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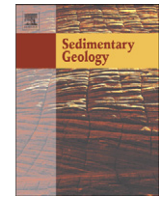

Simulation of the interactions between gravity processes and contour currents on the Algarve Margin (South Portugal) using the stratigraphic forward model Sedsim

T. Salles [a,*], E. Marchès [b], C. Dyt [a], C. Griffiths [a], V. Hanquiez [b], T. Mulder [b]

[a] *CSIRO Predictive Geosciences Group, 26 Dick Perry Ave, Kensington, WA 6151, Australia*
[b] *Université Bordeaux 1, UMR CNRS 5805 EPOC, av. des Facultés, 33405 Talence Cedex, France*

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ABSTRACT

The margin of the Gulf of Cadiz is swept by an intermediate current 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 alignment. Recent sedimentological studies emphasize the presence of complex process interactions resulting in the formation of a unique depositional architecture. Alongslope processes related to contour currents generate contourite drift, while downslope processes form canyons and channels aligned on deep faults. This paper uses a combined oceanographic and geological dataset to simulate the different types of interactions between gravity processes and contour currents, which were evidenced on this margin. An extrapolation of the contour current intensity has been used based on the present day velocity field and sea-level fluctuations over the simulated geological time-scale. According to our model results, the construction of the contourite drift is closely linked to contour current velocities and directions, the types of sediments transported and the existing topography. Using modern sedimentological understanding of the area, we have correlated gravity flow's strongest activity to sea level lowstand periods mainly due to a closer connection between canyon's mouth and river or deltaic systems. The simulated gravity flows are initialized at different locations and times on the margin depending on the preserved lobes retrieved from seismic analysis. Their resulting morphological features are identified as perched-lobes with volumes and forms close to the ones observed on Portimão and Lagos Drifts. This study provides a process-based understanding of the construction of contourite system and a physical evaluation of the interactions between gravity flows perpendicular to the slope, and alongslope processes. In addition, it shows the influence of autocyclic factors in the construction of contourite sedimentation, which is important to consider in future sedimentary paleo-reconstruction interpretations.

1. Introduction

The Gulf of Cadiz is located in the eastern part of the Atlantic Ocean. It extends from the Strait of Gibraltar (Spain) to Cape San Vicente (Portugal). The water masses of the Atlantic Ocean and the Mediterranean Sea first mix in this area. The large density difference between the warm, highly saline waters that flow at depth out of the Mediterranean through the Strait of Gibraltar and the cooler and less saline waters of the Atlantic, which flow at the surface into the Mediterranean, result in the high-velocity density current known as the Mediterranean Outflow Water (MOW; e.g. Ambar and Howe, 1979; Ambar et al., 1999; Baringer and Price, 1999). For this reason, the area has been the focus of both geological (Heezen and Johnson, 1969; Kenyon and Belderson, 1973; Gonthier et al., 1984; Faugères et al., 1984, 1985; Nelson et al., 1993; Maldonado et al., 1999; Habgood et al., 2003; Hernández-Molina et al., 2003; Mulder et al., 2006, Hernández-Molina et al., 2006; Llave et al., 2007) and oceanographic (Swallow, 1969; Ambar and Howe, 1979; Armi and Farmer, 1985; Baringer and Price, 1997a,b; Johnson et al., 2002) studies for over three decades. The area investigated is located in the NW part of the Gulf on the Algarve Margin (South Portugal) (Mougenot and Vanney, 1982; Barnolas et al., 2000; Vásquez et al., 2000; Llave et al., 2007; Marchès et al., 2007). Both alongslope (related to contour currents, generating contourite drift) and downslope processes (which form canyons and channels, aligned with deep faults) control the area (Mougenot and Vanney, 1982; Hernández-Molina et al., 2006; Lopes et al., 2006). This dual control on sedimentation suggests the presence of interactions between the two types of processes. Different types of interactions between gravity processes and contour currents were evidenced on this margin, such as submarine canyon capture of MOW (Marchès et al., 2007) or deep-sea lobe formation due to turbidite flow induced by bottom current (Habgood et al., 2003; Hanquiez, 2006; Mulder et al., 2006). A recent study (Marchès, 2008) has emphasized the presence of buried perched lobes on the Algarve Margin. These perched lobes are a newly described type of sedimentary deposit resulting from the interactions

* Corresponding author. Tel.: +61 8 6436 8779.
E-mail address: Tristan.Salles-Taing@csiro.au (T. Salles).

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between gravity processes and contour currents in the Gulf of Cadiz. The circumstances of their formation are different to the classical circumstances described by Reading and Richards (1994) only dependent of margin morphology. Using bathymetry, seismic and core datasets, it has been postulated that the relative sea level controls the alternating relative dominance of the two processes. Indeed lobes seem to form on the Algarve Margin during low sea level stands in contrast with contourite construction that reaches a maximum during the highstand (Marchès, 2008). The dominance of alongslope and downslope processes alternate and turbidite and contourite deposits are intercalated. This unusual sedimentary feature where sandy deposits are preserved confers to the Algarve Margin a new potential sedimentary interest.

Despite many observations of interactions between gravity processes and contour currents in the construction of deep sedimentary architectures (Mountain and Tucholke, 1983; Howe et al., 1994; Faugères et al., 1999; Weaver et al., 2000; Stow et al., 2002; Mulder et al., 2006), the literature relating to numerical modelling of such complex behavior is poor. In this paper, we propose to simulate the evolution of the Algarve Margin using the stratigraphic forward-model Sedsim. The model enables us to recreate the way sedimentary systems were deposited (Tetzlaff and Harbaugh, 1989; Griffiths and Paraschivoiu, 1998) and also allows us to predict how sedimentary systems may evolve in the future (Li et al., 2006). This model has already proved its efficiency in the simulation of various phenomena such as the prediction of seabed evolution due to climate change or wind-driven circulation (Li et al., 2007, 2008), the impact of erosion on submarine infrastructures (Liang et al., 2005) or the modelling of isostatic flexural deformation as a response to sediment deposition (Li et al., 2004). This paper helps to constrain environmental factors influencing the dominance of one process over the other. Moreover, it allows a better identification of the formation of typical sedimentary features such as the perched lobes found on the Algarve Margin. It improves our knowledge of the sedimentary heterogeneities of deep-ocean deposits and provides a more global understanding of the organization of deep-ocean deposits in nature.

2. Regional setting

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 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. 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 (Hernández-Molina et al., 2003).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 (Vanney and Mougenot, 1981; Terrinha et al., 2003; Marchès et al., 2007). This important fault stretching to Algarve lands is active since Cenozoic (Lopes et al., 2006). Two other fault systems are observed to the north of channels located at longitude 8°45 W and 8°52 W on the bathymetry (Terrinha et al., 2003). Their orientation is NNE–SSW (Vanney and Mougenot, 1981).

2.2. Oceanography

The MOW is initially confined by the channelized nature of the seafloor that extends west out of the Strait of Gibraltar, and flows as a narrow, 12 km wide, 100 m thick core (Baringer and Price, 1999; Fig. 1 from Marchès et al., 2007). The flow is strongly affected by the effect of the Coriolis force which is deflecting the current to the right (looking in a downstream direction) and therefore along the slope, rather than directly west. As it moves westward, the MOW progressively registers a drop in temperature, salinity and velocity and, as it veers north-westwards under the influence of Coriolis force,, it splits into two cores, with a shallower, alongslope geostrophic component and a deeper, ageostrophic component that descends downslope (Madelain, 1970; Pickering et al., 1989, 1994; Armishaw et al., 2000; Weaver et al., 2000; Rebesco et al., 2002; Hernández-Molina et al., 2004; Laberg et al., 2005; Hanquiez, 2006; Hernández-Molina et al., 2006). The shallower core (Mediterranean Upper Water: MUW), which is the warmer branch of the MOW, flows parallel to the slope in a N–NW direction between 400 m and 600 m water depth (Fig. 1 from Marchès et al., 2007). The MUW maintains contact with the seabed all along the Portuguese middle continental slope of the Gulf of Cadiz, although the velocity of this core is gradually reduced through the process of entrainment and mixing with the overlying North Atlantic waters (Ambar and Howe, 1979). The deeper, saline and colder offshore core (Mediterranean Lower Water MLW) descends down the slope towards the SW, eventually lifting off the seafloor at depths of between 1200 and 1350 m. The MLW then turns to the NW to flow parallel to the contours at this water depth. Due to the presence of the Guadalquivir Bank and Ridge, the MLW divides into three minor branches: the Intermediate Branch (IB), the Principal Branch (PB), and the Southern Branch (SB).

2.3. Regional morphology

The Algarve Margin is located between 36°–37°N and 7°50–9°25 W (Marchès et al., 2007; Marchès, 2008). It is characterized by a rough morphology underlined by the presence of canyons, channels and contourite drifts indicating a lesser influence of the MOW than in the eastern part of the Gulf (Ambar and Howe, 1979; Hernández-Molina et al., 2006). The general margin morphology shows an important slope break at 700 m water depth corresponding to marginal plateaus and later interpreted as contourite drifts (Albufeira, Portimão and Lagos drifts; Fig. 1; Vanney and Mougenot, 1981). The Algarve Margin is characterized by the presence of alongslope processes linked to contour current activity, and downslope processes linked to gravity phenomenon (Mulder et al., 2006). These processes respectively generate two major types of morphology:

1. alongslope structures including the contourite drifts and associated moat (Alvarez Cabral Moat),
2. downslope structures with the Portimão and Lagos canyons and Channels 1, 2 and 3.

The three channels are disconnected from the southern deep valleys whereas Lagos Canyon is disconnected from the upper slope. The three channels have a NW concave morphology more marked for Channel 3 and almost indistinguishable for Channel 1. Morphological characteristics of these channels are described in details in Marchès et al. (2010-this issue).

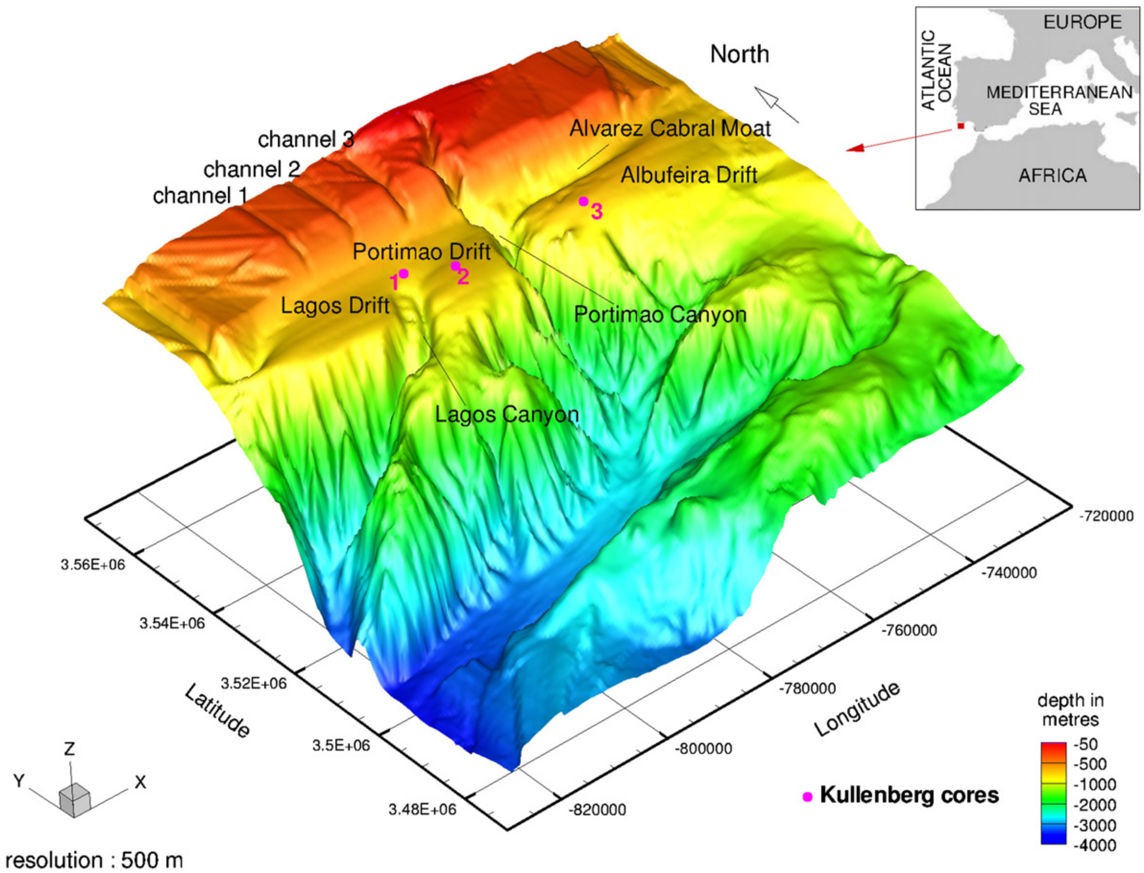

Fig. 1. Bathymetry of the Algarve region used in Sedsim simulation. Kullenberg cores 1, 2, 3 correspond to Cadi2KS14, Cadi2KS25 and Cadi2KS10 respectively.

The morphology of the Lagos Canyon is more complicated. Its head is located at 760 m water depth, partly separating the Portimão drift and the Lagos drift (Mougenot, 1988; Marchès et al., 2007, 2010-this issue). Between the three channels and the Lagos Canyon, the Portimão and Lagos drifts show a smooth morphology with a gentle slope (0.5°).

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). Its general orientation is NNE–SSW then N–S. The canyon head starts at about 100 m water depth (≈35 km from the shoreline) and spreads over 53 km, reaching a maximal depth of 338 m in its northern part (Marchès et al., 2007; Marchès, 2008).

The Albufeira Drift is about 50 km long and 9.6 km wide (Marchès et al., 2007). It is characterized by a rounded form and is separated from the upper slope by a large channel named Alvarez Cabral Moat (Fig. 1). 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 MUW in this area (Faugères et al., 1984, 1985).

3. Sedsim model

3.1. General overview of the basic principles

Sedsim model has been used to evaluate the interactions between the seabed and the hydrodynamic forces acting on the Algarve region. In the model, the fluid flow is discretized in time and space using the concept of fluid elements (Tetzlaff and Harbaugh, 1989, Chapter 2). The Navier–Stokes equations and the continuity equation are simplified and solved by using a marker-in-cell technique in two horizontal dimensions (Tetzlaff and Harbaugh, 1989). It means that the flow is assumed to be uniform in the vertical direction (i.e. the whole of a body of fluid has the same velocity at a given grid point but can change velocity and depth in all horizontal directions). Flow velocity and sediment load are represented at points that move with the fluid. At each time step each fluid element position and velocity are recalculated. This technique combines the advantages of Eulerian and Lagrangian representations of fluid flow.

So far Sedsim has been tested for simulating sediment transport over long time periods controlled by many of the major depositional processes, including fluvial, aeolian system, sea level change, coastal waves and storms, carbonate growth, slope failure, density flows and deep ocean geostrophic currents (Tetzlaff and Harbaugh, 1989; Griffiths and Paraschivoiu, 1998; Liang et al., 2005; Li et al., 2007, 2008).

3.2. Sedsim modules used for the simulation

3.2.1. Sediment transport

Sediment is transported across a bathymetry (bypassed), or deposited on its surface, according to the principle of conservation of mass. In Sedsim the sediment moves at exactly the same rate as a fluid element, because there is neither a velocity gradient in the fluid nor any distinction between suspended and bed load. The boundary between erosion and transportation is determined by the critical shear stress, calculated as a function of particle diameter (threshold shear stress increases linearly with particle diameter above 0.1 mm). The rate of sediment deposition is proportional to the excess “effective sediment concentration” which is a function of volumetric sediment concentration and flow rate. Sediment sinks within a fluid element as a function of its excess density over the fluid, its diameter, and the viscosity of water at 15 °C. For more detailed consideration of the algorithms used by Sedsim the reader is referred to the book by Tetzlaff and Harbaugh (1989).

3.2.2. Stable slope

To avoid unrealistic simulation results, a set of maximum stable slopes for each grain size may be specified. Each grain size has a maximum slope angle that it can be deposited at for when it has be reworked below sea level. Sediment is transferred through neighbouring cells until it reaches the equilibrium slope.

3.2.3. Slope failure and turbidites/gravity flows

Slope failure is triggered by over-steepening of sediment. This over-steepening can be generated in many ways such as tectonic movement, storm events, or the exposure of sediment due to sea level fall. The material is then progressively failed upslope until a stable profile is obtained, with often multiple failures occurring at one time. The composition of the underlying sediment is transferred into a new fluid element (or series of fluid elements), which is then treated as a regular fluid element. Due to high sediment concentration, these flows can often develop into large gravity and turbidity flows.

4. Method and data

The Gulf of Cadiz is a well-studied area where many observational surveys and data are available. This is a critical point in the choice of location as the numerical simulation of such complicated processes needs numerous parameters: oceanographic patterns (bottom current velocities), seabed mobile sediment thickness and composition, sediment load estimation across boundaries of simulated space, and also the sedimentary environment of the site and evolution of external factors such as sea-level and river input. Except for the MOW bottom velocity that came from the regional-scale numerical model, the other data presented in this paper were collected during the Cadisar 2 cruise on the RV Le Suroît in 2004.

4.1. 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 EM300 and MOW location was assessed using three CTDs (SBE19 probes) and 84 thermoprobes (Sippican). The resulting bathymetry was then interpolated on a Cartesian coordinate system.

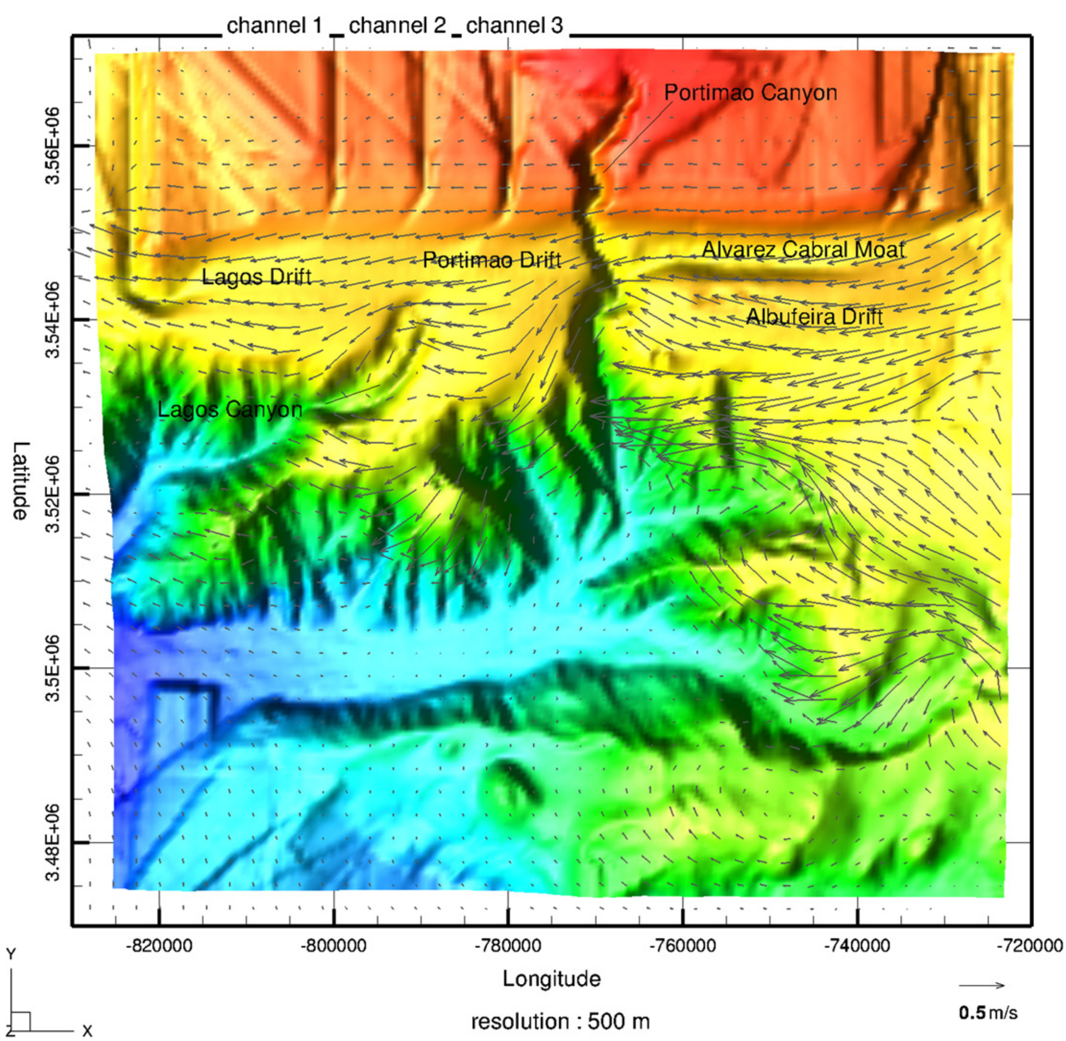

Fig. 2. 2005 MUW annual mean bottom velocities computed with the numerical model from Serra et al. (2005).

The studied area is represented by a 200 × 186 mesh composed of square cells with a spatial resolution of 500 m (Fig. 1).

This bathymetry has been used as the initial basement upon which the sedimentary architecture is then simulated. This initial surface does not correspond to the bathymetry in place at the time of our simulation (430,000 and 135,000 years before present day). Using seismic data, a more realistic surface could have been used. However, it would have been impossible for us to adjust the MOW patterns (which are highly dependent to topographic changes) to this bathymetry. Therefore we have made the assumption that the basement corresponds to the actual bathymetry and that there is no major tectonic movements or subsidence during the entire simulation. On one hand and given the complex tectonic activity in the region, it could seem a bit too simplistic. On the other hand, it is ensuring the consistency between the topography and the MOW velocity and direction over the region.

4.2. MOW input

The complex pattern of the MOW in the Gulf has been simulated using the numerical model from the Oceanographic Institute of Lisbon University (Ambar et al., 1999; Bower et al., 2002; Borenas et al., 2002; Serra and Ambar, 2002; Serra et al., 2005). The observational data used to calibrate and validate the obtained bottom velocity directions and intensities come from several international observational programs (Gulf of Cadiz Experiment, AMUSE, CANIGO, AMPOR, MEDTOP and SEMANE). In the region, the Portimão Canyon was first clearly identified as a meddy formation site with the CANIGO and MEDTOP observations (Serra and Ambar, 2002). Here, dipoles form by a mechanism that involves either mixed barotropic–baroclinic instability of the MUW or a topographically induced generation of vorticity. Serra et al. (2005) used a 3D bottom-following primitive equations model to study the role of detailed bottom topography on the hydraulic control of the Strait of Gibraltar exchange, the MOW plume descent and the eddy generation at Portimão Canyon and Cape St. Vincent. The resulting annual mean bottom velocities for the studied area are plotted in Fig. 2.

4.3. Seabed sediment

Marchès (2008) have identified four superposed seismic units that form the contourite deposits related to drift construction. The different sedimentary units are separated by discontinuities. To estimate the volume of sediment deposited by the MOW in the area, isopach maps have been used. Even if the bypassed sediments are not taken into account it gives an idea of the quantity transported and deposited by the MOW. Table 1 shows the sediment volume deposited by the MOW over 1800 ka. The obtained values show the change of sedimentation rate between east and west sides of the Portimão Canyon. Two Kullenberg cores (Cadi2KS10 and Cadi2KS25) were used to define the mean grain size distribution in the drifts (Marchès et al., 2007). These cores are located on each side of the Portimão Canyon (Fig. 1). Cadi2KS10 is located on the southern flank of the Albufeira Drift and the Cadi2KS25 core was sampled on the Portimão Drift. Measurements of mean grain size distribution of the sediment deposited are given in Table 2. Using seismic data, Marchès (2008) showed the presence of 6 lenticular chaotic bodies corresponding to perched lobes (Fig. 3). Information on the nature and texture of the perched-lobe sediments has been obtained from the study of the Cadi2KS14 core (see Fig. 1 for location). The core is composed of about 80% sand, but two sedimentary facies are observed. The first consists of structureless coarse sand and shell debris with a D_{50} of approximately 200 μm. The second facies is composed of grey silty-clay with a D_{50} generally less than 30 μm. The mean grain size distribution of the sediment deposited in the lobe is presented in Table 2. Moreover, sediment volumes for each chaotic body are shown in Table 3.

Table 1
Sediments deposited by the MUW.

Time in ka BP	Total volume in km^3	Albufeira Drift in km^3	Portimão Drift in km^3
1800–880	63.7	32.9	30.8
880–430	47.6	26.04	21.56
430–135	46.4	27	19.4
135–0	12.6	7.46	5.14

Table 2
Mean grain size distribution of the sediment deposited in the studied area.

Location	<63 μm	63–125 μm	>500 μm
Albufeira Drift Cadi2KS10	88%	5.4%	0.1%
Portimão Drift Cadi2KS25	93.3%	3.6%	0.1%
Lobe deposits Cadi2KS14	18.4%	12.4%	55.8%

4.4. Sea-level changes

Algarve Margin sedimentary history is controlled by the combined action of alongslope and downslope processes. The dominance of one over the other suggests that an environmental factor is responsible for these sedimentary regime changes. According to the deposit stratigraphy proposed by Marchès (2008), the sedimentary architecture in the area is mainly controlled by sea-level changes. During sea level lowstand canyons are directly connected to rivers increasing the transport of sediment through these conduits. Moreover, the sediment supply increase due to direct river input induces an augmentation of available sediment on the shelf. When sediment storage is destabilized at the shelf break, it is canalized in the channels thus reactivated. The correlation between climatic and sea-level changes and MOW intensity in the northern area of the Gulf of Cadiz has been studied by Llave et al. (2006). They show that during sea-level highstands, the interaction of the MOW with the sea floor is more intensive at shallower depths. At these high sea-level conditions, sandy contourites developed in Algarve Margin area where the Upper Mediterranean branches were enhanced.

4.5. River sediment load and distribution

On the Algarve Margin, a river is present upstream of the Portimão Canyon. Its small size is further evidence supporting a tectonic initiation of the Portimão Canyon. However it is possible that the canyon was directly connected to this river during sea-level lowstands. A deltaic system could have been created feeding the western channels when the sediment input was very important (Marchès, 2008). Thus, depending on the distance between channels and the deltaic system, gravity flow activity related to river discharges varies and sediment supply is greater close to the main river mouth and decrease westward (Marchès, 2008). This hypothesis is well supported by the channel activity recorded in the stratigraphy. Channel 2 was activated later than channel 3. Channel 1 is the last of the three experiencing a gravity flow.

4.6. Sediment sources

Fig. 4 shows the source locations used in Sedsim. A velocity, a discharge rate, a sediment concentration and a sediment composition define each source. Four different grain sizes, defined in Table 4, are taken into account based on the distribution of the sediment deposited in the studied area. The sediment sources are divided in two types. On the North side, sources define the various turbiditic

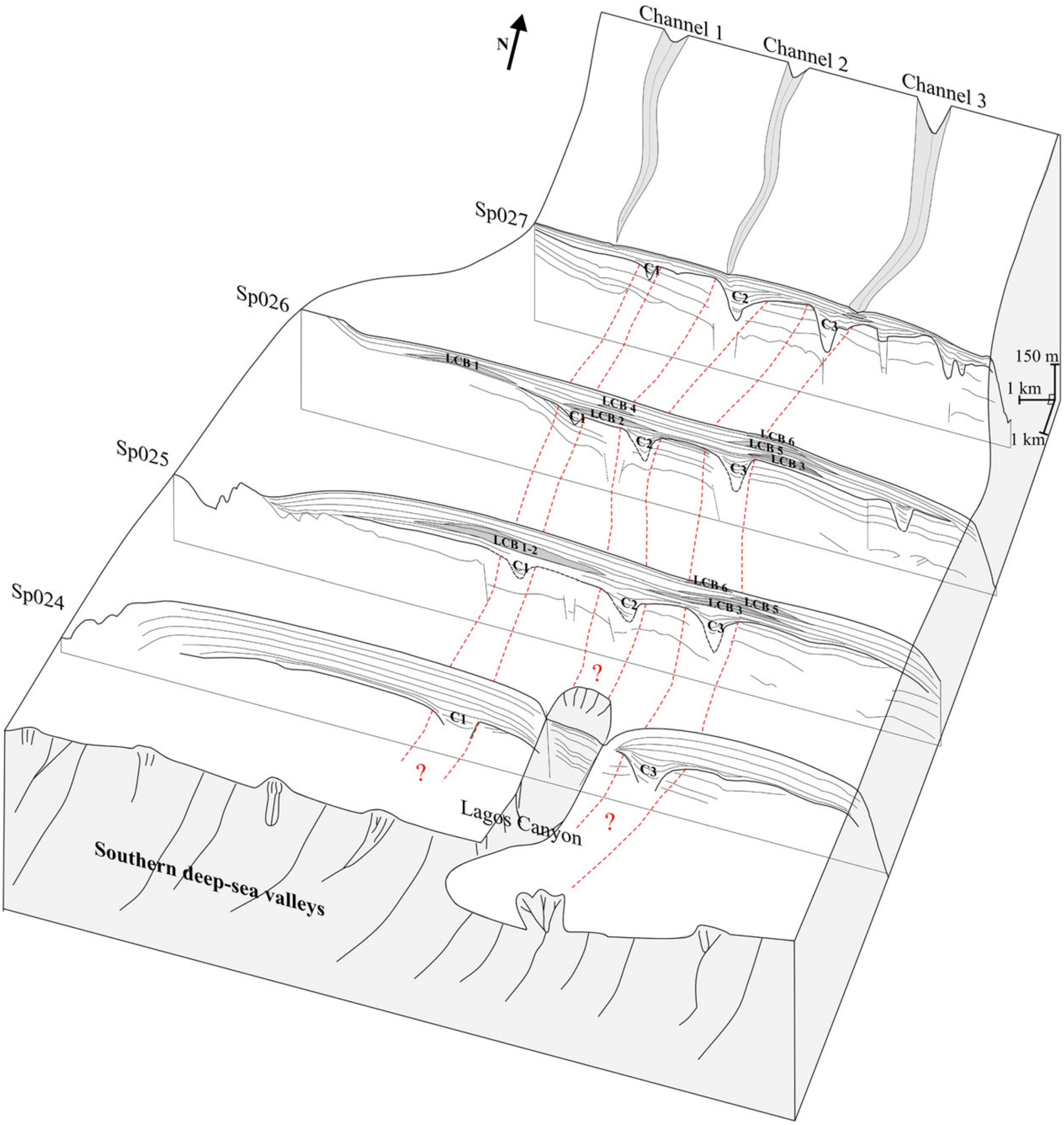

Fig. 3. Perched-lobes on the Lagos Drift obtained from Marchès (2008).

flows that come from channels 1, 2, 3 and Portimão Canyon. Sources on the East side define sediment transport from the MUW into the area. Table 5 presents the parameters that define these sources. Several tests have been necessary to characterize the source to be consistent with the volume deposited by the MUW (Table 1) and the anticipated gravity processes (Table 3).

Table 3
Sediment volume (in km^3) deposited by gravity processes (LCB: Lenticular Chaotic Bodies).

Time in ka BP	LCB1	LCB2	LCB3	LCB4	LCB5	LCB6
880	2.47		1.1	×	×	×
430	×	×	×	0.03	1.2	×
135	×	×	×	×	×	0.05

4.7. Bottom velocity field

According to the velocity data obtained from Serra et al. (2005), six bottom velocity fields and associated seabed mobility indices have been computed and added as input parameters for the Sedsim simulation. The seabed mobility index is defined as the ratio between the current skin-friction Shields parameter and critical Shields parameter. It serves as an indicator of the level of intensity and frequency of seabed sediment available for movement. During the simulation, we have explored the hypothesis that the MOW direction is preserved but its intensity varies according to sea-level changes. Due to the lack of information about the impact of sea-level changes on the evolution of the MOW, we have simply, in a first attempt, used a linear regression based on the sea-level curve proposed by Bintanja et al. (2005) and the actual annual mean bottom current velocity from Serra et al. (2005). Between 430,000 and 135,000 years before present

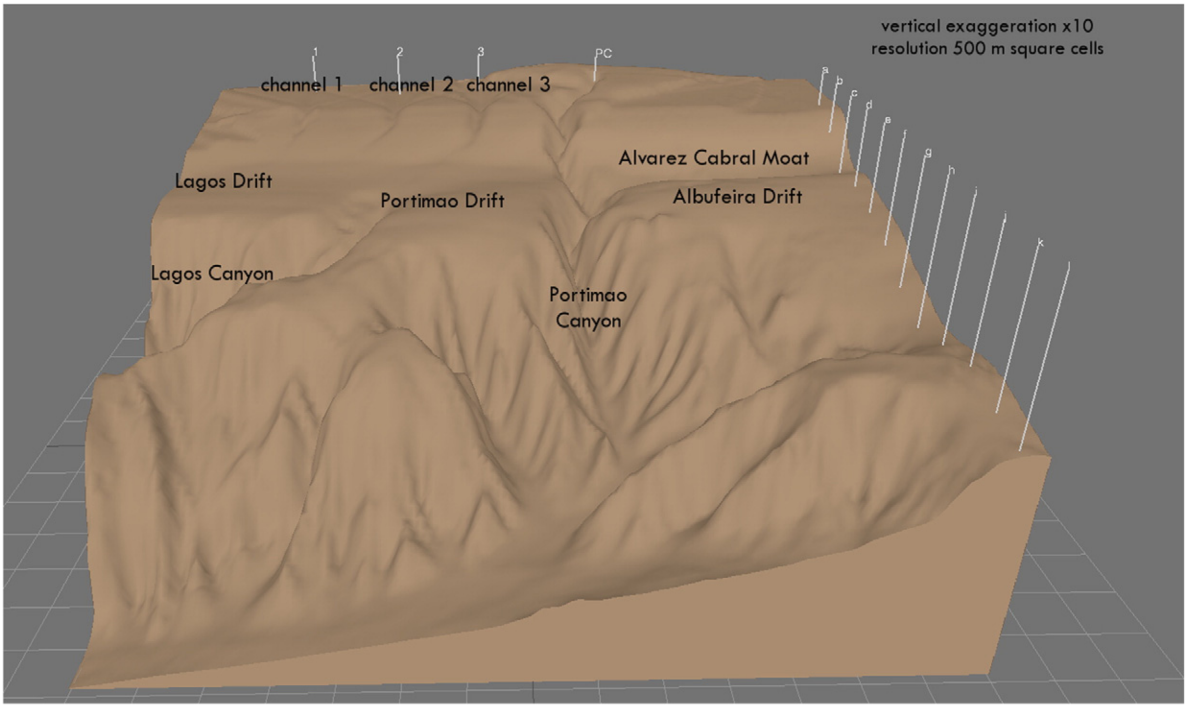

Fig. 4. Location of the different sources defined in the simulation. Sources from a to l are used to define the MUW sediment load, sources 1, 2, 3 and PC define the active channels.

day, the sea-level curve has been averaged by six mean elevations (Fig. 5). According to previous paleoceanographic works considering that MUW is more active during sea-level highstands, three of them correspond to high-intensity contour currents with MUW intensity equal to 82, 79 and 74% of the actual one. The three other ones are low-intensity contour currents with values equal to 51, 42 and 28% of the present MUW velocity. The choice of a step-by-step evolution of the contour current intensity may seem a bit too simple but it was decided to look at an averaged scale due to the huge uncertainties on the MOW evolution over geological time scales. Moreover, the use of a step function has a lower computational cost and represents an undeniable advantage when such long time scale simulations are involved.

4.8. Event organization

All the sources are activated at various times according to the geological history and our concept of the interaction between the contour current and the gravity processes.

Thus, we simulate a first phase corresponding to the construction of the contourite deposits on the Albufeira, Portimão and Lagos drifts. This phase simulates 295,000 years of sedimentation dominated by contour current activity. This period corresponds to the formation of the seismic unit U3 created between MIS 12 (430,000) and present day (Table 1) according to the stratigraphic work described by Marchès (2008). As the MUW intensity varies during this period (Fig. 5), we have defined two sets of gravity processes. When the intensity of the contour current is high, some small turbiditic events are initialized in the canyon (Table 5). These gravity events have a short duration and simulate catastrophic events such as storms, which may trigger some major gravity flows (Mulder et al., 2001; Salles et al., 2008). Moreover, low-concentration turbiditic flows composed of fine sediments are initialized in channels 1, 2 and 3 (Table 5). They are related to the action of coastal currents, which transports sediment on the edge of the Algarve margin where the channels and the canyon are used as natural sinks to move these unconsolidated deposits down slope. During this phase, sea-level fluctuates and three low-stands have already been defined (Fig. 5; 390,000–330,000; 275,000–240,000; and 190,000–135,000 years before present). Marchès (2008), notes that possibly due to the seismic data resolution, no evidence of gravity processes has been recorded in the sedimentary deposits on the Lagos and Portimão drifts. Even if these low-stands are not associated with the construction of lobes on the drifts, some turbiditic flows may be initialized in the channels and the canyon as discussed above. These flows are more frequent and stronger than the ones simulated during MUW high-intensity periods but their composition is unchanged (Table 5).

The second phase simulates a sea level low-stand that combined both an attenuation of the MUW influence in the area and the formation of a fluvio-deltaic system that feeds the western channels and the Portimão Canyon. This period simulates 5000 years with a decreasing westward intensity of the initialized gravity flows. The average duration of the gravity events in the canyon and the channels 3, 2 and 1 are respectively, 200, 150, 130 and 100 years per thousand years. The source's sedimentary compositions and concentrations are described in Table 5.

Table 4
Sediment characteristics used in Sedsim.

Sediment type	Diameter of each grain size [mm]	Density of each grain size [kg/m^3]
Coarse sand	1.0	2650.00
Fine sand	0.2	2600.00
Silt	0.063	2600.00
Clay	0.001	2550.00

5. Results

Results from the Sedsim simulation are shown in Fig. 6. When the MOW activity is predominant, contour currents deposit sediments on the drifts. Thanks to the small activity of gravity currents in the Portimão Canyon mixed deposits resulting from both contour currents

Table 5
Source characteristics and organization.

Sources	Average duration per thousand years (year)	Velocity (v_x,v_y) (m s^{-1})	Discharge rate (m^3/s)	Concentration (kg/m^3)	Composition in % (coarser, medium, fine, finest)
Predominance of MUW activity					
High-intensity contour currents					
MOW inputs	1000	(−0.50,−0.50)	20	3	(0,0,10,90)
Portimão Canyon	10	(2.50,−2.50)	50	5	(0,3,7,90)
Channel 1	4	(1.00,−1.00)	20	4	(0,1,4,95)
Channel 2	6	(1.50,−1.50)	30	4	(0,1,4,95)
Channel 3	8	(2.00,−2.00)	40	4	(0,1,4,95)
Low-intensity contour currents					
MOW inputs	1000	(−0.40,−0.40)	15	3	(0,0,10,90)
Portimão Canyon	20	(2.50,−2.50)	55	5	(0,3,7,90)
Channel 1	10	(0.00,−1.00)	30	4	(0,1,4,95)
Channel 2	12	(0.00,−1.50)	40	4	(0,1,4,95)
Channel 3	15	(0.00,−2.00)	45	4	(0,1,4,95)
Predominance of gravity processes activity					
MOW inputs	1000	(−0.10,−0.10)	05	3	(0,0,10,90)
Portimão Canyon	200	(2.50,−2.50)	65	5	(2,12,25,60)
Channel 1	100	(0.00,−2.50)	40	5	(0.5,12,25.5,62)
Channel 2	130	(0.00,−3.00)	45	5	(1,13,26,60)
Channel 3	150	(0.00,−3.50)	50	5	(3,13,24,60)

and gravity flows processes are visible at the bottom of the canyon slope (Fig. 6a). When gravity processes predominate (Fig. 6b) lobes are formed on the Lagos and Portimão drifts and overly the previous contourite depositional system. The following sections explain in more details the obtained general morphology.

5.1. Contourite depositional system

When the MUW is the predominant process active in the area, six different phases have been defined and characterize the variation of the current intensity according to sea level fluctuations (Fig. 5).

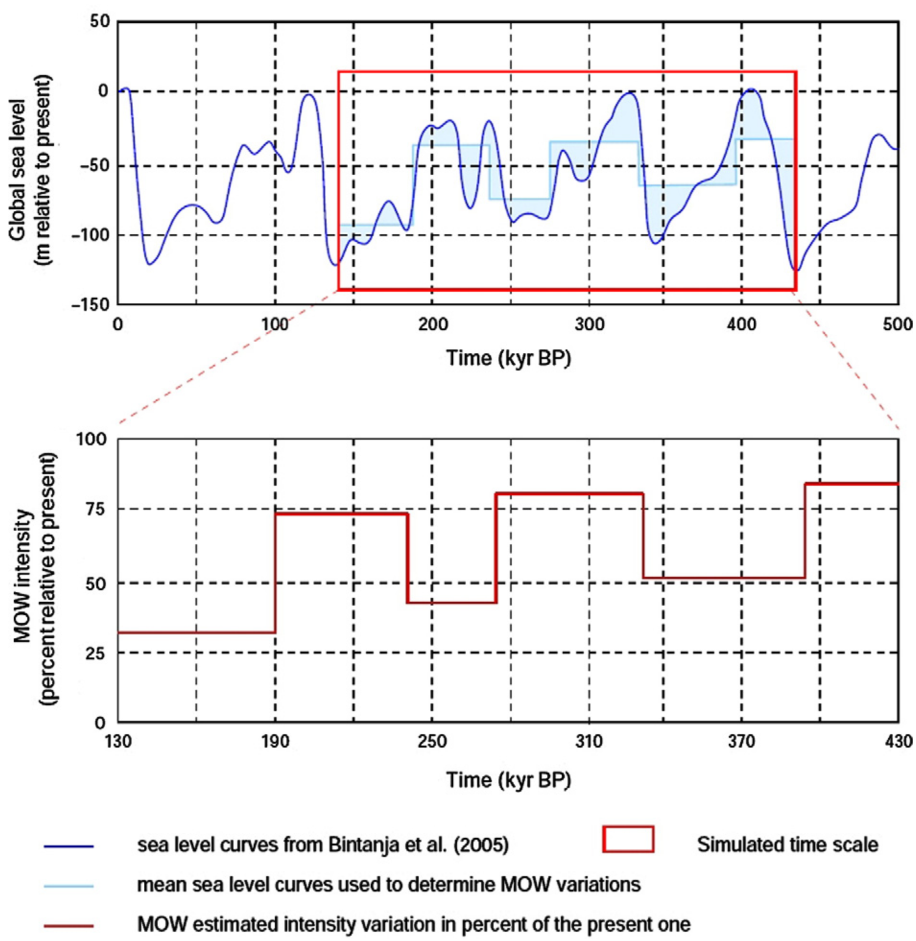

Fig. 5. Variation of the MOW intensity as a function of sea level curve.

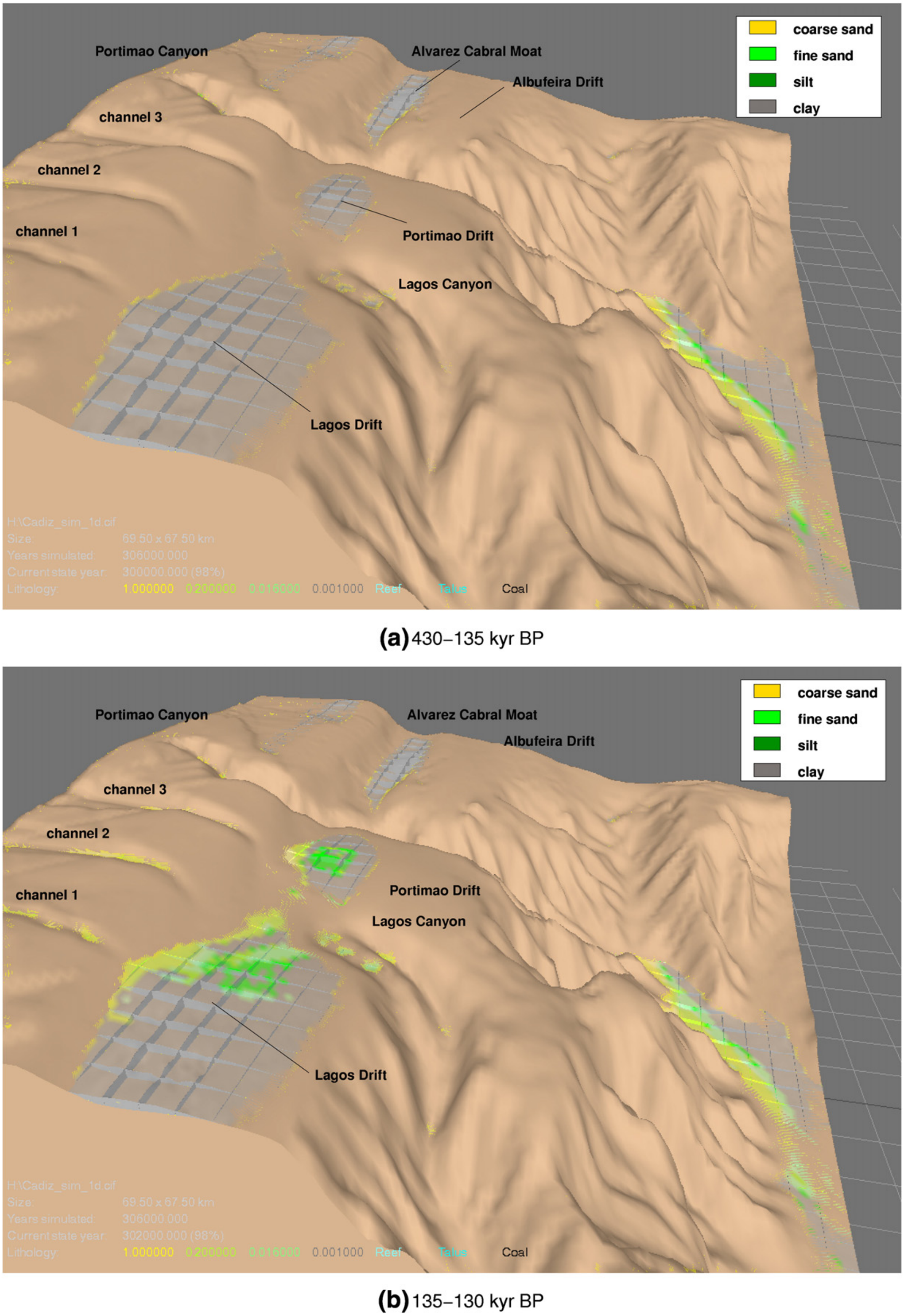

Fig. 6. Results from Sedsim simulation showing in (a) sedimentary deposits resulting from the predominance of MUW activity and (b) perched lobes deposition due to both a decrease of MUW velocity and a sea level low stand.

Depending on this variation, some gravity currents mainly composed of fine particles are initialized in the three paleo-channels and in the Portimão Canyon (Table 5). The resultant morphology shows three contourite drifts which have developed over the two margins west and east of Portimão Canyon: the thick deposit associated to the Alvarez Cabral Moat channel, the sheeted Portimão drift and the well-developed Lagos drift (Fig. 6a).

The simulated Albufeira drift is an elongate and thick deposits which extents over 17.6 km length and 4.2 km wide. The maximum sediment thickness is about 123 m and its volume is approximately 7.6 km^3 (Fig. 7). The higher intensity of the MUW on the east side of the Portimão Canyon accounts for the equilibrium profile of the Albufeira Drift. Indeed the MUW pattern shows a strong velocity around 0.4 m/s on the drift and decrease northward in the vicinity of the Alvarez Cabral Moat (Fig. 2). On the south part of the drift the MUW is not intense enough to erode the seabed but is still too strong to allow the deposition of the fine sediments carried by the current.

According to Serra et al. (2005), MUW bottom velocities suggest that a fraction of the current flows down-canyon (Fig. 2). This capture of the MUW by the Portimão canyon induces the deposition of fine sediments inside the canyon. These deposits are then removed and settled downslope when gravity currents are initialized at the head of the Canyon. Thus turbiditic events prevent the accumulation of large amount of material inside the canyon, suggesting that deposits in the deep valley result from the action of gravity currents but are composed of mixture of both original turbiditic flows sediments and re-transported contour current material.

West of the canyon, the contour current intensity diminishes due to the presence of the Portimão Canyon. On the Portimão Drift the MUW has a SSW direction and an average velocity of 0.3 m s^{-1}. Combined with the action of the MUW, gravity flows coming from channel 3 feed the drift with fine particles (Fig. 7). The simulated deposit has a maximum sediment thickness of 63 m; it is a 10.2 km wide and 6.7 km long deposit with a volume of 3.6 km^3. The Portimão Drift is still under the influence of a strong current and sediments tend to be dragged along the drift by the flow. Most of the sediments migrate westward and are captured by the Lagos Canyon. Thus only a small amount of the sediments that pass over the drift are recorded in the deposits.

West of the Portimão Drift, the Lagos Canyon plays a role similar to the Portimão Canyon, a small part of the MUW is trapped by the canyon and sediments flow down-slope to the southern deep valley. Fig. 2 shows that the intensity of the MUW west of the Lagos Canyon decreases again and drops to 0.13 m s^{-1}. When the contour current reaches the Lagos drift, most of the sediment initially transported by the MUW has been lost due to either deposition on the drift or capture by canyons. Nevertheless, the flow is still supplemented by infrequent gravity flows initialized in paleo-channels 1 and 2. The simulated deposit is a 13.2 km long and 11 km wide contourite drift with a maximum thickness of 75 m and a volume of 9.1 km^3 (Fig. 7). The

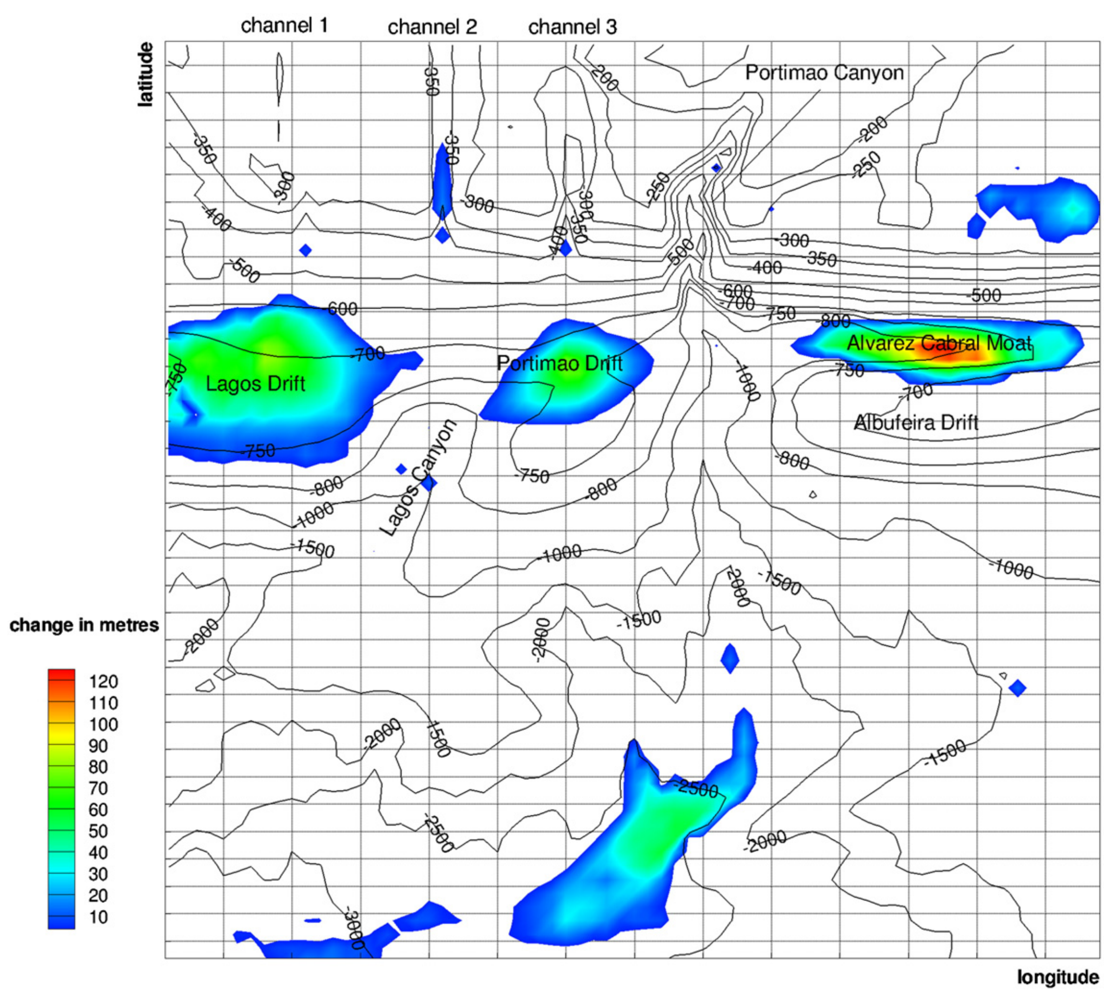

Fig. 7. Deposit thickness between 135 and 430 ka BP.

deposit is the largest one in the simulation and is the result of the combined action of gravity and contour currents.

5.2. Lobe formation

Deposits from gravity events are located at the mouth of paleo-channels 1, 2 and 3. However, several differences are identified between these deposits. Fig. 8 shows the morphology and thickness of the resultant sedimentary structures.

During the simulation, channel 3 is supposed to be the most active of the paleo-channels (Table 5). Indeed, we have assumed that this channel is closely connected to a fluvio-deltaic system, which may have developed on the Algarve Margin during sea level low-stand. As a result the deposits located at the mouth of this channel are well developed when compared to the two others. The constructed body has a maximum thickness of 22.5 m; the structure is an 11.2 km wide and 8.3 km long deposit with a volume of approximately 1.1 km^3. The sediment distribution in the deposit is composed of the four grain sizes considered in the input parameters and are well sorted by the gravity flow. Indeed close to the channel mouth the deposit is composed of the coarsest particles and the composition is fining down-slope as the flow competence is decreasing. This lenticular chaotic body has thus the general morphologic and sedimentary characteristics of lobe sediment (Marchès, 2008).

Even if channel 2 is not directly connected to the Lagos Canyon, the relatively short distance between the paleo-channel mouth and the canyon head confers to the resulting sedimentary structure a totally different morphology. Indeed sediments carried by gravity flows are deposited in two preferential zones. A majority of the coarsest particles settle inside the channel. Due to a low dip, the gravity flows are not able to maintain the sediments in suspension along all of the channel length (10 km). Deposits inside the channel have a maximum thickness of 7.6 m. Just before reaching the marginal plateau the currents gain energy thanks to a slope increase, enabling the gravity flows to carry the remaining suspended particles down the drift. The coarsest particles tend to settle close to the Lagos Canyon head (Fig. 8). Resultant deposits at the head of the canyon have a maximum thickness of 3.5 m, covering an area 8 km long by 2.5 km wide. The finest particles are transported downslope and reach the southern deep valley.

Gravity events flowing in channel 1 have a finer composition and a lower energy than the ones initialized in the two other channels (Table 5). The resulting deposits show some specific features. These deposits are influenced by the topographic evolution of the drift. Indeed, in this area a large contourite drift has been formed due to the MUW activity (Fig. 7). The gravity flow is largely influenced by bathymetric morphology and currents are slightly deviated towards the east even if a low contour current is still active in the westward direction (Figs. 6b and 8). This lobe is smaller than the first one and

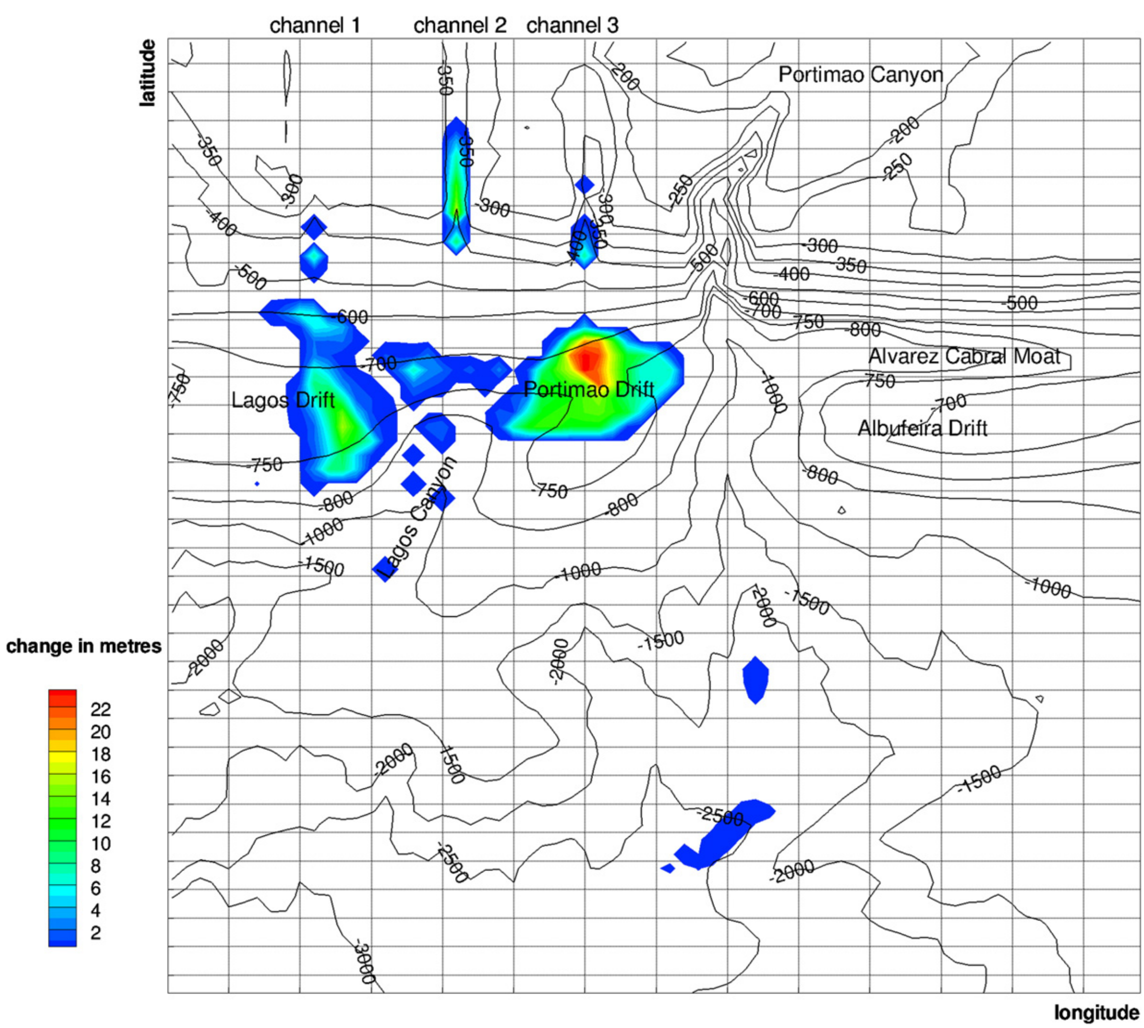

Fig. 8. Deposit thickness due to paleo-channel activity between 130 and 135 ka BP.

has a maximum thickness of 17.1 m. The lobe is 12 km wide and 5.7 km long with a volume of 0.4 km^3.

6. Discussion

6.1. Comparison between observations and results

Recent sedimentological studies from Marchès et al. (2007, 2010-this issue) are used to discuss the obtained results. The comparison is mainly based on the morphological differences between the sedimentary bodies.

6.1.1. Contourite deposit

When MUW is the predominant process active in the area, simulation results and *in situ* observations are consistent. Simulated sediment deposits on each side of the Portimão Canyon well represent the observed construction of contourite drifts on the Algarve Margin (Fig. 7).

On the eastern side of Portimão Canyon, the MUW is very channelized in the Alvarez Cabral Moat where the simulation shows maximum deposition. This observation matches Albufeira Drift geometry showing important northward migration of deposits in this area (mounded separated drift, Vanney and Mougenot, 1981; Hernández-Molina et al., 2003; Marchès et al., 2007; Marchès, 2008). The relative order of magnitude of the deposit thickness is also in agreement with Quaternary deposit thickness studied by Marchès (2008). The simulation shows a maximum of 123 m sediment deposited on the Albufeira Drift. In Marchès (2008) the most prograding sub-unit (corresponding to an average of 400 ka sedimentation) is 145 m. Over the same order of time scale the simulation thus represents a reasonable reproduction of sedimentary deposition in term of depocenter location, geometry and thickness.

On the western side of Portimão Canyon, simulated contourite deposits are larger then the ones form on the eastern side, which is consistent with seismic data observation. The Portimão and Lagos drifts appear to be more related to 'sheeted drifts' due to the absence of MUW channeling on this side of Canyon (Marchès, 2008). In this case, sedimentary deposits cover a greater area and only aggradation (no progradation) is observed. However on seismic data a good continuity is observed between the two drifts which are only separated in their southern part by the head of Lagos Canyon. This difference between the simulation results and observed sediment accumulation is probably due to the MUW capture by the Lagos Canyon simulated in the hydrodynamical model (Fig. 2). The sediment load captured and transported by the MUW limits the deposition of contourite drift in the region of the canyon head. The numerical model from Serra et al., (2005) is based on 2005 MOW annual mean bottom velocities. The actual MUW hydrodynamic applied on an average of 400 ka sedimentation causes, in this side of Portimão Canyon, a distorted result. It could be linked to a recent Lagos Canyon evolution that modify MUW hydrodynamics or to an overestimation of sediment load capture in this canyon. However the simulated deposit thickness is close to that observed on seismic data (average of 65 m for the last 400 ka). The overestimation of sediment load captured does not seem to be sufficient explanation of the differences between simulation and seismic observation in Portimão and Lagos drifts geometry. A more probable explanation is the paleomorphology. This simulation is based on the actual (present day) morphology of the area (Fig. 1). Difference in morphology through time, notably the Lagos canyon growth, can explain the absence of deposits at the head of this canyon in this simulation.

Despite the fact that the simulated Portimão and Lagos drifts are not connected in their northern part (which is the case in seismic data), the simulation shows good results for general margin sedimentary architecture, depocenter formation and grain size distribution. The MUW capture by the Portimão Canyon and its influence on the sediment repartition (Hernández-Molina et al., 2003; Llave et al., 2006; Marchès et al. (2010-this issue) is well illustrated in the model (decrease in MUW intensity, sediment capture in canyon and development of two types of contourite drifts on each side of canyon) and constitutes a major improvement in our understanding of the mechanisms behind the margin construction.

6.1.2. Lobe formation

The simulation results show two lobes forming at the mouth of channels 1 and 3. This result is in agreement with the observation of seismic data detailed in Marchès (2008), Marchès et al. (2009-this issue). For the lobe associated with channel 3, the length and width obtained are of the same order as those observed in seismic data (length of 8.3 km for 15 km observed and width of 11.2 km for 15 km observed). The thickness and volume implied are also well represented (thickness of 22.5 m for 34 m observed and volume of 1.1 km^3 for 1.5 km^3 observed).

For the lobes associated with channels 1 and 2, some differences are noted. In Marchès (2008), the two lobes merge southward inducing important sediment accumulation (3 km^3). In the simulation no lobe forms at the mouth of channel 2. This is consistent with the morphologic presence of Lagos Canyon, which traps sediment input by channel 2 due to the short distance separating channel 2 and Lagos Canyon head. So even if this result is not in agreement with geologic observations, it seems to be consistent with margin morphology and the associated sedimentary processes. Again, the morphology that formed the basis for the simulation corresponds to present-day margin morphology whereas LCB 1, 2 and 3 in Marchès (2008) relates to 880 ka ago when margin morphology was different from today. Changes in margin morphology closely influence direction and importance of gravity processes. The sediment loss to the Lagos Canyon with present-day morphology probably did not occur in the same proportion 880 ka ago.

As the aim of this work was to compare geologic data when all three channels were active, the results present some differences mainly due to the fact that the margin configuration was dissimilar in the two cases of the three channels activity.

As expected, the bathymetric morphology seems to be of great significance in perched lobe formation (Reading and Richards, 1994; Gervais, 2002; Bonnel et al., 2005). The model recreates with accuracy geologic records in term of size, shape, grain size, and location, but the bathymetry influences some aspects of lobes formation notably through the sediment capture by Lagos Canyon precluding lobe formation at the base of channel 2 in the simulation.

6.2. Impact of sea-level fluctuations on contour current strength and direction

Variation in sea level is expected to have a significant effect on the MOW (Bryden and Kinder, 1991; Habgood et al., 2003) and hence should affect the deposit evolution on the Algarve Margin. The shallower depth of the Gibraltar sill during periods of lower sea level and a reduced volume of MOW transport, as indicated by Bryden and Kinder (1991), should have decreased the current intensity. Bryden and Kinder (1991) suggested that a reduction of the sill depth to half the present depth would increase the salinity of the MOW, leading to reduce outflow transport. Despite the lack of oceanographic modelling of the historical intensity and direction of this deep current, geological interpretations suggest that observed Cadiz depositional geometry support this supposition (Nelson et al., 1993; Toucanne et al., 2007). This suggestion has been used to define the evolution of the sources in the simulation and the obtained results are compatible with the overall geological morphology of the margin described by Marchès (2008), Marchès et al. (2009-this issue). During highstand, the simulated MUW intensity has been reduced by at least 18% (Fig. 5) and its direction unchanged compared to the present condition. As previously discussed, this resulted in the formation of smaller simulated contourite deposits on the margin. It suggests also that the MOW in the region could have been weaker, which would induce the deposit of a larger amount of fine particles on the Albufeira, Portimão and Lagos drifts. Moreover, according to the morphology of the eastward drift, the direction of the MUW could have been different during past sea-level highstands. The present MUW is not well-channelized in the Alvarez Cabral Moat as shown in Fig. 2. It seems inconsistent with the interpretation of Marchès (2008) that link the widening and deepening of the moat near the Portimão Canyon to the capture of the deep current. Moreover the actual MUW has an intensity, which is strong at the Albufeira Drift, decreasing northward in the vicinity of the moat. It led to an accumulation of sediments inside the channel that is inconsistent with the geological interpretation. It emphasizes the complex variations of the MOW over time both in intensity and direction (Baringer and Price, 1999; Johnson et al., 2002; Hanquiez, 2006; Hernández-Molina et al., 2006). In addition, an expected channelized alongslope current in the moat should interact with the Portimão Canyon up-slope at a depth where the canyon morphology is less developed. It would decrease the capture of the flow by the canyon and thus would increase the contourite deposition on the Portimão and Lagos drifts.

6.3. Interaction between gravity processes and contour currents

The results detailed in this paper highlight the complexity of the Algarve Margin in relation to the interactions between deep currents and seafloor morphology inherited from gravity process activity (Llave et al., 2001; Hernández-Molina et al., 2004, 2006; Llave et al., 2006, 2007). Periods with dominant alongslope processes alternate with periods of dominant downslope processes. The disconnection of the three channels and the southern deep valleys illustrates this interaction (Mulder et al., 2006). Seismic profiles show that an ancient connection existed between channels and deep valleys (Marchès et al., 2007). However, the present disconnection can be related to climate and sea level change (Hernandez-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 differs from the present (Llave et al., 2006). During cold periods, downslope processes predominate resulting in channels and canyons incising the slope. During warm periods such as the present, the sediment load reaching the canyons from the continent is relatively low and the MOW-related processes dominate over downslope gravity processes. Channels are filled and disconnected from deep valleys (Mulder et al., 2006).

During sea-level highstands, we have postulated that gravity processes are weakened but still active. This activity could be directly correlated to the changes in the intensity and direction of storms. Periods of increased storminess have been related to increased bottom current energy, with enhanced sediment transport from the coastal zone to the deep ocean (Andresen et al., 2005). Swell and wave stress can generate excess pore pressure in sediments and reduce the shear resistance of the sea floor sediments leading to failure. During storms, high waves could have destabilized sediment on the shelf break near the canyon and heads of paleo-channels. Shelf currents and coastal drift can be intensified during a storm, large amount of particles can then be captured and progressively create gravity flows. Storm winds could also create a water bulge along the coast, which could dissipate, using the canyon and channels as natural sinks. According to our simulation, the contribution of these gravity flows is essential in the construction of the Lagos and Portimão drifts. It increases the quantity of sediments deposited on the westward plateau and must have been necessary to create the actual margin morphology as a large amount of particles carried by the contour current are trapped by the Portimão and Lagos canyons. It highlights the complex interactions between the MOW and down-slope processes during sea-level highstands.

During sea-level lowstand, the simulation shows the presence of lobe deposition on the slope. The sedimentary structure of the Algarve Margin and especially the paleo-morphology characterised by the presence of paleo-channels, clearly shows that the formation of these perched lobes is linked to contourite construction. If paleo-channels have not been filled, gravity processes through these incisions still reach southern deep valleys such as the Portimão Canyon and there would not be formation of a perched lobe. It is the filling of paleo-channels by contourite deposit that have led to lobe formation in the slope. During gravity process reactivation the channel systems do not reach any more southern deep valleys and the system retrogrades leading to immature pounded lobe formation on the slope.

In a geological time frame, the Algarve Margin displays gravity deposits intercalated and preserved in the contourite drift suggesting an alternation in the dominance of gravity processes and contourite processes (Pickering et al., 1994; Rebesco et al., 2002; Armishaw et al., 2000; Weaver et al., 2000; Laberg et al., 2005). According to the classification of Locker and Laine (1992), the Algarve Margin constitutes an example of overlapping fan/drift with contourite sedimentation at a rate high enough for pounded lobe preservation.

7. Conclusion

Using a process-based model, the goal of this study has been to combine both geological and oceanographic data to simulate and validate the recent geological interpretations made on the Algarve Margin. This work emphasizes: (1) Sea level control of the alternating dominance of gravity processes and contour currents: lobes form on the Algarve Margin during sea level lowstand in contrast with contourite construction during highstand; (2) The morphology seems to be a key-player in perched lobe formation. The model reproduces with accuracy geologic records (in term of size, shape, grain size and location) but the bathymetric morphology influences some aspects of lobe and drift formation notably through sediment capture by canyon; (3) During sea level highstands, the contribution of gravity flows is essential in the construction of contourite drifts. It increases the quantity of sediment available for deposition, and the simulation shows that it must have been necessary to create the present-day Algarve margin morphology.

This study has provided a better understanding of the interactions between gravity and contourite processes on a margin. Moreover, it has demonstrated the influence of environmental factors that constrained the dominance of one of these processes over the other. Finally, it suggests new elements in the potential formation and preservation of coarse-grained deposits along a margin that may confer to several margins a new potential sedimentary interest.

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References

Ambar, I., Howe, M.R., 1979. Observations of the Mediterranean outflow? II. The deep circulation in the vicinity of the Gulf of Cadiz. Deep-Sea Research 26A, 555–568.
Ambar, I., Armi, L., Bower, A., Ferreira, T., 1999. Some aspects of time variability of the Mediterranean water off south Portugal. Deep-Sea Research—I 46, 1109–1136.
Andresen, C.S., Bond, G., Kuijpers, A., Knutz, P.C., Bjorck, S., 2005. Holocene climate variability at multidecadal time scales detected by sedimentological indicators in a shelf core NW off Iceland. Marine Geology 214, 323–338.
Armi, L., Farmer, D., 1985. The internal hydraulics of the Strait of Gibraltar and associated sills and narrows. Oceanologica Acta 8 (1), 37–46.
Armishaw, J.E., Holmes, R., Stow, D.A.V., 2000. The Barra Fan: a bottom-current reworked, glacially-fed submarine fan system. Marine and Petroleum Geology 17, 219–238.

Baringer, M.O., Price, J.F., 1997a. Mixing and spreading of the Mediterranean outflow. Journal of Physical Oceanography 27, 1654–1677.
Baringer, M.O., Price, J.F., 1997b. Momentum and energy balance of the Mediterranean outflow. Journal of Physical Oceanography 27, 1678–1692.
Baringer, M.O., Price, J.F., 1999. A review of the physical oceanography of the Mediterranean outflow. Marine Geology 155 (1–2), 63–82.
Barnolas, A., Díaz del Río, V., Somoza, L., Maestro, A., Vásquez, J.T., Hernández-Molina, F.J., Fernández-Puga, M.C., Llave, E., Lobo, F.J., Alveirinho Dias, J.M., 2000. El cañón de Portimao y su relación con los depósitos contorníticos del margen del Algarve (Portugal). V Congreso Geológico de España. In: Geotemas, vol. 1 (4). Sociedad Geológica de España, Spain, pp. 101–104.
Bintanja, R., van de Wal, R.S.W., Oerlemans, J., 2005. Modeled atmospheric temperatures and global sea levels over the past million years. Nature 437, 125–128.
Bonnel, C., Dennielou, B., Droz, L., Mulder, T., Berne, S., 2005. Architecture and depositional pattern of the Rhone Neofan and recent gravity activity in the Gulf of Lions (western Mediterranean). Marine and Petroleum Geology 22 (6–7), 827–843.
Borenas, K.M., Wahlin, A.K., Ambar, I., Serra, N., 2002. The Mediterranean outflow splitting — a comparison between theoretical models and CANIGO data. Deep-Sea Research II 49 (19), 4195–4205.
Bower, A., Serra, N., Ambar, I., 2002. Structure of the Mediterranean Undercurrent and Mediterranean Water spreading around the southwestern Iberian Peninsula. Journal of Geophysical Research 107 (C10), 1–19.
Bryden, H.L., Kinder, T.H., 1991. Recent progress in strait dynamics. Reviews of Geophysics Supplement 29, 617–631.
Faugères, J.-C., Gonthier, E., Stow, D.A.V., 1984. Contourite drift moulded by the deep Mediterranean outflow. Geology 12, 296–300.
Faugères, J.-C., Cremer, M., Monteiro, H., Gaspar, L., 1985. Growth pattern processes of the Faro Drift (South Portugal). Bulletin de l'Institut de Geoologie du Bassin d'Aquitaine 37, 229–258.
Faugères, J.-C., Stow, D.A.V., Imbert, P., Viana, A.R., 1999. Seismic features diagnostic of contourite drifts. Marine Geology 162 (1), 1–38.
Gervais, A., 2002. Analyse multi-échelles de la morphologie, de la géométrie et de l'architecture d'un système turbiditique sableux profond (Système du Golo, Marge est-Corse, Mer méditérannée). Doctoral Thesis, L'Universite Bordeaux, Bordeaux, 315 pp.
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: Geological Society of London, Special Publication, vol. 15, pp. 275–292.
Griffiths, C.M., Paraschivoiu, E., 1998. Three-dimensional forward stratigraphic modelling of Early Cretaceous sedimentation on the Leveque and Yampi Shelves, Browse Basin. APPEA Journal 38, 147–158.
Gutscher, M.A., Malod, J., Rehault, J.P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. Geology 30, 1071–1074.
Habgood, E.L., Kenyon, N.H., Masson, D.G., Akhmetzhanov, A., Weaver, P., Gardner, J., Mulder, T., 2003. Deep-water sediment wave fields, bottom current sand channels and gravity flow channel-lobe systems: Gulf of Cadiz, NE Atlantic. Sedimentology 50 (3), 483–510.
Hanquiez, V., 2006. Processus sédimentaires et évolution récente (Quaternaire terminal) du Golfe de Cadix. Doctoral Thesis, L'Universite Bordeaux, Bordeaux: 278 pp.
Heezen, B.C., Johnson, G.L., 1969. Mediterranean undercurrent and microphysiography west of Gibraltar. Bulletin de l'Institut Oceanographique (Monaco) 1218 (A), 1–28.
Hernandez-Molina, F.J., Somoza, L., Vasquez, J.T., Lobo, F., Fernndez-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. Quaternary International 92, 5–23.
Hernández-Molina, F.J., Llave, E., Somoza, L., Fernández-Puga, M.C., Maestro, A., León, R., Barnolas, A., Medialdea, T., García, M., Vázquez, J.T., Díaz del Río, V., Fernández-Salas, L.M., Lobo, F., Alveirinho Dias, J.M., Rodero, J.Y., Gardner, J., 2003. Looking for clues to paleoceanographic imprints: a diagnosis of the Gulf of Cadiz contourite depositional systems. Geology 31 (1), 19–22.
Hernández-Molina, F.J., Larter, R.D., Rebesco, M., Maldonado, A., 2004. Miocene changes in bottom current regime recorded in continental rise sediment on the Pacific Margin of the Antarctic Peninsula. Geophysical Research Letter 31, L22606–L22611.
Hernández-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 Research II 53, 1420–1463.
Howe, J.A., Stoker, M.S., Stow, D.A.V., 1994. Late Cenozoic sediment drift complex, northeast Rockall Trough, North Atlantic. Paleoceanography 9, 989–999.
Johnson, J., Ambar, I., Serra, N., Stevens, I., 2002. Comparative studies of the spreading of Mediterranean Water through the Gulf of Cadiz. Deep-Sea Research II 49 (19), 4179–4193.
Kenyon, N.H., Belderson, R.H., 1973. Bedforms of the Mediterranean undercurrent observed with sidescan sonar. Sedimentary Geology 9, 77–99.
Laberg, J.S., Stoker, M.S., Torbjørn Dahlgren, K.I., de Haas, H., Haflidason, H., Hjelstuen, B.O., Nielsen, T., Shannon, P.M., Vorren, T.O., van Weering, T.C.E., Ceramicola, S., 2005. Cenozoic alongslope processes and sedimentation on the NW European Atlantic margin. Marine and Petroleum Geology 22, 1069–1088.
Li, F., Dyt, C., Griffiths, C., 2004. 3D modelling of the isostatic flexural deformation. Computers & Geosciences 30, 1105–1115.
Li, F., Dyt, C., Griffiths, C., 2006. Multigrain coastal sedimentation model based on equilibrium sediment distribution: application to nourishment design. Estuarine, Coastal and Shelf Science 67 (4), 543–730.
Li, F., Dyt, C., Griffiths, C., McInnes, K., 2007. Predicting seabed change as a function of climate change over the next 50 years in the Australian southeast? In: Harff, J., Hay, W.W., Tetzlaff, D.M. (Eds.), Coastline Changes: Interrelation of Climate and Geological Processes, pp. 43–64. GSA Book.
Li, F., Griffiths, C.M., Salles, T., Dyt, C., Oke, P., Feng, M., Jenkins, C., 2008. Climate change impact on NW Shelf seabed evolution and its implication on offshore pipeline design. APPEA Journal 48, 171–189.
Liang, D., Cheng, L., Li, F., 2005. Numerical modelling of scour below a pipeline in currents. Coastal Engineering 52, 43–62.
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. Marine Geophysical Researches 22, 487–508.
Llave, E., Schonfeld, J., Hernández-Molina, F.J., Mulder, T., Somoza, L., Diaz Del Rio, V., Sanchez-Almazo, I., 2006. High-resolution stratigraphy of the Mediterranean outflow contourite system in the Gulf of Cadiz during the late Pleistocene: the impact of Heinrich events. Marine Geology 227 (3–4), 241–262.
Llave, E., Hernández-Molina, F.J., Somoza, L., Stow, D.A.V., Diaz del Rio, V., 2007. Quaternary evolution of the contourite depositional system in the Gulf of Cadiz. In: Viana, A., Rebesco, M. (Eds.), Economic and Paleoceanographic Importance of Contourites, Geological Society of London, Special Publication, pp. 49–80.
Locker, S.D., Laine, E.P., 1992. Paleogene–Neogene depositional history of the middle U.S. Atlantic continental rise: mixed turbidite and contourite depositional systems. Marine Geology 103 (1–3), 137–164.
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). Marine Geology 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., vol. 22, pp. 43–61 (Paris).
Maldonado, A., Somoza, L., Pallarés, L., 1999. The Betic orogen and the Iberian–African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic). Marine Geology 155, 9–43.
Marchès, E., 2008. Le système contouritique de la marge de l'Algarve: processus sédimentaires et enregistrement au cours du Quaternaire. Doctoral Thesis, L'Universite Bordeaux, Bordeaux: 385 pp.
Marchès, E., Mulder, T., Cremer, M., Bonnel, C., Hanquiez, V., Gonthier, E., Lecroart, P., 2007. Contourite drift construction influenced by capture of Mediterranean Outflow Water deep-sea current by the Portimão submarine canyon (Gulf of Cadiz, South Portugal). Marine Geology 242, 247–260.
Marchès, E., Mulder, T., Gonthier, E., Cremer, M., Hanquiez, V., Garlan, T., Lecroart, P., 2010. Perched lobe formation in the Gulf of Cadiz: interactions between gravity processes and contour currents (Algarve Margin, Southern Portugal). Sedimentary Geology 229, 81–94 (this issue).
Mougenot, D., 1988. Geologie 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, pp. 131–139.
Mountain, G.S., Tucholke, B.E., 1983. Abyssal sediment waves. In: Bally, A.W. (Ed.), Seismic Expression of Structural Styles: American Association of Petroleum Geologists Studies in Geology Series, vol. 15, pp. 22–24.
Mulder, T., Weber, O., Anschutz, P., Jorissen, F.J., Jouanneau, J.-M., 2001. A few months-old storm-generated turbidite deposited in the Capbreton Canyon (Bay of Biscay, S-W France). Geo-marine Letters 21, 149–156.
Mulder, T., Voisset, M., Lecroart, P., Le Drezen, E., Gonthier, E., 2006. The western part Gulf of Cadiz: interaction between contour and turbidity currents. Geo-Marine Letters 26 (1), 31–41.
Nelson, C.H., Baraza, J., Maldanado, A., 1993. Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. Sedimentary Geology 82, 103–131.
Nelson, H.C., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., Barber, J.H.J., 1999. Influence of the Atlantic inflow and Mediterranean outflow currents on the Late Quaternary sedimentary facies of the Gulf of Cadiz continental margin. Marine Geology 155, 99–129.
Pickering, K.T., Hiscott, R.N., Hein, F.J., 1989. Deep Marine Environments. Clastic Sedimentation and Tectonics. Unwin Hyman Ltd., London. 416 pp.
Pickering, K.T., Hiscott, R.N., Kenyon, H.H., Ricci-Lucchi, F., Smith, D.A., 1994. Atlas of Deep Water Environments Architectural Style in Turbidite System. Chapman & Hall, London. 344 pp.
Reading, H.G., Richards, M., 1994. Turbidite systems in deep-water basin margins classified by grain-size and feeder system. American Association of Petroleum Geologists Bulletin 78, 792–822.
Rebesco, M., Pudsey, C., Canals, M., Camerlenghi, A., Barker, P., Estrada, F., Giorgetti, A., 2002. Sediment drift and deep-sea channel systems, Antarctic Peninsula Pacific margin. In: Stow, D.A.V., Pudsey, C.J., Howe, J.A., Faugeres, J.C., Viana, A.R. (Eds.), Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics: Geological Society of London, London, Memoirs, vol. 22, pp. 353–371.
Rolhing, E.J., Bryden, H.L., 1994. Estimating past changes in the Eastern Mediterranean freshwater budget, using reconstructions of sea level and hydrography. Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen. Series B, Palaeontology, Geology, Physics, Chemistry, Anthropology 97, 201–217.
Salles, T., Mulder, T., Gaudin, M., Cacas, M.C., Lopez, S., Cirac, P., 2008. Simulating the 1999 Capbreton canyon turbidity current with a Cellular Automata model. Geomorphology 97 (3–4), 516–537.
Serra, N., Ambar, I., 2002. Eddy generation in the Mediterranean undercurrent. Deep-Sea Research II 49 (19), 4225–4243.
Serra, N., Ambar, I., Kaese, R.H., 2005. Observations and numerical modeling of the Mediterranean outflow splitting and eddy generation. Deep-Sea Research II 52, 383–408.

Stow, D.A.V., Faugères, J.C., Gonthier, E., Cremer, M., Llave, E., Hernández-Molina, F.J., Somoza, L., Díaz del Río, V., 2002. Faro–Albufeira drift complex, Northern Gulf of Cádiz. In: Stow, D.A.V., Pudsey, C.J., Howe, J., Faugères, J.C. (Eds.), IGCP 432. Deep-water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics: Geological Society of London, Special Publication, vol. 22, pp. 137–154.
Swallow, J.C., 1969. A deep eddy off Cape St. Vincent. Deep-Sea Research 16, 285–295 (Suppl.).
Terrinha, P., Pinheiro, L.M., Henriet, J.-P., Matias, L., Ivanov, M.K., Monteiro, J.H., Akhmetzhanov, A., Volkonskaya, A., Cunha, T., Shaskin, P., Rovere, M., and the TTR10 Shipboard Scientific Party, 2003. Tsunamigenic–seismogenic structures, neotectonics, sedimentary processes and slope instability on the southwest Portuguese Margin. Marine Geology 32 (66), 1–19.
Tetzlaff, D.M., Harbaugh, J.W., 1989. Simulating Clastic Sedimentation; Computer Methods in Geosciences. Van Nostrand Reinhold, New York. 196 pp.
Toucanne, S., Mulder, T., Schonfeld, J., Hanquiez, V., Gonthier, E., Duprat, J., Cremer, M., Zaragosi, S., 2007. Contourites of the Gulf of Cadiz: a high-resolution record of the paleocirculation of the Mediterranean outflow water during the last 50,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 354–366.
Vanney, J.R., Mougenot, D., 1981. La plate-forme continetale du Portugal et les provinces adjacentes: Analyse Géomorphologique. Memorias dos servicos geologicos de Portugal. 86 pp.
Vásquez, J., Díaz del Río, V., Maestro, A., Barnolas, A., Fernández-Puga, M.C., Somoza, L., Hernández-Molina, F.J., Alveirinho Dias, J.A., 2000. Características del Cañon submarino de Portimao (SW Margen Ibérico). 2 Asambla Luso Española de Geodesia y Geofísica; Secçao Portuguesa das Uniões Internacionais Astronómica e Geodésica e Geofisica, Lagos, Portugal, Resumos, vol. S15-22, pp. 675–676.
Weaver, P.P.E., Wynn, R.B., Kenyon, N.H., Evans, J., 2000. Continental margin sedimentation, with special reference to north-east Atlantic margin. Sedimentology 47, 239–256.