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Perched lobe formation in the Gulf of Cadiz: Interactions between gravity processes and contour currents (Algarve Margin, Southern Portugal)

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ABSTRACT

The Gulf of Cadiz is swept by the strong saline Mediterranean Outflow Water (MOW). On the Algarve Margin (South Portugal), this current has constructed fine-grained contourite drifts. This margin is dissected by the Portimao Canyon and three short channels that only incise the upper slope, and are absent on a terrace located at mid-slope depths along the Algarve Margin. High-resolution seismic profiles and sediment cores highlight the original architecture of the sedimentary deposits on this terrace. Coarse-grained lenticular chaotic bodies formed during major relative sea-level lowstands are intercalated within the drift. The lobate shape and sandy nature of the lenticular chaotic bodies and their location at the mouths of the three short channels suggest they are gravity-generated deposits that are perched on the middle continental slope.

In the Gulf of Cadiz, the interaction between contour current and gravity processes is strongly controlled by climatic variations and relative sea-level changes during the late Quaternary. During cold periods when sea-level was low, erosion intensified on the continental shelf and the deepest part of MOW was active. Sediment was transported downslope through the channels and deposited on sedimentary lobes perched on the mid-slope terrace. During warm periods when relative sea-level was high, the supply of sediment from the shelf was shut off and the shallowest part of MOW was more active. Contourite drifts fill the channels and bury the sandy lobes.

1. Introduction

Several studies of deep-water sedimentary deposits show the combined action in the margin construction of downslope gravity-driven processes (turbidity current, debris flow and mass wasting) and alongslope processes linked to contour currents (Mountain and Tucholke, 1983; Tucholke and Laine, 1983; Mountain and Tucholke, 1985; Tucholke and Mountain, 1986; Hesse, 1992; Locker and Laine, 1992; Howe et al., 1994; Massé et al., 1998; Viana and Faugères, 1998; Faugères et al., 1999; Michels et al., 2001).

The Gulf of Cadiz shows morphologies, sedimentary facies and deposits reflecting the influence of both alongslope (i.e. contourite) and downslope (i.e. gravity) processes (Hanquiez, 2006; Mulder et al., 2006; Marchès et al., 2007). The continental slope of the Gulf of Cadiz is swept by a strong current originating from the Mediterranean Sea, the Mediterranean Outflow Water (MOW), which had formed large contourite drifts along the northern margin of the Gulf of Cadiz (Faugères et al., 1984). These peculiar deposits record paleo-environmental changes (e.g. Faugères et al., 1999; Hernandez-Molina et al., 2002; Maldonado et al., 2003; Llave, 2004; Gilli et al., 2005; Hernandez-Molina et al., 2006a; Llave et al., 2006; Marchès et al., 2007; Toucanne et al., 2007). In addition to contour current-generated deposits, Habgood et al. (2003) and Hanquiez (2006) have highlighted the presence of submarine fans (channel–lobe systems) in the eastern part of the Gulf of Cadiz indicating that gravity-generated processes are also active. The western part of the Gulf, the Algarve Margin, is dissected by several canyons that were formed by downslope processes (Mulder et al., 2006), although large accumulations of gravity deposits have never been found at the downslope ends of these canyons.

Using multibeam bathymetry, acoustic imagery, high-resolution seismic data and a gravity core, this study presents evidence for the interbedding of gravity deposits with current-controlled sediment drifts on the Algarve Margin. Additionally, this paper provides a better understanding of the interactions between gravity and contourite processes on a margin, giving an opportunity to constrain environmental factors influencing the dominance of one of these processes over the other. Finally, this paper brings new elements on potential formation and preservation of coarse-grained deposits along a margin.

2. Background

2.1. Lobe definition

Submarine gravity systems constitute important conduits for sediment transfer to the deep-sea. Because they can form important hydrocarbon reservoirs, they have been extensively studied in both

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modern and ancient examples. Usually, lobes are defined as several meter-thick sandy bodies with good lateral continuity (sheet sands of Mutti and Normark, 1991). Since the 1990s, the term "lobe" has been used to define deposits located at the distal end of a turbidite system. Previously, however, the term "lobe" was applied to describe a wide range of submarine fan facies producing considerable confusion (Shanmugam and Moiola, 1991a,b). In this study, the term "lobe" is used to define the sedimentary body formed by deposition resulting from gravity flows located at the end of a canyon or a channel. The term "fan" is used to define the whole system including the feeding conduit (canyon, channel) and all the associated deposit (lobe).

2.2. Processes interactions

Several authors have studied the interactions between downslope processes and alongslope contourite processes (Hesse, 1992; Locker and Laine, 1992; Howe et al., 1994; Massé et al., 1998; Viana and Faugères, 1998; Faugères et al., 1999; Michels et al., 2001, among others). Different responses were recognized according to the dominance of one of these processes over the other.

(1) When contour current activity dominates over downslope processes, the downslope system is truncated and partly eroded. There is no deposition by any process and erosive features are developed (Faugères et al., 1999).
(2) When contour current activity is somewhat larger than the downslope processes, channel systems and associated gravity deposits tend to migrate in the contour current direction (Faugères et al., 1999). They form a transitional fan-drift system (Locker and Laine, 1992).
(3) When the two processes are balanced, the course of the gravity system is influenced by contourite drift construction and goes around it, but the two systems growth simultaneously (Faugères et al., 1999). They form adjacent fan and drift systems (Locker and Laine, 1992).
(4) When the alongslope and downslope processes dominate alternately, gravity-driven deposits and contourite beds can be intercalated and preserved if the accumulation rate is high. This situation forms an overlapping fan/drift (Locker and Laine, 1992).
(5) When downslope processes are dominant, the channel trajectory is only dependant on gravity flows frequency and topography. Only gravity deposits are observed.

3. The Gulf of Cadiz: morphology and hydrography

3.1. Regional morphology

The Gulf of Cadiz is located at the African–Eurasian plate boundary. The evolution of the margin was influenced by successive phases of extension and compression (Maldonado et al., 1999). The opening of the Strait of Gibraltar at the end of the Miocene allowed the present connection between the Atlantic Ocean and the Mediterranean Sea. The Gulf margin shows a concave shape. The eastern area is marked by the presence of several main tectonic features such as the Cadiz and Guadalquivir diapiric ridges and the Guadalquivir Bank (Medialdea et al., 2004; Hernandez-Molina et al., 2006b; Fig. 1). The western part

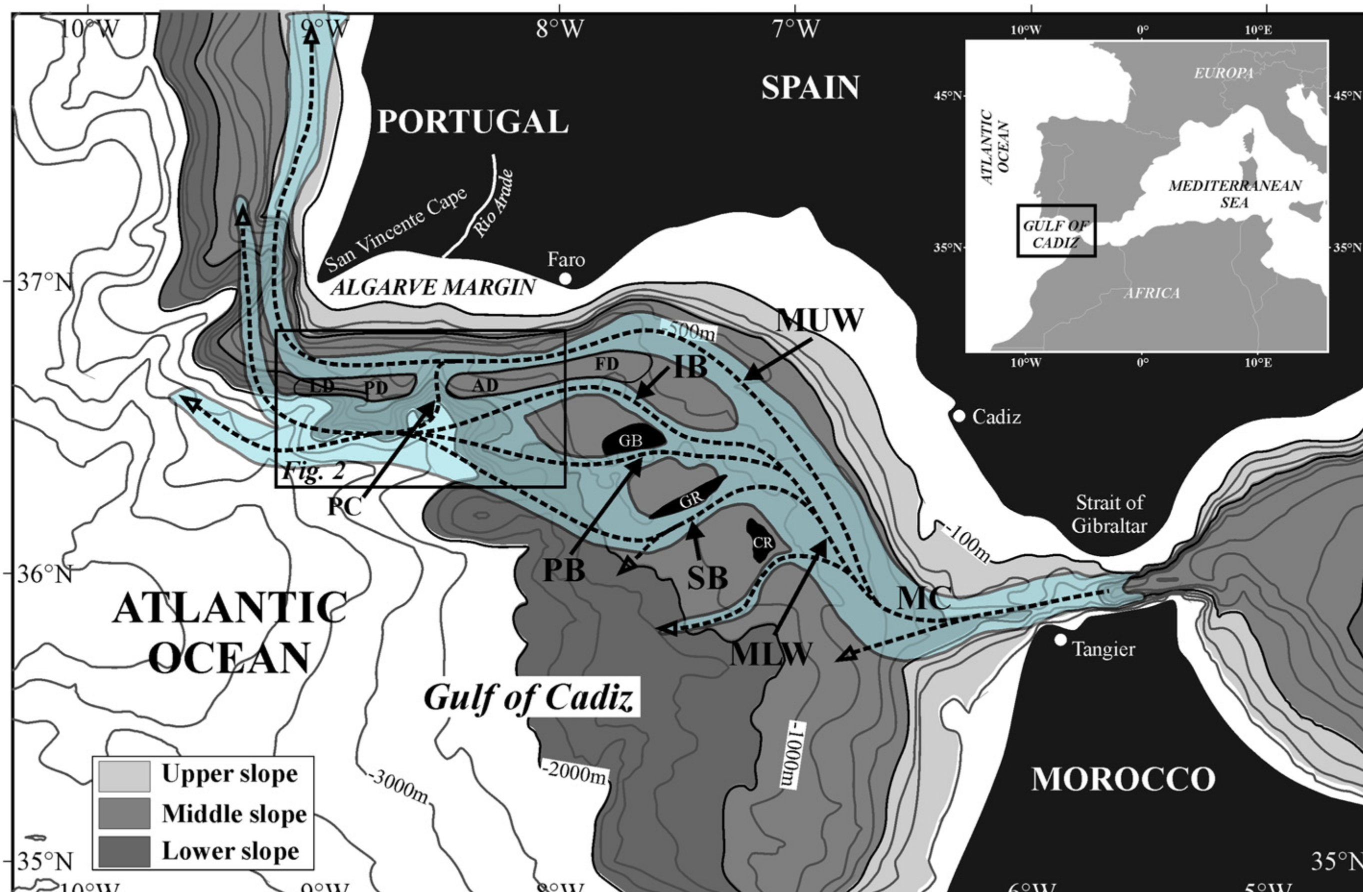

Fig. 1. Map of the Gulf of Cadiz showing the general MOW pathway (blue–grey area) and slope physiography (grey areas); black dotted arrows indicate MOW direction; MC: Main Core; MUW: Mediterranean Upper Water; MLW: Mediterranean Lower Water; IB: Intermediate MOW Branch; PB: Principal MOW Branch; SB: Southern MOW Branch; AD: Albufeira Drift; CR: Cadiz Ridge; FD: Faro Drift; GB: Guadalquivir Bank; GR: Guadalquivir Ridge; LD: Lagos Drift; PC: Portimao Canyon; PD: Portimao Drift. Modified from Madelain (1969) and Hernandez-Molina (2003).

of the Gulf, Algarve Margin, is characterized by the presence of marginal plateaux between 600 and 800 m water depths (Mougenot, 1988). These marginal plateaux were later capped by contourite drifts (Faro, Albufeira, Portimão and Lagos Drifts; resp. FD, AD, PD and LD in Fig. 1). The mid-slope terrace of the Algarve Margin is dissected by the Portimao Canyon; a large canyon whose location and size are related to deep faults (Vanney and Mougenot, 1981).

3.2. Oceanographic setting

After the opening of the Strait of Gibraltar, the Gulf of Cadiz was subjected to the action of a permanent bottom current, the Mediterranean Outflow Water (MOW; Mougenot and Vanney, 1982).

The MOW divides into two main branches (Gardner and Kidd, 1987) because of the sea floor morphology (Fig. 1): (1) The Mediterranean Upper Water (MUW in Fig. 1), is the warmer branch of the MOW which flows along the continental margin between 400 and 600 m water depth (Ambar, 1983; Baringer and Price, 1999) and (2) the saline and colder Mediterranean Lower Water (MLW in Fig. 1), flowing cross-slope between 600 and 1500 m water depths (Madelain, 1969). Because of the presence of the Guadalquivir Bank and the Guadalquivir Ridge (respectively GB and GR in Fig. 1), the MLW divides into three minor branches: the Intermediate Branch (IB in Fig. 1), the Principal Branch (PB in Fig. 1), and the Southern Branch (SB in Fig. 1).

The MOW strongly controls sediment distribution in the Gulf (Kenyon and Belderson, 1973). Three main sectors among the five proposed by Hernandez-Molina et al. (2003) can be considered in the Gulf of Cadiz: (1) an erosion sector close the Strait of Gibraltar, due to the high MOW energy, (2) a coarse-grained deposit sector, adjacent to the erosion sector where the deposits are sandy (Nelson et al., 1999) and (3) a fine-grained deposit sector in the northwestern part of the Gulf (Gonthier et al., 1984; Hernandez-Molina et al., 2003; Hernandez-Molina et al., 2006b). This last sector includes several contourite drifts (Faro, Albufeira, Portimão, Lagos and Sagres Drifts; resp. FD, AD, PD and LD in Fig. 1).

4. Methods

The data were collected during the Cadisar 2 cruise on the RV "Le Suroît" in August 2004. The study area is located south of the Algarve Margin, between 36°N and 37°N and 8°W and 9°20 W (Fig. 1).

4.1. Bathymetry and backscattering

Multibeam bathymetry and acoustic imagery were acquired using 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 respectively. Ship speed was 5–5.5 knots. Calibration of EM300 was assessed using three CTDs (SBE19 probes) and 84 thermoprobes (Sippican).

4.2. Seismic profiles

High-resolution seismic profiles were recorded with a 2000 J Sparker and a 12 hydrophone monotrace streamer. The profiles were collected at water depths between 500 and 1500 m. Four profiles are used in this study (Fig. 2).

The seismic interpretation is based on seismic stratigraphy analysis (seismic facies and discontinuities). Three main seismic facies (facies

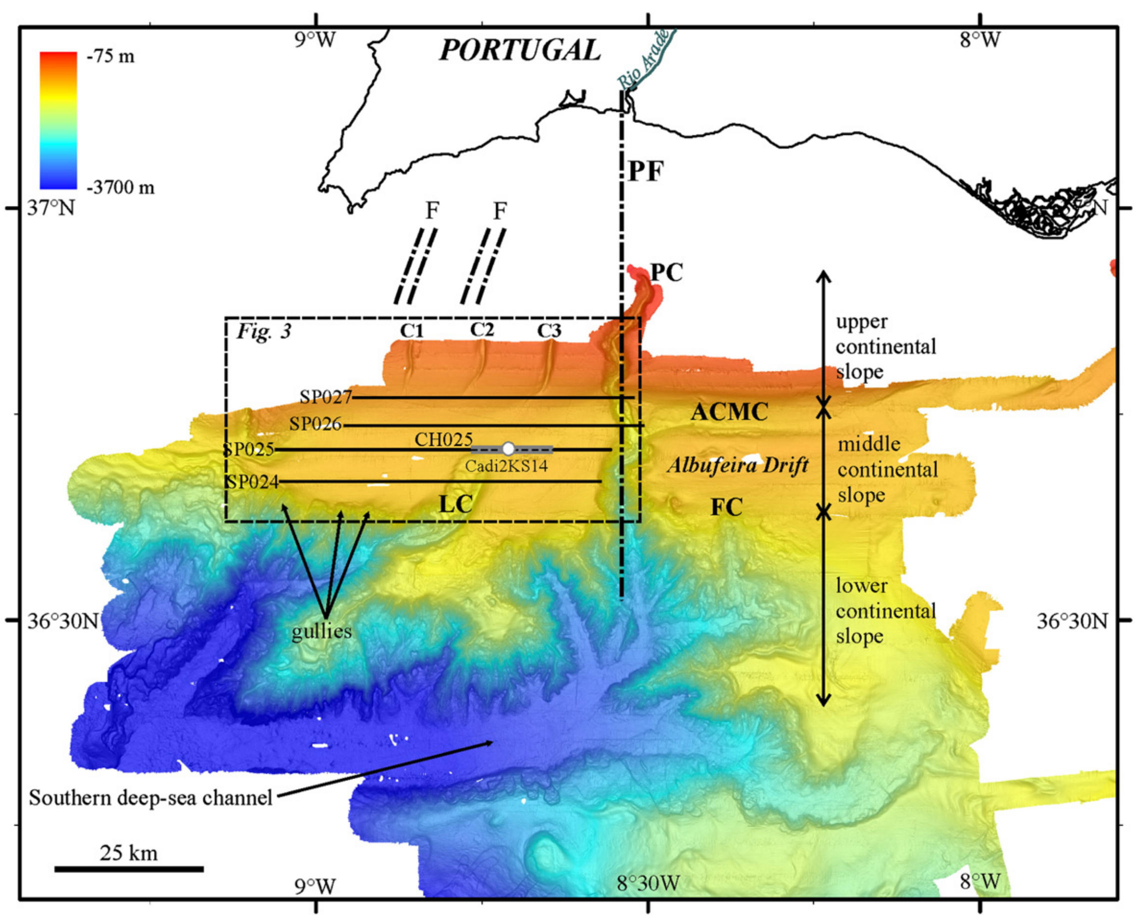

Fig. 2. Bathymetric map with location of tectonic features (from Lopes et al., 2006) and seismic profiles and core using in this study; ACMC: Alvarez Cabral Moat Channel; C1, C2 and C3: Channels 1, 2 and 3; FC: Faro Canyon, F: Fault; LC: Lagos Canyon; PC: Portimao Canyon, PF: Portimao Fault.

1, 2 and 3) already recognized in this area (Marchès et al., 2007), are observed. Reflection terminations (toplap, onlap, and truncation) are used to distinguish unconformities and erosional surfaces.

Very high-resolution seismic data were collected using a sub-bottom profiler. This system acquires very high-resolution seismics using the Chirp mode. It operates at a 2 to 5 kHz interval frequency and allows as much as 75 m of penetration and a 0.75 m vertical resolution.

4.3. Core analyses

One sediment core that is 4.46 m long was collected on the Portimao Drift (Fig. 2) using a Küllenberg piston corer. The core was photographed and X-radiographs were taken. Grain-size analyses were completed using sieving for the coarse fraction and particle counter for the fine fraction. Thin slides of impregnated sediment (Zaragosi et al., 2006) were used to analyse the sediment facies.

5. Morphology

The Algarve Margin is located in the Contourite Depositional System between 36°–37°N and 7°50–9°25 W (CDS; Hernandez-Molina et al., 2003) and is under the influence of the MUW. It is characterized by a rough morphology underlined by the presence of gullies, canyons, channels and contourite drifts (Fig. 2) indicating a lesser influence of the MOW than in the eastern part of the Gulf of Cadiz (Madelain, 1969). The general margin morphology shows important slope breaks delimiting the upper, middle and lower continental slope (Fig. 2).

The upper slope is dissected by three channels (C1, C2 and C3; Fig. 2). The three channels disappear at the base of the upper continental slope and are actually disconnected from the deep valleys seaward of the plateau. They have a NW concave morphology that is especially marked for Channels 2 and 3 (Fig. 3B). Channel 1 is 10 km long with a maximum width of 1.2 km. Its maximum relief is 70 m. It disappears at 570 m water depth (Fig. 3A). Channel 2 has a maximum relief of 100 m and is 2 km wide. It is 10 km long and disappears at 550 m water depth (Fig. 3A). Channel 3 is 12 km long. It narrows after 3 km and disappear at 700 m water depth where a slope break is observed. At this break, the slope changes abruptly from 2.8° to 0.7°. The maximum relief of this channel is 150 m and the mean slope of the channel axis is 1.78° (Fig. 3).

The slope break at 600 m water depth delimits the middle slope and corresponds to the “marginal plateaux” (Vanney and Mougenot, 1981) that were later recovered by contourite drifts (Albufeira and Portimao-Lagos drifts separated by Portimao Canyon). Portimao and Lagos drifts show a smooth morphology with a gentle slope (0.5°) whereas Albufeira Drift shows a relief with rounded form and separated from the upper slope by a moat channel carved by contour currents (Alvarez Cabral Moat Channel; Fig. 2). The Lagos Canyon, incising middle slope, is disconnected from the upper slope. Its morphology is more complicated. Its head is located at 760 m water depth and partly separates the Portimão drift and the Lagos drift. Two bends affect the canyon course. It has a NNE–SSW orientation over less than 10 km in the northern part, and then runs westward before joining the southern deep valley. Its relief reaches 1000 m and its talweg is narrow (2 km; Fig. 3B). The eastern side is steep whereas the western side of the canyon is smoother and characterized by terraces probably formed by instabilities along this flank.

The seaward edge of the plateau is in 800 m water depth, and the lower slope is incised by numerous gullies down to 3500 m water depth (Fig. 2).

The most northwestern part of the plateau is characterized by a homogenous moderate backscatter. At the mouth of Channel 3, a higher backscatter signature is observed (Fig. 3C and D). The western limit of

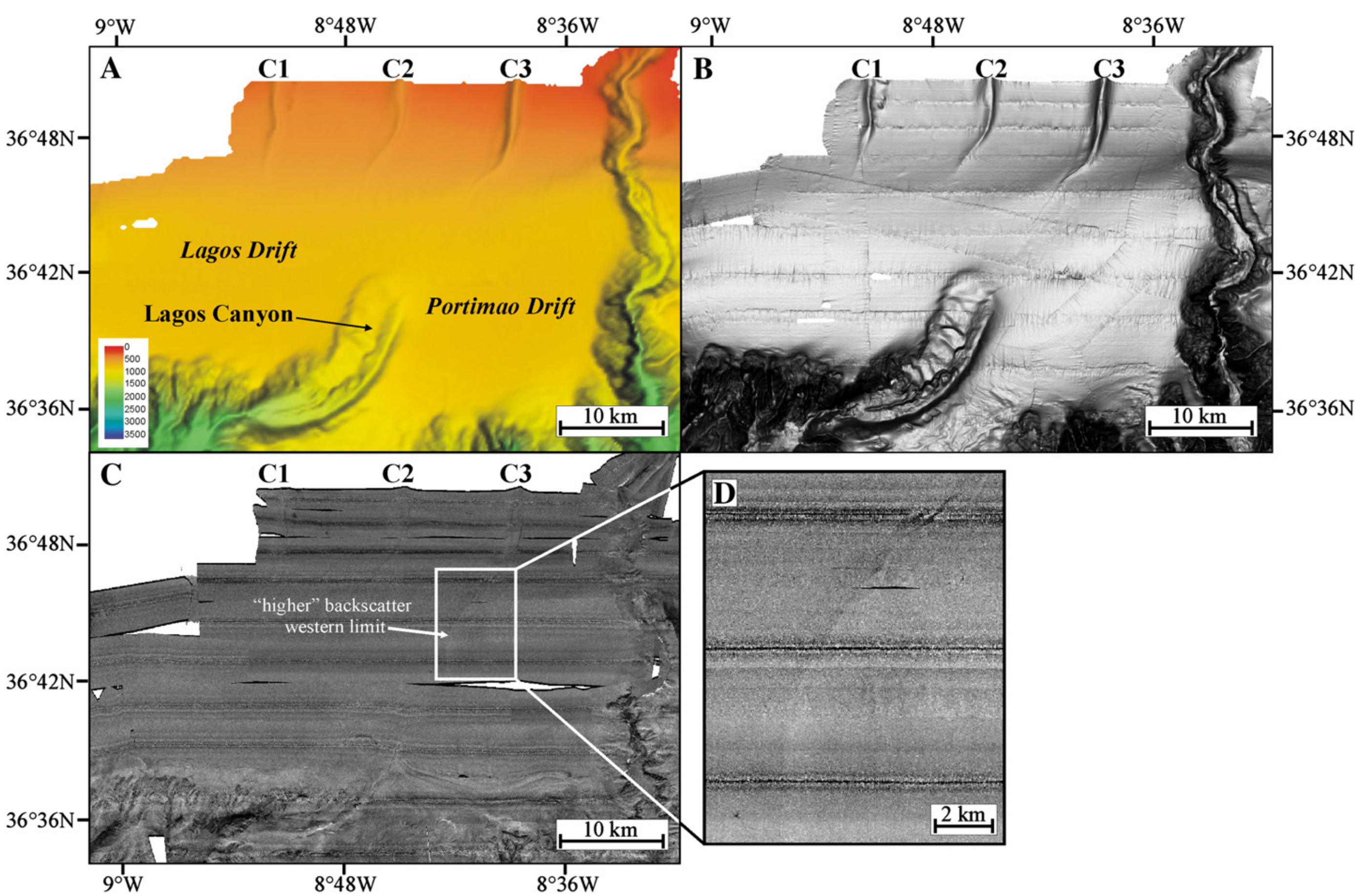

Fig. 3. Bathymetric map (A), slope gradient map (B) and EM300 acoustic map (C) of the study area (see location in Fig. 2); C1, C2 and C3: Channels 1, 2 and 3.

higher backscatter is visible and shows a lobed shape. The eastern boundary is gradational, and thus not clearly defined. No topographic changes can be resolved across this higher backscatter lobe.

6. Seismic data analysis

The seismic data allowed identifying five seismic units: U0, U1, U2, U3 and U4 (Fig. 4). Units U1, U2, U3 and U4 form the four phases of contourite drift construction. Each of these four sedimentary units lies on a discontinuity respectively named D1, D2, D3 and D4.

6.1. Unit U0

Unit U0 is characterized by seismic facies 2 first described by Marchès et al. (2007). Facies 2 is characterized by a moderate amplitude and discontinuous parallel reflectors (Fig. 4). It shows 350 m of aggrading deposits (460 ms TWT; Fig. 4). This unit is limited at its base by the acoustic basement and at its top by the major erosional discontinuity D1. A westward thinning down of this unit is observed on each profile (Fig. 4). It can be related to the rising of acoustic basement westward.

6.2. Discontinuities D1, D2, D3 and D4

On each profile, D1 shows three V-shaped incisions under the drift deposits located between the southern termination of the actual three channels and the northern head of Lagos deep valley. The acoustic basement below the paleochannels is very rough and suggests that buried faults control the location of these channels. Paleomorphology reconstruction suggests that these three channels originally extended from the upper slope across the marginal plateau and connected with Lagos Canyon or other deep valleys along the seaward side of the marginal plateau (Fig. 6). The three paleochannels have a N–S orientations, relatively straight courses, and are over 30 km long. Their relief can reach 180 m (C3; Fig. 6) and they can be as much as 1.5 km wide. Paleochannel 2 seems to have been connected to Lagos Canyon. Paleochannels 1 and 3 are absent on southernmost seismic profiles. The absence of the channels here may be because the seismic system could not penetrate the thick sediment accumulation. Discontinuities D2, D3 and D4 show discordances with reflector truncations and are interpreted as erosional surfaces (Fig. 4).

6.3. Unit U1

Seismic unit U1 is bounded by the major erosional surface D1 at its base and by D2 at its top. This unit is characterized by seismic facies 2 (Fig. 4). It corresponds to the filling of the paleochannels and presents an important lateral variability in thickness. Its maximum thickness is 270 ms TWT (200 m using a mean velocity of 1500 m/s in Quaternary sediments) where it fills the paleochannels but it is less than 10 m-thick away from the channels and pinches out at both its eastern and western edges. The top surface of unit U1 corresponds to discontinuity D2.

6.4. Unit U2

Seismic facies 1 and 3 are observed in unit U2 (Fig. 4), between discontinuities D2 and D3. Seismic facies 3 is characterized by continuous high-amplitude, parallel reflectors whereas seismic facies 1 is chaotic. U2 reaches a thickness of 52 m on profile SP024, decreasing to 25 m northward (Fig. 4).

In this unit, several sedimentary bodies are identified. They are characterized by seismic facies 1, have a lenticular shape and are observed in profiles SP025 and SP026. They are called lenticular chaotic bodies (LCBs in Figs. 4, 5 and 6). Three LCBs are identified above D2: LCB1, LCB2 and LCB3 (Fig. 4). They are located at the mouths of paleochannels 1, 2 and 3 respectively, suggesting they have been connected to paleochannels 1, 2 and 3 (Fig. 7). The isopach maps show they have a lobate shape (Fig. 7). LCB1 extends over 20 km with a maximum width of 6 km. LCB2 is 15 km long and 10 km wide. LCB1 and 2 merge together by profile SP025 where their thickness is 38 m. They represent a volume of 3 km^3. LCB1 and LCB2 are composed of two sub-units that suggest a polyphased construction with a westward migration (Fig. 4).

LCB3 is 15 km long and 15 km wide. It reaches a maximum thickness of 45 ms TWT (34 m, Figs. 4 and 7) and has a volume of 1.5 km^3 (Fig. 7). LCB3 is formed by three sub-units that show a three-phases construction. On profile SP026, the units aggrade. On profile SP025, a lateral westward migration like LCB1 and LCB2 bodies is observed.

6.5. Unit U3

Unit U3 is characterized by the seismic facies 1 and 3. Its maximum thickness is 67 m (90 ms TWT in profile SP024; Fig. 4). The thickness of U3 decreases northward but is relatively uniform along E–W section (22 m in profile SP027, Fig. 4).

In profiles SP025 and SP026, two chaotic bodies (facies 1) similar to those in unit U2 are observed: LCB4 and LCB5 (Fig. 4). They formed above D3. They seem to have been connected to paleochannels 2 and 3 and have a lobate shape (Fig. 7). LCB4 has a limited extent. It is 5.5 km long and 2 km wide. It is composed of a single unit reaching 15 ms TWT (11 m, Fig. 7) and with a volume of 0.03 km^3.

LCB5 is 15 km long, 12 km wide and 40 ms TWT thick (30 m, Fig. 6). It is formed of two units that show a westward migration on SP026 and an eastward migration on SP025. It corresponds to a volume of 1.2 km^3.

6.6. Unit U4

This unit is characterized by seismic facies 1 and 3. It is the thinnest unit only reaching 15 m at maximum. In this unit only one lenticular chaotic body is observed: LCB6.

It is the youngest LCB and is located just below the seafloor. Its westward and eastward limits correspond to low backscatter area on acoustic imagery (Fig. 3). It is only 7.5 m thick, 10 km long and 3.5 km wide (Fig. 7) and has an approximate volume of 0.05 km^3.

7. Age and nature of sediments

7.1. Stratigraphy

The age of the five seismic units is based on works of Hernandez-Molina et al. (2003), Llave et al. (2006) and Llave et al. (2007). These authors defined the chronology of contourite deposits in the Gulf of Cadiz based on seismic profiles correlated with oil companies drill sites (Llave et al., 2001, 2007). The seismic units defined in this study are based on correlations with these previous works in which the same discontinuities were dated (Fig. 8).

Unit U0 is Pliocene in age and U1, U2, U3 and U4 are Quaternary in age. Discontinuities D1, D2, D3 and D4 correspond to the Plio-Pleistocene boundary, the Mid-Pleistocene Revolution (MPR), MIS12 and MIS6, respectively, as defined by Llave (2004). These discontinuities in sediment record correspond to important climate and sea-level changes. Discontinuity D1 is Plio-Pleistocene in age (1.8 Ma BP) and corresponds to the first global climate deterioration and a major erosional surface in the Gulf of Cadiz due to a sea-level lowstand (Blavoux et al., 1999; Llave, 2004). D2 corresponds with the MPR discontinuity (880 ka BP) and is related to the important sea-level fall associated to this period described as the first major cold event of the Pleistocene (Llave, 2004; Hayward et al., 2005; Head and Gibbard, 2005; Ehlers and Gibbard, 2007). MIS12 (D3) is described as the most extreme climate conditions of the Late Pleistocene (430 ka BP). It is marked by a large glaciation, important changes in oceanic circulation and sea-level fall (Thunell et al., 2002; Chaisson et al., 2002; Head and Gibbard, 2005).

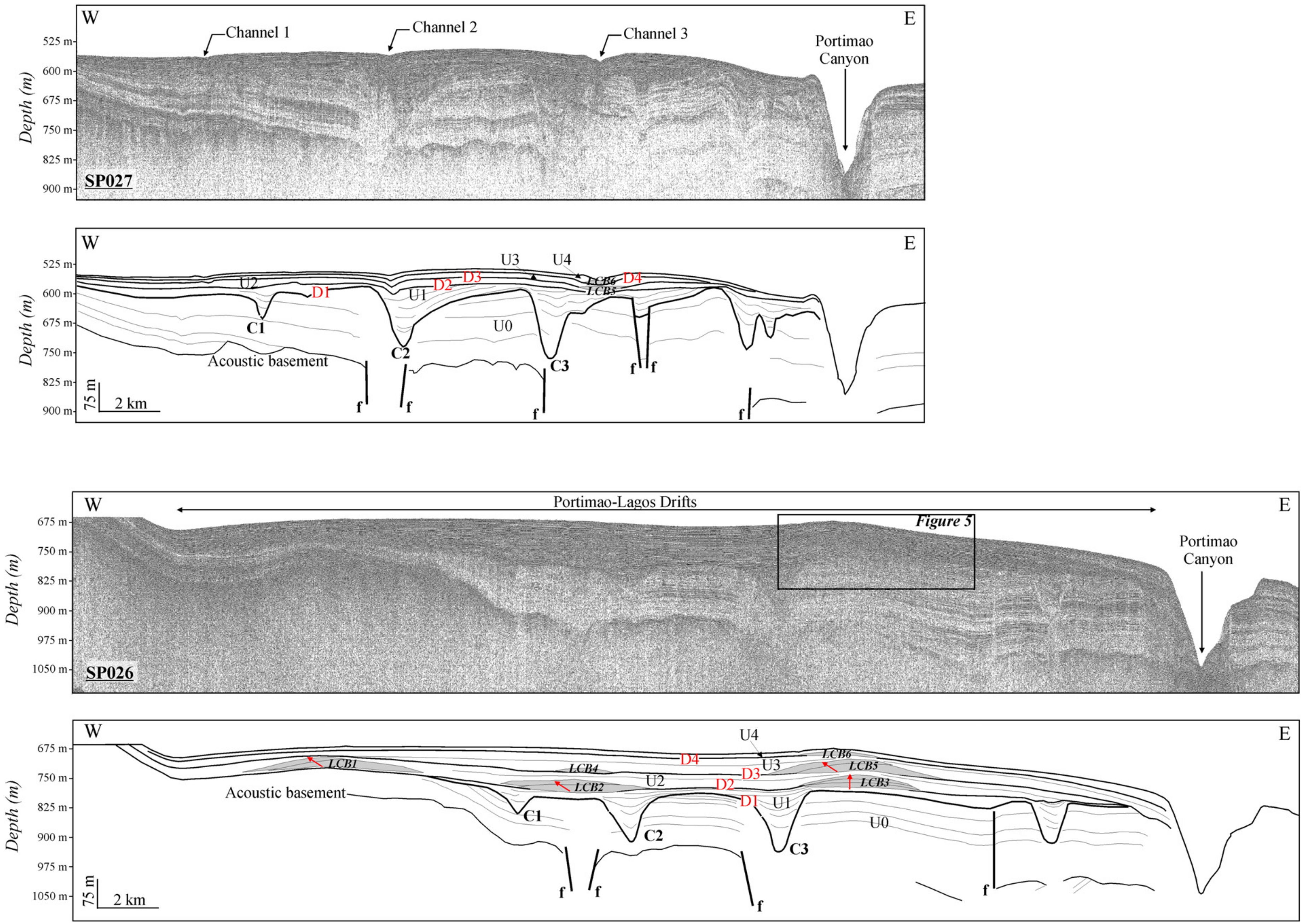

Fig. 4. Sparker seismic profiles and their interpretation; f: fault; C1, C2 and C3: Channels 1, 2 and 3; LCBs: lenticular chaotic bodies.

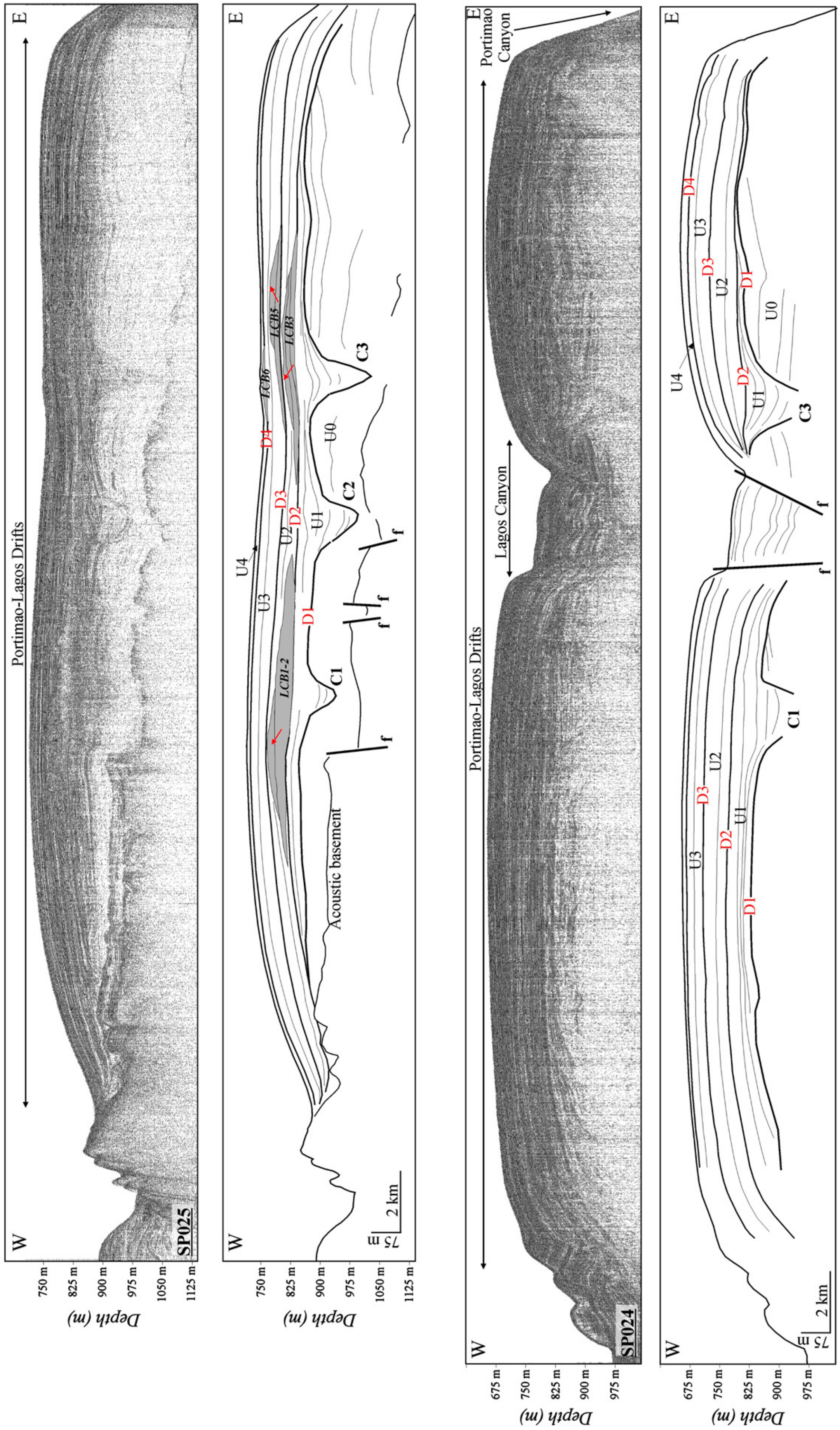

Fig. 4 (*continued*).

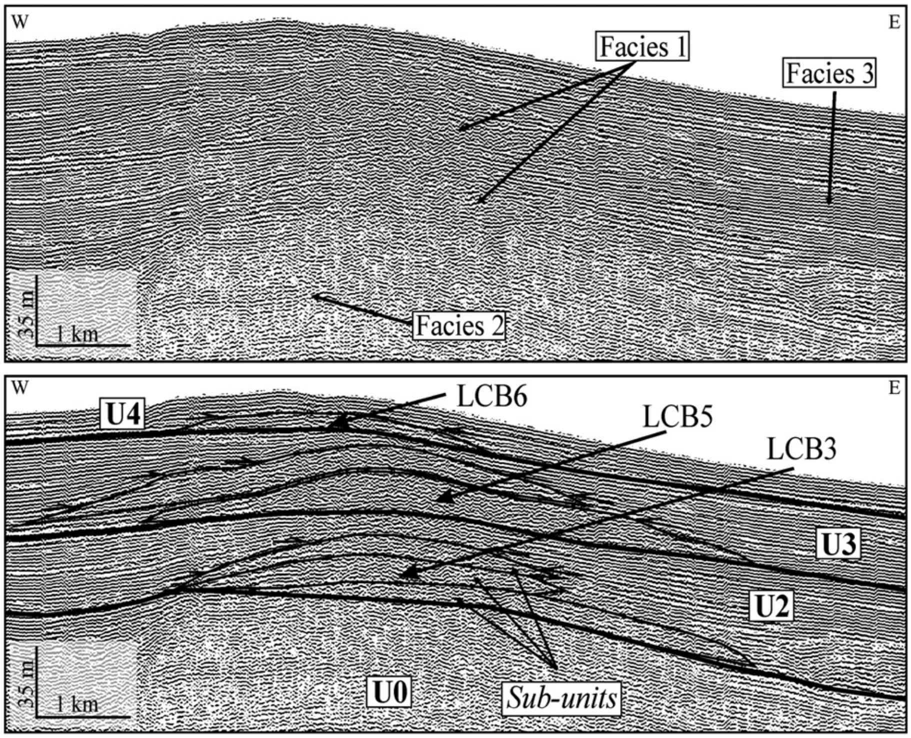

Fig. 5. Zoom of SP026 sparker seismic line on LCB3, 5 and 6 (see location on Fig. 4).

MIS6 (D4; 135 ka BP) is characterized by high benthic $\delta^{18}O$ values (Lisiecki and Raymo, 2005). It is known as the second most important glaciation during Quaternary after MIS12 (Ehlers and Gibbard, 2007).

7.2. Nature of sediment in lenticular chaotic bodies

Information on the nature and texture of sediments associated with the LCBs was obtained from one short gravity core that penetrated only 4.5 m into LCB6. Even though it was short, it penetrated the two seismic facies that comprise the studied system. The core presents two sedimentary facies. The first facies consists of structureless coarse sand and shell debris. D50 is approximately 200 µm and the particle distribution is unimodal (mode = 300 µm; Fig. 9D) with a very small additional mode at 6 µm. The thin-section shows detritical material without any visible fine matrix. This first facies has been associated to LCBs and gravity processes. The second facies is composed of grey silty-clay. D50 is generally less than 30 µm and the particle distribution is bimodal (modes at 6 and 200 µm; Fig. 8). On thin-section, a fine matrix with coarser sediment pockets is observed. This facies has been assimilated to contourite. The contact between the two facies is sharp and erosional (Fig. 9D).

8. Discussion

8.1. Origin of the lenticular chaotic bodies

The lenticular chaotic bodies (LCBs) are all located at the mouths of channels that cross the upper slope. The isopach maps (Fig. 7) show they mostly have lobate shapes. The seismic profiles show that three of them lie directly above disconformity D2, two lie above disconformity D3, and one lies above discontinuity D4. The one above D4 coincided with the area of high backscatter in Fig. 3C and D. These characteristics have been described for most terrigenous deep-sea lobes (Gervais, 2002; Bonnel, 2005; Bonnel et al., 2005). Deep-sea fan studies show that the terminal parts of gravity systems are composed of graded coarse sediment that accumulates at the channel mouth. In this study, sediment core analyses and chaotic seismic facies indicate that the LCBs are composed of sandy sediment corresponding to large deposit volumes (total accumulated volume of the three LCBs = 5.78 km^3).

The LCB observed in this study have the general morphology and sedimentary characteristics of lobes. (1) They are located on gentle slopes at the mouths of canyons. (2) The lobe sand content is about 35%. The sand particles include mainly shell debris. The composition of the sand suggests a shelf source and can be explained by the short length of the channels. The composition of the lobe is similar to the composition of the source sediment on the continental shelf because channelled gravity flows have not enough time to sort particles. This feature corresponds to an immature system. (3) Their seismic architecture is characterized by mound with chaotic seismic facies that differs with facies observed in contourite deposits (continuous, high-amplitude reflectors). (4) Recent studies have showed the several phased construction lobes (Gervais, 2002) with successive sedimentary units migrating according to topographic compensation. In this work, seismic data show that several migrating units form the lenticular body (Fig. 4).

These similarities between LCB and terminal deep-sea lobes described by Reading and Richards (1994) allow associating LCBs to lobes. Their location on the middle continental slope suggests they are “perched” lobes. This stop at mid-slope can be explained by the small size of the flows (or flows that are not active for a long enough time) to cross over this middle slope terrace. On the contrary, at Plio-Pleistocene limit (D1), conditions were more erosive because they permit incision of Algarve Margin from upper slope to deep valleys (formation of paleochannels 1, 2 and 3; Fig. 4 and 5). This observation could be explained by more extreme conditions during Plio-Pleistocene limit that subsequent discontinuities. It is possible that climatic conditions, sea-level fall and sediment supply associated to D1 discontinuity were more favourable to erosion than conditions associated to discontinuities D2, D3 and D4 that formed LCB in the slope.

8.2. Alternation of sedimentary processes

The Algarve Margin is characterized by the presence of alongslope processes linked to contour current activity and cross-slope processes linked to gravity-driven processes (Mulder et al., 2006; Marchès et al.,

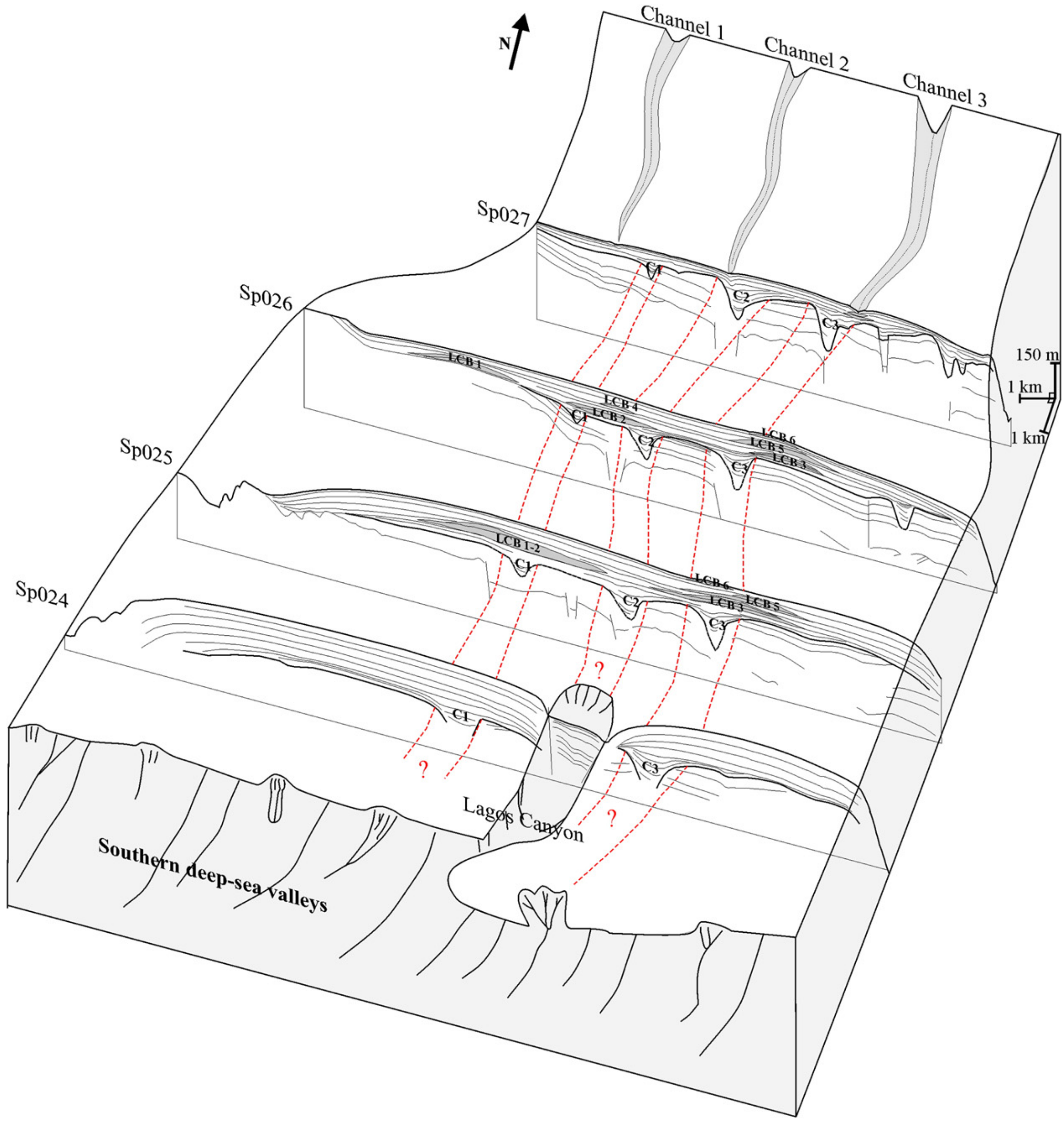

Fig. 6. Pseudo 3D assemblage of sparker seismic profiles showing the LCB location on the margin and the continuity between paleochannels and actual channels.

2007). These processes generate two major types of morphology (Fig. 2): (1) the alongslope structures including the contourite drifts and associated moat channel (e.g. Alvarez Cabral channel) and (2) the downslope structures such as the Portimao, Lagos and Faro canyons and Channels 1, 2 and 3 (C1, C2 and C3; Fig. 2).

Seismic data show alternation between downslope sediment transport forming the LCBs, and alongslope sediment transport generating drifts that encase the LCBs. Contourite construction represents the largest part (93%) of the total volume of accumulated sediment on Algarve Margin during the Pleistocene (76.9 km^3 vs 5.78 km^3 for total LCB deposit). This observation can be related to the high sedimentation rate of contourite deposits and the permanent activity of the MOW. In opposition, the duration of gravity flow activity in channels is short because the triggering of gravity flow is strongly dependant of the sediment supply from the continental shelf.

Contourite drift growth shows important aggradation on the western part of Portimao Canyon. Because of the MUW capture by the Portimao Canyon, the MUW is not intense enough to erode the north side of Portimao and Lagos drifts and form moat channel on Portimao and Lagos drifts (Marchès et al., 2007). Thus, the MUW spreads over, in this area, because it is no longer channelled. The pronounced progradation observed on the Albufeira drift is thus not observed on the Portimao and Lagos drifts (Marchès et al., 2007). The influence of seafloor morphology on the hydrodynamics explains the difference in drift construction in each side of Portimao Canyon resulting in the asymmetry of the Algarve Margin.

Location of LCB above discontinuities corresponding to major climatic event and sea-level changes, suggests that the alternation of sedimentary processes is controlled by relative sea-level.

8.3. Sea-level control

The stratigraphy showed that perched lobe formation occurred during relative sea-level lowstands associated with cold climatic

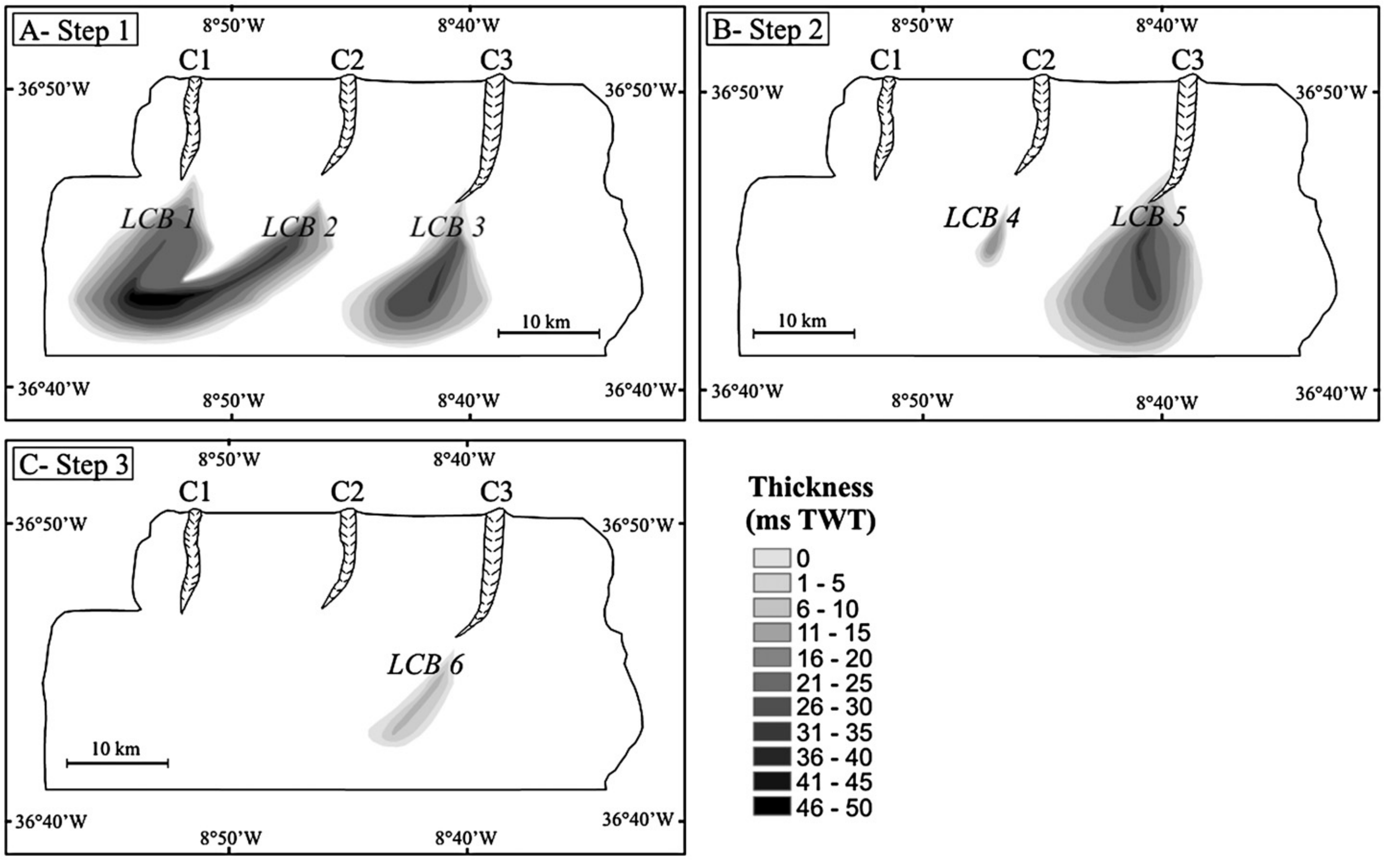

Fig. 7. LCB isopach maps; (A) Step 1 (MPR: 880 ka BP): LCB1, LCB2 and LCB3 deposit; (B) Step 2 (MIS12: 430 ka BP): LCB4 and LCB5 deposit; (C) Step 3 (MIS6: 135 ka BP): LCB6 deposit.

periods. This result is consistent with numerous studies that show an increase in channel activity on siliciclastic margins during sea-level fall (e.g. Bouma et al., 1989). During sea-level lowstand, activity of turbidite systems increases because of the direct connection of river systems to the heads of canyons.

During sea-level falls and lowstands dominated by gravity processes, several authors have noted important changes in MOW circulation (Chaisson et al., 2002; Thunell et al., 2002; Hayward et al., 2005; Head and Gibbard, 2005; Llave, 2004; Hanquiez, 2006; Llave et al., 2006). The gravity process activity increases during relative

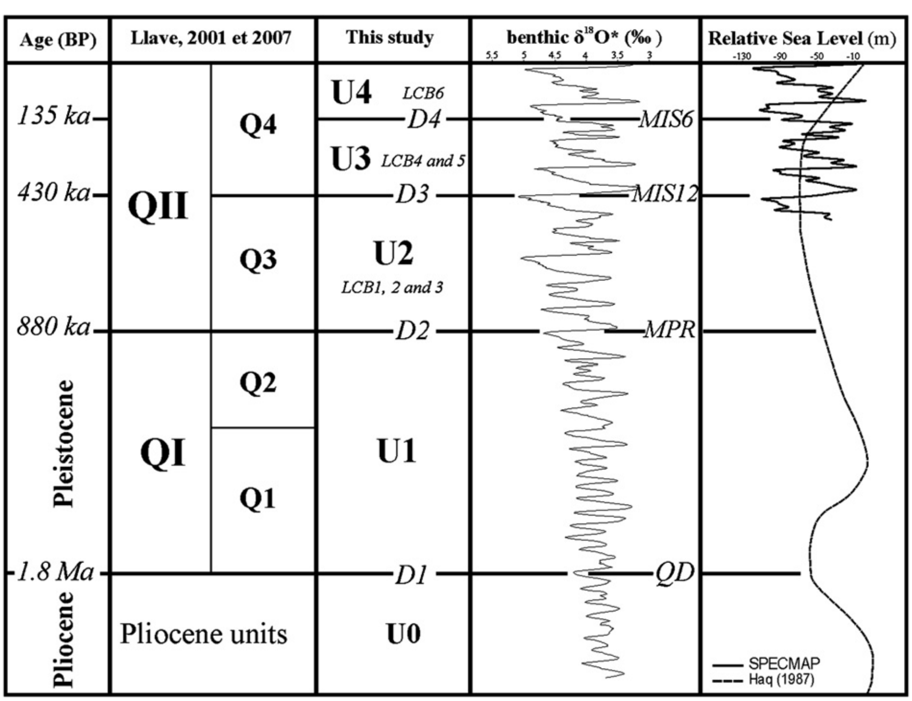

Fig. 8. Seismic stratigraphy based on Llave (2004 and 2007). Benthic δ^{18}O curve is "LR04" stack from Lisiecki and Raymo (2005) and relative sea-level is a compilation from Haq et al., 1987 and Martinson et al., 1987 (SPECMAP).

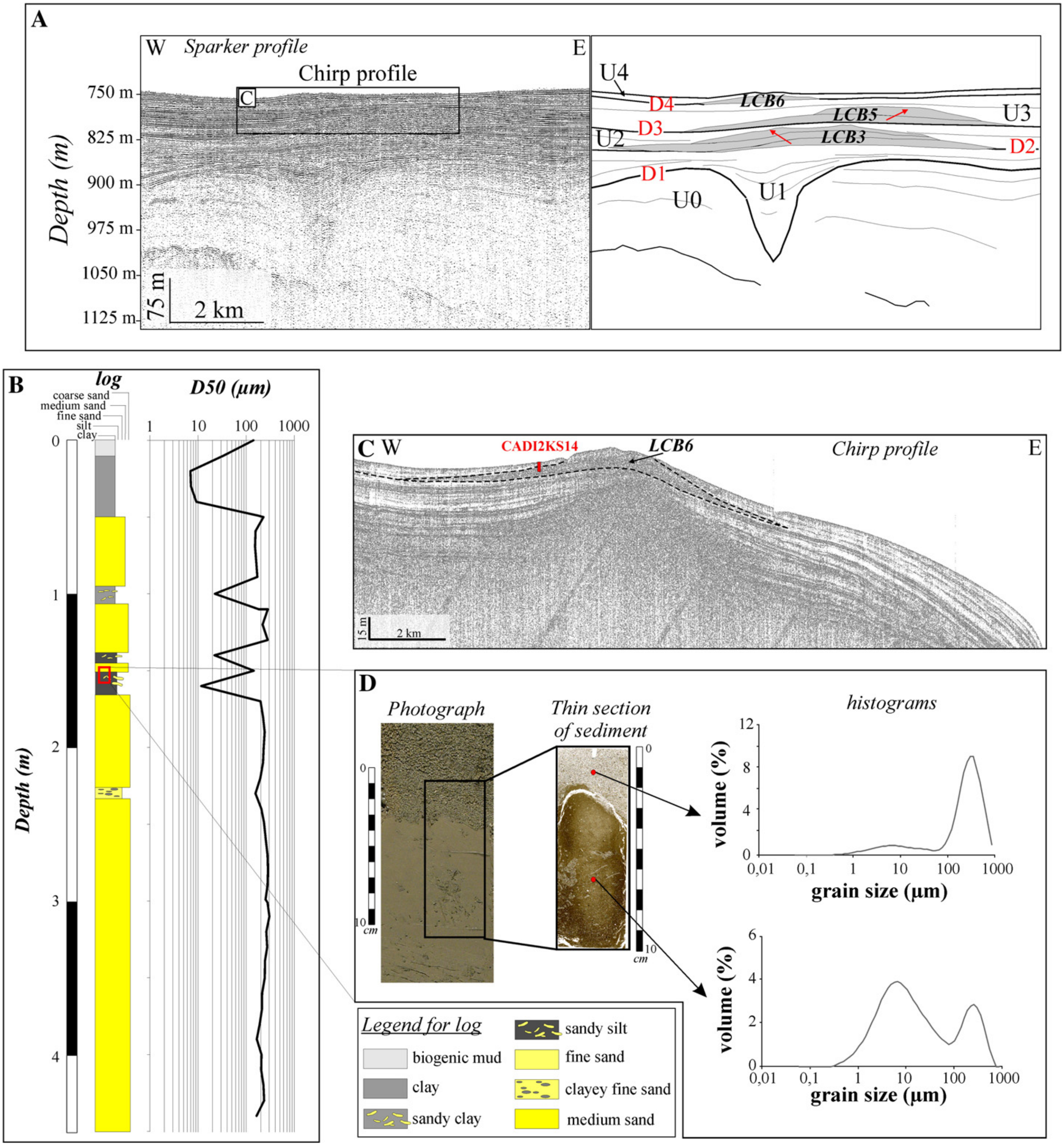

Fig. 9. Determination of LCB sedimentary composition. A: Sparker profile showing the location of chirp profile; B: Cadi2KS14 kullenberg core, facies description and grain-size curve; C: Chirp profile crossing Cadi2KS14; D: Thin section illustrating the two different sedimentary facies with grain-size distribution associated.

sea-level fall and corresponds to periods of decreased MUW intensity (Llave, 2004; Hanquiez, 2006). Conversely, MUW increases during relative sea-level rises and highstands (Hanquiez, 2006). On the Algarve Margin, formation of gravity deposits is increased when MOW activity is reduced (Plio-Pleistocene limit, MPR, MIS12 and MIS6; Fig. 10A, C, E and G). This study is consistent with the MUW being the most active branch of the MOW during period of relative sea-level highstand (Fig. 10). During these periods, contourite deposition increases (Fig. 10B, D, F and H). During falls in relative sea-level, the increase of river load and the reduction of the MUW activity allow the reactivation and preservation of gravity deposit (Fig. 10A, C, E and G). The strong interaction between gravity processes and contour current is thus closely linked to relative sea-level variations (Fig. 10).

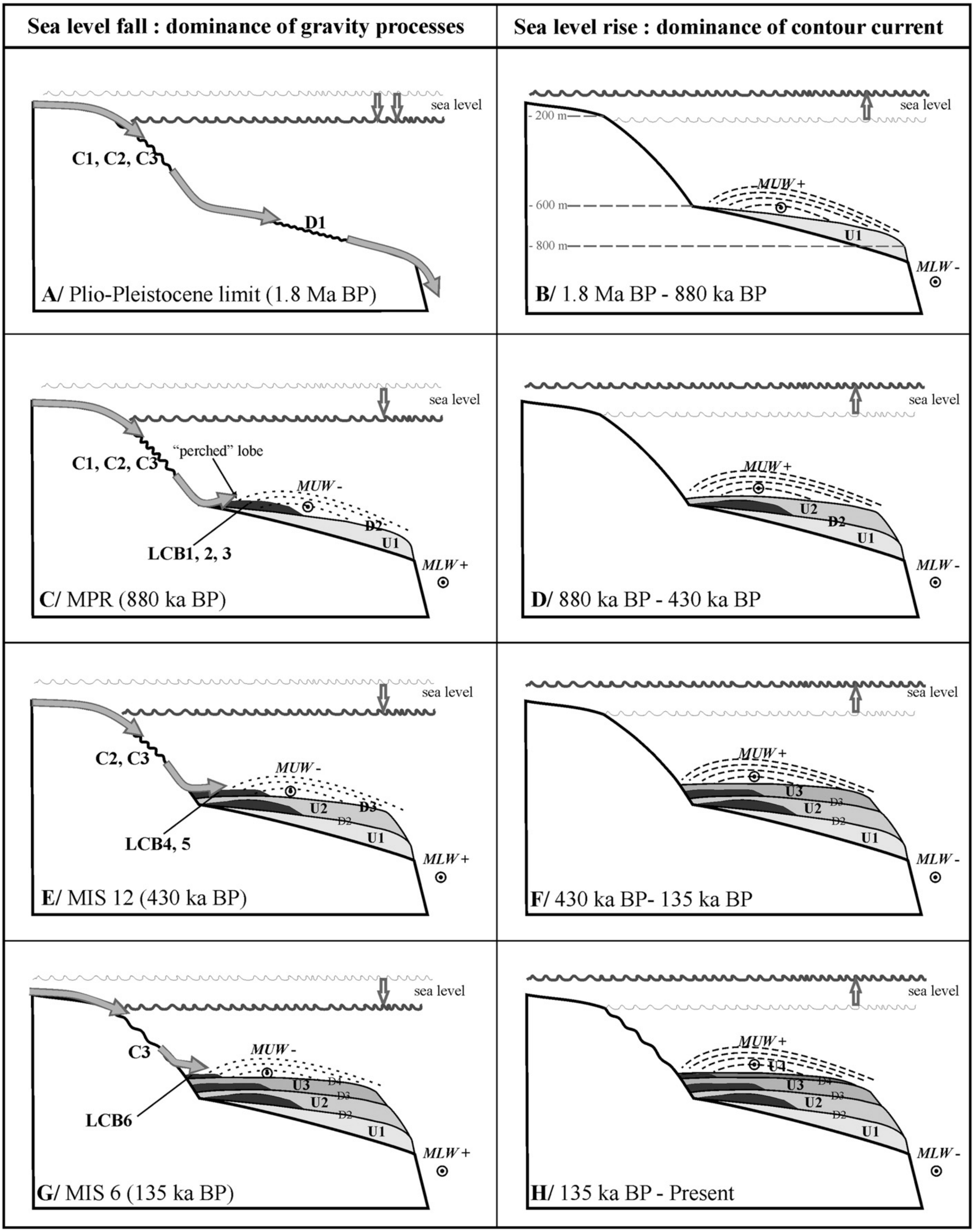

Fig. 10. Conceptual model of the margin construction and sedimentary processes associated during the last 1.8 Ma. A: Plio-Pleistocene limit (1.8 Ma BP); B: between Plio-Pleistocene limit and MPR (880 ka BP); C: MPR (880 ka BP); D: between MPR and MIS 12 (430 ka BP); E: MIS 12 (430 ka BP); F: between MIS 12 and MIS6 (135 ka BP); G: MIS6 (135 ka BP); H: between MIS6 and present.

8.4. Perched lobe formation: interactions between gravity processes and contour current

The depositional environment of the observed perched fans is different than those described by Reading and Richards (1994) or Nelson and Maldonado (1988). The sedimentary structure of Algarve Margin and particularly the paleo-morphology underlined by the presence of paleochannels below contourite drifts shows that the development of these lobes is related to contourite construction. Channel filling by contourites, when the MOW was initiated in the Gulf of Cadiz after Messinian, disconnected the upper slope from deep valleys. Gravity flows could no longer reach deep basins and gravity deposits (i.e. lobes) formed on the middle slope. North to 36°45 N, upper channels are not filled because they are not submitted to drift deposition. During period of gravity processes activity, corresponding to sea-level falls and lowstands, the channel system becomes active and forms perched lobes on the mid-slope terrace at the mouths of the channels. This observation is true for small channels, like those underlined in this study, but not for larger canyons like the Portimao Canyon. Portimao Canyon is not filled. On one hand, it may be explained by MUW capture phenomenon by this canyon. Its larger size can influence bottom current circulation that contributes to canyon preservation. However the downslope morphology of lower size are only submitted to nonpermanent gravity flows and in this way are rapidly filled by contourite construction. On the other hand, this canyon incises the shelf and enough sediment could continue to be swept off the shelf into Portimao Canyon head. This sediment could generate enough gravity flows to keep this canyon open.

Core lithology associated to seismic profiles interpretation shows that gravity lobes are interbedded within the contourite drift construction. This suggests an alternation with time of turbidite and contourite processes. When gravity processes are dominant they are not energetic enough, or their period of activity is too short, to re-incise paleochannel valleys across the plateau. Algarve Margin constitutes an example of overlapping fan-drift with contourite sedimentation rate high enough for deposit preservation according to the classification of Locker and Laine (1992). However, it seems to be different than companion fan/drift systems described by Locker and Laine (1992) and Faugères et al. (1999). In their studies, seismic geometry reveals cut-and-fill processes that suggest the presence of channel–levee systems buried by contourite construction. The distal deposits of the gravity system (lobe) was never observed in this type of interaction. In this study, the straight course of channels and the topographic change, induced by the drift construction, allow us to observe the whole fan system. In that sense, the Algarve Margin drifts constitute a new type of deposit resulting from the interaction between gravity processes and contourite processes.

9. Conclusions

The geometry of depositional sequences and associated seismic facies west of the Portimao Canyon shows the presence of coarse sedimentary bodies interpreted as perched lobes intercalated in contourite deposits. These gravity deposits, preserved by drift construction, show the combined activity of submarine fans (channel–lobe system) and contourite drifts. Construction of the middle Algarve Margin slope is, thus, controlled by alongslope processes related to contour currents that form contourite drift, and downslope processes that form canyons and small perched fans. This alternation of sedimentary processes appears to be controlled by changes in relative sea-level that alternately affect MOW course and intensity of downslope transport and terrigenous sediment input from the continental shelf. The main conditions for development of perched fans are: (1) the presence of terraces on the slope, (2) sandy sediment availability at the shelf edge, (3) sea-level lowstand conditions for downslope sediment transfer and (4) the low activity of bottom current flowing on drifts. The perched lobes constitute a new type of sedimentary deposits resulting from the interaction between gravity processes and contour currents in the Gulf of Cadiz. Their composition suggests a good reservoir potential. This work brings new elements on potential formation and preservation of coarse-grained deposits along a margin and confers to contourite margins a new potential industrial interest.

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