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Contourite distribution and bottom currents in the NW Mediterranean Sea: Coupling seafloor geomorphology and hydrodynamic modelling

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Abstract :

Contourites are common morphological features along continental margins where currents encounter the seafloor. They can provide long-term archives of palaeoceanography, may be prone to sediment instability, and can have a great potential for hydrocarbon exploration. Despite their importance and increasingly recognised ubiquitous occurrence worldwide, the link between oceanographic processes and contourite features is poorly constrained. In particular, it is unclear under which specific conditions sediments are mobilised, modified and deposited by bottom currents. Here, we aim to determine key bottom current characteristics (velocity and bottom shear stress) affecting contourite deposition, by assuming that recent oceanographic regimes may be extended back in time over the past glacial-interglacial cycles, with strong winter circulation assumed similar to glacial conditions and weak summer circulation to interglacials. We present an integrated study from the NW Mediterranean Sea that couples results of the MARS3D hydrodynamic model with high-resolution sedimentological and geophysical data (piston cores, multibeam bathymetry and high resolution seismic data). Near bottom circulation was modelled during winter and summer 2013 as representative of past periods of high and low current intensity, respectively. Model results match well with the extent of contourite depositional systems and their different localised morphologic elements. We deduce that higher intensity events control the formation of erosional features such as moats and abraded surfaces. The heterogeneous distribution of bottom-current intensity on slopes explains the development of different types of contourite drifts. Plastered drifts form in zones of low bottom-current velocities constrained upslope and downslope by higher current velocities. Separated elongated mounded drifts develop where fast bottom-currents decelerate at foot of the slope. In contrast, no mounded contourite morphologies develop when the current velocity is homogeneous across the slope, especially in margins prone to downslope sediment transport processes. In confined basins, gyres may transport sediment in suspension from a margin with a high sediment supply to an adjacent starved margin, favouring the development of fine-grained contourites in the latter. Our results provide new insights into how detailed bottom-circulation modelling and seafloor geomorphological analyses can improve the understanding of palaeoflow-regimes, at least over time spans when the overall paleogeography and the distribution of contourite drifts is comparable to present-day conditions. The approach of coupled hydrodynamic models and geomorphological interpretations proposed here for depositional, erosional and mixed contourite features may be used to understand other areas affected by bottom currents, and for a better conceptual understanding of bottom-current processes and their interactions with the seafloor.

Highlights

► Hydrodynamic modelling is a useful tool to understand the formation of contourites. ► Contourite drifts develop in zones of minimum bottom currents. ► Plastered drifts develop in a zone of weak currents between two zones of stronger currents. ► High intensity events control the formation of erosional features as moats. ► Gyres favour the formation of contourites along starved margins in confined basins.

Keywords : Sediment drift, Erosion, Oceanic circulation, Bottom shear stress

1. Introduction

Oceanic currents play a major role in controlling the morphological and sedimentary evolution of continental margins (Rebesco and Camerlenghi, 2008). Bottom current-induced sediment winnowing, remobilisation and erosion sculpt the seafloor on a wide variety of scales, and can have a profound influence on local to regional sediment accumulation rates (Hernández-Molina et al., 2008; Stow et al., 2009). Large contourite sedimentary accumulations are known as "drifts", which may be more than 100 km wide, hundreds of kilometres long and up to 2 km thick (Stow et al., 2002; Rebesco and Camerlenghi, 2008; Rebesco et al., 2014). As contourite drifts typically have higher sedimentation rates than pelagic sediments, the resultant expanded stratigraphy can provide long-term, high-resolution archives of palaeoceanography and palaeoclimate (Knutz, 2008; McCave, 2008). Due to their depositional geometries, contourites may be prone to instability, thus posing a hazard for seafloor infrastructure (Laberg and Camerlenghi, 2008; Miramontes et al., 2018), and they may be economically viable prospects for hydrocarbon exploration (Viana, 2008).

Contourite drifts are commonly associated with persistent bottom currents related to long-term thermohaline circulation patterns (Stow et al., 2002), although the physical processes that control their formation are still poorly understood due to the paucity of direct observations and modelling studies (Hunter et al., 2007; de Lavergne et al., 2016; Hernández-Molina et al., 2016). Persistent bottom currents can be affected by many intermittent oceanic processes, such as eddies, internal waves, deep-sea storms, rogue waves and/or tsunami related currents (Shanmugam, 2013; Rebesco et al., 2014). In addition, thermohaline circulation is often highly variable at seasonal (Astraldi and Gasparini, 1992), interannual (Pinardi et al., 2015) and geological (thousands to millions of years) timescales (Cacho et al., 2000).

The first attempts to explain the effect of bottom currents on sedimentation in deep settings using *in situ* measurements were carried out in the 1970's (Gardner et al., 2017; and references therein). However, oceanographic measurements are scarce in deep areas, and they are also limited in time and space (de Lavergne et al., 2016). Numerical modelling thus provides a useful tool to study the interactions between bottom currents and seafloor, since it can cover larger areas and longer periods of time. New advances in modelling submesoscale circulation (scale ranges 0.1–10 km in the horizontal, 0.01–1 km in the vertical, and hours-days in time; McWilliams, 2016) allow the comparison between hydrodynamic modelling and geophysical data. Numerical simulations are a valuable tool to understand the influence of present-day hydrodynamics on sedimentary processes along continental slopes (e.g. Bellacicco et al., 2016; Bonaldo et al., 2016), and have been used to test the effects of different contemporary hydrodynamic processes on contourite systems (Dutkiewicz et al., 2016; Zhang et al., 2016; Thran et al., 2018). However, these modelling studies cannot fully explain the sedimentary processes that control the formation of depositional and erosional contourite features over long time scales. A key outstanding question concerns the relative significance of short-term intensifications in bottom current activity. Are geologically brief periods of extreme near-bed currents the dominant controlling factor on the inception of contourites and correlated seafloor features? Are persistent background conditions more important in shaping distinct depositional architectures instead? To address these questions, it is necessary to integrate calibrated numerical modelling with evidence of past bottom-current activity over geological time scales. In a recent study, Thran et al. (2018) compared at a global scale (low resolution) the extent of known contourite deposits and modelled bottom current velocity, showing an overall matching of the two datasets. Here we examine the output of a high resolution numerical oceanographic model, calibrated on short-term (seasonal) hydrodynamic variations, to propose an explanation of how, where and why contourite-related features may develop or may be sustained by present-day oceanic conditions at the seafloor. We then attempt to extrapolate those results to provide inference on the development of contourites over longer (>millennial) time scales.

In the present study, we examine the output of a high resolution numerical oceanographic model, to propose an explanation for the distribution of contourite-related features in the Northwestern Mediterranean Sea. We focus our study on the NW Mediterranean Sea because: i) the oceanic circulation of this area has been well studied from measurements and numerical modelling (Pinardi et al., 2015; and references therein); ii) it has a well-known seasonal variability (intense circulation in winter and weak in summer; Astraldi and Gasparini, 1992; Artale et al., 1994; Rubio et al., 2009); and, iii) it is a region where many contourites have been identified. Contourites have been identified in the Balearic Sea (Velasco et al., 1996; Vandorpe et al., 2011; Lüdmann et al., 2012), the Ligurian Sea (Soulet et al., 2016; Cattaneo et al., 2017) and the northern Tyrrhenian Sea (Roveri, 2002; Cattaneo et al., 2014; Miramontes et al., 2016). In particular, we focused on three areas of the NW Mediterranean Sea: (1) the Balearic Sea (Liguro-Provençal Basin), (2) the Ligurian Sea (offshore the Portofino Promontory) and (3) the Northern Tyrrhenian Sea (Corsica Trough and a seamount off southeast Corsica; Fig. 1). The aims of this study are to: i) identify how present-day current velocities and bottom shear stresses are spatially distributed with respect to the location of long lasting bottom-current influenced seafloor morphologies and deposits (contourite drifts, seafloor erosion features); ii) explore the contrasted scenarios of contourite drifts as mainly controlled by constant currents of moderate intensity or by short-term events of high intensity; and iii) evaluate how bottom currents might redistribute sediment within a confined basin from a margin with high sediment supply to a starved margin.

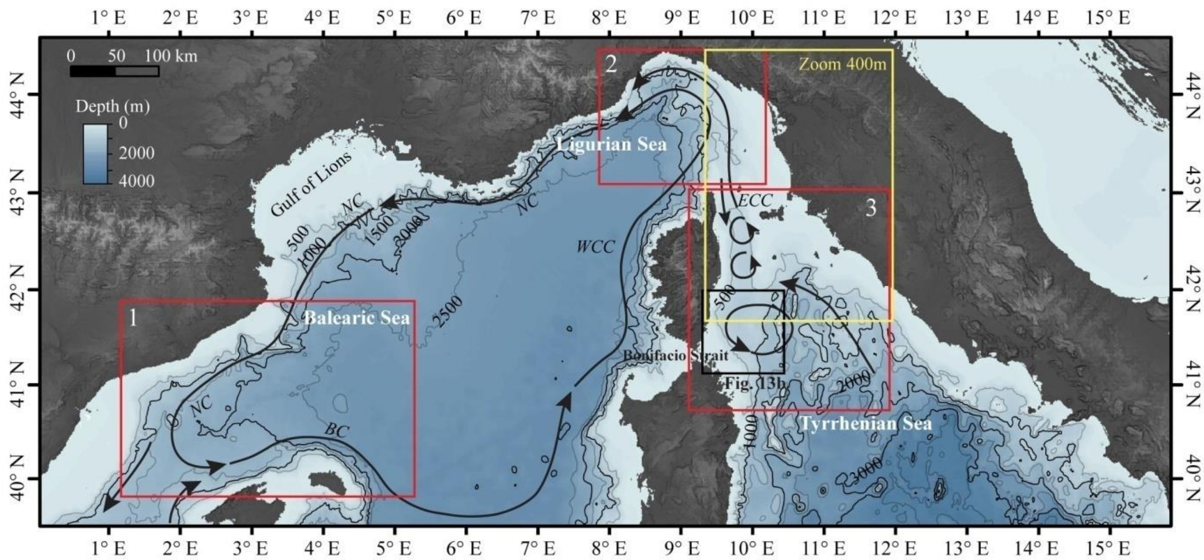

Fig. 1. Bathymetry of the NW Mediterranean Sea (GEBCO) showing the main circulation structures at 200-300 m based on Pinardi et al. (2015) and the present study, and location of the three study areas: 1-Balearic Sea, 2-Ligurian Sea, 3-Northern Tyrrhenian Sea. NC: Northern Current; BC: Balearic Current; WCC: Western Corsica Current; ECC: Eastern Corsica Current. The map shows the extension of the zone

simulated with the MARS3D hydrodynamic model in the MENOR configuration (resolution of 1.2 km), and the yellow rectangle shows the location of the zoom of the model simulated with a higher resolution (400 m).

2. Regional setting

The Mediterranean Sea is a mid-latitude semi-enclosed sea connected with the Atlantic Ocean through the Strait of Gibraltar. At present, it has an anti-estuarine circulation (inflow of low salinity surface water and outflow of a deep denser water with high salinity) forced by wind stress and buoyancy fluxes (Pinardi et al., 2015). The negative heat and fresh water budgets of the Mediterranean Sea are balanced over a multidecadal timescale by the entrance of Atlantic Water (AW) through the Strait of Gibraltar (Pinardi et al., 2015). As the AW flows through the Mediterranean Sea, it evolves to a water mass named Modified Atlantic Water (MAW). The MAW is a fresher water mass present in the upper 100-200 m of the water column (Millot and Taupier-Letage, 2005; Millot, 2009). The MAW overlies the Levantine Intermediate Water (LIW), which is formed in the Levantine Basin by a process of evaporation during the summer and by a winter cooling (Lascaratos et al., 1993; 1999). After passing the Strait of Sicily, the LIW flows northwards along the eastern and western coasts of the Corsica Island as part of the Eastern and Western Corsican Currents (ECC, WCC; Millot et al., 1999; Fig. 1). The ECC can reach current speeds of more than 40 cm s^{-1} near the surface and more than 20 cm s^{-1} near the seafloor at the Corsica Strait (Vignudelli et al., 2000). The currents are more intense and with a northwards direction in winter, while in summer they are weaker and occasionally flow southwards (Astraldi and Gasparini, 1992; Vignudelli et al., 2000; Ciuffardi et al., 2016). The ECC (at the depth range of the LIW) is related to the formation of contourite systems in the Corsica Trough (Table 1; Miramontes et al., 2016).

Study area	Current velocity from literature	Water masses	Drift water depth	Water mass at drift location
Balearic Sea	Northern Current (NC): westwards along the Iberian slope. Balearic Current (BC): eastwards along the Balearic Islands (Pinardi et al., 2006). In winter, deep convection and dense shelf water cascading: up to 55 cm s^{-1} in the continental slope (Palanques et al., 2012; Durrieu de Madron et al., 2017).	MAW (0-200 m), WIW (200-400 m, if present), LIW (400-700 m), WMDW (>700 m) (Salat and Font, 1987; Font et al., 1988).	2000-2700 m	WMDW
Ligurian Sea	Northern Current (NC): westwards; NC more intense (max. 30-50 cm s^{-1} near the surface), narrower and deeper in winter (Albérola et al., 1995).	MAW (0-150 m), LIW (150-1000 m, when the WIW is not present), WMDW (>1000 m) (Gasparini et al., 1999; Millot et al., 1999).	900 m	LIW
Northern Tyrrhenian Sea	East Corsica Current (ECC): northwards, episodically southwards (in summer); more intense in winter, more than 40 cm s^{-1} near the surface and 20 cm s^{-1} near the seafloor (Vignudelli et al., 2000).	MAW (0-200 m), LIW (200-1000 m), WMDW (>1000 m) (Millot et al., 1999).	170-850 m in the Corsica Trough and 820-900 m in the seamount south of the Corsica Trough.	LIW

Table 1. Summary of the overall current characteristics, water masses distribution, water depth of the studied sediment drifts and identification of the water mass in contact with contourite morphologies in the three study areas: Balearic, Ligurian and Northern Tyrrhenian Seas. MAW: Modified Atlantic Water; WIW: Western Intermediate Water; LIW: Levantine Intermediate Water; WMDW: Western Mediterranean Deep Water.

The ECC and WCC feed the Northern Current (NC), which is a slope current flowing along the Ligurian Sea up to the Balearic Sea (Astraldi et al., 1994; Fig. 1). The NC closes cyclonically in the Balearic Sea, flowing along the northern Balearic margin as the Balearic Current (BC; Pinot et al., 2002; Fig. 1), and forming part of the Gulf of Lions gyre (Pinardi et al., 2006). The NC also presents a seasonal variability: in summer the NC is weak, wide (about 50 km) and shallow (down to 250 m); while in winter the NC stronger (maximum velocity near the surface of 30-50 cm s^{-1}), narrow (about 30 km) and deep (down to about 450 m) (Albérola et al., 1995). The NC (at the depth range of the LIW) is at the origin of contourite features along the Ligurian margin located at 200-1000 m water depth (Table 1; Soulet et al., 2016; Cattaneo et al., 2017).

The deep part of the NW Mediterranean Sea (below 1000 m water depth) is characterised by the presence of the Western Mediterranean Deep Water (WMDW) (Millot, 1999). This water mass is mainly formed in the Gulf of Lions by surface cooling and evaporation due to cold and dry northern winds, and open-sea convection (Durrieu de Madron et al., 2013). Bottom-reaching convection events can generate intense currents near the seafloor with speeds up to 45 cm s^{-1}, strong enough to locally resuspend sediment (Durrieu de Madron et al., 2017). Dense shelf water cascading also generates strong bottom currents up to 95 cm s^{-1} in canyons and 40-55 cm s^{-1} in the slopes. Between January and April, these currents very often erode the seafloor and transport large amount of particles in the bottom layer (Palanques et al., 2012). All these events may affect the formation of contourites in the Balearic Sea. Contourites in this area are located at 2000-2700 m in the depth range of the WMDW (Table 1; Velasco et al., 1996).

3. Materials and methods

3.1. Geophysical, sedimentological data and terminology

Various bathymetric data sets were used to enable geomorphological analysis and oceanographic modelling, detailed in Table 2. Seismic data were used to characterise the sub-surface architecture of contourite depositional and erosional features. The seismic data set used for this study was acquired with four different types of seismic sources (Table 2).

The piston cores shown in this study were collected along the Pianosa Ridge in 2013 during the PRISME3 cruise (Cattaneo, 2013b) onboard the R/V Pourquoi pas?, and along the Minorca margin in 2018 during the WestMedFlux2 cruise (Poort and Gorini, 2018) onboard the R/V L'Atalante. The cores of the Pianosa Ridge are 9 to 22 m long and were collected between 176 and 342 m water depth, and the core of the Minorca margin is 8 m long and was collected at 2694 m water depth.

The criteria used in the present study to identify contourites and bottom–current related features followed the concepts proposed by Faugères et al. (1999), Faugères and Stow (2008), Nielsen et al. (2008) and Rebesco et al. (2014). In this study we identified two main types of contourite drifts: separated elongated mounded drifts and plastered drifts. Separated elongated mounded drifts are often found on the lower slope, associated with steep slope gradients. They are separated from the slope by a linear depression (moat) that can be formed by erosional or non-depositional processes

(Rebesco et al., 2014). We mapped the offshore limit of the drifts as the inflexion point of the slope, where the mounded shape ends. Plastered drifts are typically found on gentle slopes (Faugères and Stow, 2008). They form a convex shape, with the predominance of sediment accumulation in the centre of the drift (Faugères and Stow, 2008). Contourite terraces are flat surfaces commonly associated with plastered drifts, which are often dominated by erosion (Hernández-Molina et al., 2016).

Zone	Bathymetry origin and horizontal resolution	Seismic data
Balearic Sea	GEBCO (GEBCO_08, version 2010-09-27, http://www.gebco.net), 30 arc-second.	Low resolution multi-channel seismic reflection data from VALSIS 2 survey (Mauffret, 1988) and Sub-Bottom Profiler (SBP) data from WestMedFlux2 (Poort and Gorini, 2018).
Ligurian Sea	GEBCO (GEBCO_08, version 2010-09-27, http://www.gebco.net), 30 arc-second.	Deep-towed SYSIF (Système Sismique Fond) seismic reflection data (220-1050 Hz) from PRISME2 survey (Cattaneo, 2013a).
Western and Central Corsica Trough	Multibeam bathymetry from CORFAN (Savoye, 1998), CORFAN 2 (Savoye, 2001) and SIGOLO surveys (Savoye, 2008), 25 m.	48-72-channel sparker seismic reflection data (130-750 Hz) from SIGOLO survey (Savoye, 2008)
Eastern Corsica Trough (Pianosa Ridge)	Multibeam bathymetry from PRISME2 (Cattaneo, 2013a), PAMELA-PAPRICA (Cattaneo and Jouet, 2013) and PRISME3 surveys (Cattaneo, 2013b), 5 and 15 m.	72-channel high resolution mini GI gun seismic reflection (50-250 Hz) and Sub-Bottom Profiler data (SBP, 1800-5300 Hz) from PRISME 2 (Cattaneo, 2013a) and PAMELA-PAPRICA surveys (Cattaneo and Jouet, 2013).
Seamount Northern Tyrrhenian Sea	Multibeam bathymetry from an industrial data set, 30 m; and detailed bathymetry acquired with AUV, 1 m.	Multi-channel ultra-high resolution seismic reflection profile from a sleeve gun array of an industrial data set.
NW Mediterranean Sea in hydrodynamic model	ETOPO2, 1.2 km	-
Zoom in the Northern Tyrrhenian Sea in hydrodynamic model	Compilation of GEBCO bathymetry and multibeam bathymetry of the Corsica Trough, 400 m.	-

Table 2. Geophysical data set (Source for morphobathymetric data: bathymetric grid and reflection seismic profiles) in the three study areas (Balearic, Ligurian and Northern Tyrrhenian Seas) and in areas with detailed analysis in the Northern Tyrrhenian Sea (Corsica Trough, Pianosa Ridge, Northern Tyrrhenian Seamounts).

3.2. Hydrodynamic modelling

The MARS3D (3D hydrodynamical Model for Applications at Regional Scale) model was used to simulate coastal and regional circulation (developed by Lazure and Dumas, 2008; revised by Duhaut et al., 2008). For this study we used the “MENOR” configuration of the MARS3D model, which extends from the Balearic Islands to the Gulf of Lions and the Ligurian Sea (longitude: 0°E 16°E, latitude: 39.5°N

44.5°N). The model space has a horizontal resolution of 1.2 km and 60 vertical levels using a generalised sigma coordinates system. Details on the model are reported in the supplementary materials. In this study, we modify the resolution based on the scale of current-related features observed on the seafloor. In the Balearic Sea contourite drifts have a maximum width of 25 km, and the moat is about 5 km wide (Velasco et al., 1996). In contrast, contourites in the northern Tyrrhenian Sea present a smaller size. Sediment drifts are less than 10 km wide, and the moat less than 2 km wide (Miramontes et al., 2016). Therefore, in order to better simulate the oceanographic processes at smaller scale, we increased the resolution of the model to 400 m in the Tyrrhenian Sea. The zone of enhanced (400 m) resolution extends from 9.39°E to 12.33°E and 41.71°N to 43.27°N, covering an area from the east Corsican coast to the Italian coast (Fig. 1). During the simulation the MENOR configuration and the zoom are computed simultaneously. Both the 400 m-resolution zone and the MENOR configuration mutually exchange information (current, temperature and salinity) at each time step. This two-way downscaling approach prevents any inconsistency between the coarser and the finer grids.

We simulated three months of winter (January, February and March) 2013 to represent a period of strong currents, and summer 2013 (July, August, September) to represent a period of weak currents. We chose the year 2013 because it is known that the oceanic circulation was very intense during this winter (Léger et al., 2016). Moreover, an intense observation experiment (HYMEX) conducted in the North Western Mediterranean Sea from summer 2012 to spring 2013 provided valuable calibration, enabling robust definition of initial and boundary conditions (Léger et al., 2016). Simulations were thus extended to include a 4 month-long interval prior to the period of interest to assess the model against HYMEX results (i.e. calculations started in September 2012 to have a more realistic initial condition in January 2013). More details on the hydrodynamic model assessment are shown in the supplementary materials.

For the present study we were interested in the near-bed circulation to study the current-seafloor interaction. Therefore, we calculated the bottom shear stress generated by currents at the seafloor based on the model results. At the bed interface the shear stress (τ) is mostly turbulent and can be related to the sea water density (ρ) and the friction velocity (u*) using:

$$\tau = \rho \, u^{*2} \tag{1}$$

In the boundary layer with a steady current, the turbulent velocity can be deduced from the current speed near the bottom with the relation:

$$u^* = \frac{\kappa \, u(z)}{\ln\left(\frac{z}{z_0}\right)} \tag{2}$$

where *κ* is the Von Karman constant (equal to 0.4; Schlichting, 1962), z_0 the bottom roughness length taken here to a constant equal to 0.0035 m and *z* the distance from the bottom where the current velocity *u(z)* is computed. The bottom shear stress (BSS) is computed over the thickness of the bottom layer. The use of the bottom stress overcomes the difference in the bottom layer thickness due to the generalised sigma coordinate. In this model we used 60 vertical sigma-levels that are parallel to the topography, therefore the cells are stretched in zones of deeper water, and squeezed where water depths are shallower. We used the 90th percentile of the bottom shear stress in order to remove the extreme and transitory events. 75th percentiles, median or even mean values were also examined without significant changes in resulting patterns.

The Brunt-Väisälä frequency (or buoyancy frequency, *N*), is the oscillation frequency of a water parcel displaced vertically in a statically stable environment, and it provides information about the water stratification (Da Silva et al., 2009). A layer of high Brunt-Väisälä frequency acts in the fluid as a focus of internal waves, and is an area of potential oscillatory current. It was used in the Corsica Trough to show the zone where internal waves could be formed. It was calculated from the modelled vertical oceanic density gradient according to:

$$N = \sqrt{\frac{g}{\rho}\frac{\partial \rho}{\partial z}} \tag{3}$$

where *g* is the gravitational acceleration, *ρ* is the density and $\frac{\partial \rho}{\partial z}$ is the vertical oceanic density gradient.

3.3. Coupling hydrodynamic modeling on short timescales (seasons) and long term sediment erosion/deposition

The locations where contourites have developed in the study areas have not changed significantly since their onset. Contourites started to develop in the Corsica Trough in the Middle-Late Pliocene (2.5-3.5 Ma ago) (Roveri, 2002; Miramontes et al., 2016). There is clear evidence for long-lived contour current activity throughout the Pliocene-Quaternary from seismic data, with remarkable consistent gross deposit architecture and orientations (e.g. Roveri, 2002). These observations suggest that the direction and location of bottom currents have not significantly changed during the same timescales. Although the general circulation pattern in the NW Mediterranean Sea may not have dramatically changed since the Pliocene, the intensity of the bottom currents has changed cyclically. The intermediate and deep bottom currents in the Mediterranean Sea were more intense during sea level low-stands, or colder stages, than during sea level high-stands, or warmer stages (Cacho et al., 2000; Toucanne et al., 2012; Minto'o et al., 2015). Therefore during sea level low-stands, bottom currents affected the contourite depositional systems by enhanced erosion and emplacement of coarser deposits (Miramontes et al., 2016).

Modelling past oceanic circulation is hampered because of the uncertainty in ancient boundary conditions. Therefore, we modelled the oceanic circulation during the winter and the summer seasons of 2013 as two representations of intense (winter) and weak (summer) oceanic circulation. Given the correlation of areas of high shear stress under winter conditions with major erosional features, we hypothesize that the circulation pattern during sea level low-stands could be similar to the present-day winter season.

4. Results

4.1. Balearic Sea (Liguro-Provençal Basin)

The Balearic Sea is located between the north of the Balearic Islands and the Iberian Peninsula, with water depths decreasing westward from 2700 m to 1000 m (Fig. 1). The modelled circulation shows the same general patterns during winter and summer 2013. Bottom currents flow westwards along the Iberian slope. They turn cyclonically due to the bathymetric and hydrologic constraints of the basin, flowing back eastwards along the northern Balearic slope (Fig. 2). Modelling of conditions during winter 2013 show dense shelf waters cascading downslope at the western output of the Gulf of Lions and then flowing along the Iberian slope (see Supplementary materials), in agreement with modelling results by Estournel et al. (2016). During that period of time, high mean velocities (20-30 cm s^{-1}; Fig. 2a) and high P90 BSS (90th percentile of the Bottom Shear Stress; > 0.2 N m^{-2}) are obtained across a large part of the Iberian slope (Fig. 2b). During winter, bottom currents are relatively vigorous along the continental slope of the Minorca Basin, especially in the lower slope between 1000 and 2000 m water depth (wd), with mean velocities ranging between 15 and 25 cm s^{-1} and P90 BSS 0.1-0.2 N m^{-2}. This circulation along the Minorca slope corresponds to the southwards outflow of WMDW formed during winter (Millot, 1999). Bottom currents remain relatively active along the Minorca slope also in summer, with mean velocities of 10-20 cm s^{-1} (Fig. 2c) and P90 BSS of 0.07-0.2 N m^{-2} (Fig. 2d). In contrast, in the Iberian slope the circulation near the seafloor is much weaker during summer with mean velocities <10 cm s^{-1} (Fig. 2c) and P90 BSS <0.03 N m^{-2} (Fig. 2d).

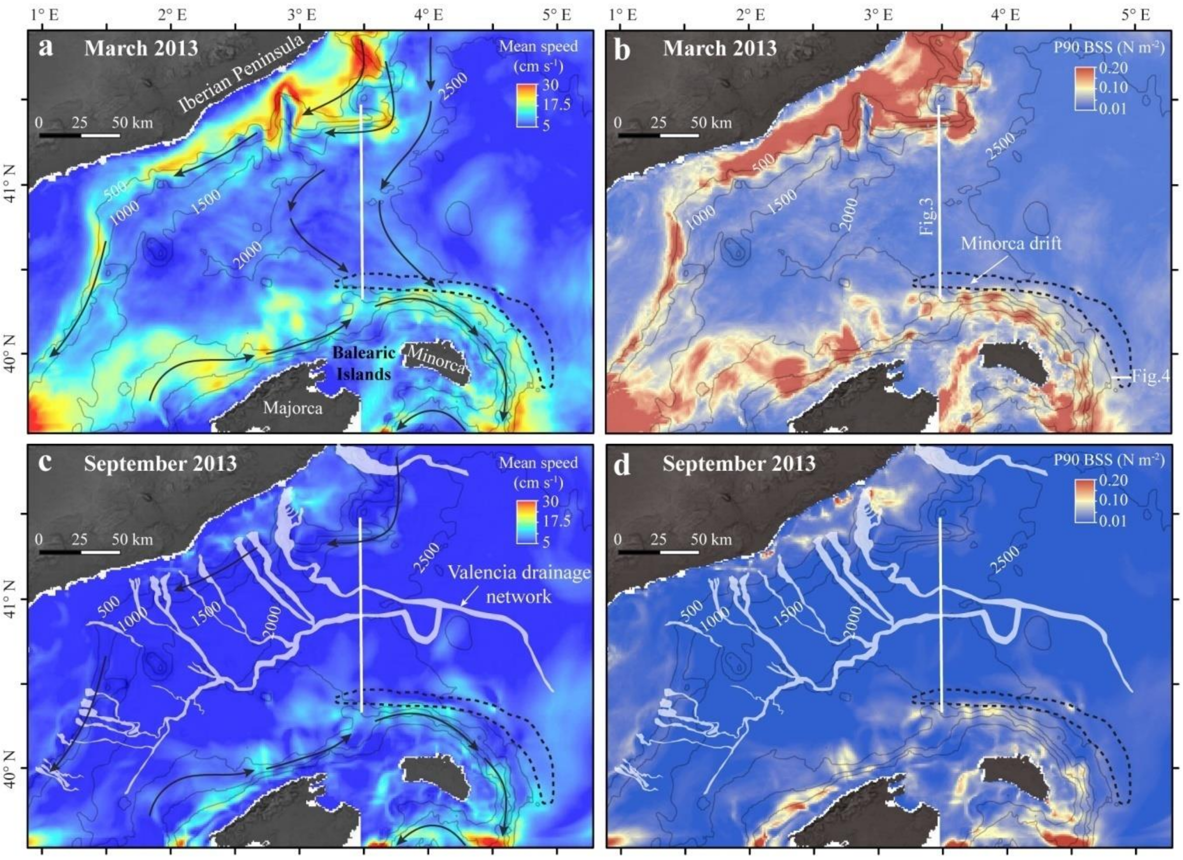

Fig. 2. Results of the MENOR model (cell size of 1.2 km) in the Balearic Sea: during March 2013, (a) mean speed and (b) 90th percentile of the Bottom Shear Stress (P90 BSS); during September 2013, (c) mean speed and (d) P90 BSS. The arrows represent the current direction. The Valencia drainage network is represented with white polygons (adapted from Amblas et al., 2011), and contourite drifts are outlined with dashed lines.

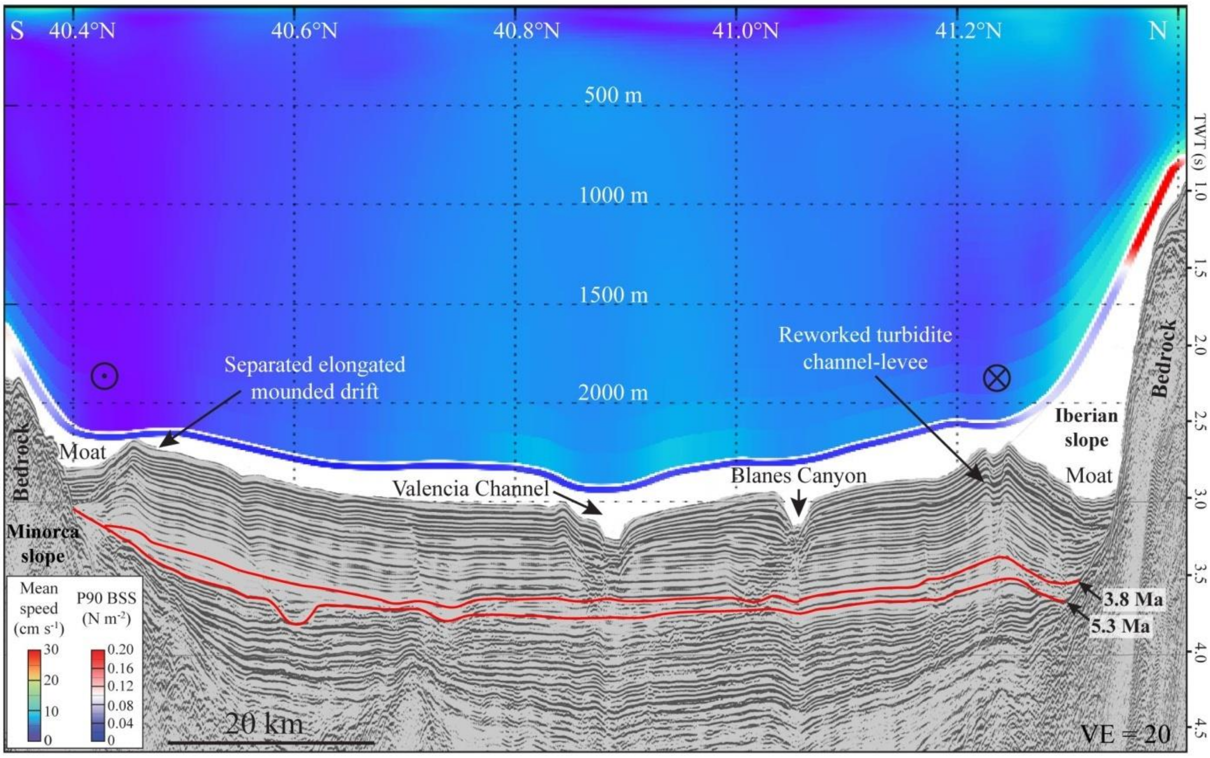

Fig. 3. Seismic reflection profile (VALS88-808) and transect at the same position of the mean speed (upper coloured plot) and 90th percentile of the BSS (bottom layer of the coloured plot) from the MENOR model during March 2013. See Fig. 2 for location. Note that the bathymetry used for the hydrodynamic model is a simplified bathymetry with a 1.2 km resolution and thus it does not perfectly fit with the seismic profile. The transect of the model and the seismic profile are not represented at the same depth to avoid overlapping between the images. The red lines represent the boundaries of the onset of the contourite development (based on Rabineau et al. (2014) and Leroux et al. (2017)). Note the two moats at the foot of the continental slope. To the South the moat is adjacent to the Minorca elongated separated mounded drift. To the North the moat erodes part of a turbiditic channel/levee system.

The morphology of the seafloor between the Iberian and the Minorca slopes is characterized by the presence of erosional features at the foot of the slope that are about 4 km wide, with an incision of about 260 m at 2250 m wd in the Iberian slope, and 150 at 2100 m wd m in the Minorca slope (Fig. 3). North of Minorca this feature can be interpreted as a moat associated with the Minorca sediment drift (dashed line, Fig. 2). The water depth at which the Minorca drift is located increases eastwards, and the height of the drift decreases in the same direction (Fig. 2; Velasco et al., 1996). The Minorca drift has a convex, arcuate morphology and presents the diagnostic shape of a separated elongated mounded drift on the northern and eastern sides of Minorca (Figs. 3 and 4a). A Sub-Bottom Profiler (SBP) image of the Minorca slope and foot of the slope shows typical contouritic features: (1) an eroded slope characterised by truncated reflections; (2) chaotic acoustic facies of strong amplitude in the moat, suggesting the presence of sediment coarser than on the drift (see core WMF2-KS01 in Fig. 4b); and (3) mounded continuous reflections commonly found in muddy drifts with thin silt layers (Fig. 4). Along the Iberian slope the construction of sedimentary bodies shows the morphology of a turbidite channel with pronounced levees north of the Blanes Canyon (Fig. 3; Amblas et al., 2011). A closer examination of the northern levee reveals an asymmetry in the levee and a flat surface at the foot of the slope (interpreted as a moat), probably due to enhanced erosion by bottom currents at the base of the slope (Fig. 3). The slopes of both Iberian and Minorca margins are strongly eroded, as indicated by exposed bedrock at the seafloor, in agreement with the high modelled P90 BSS (Fig. 3). Separated elongated mounded drifts develop in the zone where bottom currents are relatively weak, with mean velocities below 7 cm s^{-1} and P90 BSS below 0.03 N m^{-2} (Figs. 2 and 3; Table 3).

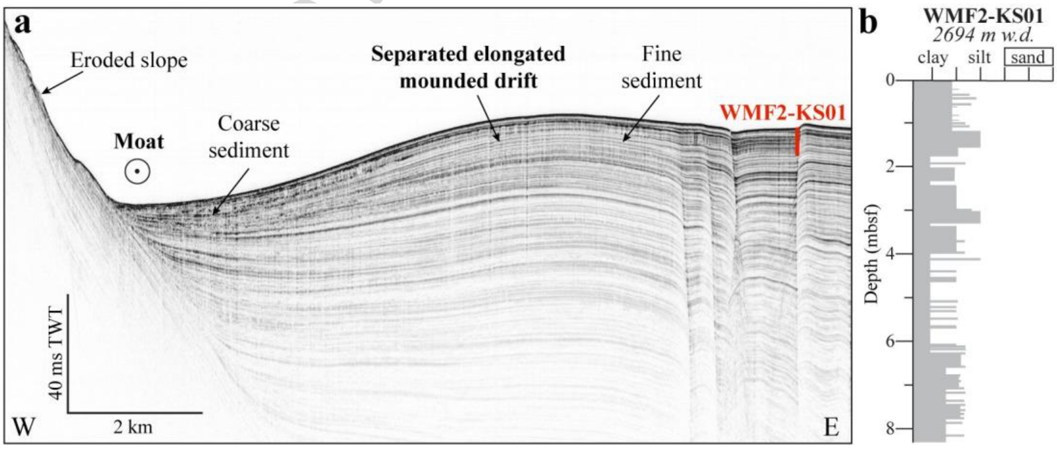

Fig. 4. (a) Sub-bottom profiler image (WMF2018-AT0006B) of the southern part of the Minorca drift showing the convex morphology and convergent seismic reflections diagnostic of a contourite drift and the location of core WMF2-KS01. See Fig. 2b for location. (b) Sediment log of core WMF2-KS01.

4.2. Ligurian Sea

Bottom currents flow northwards and westwards along the Ligurian slope during winter and summer 2013. Currents are vigorous on the continental shelf during winter (related to the MAW) with mean bottom velocities ranging between 15 and 20 cm s^{-1} (Fig. 5a) and P90 BSS of 0.2-0.4 N m^{-2} (Fig. 5b). Similar values are found related to the LIW between 600 and 800 m wd offshore Portofino, although in this area P90 BSS is lower; between 0.1 and 0.2 N m^{-2} (Fig. 5b). In summer, bottom currents on the shelf become less active, with mean velocities <7 cm s^{-1} (Fig. 5c) and P90 BSS <0.04 N m^{-2} (Fig. 5d), but they remain important on the slope between 400 and 1000 m wd with mean velocities between 10 and 15 cm s^{-1} (Fig. 5c) and P90 BSS between 0.06 and 0.13 N m^{-2} (Fig. 5d). Contourite features are related to this zone of permanent vigorous currents. A separated elongated mounded drift developed in the adjacent deeper zone with lower currents at about 900 m wd, that corresponds to the depth of the drift crest (Fig. 6). The separated elongated mounded drift is mainly composed of mud (Cattaneo et al., 2017). Plastered drifts have been identified by Soulet et al. (2016) and Cattaneo et al. (2017) at 200-600 m in the zone of weaker currents located between two zones of intense bottom currents, as indicated by the model during winter (Fig. 5a). Off Portofino, Cattaneo et al. (2017) also identified a contourite terrace in a zone where modelled bottom currents are strong, 12-17 cm s^{-1} in winter (Fig. 5a,b).

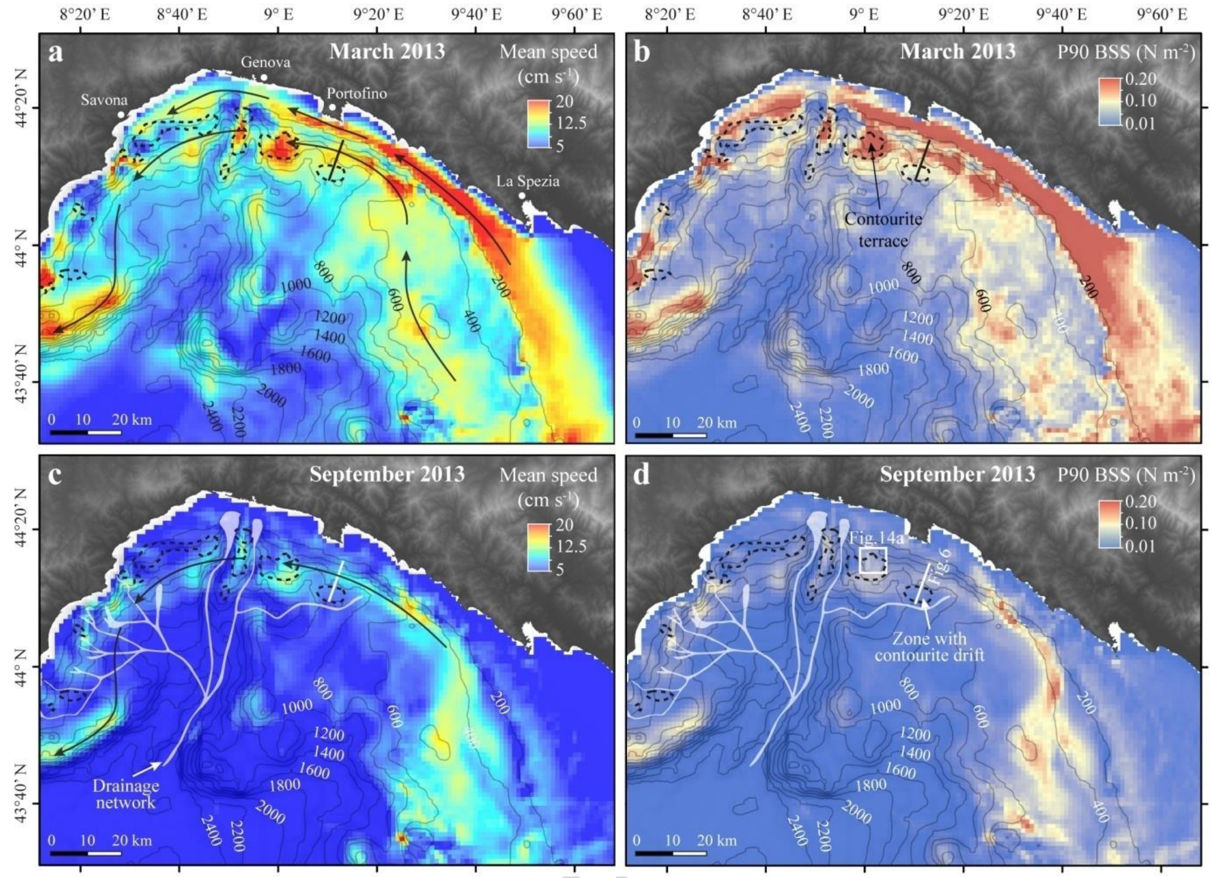

Fig. 5. Results of the MENOR model (cell size of 1.2 km) in the Ligurian Sea: during March 2013, (a) mean speed and (b) 90th percentile of the Bottom Shear Stress (P90 BSS); during September 2013, (c) mean speed and (d) P90 BSS. The arrows represent the current direction. The drainage network is represented with white polygons, and contourite drifts are outlined with dashed lines (adapted from Soulet et al., 2016 and Cattaneo et al., 2017).

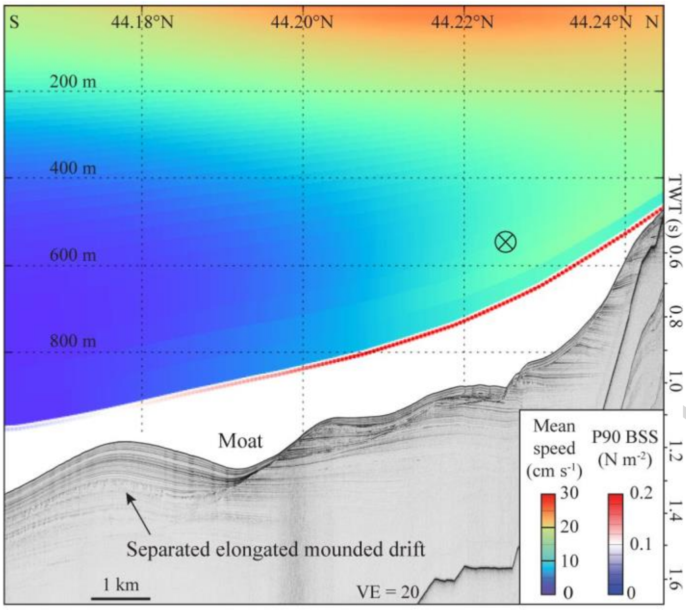

Fig. 6. Deep-towed SYSIF seismic reflection profile (PSM2-15B-PL07-PR01) and transect at the same position of the mean speed (upper coloured plot) and 90th percentile of the bottom shear stress (bottom layer of the coloured plot) from the MENOR model during March 2013. Note that the bathymetry used for the hydrodynamic model is a simplified bathymetry with a 1.2 km resolution and thus it does not perfectly fit with the seismic profile. The transect of the model and the seismic profile are not represented at the same depth to avoid overlapping between the images. See Fig. 5 for location.

4.3. Northern Tyrrhenian Sea

Bottom currents in the Corsica Trough are mainly dominated by two cyclonic gyres in the middle of the basin; one offshore the Elba Island and one at about 42°20’N, as well as by alongslope currents flowing northwards along the eastern margin (Pianosa Ridge) and southwards along the western slope (Fig. 7). This circulation pattern is the direct consequence of the seafloor morphology. Bottom currents are weak on the shelf, on the central part of the basin and on the Pianosa Ridge during summer, as the northwards total flux through the strait halts or even reverses in this season (Fig. 7; Vignudelli et al., 2000). Bottom-current velocities increase during summer along the Corsican slope due to an enhanced entrance of water from the Ligurian Sea southwards into the Corsica Trough (Fig. 7c).

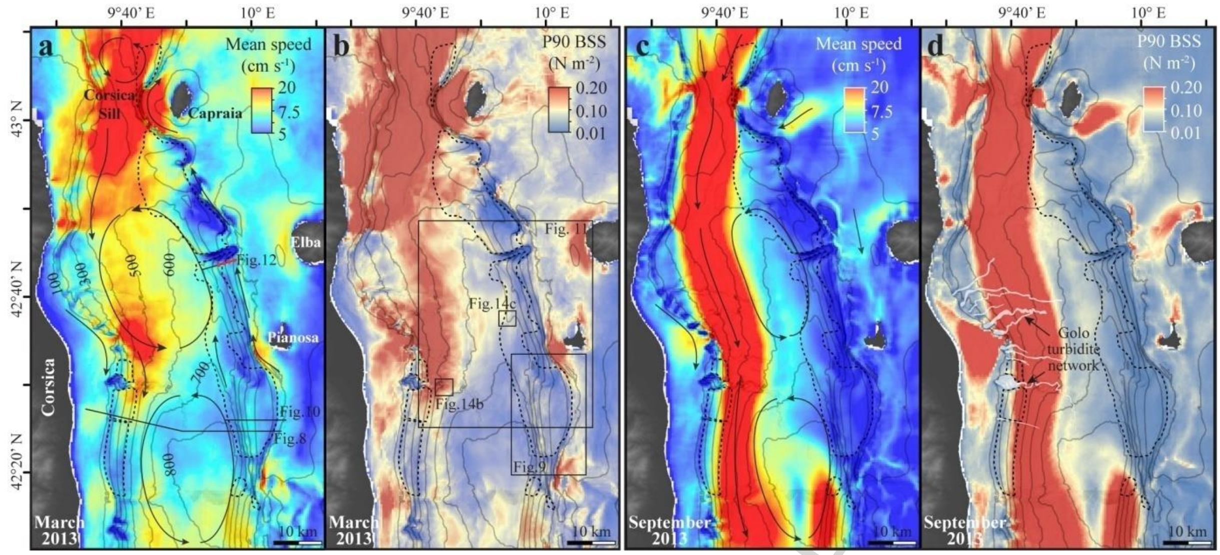

Fig. 7. Results of the MENOR model (zoom with cell size of 400 m) in the Corsica Trough: during March 2013, (a) mean speed and (b) 90th percentile of the Bottom Shear Stress (P90 BSS); during September 2013, (c) mean speed and (d) P90 BSS. The arrows represent the current direction near the seafloor. Contourite drifts are outlined with dashed lines, and the Golo turbidite network is represented with white polygons. Isobaths are represented every 100 m, starting at 100 m water depth. Red dots in Figure 7a represent the location of piston cores.

4.3.1. Eastern slope of the Corsica Trough

Pianosa Ridge

The Pianosa Ridge presents a wide range of drift morphologies. The southern slope, located to the south of the Pianosa Island, is mainly dominated by a plastered drift, a convex-shaped sediment deposit that extends between 150 and 700 m wd (Figs. 8, 9 and 10). The drift is characterised by a contourite terrace in the upper part with lower sedimentary accumulation and lower slope gradients landward. In a seaward direction, a zone of highest sedimentary accumulation occurs on the middle slope (Fig. 10). The hydrodynamic model shows that during the month of March 2013, bottom currents are weaker (mean velocity of 7 cm s^{-1} and P90 BSS of 0.04 N m^{-2}) in the middle and lower slope than in the distal part of the lower slope, foot of the slope and shelf edge (Figs. 8 and 9). In the lower slope and below 400 m wd bottom currents are faster during the same period, with mean velocity of 10 cm

s^{-1} and P90 BSS of 0.08 N m^{-2}. Similar values are found at the shelf edge. Therefore, the zone of the plastered drift development is in an area of weaker currents constrained upslope and downslope by two areas of stronger currents. Besides the differences in speed, the direction of the currents is also different in the zone of the plastered drift. At the shelf edge and at the lower slope bottom currents flow northwards alongslope, thus presenting a higher meridional (N-S) component of the velocity (Fig. 9). Conversely, the bottom currents show a mainly across-slope direction along the plastered drift; west-northwestwards in the middle slope and southeastwards in the upper slope (Fig. 9). The modelled Brunt-Väisälä frequency (a measure of oceanic stratification) in March 2013 is higher along the contourite terrace (Fig. 8c). The terrace zone is thus potentially more affected by internal waves. In summer, the Brunt-Väisälä frequency is only high near the sea surface; therefore, the plastered drift would be less affected by internal waves than in winter (Fig. 8a). Bottom currents have generated erosional features, such as moats on the lower slope, which become deeper northwards (Miramontes et al., 2016). In plan view, these incisions are oriented north-northeast (Fig. 9a). North of the plastered drift, the separated elongated mounded drift is bounded from the shelf by an abraded surface; a zone almost devoid of Pliocene-Quaternary sediment (Miramontes et al., 2016). The model shows that this area is at present under the influence of weak near-bed currents. The modelled bottom currents are consistent with the presence in this area of a thin layer of Holocene muddy sediment, deposited directly on the Messinian surface (Miramontes et al., 2016). Therefore, the present-day currents in this area are weak but this zone was apparently under erosive conditions in the past due to enhanced bottom currents.

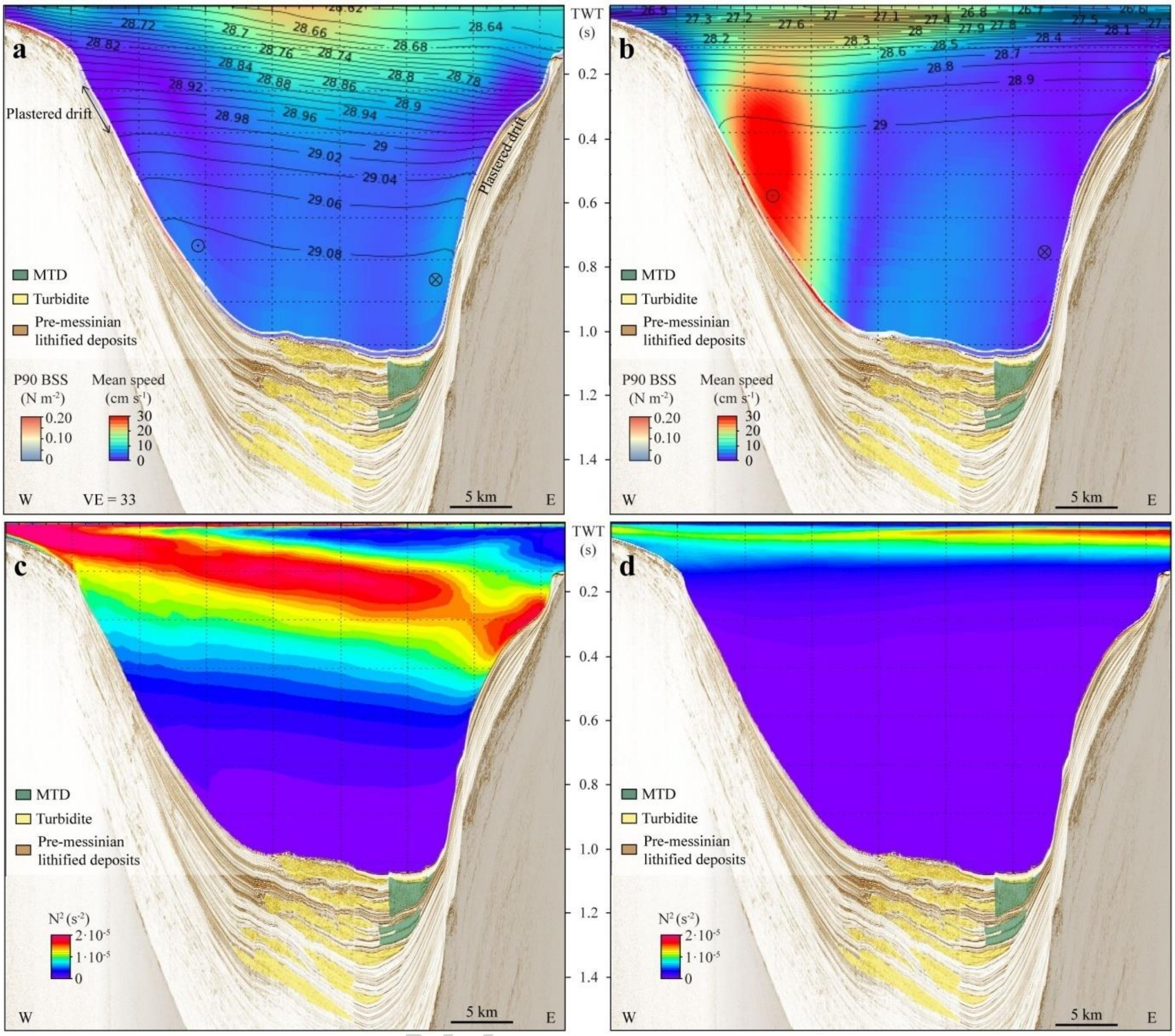

Fig. 8. Composite of multi-channel high resolution mini GI gun seismic reflection profiles (Sigolo-MC069, Sigolo-MC054 and PSM2-HR033) coupled with a transect at the same position from of the MENOR model (zoom 400 m): mean speed (main surface plot) and 90th percentile of the bottom shear stress (bottom layer of the plot) and isopycnal lines (kg m^{-3}) during (a) March 2013 and (b) September 2013; and Brunt-Väisälä frequency squared (N^2) during (c) March 2013 and (d) September 2013. MTD: Mass Transport Deposit. See Fig. 7a for location.

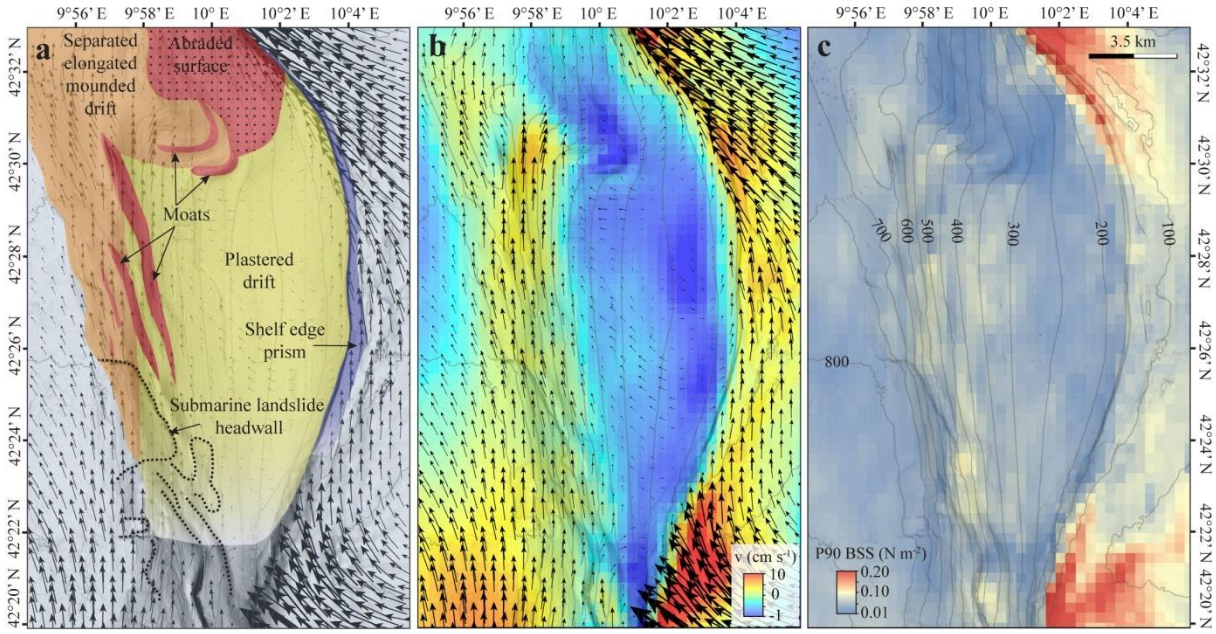

Fig. 9. Zoom on the southern part of the Pianosa Ridge showing the results of the 400 m zoom of the MENOR model during March 2013: (a) Morphosedimentary map showing the location of the main depositional and erosive features, and vectors of the mean velocity current; (b) meridional component of the mean velocity and vectors of the mean velocity current; (c) 90th percentile of the bottom shear stress. See Fig. 7b for location.

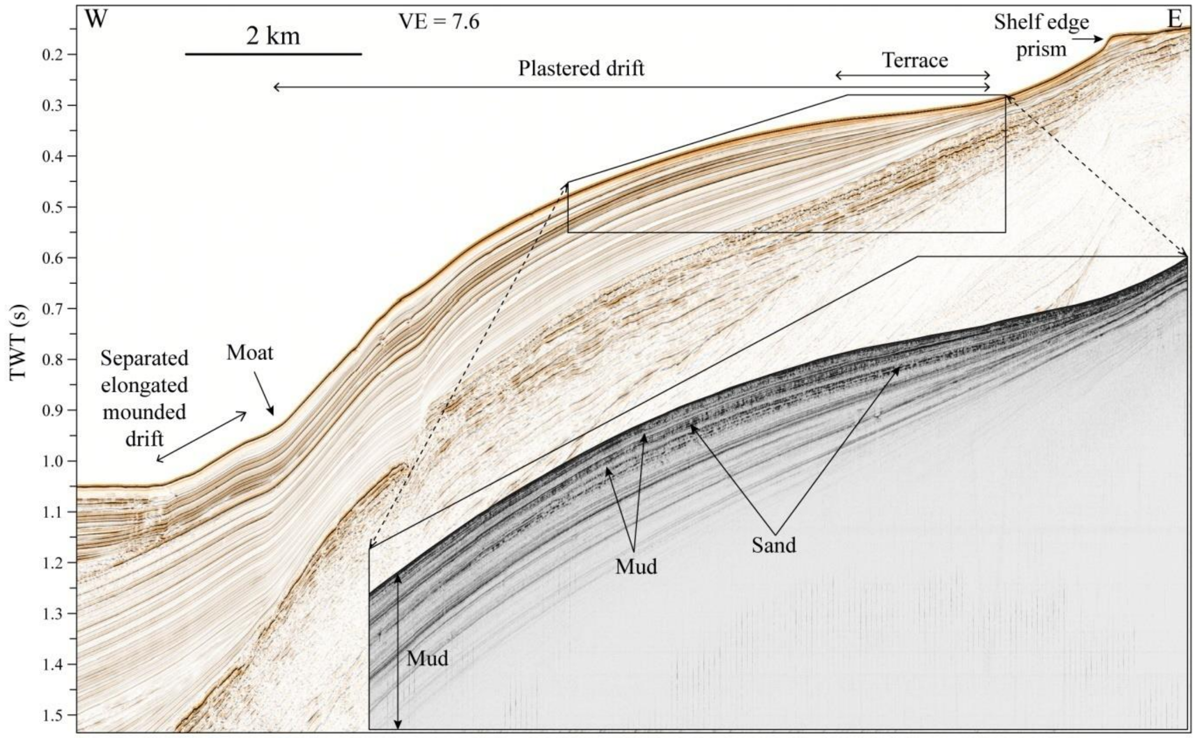

Fig. 10. Multi-channel high resolution mini GI gun seismic reflection profile (PSM2-HR-068) and sub-bottom profiler image (PSM2-CH-068) showing a plastered drift characterised by sandy material in the upper and proximal part, and muddy sediment in the lower and more distal part. See Fig. 7a for location.

Pianosa Island-Elba canyon

Further north, between the Pianosa Island and Elba Canyon, the drift morphology changes and the slope is dominated by multicrested drifts, which are separated from the shelf edge by an eroded zone (Fig. 11). The crests have variable orientations. To the south there is a single NE-SW-orientated crest, while to the north the crests are multiple and parallel, presenting a NW-SE orientation. The moats that separate these crests have a NW-SE orientation. The variable crest orientation can be explained with the circulation pattern near the seafloor during winter. In the central part of the basin there is a cyclonic gyre that affects the lower slope and forms the crest with the NE-SW orientation. The alongslope currents flowing towards the north at 500-700 m wd affect the shallower part of the NE-SW-oriented crest. Therefore, the drift crest with a NE-SW orientation is the result of predominantly depositional processes in a zone of slower currents between a cyclonic gyre and alongslope currents. The multicrested drifts with a NW-SE orientation are related to the alongslope bottom currents. In the upper slope, where seismic data show a zone of erosion, the model indicates fast currents during winter of 7-10 cm s^{-1} and P90 BSS of 0.05-0.1 N m^{-2}.

Faster bottom currents at the shelf edge and at the upper slope favour the transport of sandy material from the shelf to the upper slope and the winnowing of fine material from the latter. Therefore, in the zone of the multicrested drifts, the grain size and the abundance of sediment layers with coarse material decrease with depth (Fig. 12). The sandy sediment is characterised by chaotic acoustic facies of high amplitude on seismic sub-bottom profiles (Fig. 12). Similar acoustic facies can be found in the upper and middle part of the plastered drift (Fig. 10) and in the moat of the Minorca drift (Fig. 4). The terrace located in the upper part of the plastered drift is mainly composed of sand, while in the middle part the sandy layers are interbedded with muddy sediment and in the lower part the plastered drift is mainly composed of mud (Fig. 10).

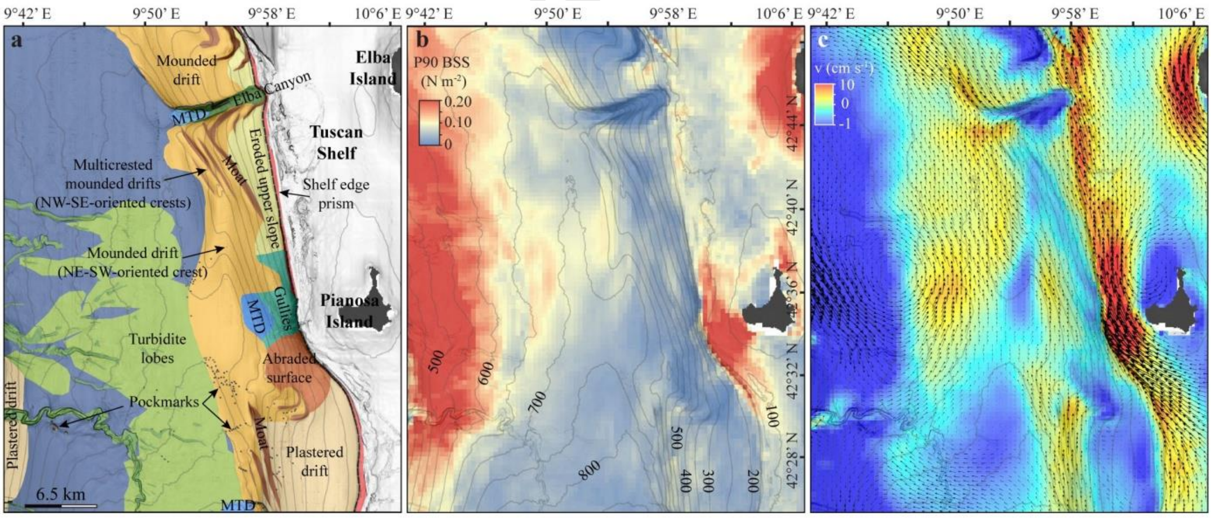

Fig. 11. Zoom on the northern part of the Pianosa Ridge showing the results of the 400 m zoom of the MENOR model during March 2013: (a) morphosedimentary map showing the location of the main depositional and erosive features; (b) 90th percentile of the bottom shear stress; (c) meridional component of the mean velocity and vectors of the mean velocity current. MTD: Mass Transport Deposit. See Fig. 7b for location.

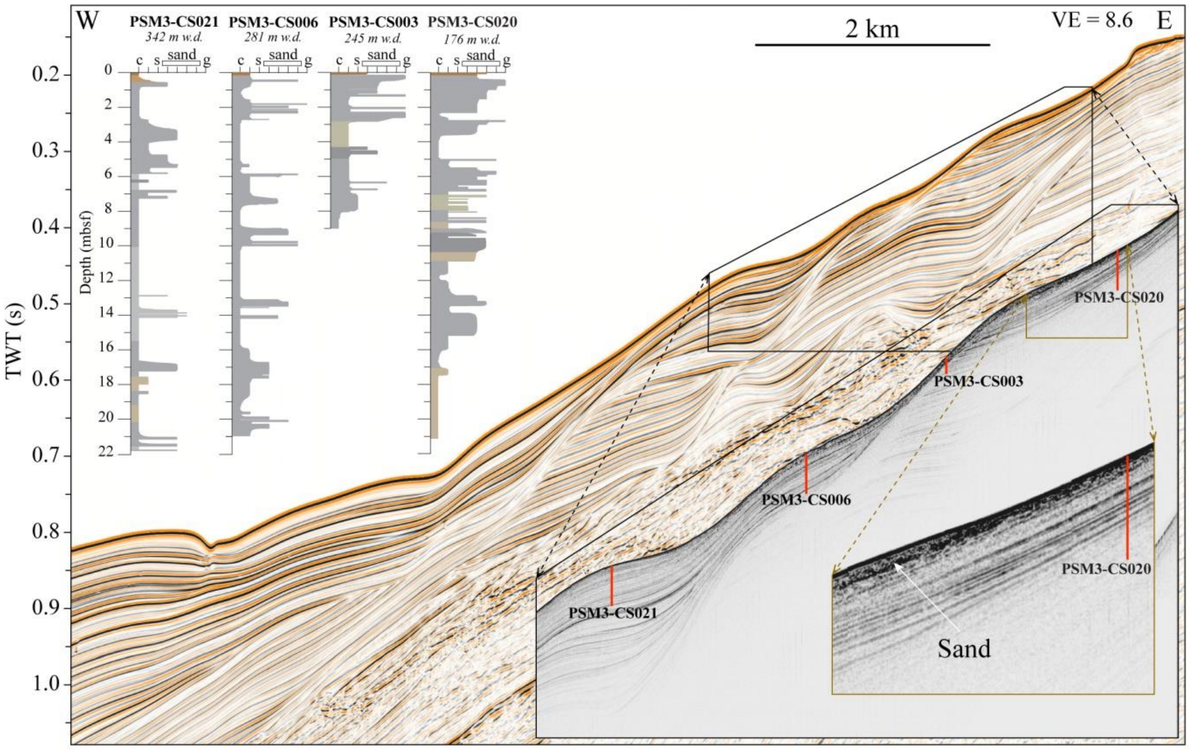

Fig. 12. Multi-channel high resolution mini GI gun seismic reflection profile (PSM2-HR-054) and sub-bottom profiler image (PSM2-CH-054) showing multicrested mounded drifts, sampled by 4 Calypso piston cores (sediment logs are shown on the left of the figure). Note that the sediment is coarser in the upper slope. See Fig. 7a for seismic profile and core locations.

4.3.2. Western slope of the Corsica Trough

Bottom currents flow southwards along the western margin of the Corsica Trough. Model results show mean velocities that can be higher than 20 cm s^{-1} and P90 BSS higher than 0.20 N m^{-2} in summer and in winter (Fig. 7). Bottom currents are weaker on the upper slope with mean velocities of 7-12 cm s^{-1} and P90 SS of 0.08-0.14 N m^{-2} both summer and winter (Fig. 7). A small plastered drift is located in this area of weak currents in the upper part of the slope at 160-400 m wd (Figs. 7 and 8).

4.3.3. Seamount south of the Corsica Trough

The bottom circulation around the seamount located at the south of the Corsica Trough, off southeast Corsica (Fig. 1) is clockwise, and the BSS can be intense in winter, reaching up to 0.05-0.1 N m^{-2} (Fig.

13a). Separated elongated mounded drifts are situated at the east of the seamount at the foot of the slope, where the results of the model show southwards bottom currents (Fig. 13b). The modelled strong currents explain the reduced sedimentation around the seamount, with a thickness of only 20-50 m during the last 5.3 Ma (Fig. 13c).

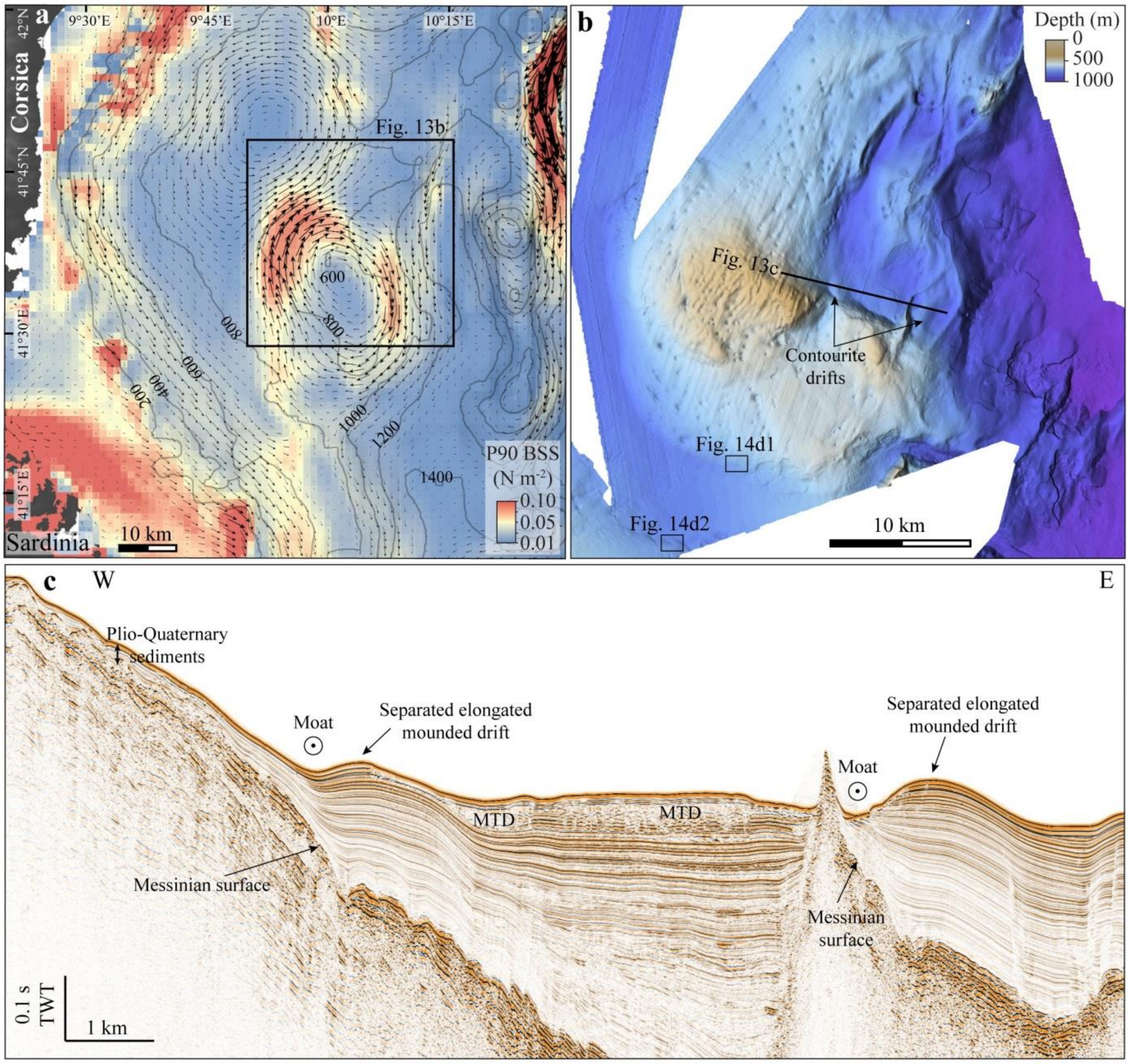

Fig. 13. (a) 90th percentile of the bottom shear stress and vectors of the mean velocity during winter 2013 from the MENOR model. See Fig. 1 for location. (a) Multibeam bathymetry of a seamount in the Northern Tyrrhenian Sea with associated contourite drifts. (c) Multi-channel high resolution seismic reflection profile showing two contourite drifts. MTD: Mass Transport Deposit.

4.4. Elongated pockmarks as bottom-current indicators

The morphologic asymmetry of pockmarks has been proven to be in agreement with bottom current direction and thus to be a useful tool to support modelling of near-seafloor circulation (Schattner et al., 2016; Picard et al., 2018). Pockmarks formed as a result of seafloor fluid expulsion are abundant in many parts of the NW Mediterranean Sea (Riboulot et al., 2014; Cattaneo et al., 2017). The morphology of these seafloor depressions is locally elongated parallel to the direction of dominant bottom currents in the Ligurian and the Northern Tyrrhenian Seas (Fig. 14). In section, pockmarks show a steep flank upstream and a flat eroded flank downstream. A mounded sediment deposit, separated from the pockmark flanks by incisions, is observed in the central part of the pockmarks in the Ligurian margin and in the western flank of the Corsica Trough (Fig. 14a,b). The deformation, elongation and erosion in all the observed pockmarks is consistent with the local current direction provided by the hydrodynamic model: bottom currents flow westwards along the slope along the Ligurian margin (Fig. 5); southwards along the western flank of the Corsica Trough (Fig. 7a); towards the northwest in the zone of pockmarks on the eastern flank of the Pianosa Ridge (Fig. 7a) and in the southern part of a seamount in the Northern Tyrrhenian Sea (Fig. 13b).

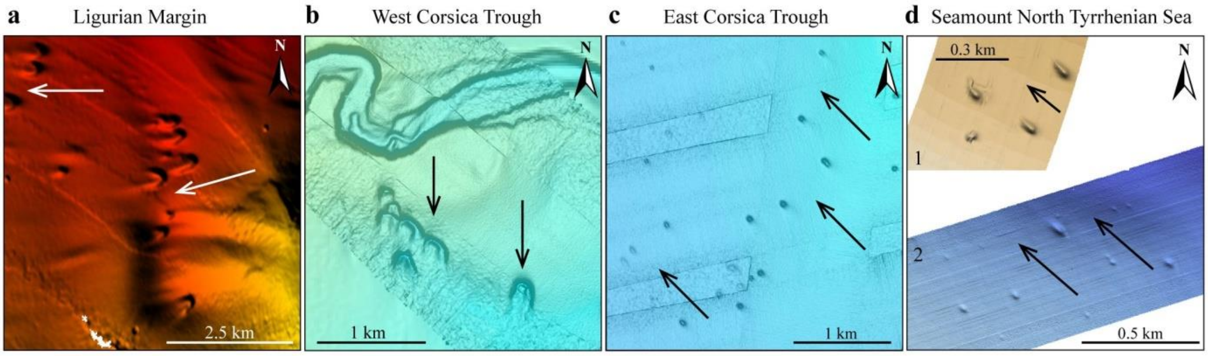

Fig. 14. Multibeam bathymetry of elongated pockmarks in: (a) the Ligurian Margin, (b) in the western flank of the Corsica Trough, (c) in the eastern flank of the Corsica Trough, and (d) at the south of the seamount in the Northern Tyrrhenian Sea. Arrows indicate direction of dominant bottom currents. See locations in Figs. 5d, 7b and 13b, respectively.

5. Discussion

5.1. The role of currents in sediment redistribution and sediment source of contourites

The MENOR hydrodynamic model shows the presence of two cyclonic gyres in the Corsica Trough that affect the whole water column. One gyre is located between the latitudes 42°30'N and 42°50'N, and the other is located between 42°N and 42°30'N (Fig. 15). The Corsica Trough is a small confined basin where turbidity currents and contouritic processes are dominant on opposite basin flanks (Miramontes et al., 2016). The eastern flank of the Corsica Trough (the Pianosa Ridge) is a sediment-starved slope, with little direct sediment supply from the adjacent continental shelf, littoral zone and continent (Roveri et al., 2002). In contrast, the western slope of the Corsica Trough is dominated by turbidity currents (Gervais et al., 2006) originated from several turbidite systems: Golo, Tavignano and Fiume-Orbo (Bellaiche et al., 1994). Hemipelagic and turbiditic deposits are dominant on the western slope, whereas contouritic deposits along the eastern slope (Cattaneo et al., 2014; Miramontes et al., 2016). An open question is the possible sediment source for contouritic deposit, but given the morphological confinement of the Corsica Trough, it is plausible that the fine sediment fraction transported in suspension by turbidity currents may be ponded within the basin, pirated by alongslope flows and transported by bottom currents to other zones of the basin, particularly during sea level low-stands, when the turbidite system is active (Calvès et al., 2013; Toucanne et al., 2015). The cyclonic gyres modelled in the Corsica Trough could be a very effective mechanism of transport for the fine sedimentary fraction carried in suspension from the western flank to the eastern flank of the Corsica Trough. The fine-grained sediment would be finally deposited on the large muddy contourite drifts along the Pianosa Ridge.

The drifts of the Balearic and Ligurian Seas are probably also formed in part by sediment carried by turbidity currents through abundant canyons and channels on the slopes (Figs. 2 and 5). Figure 3 shows a turbidite channel and a submarine canyon in the centre of the Minorca basin, the Valencia Channel and Blanes Canyon. The Valencia Channel routes a network of submarine canyons from the eastern Iberian margin and is the main conduit of sediment transport to the deep Liguro-Provençal basin

(Amblas et al., 2011). The sediment carried by turbidity currents is probably transported by bottom currents and deposited in the contourite systems along the Iberian and Minorca slopes. In the Ligurian Sea, contourite drifts are located on ridges between canyons and are probably often fed by overbanking downslope processes (Fig. 5).

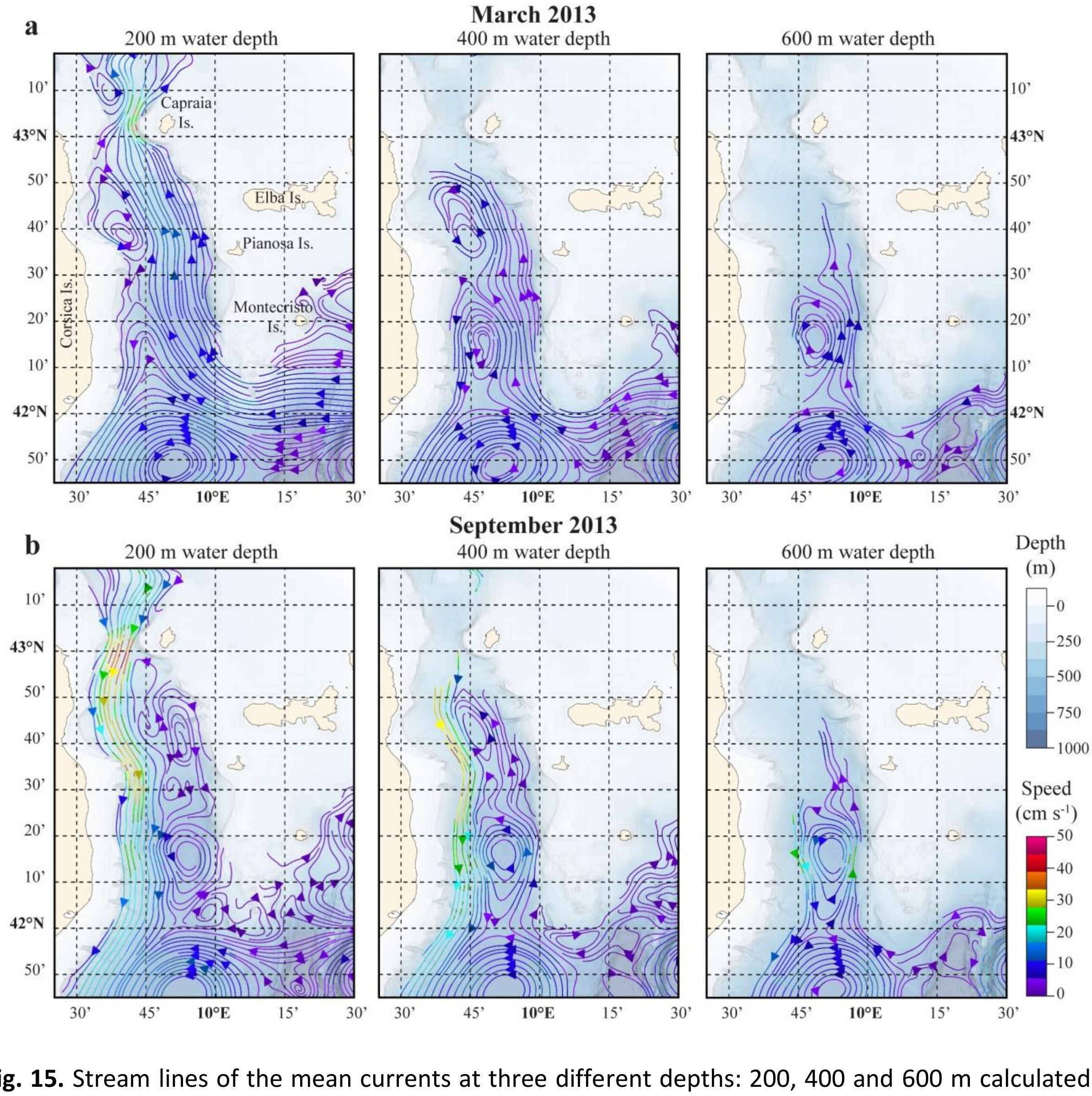

Fig. 15. Stream lines of the mean currents at three different depths: 200, 400 and 600 m calculated with the 400 m zoom of the MENOR model during (a) March 2013 and (b) September 2013; and bathymetry map. Note the presence of cyclonic gyres in the basin at all depths and seasons.

5.2. Seasonal variability in circulation and the impact of extreme events

The results of the hydrodynamic model show that the areas identified from seismic and bathymetric data as foci for erosion (e.g. moats and eroded continental slopes) present P90 BSS during winter that exceeded the critical shear stress required to erode unconsolidated mud (above 0.05 N m^{-2}; Schaaff et al., 2002) (Table 3; Fig. 16a). In some cases P90 BSS was even higher than the critical shear stress of erosion of fine sand (above 0.1 N m^{-2}, according to the Shields curve; Soulsby, 1997) (Table 3; Fig. 16a). Durrieu de Madron et al. (2017) observed local sediment resuspension during the major winter open-ocean convection events and estimated that the critical BSS of fine and medium silts in the Liguro-Provençal basin ranges between the 0.04 and 0.13 N m^{-2}. In contrast, during summer the areas identified as foci for erosion typically present much lower P90 BSS and thus may not always be under erosive conditions (Table 3; Fig. 16a). If we consider acceptable the assumption that winter 2013 conditions could be considered as a proxy for oceanographic conditions during cold periods (glaciations), then the eroded features observed in the geophysical data could be the result of erosion due to more vigorous bottom currents during colder climatic periods. Even if sediment is deposited during warm climatic periods in these areas (when shear stresses are lower), it is probably removed during cold climatic periods, resulting in net erosion or in a lower sediment accumulation.

Zone	Environment	Mean speed winter (cm s^{-1})	90^{th} percentile BSS-winter (N m^{-2})	Mean speed summer (cm s^{-1})	90^{th} percentile BSS-summer (N m^{-2})
1	Minorca moat	10	0.10	8-9	0.03-0.06
1	Minorca slope	17-24	0.20-0.34	14-20	0.10-0.20
1	Minorca drift	5-7	0.02-0.03	6-7	0.01-0.02
1	Iberian moat	11-13	0.07-0.10	5-6	0.02
1	Iberian slope	18-20	0.20-0.30	8-9	0.03-0.04
1	Iberian reworked levee	5-7	0.02-0.03	3-4	0.005-0.01
2	Portofino moat	15-17	0.14-0.18	11-12	0.06-0.08
2	Portofino drift	9-10	0.05-0.07	5-7	0.017-0.02
3	Pianosa moats	8-10	0.05	5	0.02-0.04
3	Shelf edge-plastered drift	10-12	0.05-0.13	4	0.01
3	Shelf edge-offshore Pianosa Island	13-17	0.13-0.23	4-6	0.02-0.04
3	Plastered drift	6-8	0.03-0.05	4	0.01
3	Separated mounded drift	7-10	0.05-0.07	5-7	0.02-0.03
3	Multicrested drift	7-11	0.05-0.10	4-8	0.02-0.05
3	Upper slope multicrested drift	7-9	0.04-0.07	4-5	0.01
3	Foot of the slope north Elba Canyon	10	0.10	6-7	0.03-0.05

Table 3. Mean speed and 90th percentile of the Bottom Shear Stress (P90 BSS) computed during winter and summer 2013 in the three study areas: (1) Balearic Sea; (2) Ligurian Sea; (3) Northern Tyrrhenian

Sea. The areas classified as depositional environments (according to geophysical data) are in grey colour, while the erosive environments are in white colour.

The Minorca slope is subject to vigorous currents, between 14 and 24 cm s^{-1}, that are capable of eroding sand continuously (Table 3; Figs. 2, 3, 16a). This is supported, over longer time scales, by geophysical evidence of truncations on the slope (Figs. 3 and 4a). Zones of deposition (identified from geophysical data) are only found in areas of lower current velocity, but the unconsolidated mud can also be eroded during enhanced bottom circulation during cold periods (Fig. 16b). Overall, sediment can be deposited and eroded several times before being definitively incorporated into the sediment record. Features such as contourite moats would likely have been continuously under erosion during sea level low-stands. A similar approach has been proposed for the Gulf of Cadiz (Llave et al., 2006, 2007; Hernández-Molina et al., 2006, 2014), the NE Atlantic Ocean (Hanebuth et al., 2015) and the SW Atlantic Ocean (Preu et al., 2013). Thran et al. (2018) also deduced in a global scale that contourite deposition is caused by high-energy intermittent events.

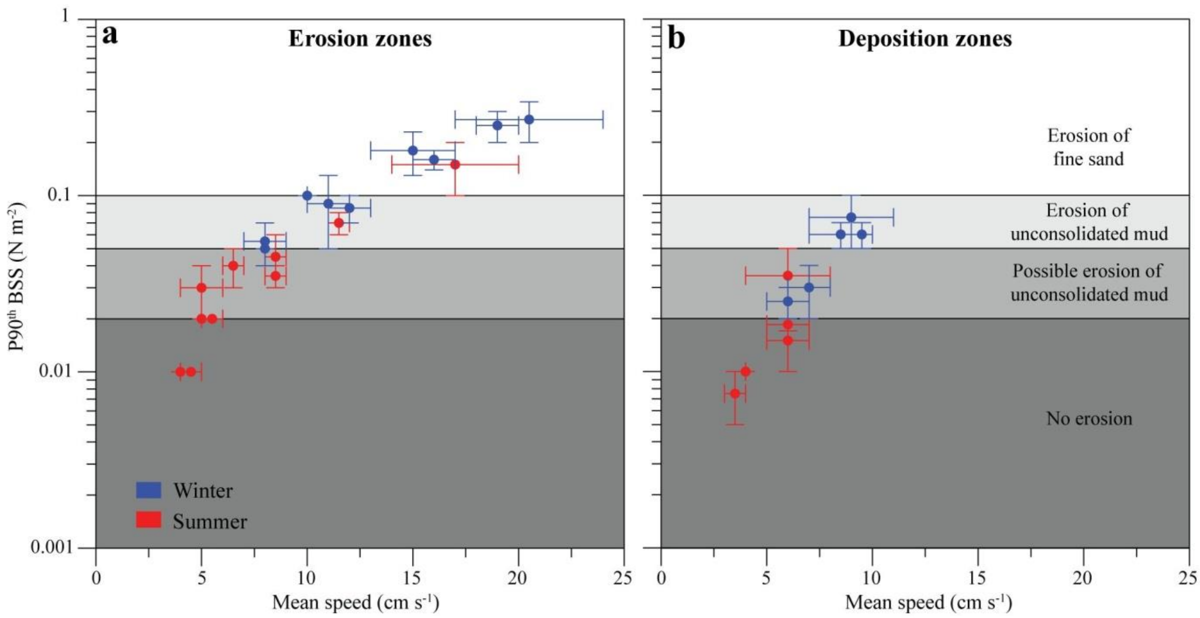

Fig. 16. Plot of the mean speed and 90th percentile of the Bottom Shear Stress (BSS) calculated with the MENOR model for the period of winter and summer 2013 in the zones previously classified

according the geophysical data as zones of erosion or sediment deposition, detailed in Table 3. The critical shear stress for erosion is based on a critical BSS for unconsolidated mud ranging between 0.02 and 0.05 N m^{-2} (Schaff et al., 2002) and a critical BSS for fine sand of 0.1 N m^{-2} according to the Shields curve (Soulsby, 1997).

5.3. Conceptual implications for continental margin morphology

Adams and Schlager (2000) and O'Grady et al. (2000) proposed a classification of modern margins and observed that a sigmoidal slope profile is the most common margin morphology (about 50% of the studied margins). Sigmoidal margins consist of a convex upper part and a concave lower part that is below the point of maximum slope (O'Grady et al., 2000). This type of shape is characteristic of margins with plastered drifts along continental slopes (Figs. 10; 17; Faugères et al., 1999; Rebesco et al., 2014; Principaud et al., 2015; Tournadour et al., 2015). Multiple contouritic terraces and plastered drifts can be associated at different depths in a margin, such as in the Argentinean and Uruguayan margins (Preu et al., 2013; Hernández-Molina et al., 2016), corresponding to the stepped margin in the classification of O'Grady et al. (2000). Deep bottom currents can thus have a very important influence in the morphology of continental margins at large scale, as proposed by Mosher et al. (2017), and they should be taken into account in the analysis of the origin of continental slope curvature.

In the NW Mediterranean Sea, three main types of margin morphology can develop, depending on the amount of sediment supply and on the distribution of the bottom-current velocities (Fig. 17). In all the described zones, the whole water column flows in the same direction. We identified: Type 1) a starved margin with an eroded continental slope and a separated elongated mounded drift at the foot of the slope; Type 2) a margin with direct sediment supply and a homogeneous bottom-current distribution, resulting in smooth regular seafloor; Type 3) a starved margin with heterogeneous bottom current distribution, resulting in the formation of a plastered drift on the slope and a separated elongated mounded drift at the foot of the slope. This classification attempts to relate bottom-current characteristics to sediment drift morphology and configuration in order to diagnostically identify current regime for other contourite features worldwide.

Type 1: A separated elongated mounded drift develops at the foot of the slope when bottom currents are vigorous along the lower slope and they become weaker basinwards, allowing the formation of a drift. Enhanced bottom currents at the foot of the slope generate a moat and may laterally induce the formation of deposits with a mounded shape, such as in the Minorca slope (Fig. 3). This particular setting would be characteristic of starved margins with little direct sediment supply from the mainland and the shelf, but with lateral supply of the fine-grained sediment by the currents. Moreover, the action of vigorous bottom currents on the slope can easily erode unconsolidated sediment and prevent sediment deposition in this area (Fig. 17a). Contourite features formed at the seamount of the Northern Tyrrhenian Sea are developed in similar conditions. They are related to escarpments with little sediment accumulation on the slope, and the drifts grow in a zone of lower bottom currents along the foot of the slope (Fig. 13). These drifts have a small size compared to the Minorca drift because they are related to obstacles and confined by seafloor irregularities, while in the case of Minorca the contourites develop all along the margin. Faugères et al. (1999) and Rebesco et al. (2014) suggested that separated elongated mounded drifts are associated with steep slopes, generally located on the lower slope and are formed due to a high current speed gradient, in agreement with our observations and modelled currents.

Type 2: In a slope where sediment is directly supplied by gravitational processes and is also affected by coeval active and strong bottom currents, the resulting morphology is a smooth regular seafloor with a progradational sedimentary stacking pattern, such as the western flank of the Corsica Trough (Fig. 8). Dominant downslope processes and a high sedimentation rate could mask the influence of bottom currents. The most important factor in the generation of mounded sedimentary morphologies is the heterogeneous distribution of bottom currents, since the sediment would preferentially accumulate in the zone of weak currents. If currents are even across the slope, either weak or vigorous, there would be no zone of preferential accumulation and thus no mounded morphology (Fig. 17b). This type of gently sloped margins is typical of regions with high sediment input (O'Grady et al., 2000). Type 3: Well-developed plastered drifts can be found on starved margins with heterogeneous bottom-current distribution. Plastered drifts are typically convex-shaped sedimentary bodies that have an oval shape in plan view, like in the Pianosa Ridge (Figs. 9 and 10). Here, they develop in a zone of weak bottom currents confined between two zones of faster bottom currents in the upper and in the distal part of the lower slope, resulting in the formation of a terrace upslope and a moat downslope (Fig. 17c). Moreover, the direction of bottom currents on the middle of the plastered drift is mainly across slope, favouring the sediment accumulation in this area. Related to a zone of slow bottom currents at the foot of the slope, a separated elongated mounded drift can develop in a similar way to Type 1 features (Fig. 17a).

The association of plastered drift in the slope and separated elongated mounded drift at the foot of the slope has been observed in other settings, such as the Alboran Sea (Ercilla et al., 2016) and the Uruguayan margin (Hernández-Molina et al., 2016). Plastered drifts with a convex shape can cover most of the slope and strongly influence the slope morphology (Principaud et al., 2015; Tournadour et al., 2015; Ercilla et al., 2016; Miramontes et al., 2016). In the study area, the formation of plastered drifts can be explained by the distribution of geostrophic currents on the slope (Fig. 17c): strong bottom currents in the upper and lower part of the plastered drifts prevent sediment deposition in these areas, while sedimentation mainly occurs in the central part of the plastered drifts where bottom currents are slow (Fig. 9). If a pycnocline is located on the terrace (as modelled in the Pianosa Ridge, Fig. 8c), the action of internal waves could enhance sediment erosion on the terrace, at the top of the plastered drift (Hernández-Molina et al., 2009; Preu et al., 2013).

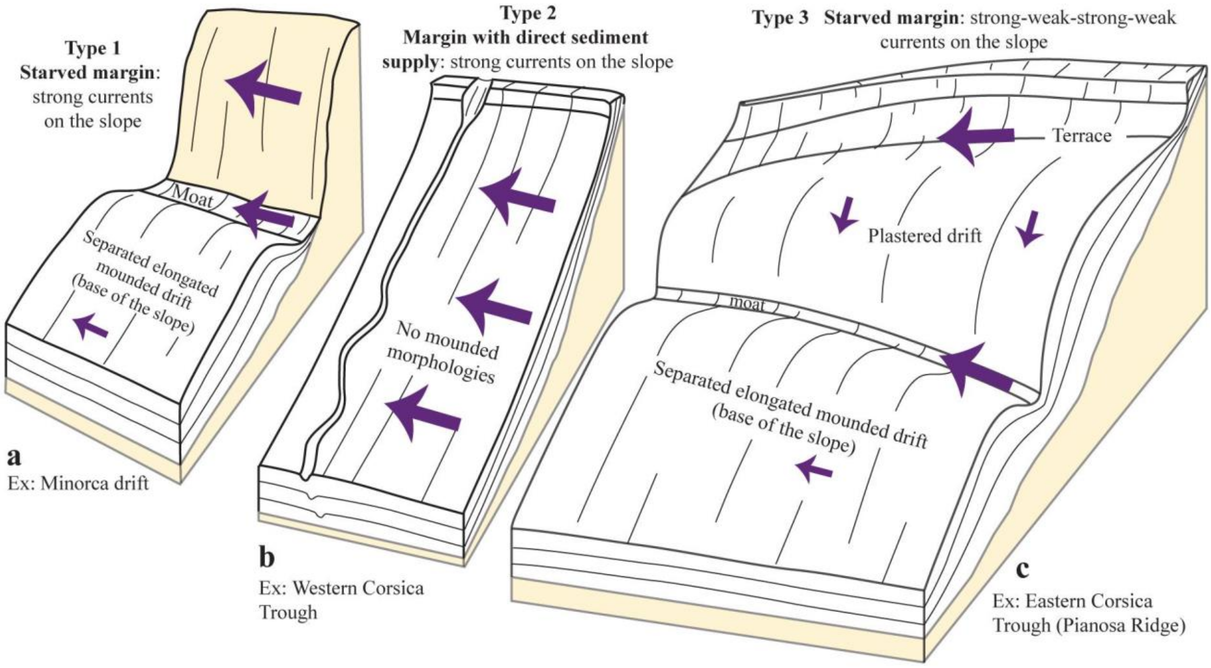

Fig. 17. 3D schematics showing three different types of continental slopes: (a) Type 1: a starved margin with an eroded continental slope and separated elongated mounded drift at the foot of the slope; (b) Type 2: a continental slope with direct sediment supply and a homogeneous bottom-current distribution; (c) Type 3: a starved continental slope with heterogeneous bottom current distribution, resulting in the formation of a plastered drift on the slope and a separated elongated mounded drift at the foot of the slope. The arrows indicate bottom current direction and intensity according to their size.

6. Conclusions

In spite of the potentially large gap in the chronological range of investigation - namely days to decades for physical oceanography and years to millions of years for sedimentology - we observe close agreement between the results of hydrodynamic modelling focussed at the seafloor and the distribution of contourite drifts and their morphological elements in three sectors of the Mediterranean Sea. The main conclusions of this study can be summarised as follows:

(1) The results of the MARS3D hydrodynamic model in the MENOR configuration are consistent with the morphology of contourites observed in three areas of the NW Mediterranean Sea: the Balearic Sea, the Ligurian Sea and the Northern Tyrrhenian Sea.

(2) By coupling the model results of winter 2013 and summer 2013 with the geophysical and sedimentological data, we suggest that events of more intense circulation are controlling the formation and evolution of moats and erosive features on the seafloor. During warm climatic periods (characterised by weak currents), fine-grained sediment could be deposited in some of these areas, but during cold climatic periods the enhanced bottom currents would generate erosion, resulting in net erosion. Therefore, the preservation potential of deposits along these erosional features is very low.

(3) The presence of gyres in confined basins with asymmetric sediment input causes the redistribution of sediment from the margin with a direct sediment supply to the opposite starved margin.

(4) The development of mounded sedimentary morphologies is favoured by heterogeneous bottom current distributions. The plastered drifts analysed in this study are formed in zones of relative low current velocity, mainly with an across-slope (oblique and/or perpendicular) direction, confined between zones of high alongslope current velocity. These morphologies are commonly observed in starved margins not affected by frequent downslope gravity flows. Separated elongated mounded drifts are formed in zones of low bottom currents at the foot of the slope associated with fast currents on the slope. In contrast, when bottom currents are homogeneous across the margin (either fast or slow), no mounded shapes can develop and the seafloor regularly deepens toward the basin.

These results provide a high resolution physical oceanographic framework to improve our understanding of palaeoceanographic conditions for the formation of contourite depositional systems. Our results provide useful guidance for the interpretation of flow regimes and sedimentary facies distribution based on the seafloor morphology found in other bottom-current dominated deep-marine settings. Further studies and new numerical modelling should be performed in other areas for determining more conceptual implications, especially about the interplay of different oceanographic processes in the formation of contourite features, and about the effects of sea-level fluctuations on bottom currents.

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Highlights

- Hydrodynamic modelling is a useful tool to understand the formation of contourites
- Contourite drifts develop in zones of minimum bottom currents
- Plastered drifts develop in a zone of weak currents between two zones of stronger currents
- High intensity events control the formation of erosional features as moats
- Gyres favour the formation of contourites along starved margins in confined basins