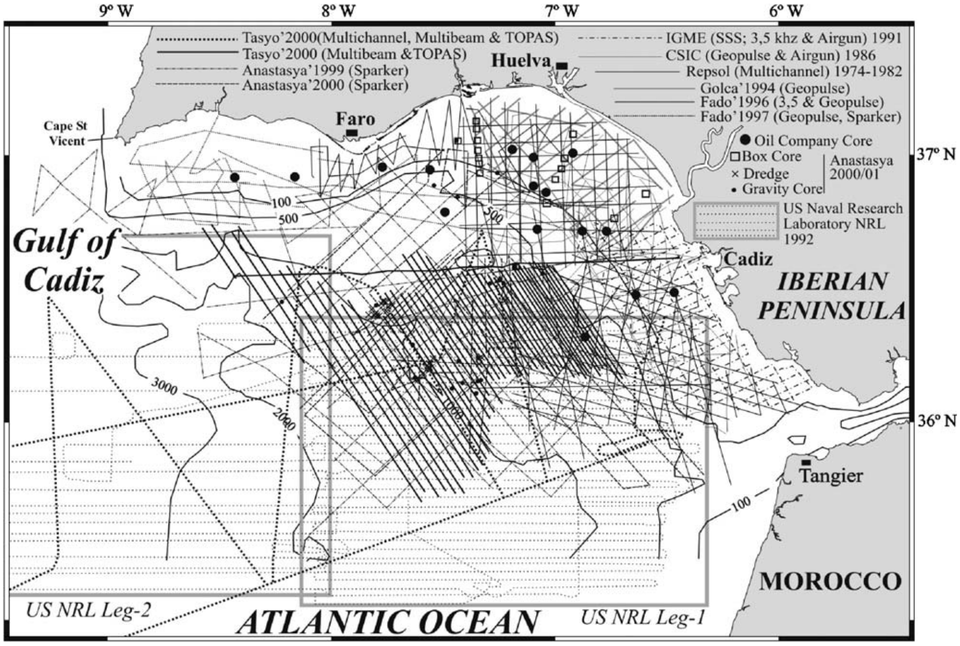


Fig. 2. Location of seismic profiles and multibeam dataset used to produce the morphosedimentary map. The data was positioned using GPS and DGPS systems. The location of sediment cores is also shown.

the depositional units and to establish the chronology of the units on the middle slope of the Gulf of Cádiz at different scales. We used cores and borehole data obtained by oil company drilling (AUXINA, CAMPSA, CHEVRON, ENIEPSA, ESSO, EXXON, REPSOL-YPF and SHELL) to establish the chronological framework for the Pliocene and Quaternary (Mougenot, 1988; Riaza and Martínez del Olmo, 1996; Terrinha, 1998; Maldonado et al., 1999; Llave et al., 2001; Hernández-Molina et al., 2002; Llave, 2003). Quaternary chronostratigraphy uses new biostratigraphic results from samples in three deep oil company boreholes, and their correlation with multi and single-channel medium and high-resolution profiles (sound velocity in sediments of 2000–1600 m/s) is considered (Llave et al., 2004b, 2006b). Upper Quaternary chronostratigraphy is based on the correlation of two Calypso piston cores (isotope-dated) with very and ultra high-resolution seismic profiles (sound velocity in sediments of 1600 m/s is considered) (Llave et al., 2004a, 2006a). The Calypso giant piston cores (MD9923-36 and MD9923-41, 20 m long) were collected during the IMAGES V scientific cruise with RV *Marion Dufresne* in 1999. Standard gravity cores (ANAS01-21 and ANAS01-22, 1–3 m long) collected during the ANASTASYA scientific cruise, on board the RV *Cornide de Saavedra* in 2001, which have been useful to determine the Holocene chronostratigraphy (Llave, 2003; Llave et al., 2006a). Sediment core can be accurately used as a reliable correlations of paleoceanographic events and for groundtruthing seismic facies patterns. Additionally, information from previous sediment cores published by others authors (Nelson et al., 1999; Sierro et al., 1999, 2000) has been taken into consideration.

(e) Ecktacrome (125 ASA) *submarine photographs* were taken with a BENTHOS-372 camera during the ANASTASYA-2001/09 cruise onboard the RV Cornide de Saavedra (IEO). Over 3000 submarine photographs from mud volcanoes, the Guadalquivir diapiric ridge, and contourite channels were taken during this cruise. For the purpose of this paper we present the results of a preliminary study of the submarine photographs from the Contourite Cádiz Channel only, using the L2, L4 and L5 photographic tracklines located on the swath bathymetric Fig. 11.

(f) Finally, *physical oceanographic information* was gathered both from bibliographic sources (Madelain, 1970; Kenyon and Belderson, 1973; Melières, 1974; Zenk, 1975; Baringer and Price, 1997; Nelson et al., 1999; Cherubin et al., 2000) and from data collected during cruises GOLFO 00/10; TASYO; GOLFO 01/05 and GOLFO 09. These data comprise CTD (MK5 and MK3-WOCE General Oceanic models) and XBT (expendable bathythermograph, XBT) profiles, which yield temperature and salinity information. Compilation and interpretation of this oceanographic data and its correlation with the morphologic features of the central sector of the middle slope have been previously made by García (2002).

2.1. Terminology

For the most part, we have followed the recent nomenclature for contourites and contourite drift deposits based on Faugères et al. (1999), Rebesco and Stow (2001), Stow et al. (2002b), and Rebesco (2005). However, our terminology differs slightly with regard to the erosive features produced by bottom currents. We identify four different types: *contourite channel*s, *moats*, *marginal valleys*, and *furrows*.

Contourite channels are erosive features with a margin-parallel trend that are formed mainly by the erosive action of bottom currents. Although their morphology is similar to that of Mid-Ocean Channels (Nelson and Kulm, 1973; Carter, 1988; Alonso and Ercilla, 2000), they are generally shorter in length and their specific association with bottom currents suggests that use of the term "contourite channel" is more appropriate. The Falkland and Vema Channels, which both developed in response to erosion by the Antarctic Bottom Current (Mézerais et al., 1993), are well studied examples of this type of erosive feature.

Contourite moats are channels with a margin-parallel trend, also generated by the erosive activity of bottom currents on the seafloor, but they differ from contourite channels in their genetic relation with *mounded and elongated separate drifts. Marginal Valleys* are defined as elongate erosive scours generated by the effects of an incoming current against a topographic elevation. They can develop at the lee, stoss or lateral margins of the obstacle (Davies and Laughton, 1972; Kennet, 1982). *Erosive furrows* are described by Kennet (1982) as smooth structures, typically with lengths of kilometres and flat bottoms with incision depths of 1–10 m. Their trends vary from parallel to lightly oblique to the current, although they can also adapt to the shape of a topographic elevation. Erosive furrows usually originate in areas with fine and cohesive sediment, and have been related to the existence of some small detached filaments of flow separated from the main current as a result of topographic effects.

3. Geological framework and margin evolution

The Gulf of Cádiz is located at the transition between the Gloria transform zone, which marks the African–Eurasian plate boundary in the Atlantic, and the westernmost part of the Alpine–Mediterranean orogenic belt, represented by the Gibraltar Arc, the western front of the Betic–Rif collisional orogen (Fig. 1A). The diffuse nature of this segment of the plate boundary is accepted on the basis of the related seismicity (Vázquez and Vegas, 2000). It represents a wide transpression zone ascribed to the slow (2–4 mm/year) oblique NW–SE convergence (Grimison and Chen, 1986; Buforn et al., 1995; Gutsher et al., 2002; Jiménez-Munt and Negredo, 2003). Geodynamic evolution of the Gulf of Cádiz is marked by three successive phases (Maldonado et al., 1999): (1) development of a passive margin of Mesozoic age, related to the opening of the Central Atlantic; (2) occurrence of a compressional regime during the Late Eocene to Early Miocene, conditioned by N–S Africa–Eurasia convergence; and (3) evolution of a Miocene foredeep associated with formation of the Betic–Rif orogen and opening of the Western Mediterranean basin. Westward drift and collision of the Alboran Domain with the north African and south Iberian margins in the Early-Middle Miocene, caused the development of the Rif and Betic orogen, and as a consequence the radial emplacement of huge allochthonous masses (the so-called "*olistostrome unit*" or *"Cádiz Allocthonous Unit"*) on the Guadalquivir Basin (Iberian foreland), Rharb Basin (North African foreland) and Gulf of Cádiz (Perconig, 1960–1962; Roberts, 1970; Flinch and Vail, 1998; Torelli et al., 1997; Maldonado et al., 1999; Gràcia et al., 2003; Medialdea et al., 2004).

Since the Tortonian, the compressional regime has changed to another, more oblique one (NW–SE), characterised in the Gulf of Cádiz by the extensional collapse of the orogenic front, and subsequently by remobilisation and emplacement westward of the *allochthonous* body (Maldonado et al., 1999; Medialdea et al., 2004). Instability within this allochthonous mass occurred, and extensional structures, migrating from NE to SW, were produced perpendicular to the convergence trend between the African and Eurasian plates. The roots of these structures are the plastic materials of the Triassic and Middle Miocene marls and salts. The migration of these marls and evaporite units drove the diapiric processes, manifested in isolated morphological highs and diapiric ridge systems, along the shelf and slope parallel to the thrust migration structures. Extensional and diapiric processes developed areas with high subsidence rates. These diapiric structures are associated with a complex tectono-sedimentary history related to down-slope gravity gliding and tectonic compression westward from the fronts of the deformed wedges of the allochthonous units, which comprise blue subcompact marls that have been sampled several times by gravity cores and dredges. At the end of the Lower Pliocene, subsidence decreased and the margin evolved towards more stable conditions during the Upper Pliocene-Quaternary (Nelson et al., 1993; Maldonado et al., 1999; Somoza et al., 1999; Maestro et al., 2003; Fernández-Puga, 2004; Medialdea et al., 2004). Sediment deposition since the Pliocene has been strongly influenced by the MOW, by changes in global climate and sea level, and by neotectonic activity (mainly diapirism) (Nelson et al., 1999; Llave, 2003; Llave et al., 2006b).

Due to its complex geodynamic evolution, the Gulf of Cádiz continental margin has three different morpho-structural zones (Fig. 1A and B): (1) the *Sudiberic Continental Margin*, located offshore the Algarve coast, which has a relatively steep slope influenced by tectonic features and crossed by submarine canyons (Baldy et al., 1977; Nelson and Maldonado, 1999; Maldonado et al., 1999; Barnolas et al., 2000; Vázquez et al., 2000); (2) the *Guadalquivir Margin*, which displays marked progradation, an absence of submarine canyons, and a broad shelf located offshore of the Guadalquivir basin and bounded toward the SE by the *Barbate High* (Lobo et al., 2000) and toward the NW by the *Guadalquivir Bank* (Roberts, 1970; Riaza and Martínez del Olmo, 1996; Maldonado et al., 1999); and (3) the *Betic domain Continental Margin*, which represents the continuation of the *Campo de Gibraltar Flysh Units* and the *External Betic Units* (Subbetic Zone). In this zone, the margin also shows a relatively steep slope influenced by tectonic features, and locally with submarine canyons (Baldy et al., 1977; Díaz del Río et al., 1998; Nelson and Maldonado, 1999; Maldonado et al., 1999; Rodero, 1999).

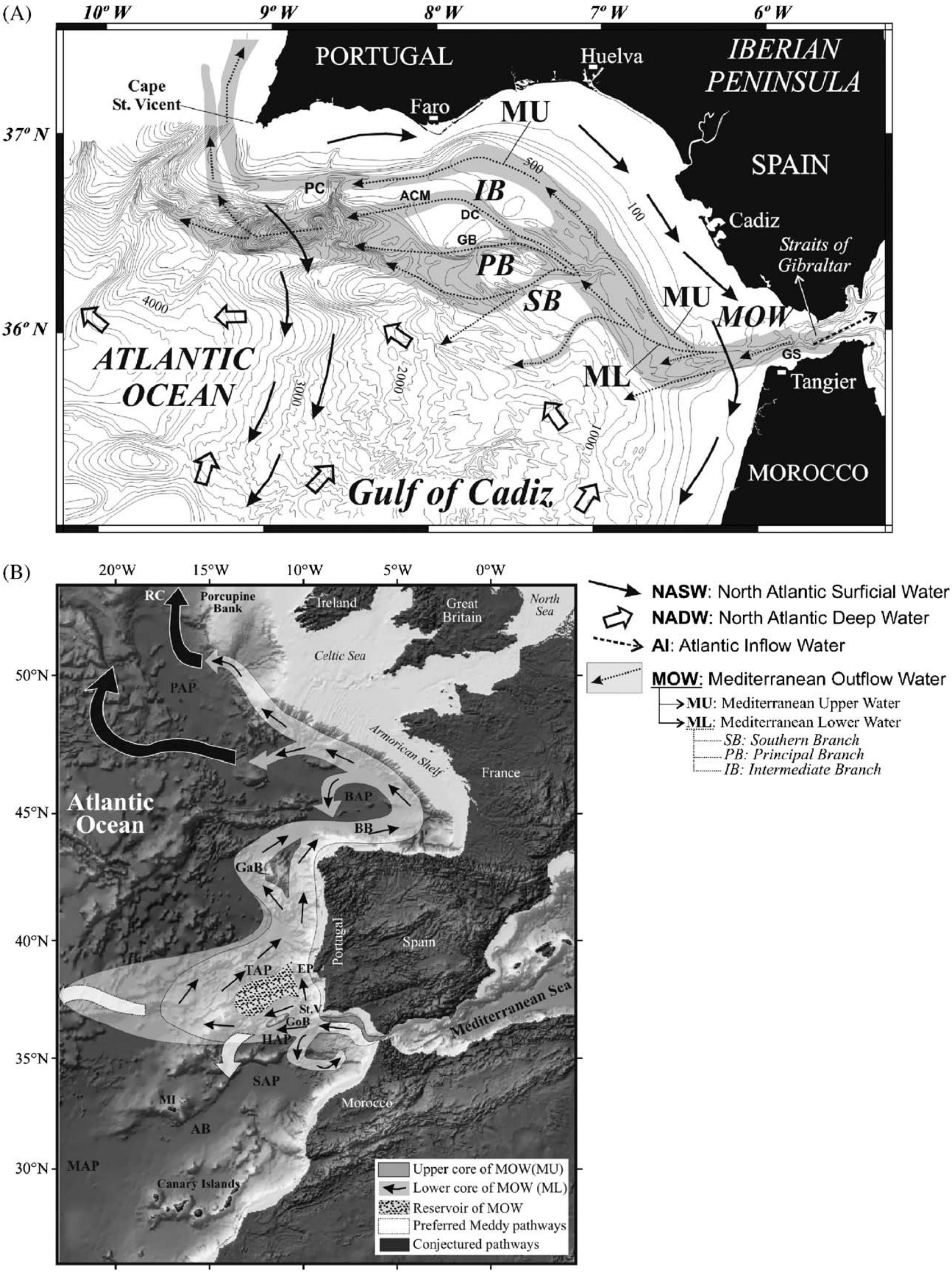
4. Oceanographic setting: the MOW pathway

4.1. The MOW bottom current pathways in the Gulf of Cádiz

The present-day circulation pattern in the Gulf of Cádiz is characterised by intense oceanographic dynamics controlled by the exchange of water masses through the Straits of Gibraltar (Fig. 3), also referred to as the Gibraltar gateway. This exchange is determined by the warm and highly saline *Mediterranean Undercurrent* or MOW near the bottom and the turbulent, less saline, cool-water mass of Atlantic Inflow (AI) water on the surface. MOW represents in the Gulf of Cádiz an independent, strong bottom current moving from the SE to the NW along the middle slope above the *North Atlantic Deep Water* (NADW) (Madelain, 1970; Melières, 1974; Zenk, 1975; Thorpe, 1975; Gardner and Kidd, 1983; Ochoa and Bray, 1991; Baringer and Price, 1999; Nelson et al., 1999). The MOW passes through the Straits beneath AI at a depth of 40–200 m (Gascard and Richez, 1985). After passing the Gibraltar seamount, the MOW forms a turbulent flux ranging from 150 to 200 m wide that moves along a channel within the Gibraltar gateway in a WSW direction at a speed of more than 200 cm/s (Ambar and Howe, 1979), locally reaching the 300 cm/s (Mulder et al., 2003). Thereafter, the MOW spreads westward into the Gulf of Cádiz, veering north-westward due to the Coriolis force, and progressively descends the continental slope driven by its excess density, eventually losing contact with the seafloor at 1000 m depth in the easternmost area and at 1400 m depth in the westernmost area, where it becomes neutrally buoyant (Baringer and Price, 1999). As a direct result of this very high flux through the Straits of Gibraltar, the MOW has a considerable influence on the salinity and temperature properties of the North Atlantic Ocean beneath the North Atlantic Central Water (NACW) (Mauritzen et al., 2001; Slater, 2003).

The MOW is characterised by a temperature around 13 °C, a high salinity of around 36.5 salinity units, and an oxygen content of 4‰ (Madelain, 1970; Ambar and Howe, 1979). The MOW represents around 1.78 Sv at the Straits of Gibraltar (Bryden et al., 1994), and is composed mainly (90%) of Levantine Intermediate Water and to a much lesser extent of Western Mediterranean Deep Water (Bryden and Stommel, 1984). The MOW is strongly affected by bottom topography, and its deceleration as it descends the continental slope is limited by four factors (Johnson et al., 1994): (1) turbulent stresses arising from bottom friction and entrainment, which produce large dissipation throughout the entire plume; (2) a decreasing density anomaly, which reduces the pressure force of the outflow; (3) the effect of the Coriolis force in deflecting the current to the right (looking in a downstream direction) and therefore along the slope, rather than directly west; and (4) the frictional effect of the channel floor (Fig. 3A). So the velocity of the MOW, in turn, is locally conditioned by the bathymetry and is a key factor in the development of different elements of the CDS. The MOW velocity data shown in Fig. 4 have been collated from several sources (Madelain, 1970; Kenyon and Belderson, 1973; Melières, 1974; Zenk, 1975; Baringer and Price, 1997; Nelson et al., 1999; Cherubin et al., 2000). Horizontal variations of the outflow properties at the exit of the Gibraltar gateway seem to promote a vertical splitting of the northern and southern part of the MOW. Irregularities in the bottom topography of the Gulf of Cádiz further control the paths of its different branches by a frictionally induced mechanism (Madelain, 1970; Shapiro and Meschanov, 1996; Borenäs et al., 2002), and contribute to the generation of "*meddies*" (Richardson et al., 2000). As it moves westward, MOW progressively registers a drop in temperature, salinity and velocity and, as it veers north-westwards under the influence of Coriolis force, it divides into two main cores (Fig. 3A)—the Mediterranean upper and lower waters (Madelain, 1970; Zenk, 1975; Ambar and Howe, 1979; Gardner and Kidd, 1983; Ochoa and Bray, 1991; Johnson and Stevens, 2000; Borenäs et al., 2002; García, 2002; Hernández-Molina et al., 2003).

(a) *Mediterranean upper water* (MU) represents the upper less-dense core moving as a warm flux between depths of 500–750/800 m at the base of the upper slope until Cape Sant Vincent, with an average velocity of 46 cm/s, a mean temperature of 3.7 °C, and 37.07 salinity units (Ambar and Howe, 1979; Ambar et al., 1999). Ambar and


(A)
10° W
9° W
8° W
7° W
6° W
37° N
36° N
PORTUGAL
Huelva
IBERIAN PENINSULA
Cape St. Vicent
Faro
MU
SPAIN
PC
ACM
IB
DC
Cadiz
GB
Straits of Gibraltar
PB
SB
MU
MOW
4000
ATLANTIC OCEAN
3000
2000
ML
GS
Tangier
500
100
1000
MOROCCO
Gulf of Cadiz
(B)
20°W
15°W
10°W
5°W
0°W
50°N
45°N
40°N
35°N
30°N
RC
Porcupine Bank
Ireland
Great Britain
North Sea
Celtic Sea
PAP
Armorican Shelf
France
BAP
BB
Atlantic Ocean
GaB
Portugal
Spain
TAP
EP
St.V
GoB
HAP
Mediterranean Sea
SAP
MI
Morocco
AB
MAP
Canary Islands
Upper core of MOW(MU)
Lower core of MOW (ML)
Reservoir of MOW
Preferred Meddy pathways
Conjectured pathways
NASW: North Atlantic Surficial Water
NADW: North Atlantic Deep Water
AI: Atlantic Inflow Water
MOW: Mediterranean Outflow Water
MU: Mediterranean Upper Water
ML: Mediterranean Lower Water
SB: Southern Branch
PB: Principal Branch
IB: Intermediate Branch

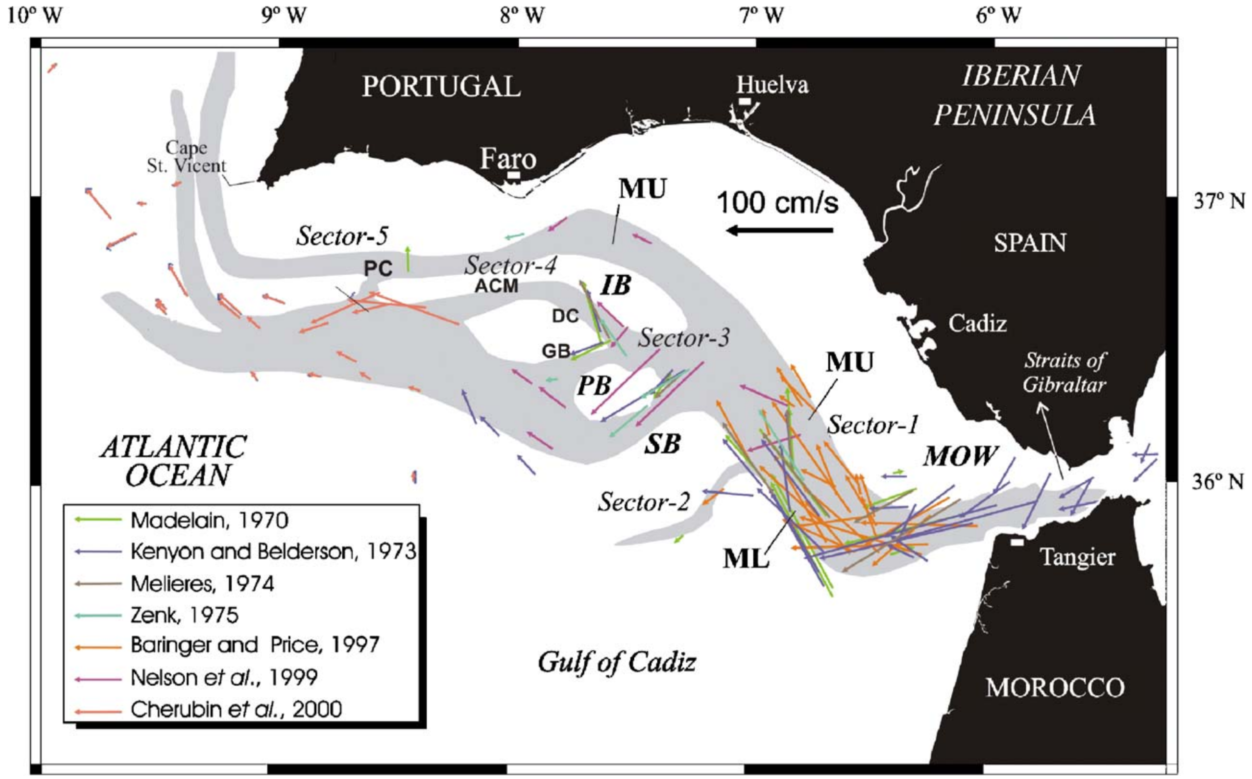


Fig. 4. *Distribution of* MOW *based on velocity data* (represented by different length segment) where the five morphosedimentary sectors of the Contourite Depositional System on the middle slope have been considered (modified from García, 2002) regarding to the data reported by several author: Madelain, 1970; Kenyon and Belderson, 1973; Mèliéres, 1974; Zenk, 1975; Baringer and Price, 1997; Nelson et al., 1999; Cherubin et al., 2000). *Legend:* ACM = Alvarez Cabral Moat; DC = Diego Cao Channel; GB = Guadalquivir Bank; MOW = Mediterranean Outflow Water; MU = upper core of the MOW; ML = Lower core of the MOW; SB = Southern branch of the ML; PB = principal branch of the ML; and IB = Intermediate branch; PC = Portimao Submarine Canyon.

Howe (1979) suggested that this core may result from a subdivision of the MOW due to the influence of the bathymetry. On the south Portuguese margin the influence of submarine canyons on the MU has been demonstrated, especially the *Portimao Submarine Canyon*, which contributes to the formation of "*meddies*" (Prater and Stanford, 1994). Jiménez (2002) also identified the influence of MOW inside the canyons, noting a warmer and denser water mass associated with greater turbidity, in the area between *Alvarez Cabral Moat* and Portimao Canyon.

(b) *Mediterranean lower water* (ML) constitutes the lower, more-saline core, and is the MOW's principal nucleus, flowing at a depth of 750/800–1200 m, with a mean velocity of 20–30 cm/s, temperature of 13.6 °C, and 37.42 salinity units (Zenk and Armi, 1990; Baringer, 1993; Bower et al., 1997). The ML is the main water flux across the study area and is affected by the slope morphology. It divides into three minor

Fig. 3. (A) Study area bathymetric map showing the general circulation patterns of MOW (Bathymetry from Heezen and Johnson, 1969) (modified from Hernández-Molina et al., 2003). (B) General circulation pattern of the MOW pathway in the North Atlantic (Modified from Iorga and Lozier, 1999a). *Legend of the physiographic reference points in A and B, in alphabetical order*: AB = Agadir Basin; ACM = Alvarez Cabral Moat; BAP = Biscay Abyssal Plain; BB = Bay of Biscay; EP = Extremadura Promontory; DC = Diego Cao Channel; GB = Guadalquivir Bank; GaB = Galicia Bank; GoB = Gorringe Bank; GS = Gibraltar Seamounts; HAP = Horseshoe Abyssal Plain; MAP = Madeira Abyssal Plain; MI = Madeira Island; PAP = Porcupine Abyssal Plain; PC = Portimao Submarine Canyon; RC = Rockall Channel; SAP = Seine Abyssal Plain; StV = Cape Sant Vicent; TAP = Tagus Abyssal Plain.

branches between the Cádiz and Huelva meridians (6°20′–7°) (Fig. 3A), which each follow separate deep channels (Madelain, 1970; Kenyon and Belderson, 1973; Melières, 1974; Nelson et al., 1993, 1999; García, 2002): (1) the *intermediate branch* (IB), which moves northwestward through the Diego Cao channel; (2) the *principal branch* (PB), which is believed to transport, at present, the MOW's major flow (Madelain, 1970), which circulates south of the Guadalquivir Bank through Guadalquivir channel; and (3) the *southern branch* (SB), which follows a steep valley towards the southwest.

At Cape San Vincent, the different strands of ML subdivide into two main cores that are clearly identified by temperature and salinity maxima (and extensively reported in the literature), with their density levels about $\delta_\theta = 27.5-6$ and 27.8, and their equilibrium depths around 700–800 and 1200–1300 m, respectively (Figs. 3A and B). These two cores are the westward continuation of the IB and PB identified in the central sector of the Gulf of Cádiz (Zenk, 1970, 1975; Ambar and Howe, 1979; Baringer and Price, 1997; Bower et al., 1997; Ochoa and Bray, 1991; Daniault et al., 1994; Iorga and Lozier, 1999a, b; Borenäs et al., 2002). A shallower core at around 400–600 m depth has also been observed with density levels between 27.25 and 27.45 (Zenk, 1975; Ambar, 1983), which corresponds to a continuation of the MU.

Beneath the MOW, the NADW shows only very slow movement (Zenk, 1975). It is a cold (3–8°) and saline (34.95–35.2 salinity units) water mass that flows southward from the Greenland–Norwegian Sea region at depths in excess of 1500 m (Caralp, 1988, 1992). In the Gulf of Cádiz, the NADW is joined by part of the deep, more-saline but warmer outflow from the Mediterranean (Fig. 3A). This mixture flows southwards down the western part of the Atlantic Ocean (Knauss, 1978).

4.2. MOW influence in the North Atlantic: global implications

Within the North Atlantic Ocean three MOW pathways can therefore be identified (Fig. 3B): to the north along the Iberian continental slope; to the west from Cape St. Vincent; and to the south–west as far as the Canary Islands and then westwards (Slater, 2003). MOW cyclonic recirculation in the western Gulf of Cádiz acts to spread the salinity signal south of 34°N (Fig. 3B). The rest of the MOW turns northwards after Cape St. Vincent and enters the *Tagus Basin* trough gateway (Zenk and Armi, 1990). Within this basin the flow diverges, with part of the water flowing northward along the Iberian continental slope and the other part deflected westward (Worthington, 1976; Iorga and Lozier, 1999a; Slater, 2003). The westward flow is divided by the *Gorringe Bank* into a southern and northern component, but reconvenes and flows anticyclonically to meet up with the northward flowing branch just off the Extremadura Promontory, creating a "*reservoir*" of MOW (Fig. 3B) (Iorga and Lozier, 1999a).

After the anticyclonic turn this branch rejoins the northward-flowing, outer-shelf branch of the MOW west–northwest of the Extremadura Promontory (Iorga and Lozier, 1999a). From there, the MOW penetrates northward along the Portugal continental slope (the *Portugal slope undercurrent* defined by Fiuza et al., 1998), and diverges downstream into two branches at Galicia Bank (Fig. 3B). North of Galicia Bank, the two branches converge and mainly turn eastward into the Bay of Biscay, following the northern Iberian slope. The MOW branch reaches the Porcupine Bank after it has penetrated poleward along the continental shelf and after it has been partially recirculated in the Bay of Biscay (Fig. 3B). It's saline signal is tracked as far north as 50°20′N, where an eastward moving branch of the North Atlantic Current (NAC) converges with the northwestward flowing MOW, reducing the salinity signal of the MOW (Iorga and Lozier, 1999a). Just west of the *Goban Spur* some of the MOW turns westwards and meets another branch of the NAC, while the remainder continues as a slope current into the Rockall Channel (Fig. 3B). Iorga and Lozier (1999a) speculate that south of the Porcupine Bank, a branch of Mediterranean Water is deflected westward until it converges with the NAC, while the rest of it continues its northward penetration as a boundary current into the *Rockall Channel* and poleward penetration over the sill of the *Wyville–Thomson Ridge*, reaching the Nordic Seas as previously proposed by Reid (1994) and also accepted by McCartney and Mauritzen (2001). Whereas the importance of MOW in the North Atlantic Ocean circulation and climate is now widely recognised, there is still much debate about its contribution as a trigger or control on Atlantic thermohaline circulation (Slater, 2003).

4.3. Paleoceanography

The opening of the Straits of Gibraltar is well documented to have occurred at the end of the Miocene (Berggren and Hollister, 1974; Mulder and Parry, 1977; Dillon et al., 1980; Maldonado et al., 1999), thereby marking the end of complete isolation of the Mediterranean Sea and global effects of the Messinian salinity crisis (Ryan et al., 1973; Hsü et al., 1978; Comas et al., 1999; Duggen et al., 2003). Following its opening, the Straits of Gibraltar (or Gibraltar gateway) became a most important ocean gateway allowing MOW circulation into the Atlantic Ocean (Nelson et al., 1993, 1999). But the nature of water mass exchange between the Mediterranean and the Atlantic, similar to the present-day situation, was established after the global cooling event at 2.4 Ma in the Late Pliocene (Loubere, 1987; Thunell et al., 1991). This cooling triggered a shift to more arid conditions in the Mediterranean region, resulting in the establishment of a negative water balance and, consequently, of an anti-estuarine water-mass exchange between the Mediterranean and the Atlantic. Since 2.4 Ma, the water-mass exchange has undergone significant variations in relation to climatic and sea-level changes (Huang and Stanley, 1972; Diester-Haass, 1973; Grousset et al., 1988; Vergnaud-Grazzini et al., 1989; Caralp, 1988, 1992; Nelson et al., 1993). The Gibraltar gateway has controlled the dynamics of water mass exchange over time, modulating that exchange between the Gulf of Cádiz and Alboran Sea, and also has been affected by sea-level changes. The effective cross-section at the Straits of Gibraltar was significantly reduced during lowstands and the MOW undercurrent outflow underwent major fluctuations (Nelson et al., 1993, 1999).

The MOW can be characterised as a warm and intermediate bottom (contour) current, not a typical cold thermohaline deep-water mass. The influence of the MOW, as a bottom current, in the sedimentary stacking pattern of the Gulf of Cádiz's northern margin, has been under study for the past 30 years (Madelain, 1970; Melières, 1974; Gonthier et al., 1984; Faugères et al., 1985; Nelson et al., 1993, 1999; García, 2002; Llave et al., 2001, 2004b, 2006b; Stow et al., 2002c; Habgood et al., 2003; Hernández-Molina et al., 2003; Llave, 2003; Mulder et al., 2003, 2006).

The MOW circulation and sea-level variations from the last glacial stage to the present have been inferred from studies of deep-sea benthic foraminifera and diatoms, as well as sedimentological, mineralogical and geochemical data. During the last glacial stage (20,000–18,000 y BP) there was an important vertical exchange between water masses (AI & MOW) (Caralp, 1988, 1992). The pattern of exchange through the Gibraltar gateway was similar to the present, but with a weak MOW flow to the west (Grousset et al., 1988; Caralp, 1988, 1992; Vernaud-Grazzini et al., 1989). During the deglaciation stage (15,000–13,000 y BP) the flow of MOW increased in intensity. Between 13,000–11,000 y BP (*Younger Dryas stage*) the MOW flows decreased. Further marked intensification of MOW flow toward the west took place between 11,000–10,000 y BP, but during the Lower Holocene (10,000–7000 y BP) the circulation again reduced and a quasi-permanent thermocline was established. Finally, in the Upper Holocene (since 7000 y BP), an increase in flow of MOW was observed to its present level (Abrantes, 1988; Caralp, 1988, 1992; Vernaud-Grazzini et al., 1989).

Nevertheless, recent studies have concluded that spatial and vertical fluctuations of MOW during the past have been strongly affected by global climate and oceanographic changes in the North Atlantic Ocean. A paleoceanographic model has been proposed where the MOW played a stronger role during cold intervals in deeper waters. An enhanced Mediterranean circulation during the cold intervals in comparison to warmer intervals has been proposed by Cacho et al. (2000) and Llave et al. (2004a, 2006a, b). A smaller and denser MOW that would mix more vigorously with North Atlantic waters is thought to have prevailed during cool stages (Baringer and Price, 1999). However, this view is controversial since the MOW volume was certainly lower due to a reduced cross-section of Gibraltar gateway during the glacial sea level lowstands (Gardner and Kidd, 1983; Bryden and Stommel, 1984; Zahn, 1997; Matthiesen and Haines, 1998). Such a setting may well have diminished the water exchange between the Mediterranean Sea and the Atlantic Ocean (Béthoux, 1984; Bryden and Stommel, 1984; Duplessy et al., 1988), but owing to this reduced exchange, the lowered temperatures (Paterne et al., 1986; Rohling et al., 1998) and a generally drier Mediterranean, the glacial MOW had a significantly higher salinity and density (Zahn et al., 1987; Thunell and Williams, 1989; Zahn, 1997; Schönfeld, 1997; Cacho et al., 2000). This may therefore have led to development of a more-intense and deeper-flowing

MOW (Thomson et al., 1999; Schönfeld and Zahn, 2000; Rogerson, 2002). A deep and vigorous MOW would result in a stronger interaction with the seafloor at greater depths, facilitating the transport and deposition of coarser material, and also leading to higher sand contents in contourites (Llave et al., 2004a, 2006a, b). A variable spatial influence of the MOW during each climatic (and sea-level) stage can be considered, as follows. The lower Mediterranean core was enhanced during cool (lowstand) periods, favouring the development of sandy contourites in the central area of the middle slope. During warm climatic periods and at high sea levels, river sediments and terrigenous sands were trapped on the shelf and predominantly fine suspension reached the distal and deeper areas of the margin. The density of the MOW was lower than during cool climatic conditions (Zahn et al., 1987; Schönfeld, 1997; Cacho et al., 2000), but the interaction of the MOW (upper core) with the seafloor was more intense at shallower depths. During these warm conditions, sandy contourites developed in shallower areas where the upper Mediterranean core was enhanced (Nelson et al., 1993; Llave et al., 2004a, 2006a, b). In this last situation upper slope sand tongue is developed (Nelson et al., 1993).

5. Margin morphology

The continental margin of the Gulf of Cádiz is characterised by the occurrence of well defined *continental shelf*, *continental slope* and *abyssal plain* physiographic domains (Fig. 1A and B), but lacks a marked continental rise.

5.1. Continental shelf

The continental shelf has been studied extensively by different authors (Vanney and Mougenot, 1981; Malod, 1982; Lobo, 1995, 2000; Gutiérrez-Mas et al., 1996; Roque, 1998; Nelson et al., 1999; Rodero, 1999; Fernández-Salas et al., 2003; Lobo et al., 2000–2003, 2005a,b; Maldonado et al., 2003b). It has an average sea-floor slope of 0.5° in the Portuguese zone, and less than 0.3° in the Spanish zone (Fig. 1). It exhibits a variable width, wider in the central area of the Spanish zone (~30 km), narrower towards Portugal (~17 km) and the Straits of Gibraltar (< 10 km). The *shelf-break* is located at a water depths between 120 and 140 m (Fig. 1), with a maximum gradient of 2° and width of 7 km. It is generally smooth since it represents the edge of the last progradational wedge generated during the last glaciation eustatic minimum (Somoza et al., 1997; Lobo, 2000; Hernández-Molina et al., 2000; Lobo et al., 2004a).

5.2. Continental slope

The *continental slope* of the Gulf of Cádiz (Fig. 1) is the widest submarine domain of the margin with a very irregular relief, and can be divided into three main sub-domains: *upper*, *middle* and *lower slope* (Heezen and Johnson, 1969; Malod and Mougenot, 1979; Nelson et al., 1993, 1999; Baraza et al., 1999; Llave, 2003; Maldonado et al., 2003b).

The *upper slope* is located between 130 and 400 m water depth, is 10 km wide on average (locally > 20 km), and has a gradient between 1° and 3° (Fig. 1). Five classes of morphological elements can be recognised in the upper slope (Figs. 5 and 6): (1) *depositional elements,* characterised by slope accumulation with a divergent to aggradational reflection configuration; (2) *erosive elements,* represented by an erosive surface in the proximal zone of the upper slope from Cádiz to Barbate, a prominent erosive surface in the upper slope between the Portimao Canyon and the Guadiana River mouth, submarine canyons and gullies; (3) *neotectonic elements,* including deformation related to diapirs and fractures; (4) *gravitational elements,* including slides, slumps and slope creep; and (5) *others,* including pockmarks due to fluid migration/escape and gas seepage from the sediment (Baraza et al., 1999; Rodero et al., 1999; Lobo, 2000; Llave, 2003; Maldonado et al., 2003b). In the central area of the upper slope, submarine canyons are not present (Fig. 1A), whereas they are well developed in the western area of the Portuguese slope (Weaver et al., 2000; Habgood et al., 2003; Maldonado et al., 2003b; Mulder et al., 2006).

The *middle slope*, located between 400 and 1200 m water depth, is characterised by an extensive marginal shelf (or *"slope terrace"*) with a maximum width of 100 km and a low average gradient between 0.5° and 1° (Figs. 1A and 6). The slope terrace has been generated by the offshore configuration of the Betic-Rifean external front and the progressive emplacement of an allochthonous wedge since the middle Miocene in the eastern and central part of the margin (Medialdea et al., 2004). Farther west along the Algarve margin, the slope terrace can be attributed to Alpine tectonic inversion of Mesozoic

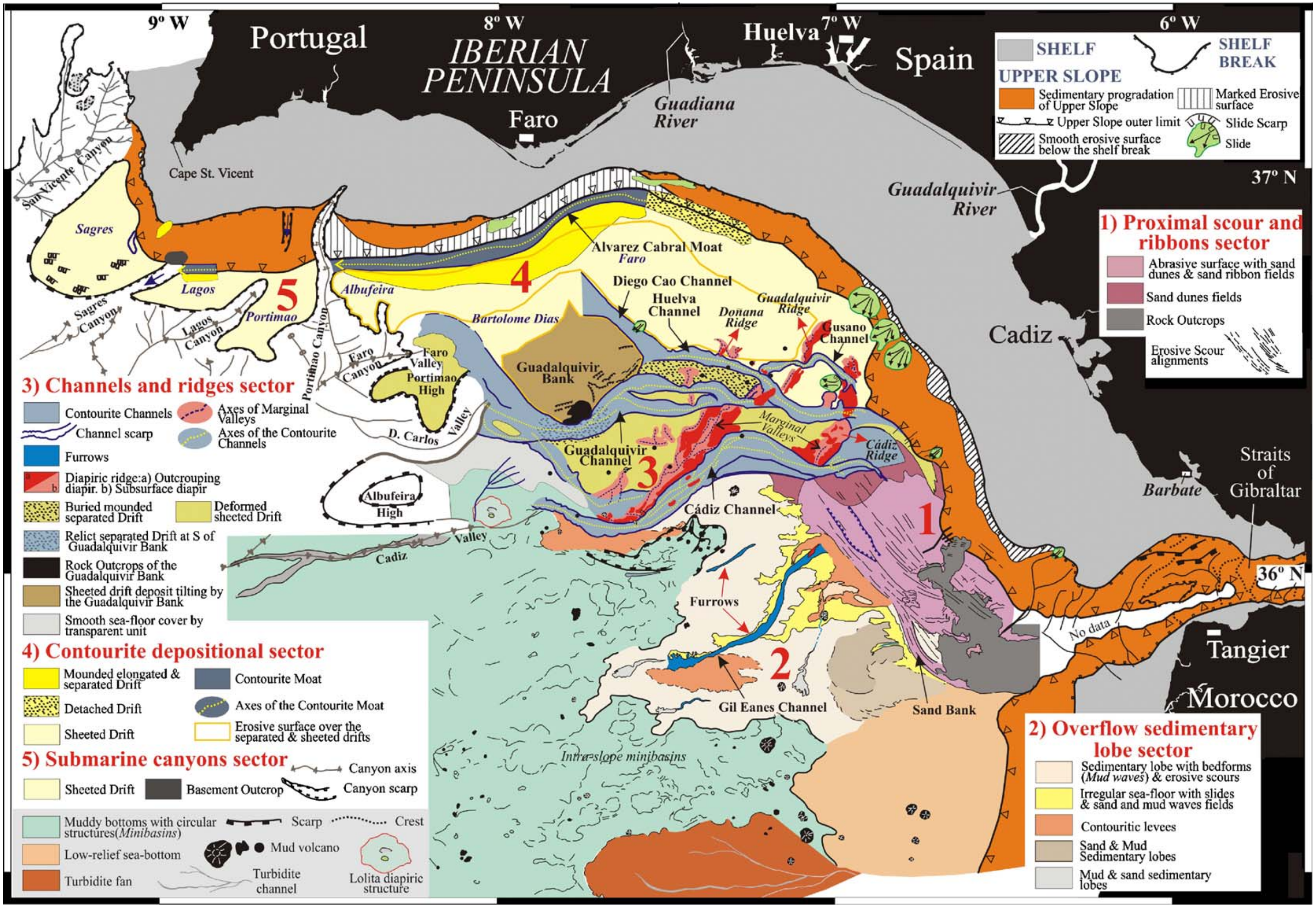


Fig. 5. Morphosedimentary map of the Contourite Depositional System on the middle slope of the Gulf of Cádiz. Morphosedimentary sectors: (1) *proximal scour and sand ribbons sector*; (2) *overflow sedimentary lobe sector*; (3) *channels and ridges sector*; (4) *contourite depositional sector*; and (5) *submarine canyon sector*. This figure is modified from Hernández-Molina et al. (2003) and includes some new sedimentary features from Llave (2003) and Medialdea et al. (2004), and incorporates the legend of the furrows from Kenyon and Belderson (1973) and Habgood et al. (2003) and the sand bank from Akhmetzhanov et al. (2002) in the Sector-2.

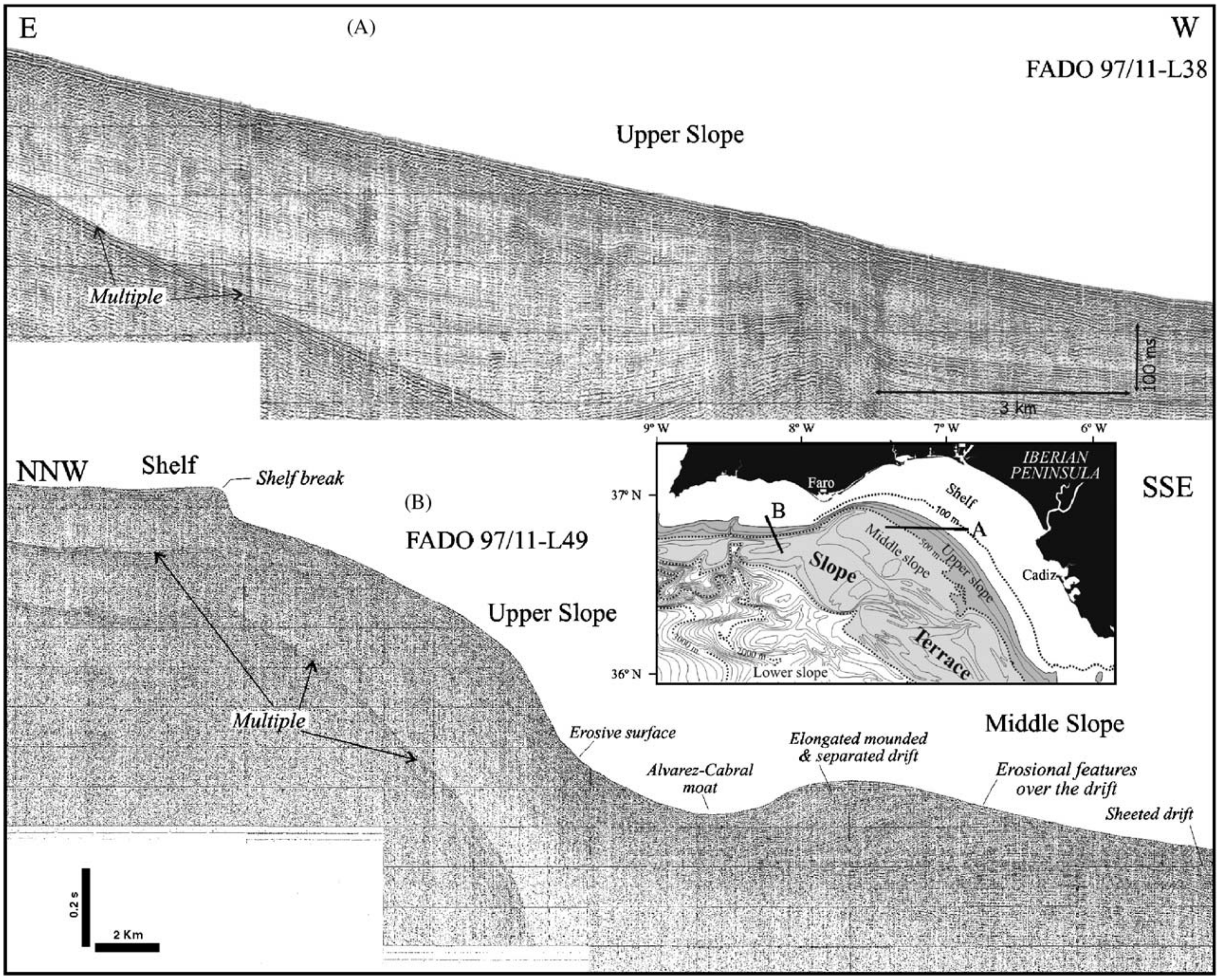


Fig. 6. Seismic profiles examples from the upper slope (Sparker) where the two different slope accumulation configuration can be noticed: (A) Guadalquivir Margin (Seismic Line FADO97/11-L38) which represents a smooth progradational upper slope without submarine canyons, with a wide shelf located offshore of the Guadalquivir basin; (B) Sudiberic Margin (seismic Line FADO97/11-L49), which represents an abrupt upper slope conditioned by the tectonic features, crossed by submarine canyons.

extensional structures (Terrinha et al., 2002). The occurrence of this slope terrace has been one key factor for the development of the CDS in the middle slope (Fig. 5) by the MOW interaction with the seafloor morphology. Morphological elements within the middle slope are described in detail in the following section.

The *lower slope* is located between 1200 and 4000 m water depth, with a slope gradient between 2° and 4°, and a width varying from 50 km in the NW to more than 200 km in the SE. On a regional scale it has a convex morphology (Fig. 1A), with a wavy to irregular physiography controlled by the underlying allochthonous unit (Madelain, 1970; Melières, 1974; Gardner and Kidd, 1983; Vázquez et al., 2004). The principal morphological elements identified in this domain are small scale depressions, including channel and ponded lows (intra-slope minibasins) and intervening irregular highs (Figs. 5 and 7). The lateral transition with the Horseshoe Abyssal Plain is abrupt in the central region at 4800 m water depth (Fig. 7B), due to the occurrence of a tectonic scarp with about 600–700 m of relief (Vázquez et al., 2004). Off the Algarve margin, the lower slope connects with the *Horseshoe Abyssal Plain* via a broad extended valley (Hernández-Molina and Lobo, 2005). Lateral transition with the *Seine Abyssal Plain* occurs

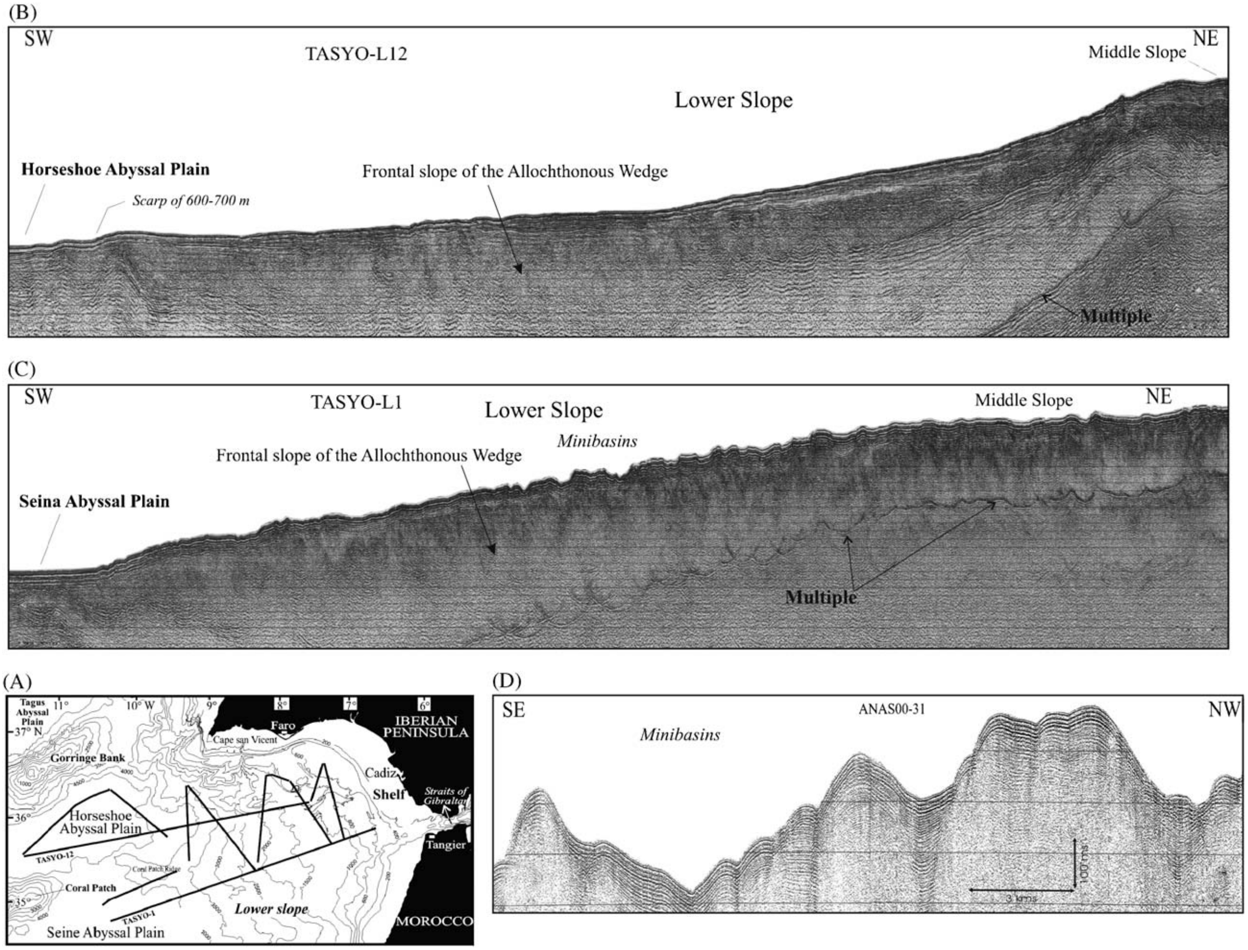


Fig. 7. Seismic profiles examples from the lower slope: (A) Sketch of the sector with the position of the multichanel seismic lines collected during the TASYO cruise (2000); (B) seismic line TASYO-1; (C) seismic line TASYO-12; (D) Detail of the minibasins identified in the proximal zone of the lower slope.

between 4300 and 4400 m water depth and is also marked by an abrupt increase in slope gradient (Fig. 7C).

5.3. Abyssal plains

Three abyssal plains are identified in the outer Gulf of Cádiz region at water depths greater than 4300 m (Figs. 1A and 7), separated by submarine banks (or seamounts), which trend broadly ENE (Melières, 1974). The Seine Abyssal Plain (SAP) and Horseshoe Abyssal Plain (HAP) are separated by the Ampere and Coral Patch seamounts, while the Horseshoe and Tagus Abyssal Plains (TAP) are separated by the Gorringe Bank and the Hirondelle Seamount (Melières, 1974; Lebreiro et al., 1997; Weaver et al., 2000).

6. The contourite depositional system on the middle slope

6.1. Morphosedimentary characteristics

The CDS comprises five morphosedimentary sectors from east to the west (Llave et al., 2001; Habgood et al., 2003; Hernández-Molina et al., 2003; Llave, 2003) as follows: (1) proximal scour and sand ribbons sector; (2) overflow sedimentary lobe sector; (3) channels and ridges sector; (4) contourite drifts sector; and (5) submarine canyons sector (Fig. 5).

6.2. Sector-1: proximal scour and sand ribbons sector

This sector is located in the SE area between Cádiz and the Straits of Gibraltar and characterised by a smooth platform oriented along-slope between 500 and 800 m water depth (Fig. 5). It was first described by Kenyon and Belderson (1973) and recently by Habgood (2002) and Habgood et al. (2003). It is an extensive area (90 km long and 30 km wide), dominated by an abrasive surface with high backscatter intensity (Figs. 8 and 9B) and several erosive scour alignments with a NW–SE orientation (Fig. 8), and with smooth "V" shape expression and truncated reflectors in seismic profiles (Fig. 9C). In the NW part of this sector there are some depositional features, including a sequence of longitudinal bedforms (also oriented NW–SE), ripple marks, sand ribbons, and sediment waves (Figs. 5 and 9D). A sand bank has been identified by Akhmetzhanov et al. (2002) and Akhmetzhanov (2003) at the SE boundary between the Sectors-1 and -2.

6.3. Sector-2: overflow-sedimentary lobe sector

This sector is adjacent to and seaward of Sector-1, at a water depth between 800 and 1600 m. It appears to be a fan-like body, 65 km long and 60 km wide (Fig. 5), with large sand and mud sedimentary lobes, and sand and mud wave-fields. In seismic profiles, these features show asymmetric morphologies, smooth topographies and medium-low reflectivity (Fig. 10).

Erosive features are also evident, including several furrows (or small discontinuous channels) with a NE–SW orientation, a U-shape cross-section,

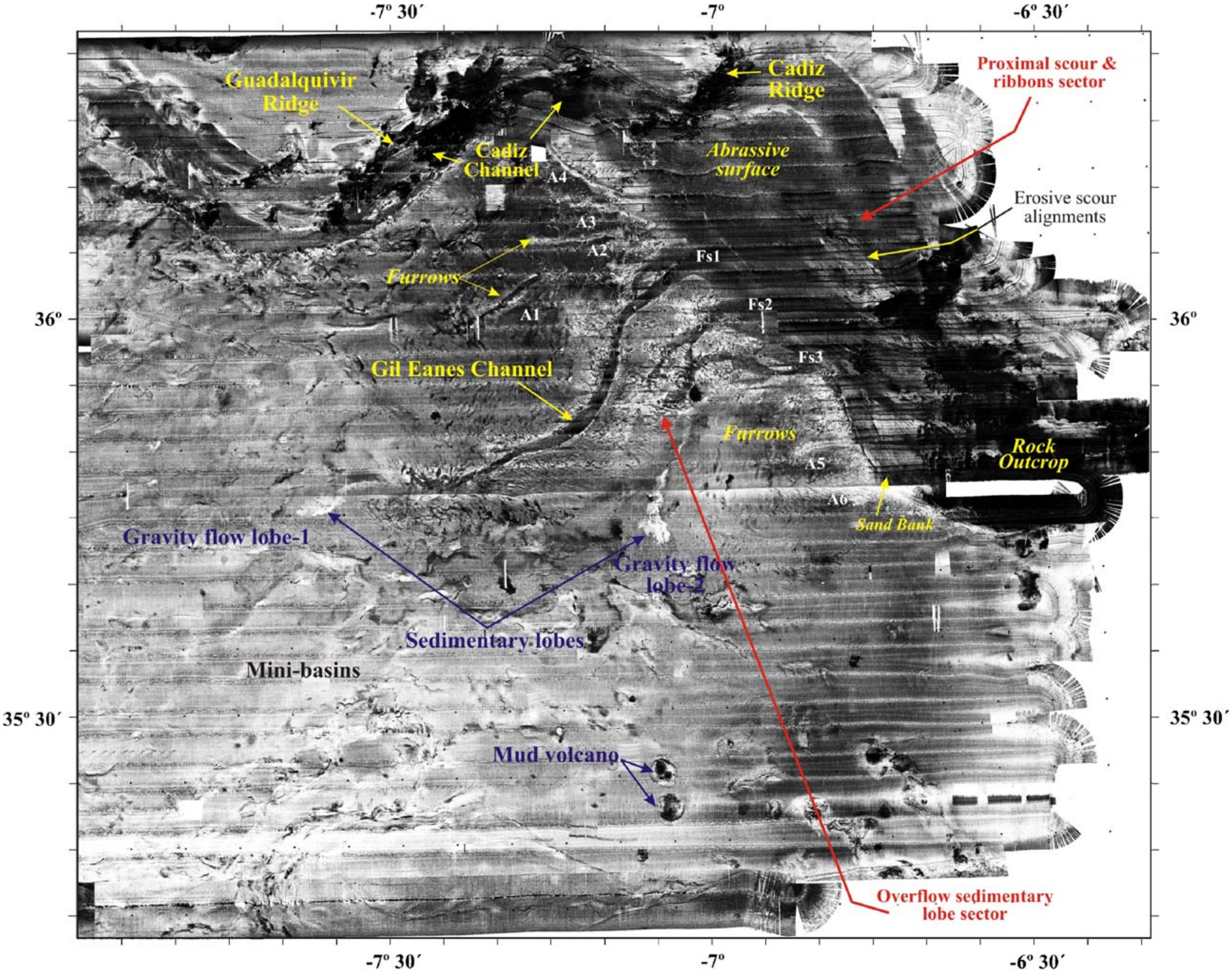


Fig. 8. Original Seamap Side-scan data including: (1) *Proximal scour and sand ribbons sector* (Sector-1); and (2) *Overflow sedimentary lobe sector* (Sector-2). See Fig. 5 for the detailed interpretation of both sectors. *Legend of the furrows from* Kenyon and Belderson (1973) and Habgood et al. (2003) (Data courtesy of Joan Gardner from Naval Research Laboratory, USA).

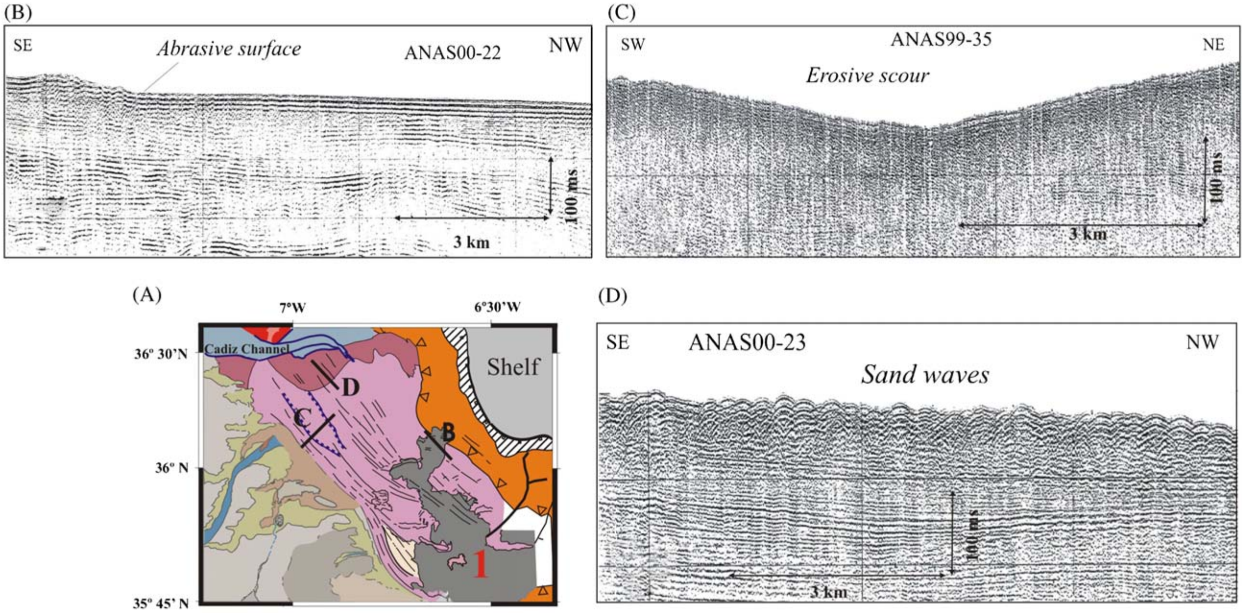


Fig. 9. Seismic profiles examples from *proximal scour and sand ribbons sector* (Sector-1): (A) sketch of the sector with the position of the seismic lines (*Legend on* Fig. 5); (B) abrasive surface with high backscatter intensity (see Fig. 8 for further detail); (C) several erosive scour alignments with a NE–SW orientation, and with smooth "V" shape expression and truncated reflectors in the seismic profiles; and (D) longitudinal bed-forms (from the SE to the NW), caused by the MOW.

and medium to high backscatter intensity (Figs. 5 and 8). The largest furrow, located between 900 and 1200 m, is around 50 km long and 0.8–1.7 km wide (Figs. 10C and D) (García, 2002). It was first described by Kenyon and Belderson (1973) as Channel-1, later denoted as *Gil Eanes Channel* by Kenyon et al. (2000), and as a furrow Fs_1 by Habgood et al. (2003). The occurrence of furrows in this sector has been described in detail recently by García (2002), Habgood (2002), Habgood et al. (2003), and new insights into the overall complex sedimentary regimen of this sector have recently been published by Akhmetzhanov et al. (2002) and Akhmetzhanov (2003). Following the recent nomenclature of Habgood et al. (2003) three furrows, Fs_1, Fs_2 and Fs_3, are connected with the slope terrace of Sector-1 (Figs. 5 and 8), whereas other furrows identified in the sidescan sonar image A1–A4 of Habgood et al. (2003) are not connected to that sector (Figs. 5, 8 and 10E). These latter furrows have been defined by Habgood et al. (2003) as "free-standing" bottom current channels. Seaward from the main furrows several sedimentary lobes have been identified (Figs. 5 and 8), and along their margins small gravitational collapse features are noted (Fig. 10). Moreover there are numerous morphologies related to gas migration as mud volcanoes (Fig. 5) (Somoza et al., 2002, 2003; Díaz del Río et al., 2003).

6.4. Sector-3: channels and ridges sector

6.4.1. General characteristics

This sector is located in the central area of the middle slope between Cádiz and Faro, in water depth of 800–1600 m (Fig. 5). It was first studied by Nelson et al. (1993, 1999) and Baraza et al. (1999), who generally described it as the "*Ridge and Valley Province*"; but it has been described in more detail recently by several authors (García, 2002; Mulder et al., 2002, 2003; Habgood et al., 2003; Hernández-Molina et al., 2003; Llave, 2003).

Within this sector the principal morphological elements are due to the strong erosive action of bottom currents and to neotectonic activity. Up to nine contourite channels have been identified in this sector by García (2002), with five larger ones known as the *Cádiz*, *Guadalquivir*, *Huelva*, *Diego Cao*, and *Gusano* channels (Figs. 5 and 11). These channels are asymmetrical in cross section, with lengths ranging from 10 to over 100 km, widths 1.5–10 km, and depths of 10–350 m where the incisions are generally greater on the N flanks (Figs. 11 and 12). The channel floors are characterised by very high

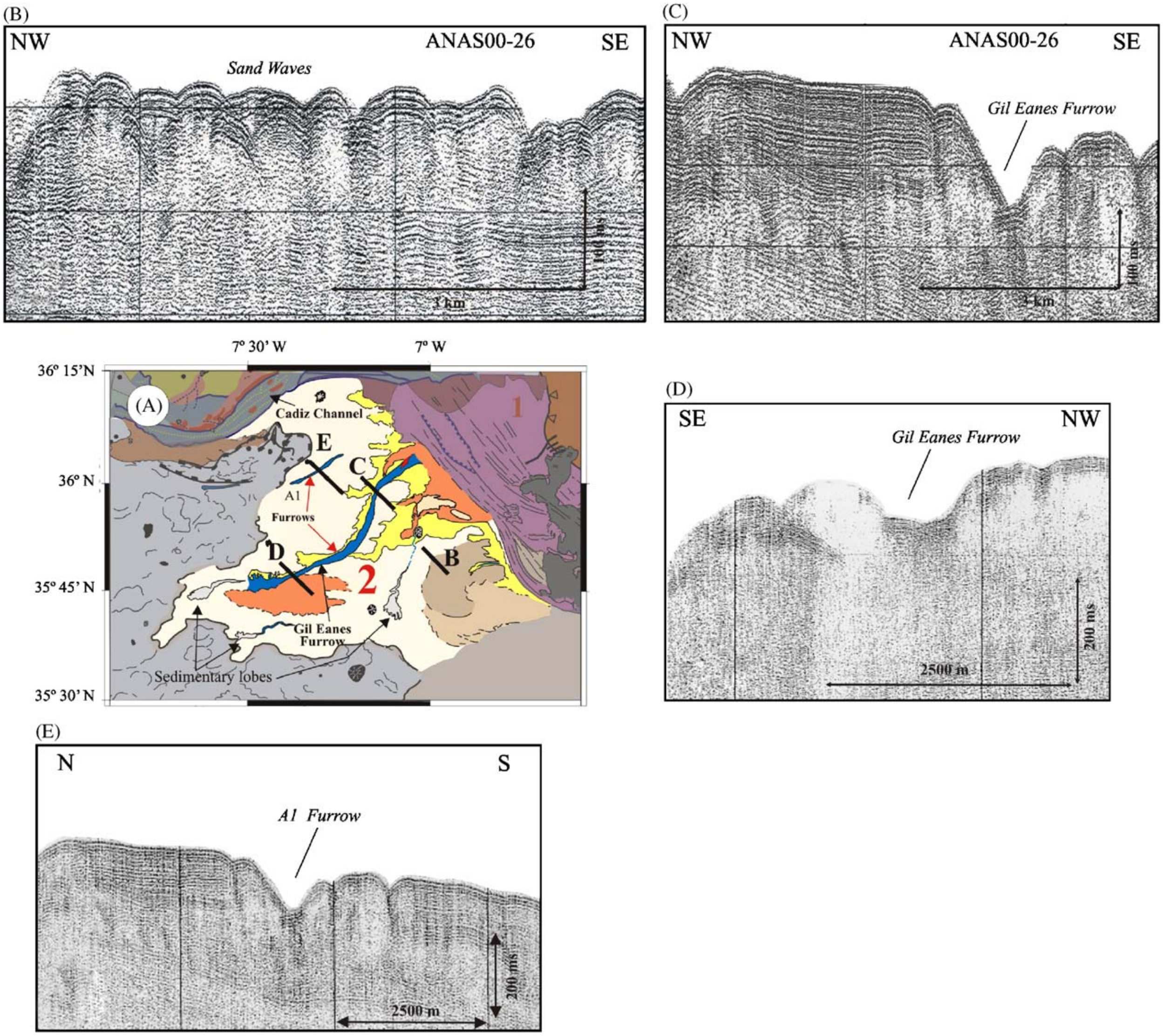


Fig. 10. Seismic profiles examples from the *overflow sedimentary lobe sector* (Sector-2): (A) sketch of the sector with the position of the seismic lines (*Legend on* Fig. 5); (B) bed-forms (sand & mud waves field) with asymmetric morphologies and sedimentary lobes are frequent in this sector; (C) proximal cross- section of the *Gil Eanes* erosive furrow with a NE trend and middle to high backscatter intensity connected with the slope terrace of the Sector-1 (*see* Fig. 8 *for further detail*); (D) distal cross- section of the *Gil Eanes* erosive furrow; and (E) cross-section of the A1 furrow, which is not connected with the slope terrace of the Sector-1. *Legend of the furrows from* Kenyon and Belderson (1973) and Habgood et al. (2003).

backscatter, representing scoured diapirs, outcrops of rock, and rubble partially covered by longitudinal bedforms and regularly spaced dunes (Figs. 8 and 12). Nelson et al. (1993) identified gravels and shelf lags in eastern channels and sand in western channels. Contourite channels are broadly "S" shaped in plan view, with NW–SE oriented along-slope segments veering to NE–SW oriented downslope segments, due to the interaction of bottom currents with the irregular morphology of the slope and diapiric ridges (Fig. 11). Several marginal valleys with irregular morphology and a NE–SW orientation are noted behind the adjacent diapiric ridge flank (Fig. 5), whereas other marginal valleys identified by García (2002) have much more irregular trends. Their morphological parameters are variable, with lengths of 3.3–28.4 km, widths of 0.5–5.2 km, and depths up to 260 m. Erosive

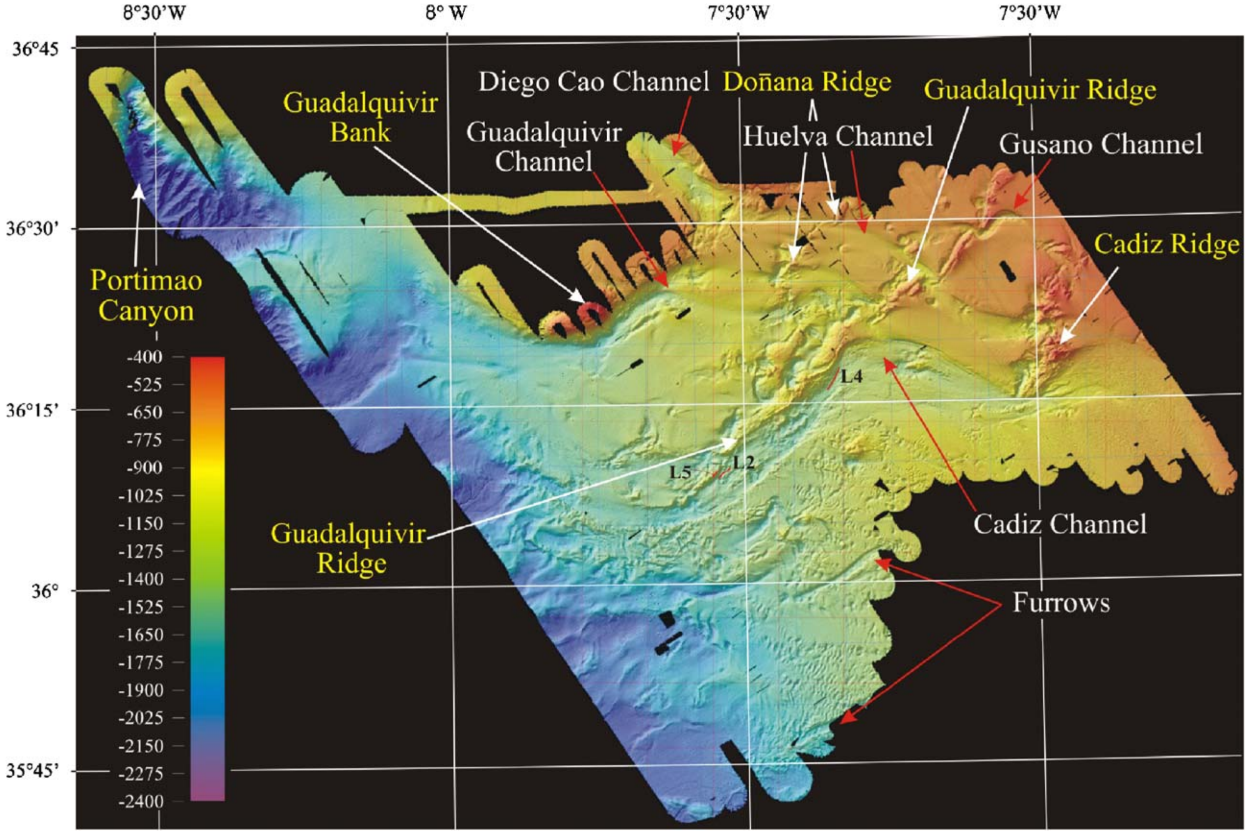


Fig. 11. Swath bathymetry of the central sector of the middle slope of the Gulf of Cádiz Contourite System, showing the main contourite channels and furrows and the main diapiric ridges, with a NNE trend. The photographic tracklines are showed in red along the Cádiz Channel.

contourite channels and marginal valleys are present over a broad *deformed sheeted drift*. This drift represents the main depositional morphology in this sector (Figs. 5 and 12). In addition, these recent erosive channels were established over a buried *contourite depositional sector* (Fig. 5), composed of fossil mounded, elongate separated, and sheeted drifts (Llave et al., 2003a, b, 2006c).

Contourite channels run adjacent to and eroded into a marked structural relief of *diapiric ridges* and the *Guadalquivir bank* uplift (GB) (Fig. 5). Some of the diapiric ridges occur as distinctly linear and segmented seafloor relief with a general NE–SW trend (Fig. 11), whereas others are buried and show an undulating deformational pattern of topographic highs and lows (Fig. 12). The following major structures can be observed, from NW to SE (Figs. 5 and 11): the GB, the *Doñana diapiric ridge* (DDR), the *Guadalquivir diapiric ridge* (GDR), and the *Cádiz diapiric ridge* (CDR). These last two are particularly prominent elongate ridges outcropping in 300–1100 m water depth (Figs. 5 and 11). Seismic profiles along the contourite channels indicate that they are maintained by mainly erosive processes, as shown by the erosional truncation of reflectors at the internal walls of the channels, both in the contourite deposits and in the ridges (Fig. 12). Gravitational processes also have been locally important, as suggested by the presence of small-scale slides on the flanks of the diapiric structures and on the margins of the contourite channels (Fig. 12). In addition, morphologies related to gas migration are frequent in this sector, including mud volcanoes, pockmarks, and gas seeps (Fig. 5) (Baraza et al., 1999; Gardner, 2001; Somoza et al., 2002, 2003; Díaz del Río et al., 2003).

6.4.2. *Main contourite channels*

The *Cádiz Channel* is the largest and the most important contourite channel, corresponding with Channel-2 identified by Kenyon and Belderson (1973). It has a total length of 110 km and an

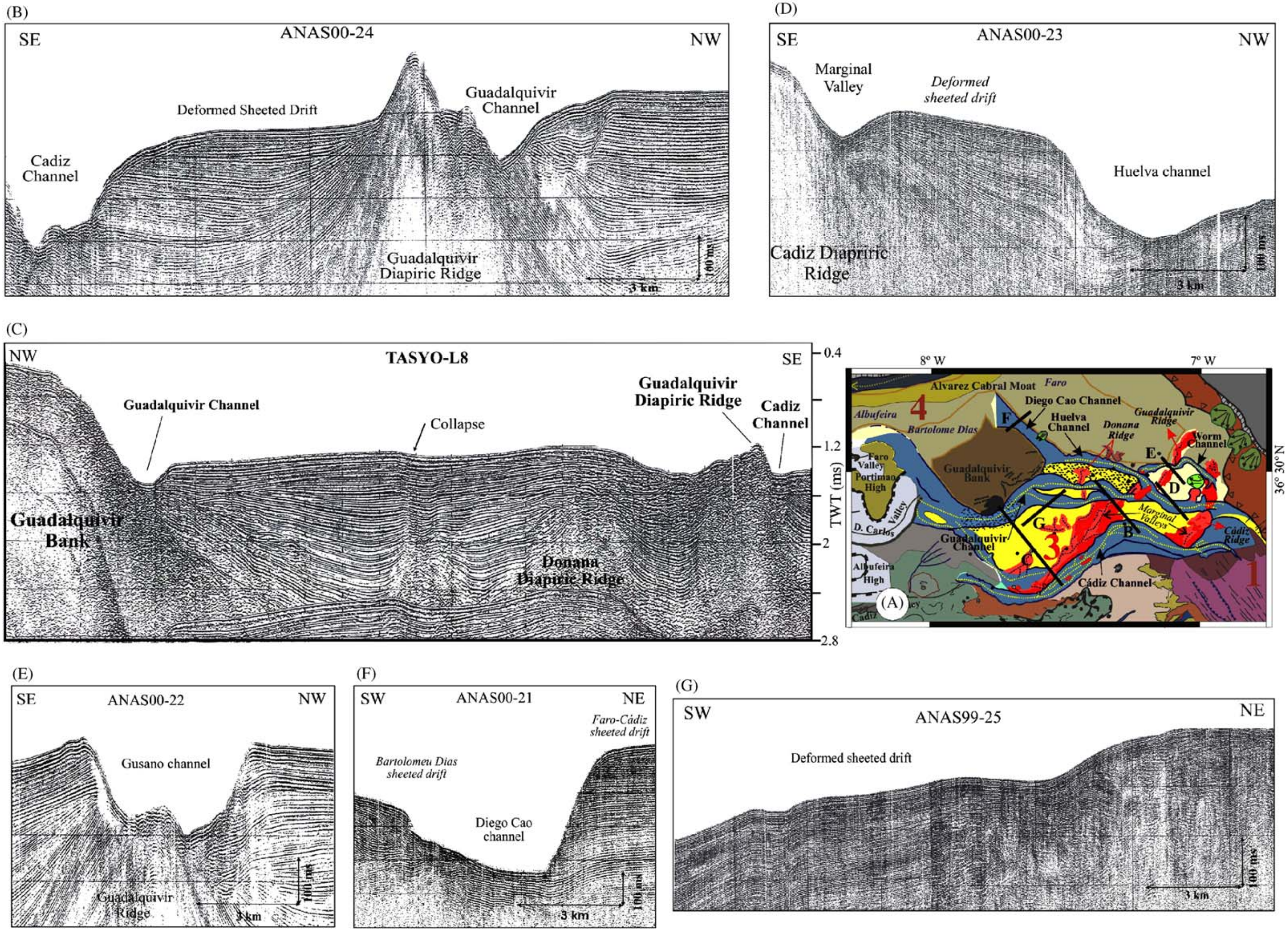


Fig. 12. Seismic profiles examples from the channels and ridges sector (Sector-3). Main contourite channels, marginal valleys and structural relief are showed: (A) sketch of the sector with the position of the seismic lines (*Legend on* Fig. 5); (B) Contourite Cádiz and Guadalquivir channels bounded by the Guadalquivir Diapiric Ridge (GDR); (C) Contourite Huelva Channel, Cádiz Diapiric Ridge (CDR) and a marginal valleys; (D) Contourite Gusano Channel; (E) Diego Cao Channel; (F) recent tectonic conditioned the occurrence of a large deformed sheeted drift in this sector. (G) Airgun deep monochannel seismic profile (TASYO L-8) and line drawing.

orientation that varies from SE–NW to NE–SW (Figs. 5 and 11). The proximal sector begins near the CDR. This channel is wider (up to 8 km wide) in the sectors that cross contourite deposits, but narrower near the CDR and GDR (~2.4 km) (Figs. 12B and C). The transverse profiles show vertical incisions up to 120 m deep. In the Cádiz Channel, two recent steep 100–200 m deep incisions have been identified by García (2002), due to recent down-cutting by the current. A secondary axis 20 km long has been identified in the contourite deposits sector between the CDR and GDR, which runs in a general direction subparallel to the principal axis and separated from it by a diapiric structure, at distances between 2 and 3.5 km (Fig. 5). The peculiarity of this morphology is that the principal axis is eroding the flat channel floor at greater depths than the secondary axis. Depth differences up to 130 m can be measured in the bathymetric charts between the principal and secondary axes.

The *Guadalquivir Channel* is the second largest contourite channel in this sector (Figs. 5 and 11), being more than 90 km long. It corresponds with the Channel-3 identified previously by Kenyon and Belderson (1973). The channel width mainly varies from 1 to 7 km, becoming wider (12 km) at its distal end. From the beginning to the end of its course, the Guadalquivir channel crosses the GDR in the proximal sector (Fig. 12B), the middle-slope contourite deposits, and the southern side of the GB (Fig. 12C). The sectors of the channel close to the GDR and GB have a general NE–SW orientation, and show highly asymmetric transverse profiles, that have the greatest channel depths of up to 130 m. The channel across the contourite deposits shows a NW trend, with the greatest widths (up to 12 km) but the lowest relief. In the contourite deposits between the ridge and the GB, there is a secondary channel 26 km long, which develops 3–5 km to the south of the principal channel (Fig. 5).

The *Huelva Channel* originates near the CDR and trends W–NW for 58 km up to the region of GB, where it appears to be connected with the beginning of the Diego Cao Contourite Channel (Figs. 5 and 11). Along its course it crosses contourite deposits and some diapiric structures (Fig. 12D) and, at its northern limit, small mud volcanoes can be found. The channel width varies between 8 and 15 km, and the transverse profiles show low relief, except in those sectors crossing diapirs, where vertical incisions up to 290 m deep can be found.

The *Diego Cao Channel* is an erosive channel that has been cut recently into the sheeted drift system (Llave et al., 2001; Llave, 2003) and now separates the Faro-Cádiz from the Bartolomeu Dias sheeted drift (Figs. 5 and 11). It appears to have been developed along the crest of a series of salt diapirs (Díaz del Río et al., 2000; García, 2002). The Diego Cao Channel corresponds with the Channel-4 identified by Kenyon and Belderson (1973) and it was defined previously as a moat by Faugères et al. (1985). Nevertheless, after the publication of Faugères et al. (1999) the term *moat* is specific for contourite channels (or valleys) parallel to the continental slope and associated with *mounded elongated and separated drifts*. Because of this, the Diego Cao moat has been redefined as another contouritic channel (García, 2002; Llave et al., 2001; Llave, 2003; Hernández-Molina et al., 2003). It is oriented in a NW–SE direction, a maximum depth around 800 m, and has steep erosive walls in the SE that gradually diminish to the NW (Fig. 12F). It is 45 km long, 4 km wide in the SE, and broadens to 12 km wide before it dies out in the NW (Fig. 5).

6.4.3. *Main structural ridges*

The CDR trends NNE at a water depth of 400–800 m. Its length is approximately 43 km, its width is variable (maximum of ~14 km), and it has an asymmetric form with greatest deformation on the eastern flank. The present-day seafloor is both deformed and pierced by the diapiric ridge (Figs. 5, 11 and 12D), but there remain several gaps that allow passage for different branches of the MOW.

The GDR trends NE–SW at a water depth of 300–1100 m (Figs. 5 and 12B, C and E). This is the most extensive of the ridge systems, presenting numerous irregular highs, lows and gaps where the MOW can pass through. Its location and relief control the location of the *Guadalquivir Channel* to the south (Fig. 11).

Both CDR and GDR exhibit evidence of several episodes of activity from the Middle Miocene to the present, with frequent mud volcanoes and gas structures (Maldonado et al., 1999; Maestro et al., 2003; Somoza et al., 2003; Fernández-Puga, 2004).

The DDR is located further to the north (Fernández-Puga, 2004) at a water depth between 500 and 1100 m (Fig. 5). This ridge outcrops in restricted areas and mud volcano structures associated with it have developed. In some places, this diapiric mass can be seen to deform the overlying sedimentary succession, but does not reach nor deforms the seafloor (Fig. 12C). The diapiric mound nearest to the GB shows recent uplift followed by the development of a collapse structure over the crestal region, which has produced small normal faults that affect the seabed (Fig. 12C).

The GB is located in the southern part of the Bartolomeu Dias sheeted drift (Fig. 5) and represents a structural high in which Paleozoic and Mesozoic rocks of the Iberian margin have been uplifted (Fernández-Puga, 2004; Medialdea et al., 2004). It has played an important role in this area, affecting the hydrodynamic system and accommodation space for the Pliocene–Quaternary sedimentation (Fig. 12C).

6.4.4. *Sedimentary processes within the contourite channels*

Previous work has shown the erosive and scoured nature of much of the channel sector, as well as terrace formation and recent incision (García 2002; Habgood et al., 2003). Limited data exist on the nature of the seafloor and current bedforms from scattered bottom photographs taken in selected channels (Melières et al., 1970) because most of the previous submarine photographs on the Gulf of Cádiz were not collected from the channels (Heezen and Hollister, 1964; Heezen and Johnson, 1969; Melières et al., 1970). Also, many of the bedform identifications and inferred sedimentary processes within the channels were realised by deeptow side scan sonar data (Nelson et al., 1993). New data are presented here from a study of over 500 bottom photographs taken on three separate transects within the Cádiz Channel: L4, L2 and L5 (Fig. 11). These help to shed further light on the channel processes and probable bottom current velocities acting at the present day. Our inference of bottom current velocities is derived from numerous sources including Heezen and Hollister (1964), Melières et al. (1970), and Masson et al. (2004), as well as from work in progress.

The L4 transect begins from near the northern margin of the Cádiz channel (Fig. 11), close to the outcropping GDR and shortly beyond where the channel orientation veers sharply towards the SW. In this region the substrate is dominantly rock-covered, showing an irregular and often fractured surface, patchily colonissed by a range of organisms, including echinoids and rare crustaceans. In parts, there is a poorly sorted rubble of blocks, boulders and pebbles, mostly angular in shape and with a dark tarnished colour, and also fragments of paler bioclastic debris. There are isolated zones of sediment cover, in some cases with deep linear scours (Fig. 13A).

The L2 and L5 transects are both more distally located within the SW-oriented sector of Cádiz Channel (Fig. 11). In both cases, bottom photographs show a channel floor partly covered with a poorly sorted rubble of dark-coloured blocks, boulders and pebbles, and partly covered by a sandy substrate clearly worked into dynamic bedforms by active bottom currents (Figs. 13B and C). Biota is much less evident than in the L4 transect, and mainly comprises echinoids. Pebbles are angular and irregular in shape, showing various orientations, although elongate clasts tend to be oriented transverse to flow and, in some cases, are streaked out into linear trains. The most common bedforms are medium-scale, transverse trains of sinuous, asymmetric ripples, with wavelengths typically between 7 and 15 cm. More rarely, large dune bedforms are observed, around 50 cm in amplitude and with an unknown wavelength, as well as zones showing clear interference ripple patterns.

The rocky floor near the channel bend (L4 transect) results from continued scouring and erosion by bottom currents with relatively high flow velocities, probably between 80 and 120 cm/s. These results are consistent with the very high backscatter signal seen in the sidescan sonar image of the Guadalquivir Channel (Fig. 8). Further to the SW the main Cádiz Channel is bathed in actively flowing bottom currents with variable velocity. The dominant ripple bedforms represent lower flow regime, around 20–50 cm/s, which is active most of the time. Periodically, flow velocity increases to in excess of around 100 cm/s, creating large-scale dune bedforms and linear trains of pebbles. Flow direction is dominantly SW–SSW, oriented along the channel trend, although locally flow directions towards the S and SE are noted.

6.5. *Sector-4: active contourite drift sector*

This sector is located in the central and NW areas of the middle slope. It is characterised by the dominance of depositional features represented by two kinds of contourite deposits: *mounded, elongate drifts* and *sheeted drifts* (Fig. 5), following the nomenclature of Faugères et al. (1999). The Faro–Albufeira contourite drift has been studied by several authors (Gonthier et al., 1984; Mougenot and Vanney, 1982; Faugères et al., 1985, 1999; Stow

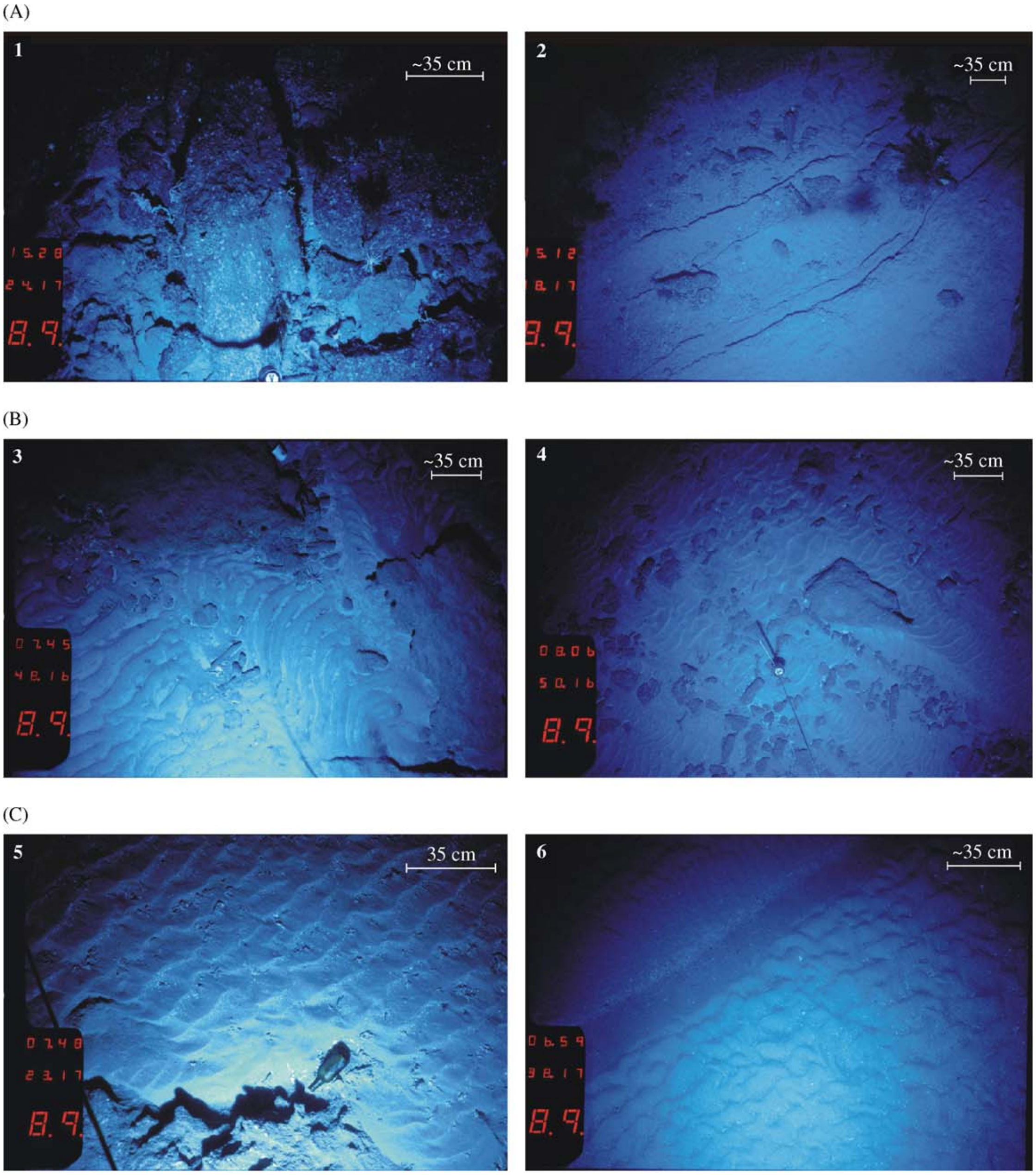


Fig. 13. Photographs obtained with the BENTHOS-372 camera during the ANASTASYA-2001/09 cruise onboard the B/O Cornide de Saavedra along the Guadalquivir Contourite Channel: (A) *L4 photographic tracklines*: Photo 1—Sea bottom is dominantly rock covered, with poorly sorted rubble of blocks, boulders and pebbles, mostly angular in shape, Photo 2—deep linear scours on the sea bottom with very rare starved ripples of coarse sediments; (B) *L2 photographic tracklines*: Photo 3—well-developed asymmetrical ripples; Photo 4—rhomboidal ripples; and (C) *L5 photographic tracklines*; Photo 5—strait to rhomboidal asymmetrical starved ripples; Photo 6—large dune bedforms with a clear interference ripple patterns. Notice how the sedimentary structures change from erosional (A) to depositional (B & C) along the channel due to decreasing in the velocity of the bottom current (see location on Fig. 11).

et al., 1986, 2002c; Llave et al., 2001). Llave et al. (2001) identified five morphological elements in this sector. From the upper slope to the middle slope, these are (Figs. 5, 6C and 14): (1) an erosive surface on the upper slope; (2) the *Alvarez Cabral Moat*, 80 km long, 4–11 km wide, and "U" shape in cross section; (3) the *Faro–Albufeira mounded, elongate (separated) drift*, 80 km long, 12 km wide, and up to

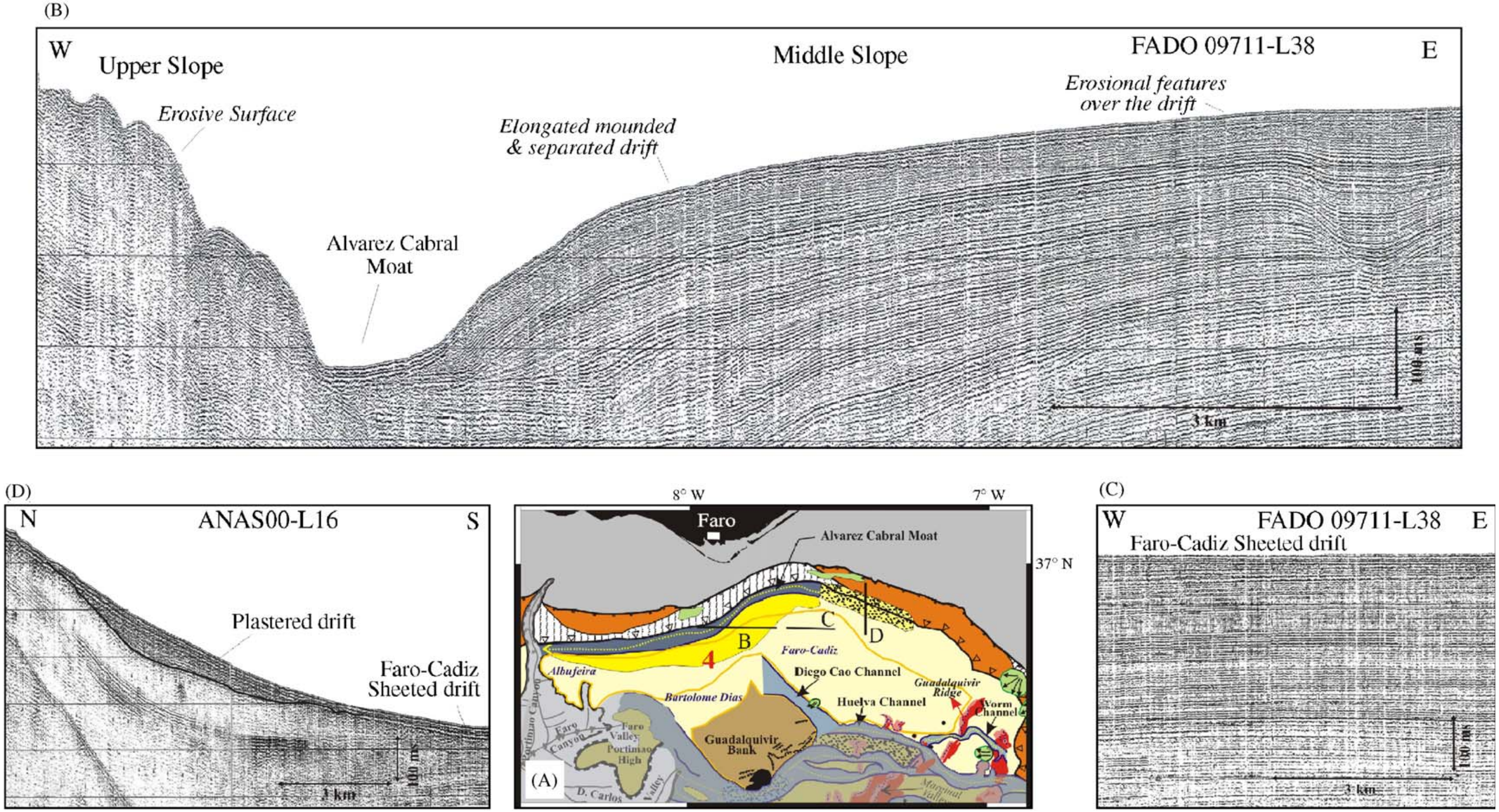


Fig. 14. Seismic profiles examples from the Contourite depositional sector (Sector-4): (A) Sketch of the sector with the position of the seismic lines (*Legend on* Fig. 5); (B) Erosive surface on the upper slope, the *Alvarez Cabral Moat*, and the F*aro-Albufeira mounded, elongated and separated drift*. (C) Faro-Cádiz *Sheeted drift*, (D) Plastered Drift.

600 m thick; (4) *sheeted drifts (Faro-Cádiz*, *Bartolomeu Dias*, and *Albufeira*), which form the extensive basinward prolongation of the mounded drift and are characterised by a planar morphology; and (5) erosive features over the drift deposits.

The Faro–Albufeira system is a partly upslope-migrating depositional sequence, which has developed parallel to the margin and separated from it by a flanking boundary channel or moat (Alvarez Cabral Moat). This moat corresponds with the Channel-5 identified by Kenyon and Belderson (1973). Towards the East, the Faro–Albufeira system merges into a plastered drift (35 km long, 12 km wide, and around 100 m thick), in the transition zone between the upper and middle slope (300–600 m water depth) (Figs. 5 and 14D). There are also some gravitational features noted on the mounded drift and Faro–Cádiz sheeted drift.

6.6. Sector-5: submarine canyons sector

This is located in the western area of the middle slope and characterised by the occurrence of erosive features like the Portimao, Lagos, Sagres and San Vicente submarine canyons orientated approximately downslope (NE–SW) (Fig. 5) with steep margins and erosive floors (Fig. 15B) (Vanney and Mougenot, 1981; Mougenot and Vanney, 1982; Barnolas et al., 2000; Vázquez et al., 2000; Mulder et al., 2006). These canyons cut through the *Portimao* (16 km long and 14 km wide) (Figs. 5 and 15C)*, Lagos* (24 km long and 12 km wide) *and Sagres* (26 km long and 30 km wide) *sheeted drifts* at 1000 m water depths (Llave et al., 2001; Llave, 2003), and the smaller *Lagos elongate mounded and separated drift* (Figs. 5 and 15D). Some gravitational features are observed on the sheeted drift near the canyons (Fig. 15).

6.7. Contourite depositional system genesis: MOW oceanographic imprint and implications

The CDS of the Gulf of Cádiz is a consequence of MOW and its interaction with the sea bottom along the middle slope, conditioned in part by Pliocene-Quaternary tectonics (Llave et al., 2001, 2006a–c). Although different parts of this CDS have been studied previously by various authors, it has never been approached as a single unique contourite system. Here we attempt a fuller consideration of the interplay of key factors controlling its nature and development as a whole.

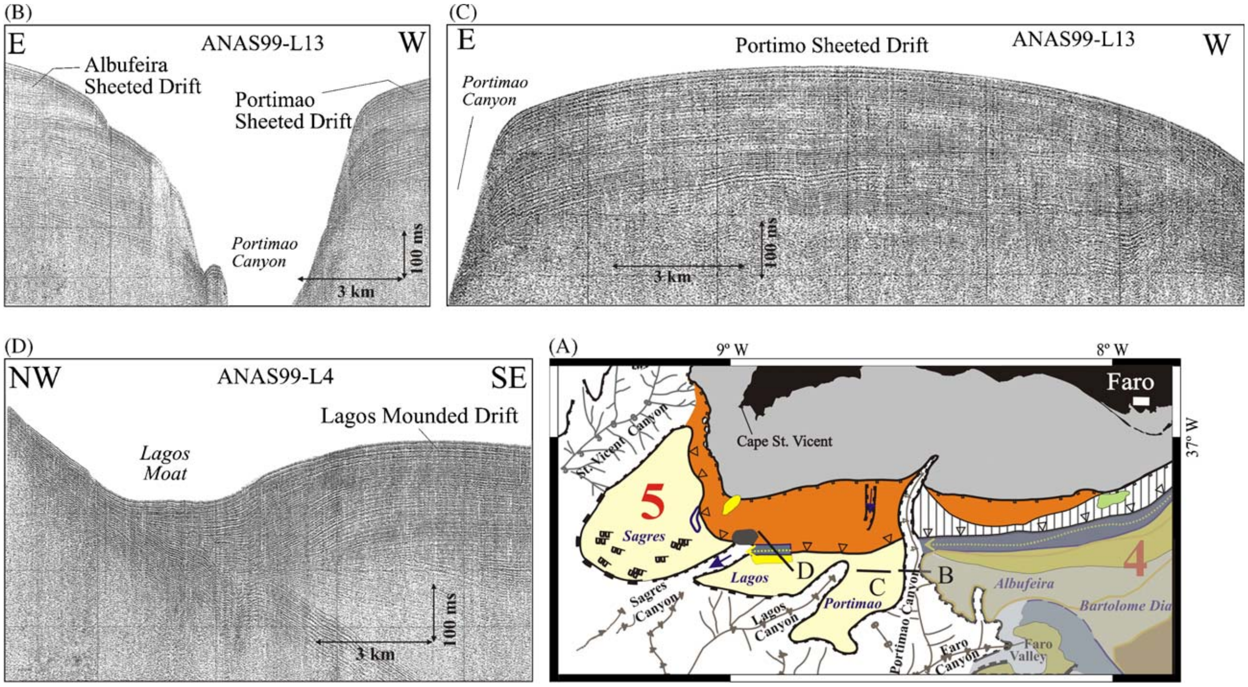


Fig. 15. Seismic profiles examples from the Submarine canyon sector Sector-5): (A) sketch of the sector with the position of the seismic lines (*Legend on* Fig. 5); (B) Portimao submarine canyon; (C) Portimao sheeted drift; and (D) Lagos elongate mounded and separated drift.

The morphosedimentary sectors defined above can be related, in the first instance, to a systematic decrease in speed of the MOW and its various branches as they move westward, influenced both by local topography and by Coriolis force. Specific sedimentary features (depositional and erosive) in every sector can be related directly to the local behaviour of different branches of MOW (IB; PB and SB), including local MOW lift-off from the seafloor by as much as several 100 m, over weekly to monthly time periods (Thorpe, 1975). The distribution of different MOW branches is controlled primarily by the distribution of bathymetric highs in Sectors 1 and 3, most of them generated by neotectonic activity.

The *proximal scour and sand ribbon sector* (Sector-1) results from the MOW's strong and turbulent flow, which contours the slope between 300 and 1000 m depth after its entrance into the Gulf of Cádiz (Kenyon and Belderson, 1973; Habgood, 2002; Habgood et al., 2003; Hernández-Molina et al., 2003). Its velocity decreases from a maximum of 240 cm/s to the W outside the Gibraltar gateway, to around 100 cm/s NW further north (Fig. 4). Beneath the high velocity zone, there are *abrasive surfaces* and *erosive scour alignments*, but as current velocity decreases, *sand ribbons* and *wave fields* are developed (Fig. 16). MOW divides into MU and ML at the NW end of this sector, as described by Madelain (1970).

The *overflow sedimentary lobe sector* (Sector-2) is a complex fan-shaped body, over which several separate small fluxes (or filaments) of MOW flow towards the W with a velocity of about 50 cm/s on average; while other small fluxes are directed more towards the SW with an average velocity of 25 cm/s. The region represents, in part, contourite deposition from these small down-slope directed small fluxes of MOW (Lower Branch, ML) and, in part, the irregular deposits of much sliding and slumping in a very unstable tectonic area (Maldonado et al., 1999). The adjacent upper slope and shelf also have been tectonically affected during the Quaternary, as reported Pérez-Fernández (1997), Rodero (1999), and Rodero et al. (1999).

We suggest two processes by which the sedimentary features are produced in the Sector-2: (1) where the ML interacts with local diapiric structures (Figs. 5 and 8), a deflection of the main flux is produced, generating smaller downslope directed small fluxes of dense water, which then carve out the NE–SW furrows, such as the Gil Eanes furrow, and carry sand and other materials downslope (Figs. 8 and 16). (2) Prior to its subdivision into MU and ML branches, the lowermost and densest part of the MOW directly overflows the sand bank between Sectors 1 and 2 (Fig. 5), veering downslope to find its geostrophic balance.

Within the c*hannels and ridges sector* (Sector-3) both the MU and ML cores flow northwestward (Fig. 3A). They show a complex interaction with seafloor topography generated by the diapiric ridges, which leads to progressive erosion of the contourite channels (Figs. 5 and 8) (Madelain, 1970; Kenyon and Belderson, 1973). As the main branch of the ML reaches the linear NE–SW trending Cádiz and Guadalquivir diapiric ridge, part of the flow is deflected by this barrier towards the SW and also increases in velocity as a result (Fig. 4 and 16) (Nelson et al., 1993, 1999). Separate branches of the ML follow and sculpt the different channels: the Southern Branch flows towards the SW in the Cádiz Channel with a velocity up to 100 cm/s; the Principal Branch follows the main Guadalquivir Channel, in which a velocity of 40–50 cm/s decreases to around 30 cm/s in the distal part; the Intermediate Branch first follows the Huelva Channel and then links up with the Diego Cao Channel showing velocities up to 40 cm/s towards the NW; and a fourth minor, unnamed branch probably follows the Gusano Channels before joining the Huelva Channel. All, the contourite channels terminate abruptly where the MOW lifts off the seafloor (Habgood et al., 2003).

Based on careful study of new multibeam data, it is possible to determine that the channel asymmetry in cross-section and their general S-shape in plan view are caused by the action of the ridges as a barrier (Figs. 5, 11 and 16), the trend of the ridges deflects the natural flow direction, and gaps in the ridge barrier allowing small fluxes to pass through to the NW. The occurrence of marginal valleys along the northern flank of parts of the diapiric ridges may be caused by a secondary circulatory flow that is developed parallel to the channel after MOW has passed through the ridge. García (2002) and Hernández-Molina et al. (2003) have further proposed that the Cádiz Channel, which currently contains the Southern Branch, may have been the major flow pathway of the ML in the recent geological past, rather than the Principal Branch today, which follows the Guadalquivir Channel.

Meanwhile, the MU flows northwestward towards the *active contourite drift sector* (Sector-4) as

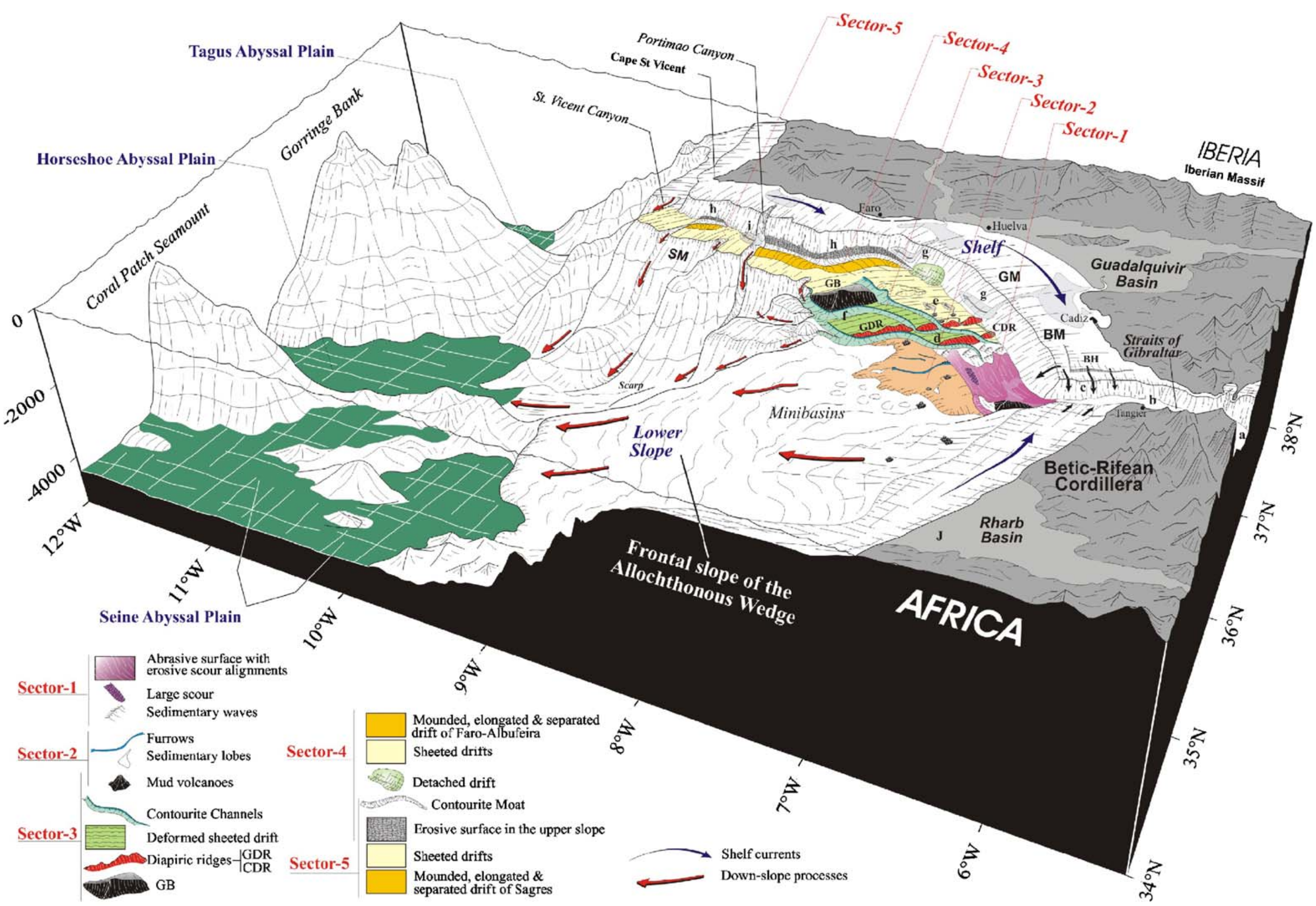


Fig. 16. Sedimentary model of the contourite depositional system (CDS) on the Gulf of Cádiz in the context of the continental margin. *Legend of the physiographic reference points, in alphabetical order*: BH = Barbate high; CDR = Cádiz Diapiric Ridge; GB = Guadalquivir Bank; GDR = Guadalquivir Diapiric Ridge. *Legend of the margins types:* SM = Sudiberic Margin; GM = Guadalquivir Margin, BM = Betic domain Margin. *Legend of the sediment source*: (A) Alboran Sea; (B) Strait of Gibraltar; (C) Spanish and Morocco shelves; (D) diapiric and channel erosion; (E) mud volcanoes; (F) Guadalquivir Bank and channel erosion; (G) suspended matter from the main rivers; (H) erosion of the upper slope; and (I) submarine canyons (see text for explanation).

a tabular water mass along the toe of the upper slope on the mid-slope terrace at a water depth of 500–800 m, generating the slope's largest sheeted drifts (Faro, Albufeira and Bartolomeu Dias) (Figs. 5 and 16). Where this flow interacts with the concave shape of the southern Iberian margin, it leads to formation of a detached drift at the transition between upper and middle slope (Fig. 16). Subsequently, it begins to erode more deeply into the slope (Llave et al., 2001), so that the MU becomes channelised within the slightly sinuous Alvarez Cabral Moat (Gonthier et al., 1984; Llave et al., 2001). As the Coriolis force deflects the flow to the right, it progressively erodes into the channel's right flank and builds up the Faro–Albufeira mounded elongate and separated drift on its left flank, where the current flow is less vigorous (Fig. 16). Average flow velocity is around 20–25 cm/s, with a general decrease from E to W and localised variations due to topographic constraints.

In the *submarine canyons sector* (Sector-5), the occurrence of Portimao, Lagos, and Sagres sheeted drifts (Figs. 5 and 16) suggests a new tabular flux of the MU. Although, in part, there must also be a localised core of MU in order to construct the Lagos elongated mounded and separated drift (Hernández-Molina et al., 2003; Llave, 2003). Localised turbulence and development of internal waves may be formed due to the submarine canyon influence on MOW circulation (Jimenez, 2002). In the southern part of Sector-5 the different branches of the lower core of MOW show velocities from around 10 up to 80–85 cm/s. In this area a filament of the MOW seems to be flowing toward the N, probably due to the influence of the Portimao Canyon.

Based on our detailed overview and results, it would seem time for a significant revision of the hydrodynamic model of the MOW within the Gulf of Cádiz in the first instance. There are two important points in this regard: (1) the start of the Huelva, Guadalquivir and Gusano Channels is quite close to the transition between the upper and middle slope. They may, therefore, have been eroded by branches developed from the MU rather than the ML. In such a model, only the Southern Branch might be generated by the ML, and this would have been more active during the glacial periods than during the interglacials (as at present), as recently proposed Llave et al. (2004a, 2006, b); (2) The origin of Ridge-marginal valleys as a result of secondary circulatory flow parallel to the channels needs investigating. Any new hydrodynamic model for the regional MOW circulation would then need to be considered in terms of its implications for North Atlantic circulation in general.

6.8. *Source and supply of sediment to the CDS*

The sedimentation rate produced in general by a bottom current is related both to the available supply of sediment and to the current velocity. Sediment is supplied to the bottom current via a range of processes including pelagic and hemipelagic settling, bottom current erosion, and pirating from low-concentration turbidity currents. Long-term rates of sedimentation in drift deposits typically average between 50 and 300 m/My, where these rates represent periods of relatively more rapid accumulation and periods of non-deposition or erosion. Longer duration hiatuses, and consequently lower overall rates of accumulation, are more common under the current core, especially where channelised (Faugères and Stow, 1993; Stow et al., 2002b).

In particular, the CDS of the Gulf of Cádiz has been constructed over the past 5 My approximately under the direct influence of the MOW (Nelson et al., 1993). Quaternary sediment thicknesses are up to 600 ms (two-way-travel-time, TWT) in the Faro–Albufeira mounded drift (Llave et al., 2001), and 400–500 ms TWT in many parts of the sheeted drifts. Absolute thicknesses, therefore, are around 300–500 m, which yields mean rates for the entire period of growth (inferred from seismic interpretations) of 60–100 m/My. This is in line with many other contourite drifts worldwide (McCave and Tucholke, 1986; Zhenzhong et al., 1998; Faugères et al., 1999; Stow et al., 2002b; Rebesco, 2005). Part of the drift accumulation is of biogenic composition, supplied from primary productivity in surface waters of the Gulf of Cádiz, as well as from reworking and transport of benthic organisms. Another part is of terrigenous composition, for which it is less possible to determine precisely the sediment source and supply routes.

There are several likely sources of this terrigenous sediment as indicated in Fig. 16: (1) *the Alboran Sea*, via the Gibraltar gateway by bottom current transport as reported by Kelling and Stanley (1972) and Stanley et al. (1975), or as fine suspended matter nearer the surface, as suggested by Melières (1974), Palanques et al. (1995) and Van Geen et al. (1997); (2) *the Straits of Gibraltar*, due to direct erosion of deposits by strong bottom currents. Esteras et al. (2000) identified several erosive discontinuities in the sedimentary record since the opening of the Strait, which can be related with more energetic stages of the MOW; (3) *the Spanish and Moroccan continental shelves*. A certain amount of this sediment is probably delivered to the western end of the Gibraltar gateway, as the shelf currents flow towards the SW on the Spanish shelf and toward the NE on the Morocco shelf, and is then incorporated into the MOW bottom current (Kenyon and Belderson, 1973; Lobo et al., 2000, 2005b). Another part may be worked across the shelf and spill onto the slope by a process of seafloor polishing (Viana and Faugères, 1998; Stow et al., 1998). Direct offshelf supply most likely would have been greater during lowstand stages when most of the shelf was subaerially exposed (Hernández-Molina et al., 2000); (4) *the diapiric ridges and contourite channels* in Sector-3, due to direct erosion by bottom currents. Sidescan sonar, multibeam and seismic data show clear erosive processes within this Sector, so that this must represent a significant sediment source from within the CDS; (5) *mud volcanoes*. As Somoza et al. (2003) and Fernández-Puga (2004) reported, numerous mud volcanoes are present, which could provide an important source of sediment, especially during active intrusive and uplift phases; (6) *and Guadalquivir Channel*. Seismic reflection data suggest that erosive processes dominated on the southern flank of the GB; (7) *suspended matter from adjacent rivers*. Plumes of sediment are periodically supplied from the principal rivers draining the southern Iberian Peninsula, contributing part of their finer load to the bottom nepheloid layer identified across the shelf. This appears to produce two distinct slope nepheloid layers, one close to the bottom and the other along the interface between the Atlantic and Mediterranean water (Palanques et al., 1986, 1995); (8) *erosion of the upper slope*. Along the Algarve upper slope a major erosive surface has been reported by Llave et al. (2001); (9) *submarine canyons*. Suspended matter flowing down submarine canyons under the influence of canyon currents or low-concentration turbidity currents are significant potential sources, especially in the canyon-channel sector; (10) aeolian dust from the African continent should be another important sediment source, as some authors demonstrated in the Aboran Sea (Moreno et al., 2002) and the Portuguese margin (Moreno et al., 2002).

Overall, the sediment contribution is very mixed, including primary biogenic, and both external (1, 2, 3, 7 and 9 above) and internal (4, 5, 6 and 8 above) terrigenous sources (Fig. 16). At different periods of time in the past record, different principal sources have been more or less important (Stow et al., 1986, 2002b). Although this has been demonstrated for variations in biogenic/terrigenous input, little work has yet been attempted to identify variations in the terrigenous supply routes. Superimposed on the sediment source is the influence of the MOW velocity. In Sectors 1 and 3, for example, relatively high velocities ensure a more sand–gravel rich accumulation associated with erosion and non-deposition, whereas lower mean velocities in Sectors 4 and 5 allow much more significant accumulation of finer-grained contourites.

7. Seismic stratigraphy overview

The total sediment thickness above basement in the Gulf of Cádiz is between 7 and 11 km, including Mesozoic to recent sediments (Mougenot, 1988; Medialdea et al., 2004). Basement is considered as the Campo de Gibraltar Flysh Units and External Betic Units (Subbetic Zone) in the SE area, and Palaeozoic rocks of the Hercynian Massif (Tortella et al., 1996) in the north. Consequently, the age of the oldest sedimentary succession overlying basement varies from Triassic in the central and NW area, to Middle Miocene in the SE (Mougenot, 1988; Riaza and Martínez del Olmo, 1996; Maldonado et al., 1999; Terrinha et al., 2002; Medialdea et al., 2004).

Since the 1970s several authors have characterised the sedimentary record of the continental margin at different temporal scales: (a) Mesozoic and Cenozoic sedimentary record (Baldy et al., 1977; Mougenot et al., 1979; Malod, 1982; Mougenot, 1988; Riaza and Martínez del Olmo, 1996; Tortella et al., 1996; Maldonado et al., 1999; Terrinha et al., 2002; Fernández-Puga, 2004; Medialdea et al., 2004); (b) Pliocene and Quaternary (Rodero, 1999; Rodero et al., 1999; Hernández-Molina et al., 2002; Llave et al., 2006b); (c) Quaternary (]Llave et al., 2001, 2004b, 2006b; Llave, 2003); (d) Late Pleistocene-Holocene (Nelson et al., 1993; Hernández-Molina et al., 1994, 2000; Lebreiro, 1995; Lobo, 1995, 2000; Lebreiro et al., 1997; Somoza et al., 1997; Lobo et al., 2001, 2002, 2005a; Llave et al., 2004a, 2006a); and (e) Late Holocene (Lobo et al., 2003, 2005b; Llave et al., 2004a, 2006a). Based on the results of these papers we can point out that sedimentation in the Gulf of Cádiz has been driven by a combination of tectonic evolution of the margin and environmental changes in oceanographic and climatic conditions. Both factors have helped to generate the principal discontinuities identified in the sedimentary record. Since the Messinian, several key erosive surfaces in the slope succession of the Gulf of Cádiz (Llave et al., 2001; Hernández-Molina et al., 2002; Llave, 2003) and in the Straits of Gibraltar (Esteras et al., 2000) have been identified. The most significant discontinuities (Fig. 17) have been identified in the Late Messinian (M) at ~5.5 Ma, in the Lower Pliocene at ~4.2 Ma (LPR), in the Upper Pliocene at ~2.4 Ma (UPR), and approximately 900–920 ky in the Mid-Pleistocene (MPR). The stacking pattern of the Pliocene and Quaternary is quite complex, and the stratigraphic analysis has been published (see for details: Hernández-Molina et al., 2002; Stow et al., 2002c; Llave, 2003; Llave et al., 2001, 2004a, b, 2006a, b). Based on these stratigraphic results, two important aspects should be highlighted for the present paper, as summarised below (Fig. 17).

1. A 'Russian doll' model of depositional sequences at different time scales has been defined, in which low-resolution depositional sequences are composed internally of higher resolution sequences. In general terms, the continental margin (including the contourite deposits) is mainly built up by the stacking of regressive and lowstand sedimentary deposits in every depositional sequence, which have conditioned its progradation and its present morphology. Transgressive and highstand deposits are also present in every depositional sequence but as condensed sections. Also, in the abyssal plains the turbidity lowstand deposits related to glacial stages are predominant between pelagic deposits.
2. The same facies trend in every depositional sequence is observed on the slope including: (a) a transparent zone at the base; (b) smooth, parallel reflectors of moderate-to-high amplitude in the upper part; and (c) an high-amplitude erosive continuous surface at the top. Since the correlation of the high-resolution seismic profiles with the calypso piston and gravity cores it has been determined that this cyclic pattern of acoustic response most likely represents cyclic lithological changes showing long-period coarsening-upward sequences to an erosive top.

Since the Messinian the major discontinuities correspond to the most drastic changes in climate and paleoceanography, which have affected the Atlantic and Mediterranean linkage area. They are especially linked to the most prominent sea-level falls in the Messinian (~5.5 Ma), Lower Pliocene (~4.2 Ma), Upper Pliocene (~2.4 Ma, UPR), and in the Mid Pleistocene (~900–920 ky, MPR). The UPR discontinuity is correlated with the major sea-level fall recorded at 2.4 Ma between MIS 101/100 (Lowrie, 1986; Haq et al., 1987; Morrison and Kukla, 1998), which was coeval with a global cooling trend (Shackleton et al., 1984; Raymo et al., 1989) and with an important change in the climatic cyclicity trend. That age corresponds with the time of formation of Northern Hemisphere ice sheets (Zachos et al., 2001). Furthermore, the UPR discontinuity is related to the establishment of the present-day regional hydrodynamics in the region of the Straits of Gibraltar (Loubere, 1987; Thunell et al., 1991). The MPR discontinuity has been dated recently by samples from oil wells and correlated (Llave et al., 2001, 2004b, 2006b; Hernández-Molina et al., 2002; Stow et al., 2002c) with an important change in the climatic trend known as the "*Mid-Pleistocene Revolution*", which occurred 900/920 ky ago (Shackleton and Opdyke, 1973; Shackleton et al., 1990; Berger and Wefer, 1992; Berger et al., 1994; Mudelsee and Stategger, 1997; Howard, 1997; Paillard, 1998; Loutre and Berger, 1999). This noticeable change at the MPR surface is interpreted as coeval with the significant sea-level fall at 900–920 ky (Lowrie, 1986; Haq et al., 1987; Llave et al., 2001; Hernández-Molina et al., 2002). The lowered sea level is related to an important change in the climatic trend, driven by a shift to longer-period glacial/interglacial cycles and an increase in the cycle amplitude since isotopic stage 22. This intensification of glacial episodes marked the beginning of the so called "*Glacial Pleistocene*" (Thunell et al., 1991). The discontinuity therefore forms the boundary between asymmetric 4th-order climatic (and sea-level) cycles of 41 ky (obliquity cycles) before the MPR, and the subsequent onset of the 100 ky eccentricity orbital cycles.

It seems clear that these major allocyclic aspects of global environmental change (climatic and eustatic) have been essential in conditioning the sedimentary evolution of the Cádiz margin during

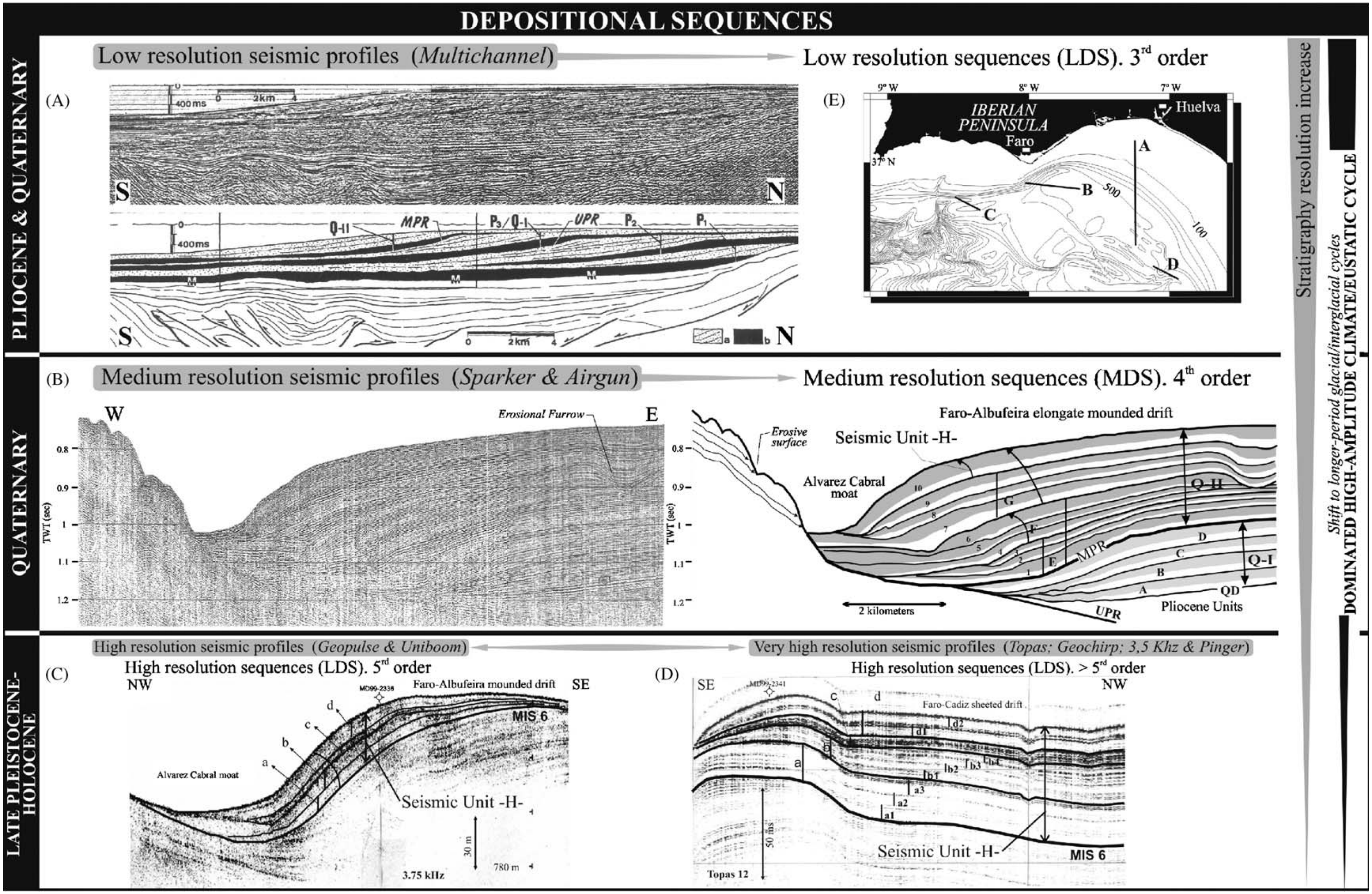


Fig. 17. Stratigraphy analysis: (A) uninterpreted and interpreted of a seismic multi-channel seismic profile (MCS) profile of the continental margin. Four major low-resolution DS (M/P1, P2, P3/Q-I & Q-II) related to 3rd-order cycles have been identified since the late Miocene. In shorter time scale, the Quaternary sedimentary record is composed by 2 DS of 4th order (QI & QII) bounded by the MPR discontinuity. *Legend of the deposits*: a = Regressive and Lowstand deposits, and b = Transgressive and Highstand deposits (*modified from* Hernández-Molina et al., 2002); (B) sparker seismic profile and line drawing through the Faro-Albufeira drift. QI & QII comprises four minor asymmetric depositional sequences each one (A, B, C, D and E, F, G, H respectively). In grey is shown the reflective seismic facies and in white the transparent seismic facies (modified from Llave et al., 2001). (C and D) 3.5 kHz and Topas seismic profile across the mounded Faro–Albufeira drift indicating the main Late Pleistocene-Holocene seismic units, where four high-resolution DS (A–D) were determined, internally structured into subunits periodicity related to the Heinrich Events (Llave et al., 2004a, 2006a). (E) Sketch with the position of the seismic lines.

the Pliocene and Quaternary, and have driven coeval cyclic changes in MOW palaeoceanography. The cyclicity of the acoustic response described above can be interpreted in terms of sedimentary processes (depositional and erosive) within the sedimentary record of each depositional sequence of the contourite deposits, and it is indicative of a close link between the margin stacking pattern and MOW variability. The acoustic facies changes in the contourite deposits, indicative of changes in the sediments texture, reflects changes in the MOW velocity, sediment input, and spatial distribution, directly related to sea-level and climate changes (Llave et al., 2006a–c).

The Pliocene and Quaternary sedimentary record also has been influenced by the recent neotectonism due to the broad NW-SE compressional regime. Tectonism has determined, in the short-term, the local thickness, geometry and present position of various contourite depositional sequences and, in the long-term, also has contributed to new paleoceanographic changes. Several features of the contourite depositional system can be related to this recent tectonic activity, which has involved the reactivation of faults and diapiric structures related to local movements (Maldonado et al., 1999; Maestro et al., 2003; Fernández-Puga, 2004; Medialdea et al., 2004). This neotectonism has increased and changed the submarine bottom relief and, consequently, controlled changes in the distribution and velocity of bottom currents and therefore contourite drift accumulation. The most recent neotectonic activity has directly conditioned several features, including: (1) the recent configuration of the c*hannels and ridges sector* (Sector-3) (Hernández-Molina et al., 2003; Llave et al., 2006a, b); (2) the inactivity of the fossil *mounded elongated drift* and *sheeted drifts* identified on the Sector-3 (Llave et al., 2003a, b, 2006c); (3) the recent genesis of the Diego Cao channel proposed by Llave et al. (2001); and (4) the recent over-excavation and northward migration of the Cádiz channel related to movements of the diapiric ridges proposed by García (2002).

8. Sedimentary model for the CDS and continental margin development

Sediment transfer in oceanic basins is produced by the interaction of *downslope* and *alongslope* processes on many continental margins, especially on the western margin of the oceanic basins, in marginal basins and all along the Antarctic continental margin (Stow and Faugères, 1998; Faugères et al., 1999; Stow et al., 2002a). That interaction has been more active since the Late Eocene, when a period with much stronger thermohaline circulation than previously was established. During the Plio–Quaternary glacial/interglacial cycles, the interaction tends to have been separated in time, with downslope processes dominating glacial periods and alongslope processes more common (or at least more obvious and less masked by downslope processes) during interglacials (Faugères et al., 1999). Where downslope processes dominate, turbidite depositional systems prevail, whereas where alongslope processes dominate, contourite depositional systems are generated. There are several examples of continental margins where downslope and alongslope processes are acting. One of the classic models was defined on the eastern margin of North America, where the margin is crossed by many submarine canyons and channels which transported sediment down-slope to the continental rise. The deep area of the rise is affected by the *western boundary undercurrent* (WBUC), especially during highstand stages when minor reworking of the surface of the dominant turbidite systems deposits took place. Both processes have generated a complex deposit defined as a *companion drift fan* (Locker and Laine, 1992; Pickering et al., 1989). On the active margin off New Zealand the *Pacific deep western boundary current* flowing along the rise interacts with the *Bounty fan* and produces a large *fan drift* (McCave and Carter, 1997). Also, in New Zealand, but in the Hikurangi fan, a mixed depositional system is formed by the interaction of turbidite and contourite processes, with turbidite processes occurring in the internal zone of the fan and contourite processes in the external zone (Carter and McCave, 1994). Off the Antarctic margin, a mixed depositional system has been identified on the rise where alongslope processes interact with the normal downslope processes (Larter and Cunningham, 1993; Rebesco et al., 1997, 2002; Escutia et al., 2002). All these examples and sedimentary models have in common that the downslope processes are effective in the proximal and middle part of the system (slope and upper rise), and the alongslope processes are active in the distal part of the system (middle and lower rise), generating fine-grained contourite sediments.

On the other hand, some continental margins show alongslope processes in the middle slope, as in the Gulf of Cádiz. For example, off southeast of Brazil, the *Brazil Current* is flowing toward the southwest along the upper and middle slope, and contourite deposits are interstratified with gravitational deposits (Viana and Faugères, 1998; Viana, 2001; Viana et al., 2002a, b). On the Rockall margin, NW of Great Britain (and NE from Rockall Trough), a complex drift system has been developed since the late Eocene, showing close interaction between downslope and alongslope processes (Howe et al., 1994; Stoker et al., 1998; Armishaw et al., 2000; Masson et al., 2002). Further north along this margin, a similar mix of deposits and processes is found in the Faeroe–Shetland Channel (Mienert et al., 1994; Nielsen and van Weering, 1998; van Weering et al., 1998). These authors refer to the mixed deposits as part of a *composite slope–front fan*, where downslope processes dominated during cold stages (lowstands), and in the warm stages (highstands) alongslope processes are more prevalent. All theses examples have in common that the alongslope processes tend to act on the middle slope.

Recently, Weaver et al. (2000) and Mienert and Weaver (2003) have characterised the Atlantic continental margin sedimentation on the basis of the sedimentary processes operating from the shelf edge to the abyssal plain. These authors considered three different types of margins in the North Atlantic: (1) the *non-glaciated margin south* of 26° (mass-wasting processes dominant); (2) the *glacially influenced margin* from 26°N to 56°N (canyon and channel processes dominant); and (3) the *glaciated margin* north of 56° (glacial and alongslope processes dominant). Within this new regional classification, the continental margin of the Gulf of Cádiz should be considered as rather atypical because, by its morphological, sedimentary, stratigraphic and tectonic characteristics, it does not correspond with a "the *glacially influenced margin*" type proposed for this latitude. The relatively rare occurrence of submarine canyons on the margin, which are located close to the Straits of Gibraltar and in the westernmost area, indicates the dominance of alongslope processes compared with downslope processes. However, from a water depth of 1200 m, the contourite system is abruptly limited seaward by downslope submarine valleys (Figs. 1A, 5, 11 and 16), which reflects the dominance of downslope processes toward the lower slope and abyssal plains (Habgood, 2002; Habgood et al., 2003; Hernández-Molina et al., 2003).

The margin of the Gulf of Cádiz has six principal characteristics, that distinguish it from the adjacent margins: (1) an active compressive framework where the "*Cádiz Allocthonous unit*" represents an unstable substratum for the overlying late Miocene, Pliocene and Quaternary sedimentation; (2) a relative lack of submarine canyons on the whole of the margin (except in the western area of the Algarve margin); (3) a broad slope making up the largest part of the margin; (4) a mid-slope terrace dominated by alongslope processes driven by MOW, and on which the CDS is constructed; (5) a dominance of downslope processes locally on the upper slope, but more especially on the lower slope and the abyssal plain, where the MOW does not affect the bottom; and (6) a lack of a distinct continental rise.

Considering all these features and after comparison with other margins, the Cádiz CDS could be considered as a mixed turbidite/contourite system (cf. Faugères et al., 1999), but with its own rather unique characteristics. Although the Gulf of Cádiz slope region has been influenced by both downslope and alongslope processes, there appears to be a marked separation between them according to depth. Contourite processes of the CDS are dominant on the middle slope, whereas downslope processes dominate mainly on the lower slope (Fig. 16). For the most part, these processes appear not to interact simultaneously. The influence of alongslope processes in the Gulf of Cádiz have been more marked and more continuous both in time and space than the downslope processes (Llave et al., 2001; Hernández-Molina et al., 2003), and the MOW has remained active through both glacial and interglacial cycles, although differing in intensity (Schönfeld and Zahn, 2000; Llave, 2003; Löwemark et al., 2004; Llave et al., 2006a–c) and lateral position (Llave et al., 2006b).

The Late Quaternary sedimentary model for the margin of the Gulf of Cádiz is, therefore, significantly different during the cold (lowstand) stages than the warm (highstand) stages. Downslope processes are active mainly during the regressive and lowstand stages, showing increased sediment input, margin progradation, and preferential development of downslope features and sediments on the lower slope. During *lowstand stages*, sea level reached the shelf edge, and North Atlantic Surface Water flowed along the upper slope toward the SE. Net sediment transport was both downslope and also towards the Strait of Gibraltar area. Where submarine canyons existed, as in the Algarve margin, shelf sediments were effectively funnelled into deep water lower slope regions. Elsewhere, a slower cross-slope diffusion of sediment occurred by hemipelagic processes feeding directly into the CDS and over other parts of the margin. During lowstand periods, the middle slope has been strongly influenced by a high-velocity lower core of MOW (Llave et al., 2006a, b), leading to alongslope distribution of sediment through contourite channels, marginal valleys, moats, and furrows. Although this view is still controversial (see *Paleoceanography* section above), we propose that lowstand stages led to development of this smaller, denser and more vigorous lower core, thereby facilitating the pirating, transport and deposition of coarser material toward the W and NW and higher sand contents in contourites.

By contrast, during the *highstand stages* much of the terrestrial sediment supply was trapped within bays, estuaries and across the broader shelf, less sediment could reach the slope, and a predominantly fine suspension reached the distal areas of the margin. On the shelf, sediments were affected by the North Atlantic Surface Water and transported toward the SE. On the slope the submarine canyons on the Algarve were less active or even inactive in effecting downslope transport, while on the middle slope of the rest of the margin MOW influence was certainly strong enough to actively maintain the CDS. The density of the MOW was lower than during cool climatic conditions, so that the upper core of the MOW was the more active one, leading to the prevalence of sandy contourites in shallower areas within the middle and upper slope (Llave et al., 2006a, b). In the upper slope a sand tongue of around 40 km wide was identified by Nelson et al. (1993) which represents a plastered drift mainly developed during the highstand stages (as the present one).

There are several possible reasons why there is a lack of submarine canyons along most parts of the continental margin of the Gulf of Cádiz: (1) the strong along-shelf (due to the AI) and alongslope (due to the MOW) processes have always been dominant and allowed little scope or time for canyon carving by turbidity currents; (2) the shelf currents (AI) at lowstands were intensified carrying sand and silt materialtowards the Straits of Gibraltar; (3) in most parts the slope gradient is insufficient (<2°) for major and repeated incision by downslope processes to generate submarine canyons; and (4) the marked density interface between Atlantic Surface Water and MOW may result in the pirating of low-concentration turbidity currents into intermediate nepheloid layers, thereby altering the normal behaviour of the turbidity currents.

Taking into consideration all the particularities of the continental margin of the Gulf of Cádiz mentioned previously the sedimentary model of the continental margin of the Gulf of Cádiz (CDS) is therefore defined as a *mixed contourite+turbidite system*, and at the same time as *a detached combined drift-fan* (Fig. 16). In this model, the alongslope processes are continually active along the middle slope, and have been constructing the CDS since the end of the Miocene. The downslope processes (mainly turbiditic) are focussed mainly on the lower slope and active during the regressive and lowstand stages. We note that this sedimentary model is markedly different from many previous conceptual models for contourite margins (Locker and Laine, 1992; Pickering et al., 1989; Faugères et al., 1999), in which alongslope and downslope processes are more closely interactive in time and space.

9. Final considerations

This synthesis of work conducted in the Gulf of Cádiz focuses on the development of the contourite depositional system (CDS) in the middle slope of the Gulf of Cádiz in the general context of the continental margin as a whole.

The Gulf of Cádiz margin is unique for several reasons: (1) the lack of a continental rise; (2) an active compressive framework where the "*Cádiz Allocthonous Unit*" represents an unstable substratum for the overlying Late Miocene, Pliocene and Quaternary sedimentation; (3) the lack of submarine canyons (except in the western area of the Algarve margin); (4) the presence of a very broad slope with a distinctive mid-slope terrace dominated by alongslope processes driven by the MOW, which has led to development of the CDS during the Pliocene and Quaternary; and (5) downslope processes that are only minimally active on the upper slope, but are dominant on the lower slope and abyssal plain regions.

Based on the distribution of depositional and erosive sedimentary features on the middle slope, five morphosedimentary sectors have been identified within the CDS, which from east to west are: (1) *proximal scour and sand ribbons*; (2) *overflow* *sedimentary lobe*; (3) *channels and ridges*; (4) *active contourite drifts*; and (5) *submarine canyons*. These sectors are related to the systematic deceleration of the MOW, its disruption by various bathymetric obstacles and features, and by the Coriolis force. Some of the results presented here would suggest that the time is right for a revision of the hydrodynamic model for the detailed circulation of the MOW. Some erosive sedimentary features are indicative of a complex circulation pattern, where a principal flux could generate a secondary flux by interaction with the bathymetric highs of Sector 3. Branches of the MOW are generated in Sector 1, but especially in Sector-3, by the influence of the tectonic highs. These branches have significant implications for climate and ocean circulation in the North Atlantic.

The sedimentary model for the CDS in the Gulf of Cádiz margin could be defined as a mixed *contourite+turbidite* system, and a *detached combined drift-fan*, as distinct from conceptual models. These differences are due to the alongslope processes being dominant on the middle slope, and downslope processes on the lower slope and abyssal plains. Several key factors have played a role since the end of the Miocene in this mixed system. Climate and sea-level changes and paleoceanographic changes in the MOW have been directly related, and the dominance of the regressive and lowstand stages (cold stages) through the late Pliocene and Quaternary have led to high sediment supply, margin progradation and a complex contourite stacking pattern by the alongslope processes. Simultaneously, recent neotectonism (faults and diapiric structures related to local movements) has strongly influenced submarine relief, controlled water masses pathways and, therefore, the type of contourite processes involved.

Our results indicate how contourite depositional (*sedimentary wave's fields and drifts*) and contourite erosive (*channels*, *furrows*, *marginal valleys* and *moats)* features present in the deep marine environment can provide evidence for the reconstruction of the present and past water-mass circulation.

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