The Contourite Depositional System in the Gulf of Cadiz: an example of drifts with reservoir potential characteristics

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Abstract

A brief state-of-the-art related to bottom currents and their deposits is presented remarking its interest in hydrocarbon exploration and complemented with a general overview of the Contourite Depositional System (CDS) of the Gulf of Cadiz generated by the Mediterranean Outflow Water (MOW). Deep water traction currents can generate large dimension deposits in deep-water environments, where the contourite drifts are particularly relevant because they are as common in modern ocean basins as turbidite bodies. These drifts can be excellent *reservoir rocks* for hydrocarbon fields, gas hydrates and shallow free gas. At present, their study and facies modelling is of great interest in hydrocarbon exploration, due to the "*clean sand*" accumulation in deep-sea environments producing good *reservoir rocks* with greater textural maturity than turbidites. Based on the depositional and erosive features distribution, five morphosedimentary sectors have been identified within the CDS of the Gulf of Cadiz, 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 these sectors is related to systematic deceleration of the MOW as it flows westwards, to the interaction with the particular margin bathymetry, and to the effects of Coriolis force. Stratigraphic architecture of the different drifts and their relation with the major structural features allow us to propose a regional Quaternary evolution for the whole system. Tectonics has represented a key factor in the seafloor morphological changes, which has controlled new pathways for the core and branches of the MOW at every stage. Consequently, the behaviour of MOW controls the contourite stratigraphy and architectural changes. Superimposed on these tectonic changes, both climatic and eustatic changes during the Quaternary have controlled the development of vertical contourite stratigraphy. Sandy deposits are mainly located on the sectors 1, 3 and 4 within the CDS, and they are a consequence of that lateral and vertical evolution.

Keywords: Contourite deposits, Mediterranean Outflow Water, hydrocarbon exploration, reservoirs deposits, seismic stratigraphy, Gulf of Cadiz.

1. Introduction

Deep water traction currents include internal tides and waves, contour and deep water currents. All these currents are capable of generating large dimension deposits in deep-water environments with enormous interest at present in palaeoclimatology, hydrocarbon exploration, and slope stability studies (Zhenzhong *et al.,* 1998; Faugères *et al*., 1999; Rebesco, 2005). Contourite deposits (*drifts*) are particularly relevant, because they have common sedimentary features in modern ocean basins, and particularly well-shown in the Atlantic Ocean (Faugères *et al*., 1999). Indeed, marine geological studies conducted over the past two decades have confirmed the essential role of bottom contour processes in marine environments, and have shown that they can generate large sedimentary bodies, as important as turbidite bodies (Stow *et al*., 1986, 2002a; Zhenzhong *et al.,* 1998). Some continental margins are built up by the interaction of *downslope* and *alongslope* sedimentary processes (Locker and Laine, 1992; Faugères *et al*., 1999; Stow *et al*., 2002a), but when *alongslope* processes dominate, a Contourite Depositional System (CDS) may develop (Hernández-Molina *et al*., 2003).

Drift deposits are important but little is still known about the CDS due to several reasons (Stow *et al.,* 2002b; Rebesco, 2005): a) the complexity of these sediments, which are founded within a broad spectrum of deep-water deposits that does not allow them to be easily recognized and decoded; b) the 50-year dominance of the *turbidite paradigm*, and the efforts to promote the turbidite depositional systems ignoring alternative and more complex deep-water models; c) the controversy that surrounds these sediments since they were first recognized, and d) the difficulties to recognised them in the ancient record. Nevertheless, despite those reasons, several contourite classifications have recently been proposed being mainly based on its morphologic, sedimentologic and seismic characteristics (McCave and Tucholke, 1986; Faugères and Stow, 1993; Faugères *et al*., 1993, 1999; Zhenzhong *et al.,* 1998; Rebesco and Stow, 2001; Stow *et al*., 2002b; Rebesco, 2005). All drifts considered are related to the regional oceanographic conditions and the physiographic domains where they developed. Thus, it is possible to deduce, from their morphologic, stratigraphic and sedimentary characteristics, the pathway and approximate flow velocity of the water mass that was responsible for their development. Flow velocity is mainly a function of local behaviour of the current due to seabottom stress (cores, vortices, local turbulence, filaments, etc.) which controls in detail the sedimentary facies distribution within a CDS (as the grain size, sedimentary structures, porosity, permeability, etc.) and in large term its interests for hydrocarbon exploration.

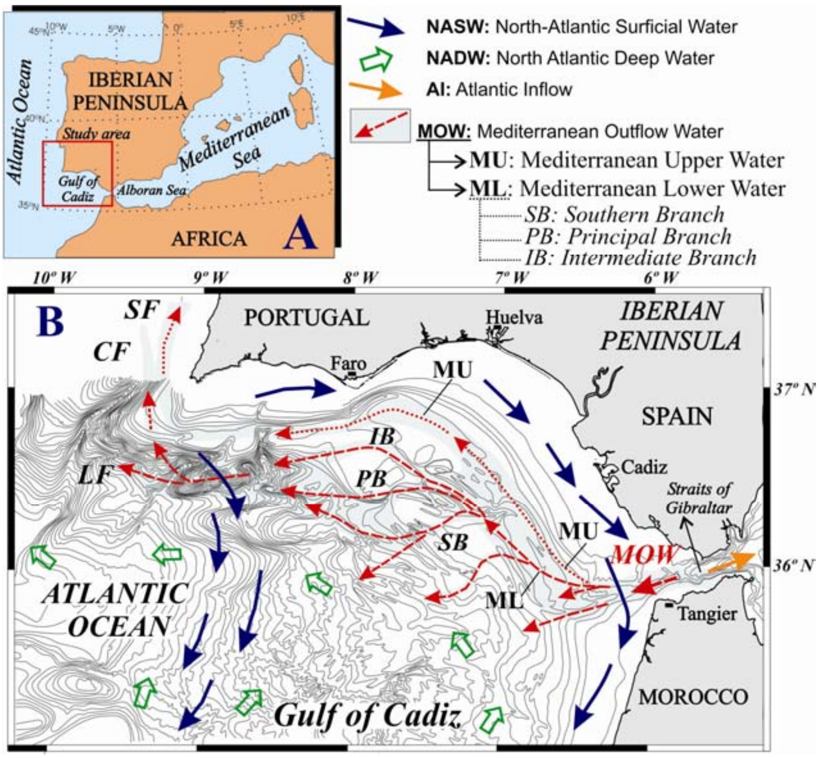


Figure 1.- A) Location of the Gulf of Cadiz. B) Regional bathymetric map indicating the general circulation patterns of MOW (Bathymetry from Heezen and Johnson, 1969).

The present contribution has two main objectives: a) To submit a brief state-of-the-art related to bottom currents and their deposits remarking its interest in hydrocarbon exploration; b) To show the CDS in the Gulf of Cadiz (Fig. 1) as an example of drifts with reservoir potential characteristics. Quaternary evolution of that CDS is also described through an integration of tectonic, stratigraphic, and paleoceanographic changes.

2. Contourites: brief state-of-the-art

There is some confusion in the terminology used related to contourite and deep-water currents. Recently, Zhenzhong *et al.* (1998), Stow *et al*. (2002b) and Rebesco (2005) published some recommendations regarding to the terminology. The term "bottom currents" is considered for those all deep currents not driven by sediment suspension that are capable of eroding, transporting, and depositing sediments on the seafloor, which can operate in deep-water due to the normal thermohaline or to the major wind-driven circulation pattern of the oceans. In general these currents are semi-permanent in nature with a net flow alongslope, but in more detail, they are extremely variable in direction and velocity, typically exhibiting giant eddies, and local downslope or oblique-to-slope flow, especially at the exit or narrow gateway. Nevertheless, "contour current" refers only to those thermohaline-driven, deep-water currents that flow parallel to the bathymetric contours. This term is frequently used by mistake as synonymous with "bottom current", but bottom current is applicable to different types of currents flowing *alongslope* as well as *upslope* and *downslope*. Another general term is referred to "deep-water traction currents" which include internal tides and waves, and contour and bottom currents.

The term "contourite" was first recognized and defined during the 1960s, being described as sediments deposited or substantially reworked in the deep sea by contour-parallel bottom currents (Heezen *et al.,* 1966; Hollister and Heezen, 1972). It was first described as being at great depths beneath deep-water bottom currents but later, *contourites* and *bottom current-controlled deposits* have been recognized in many settings and depths.

"Sediment drift" is the generic term for a sediment accumulation that was appreciably controlled by the action of a *bottom current*. It is often used synonymously with "contourite drift", which in contrast should be specifically used for sediment accumulations deposited principally by contour currents. Therefore, the most appropriate term for contourite accumulations is in most cases the wide-ranging designation "sediment drift" or simply "drift" as proposed Stow *et al*. (2002b) and Rebesco (2005). Nevertheless, the occurrence of mixed system is quite normal in ocean basins with sediment drifts. For this reason, the aforementioned authors proposed, a qualified modifier like bottom current controlled (modified, reworked, etc.) for *turbidite systems* and *hemipelagic deposits* that were significantly affected by interaction with bottom currents. Similarly, when *mounds*, *levees*, *fans*, *lobes*, *channels*, and other terms closely associated with downslope systems, which are applied to contourite systems, they must be preceded by the term *contourite*.

2.1. Contourite characteristics

Contourite characteristics could be considered both on a large or small scales:

A) The *large-scale* features of these accumulations reflect long-lasting stable conditions in the bottom current regime and/or oceanographic setting being based on the morphology and internal architecture. The main large scale characteristics are the following (Pickering *et al.,* 1989; Faugères and Stow, 1993; Faugéres *et al.,* 1993, 1999; Stow *et al.,* 2002b; Rebesco, 2005, among others): 1) *Large dimensions,* being the contourite drifts up to hundreds of km long, tens of km width and about 200-2000 m thick. Its dimensions are directly comparable to those of deep-sea fans constructed by turbidity current and related processes, which ranges from small patch drifts (100 km^2 in area and equivalent in size to isolated turbidite lobes or debris flow masses on slopes) to giant elongate drifts (100,000 km^2 in area, which match many of the world's large muddy elongate fans) (Stow *et al.,* 1996). 2) *Drift geometry*. Drifts with a more distinctly asymmetric mounded-shape can be better recognized rather than low-relief sheet-like geometry; 3) *Drift elongation*. An overall downcurrent elongation direction is typical of most drifts; 4) *Uniform reflector pattern.* Contourites present sub-parallel, moderate-to low-amplitude reflectors, with mainly gradational changes between seismic facies; 5) *Widespread regional discontinuities*, both at the base and within the drift are characteristic; 6) *Accumulation rates* are rather variable, from a few tens to hundreds meters per million years, depending on regional conditions, specific age, and evolutionary stage; 7) *Seismic units* are characterised by an overall downcurrent migration of the stacked lenticular, upward-convex, well-layered seismic units with high lateral continuity along both strike and dip; 8) *Migration direction*. The stacking pattern shows downlapping (onlapping on steep slopes) and sigmoidal progradational reflector patterns where downstream and upslope migration occurred. Any lateral migration is influenced (significantly at high latitudes) by the *Coriolis Force*; and 9) *Seismic facies are generally* semi-transparent, reflector-free intervals; continuous, sub-parallel, moderate- to low-amplitude reflectors; regular, migrating-wave, moderate- to low-amplitude reflectors; irregular, wavy to discontinuous, moderate-amplitude reflectors, and irregular, continuous, single high-amplitude reflector.

B) *Particular characteristics*. Most typically, contourites are composed of fine grained, structureless, highly bioturbated mud. However, they show a wide range of grain-sizes, composition, and preserved sedimentary structures, being the most frequent the following four types (Stow and Lowell, 1979; Stow and Holbrook, 1984; Pickering *et al.,* 1989; Faugères and Stow, 1993; Zhenzhong *et al.,* 1998; Faugères *et al.,* 1999; Stow *et al.,* 2002b): a) Siliciclastic contourites (Muddy, silty, sandy & gravel-rich variations); b) Shale-clast/shale-chip contourites (all compositions possible); c) Volcanoclastic contourites (muddy, silty, sandy & gravel-rich variations), and d) Calcareous bioclastic contourites (calcilutite, calcisiltite, calcarenite & calcirudite variations).

They normally occur as thick (tens to hundreds of metres), uniform, fine-grained sequences (including thin to medium coarser-grained beds), or interbedded with hemipelagites, turbidites, and other resedimented facies (Stow *et al.,* 2002b). However, sometimes thick sand accumulation or coarse lags are common, especially within or close to gateways and contourite moats (Buitrago *et al.,* 2001; Llave *et al.,* 2001, 2005a; Hernández-Molina *et al.,* 2003, 2005). They are dominantly homogeneous, poorly bedded, and mostly bioturbated and mottled throughout, with little primary structures preserved. A standard sequence has been defined in contourites (Gonthier *et al.*, 1984; Faugères *et al.,* 1984; Stow *et al.,* 1986, 1996; 2002b) where the grain size gradually increases from fine clay, silty clay, silt to fine sand and then grades back through silty to muddy contourite facies. This succession reflects changes from a weak to a strong current and back to a gentle current.

2.2. Current contourite classification

Contourite deposits have been grouped into eight main classes (McCave and Tucholke, 1986; Faugères *et al.,* 1993, 1999; Rebesco and Stow, 2001; Rebesco, 2005) (Fig. 2):

A. *Contourite sheeted drifts*. These form a very broad low-relief accumulation (up to a few hundred metres) over a very large area (up to 1.106 km^2), showing a slight decrease in thickness towards the margins. Two kinds of sheeted drift may be identified: a) *abyssal sheeted*, which fills basin plains whose margins trap the bottom currents within a complex gyratory circulation, and b) *slope plastered sheeted*, which is coated against continental margins where a gentle and smooth topography favours a broad non-focused current.

B. *Elongated mounded drifts*. This type of contourite accumulation is distinctly elongated and mounded in shaped, with a very variable extension from tens of km to over thousand km long, an elongation ratio of at least 2:1 to 10:1, and several hundred metres above the surrounding seafloor (total thickness up to 2 km). Elongation is generally parallel to the margin, which means that the crest of the drift is parallel to the current axis. Nevertheless, elongation and progradation trends are variable, depending on the current system and intensity, the bathymetry, and the Coriolis Force. Two types of mounded drifts may be identified: a) *Separated drift*, which is kept apart from the adjacent continental slope by a distinct moat; b) *Detached drift*, which is removed from that part of the continental slope where it originally enucleated and has oppositely directed currents flowing along its two flanks.

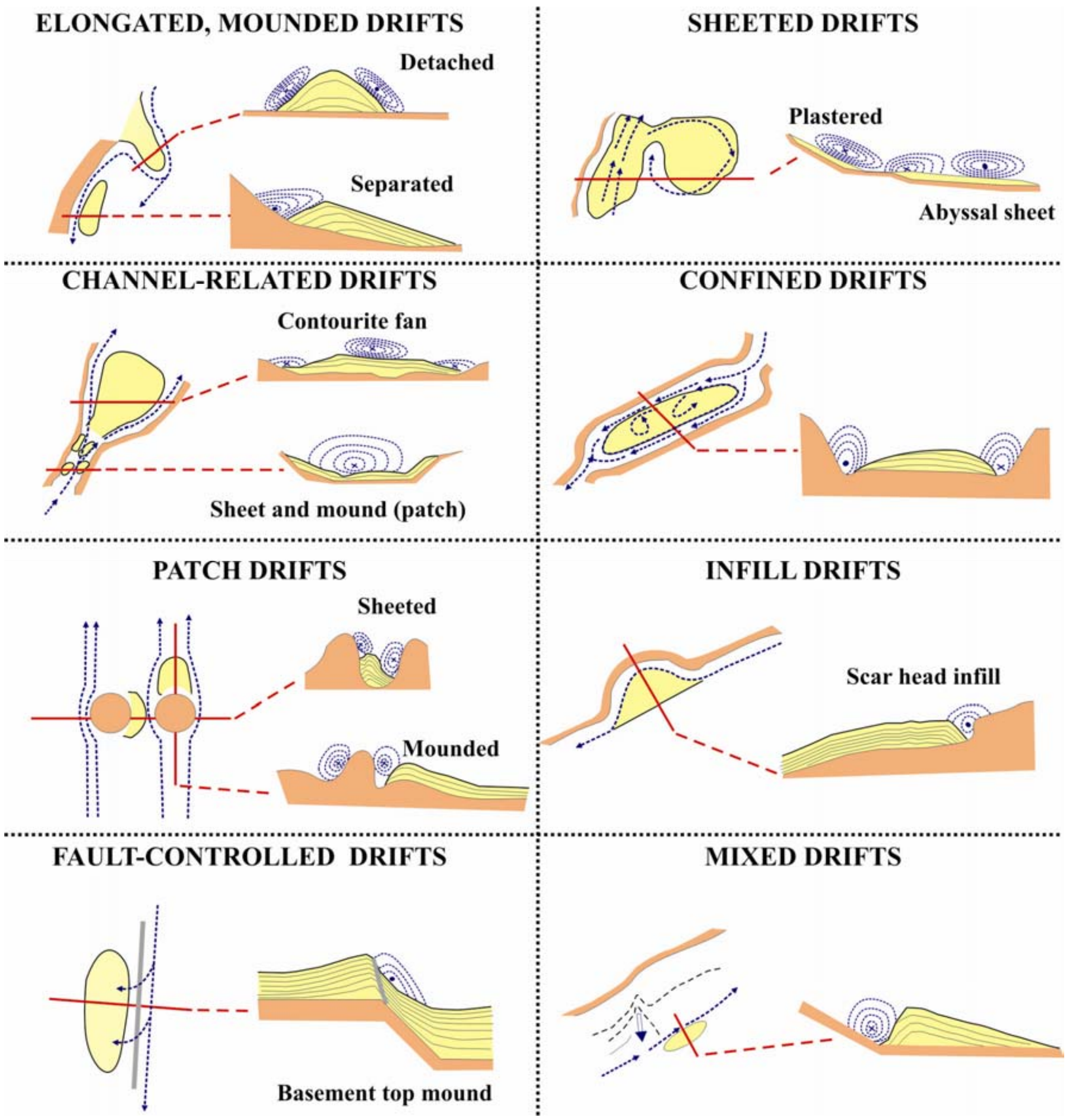


Figure 2.- Sediment drift types and inferred bottom current paths (Modified from Rebesco, 2005 and Rebesco and Stow, 2001).

C. *Channel-related drifts*. These deposits are characterised by its relationships with narrow conduits (deep channels, passageways or gateways, trenches, moats, etc.) where bottom currents are constricted so that flow velocities increased. Two types of channel-related drifts may develop: a) *Patch drifts*, which are typically small (a few tens of km^2 in area and 10.150 m thick) deposited within the conduits, either as axial mounds on the floor or as lateral sheets on the flanks of the channel; b) *Contourite-fans* are much larger, cone-shaped deposits (100 km or more in width and radius, and 300 m thick) developed at the downcurrent exit of the conduits.

D. *Patch drifts*. They are characterised by a random distribution controlled by the intricate interaction of the bottom current system with a complex seafloor morphology. It occurs plastered against relieves or within a trough where the irregular topography may modify both direction and velocity of the local current flow. Such a small-scale (a few tens of km^2), elongated, irregular drift may be either relatively mounded or thinly sheeted.

E. *Confined drifts*. These typically occur within relatively small enclosed basins, eventually actively subsiding, and generally show a complex staking of upward-convex lenticular depositional units. They are characterised by a mounded shape elongated parallel to the basin axis and distinct moats along both flanks.

F. *Infill drifts*. They typically form at the head of the scar or at the margin of the toe of slumps developed beneath the path of a bottom current. This drift type is characterised by a moderate relief (mounded geometry) and extent, variable shape, and downcurrent progradation that progressively infill the topographic depression or irregularity in which it occurs.

G. *Fault-controlled drifts*. They develop either at the base or at the top of a fault-generated basement relief in response to perturbations in the bottom current flow pattern. A supplementary characteristic may be (subsequently reactivated) syn-depositional faulting that affects the relatively steeper side of such drifts.

H. *Mixed drift systems*, which are characterised by the interactions of alongslope currents with other depositional processes (interfingering, intercalation, imbrication, incorporation, winnowing, entrainment, etc.). The most effective interplay is between contourites and turbidites, but drift development may be variously affected by the association with debrite, hemipelagite, and glacigenic systems.

2.3. Differences between contourites and turbidites

The identification of contourites is complex since bottom currents affect to a greater or lesser extent ambient sedimentation by other processes (pelagic, hemipelagic and turbiditic) resulting a blend of common characteristics. Drifts in continental slope settings have often been related to a combined action of downslope gravity-driven processes which are progressively subjected to winnowing and preferential settling by slow moving, but semi-permanent geostrophic currents. This is why although the distinction between contourites and turbidites is very fine, different criteria have been proposed to characterise them (Bouma, 1962; Hollister and Heezen, 1972; Stow and Lowell, 1979; Gonthier *et al.,* 1984; Stow and Piper, 1984; Faugères *et al.,* 1984, 1999; Mitchum, 1985; Pickering *et al.,* 1989*;* Faugères and Stow, 1993; Maldonado *et al.,* 2005): 1) The asymmetric mound-and-moat contourite geometry in contrast to the symmetric *gull-wing* geometry typical of turbidite channel-levee system, and versus the fan-shape of turbidites; 2) Lesser extent than turbidite-fan but larger on average than turbidite channel-levee; 3) Turbidite deposits do not have internal continuous reflectors in a longitudinal section and could have toplap reflectors; 4) Contourites are physically disconnected from the sedimentary apply, and they don't have a perpendicular morphology to the continental margin; 4) In the North Hemisphere the development of a turbidite levee is in the right flank due to the Coriolis Force, whereas in contourite drifts it is in the left one; 5) Contourite facies could have coarse grain size lags, negative gradation, with a net upper contact, and particular grain fabric orientated parallel to the slope, whereas turbidites may be cleaner, better sorted, more negatively skewed, and with a more bimodal fabric.

3. The Contourite Depositional System in the Gulf of Cadiz

The Contourite Depositional System (CDS) of the Gulf of Cadiz has been defined and characterised very recently, along the northern margin of the Gulf of Cadiz, as an unique system that results from Mediterranean Outflow Water (MOW) interaction with the seafloor (Fig. 1) (Hernández-Molina, *et al*., 2003; Llave, 2003). The *CDS* has imprinted significant variations as a function of global climatic and eustatic conditions since it began to develop in the Early Pliocene (about 5 Ma), when the Strait of Gibraltar opened and the *MOW* circulation pattern established (Kenyon and Belderson, 1973; Nelson *et al.,* 1993; Maldonado and Nelson, 1999). The high rates of accumulation and expanded sedimentary records of the *CDS* permit high-resolution examination of past environmental change (Llave *et al.,* 2001, 2005a and b; Stow *et al.,* 2002c; Voelker *et al.,* 2005). Over the last decades, there have been numerous studies focused on the influence of the MOW on the sedimentary stacking pattern of some specific parts of the CDS (e.g. Madelain, 1970; Kenyon and Belderson, 1973; Melières, 1974; Gonthier *et al.,* 1984; Faugères *et al.,* 1985; Stow *et al*., 1986, 2002c; Nelson *et al.,* 1993, 1999; Llave *et al.,* 2001, 2004a, 2005a, b and c; García, 2002; Mulder *et al*., 2003; Habgood *et al*., 2003). A cyclic pattern of deposition and erosion as a consequence of changes in the intensity of MOW through time has been recognized (Nelson *et al.,* 1993). Cyclicity has also been described from the CDS seismic and sediment facies, which are interpreted as resulting from fluctuations in grain size as a consequence of varying MOW intensity, which in turn can be related to palaeoclimatic changes (Llave *et al.,* 2001; Stow *et al.,* 2002c; Llave, 2003).

3.1. Oceanographic setting

The oceanographic setting in the Gulf of Cadiz is characterised by intense hydrographic dynamics controlled by the exchange of water masses through the Strait of Gibraltar, determined by the overflow at a depth of 40-200 m, of dense, highly saline and warm Mediterranean Outflow Water (*MOW*) near the bottom, and the turbulent, less saline, cool-water mass of Atlantic Inflow Water (*AI*) on the surface (Fig. 1) (e.g. Madelain, 1970; Melières, 1974; Zenk, 1975; Ambar *et al.,* 1976; Ambar and Howe, 1979; Baringer and Price, 1999; Nelson *et al.,* 1999). After passing the Strait of Gibraltar, MOW progressively sinks northwestwards, entraining the overlying, less dense North Atlantic Central Water (*NACW*), and flowing above the North Atlantic Deep Water (*NADW*) (e.g. Madelain, 1970; Melières, 1974; Zenk, 1975; Thorpe, 1975; Gardner and Kidd, 1983; Ochoa and Bray, 1991; Baringer and Price, 1999; Nelson *et al.,* 1999).

As it moves westwards, MOW registers a decrease in temperature, salinity and velocity, and is influenced by both Coriolis force and topography, being divided into two main cores (Fig. 1): (a) *Mediterranean Upper Water* (*MU*), which moves as a warm, moderately saline flux (3.7º C, 37.07 $^{o}/_{oo}$) between depths of 400-600 m at the base of the upper slope as far west as Cape San Vicente, with an average velocity of about 46 cm/s (Ambar and Howe, 1979); and (b) *Mediterranean Lower Water* (*ML*), which constitutes the more saline (37.42 $^{o}/_{oo}$), lower core and the *MOW's principal nucleus,* at a depth of 600-1200 m and with an average velocity of approximately 20-30 cm/s (Zenk and Armi, 1990; Baringer, 1993; Bower *et al*., 1997). The irregularities of the seafloor between the Cadiz and Huelva meridians divert the ML flow, and it subdivides into three minor branches (Fig. 1) (Madelain, 1970; Kenyon and Belderson, 1973; Melières, 1974; Zenk, 1975; Ambar, 1983; Nelson *et al*., 1993, 1999; Borenäs *et al*., 2002): the *Intermediate Branch* (*IB*), the *Principal Branch* (*PB*), and the *Southern Branch* (*SB)*.

3.2. Methodology

Present knowledge about the CDS of the Gulf of Cadiz has been obtained thanks to a broad database, collected over the past 30 years by many different nations and cruises. It comprises (Fig. 3): (a) *bathymetric data*, including swath bathymetry of the middle slope using the Simrad EM12S-120 & EM300 multibeam echo-sounder system; (b) *side-scan sonar image data*, using the Seamap, OKEAN, Gloria and TOBI systems; (c) an *extensive seismic data grid*, including low-resolution MCS profiles from oil companies, medium-resolution seismic profiles from Sparker, high-resolution profiles from Airgun, Geopulse and Uniboom systems, and very and ultra high-resolution seismic profiles using a 3.5-kHz system and TOPAS; (d) a variety of *core data*, ranging from box cores and short gravity cores to giant piston and oil company cores; (e) Over 3000 *submarine photographs* taken with a BENTHOS-372 camera and (f) *physical oceanographic information*.

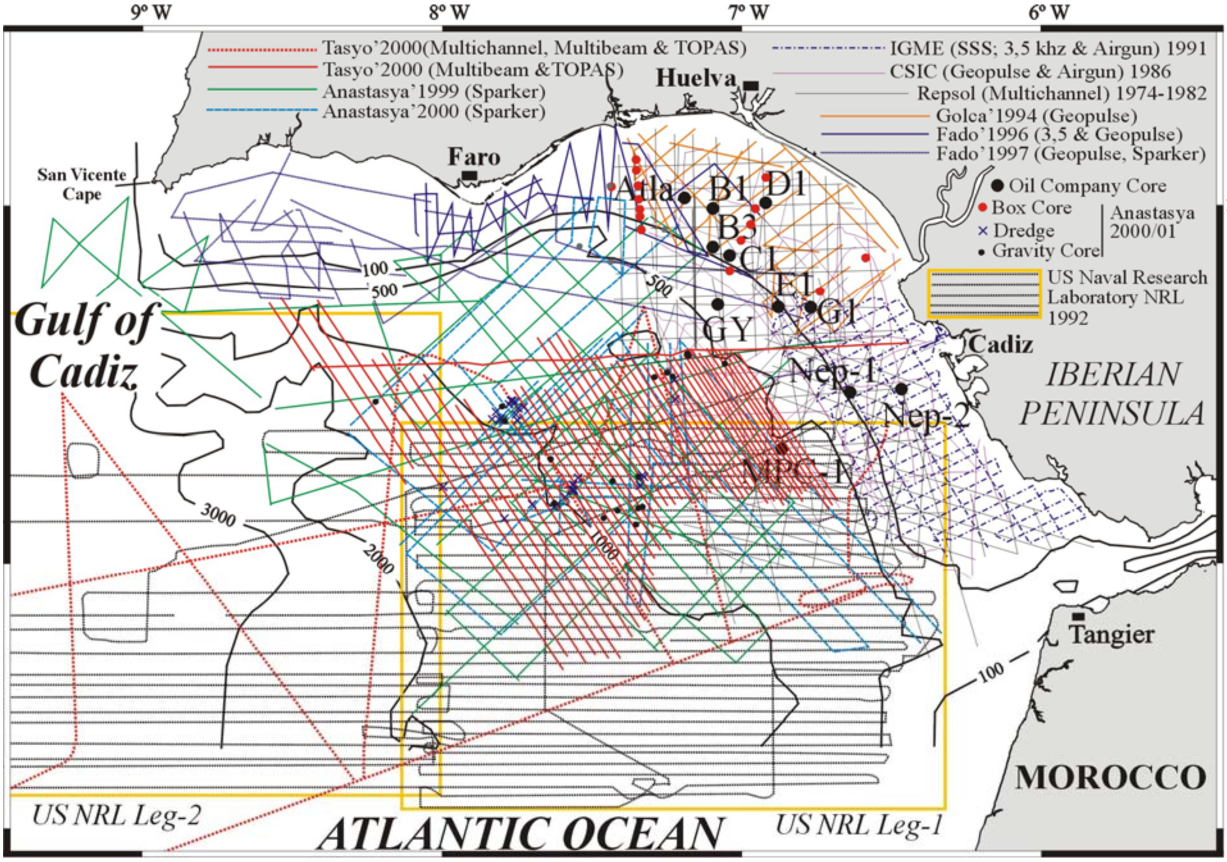


Figure 3.- Location of seismic profiles, multibeam, side scan sonar and core dataset compiled for the characterization of the contourite depositional system of the Gulf of Cadiz. Most of the data was positioned using GPS and DGPS systems.

The seismic and core data have been interpreted in the following main stages: (i) Main discontinuities, seismic units and depositional sequences identification from seismic profiles analysis. (ii) Correlation between the main discontinuities and depositional sequences identified with the equivalents defined on the Faro-Albufeira drift system (Llave *et al.,* 2001; Llave, 2003), and with continental shelf studies (Hernández-Molina *et al.,* 2002). (iii) Late Miocene to Pliocene chronostratigraphic framework based mainly in oil company borehole data (Mougenot, 1988; Terrinha, 1998; Llave *et al.,* 2001; Hernández-Molina *et al.,* 2002; Llave, 2003). (iv) Quaternary chronostratigraphy using 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.,* 2004a and b, 2005b). (v) Upper Quaternary chronostratigraphy based on the correlation of two Calypso piston cores (isotopedated) with very and ultra high-resolution seismic profiles (sound velocity in sediments of 1600 m/s is considered) (Llave *et al.,* 2004a, 2005a). (vi) Interpretation of climatic changes in relation to paleoceanographic evidences within the CDS. (vii) Consideration of the tectonic influence on paleoceanography and the evolution of contourite depositional architecture.

3.3. Present morphosedimentary features of the contourite depositional system

Five morphosedimentary sectors within the CDS in the middle slope of the Gulf of Cadiz have been distinguished by Hernández-Molina *et al.* (2003, 2005) and Llave (2003) (Fig. 4):

- Sector 1: *Proximal scour and sand ribbons.* It is characterised by a smooth *alongslope* terrace close to the Strait of Gibraltar (500-800 m depth), dominated by an abrasive surface and several NE-SW erosive scour alignments. There are also some depositional features as SE-NW orientated bed-forms (ripple marks, sand ribbons and sand waves) have been especially identified in the northwest zone. These features are result from the MOW's strong and turbulent flow, with a maximum velocity outside the Gibraltar gateway (240 cm/s) that decreases to the W and NW (around 100 cm/s).

- Sector 2: *Overflow-sedimentary lobe.* It is located at 800-1600 m depth, being characterised by a fan shape with surface bed-forms (sand and mud small lobate bodies and wave-fields). There are several NE-SW large furrows displaying gravitational features on their margins. This sector result from several separate MOW filaments flowing towards the W with a velocity of 50 cm/s on average; while other filaments flow towards the SW with an average velocity of 25 cm/s. Many fields of mud volcanoes, hydrocarbon seepage and hydrocarbon-derived carbonate chimneys can be identified (Diaz del Río *et al*., 2003; Somoza *et al.,* 2002, 2003).

- Sector 3. *Channels and Ridges.* It is located in the central area of the middle slope (800-1600 m depth), being characterised by the complex interaction of the ML core with the irregularities of the seafloor generated by the NE-SW diapiric ridges (*Guadalquivir* and *Cadiz*) and by the *Guadalquivir Bank* uplift. This leads to progressive erosion of the contourite channels (Madelain,1970; Kenyon and Belderson, 1973; García, 2002; Hernández-Molina *et al.,* 2003) known as (Fig. 4): Cadiz (up to 100 cm/s MOW velocity), Guadalquivir (40-50 cm/s MOW velocity), Huelva and Diego Cao (40 cm/s MOW velocity), and Gusano channels. These contouritic channels are located along the SE flank of the diapiric ridges; however, several NE-SW *marginal valleys* have been detected on the NW flanks. Some mass movement elements are described both on the flanks of the diapiric structures and contourite channels, and also several mud volcanoes can be observed (Somoza *et al*., 2002, 2003).

- Sector 4: *Active contourite depositional.* It is developed in the central and NW areas of the middle slope (300-600 m depth) by the interaction with the seafloor of the MU core flowing northwestward with an average velocity around 20-25 cm/s. It is characterised by the dominance of depositional features represented by (Fig. 4): (a) The *elongated mounded, and separated Faro-Albufeira drift,* located on the South-Portuguese margin. (b) A *sheeted drift complex,* forming the basinward prolongation of the mounded drift. Three sheeted drifts have been differentiated: *Faro-Cadiz*, *Bartolomeu Dias* and *Albufeira.* (c) A *plastered* drift, located to the E of the mounded drift. An important erosive contouritic channel parallel to the slope is described, named Alvarez Cabral Moat and also gravitational features are defined on the mounded drift and Faro-Cadiz sheeted drift.

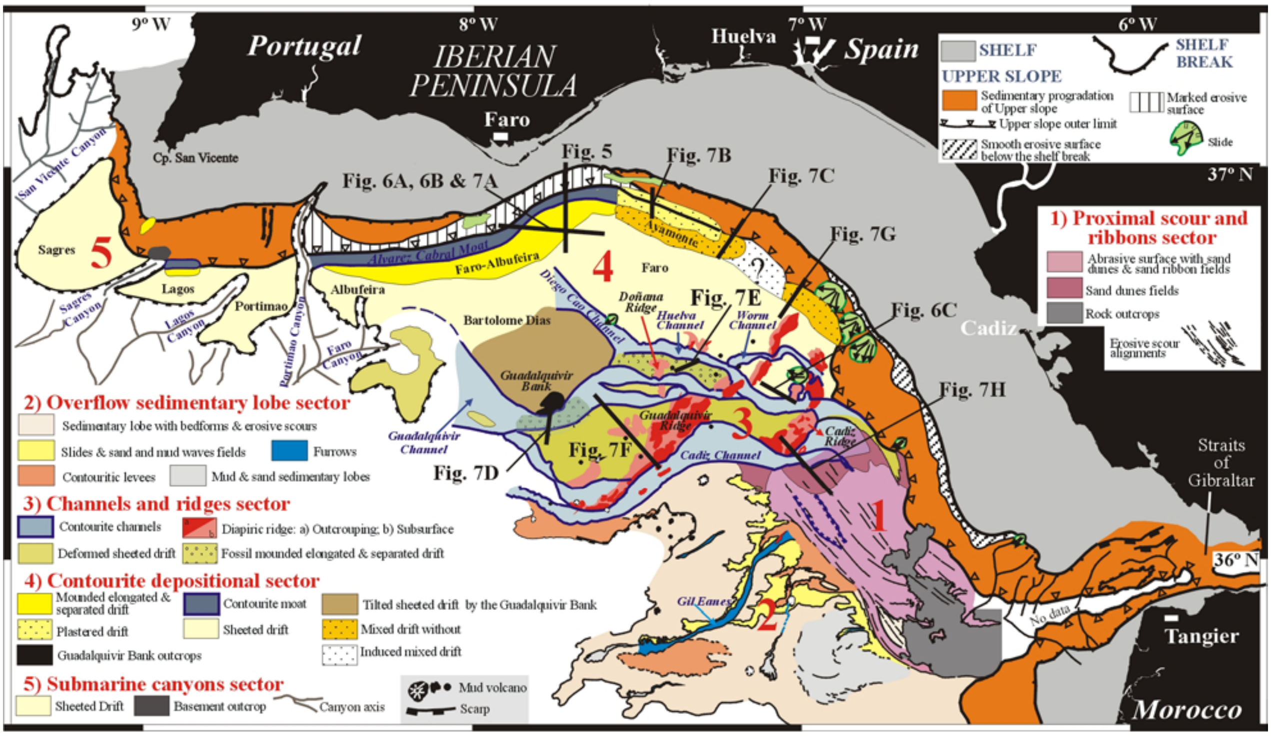


Figure 4.- Morphosedimentary map of the Contourite Depositional System on the middle slope of the Gulf of Cadiz (Modified from Hernández-Molina *et al*., 2003). Morphosedimentary sectors: 1) *proximal scour and sand ribbons sector;* 2) *overflow sedimentary lobe sector*; 3) *channels and ridges sector*; 4) *contourite depositional sector*, and 5) *submarine canyons sector*.

- Sector 5: *Submarine canyons.* This sector is located in the western area of the middle slope dominated by the interaction of the MU core and by the occurrence of a number of NNE-SSW and NE-SW canyons cutting across the slope: the Portimao, Lagos, Sagres and San Vicente canyons. These erosive features cut through and delineate several sheeted drifts at around 1000 m water depth: *Portimao, Lagos* and *Sagres sheeted drifts*. There is also a small elongated mounded and separated drift, at a water depth of 950 m, named *Lagos mounded drift*. Some mass wasting elements are observed on the sheeted drifts near the canyons.

3.4. Seismic stratigraphic framework

Four major low-resolution depositional sequences have been recognised in the Pliocene and Quaternary sedimentary record which must be related to MOW paleoceanographic changes. They are separated by four relevant regional discontinuities (Fig. 5): M (Messinian), LPR (Early Pliocene), UPR (Late Pliocene) and MPR (Mid Pleistocene) (Llave *et al.,* 2001, 2005a and b; Hernández-Molina *et al*., 2002, 2005; Stow *et al*., 2002c; Stow and Hernández-Molina, 2005). This could be in agreement with the sedimentary record identified in the Strait of Gibraltar where four major depositional phases can be recognized bounded by three major erosive stages (Esteras *et al.,* 2000).

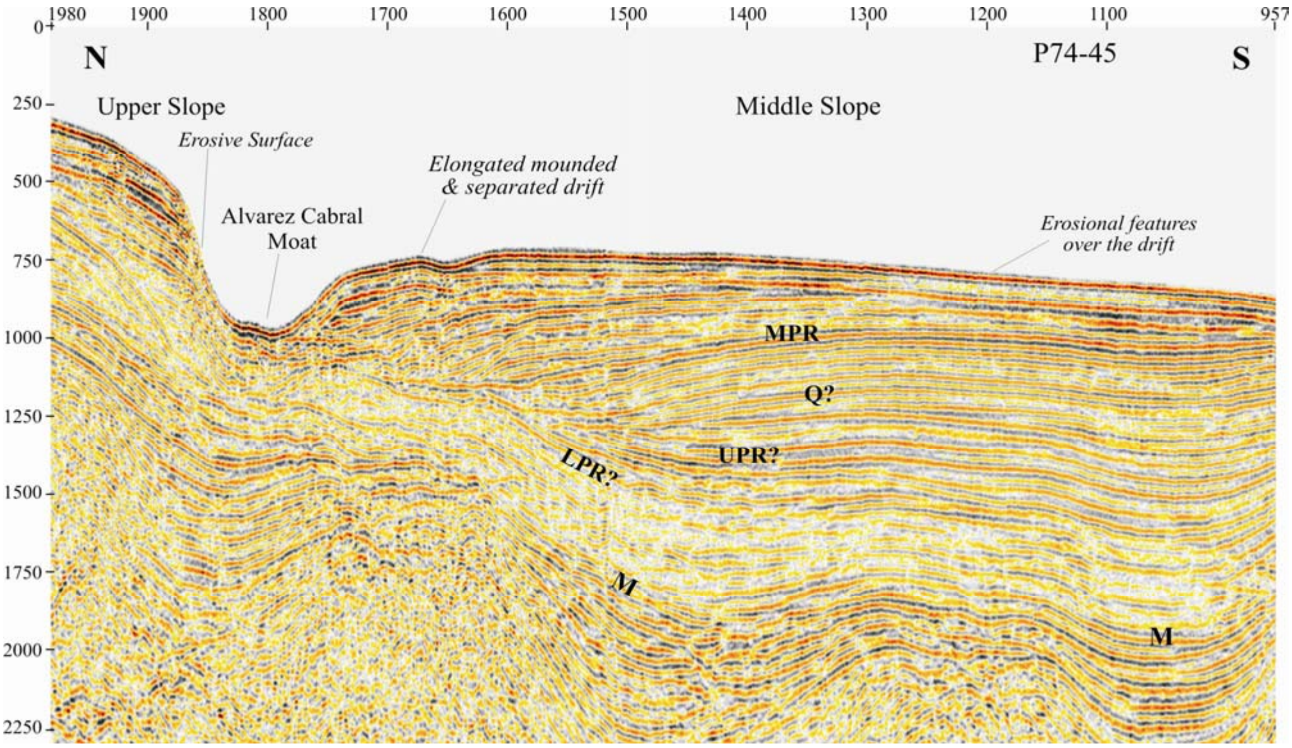


Figure 5.- Uninterpreted multichannel seismic reflection profile across the Faro-Albufeira drift on the middle slope (Line P74-75 given by REPSOL-YPF Oil Company for the present work). Four major low-resolution depositional sequences have been recognised by MCS profiles in the Pliocene and Quaternary sedimentary record (Llave *et al.,* 2001; Hernández-Molina *et al.,* 2002, 2005). They are separated by four relevant discontinuities: M (Late Messinian), LPR (Early Pliocene), UPR (Late Pliocene) and MPR (Mid Pleistocene).

Within the Quaternary sedimentary record of the contourite deposits, two main depositional sequences have been identified (see details in Llave *et al.,* 2001, 2005a and b; Hernández-Molina *et al.,* 2002; Llave, 2003): Q-I and Q-II, separated by a marked continuous reflector of strong amplitude and high reflectivity defined as the MPR discontinuity (Fig. 6A). This discontinuity marks a change in seismic facies, separating deposits with a more aggrading pattern (Q-I) from those above with a more progradational stacking pattern (Q-II).

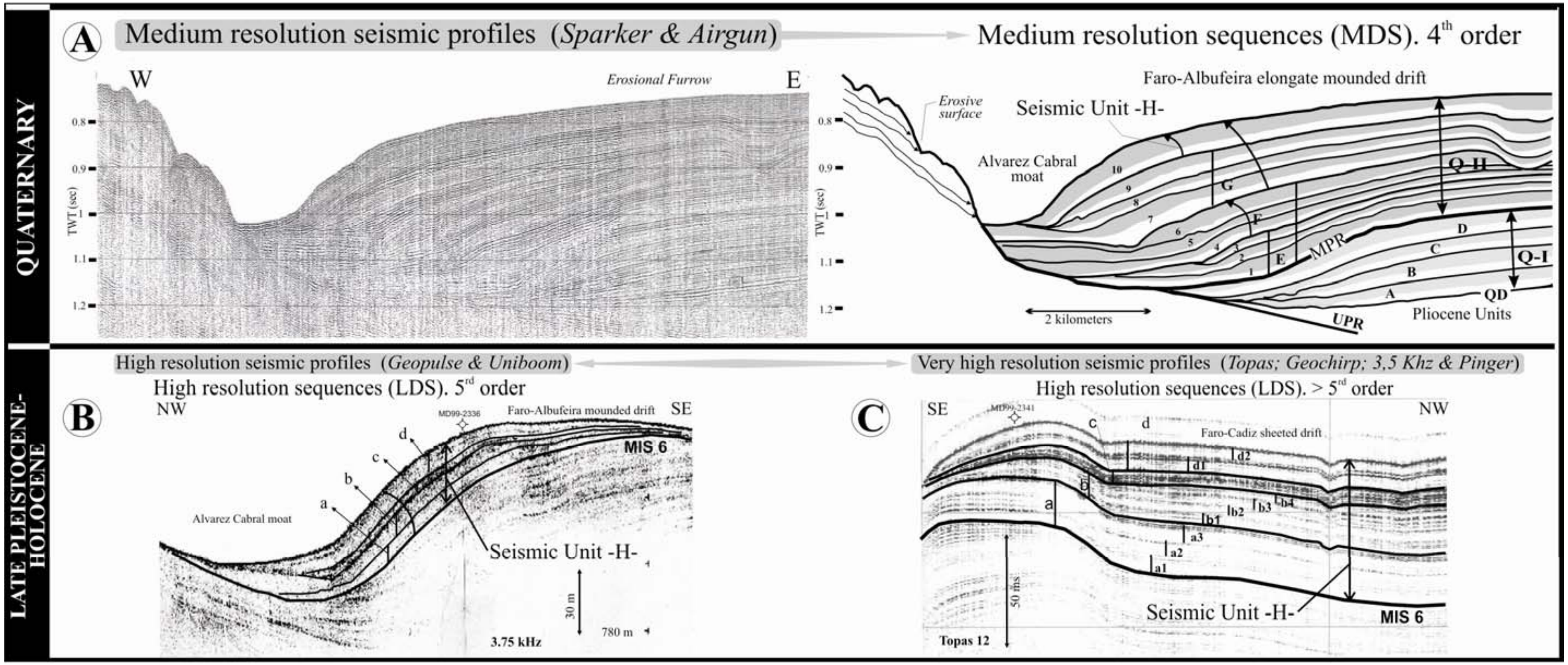


Figure 6.- A) Sparker seismic profile and line drawing through the Faro-Albufeira drift. QI & QII comprises 4 minor asymmetric depositional sequences each one (A, B, C, D and E, F, G, H respectively). In grey is shown the reflective seismic facies and in white the transparent seismic facies (modified from Llave *et al*., 2001). B and C) 3.5 kHz and Topas seismic profile across the mounded Faro-Albufeira drift and Faro-Cadiz sheeted drift respectively, indicating the main Late Pleistocene-Holocene seismic units, where 4 high-resolution DS (a-d) were determined, internally structured into subunits periodicity related to the Heinrich Events (Llave *et al*., 2004a, 2005a). E) Sketch with the position of the seismic lines.

Both depositional sequences show a general progradational stacking pattern in the *mounded* drift (Fig. 6A) that laterally tends to become aggradational in the *sheeted* drift (Fig. 6A). These two main depositional sequences comprise eight minor units (from A to H), bounded by minor erosive and reflective surfaces, which are interpreted as discontinuities (Fig. 6A). Very recently, Llave *et al.* (2005a) carried out a detailed seismic stratigraphic analysis of the last minor depositional sequence within Q-II (named H) describing four minor units: *a, b, c* and *d,* bounded by minor discontinuity surfaces. These minor units show vertical and gradual changes from transparent facies at the bottom to reflective facies near the top, which has allowed the differentiation of ten subunits: a_1, a_2 and a_3; b_1, b_2, b_3 and b_4; *c;* d_1 and d_2 (Fig. 6B and C).

The same facies trend is observed in each major and minor depositional sequences: (1) a transparent zone at the base; (2) smooth, parallel reflectors of moderate-to-high amplitude in the upper part; and (3) a high-amplitude erosive continuous surface at the top (Fig. 6). 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 (Fig. 6).

The general spatial distribution of Q-I and Q-II depositional sequences has been mapped from the central sector (sector 3) towards the north and west (sectors 4 & 5) (Llave *et al.,* 2001, 2005b). The main structural features in the region, including the diapiric mounds and ridges and the Guadalquivir Bank uplift, have had a marked effect on the distribution of these depositional sequences. The most important depocenters for the Q-I depositional sequence are located in the following areas: (a) *Faro-Albufeira drift*, where the maximum thickness is about 200 ms (TWT); (b) south of *Faro-Cadiz sheeted drift*, with a maximum thickness of 250 ms (TWT); and (c) the central part of *Bartolomeu Dias sheeted drift*, where a depocenter up to 300 ms (TWT) thick is observed. The main depocenters of the Q-II depositional sequence are located in similar areas and with similar orientations to those of sequence Q-I, as follows: (a) *Faro-Albufeira drift*, where the maximum thickness is about 375 ms (TWT); (b) south of *Faro-Cadiz sheeted drift*, up to 250 ms (TWT) thick; and (c) the central part of *Bartolomeu Dias sheeted drift*, where the depocenter is up to 300 ms (TWT) thick.

3.5. Chronostratigraphic framework

A regional Quaternary chronostratigraphic framework is shown in Table I (Llave *et al*., 2001, 2004 a and b; 2005a, b and c; Llave, 2003): QI and QII depositional sequences are Quaternary in age (Table I), and the main discontinuities QD, MPR and MIS12 are dated as around 1.8 Ma; 900

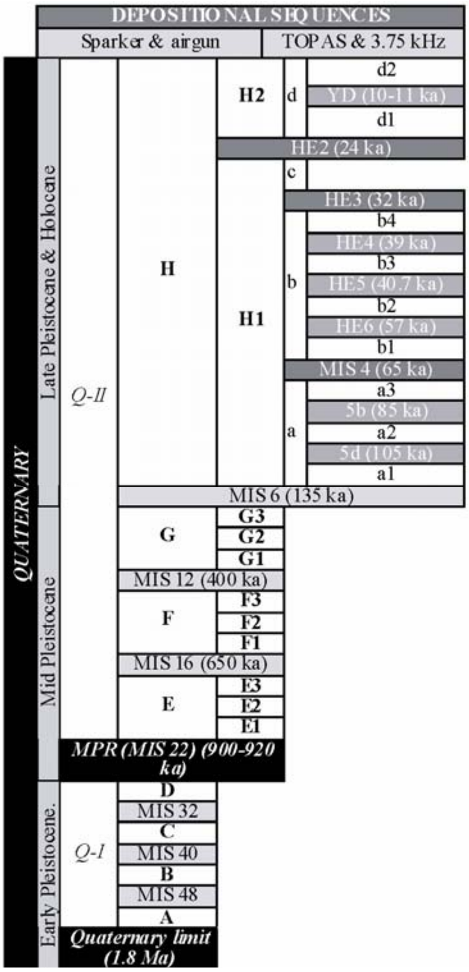


Table 1.- Chronostratigraphic table of the Quaternary depositional sequences described**.**

ka and 400 ka respectively (Llave, 2003; Llave *et al*., 2004 a and b,, 2005b), corresponding in age with the base of the Quaternary, the mid Pleistocene and the end of middle Pleistocene respectively (Fig. 5). In more detail, the youngest H depositional sequence is Late Pleistocene-Holocene in age (Llave *et al.,* 2005a) (Fig. 6). The oldest seismic unit *a* within H sequence was deposited between MIS 6 (135 ka) and Heinrich event H6 (57 ka), seismic unit *b* was deposited between H6 (57 ka) and H3 (32 ka), seismic unit *c* between H3 (32 ka) and H2 (24 ka), and the youngest seismic unit *d* was deposited between H2 (24 ka) and the present.

3.6. Stratigraphic architecture of the major drift deposits

Within the CDS, significant differences in the Quaternary stratigraphic stacking pattern of the same major and minor depositional sequences are identified in the active and buried drifts. These changes are essential to understand the evolution of the depositional system and to identify major paleoceanographic events. Six different architectural elements have been identified (Table II and Fig. 7) (Llave *et al.,* 2005b and c): (a) *elongated mounded & separated*, (b) *sheeted,* (c) *plastered*, (d) *fossil mounded drifts*, (e) *mixed drifts* and (f) *wave fields* on the present seafloor.

Active drifts

a) Elongate mounded and separated drifts (Table II and Fig. 7A). These drifts are located in Sectors 4 and 5 of the CDS. Three elongated mounded and separated drifts (hereinafter referred to as mounded drifts) are identified: *Faro-Albufeira*; *Lagos* and *Sagres* drifts. These drifts display an asymmetric mound shape with a steep, slump-prone northern flank, and a gentle, smooth southern flank. Sequences exhibit a sigmoid to oblique-parallel progradational stacking pattern towards the north with a significant discontinuity at the base.

c) Plastered drift (Table II and Fig. 7B). This drift is located eastward from the mounded Faro-Albufeira drift. It has a convex shape on the upper slope to a concave on the middle slope. The depositional sequences (mainly H) that comprise this drift (100 ms twtt) show an aggradational stacking pattern and lens shape.

Fossil drifts

In Sector 3 and part of Sector 4 of the middle slope, the main Late Quaternary deposits are deformed sheeted drifts. However, beneath these deposits, three main fossil elongated mounded and separated contourite drifts (hereinafter referred to as *fossil mounded drifts*) have been identified, which characterise a *fossil contourite depositional system* (Hernández-Molina *et al*., 2003; Llave *et al*., 2003a and b, 2005c). These fossil mounded deposits are: (a) *Cadiz fossil mounded drift* (CFD), (b) *Guadalquivir fossil mounded drift* (GFD), and (c) *Huelva fossil mounded drift* (HFD):

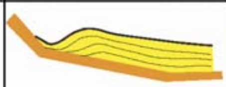
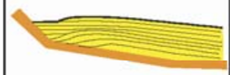
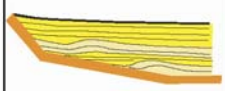
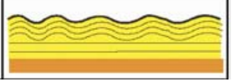
TYPES OF CONTOURITES					
Deposits		Location	Name	Stacking pattern	Sketch
ACTIVE DRIFTS	Elongated mounded & separated	Distal part of upper slope-Middle	Faro-Albufeira	Vertical and lateral prograding stacking pattern with donwlap terminations	
		Upper slope	Sagres		
	Plastered	Upper slope	Ayamonte	Parallel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

Table 2.- Summary of the different types of contourite drifts described in the middle slope of the Gulf of Cadiz.

a) The *Cadiz fossil mounded drift* (CFD) (Table II and Fig. 7C), is located in the northeast zone of Sector 4, in the transition between the upper and middle slope. The CFD is composed of the Q-I sequence displaying a progradational configuration towards the upper slope that constitutes the eastern prolongation of the Faro-Albufeira mounded drift. It is fossilized by the youngest aggrading Q-II sequence.

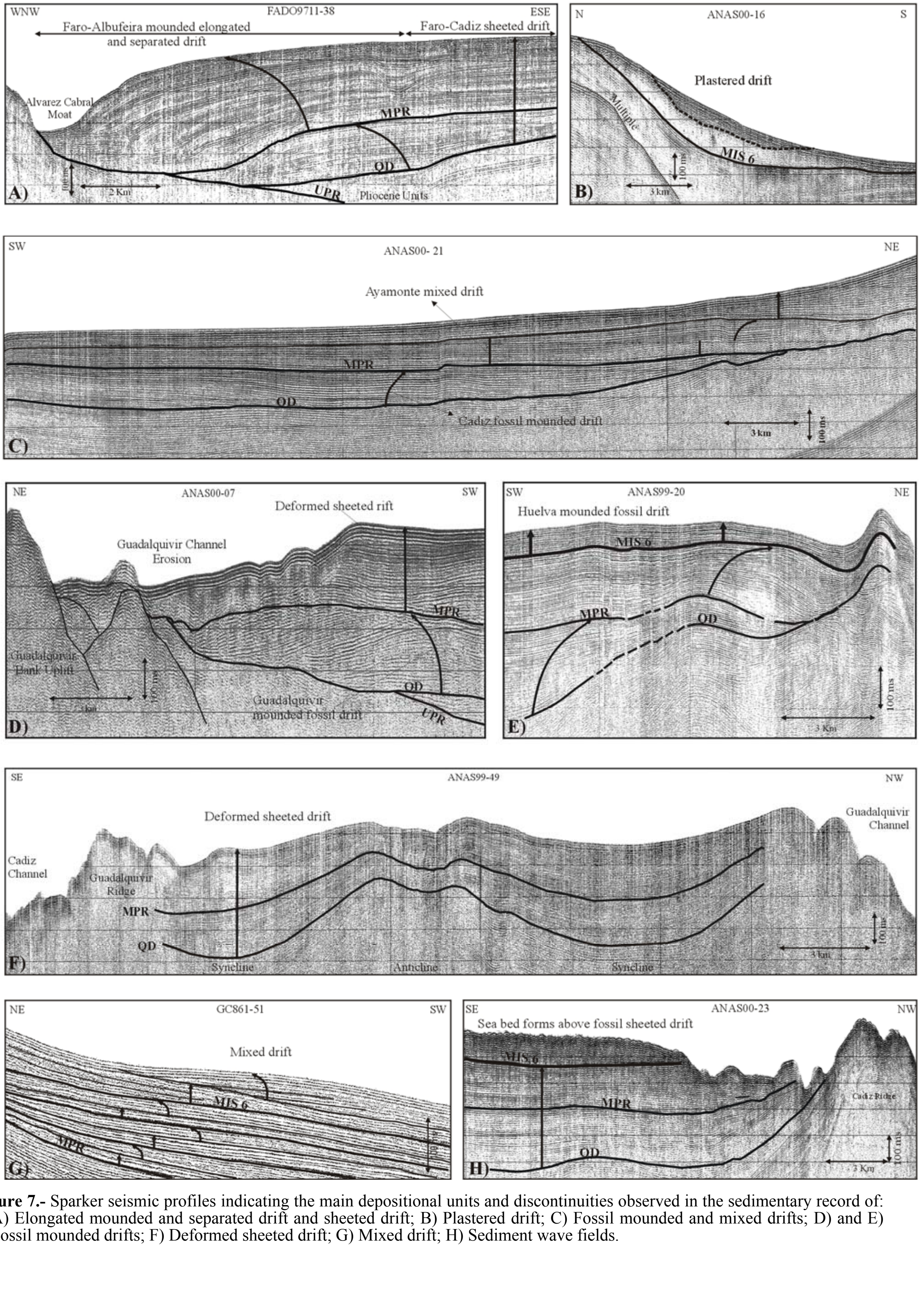


Figure 7.- Sparker seismic profiles indicating the main depositional units and discontinuities observed in the sedimentary record of: A) Elongated mounded and separated drift and sheeted drift; B) Plastered drift; C) Fossil mounded and mixed drifts; D) and E) Fossil mounded drifts; F) Deformed sheeted drift; G) Mixed drift; H) Sediment wave fields.

b) The *Guadalquivir fossil mounded drift* (GFD) (Table II and Fig. 7D), is located to the south of the Guadalquivir Bank and it can be observed that the MPR discontinuity constitutes in this sector an important erosive truncated surface which separates the prominent northeasterly prograding body (QI), from a more aggrading one (QII).

c) The *Huelva fossil mounded drift* (HFD) (Table II and Fig. 7E), is located on the southern margin of the present-day Huelva Channel and is characterised by a change in the depositional style from a northeasterly mounded drift (from A to G depositional sequences) fossilized by the most recent seismic unit (H), showing an aggrading stacking pattern.

The basinward prolongation of the three fossil mounded drifts (CFD, GFD & HFD) has an aggrading stacking pattern with alternating transparent and reflective units, constituting a sheeted-deformed contourite drift in Sector 3 and sheeted contourite drift in Sector 4. Additionally, in this Sector 3, the sequences are affected by low frequency and amplitude anticline/syncline structures. (Table II and Fig. 7F).

Mixed drift

The mixed drift is located in the northeastern and eastern zone of Sector 4 and named *Ayamonte mixed drift* (Table II and Fig. 7A and G). It was developed during Q-II sequence above the *Cadiz fossil mounded drift* described previously, comprising an alternation of sequences with sheeted drift seismic facies alternating with mounded and separated drift characteristics facies.

Sediment wave fields

Sedimentary wave fields are widespread on the present seafloor in Sector 2, and especially in Sector 1 of the CDS representing secondary sedimentary features superimposed on the most recent sequence (H) (Table II and Fig. 7H).

3.7. Major morphostructural features

The development and distribution of contourite deposits have been strongly influenced by recent tectonics, including the movement of diapirs leading to both outcropping and buried diapiric ridges as Cadiz and Guadalquivir Diapiric Ridges *(GDR and CDR)* and Doñana Buried Diapiric Ridge (*DBDR*), and by the uplift of the Guadalquivir Bank (*GB*), displacement along several fault systems, and the evolution of anticline/syncline structures (Maldonado *et al.,* 1999; Maestro *et al.,* 2003; Medialdea *et al.,* 2004; Fernández-Puga, 2004; Llave *et al.,* 2005b and c) (Fig. 8). These structures have played an important role in this area, affecting the hydrodynamic system, the accommodation space for Pliocene-Quaternary sedimentation and then producing changes in the depositional geometry and several discontinuities in the sedimentary record (Figs. 8B, C and D). In general, it has been observed that the contourite sequences are syn-sedimentary with the emplacement of these tectonic structures being characterised during diapiric dome growths by (Figs. 8B): (1) thinning toward the axis of the diapiric uplift; and (2) only minor thickening into relatively distant peripheral sinks (Fig. 8).

3.8. CDS Quaternary evolution

Since the CDS of the Gulf of Cadiz began its development after the opening of the Strait of Gibraltar at the end of the Messinian (Nelson *et al.,* 1993), it has been driven by a combination of tectonic evolution of the margin, and environmental changes in oceanographic and climatic conditions.

The depositional sequences QI and QII constitute high-order depositional sequences related to a 3rd-order cycle at 800 ka, separated by the most important erosive reflective surface (MPR) correlated regionally with an important change in the climatic trend known as the *Mid-Pleistocene Revolution*, which occurred 900-920 ka ago (Llave *et al*., 2001, 2004a, 2005b and c; Hernández-Molina *et al*., 2002) (Fig. 9). This represents a shift to longer glacial/interglacial cycles, an increase in the cycle amplitude since and the boundary between asymmetric 4th-order sea-level cycles of 41 ka (obliquity cycles) and the subsequent onset of 100 ka eccentricity orbital cycles. Recent detailed studies in the Late Pleistocene sedimentary record revealed high frequency cyclicity in the contourite sedimentary record, with a frequency range below the Milankovitch band that corresponds to cooling Bond Cycles (10-15 ka), which ended in an Heinrich climatic event (Llave *et al.,* 2004a, 2005a) (Fig. 9). The coincidence between climate and contourite cyclicity discloses a straightforward interpretation of Late Pleistocene-Holocene *MOW* dynamics in the context of northern hemisphere climate variability.

A variable spatial influence of the MOW during each climatic stage has been carried out (Llave *et al*., 2001, 2004 a and b, 2005 a, b and c; Hernández-Molina *et al*., 2002, 2004, 2005; Llave, 2003): These studies have suggested that the MOW had a significantly higher salinity and hence greater density and then it played a stronger role during cold intervals and Heinrich events. This creates a stronger interaction with the seafloor at greater depths, hence facilitating the transport and deposition of coarser material, and so also leading to higher sand contents in contourites. Therefore, the ML core was enhanced during cool periods, favoring the development of sandy contourites in the central area of the middle slope. During warm climatic periods the interaction of the MU core with the seafloor was more intense at shallower depths, where sandy contourites developed.

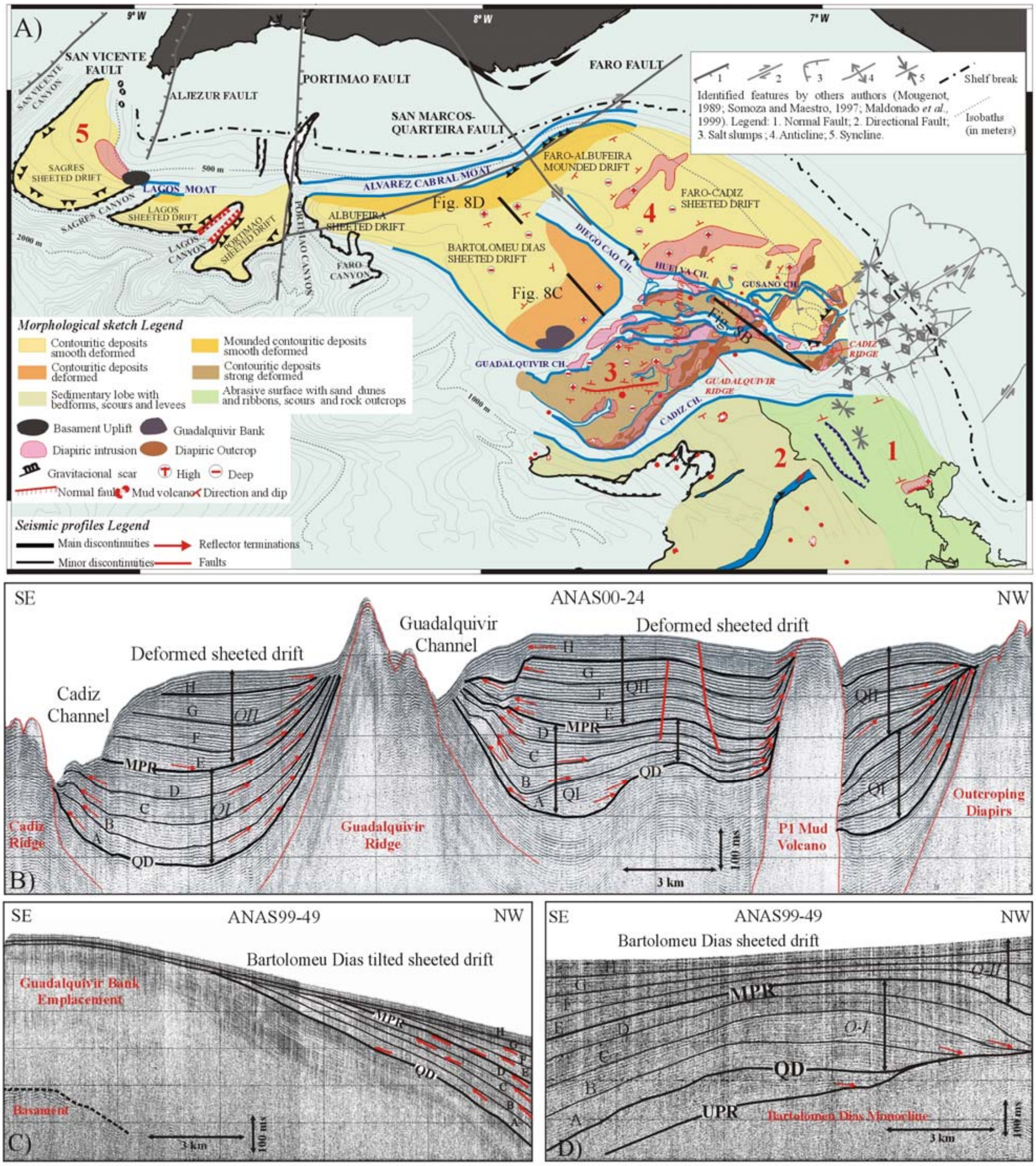


Figure 8.- Morphostructural sketch of the main geological features that affect the Contourite Depositional System on the middle slope of the Gulf of Cadiz with some examples of these structural characteristics on examples from sparker seismic profiles (Modified from Llave *et al*., 2005b).

In addition to paleoclimatic changes, the tectonic influenced has been observed in the stratigraphy architecture changes of the six types of contourite drifts (Llave *et al.,* 2005b; Hernández-Molina *et al.,* 2005): (A) During the Mid Pleistocene Revolution (Fig. 9A and B) and (B) during the Late Pleistocene-Holocene (Fig. 9B and C).

A) Mid Pleistocene Revolution (MPR): CDS depositional change. Sectors 1 and 2 of the CDS were characterised by the development of broad sheeted drifts bounded by extensive abrasion surfaces during the Early and Mid Pleistocene (Fig. 9A and C). In the northern part of Sector 3 an important change was produced: Whereas before the MPR there was developed a wide *elongate mounded and separated Huelva and Guadalquivir drifts* (the defined fossil HMD & GMD drifts (Fig. 9A and C), after the MPR, the fossil HMD was still active but the fossil GMD became inactive, and extensive sheeted drifts sequences were generated fossilizing the previous mounded deposits (Fig. 9A and B). A change is also observed in eastern part of the Guadalquivir Moat, that after MPR became a contouritic channel (Fig. 9A and B). In Sector 4 it is observed that before MPR the *elongate mounded and separated Cadiz-Faro-Albufeira drift* was extended close to the diapiric structures of Sector 3 as far west as Portimao Canyon, and after MPR the *Ayamonte mixed drift* is developed fossilizing the *Cadiz mounded drift* (Fig. 9A and B). The paleogeographic situation of the rest of Sectors 4 and 5 before and after MPR was quite similar than present.

These changes in the architecture style of CDS during the Mid Pleistocene are most likely related to tectonic activity in the Guadalquivir Bank and diapiric ridge area, generating new MOW pathways and oceanographic conditions (Llave *et al.,* 2005b) (Fig. 9A and B). Diapiric ridge movements and Guadalquivir Bank uplift were most probably related to the compressive regimen that took place between 740-450 and 295-225 ka, and described by Rodero (1999) and Rodero *et al.* (1999).

B) Late Pleistocene to Holocene CDS: change to present configuration. During this stage most of the present contouritic features were developed, especially most of the erosive characters observed in Sector 3 (Fig. 9B and C). In Sector 1, more erosive features began to be developed, as an abrasive surface and erosive scours alignment and furrows. Numerous sedimentary waves were also developed, not only in Sector 1 but also in Sector 2. In Sector 3, the *fossil HMD* disappeared completely being buried and fossilized by the youngest sheeted drift (Fig. 9B and C). New contourite channels, including the Gusano, Huelva and Diego Cao, and other minor branches related to the Guadalquivir channel are formed (Fig. 9B and C). In Sector 4 an aggradational stacking pattern was developed above the *Ayamonte mixed drift* (Fig. 9B and C). Laterally, the *plastered drift* started to develop in the transition zone between the upper and middle slopes, to the east of the *Faro-Albufeira mounded drift*, which reached its present location (Fig. 9B and C).

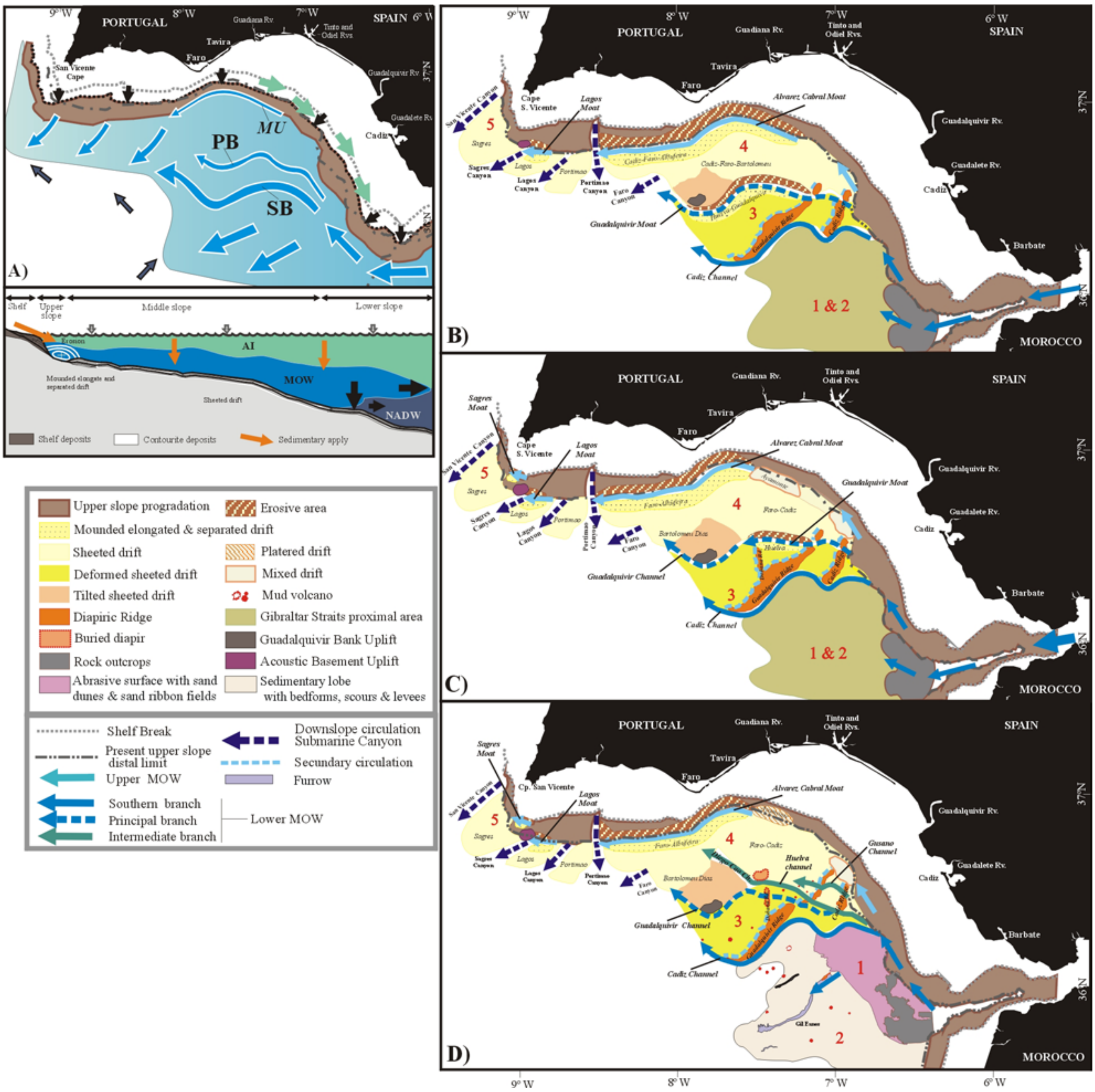


Figure 9.- A) Paleocirculation sketch during glacial conditions, when the *MOW* is denser, deeper and then the principal and southern branches (*PB and SB*) are the main fluxes. B, C, and D) Interpretative sketch of paleogeographic and paleoceanographic reconstruction of the evolution of the contourite depositional system during: the Early to Mid-Pleistocene; **(B)** the Mid- to Late Pleistoceneand **(C)** the Late Pleistocene and Holocene **(D)**. (Modified from Llave *et al.,* 2005b).

These new depositional style changes can be related with coeval tectonic movements registered in the Strait of Gibraltar by Zazo *et al.* (1999), and in the reactivation of the diapiric ridges and isolated diapiric bodies of Sector 3 (Pérez-Fernández, 1997; Llave *et al.,* 2005b). Our hypothesis is that recent tectonic activity conditioned a new sea bottom morphology, especially regarding the Guadalquivir and Cadiz diapiric ridge configuration on the seafloor (Fig. 9B and C), and this controlled new flow pathways, with the strongest flowing branches of the MOW over the middle slope. Consequently, a general circulation of the MOW similar to the present was established during this stage.

4. Economic relevance of contourite deposits and its interest as potential reservoirs

Contourite deposits, and in general all deep-water traction current deposits, are of great interest to the mineral and energy resources sector (Teleki *et al*., 1987; Earney, 1990; Seibol and Berger, 1993). This is especially so because mineral and oil companies are progressively exploring the deeper submarine domains of continental margins and abyssal plains, where these deposits are very common.

Contourite deposits have in the past been considered as potentially good hydrocarbon source rocks, but less good as reservoir rocks in comparison with turbidites (Pickering *et al.,* 1989). Nevertheless, more recent work has proposed that contourite deposits can be excellent *reservoir rocks* for hydrocarbon fields (oil & gas), gas hydrates and shallow free gas, and their study and facies modelling is at present of interest for oil companies (Stow *et al*., 2002a; Rebesco, 2005). Bottom currents are a crucial factor in hydrocarbon reservoir development because weak flows may allow the accumulation of *source rocks* whereas high velocity flows may represent a mechanism for "*clean sand*" accumulation in deep-sea environments producing good *reservoir rocks*. This is based on the premise that some sandy contourites and related deposits, due to the long-term effects of current winnowing, may have greater textural maturity and thus better developed primary interstices than turbidites, so that their reservoir potential is much better. In addition, sandy contourites, internal-tide and internal-wave deposits typically are interbeded with deep-water fine-grained sediments that can form good *traps* (Zhenzhong *et al.,* 1998; Rebesco, 2005).

Although there is growing evidence that bottom currents affect the distribution and occurrence of sandy (reservoir-prone) deposits in deepwater (e.g. Viana *et al.,* 1998; Moraes *et al,* in press), there is currently a lack of convincing descriptions of sandy contourites as hydrocarbon reservoirs. The few published examples (Shanmugam *et al.,* 1993) are considered of dubious interpretation, and may be better re-interpreted as turbidites (Stow *et al.,* 1998). Clearly much more work is required on this important topic.

One well established example of reservoir prone sandy contourites is from the Paleogene sequence of the Campos Basin, offshore SE Brazil (Moraes *et al.,* in press). Much of the reservoir succession comprises massive to normally-graded, unstratified sandstones, which are interpreted as turbidites. These are interbedded with thinner horizons of moderately to heavily bioturbated sandstones, which are interpreted as bottom-current deposits. The turbidite sandstones form the better quality reservoirs, the sandy contourites provide lower quality reservoir units.

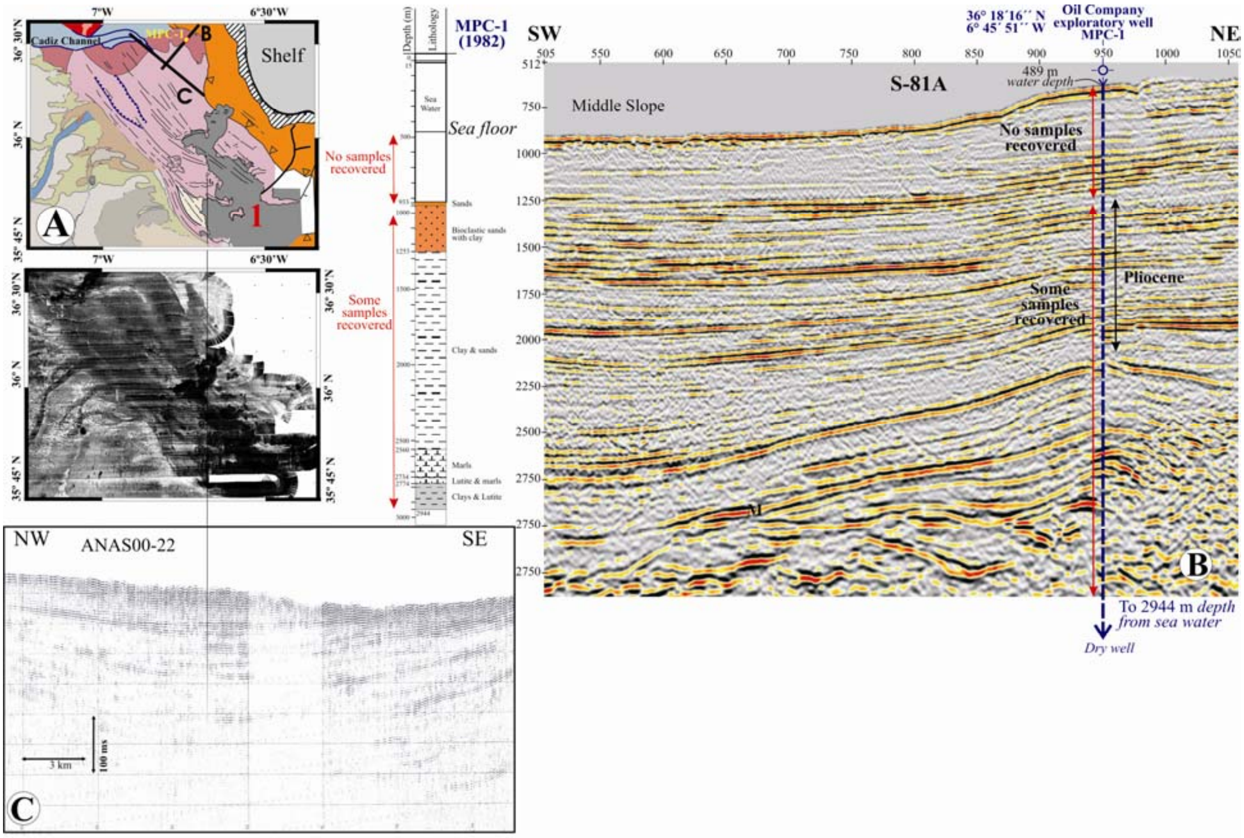


Figure 10.- A) Sketch of the Sector- 1 (*Legend on Fig. 4*) of the Contourite Depositional System on the middle slope of the Gulf of Cadiz (*proximal scour & ribbons sector* of Hernández-Molina *et al*., 2003); B) Uninterpreted Multichannel seismic reflection (MCS) profile across the middle slope (Line S-81A) given by REPSOL-YPF Oil Company for the present work. C) Uninterpreted high resolution sparker seismic profile (ANAS00-22) of the Sector-1.

An exceptional example of reservoir rocks is the sandy contourite drift of the contourite depositional system of the Gulf of Cádiz was described by Buitrago *et al.* (2001), in the *proximal scour and sand ribbons* (Sector 1. Fig. 10) close to the Straits of Gibraltar. Here an exploratory well (MPC-1) drilled in 1982 by Repsol-YPF, identified between 925 and 1740 m depth a Pliocene sandy/clayey interval with a porosity between 38% to 34% with the following main characteristics: sand-clay thickness of 815 m, net sand thickness of 600, net/total relation of 74%, 80 reservoirs layers, average thickness of the frequent layer of 12 to 15 m, minimum layer thickness of 1.5 m, maximum layer thickness of 40 m and net in major layers of 10 m of 168 m (Buitrago *et al.,* 2001). Stacking pattern of these deposits show tabular aggradational sequences without any defined vertical trend, but with the thickest layer located usually in the base and small channels morphologies in the top (Buitrago *et al.,* 2001). Contourite processes in that sector were defined by Hernández-Molina *et al*. (2003, 2005) where mainly erosive scour alignments and an abrasion surface are dominant at the present-day sea-floor, but depositional features, such as extended sand dunes and sand-ribbon fields, have also been identified.

5. Conclusions

- Contourite *drifts* are common sedimentary features in modern ocean basins. They can be large sedimentary bodies (hundreds of km long, tens of km wide, and with variable heights between 200 and 2000 m), as important as turbidite bodies.
- Contourite *drifts* can be excellent *reservoir rocks* for hydrocarbon fields, gas hydrates and shallow free gas, and at present their study and facies modelling is of interest in oil exploration. Bottom currents are a crucial factor in hydrocarbon reservoir development because weak flows may develop the accumulation of *source rocks* and high velocity flows may represent a mechanism for the "*clean sand*" accumulation in deep-sea environments producing good *reservoir rocks*. Moreover, the contourite deposits, due to their long term winnowing, may have greater textural maturity and thus better developed primary interstices than turbidites being their reservoir potential much better. In addition, sand-size contourites, internal-tide and internal-wave deposits typically are interbeded with deep-water fine-grained sediments that can form good *traps*.
- A overview of the Contourite Depositional System (CDS) in the middle slope of the Gulf of Cadiz is presented based on morphologic and stratigraphic data, where six types of drifts are identified including: *mounded elongated & separated drifts*, *sheeted drifts*, *plastered drifts*, *buried mounded drifts, deformed sheeted drifts and mixed drifts*. On the other hand, the principal erosive features identified include: *contourite channels*, *moats, furrows and marginal valleys*. Based on the distribution of depositional and erosive sedimentary features, 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's westward branches, bathymetric stress on the margin, and the Coriolis force.
- The understanding the stratigraphic stacking pattern of the major drifts within the contourite depositional system (CDS) of the Gulf of Cadiz has allowed us to identify some important changes in the contourite deposition style, and to reconstruct a regional Quaternary evolution. Three main stages have been recognized in the evolution of the CDS: (A) Early Pleistocene to Mid Pleistocene, (B) Mid Pleistocene to Late Pleistocene, and (C) Late Pleistocene to Holocene.

These evolutionary stages are most probably a function of changes in the interaction of the bottom current with the complex morphology of the continental margin caused by neotectonics.

- The sedimentary model of the CDS in the context of the continental margin of the Gulf of Cadiz could be defined as a mixed *contourite+turbidite* system, and as a *detached combined drift-fan*, as distinct from conceptual models of other North Atlantic margins. 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, synsedimentary tectonic activity, including diapiric ridge movement, bank uplift and compressive structures has represented a key long-term factor in seafloor morphology changes, which has controlled in every stage new pathways in the cores and branches of the MOW and, therefore, the type of contourite processes involved.

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