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Contourite drift construction influenced by capture of Mediterranean Outflow Water deep-sea current by the Portimão submarine canyon (Gulf of Cadiz, South Portugal)

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Abstract

The margin of the Gulf of Cadiz is swept by the deep current formed by the Mediterranean Outflow Water (MOW) flowing from the Mediterranean to the Atlantic. On the northern margin of the Gulf (Algarve Margin, South Portugal), the MOW intensity is low and fine-grained contourite drifts are built up with an alongslope development. From new sedimentological data, this study emphasizes the presence of two types of contourite drifts separated only by a deep submarine canyon incising the slope with a north-south orientation (Portimão Canyon). High-resolution seismic and bathymetry interpretation shows that on the eastern side of the canyon, the MOW forms a thick and large detached drift (Albufeira Drift) prograding toward both north and west, as shown in seismic profiles, with a high sedimentation rate. On this side of the canyon, the MOW intensity is high enough to erode the slope forming a moat channel (Alvarez Cabral). On the western side of Portimão Canyon, the MOW energy is lower, preventing moat channel erosion. Only flat and thin drift develops (Portimão and Lagos Drifts) with slow aggradation and a low sedimentation rate. This difference in drift development is due to the presence of the canyon which generates an important change in hydrodynamic of the MOW, confirmed by temperature-density measurements showing that MOW flows down Portimão Canyon. The canyon is responsible for the deviation of the direction of the MOW as it partly catches the deep-sea current flowing westward (i.e. capture phenomenon). It creates, thus, a decrease of the flow energy, competency and capacity between the east and west sides of the canyon. Through this phenomenon of MOW deep-sea current capture, the canyon constitutes a morphologic feature generating an important change in the contourite deposition pattern.

In addition to already known climatic and oceanographic influences, our results show the role of canyons on contourite drift building. This study provides new elements on autocyclic factors influencing the contourite sedimentation, which are important to consider in future sedimentary paleo-reconstruction interpretations.

Keywords: contourite drift; Mediterranean Outflow Water; contour current capture; submarine canyon; Gulf of Cadiz

1. Introduction

The Gulf of Cadiz represents a key zone for the global deep thermohaline circulation. It is the exchange zone between the Mediterranean Sea and the Atlantic

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Ocean and is swept by a strong deep current originating from the Mediterranean: the Mediterranean Outflow Water (MOW). This current is at the origin of various sedimentary processes, among which is contourite drift construction (Faugères et al., 1984).

A good understanding of drift formation explains the large diversity in their morphology and geometry. A drift classification including their evolution as a response to specific hydrologic and morphologic contexts was published by Faugères et al. (1999).

The interest in detailed contourite study increased because it brings understanding of deep current modifications and erosion/deposit processes. In that sense, these sedimentary bodies constitute a record of environmental changes. Several studies (e.g. Hernández-Molina et al., 2002; Llave, 2004; Llave et al., 2006) have emphasized the relationship between drift construction, paleoceanography and paleoclimate.

Two different drift morphologies are observed on the Algarve Margin (Gulf of Cadiz), providing an example of contourite drift diversity. The main aim of this study is to address the processes driving lateral differential growth of the drifts, using morphologic and seismic characteristics of these deposits. This work emphasizes the influence of the Portimão canyon on the different processes determining the present margin configuration.

Using a new bathymetric and high resolution seismic data set, this paper presents a detailed study of the geometry and evolution of two drifts. It gives an opportunity to constrain the interactions between drift construction processes, deep water circulation and canyon development. This paper presents the role of a canyon on the contourite sedimentation that was never considered before. In that sense, this work brings new element on autocyclic environmental factors influencing the contourite drift development which is important to consider in future sedimentary reconstructions.

2. Background

The Gulf of Cadiz is located in the eastern Atlantic Ocean, along the Spanish and Portuguese margins (Fig. 1). It stretches from the Strait of Gibraltar (south of Spain) to Cape St Vincent (south of Portugal).

2.1. Tectonic setting

The Gulf of Cadiz is situated on the African-Eurasian plate boundary. The evolution of the margin was influenced by three successive phases of extension and compression (Maldonado et al., 1999): (1) the development of a passive margin during the Mesozoic, related to

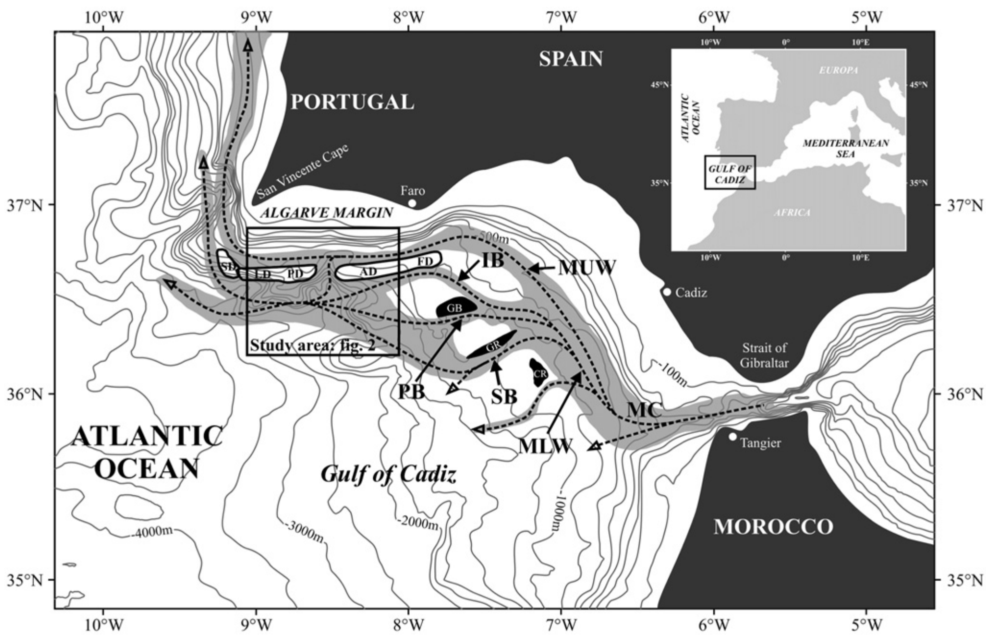


Fig. 1. Location of the study area on a regional map indicating the general circulation pattern of MOW; MC: Mediterranean Core; MUW: Mediterranean Upper Water; MLW: Mediterranean Lower Water; IB: Intermediate Branch; PB: Principal Branch; SB: Southern Branch; CR: Cadiz Ridge; GB: Guadalquivir Bank; GR: Guadalquivir Ridge; AD: Albufeira Drift; FD: Faro Drift; LD; Lagos Drift; PD: Portimão Drift; SD: Sagres Drift (modified after Hernandez-Molina et al., 2003).

the opening of the North Atlantic, (2) the Tethys Alpine Sea closure during the late Eocene to early Miocene, due to a compressional regime and (3) a Miocene foredeep evolution associated with the formation of the Betic-Rif orogen and the opening of the western Mediterranean basin (Llave et al., 2001; Hernández-Molina et al., 2002). This later stage was characterized by the collision of the Betic-Rif accretionary front with the passive margins of the Iberian Peninsula and Africa. This collision involved the emplacement of an olistostrome during the middle Miocene in the east of the Gulf, now re-interpreted as an accretion prism (Gutscher et al., 2002). Later, the opening of the Strait of Gibraltar at the end of the Miocene allowed a final connection between the Atlantic Ocean and the Mediterranean Sea.

Several tectonic features are observed in the present Gulf of Cadiz such as the Cadiz and Guadalquivir diapiric ridges and the Guadalquivir Bank (Fig. 1). They have a very important influence on the morphology and the hydrodynamics because they form topographic highs that constrict deep water circulation pathways (Nelson et al., 1993, 1999; Hanquiez, 2006).

Several major faults have been described on the Algarve Margin (Vanney and Mougenot, 1981). A deep NS orientated fault is located under the Portimão Canyon, named the Portimão Fault (Fig. 2). This important fault stretching to Algarve lands is active since Cenozoïc (Lopes et al., 2006). Two other fault systems are observed to the north of channels located at longitude 8°45W and 8°52W on the bathymetry (Fig. 2). Their orientation is NNE–SSW (Vanney and Mougenot, 1981).

2.2. Oceanographic setting

After the opening of the Strait of Gibraltar, the Gulf of Cadiz was directly influenced by a permanent deep current, the Mediterranean Outflow Water (MOW; Mougenot and Vanney, 1982). This current has a high density due to a high salinity (>38‰; Ambar and Howe, 1979a,b). It flows between 600 and 1400 m water depths. Its velocity reaches 2.5 m s^{-1} (Boyum, 1967) at the end of the Strait of Gibraltar and decreases toward Cape St Vincent (0.2 m s^{-1}; Johnson et al., 2002). The MOW is deflected northward, against the Iberian-Portuguese margin, under the action of the Coriolis force.

The MOW divides into two main branches (Gardner and Kidd, 1987) due to the influence of the sea floor morphology, mainly the Cadiz Ridge (Fig. 1). The first is the Mediterranean Upper Water (MUW in Fig. 1). It is a geostrophic current which flows along the continental margin between 400 and 600 m water depths (Ambar, 1983; Baringer and Price, 1997, 1999). It is the warmer branch of the MOW (T>13.7 °C and S=37‰; Ambar et al., 1999). The second is the Mediterranean Lower Water (MLW in Fig. 1). It is a deeper ageostrophic current flowing between 600 and 1500 m water depths

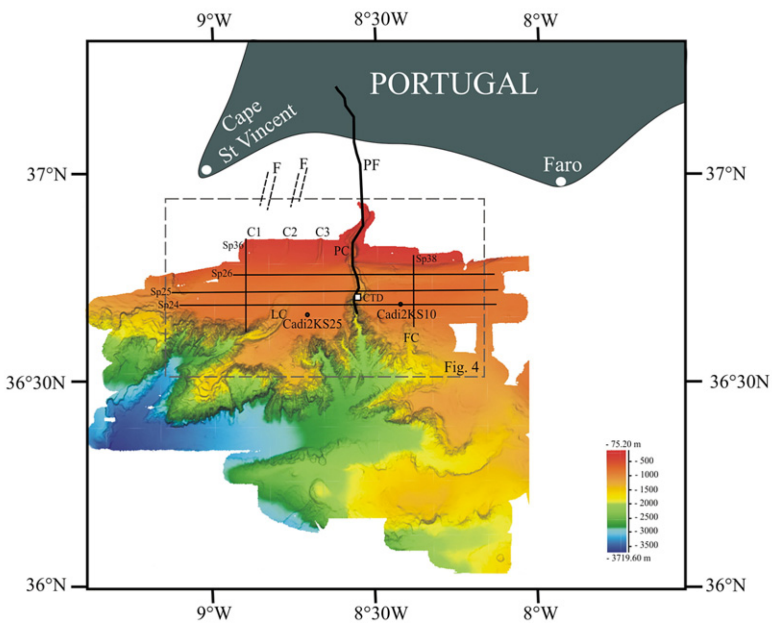


Fig. 2. Bathymetric map with location of seismic profiles, cores and CTD using in this study; PC: Portimão Canyon; LC: Lagos Canyon; FC: Faro Canyon; C1, C2 and C3: Channels 1, 2 and 3; PF: Portimão Fault (after Lopes et al., 2006); F: faults described by Vanney and Mougenot (1981).

(Madelain, 1970) which flows cross-slope. This branch is more saline and colder ($S>37.4$‰ and $T<13.5$°C; Zenk and Armi, 1990; Ambar et al., 1999). The MLW divides into three minor branches because of the presence of the Guadalquivir Bank and the Guadalquivir Ridge: the Intermediate Branch (IB in Fig. 1) which flows north-westward, along the south of the Faro, Albufeira, Portimão, Lagos and Sagres drifts (Heezen and Johnson, 1969); the Principal Branch (PB in Fig. 1) which flows westward through the Guadalquivir Contourite Channel; and the Southern Branch (SB in Fig. 1) which flows south-westward through the Cadiz Contourite Channel (Hernández-Molina et al., 2003).

The MOW is a contour current strongly directing the sediment distribution in the Gulf (Kenyon and Belderson, 1973). Thus, three sectors can be distinguished in this part of the Gulf of Cadiz (Hernández-Molina et al., 2003): (1) an erosional sector in the southeast area close the Strait of Gibraltar, due to the high energy of the deeper current, (2) a coarse-grained depositional sector, adjacent to the precedent sector where the most important sedimentary features are sand lobes (Nelson et al., 1999) and (3) a fine-grained depositional sector which corresponds to the Contourite Deposition System (CDS; Gonthier et al., 1984; Hernández-Molina et al., 2003, 2006). This last sector is located in the westernmost area of the Gulf of Cadiz and includes several contourite drifts from East to West: the Faro Drift, the Albufeira Drift, the Portimão Drift, the Lagos Drift and the Sagres Drift (respectively FD, AD, PD, LD and SD in Fig. 1).

3. Material and methods

The data presented in this paper were collected during the Cadisar 2 cruise on the RV "Le Suroît" in August 2004. The area mapped is located south of the Algarve Margin which extends from Faro to Cape St Vincent, between 36°N and 37°N and 8°W and 9°20W. The bathymetry of the area ranges from 100 to 3700 m (Fig. 2).

3.1. Bathymetry

Bathymetric data were acquired with a SIMRAD EM300 multibeam echosounder. This system operates at a frequency of 30 kHz and a maximum angle of 150°, the swath width varies between 300 and 5000 m at a water depth of 100 and 3700 m. Ship speed was 5–5.5 knots. Calibration of the EM300 and MOW location was assessed using three CTDs (SBE19 probes) and 84 thermoprobes (Sippican).

3.2. High resolution seismic study

High resolution seismic profiles were recorded with a 2000 J sparker and a 12-hydrophone monotrace streamer. The profiles were acquired at water depths between 500 to 1500 m. Five seismic profiles recorded during this cruise, perpendicular and parallel to the slope, have been used for this work (Fig. 2).

The seismic interpretation is realised using two characteristics: (1) the seismic facies and (2) the reflector terminations along the discontinuities. Three main seismic facies are observed (Fig. 3): (1) a reflector free facies, (2) a facies with moderate amplitude and more or less continuous parallel reflectors and (3) a facies with high amplitude and continuous parallel reflectors. The reflector terminations (toplap, onlap, truncations…) are observed in order to distinguish the unconformities from the erosional surfaces.

3.3. Core analyses

The top of two Kullenberg cores (Cadi2KS10 and Cadi2KS25) were used in this study. These cores are located on each side of the Portimão Canyon. The Cadi2KS10 core is located on the southern flank of the Albufeira Drift and the Cadi2KS25 core was sampled on the Portimão drift (Fig. 2). Measurement of core-top D50 grain size allowed comparison of MUW competency on the drift (Faugères et al., 1986).

3.4. CTD

The CTD record (location in Fig. 2) is used to define the water masses present in the Portimão Canyon. Compared with the physical characteristics of the known water masses, the temperature and salinity variations along the water column allow the characterization of the location of the VEM branches.

4. Results

4.1. Morphology

The study area is located in the Contourite Depositional System (CDS) defined by Hernández-Molina et al. (2003), between 36°30N and 37°N. This area is influenced by the MUW to the north and the IB to the south.

The general morphology observed on the bathymetry (Fig. 4) presents marginal plateaux between the continental slope and deep valley areas, named Albufeira, Portimão and Lagos from east to west.

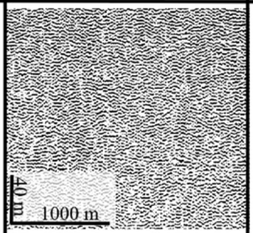
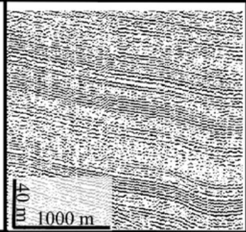
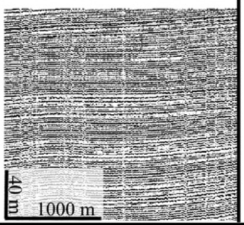
Facies	Seismic signature	Description
Seismic facies 1		Reflector free facies. No penetration of signal.
Seismic facies 2		More or less continuous reflectors with moderate amplitude.
Seismic facies 3		High amplitude of the continuous parallels reflectors.

Fig. 3. Seismic facies catalog and description defined in the seismic interpretation.

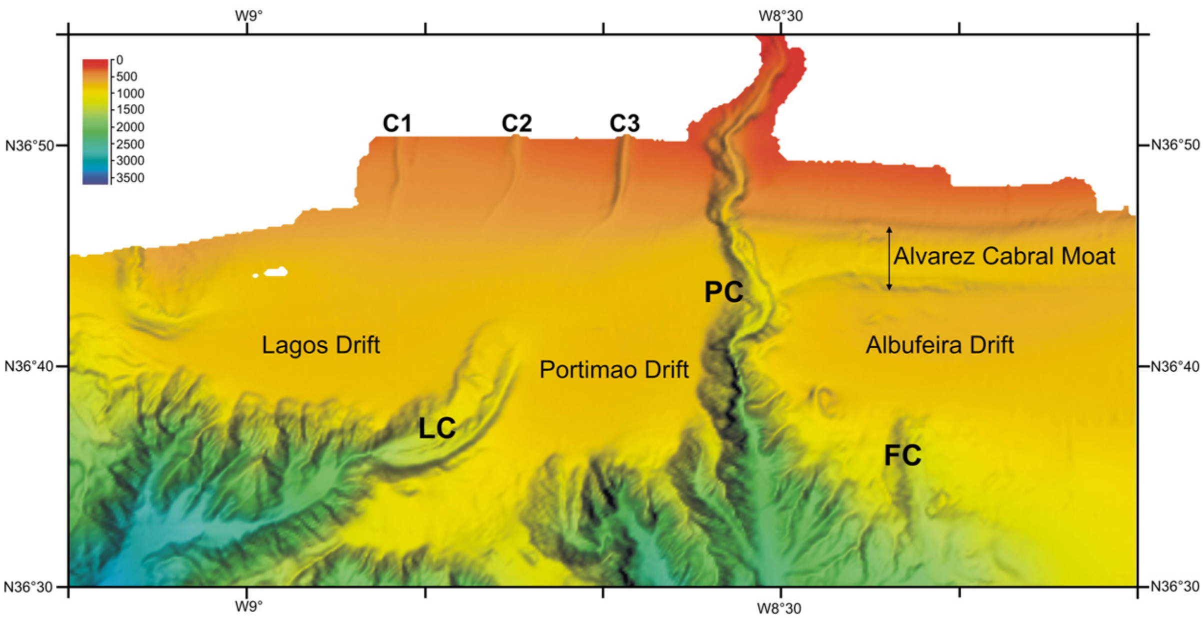


Fig. 4. 3D bathymetry showing the main morphologic features of the study area (PC: Portimão Canyon; LC: Lagos Canyon; FC: Faro Canyon; and C1, C2 and C3: Channels 1, 2 and 3).

These plateaux, that form an abrupt slope change between 600 and 800 m water depth, have a gentle slope (0.5°) in comparison with the northernmost part (slope of 1.78°). They finish abruptly southward in a ragged surface leading to the southern deeply incised valleys.

The marginal plateaux are described as contourite drifts because they are covered by a sedimentary pile built under the deep current action (Mougenot and Vanney, 1982). The Albufeira Drift is about 50 km long and 9.6 km wide. It is characterized by a rounded form and is separated from the upper slope by a large channel named Alvarez Cabral Moat (Fig. 4). The maximum depth of the Alvarez Cabral Moat reaches 90 m from the top of the Albufeira Drift. Its width increases westward (3.5 km to 6 km) and reaches its maximum where it joins the Portimão Canyon. This morphologic feature effectively channelizes the Mediterranean Upper Water (Faugères et al., 1984, 1985).

The Portimão and Lagos drifts have a flat morphology without topographic highs. They seem to develop a sedimentary cover of the plateaux. The Portimão drift has a more complicated shape because it is affected by instability incisions southward that confer it a nonlinear morphology in contrast to Lagos drift. The Portimão drift is about 15 km wide (westward) and about 17 km long south-westward. The Lagos drift is about 30 km long and 12 km wide. These two drifts are connected in their northern sectors but separated by the head of Lagos Canyon in the south (Fig. 4).

The contourite deposits are dissected by morphologic features such as canyons, channels and moat.

Three major canyons connected to the deep valleys, are visible in Fig. 2: the Faro Canyon (FC), the Portimão Canyon (PC) and the Lagos Canyon (LC).

The Faro Canyon has N–S orientation and partly incises the Albufeira plateau. It appears at 940 m water depth and spreads over 20 km with a width of 5 km, a maximal depth of 260 m, and is rectilinear in form (Fig. 2).

The Portimão Canyon extends from the shelf to the deep basin and separates the Albufeira Drift from the Portimão and Lagos drifts. This canyon is located on the deep Portimão Fault (Mougenot, 1988; Fig. 2). Its general orientation is NNE–SSW then N–S. The canyon head starts at about 100 m water depth (~35 km to the shoreline) and spreads over 53 km, reaching a maximal depth of 338 m in its northern part. Its width increases downward from 2.3 to 5.7 km. Six large bends generate a low sinuosity (1.125). The meanders are bordered by elongated terraces (width close to 850 m) plastered along the canyon flanks and elevated of 140 m above the axial thalweg.

The morphology of the Lagos Canyon is more complicated. Its head is located at 760 m water depth and partly separates the Portimão Drift and the Lagos Drift. Two bends affects the canyon orientation. It has a NNE-SSW orientation for less than 10 km, and then runs westward and finishes with a NNE-SSW orientation before joining the Lagos deep valley.

Three additional channels in the northern part of the study area incise the continental shelf (C1, C2 and C3; Fig. 4). They have a straight course (7 km; Mulder et al., 2006) and disappear at a water depth ranging from 560 to 700 m. They are not currently connected to any deep valley. They have N–S orientation but then bend to become more NNE–SSW downward. The easternmost channel is deeper (150 m) than the two others (70 m). Their maximal width varies between 1.2 km and 2.4 km.

4.2. Main seismic units

The seismic analysis reveals two main units named units I and II. They are distinguished by the presence of two different seismic facies lying on an acoustic basement (facies 1, Fig. 3) and separated by an erosional surface. Seismic facies 2 (moderate amplitude, intermediate continuity) characterizes unit I whereas seismic facies 3 (high amplitude and important continuity) characterizes unit II (Fig. 3). The boundary between these two units is clearly an erosional surface corresponding to the Plio-Pleistocene boundary as reported by Llave et al. (2001) and Llave (2004). On slope-parallel profiles, on the west side of Portimão canyon, this boundary is deeply incised by three paleochannels (C1, C2, and C3 in Fig. 5). To the east of Portimão Canyon, this erosion surface shows irregular topography with reflector truncation at the boundary between the two seismic facies (Fig. 5).

The acoustic basement below Unit I is characterized by seismic facies 1, and it is only visible northward where seismic unit I and II are thinner.

Observation of reflector configuration change in each seismic unit allows characterization of the geometry of the sedimentary bodies and analysis of the evolution of drift construction on both side of Portimão Canyon.

4.3. Drift geometry

A summary of the deposit geometry is given in Table 1.

4.3.1. East side of Portimão Canyon: Albufeira Drift

On the parallel to slope profiles (SP25 and SP24), the acoustic basement is poorly observed due to the

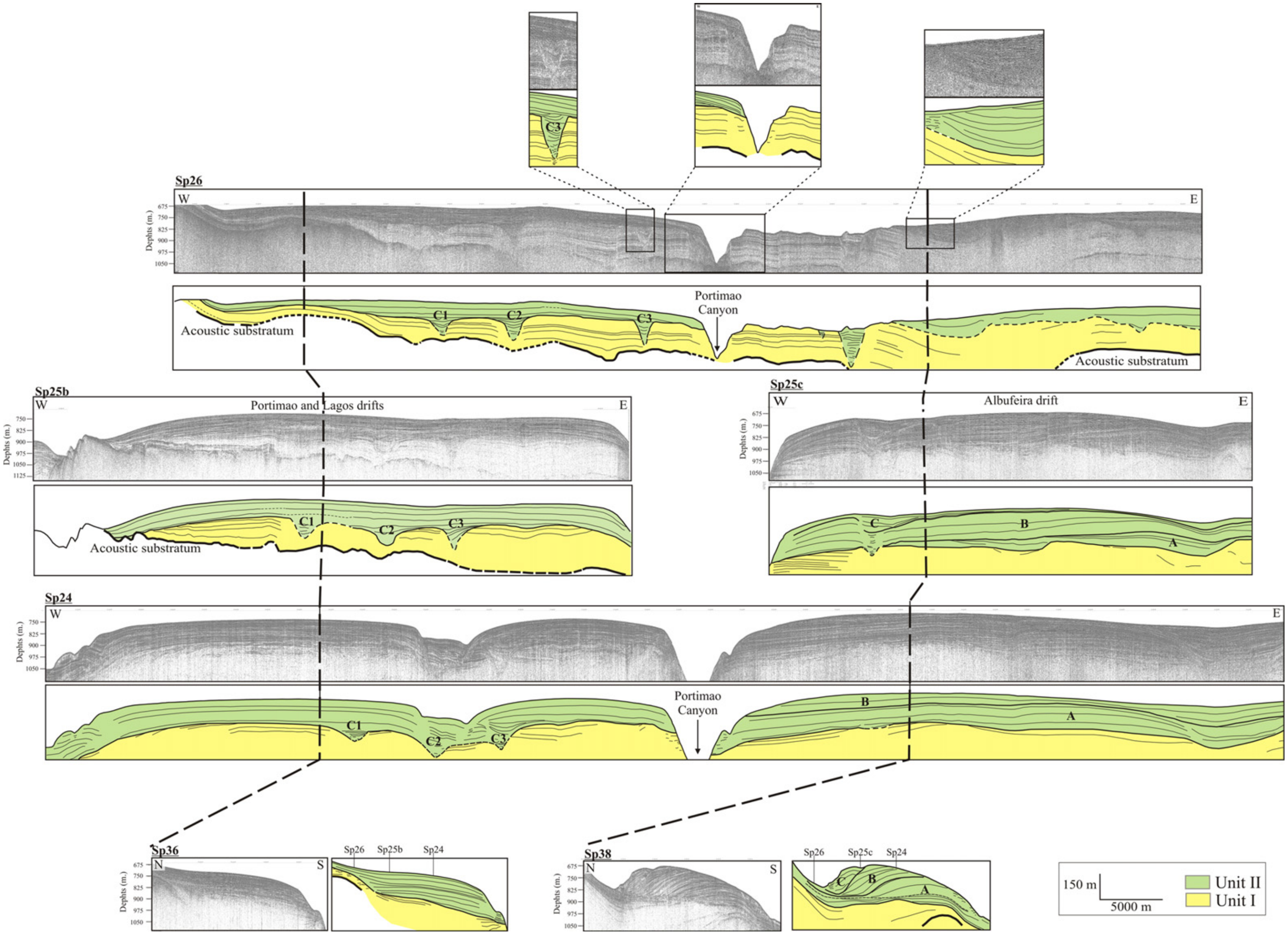
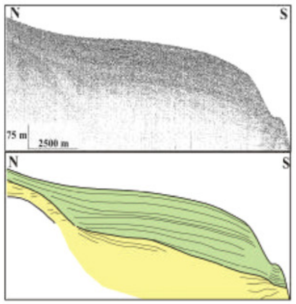
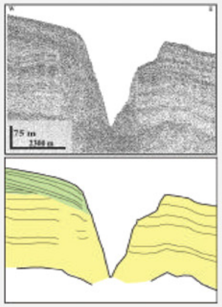
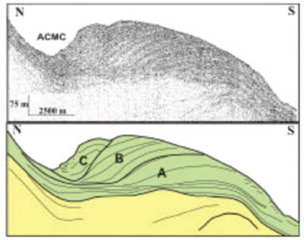


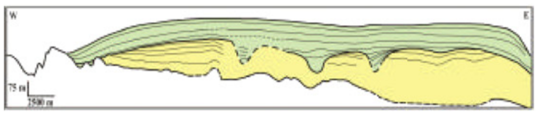
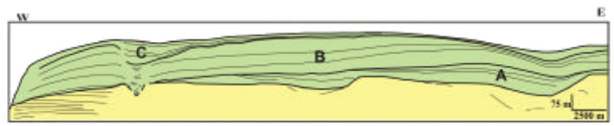
Fig. 5. Sparker seismic profiles and their interpretation.

Table 1
Synthesis of main morphologic and seismic characteristics of Portimão-Lagos Drifts, Albufeira Drift and Portimão Canyon deduced from Cadisar 2 cruise

<table>
<tr><th>Time ↑</th><th colspan="4">W ← → E</th></tr>
<tr><th></th><th>Portimao and Lagos drifts</th><th>Portimao canyon</th><th colspan="3">Albufeira drift</th></tr>
<tr><td>Morphology</td><td>- Smooth morphology
- Relatively flat deposits</td><td>- V-shape canyon
- Low sinuosity
- A depth increase southward</td><td colspan="3">- Rounded form and marked morphology
- Alvarez Cabral moat channel (ACMC) separates drift from slope</td></tr>
<tr><td>Deposit Evolution</td><td>- No significant deposit evolution or migration
- Only Unit II aggradation on 160 m thickness</td><td>- Instabilities on the inner side, emphasized by chaotic seismic facies</td><td colspan="3">- Westward motion and important northward migration of the sedimentary body
Unit II thickness reaches 225 m</td></tr>
<tr><td rowspan="3">Seismic Unit II</td><td rowspan="3">

- Characterized by seismic facies 3
- Simple geometry: reflectors are parallel and relatively horizontal
- Reflector configuration shows aggradation</td><td rowspan="3">

- Unit II reflectors are curved on canyon flanks</td><td rowspan="3">

- Composed by three sub-units: A, B and C separated by discontinuities
- Characterized by seismic Facies 3
- Complex reflector geometry
- Clear progradation</td><td>Sub-Unit A</td><td>- Aggradant at its base in filling on the discontinuity
- Begins to be progradant at its top</td></tr>
<tr><td>Sub-Unit B</td><td>- Sigmoid reflectors geometry
- Reflector dip increases northward
→ Progradant sub-unit</td></tr>
<tr><td>Sub-Unit C</td><td>- Very progradant sub-unit
- Important reflector dip</td></tr>
<tr><td>Major Discontinuity</td><td>- Emphasized by paleochannels presence: erosion surface with Unit I reflector truncated on the discontinuity

</td><td></td><td colspan="3">- Unit I and Unit II reflectors are discordant
- Unit I reflectors are truncated → erosional surface

</td></tr>
<tr><td rowspan="2">Seismic Unit I</td><td colspan="5">- In filling of the morphology inherited from the acoustic substratum
- Unit in aggradation with parallel reflectors characterized by seismic facies 1</td></tr>
<tr><td></td><td>- Incised by canyon: truncated reflectors</td><td colspan="3">- Acoustic substratum not always visible</td></tr>
</table>

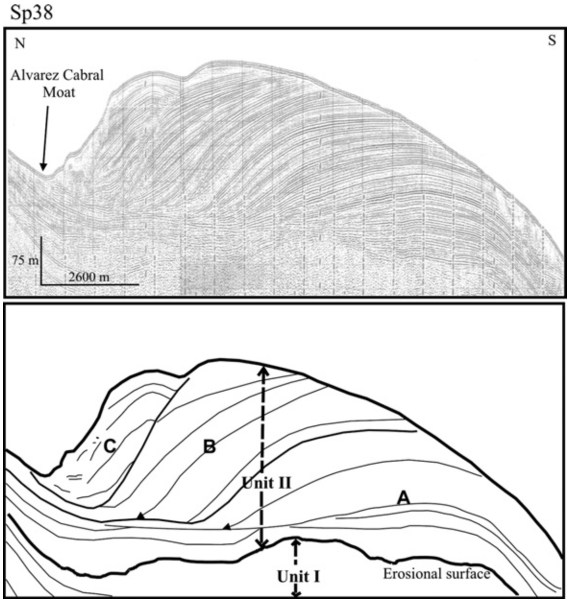


Fig. 6. Sparker seismic profile SP38 crossing Albufeira Drift and its interpretation (see text for signification of sub-unit A, B and C).

lack of signal penetration of the system (Fig. 5). However, on profile SP26, located in the Alvarez Cabral Moat channel, the acoustic basement is visible and shows that seismic unit I seems to infill this irregular morphology. Here, unit I is outcropping and its erosion can be explained by the Mediterranean Upper Water transit constricted along this channel. In the eastern extremity of this profile, unit II is observed infilling valleys (Fig. 5) with 175 ms TWT thickness (130 m).

Unit II reaches a maximal thickness of 300 ms TWT (225 m) on the profile SP25 (Fig. 5). Its thickness decreases southward (250 ms TWT on profile SP24, 187 m). In the unit II, three sub-units can be defined on the east flank of Portimão Canyon, named sub-units A, B and C from the oldest to the youngest (Fig. 5). They are separated by discontinuities and changes in the reflector inclination, corresponding to unconformity surfaces characterized by truncation of reflectors (Fig. 6).

Sub-unit A reaches its maximal thickness on profile SP24 (36°41N; Fig. 5): 260 ms TWT (197 m). This sub-unit pinches out eastward on profile SP25. Its upper boundary is characterized by a large unconformity which separates it from sub-unit B.

Sub-unit B has a maximal thickness of 237 ms TWT (137 m) on the SP25 profile (36°43N). It pinches out more clearly westward than sub-unit A suggesting a westward migration of the deposits. On profile SP24, this sub-unit outcrops and is undergoing erosion as evidenced by the reflector truncations on the seafloor.

Sub-unit C is only present on the western part of the SP25 profile with a maximal thickness of 237 ms TWT (137 m). Here again it pinches out farther westward than sub-unit B which suggests a westward migration of the deposits. On this profile, the seafloor truncates the reflectors at the top of the unit.

On perpendicular to slope profile profile SP38 (Figs. 5 and 6) sub-unit A shows aggradation at the bottom, with parallel reflectors filling the erosion surface below. The upper part, in contrast, shows progradation with a northward downlap.

Sub-unit B is characterized by a very pronounced progradation with downlap terminations on the underlying unconformity. These downlap reflectors have a dip that becomes steeper northward. The reflector configuration forms a sigmoid wedge. On the south flank of this drift (here visualised in transverse section), truncation of reflectors reveals southward erosion of the sea floor.

Sub-unit C corresponds to the most prograding sub-unit, separated from sub-unit B, on profile SP38, by a boundary with sea floor expression. Toward the Alvarez Cabral Moat, the reflectors of this sub-unit become disorganized. This could be interpreted as the result of important erosion by the MUW constricted into this channel or/and slope instabilities.

In the Alvarez Cabral Moat, unit II deposits are present but they are eroded by the MUW. This result is consistent with the interpretation of profile SP26 (Fig. 5)

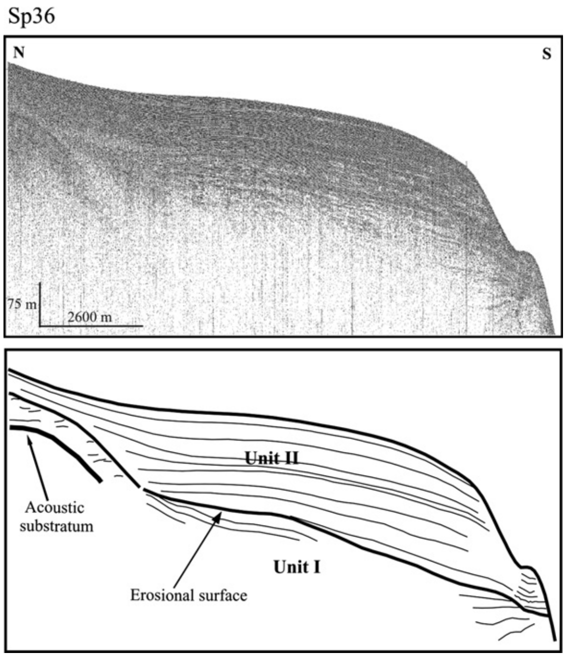


Fig. 7. Sparker seismic profile SP36 crossing Lagos Drift and its interpretation.

because profile SP38 crosses SP26 at the location of the valley filled by unit II. This cross profile analysis shows clearly a northward progradation of the unit II deposits trough time.

The Albufeira Drift morphology shows a rounded form and the presence of a moat channel related to a mounded separated drift (Faugères et al., 1999). This drift has migrated northward and westward.

4.3.2. West side of Portimão Canyon: Portimão and Lagos Drifts

The acoustic basement is observed in the western area where units I and II are thinner (Fig. 5). Unit I can reach a maximal thickness of 240 m (profile SP25). The three paleochannels incised on top of unit I have a N–S direction and can be correlated with the three channels that are at present observed upslope on the seafloor (Fig. 4). This suggests that both systems were previously connected.

Maximal thickness of unit II is 220 ms TWT (160 m) on profile SP25 (Fig. 5) and decreases northward (110 m on profile SP26; Fig. 5). The three sub-units observed on the Albufeira Drift (A, B and C) cannot be distinguished on this canyon side. Change in drift geometry is not observed through time. Aggradation predominates with an internal configuration of parallel reflectors and a lenticular shape.

On cross profile SP36 (Fig. 7) no significant progradation is visible and only a weak thinning is observed near the slope break. On the south flank of the drift, toward the southern deep valleys, reflectors are truncated showing erosion probably due to sediment instabilities.

The morphological and seismic study of Portimão and Lagos Drifts shows a flat morphology and no progradation. They are related to sheeted drifts (Faugères et al., 1999).

4.3.3. Portimão Canyon flanks

Seismic lines crossing the Portimão Canyon show differences in seismic facies on the inset of the canyon with more chaotic reflectors in seismic facies 2 and 3. The reflectors of unit I are truncated on the flank of the canyon and a clear asymmetry in the deposit of unit I at both sides of the canyon is observed (Fig. 5). Contrary, the reflectors of unit II are only curved indicating that Portimão Canyon incised the unit I deposits. Inferred incisions of canyons and channels affect only unit I

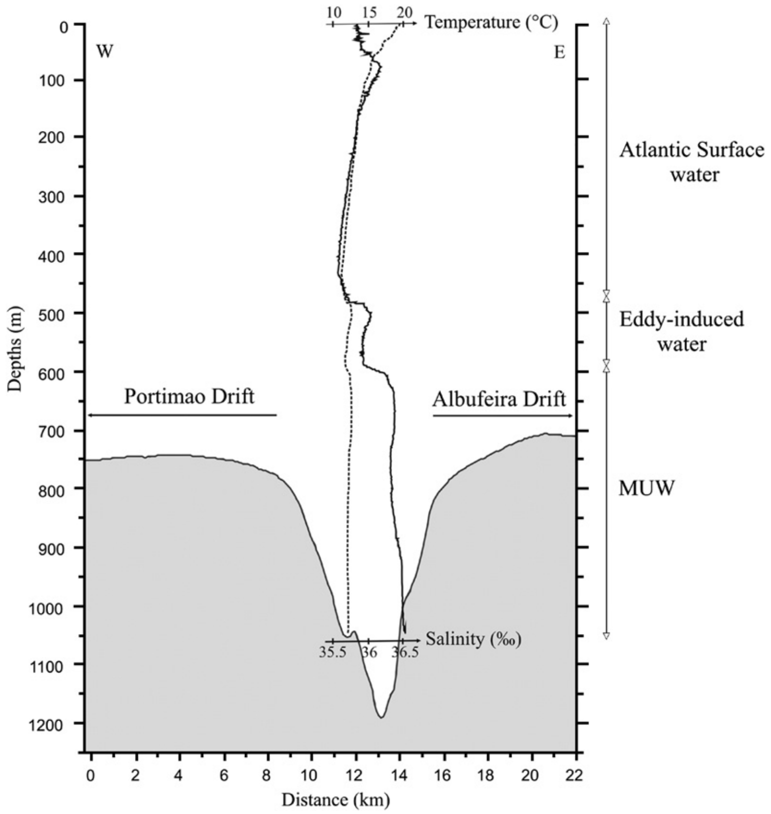


Fig. 8. Salinity (black line) and temperature (black broken line) depth-profiles from CTD.

deposits. In contrary, Unit II seems to fill and drape previous deposits softening the morphology let by this major discontinuity.

4.4. Grain size study and CTD record analysis

The mean grain size (median) of the first 20 cm of the core Cadi2KS10 located on the eastern side of the canyon is 31.5 μm. The sediment is constituted of silt and clay with shell debris. On the western side of Portimão Canyon (Cadi2KS25 core) the average grain size (D50) of the first 20 cm is 22.5 μm. This grain size diminution suggests a decrease of MOW competency (i.e. maximum grain size that a flow can transport) between east and west of Portimão Canyon.

A CTD record (location in Fig. 2) clearly reveals the presence of a Mediterranean type water mass ($T\sim13.6$ °C and $S\leq36.5$‰; Fig. 8) between 600 and 1000 m water depth in the Portimão Canyon. The CTD record stops on a canyon terrace located at 1100 m water depth. From 500 m to 600 m water depths, the record shows an inflexion indicating the presence of another water mass with different physical characteristics ($T\sim13.6$ °C and $S\sim36.1$‰). The presence of topographic irregularity such as a canyon together with the MOW barocline instability provokes submarine vortices or eddies (Cherubin et al., 2000). A fragment of MOW can thus breaks away and mix with the water above. This phenomenon creates a new water mass generation with different physical characteristics. Moreover, several authors (e.g. Ambar et al., 1999; Serra and Ambar, 2002; Serra et al., 2005) have shown that the Portimão Canyon region constitutes a privileged place for eddy formation and internal waves (Bruno et al., 2006; Garcia-Lafuente et al., 2006; Hernandez-Molina et al., 2006). Changes in water column stratification are induced by these hydrologic phenomena and they probably explain the CTD record obtained with: (1) from sea surface to 500 m water depth the Atlantic surface waters, (2) from 500 to 600 m water depth a water mass originally from the Atlantic surface water and Mediterranean deep water mixing and (3) from 600 to canyon bottom the Mediterranean deep water (Fig. 8).

5. Discussion

5.1. Two types of contourite drifts on the Algarve Margin

On the Algarve Margin, two types of contourite drifts have developed over the two margins of Portimão Canyon: the mounded separated drift of Albufeira and the sheeted Portimão and Lagos drifts. Important differences between the east and west sides of the Portimão Canyon are observed on the bathymetric and high resolution seismic profiles. (1) The Albufeira Drift has a marked rounded morphology accentuated by the presence of a moat channel that separates it from the continental slope, whereas the Portimão and Lagos drifts have a flat morphology without any moat channel. (2) The Albufeira Drift aggrades with a pronounced progradation toward the northwest whereas Portimão and Lagos Drifts aggrade without significant progradation. (3) Sediment accumulation is more important on the Albufeira Drift where there is a maximum sediment thickness of 225 m, in comparison to the Portimão and Lagos drifts which have a maximum sediment thickness of 160 m. (4) The surface particles are coarser in the Albufeira Drift than in the Portimão and Lagos drifts with average grain sizes of 31.5 μm and 22.5 μm, respectively.

These observations suggest that hydrodynamical processes related to the presence of the Portimão Canyon generate variations in the deposition rates of the Albufeira Drift and the nearby Portimão and Lagos Drifts.

5.2. MOW capture by the canyon

The CTD site is located in the lower part of the Portimão canyon, south of the MUW main pathway (Alvarez Cabral Moat Channel). The CTD shows the presence of a Mediterranean type water mass in the Portimão Canyon with physical characteristics comparable to MUW characteristics. This demonstrates that a fraction of the MUW flows down-canyon.

Investigation of the contourite drifts demonstrates that the moat channel disappears in a westerly direction, with an associated decrease in the sediment grain size and thinning of the contourite deposits, thus further supporting the supposition that the upper branch of the MOW is captured by the Portimão Canyon. More particularly, the higher intensity of the MUW on the east side of the Portimão Canyon accounts for the erosion of the upper slope and the formation of the Alvarez Cabral Moat. The capture of a fraction of the MUW by the Portimão canyon generates a diminution of the main flow intensity. West of the canyon, the MUW is hereafter not intense enough to erode the north side of the Portimão and Lagos drifts and no moat channel is formed. The deep-current capacity diminishes generating a lower sedimentation rate and a westward thinning of the contourite drifts. This decrease in capacity is associated with a drop in competency. Both hydrodynamical characteristic changes are due to the trapping of the sediment load by the canyon. The coarsest particles transported by the MUW are in the flow down the Portimão Canyon.

In addition, the widening and deepening of the Alvarez Cabral Moat near the canyon is consistent with the capture of this deep current. Turbulent eddies form where the canyon catches the upper branch of the MOW, which probably intensifies erosion near the junction between the canyon and the moat channel. Seismic-inferred erosion on the back side of the Albufeira Drift may similarly be related to turbulent eddy formation and increase in strength of the MUW during contour current capture.

In conclusion, our investigation highlights the importance of the MUW capture by the Portimão Canyon in development of the nearby, but dissimilar contourite drifts.

5.3. Algarve Margin: interaction between gravity processes and processes linked to deep circulation

The results detailed in this paper highlight the particularity of the Algarve Margin related to the interactions between deep currents and seafloor morphology inherited from gravity process activity and tectonics. The canyon and channels along the margin are the result of gravity process activity initiated along the zone of weakness formed by deep faults, while the drift construction is related to deep water circulation. Periods with dominant alongslope processes (contour current) alternate with periods of dominant downslope processes (gravity processes). An illustration of this interaction is provided by the disconnection of the three channels and the southern deep valleys (Mulder et al., 2006). Seismic profiles show that an ancient connection existed between channels and deep valleys (Fig. 5). However, the present disconnection can be related to climate and sea level change (Hernández-Molina et al., 2002). During cold periods, the water mass exchange in the Strait of Gibraltar is reduced (Rolhing and Bryden, 1994) and the MOW pathway in the Gulf of Cadiz is different than at present (Llave et al., 2006). During cold periods, downslope processes are the dominant processes resulting in channels and canyons incising the slope, as illustrated by the northern channels formation corresponding to Plio-Pleistocene limit, a major erosion period in the Gulf of Cadiz related to a global sea level lowstand (Llave, 2004). During warm period such as present days, the sediment load from the continent is low and the MOW-related processes dominate over downslope gravity processes (Hernández-Molina et al., 2002). Channels are filled and disconnected from deep valleys (Mulder et al., 2006).

However, the Portimão Canyon is not filled in contrast to the Lagos and the Faro Canyons. Analysis of local bathymetric maps clearly demonstrates evidence of erosional features on its flanks, which is confirmed by the presence of chaotic seismic facies on seismic profiles (Table 1). The canyon is preserved even during the present period of dominant alongslope processes. This unusual preservation is probably due to the larger size of the canyon that results in the capture of a fraction of the MOW. At present, MUW is continuously advected downslope within the canyon. This process prevents the canyon filling, at least in its lower part. Downslope enlargement of the Portimão canyon is consistent with the combination of the MOW flow and gravity processes. However, the role of tectonic in development and preservation of the Portimão Canyon may not be negligible. The Portimão Fault located under the canyon was active before the Plio-Pleistocene global cooling (Lopes et al., 2006) and dissymmetry of the margins observed since the unit I deposit on both sides of canyon shows that the Portimão canyon is an older feature than the three other channels. The major erosion period that formed the three channels has just refreshed the canyon existing earlier. Recent Portimão fault activity may help to maintain the modern canyon structure and relief. Tectonic control is consistent with the preservation of the northern part of the canyon beyond the capture point and therefore not influenced by the MUW capture.

Hydrological interpretation inferred from analysis of seismic profiles covering the Algarve Margin shows that interactions between gravity processes and contour currents are expressed differently west and east of the Portimão canyon. West of Portimão Canyon, we observe a climate-related shift of sedimentary processes dominated by gravity processes during cold periods to contour current-linked processes during warm periods, hence resulting in alternative phases of incision and infilling. Conversely, east of Portimão Canyon, both downslope and alongslope processes are combined, which intensifies incision and sediment purge, thus enhancing the canyon preservation.

6. Conclusion

The Algarve Margin is under the control of downslope gravity processes which form canyons and channels aligned along deep fault directions, and alongslope thermohaline current generating sediment drifts. Canyon formation and filling or contourite drift formation are under the control of the amount of available sediment and depend on the sedimentary input and the strength hydrodynamic processes, both related to climate and sea level changes.

This study shows that the margin displays two types of contourite drifts separated by the Portimão Canyon. On the East side the Albufeira Drift is a separated drift and on the West side the Portimão and Lagos drifts are sheeted drifts. On the Albufeira Drift, the sedimentation rate is high and the grain size of particles is medium. This result can be related to an energetic flow with high capacity and competency. High energy explains the presence of the Alvarez Cabral Moat and thus, the rapidly upslope drift progradation and rapid accumulation on sheltered area. On Portimão and Lagos drifts, the sedimentation rate is low and the grain size of particles is small suggesting little flow capacity and competency. This explains the absence of moat channel and drift progradation.

The presence of two types of contourite drift, due to a decrease in MUW intensity induced by its capture by the Portimão Canyon, underlines the different interactions between tectonics, morphology, hydrodynamics and sedimentary processes.

This work underlines: (1) the impact of seafloor morphology on the dynamic of deep currents through the MUW channelling by the Alvarez Cabral Moat; (2) the gravity process/contour current interactions with alternation of periods with dominant gravity processes (canyon and channels formation) and periods where contouritic processes are dominant (drift formation, filling and disconnection of channels); (3) the unusual capture phenomenon of a deep current by a canyon. This phenomenon explains the particular morphology of the Algarve Margin and constitutes a new internal parameter able to influence the contourite sedimentation along margins.

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References

Ambar, I., 1983. A shallow core of Mediterranean water off western Portugal. Deep-Sea Res. 30, 677–680.

Ambar, I., Howe, M.R., 1979a. Observations of the Mediterranean outflow. I. Mixing in the Mediterranean outflow. Deep-Sea Res. 26, 535–554.

Ambar, I., Howe, M.R., 1979b. Obsevations of the Mediterranean outflow. II. The deep circulation in the vicinity of the Gulf of Cadiz. Deep-Sea Res. 26, 555–568.

Abar, I., Armi, A., Bower, Ferreira, T., 1999. Some aspects of time variability of the Mediterranean Water off south Portugal. Deep-Sea Res., Part 1, Oceanogr. Res. Pap. 46, 1109–1136.

Baringer, M.O., Price, J.F., 1997. Mixing and spreading of the Mediterranean outflow. J. Phys. Oceanogr. 27, 1654–1677.

Baringer, M.O., Price, J.F., 1999. A review of the physical oceanography of the Mediterranean outflow. Mar. Geol. 155, 63–82.

Boyum, G., 1967. Hydrological observations of the M.S-1 Helland-Hansen and current measurements in the area west of Gibraltar. May 1965 NATO Sub-Comm. Oceanogr. Res. Tech. Rep. 34, 35–36.

Bruno, M., Vazquez, A., Gomez-Enri, J., Vargas, J.M., Garcia Lafuente, J., Ruiz-Canavate, A., Mariscal, L., Vidal, J., 2006. Observations of internal waves and associated mixing phenomena in the Portimão Canyon area. Deep-Sea Res., Part 2, Top. Stud. Oceanogr. 53 (11-13), 1219–1240.

Cherubin, L., Carton, X., Paillet, J., Morel, Y., Serpette, A., 2000. Instability of the Mediterranean Water undercurrents southwest of Portugal: effects of baroclinicity and of topography. Oceanol. Acta 23, 551–573.

Faugères, J.-C., Gonthier, E., Stow, D.A.V., 1984. Contourite drift molded by deep Mediterranean outflow. Geology 12, 296–300.

Faugères, J.-C., Frappa, M., Gonthier, E., Grousset, F., 1985. Impact of the Mediterranean water on the south and west Iberian margin sedimentation during the recent quaternary. Bull. Inst. Geol. Bassin Aquitaine 37, 259–287.

Faugères, J.-C., Gonthier, E., Peypouquet, J.-P., Pujol, C., Vergnaud-Grazzini, C., 1986. Distribution et variations des courants de fond sur la ride de Faro (Golfe de Cadix), témoins des modifications des échanges Méditerranée-Atlantique au Quaternaire récent. Bull. Soc. Géol. France 3, 423–432.

Faugères, J.C., Stow, D.A.V., Imbert, P., Viana, A., 1999. Seismic features diagnostic of contourite drifts. Mar. Geol. 162, 1–38.

Garcia-Lafuente, J., Delgado, J., Criado-Aldeanueva, F., Bruno, M., Del Rio, J., Miguel Vargas, J., 2006. Water mass circulation on the continental shelf of the Gulf of Cadiz. Deep-Sea Res., Part 2, Top. Stud. Oceanogr. 53 (11-13), 1182–1197.

Gardner, J.V., Kidd, R.B., 1987. Sedimentary processes on the Iberian continental margin viewed by long-range side-scan sonar and seismic data. J. Sediment. Petrol. 57 (3), 397–407.

Gonthier, E., Faugères, J.-C., Stow, D.A.V., 1984. Contourite facies of the Faro drift, Gulf of Cadiz. In: Stow, D.A.V., Piper, D.J.W. (Eds.), Fine-Grained Sediments: Deep Water Processes and Facies. Geologica Society by Blackwell Scientific Publications, Oxford London Edinburg, pp. 245–256.

Gutscher, M.A., Malod, J., Rehault, J.P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. Geology 30, 1071–1074.

Hanquiez, V., 2006. Processus sédimentaires et activité de la Veine d'Eau Méditerranéenne au cours du Quaternaire terminal dans le Golfe de Cadix. Thesis, Bordeaux 1 University, 352 pp.

Heezen, B.C., Johnson, G.L., 1969. Mediterranean under-current and microphysiography west of Gibraltar. Bull. Inst. Oceanogr. (Monaco) 67, 1–97.

Hernández-Molina, F.J., Somoza, L., Vasquez, J.T., Lobo, F., Fernández-Puga, M.C., Llave, E., Diaz-del Rio, V., 2002.

Quaternary stratigraphic stacking patterns on the continental shelves on the southern Iberian Peninsula: their relationship with global climate and paleoceanographic changes. Quat. Int. 92, 5–23.

Hernández-Molina, F.J., Llave, E., Somoza, L., Fernández-Puga, M.C., Maestro, A., León, R., Medialdea, T., Barnolas, A., García, M., Díaz del Río, V., Fernández-Salas, L.M., Vásquez, J.T., Lobo, F.J., Alveirinho-Dias, J.A., Rodero, J., Gardner, J., 2003. Looking for clues to paleoceanographic imprints: a diagnosis of the Gulf of Cadiz contourite depositional systems. Geology 31, 19–22.

Hernandez-Molina, F.J., Llave, E., Stow, D.A.V., Garcia, M., Somoza, L., Vazquez, J.T., Lobo, F.J., Maestro, A., Diaz del Rio, V., Leon, R., 2006. The contourite depositional system of the Gulf of Cadiz: a sedimentary model related to the bottom current activity of the Mediterranean outflow water and its interaction with the continental margin. Deep-Sea Res., Part 2, Top. Stud. Oceanogr. 53 (11-13), 1420–1463.

Johnson, J., Ambar, I., Serra, N., Stevens, I., 2002. Comparative studies of the spreading of Mediterranean water through the Gulf of Cadiz. Deep-Sea Res. 49, 4179–4193.

Kenyon, N.H., Belderson, R.H., 1973. Bed-forms of the Mediterranean undercurrent observed with side-scan sonar. Sedim. Geol. 9, 77–79.

Llave, E., 2004. Análisis morfosedimentario y estratigráfico de los depositos contorníco del Golfo de Cádiz: implicaciones pleaoceanográficas. PhD Thesis, Cadix University, Publicaciones del instituto geologico y minero de Espana, 292 pp.

Llave, E., Hernández-Molina, F.J., Somoza, L., Diaz-del-Rio, V., Stow, D.A.V., Maestro, A., Alveirinho Dias, J.M., 2001. Seismic stacking pattern of the Faro-Albufeira contourite system (Gulf of Cadiz): a Quaternary record of paleoceanographic and tectonic influences. Mar. Geophys. Res. 22, 487–508.

Llave, E., Schönfeld, J., Hernández-Molina, F.J., Mulder, T., Somoza, L., Diaz del Rio, V., 2006. High-resolution statigraphy of the Mediterranean outflow contourite system in the Gulf of Cadiz during the last Pleisticene: the impact of Heinrich events. Mar. Geol. 227, 241–262.

Lopes, F.C., Cunha, P.P., Le Gall, B., 2006. Cenozoic seismic stratigraphy and tectonic evolution of the Algarve margin (offshore Portugal, southwestern Iberian Peninsula). Mar. Geol. 231, 1–36.

Madelain, F., 1970. Influence de la topographie du fond sur l'écoulement méditerranéen entre le détroit de Gibraltar et le Cap St Vincent. Cah. Océanogr. (Paris) 22, 43–61.

Maldonado, A., Somoza, L., Pallares, L., 1999. The Betic orogen and the Iberian-African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic). Mar. Geol. 155, 9–43.

Mougenot, D., 1988. Géologie de la marge portugaise. PhD Thesis Paris University, 257 pp.

Mougenot, D., Vanney, J.-R., 1982. The Plio-Quaternary sedimentary drifts of the south Portuguese continental slope. Bull. Inst. Geol. Bassin Aquitaine 131–139.

Mulder, T., Lecroart, P., Hanquiez, V., Marches, E., Gonthier, E., Guedes, J.-C., Thiébot, E., Jaaidi, B., Kenyon, N., Voisset, M., Perez, C., Sayago, M., Fuchey, Y., Bujan, S., 2006. The western part of the Gulf of Cadiz: contour currents and turbidity currents interactions. Geo-Mar. Lett. 26, 31–41.

Nelson, H.C., Baraza, J., Maldonado, A., 1993. Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. Sediment. Geol. 82 (1-4), 103–131.

Nelson, C.H., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., Barber Jr., J.H., 1999. Influence of the Atlantic inflow and Mediterranean outflow currents on Late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. Mar. Geol. 155, 99–129.

Rolhing, E.J., Bryden, H.L., 1994. Estimating past changes in the Eastern Mediterranean freshwater budget, using reconstructions of sea level and hydrography. Proc. K. Ned. Akad. van Wet. Ser, B Palaeontol. Geol. Phys. Chemistry, Anthropol. 97, 201–217.

Serra, N., Ambar, I., 2002. Eddy generation in the Mediterranean undercurrent. Deep-Sea Res., Part 2, Top. Stud. Oceanogr. 49 (19), 4225–4243.

Serra, N., Ambar, I., Kase, R.H., 2005. Observations and numerical modelling of the Mediterranean outflow splitting and eddy generation. Deep-Sea Res., Part 2, Top. Stud. Oceanogr. 52 (3-4), 383–408.

Vanney, J.R., Mougenot, D., 1981. La plate-forme continentale du Portugal et les provinces adjacentes: Analyse Géomorphologique. Mem. Serv. Geol. Port. 28 81 pp.

Zenk, W., Armi, L., 1990. The complex spreading pattern of Mediterranean Water off the Portuguese continental slope. Deep-Sea Res. 37, 1805–1823.