

Along-slope oceanographic processes and sedimentary products around the Iberian margin

Francisco Javier Hernández-Molina · Nuno Serra ·
Dorik A. V. Stow · Estefanía Llave · Gemma Ercilla ·
David Van Rooij

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Abstract This contribution to this special volume represents the first attempt to comprehensively describe regional contourite (along-slope) processes and their sedimentary impacts around the Iberian margin, combining numerically simulated bottom currents with existing knowledge of contourite depositional and erosional features. The circulation of water masses is correlated with major contourite depositional systems (CDSs), and potential areas where new CDSs could be found are identified. Water-mass circulation leads to the development of along-slope currents which, in turn,

generate contourite features comprising individual contourite drifts and erosional elements forming extensive, complex CDSs of considerable thickness in various geological settings. The regionally simulated bottom-current velocities reveal the strong impact of these water masses on the seafloor, especially in two principal areas: (1) the continental slopes of the Alboran Sea and the Atlantic Iberian margins, and (2) the abyssal plains in the Western Mediterranean and eastern Atlantic. Contourite processes at this scale are associated mainly with the Western Mediterranean Deep Water and the Levantine Intermediate Water in the Alboran Sea, and with both the Mediterranean Outflow Water and the Lower Deep Water in the Atlantic. Deep gateways are essential in controlling water-mass exchange between the abyssal plains, and thereby bottom-current velocities and pathways. Seamounts represent important obstacles for water-mass circulation, and high bottom-current velocities are predicted around their flanks, too. Based on these findings and those of a selected literature review, including less easily accessible “grey literature” such as theses and internal reports, it is clear that the role of bottom currents in shaping continental margins and abyssal plains has to date been generally underestimated, and that many may harbour contourite systems which still remain unexplored today. CDSs incorporate valuable sedimentary records of Iberian margin geological evolution, and further study seems promising in terms of not only stratigraphic, sedimentological, palaeoceanographic and palaeoclimatological research but also possible deep marine geohabitats and/or mineral and energy resources.

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F. J. Hernández-Molina
Facultad de Ciencias del Mar, Universidad de Vigo,
36200 Vigo, Spain

N. Serra (✉)
Institute of Oceanography, University of Hamburg,
Bundesstr. 53,
20146 Hamburg, Germany
e-mail: nuno.serra@zmaw.de

D. A. V. Stow
IPE-ECOSSE, Heriot-Watt University,
Edinburgh EH14 4AS, UK

E. Llave
Instituto Geológico y Minero de España,
Ríos Rosas 23,
28003 Madrid, Spain

G. Ercilla
Instituto de Ciencias del Mar, CMIMA-CSIC,
Paseo Marítimo de la Barcelonesa 37–49,
08003 Barcelona, Spain

D. Van Rooij
Renard Centre of Marine Geology (RCMG), Ghent University,
Krijgslaan 281 S8,
9000 Ghent, Belgium

Introduction

Along-slope oceanographic processes related to near-bottom currents generate large erosional and depositional

features (drifts) which together shape contourite depositional systems (CDSs) or mixed contourite–turbidite systems, where bottom currents have interacted with downslope processes (e.g. Faugères et al. 1999; Stow et al. 2002a; Viana and Rebesco 2007; Rebesco and Camerlenghi 2008; Hernández-Molina et al. 2008a, b). When water masses flowing along continental slopes are energetic enough, however, they can mask the effects of downslope processes and generate complex CDSs of huge dimensions (10^3 – 10^6 km²) and sedimentary thicknesses (>2,000 m), comparable to large turbidite depositional systems (e.g. Gao et al. 1998; Faugères et al. 1999; Stow et al. 2002a). Some of the better-known ones are located along-slope of the Gulf of Cadiz (Nelson et al. 1993, 1999; Llave et al. 2001, 2007; Habgood et al. 2003; Hernández-Molina et al. 2003, 2006; Mulder et al. 2003, 2006), in the Porcupine Seabight (Van Rooij et al. 2003; Øvrebø et al. 2006), offshore southern Greenland (e.g. Hunter et al. 2007) and Brazil (Viana et al. 2002a, b; Viana and Rebesco 2007), and along the Argentine margin (Hernández-Molina et al. 2009a; Krastel et al. 2011).

The study of along-slope processes and their deposits in general, and CDSs in particular, has been one of the most active lines of research in marine geology during the last decade, mainly because of their high stratigraphic, sedimentological, palaeoceanographic and palaeoclimatological significance, their close link with sediment instability on continental slopes, and their direct relation with possible mineral and energy resources (e.g. Pickering et al. 1989; Stow et al. 2002b; Rebesco 2005; Viana and Rebesco 2007; Rebesco and Camerlenghi 2008; Hernández-Molina et al. 2010a; Krastel et al. 2011). International projects such as the DSDP (Deep Sea Drilling Project), ODP (Ocean Drilling Program) and IODP (Integrated Ocean Drilling Program) have corroborated this importance by underlining their very common occurrence along many ocean margins and in deep basins worldwide. Cumulatively, this work has also served to demonstrate that our understanding of such systems is still in its infancy.

The Iberian continental margins have had a very complex and varied origin as well as geodynamic and sedimentary evolution. For several decades, many studies have been carried out on the structure and evolution of these margins (e.g. Boillot et al. 1972, 1975, 1979, 1987; Derégnaucourt and Boillot 1982; Comas and Maldonado 1988; Maldonado and Nelson 1988, 1999; Nelson and Maldonado 1990; Maldonado and Comas 1992; Estrada et al. 1997; Pérez-Belzuz et al. 1997; Pérez-Belzuz 1999; Maldonado et al. 1999; Vázquez 2001; Iglesias 2009). The circulation of water masses around Iberia leads to the development of along-slope currents in turn generating contourite erosional and depositional features which form extensive, complex and often poorly known CDSs in various geological settings. These contain valuable

sedimentary records of margin evolution, since the Iberian margins and adjacent abyssal plains lie under the influence of several distinct water masses, some of which impinge upon the seafloor with relatively high velocity and interact along the middle and upper continental slope. Although many scattered bottom-current measurements have been conducted along the margin, there is a major lack of long-term records and some areas have not been investigated at all. Whereas velocities are commonly relatively low (5–15 cm/s), these are greatly exceeded in places, reaching background values of >80 cm/s and rarely almost 300 cm/s, as at the exit of the Strait of Gibraltar (Madelain 1970; Mélières et al. 1970; Ambar and Howe 1979; Iorga and Lozier 1999; Candela 2001).

Clearly, bottom currents can be a major factor controlling along-slope sedimentation and shaping the deep seafloor (Stow et al. 2009). They are semi-permanent features of deep ocean circulation, characterized by strong spatiotemporal variations. They operate at a wide range of spatial scales, from the construction of small bedforms (surface lineation, crag and tail structures, small ripples, etc.) to the maintenance of large-scale drifts (Stow et al. 2008) and even the generation of large-scale erosional features, such as erosional terraces, abraded surfaces, channels, moats and furrows (Hernández-Molina et al. 2008b). Stow et al. (2009) recently published a *bedform-velocity matrix* which facilitates the estimation of bottom-current velocity based on bedform type but can also be applied in reverse to deduce likely contourite features under particular bottom-current velocity regimes.

As part of this special volume of contributions from the international congress on *Deep-water Circulation: Processes and Products* held in Baiona, Spain on 16–18 June 2010, this paper represents the first attempt to comprehensively describe along-slope processes and products along the Iberian margin (Fig. 1). There are three main objectives: (1) to combine previous work and new regional data on along-slope processes and their sedimentary impacts around Iberia; (2) to combine for the first time numerically simulated bottom currents with existing knowledge of contourite depositional and erosional features; and (3) to use these data to better link the circulation of water masses with the main CDSs, both known and suspected, and to consider the implications of these findings.

Methods and database

Characterization of water masses

Data on water masses along the Iberian margin and their dynamics, both in the Mediterranean Sea and in the Atlantic Ocean, were compiled from numerous bibliographic sources.

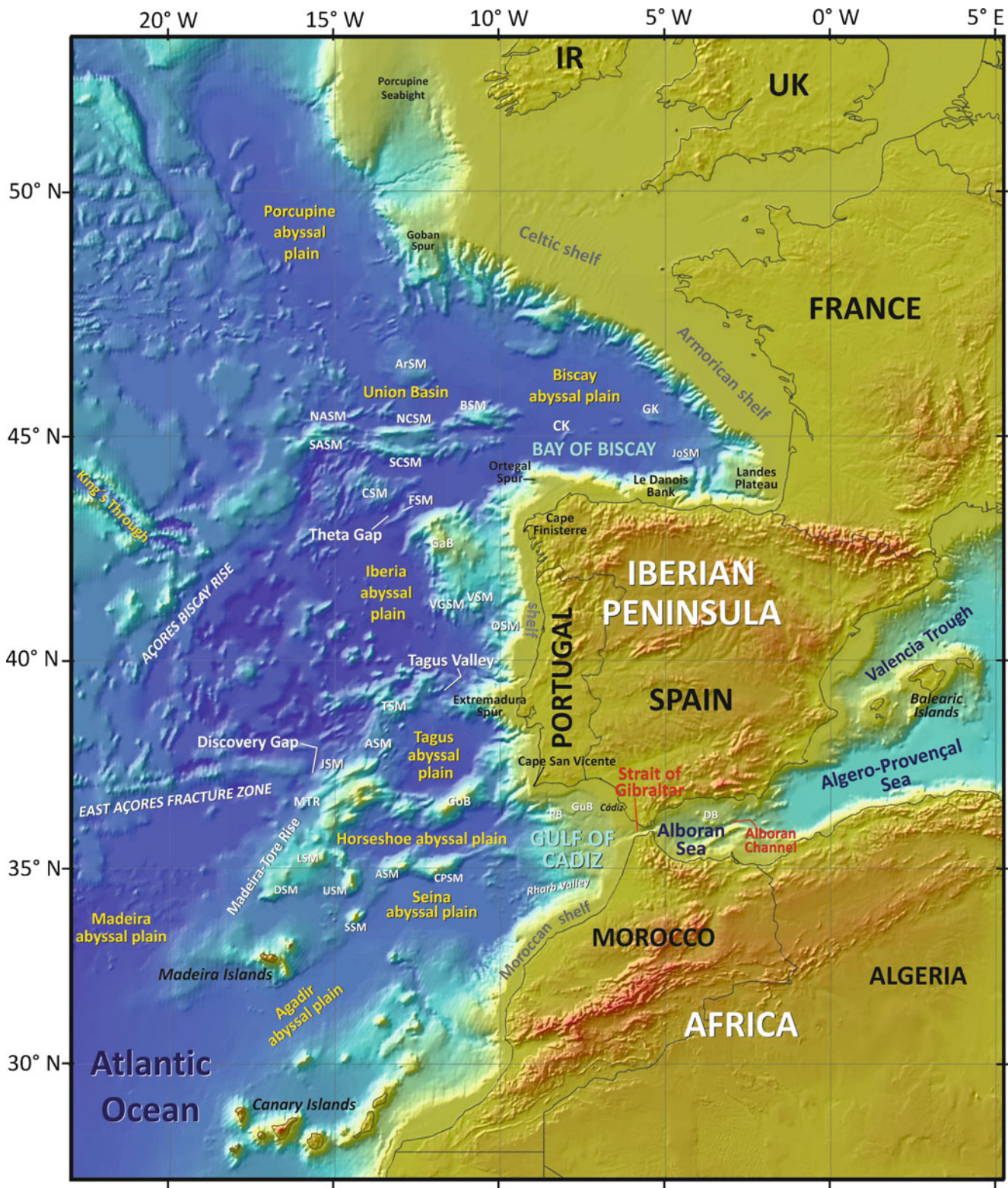


Fig. 1 Location and bathymetric map with continental margins and abyssal plains around Iberia (base bathymetric map from R. León (personal communication), based on satellite data from Smith and Sandwell 1997). *ArSM* Armorican Seamount, *ASM* Ampere Seamount, *BH* Barbate high, *BSM* Biscay Seamount, *CK* Cantabrian Knoll, *CPSM* Coral Patch Seamount, *DSM* Dragon Seamount, *FSM* Finisterre Seamount, *GaB* Galicia Bank, *GB* Guadalquivir Bank, *GK*

Gascone Knoll, *GoB* Goringe Bank, *HSM* Hirondele Seamount, *JoSM* Jovellanos Seamount, *JSM* Josephine Seamount, *LCSM* La Coruña Seamount, *LSM* Lion Seamount, *NASM* North Atlante Seamount, *NCSM* North Charcot Seamount, *OSM* Oporto Seamount, *SASM* South Atlante Seamount, *SCSM* South Charcot Seamount, *SSM* Sea Seamount, *TSM* Tore Seamount, *USM* Unicorn Seamount, *VGS* Vasco de Gama Seamount, *VSM* Vigo Seamount

ces (see below and [Appendix](#)). Such a compilation is extremely difficult, since there is a high degree of heterogeneity in both data coverage and terminology. Therefore, it should be considered as a preliminary sketch for evaluating along-slope processes around Iberia, and one which can undoubtedly be improved in future work. Particular emphasis has been placed on the Mediterranean water masses, especially the Mediterranean Outflow Water (MOW) in view of its key role in modulating along-slope processes in the region.

Numerical bottom-current circulation

Numerical bottom-current simulations were performed with the MIT general circulation model (Marshall et al. 1997), a primitive-equation z-coordinate ocean model. The computational domain included the Northeast Atlantic and Western Mediterranean regions, extending from 9°E to 24°W and from 30°N to 48°N. In the horizontal, a resolution of 1/30° (approx. 2.8 km) was employed; 140 levels were used in the vertical, with resolutions varying from 5 m in the upper ocean to 100 m in the deep ocean. The model was initialized with temperature and salinity values from the January climatology of the World Ocean Atlas 2005 (Boyer et al. 2005), and bottom topography from the ETOPO2 database. Surface fluxes of momentum, heat and freshwater were computed internally using bulk formulae and the 6-hourly atmospheric state from the NCEP reanalysis 1 (Kalnay et al. 1996). Since the configuration featured a limited area, volume-balanced open boundary conditions were constructed from a 1/6° resolution Atlantic solution of the same model forced by the same NCEP dataset (Serra et al. 2010a), and applied at the four boundaries. Unresolved vertical mixing was parameterized by the KPP formulation (Large et al. 1994) and horizontal mixing by a biharmonic operator with coefficients of 1×10^3 and 5×10^8 m⁴/s for diffusion and viscosity respectively.

The model was integrated for the 6-year period 1990–1995 and the mean daily values assessed for the 3-year period 1993–1995. Some results have been reported by Serra et al. (2010b) with focus on the vertical structure of model-generated Mediterranean water eddies (Meddies) and their interaction with upper ocean layers. The good agreement with observations reported in that work built confidence on the realism of the simulations, which in the present work are analysed for near-bottom properties. Tidal forcing is not considered in this numerical model.

Characterization of along-slope (contourite) features

A broad database was compiled from numerous international publications as well as less readily accessible theses, internal reports, etc., noting currently available details of

contourite depositional and erosional features, bedforms, substrate, and current velocity around Iberia. These data served to (1) provide a synthesis of known CDS locations; (2) determine their major similarities and differences, outlining their role in recent slope evolution; and (3) combine along-slope (contourite) sea-bottom feature characterization with numerically simulated bottom currents.

Characterization of contourite features is based on published information for the Western Mediterranean Sea (e.g. Canals 1985; Velasco et al. 1996; Esteras et al. 2000; Ercilla et al. 2002; Frigola et al. 2007, 2008) and the Atlantic Iberian margin (e.g. Madelain 1970; Kenyon and Belderson 1973; Gonthier et al. 1984; Stow et al. 1986, 2002c; Nelson et al. 1993, 1999; Buitrago et al. 2001; Llave et al. 2001, 2005, 2006, 2007; Alves et al. 2003; Habgood et al. 2003; Hernández-Molina et al. 2003, 2006, 2010a; Mulder et al. 2003, 2006; Van Rooij et al. 2003, 2010a; Toucanne 2005; Øvrebø et al. 2006; Hanquiez et al. 2007; Marchès et al. 2007; Toucanne et al. 2007; Ercilla et al. 2008a, b, 2009, 2010; Hernández-Molina 2009; Iglesias 2009; García et al. 2009; Bender et al. 2010; Mena et al. 2010). This includes (1) bathymetric data, mainly regional from mono- and multibeam echosounders; (2) sidescan sonar images, available for some areas; (3) seismic reflection profiles, including low-resolution reflection multichannel seismic (MCS) profiles, medium/high-resolution sparker and airgun seismic profiles, and very high-resolution 3.5-kHz and topographic parametric sonar (TOPAS) seismic profiles; (4) core and borehole data, available for some areas and serving for the groundtruthing of seismic facies patterns, and to establish the chronology of depositional units; (5) underwater photographs, locally available (mainly for the Gulf of Cadiz); and (6) physical oceanographic data, comprising CTD and XBT profiles. Compilation and interpretation of these oceanographic data in terms of regional morphologic features have already been published for some areas (García 2002; Mulder et al. 2003, 2006; Hernández-Molina et al. 2006, 2009b; Stow et al. 2009).

Terminology

There is a growing consensus within the marine science community about the terminology to be used for these along-slope sedimentary systems, an aspect which has been heeded as far as possible in the present study. The general term *bottom current* is preferred to denote those semi-permanent deep-water currents capable of eroding, transporting and depositing sediments on the seafloor (Rebesco and Camerlenghi 2008). Bottom currents are the result of both thermohaline and wind-driven circulation of the oceans. Generally, these currents are semi-permanent in nature with a net flow along-slope. Nevertheless, they can

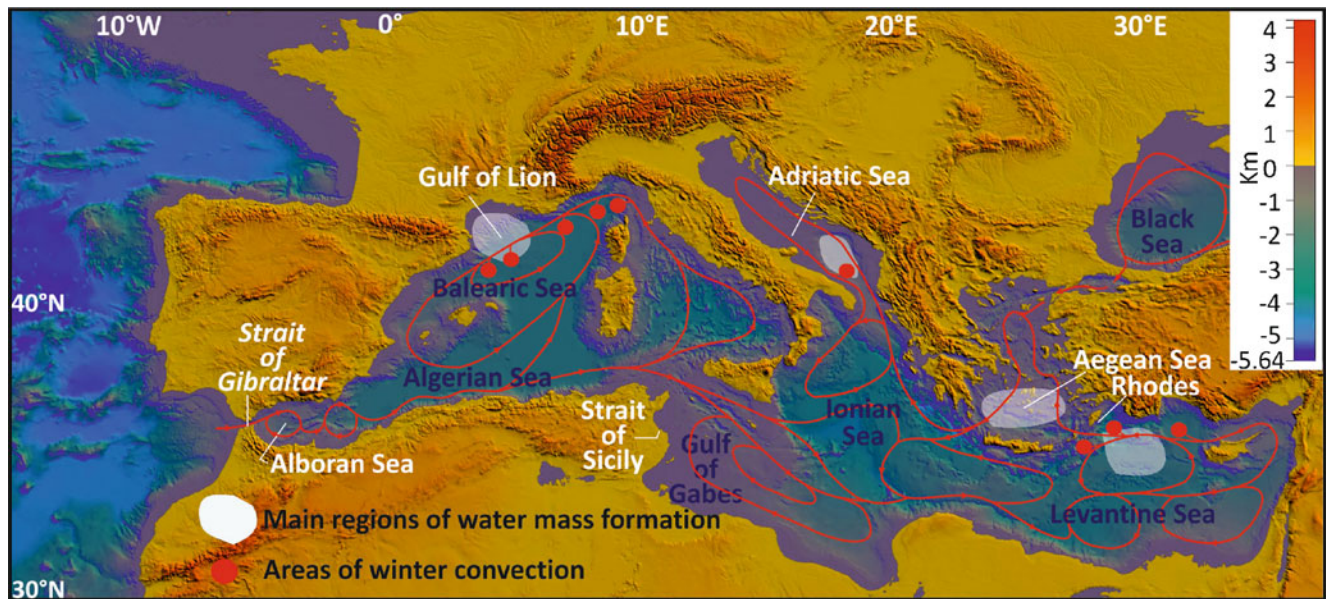


Fig. 2 Mediterranean Sea sketch with the general surficial water-mass circulation, the winter convection areas and the main water-mass formation zones (adapted from Arnone et al. 1990 and Candela 2001)

be extremely variable in direction and velocity, in addition to exhibiting giant eddies as well as local downslope, upslope or oblique-to-slope flow, especially near the entrance or exit gateways of basins (Barusseau and Vanney 1978; Rebesco and Camerlenghi 2008).

The term *contourite* is now generally accepted for those sediments deposited or substantially reworked by bottom currents and contour currents sensu stricto. Major accumulations of contourite deposits are referred to as *drifts* or *contourite drifts*, for which several classifications have been proposed based mainly on their morphological, sedimentological and seismic characteristics (Gonthier et al. 1984; McCave and Tucholke 1986; Faugères and Stow 1993; Faugères et al. 1993, 1999; Rebesco and Stow 2001; Stow et al. 2002b; Rebesco 2005; Rebesco and Camerlenghi 2008). An association of various drifts and related erosional features is commonly termed a *contourite depositional system*, by analogy with and of equal importance to *turbidite depositional systems* (Stow et al. 1986, 2002b; Hernández-Molina et al. 2003, 2006, 2008a). Where different CDSs are connected laterally (and vertically) and associated with the same water mass in the same or adjacent basins, they can be considered as a *contourite depositional complex* (Hernández-Molina et al. 2008a).

Circulation of water masses: oceanographic processes

Water masses and dynamics

Around the Iberian margin, both in the Mediterranean Sea and the Atlantic Ocean, there are several water masses

flowing at different depths either in the same or in opposite directions and which generate important along-slope sedimentary processes at the seafloor.

In the Mediterranean, there are several places where dense water masses are generated (Fig. 2 and Table 1), such that the Western Mediterranean off the Iberian Peninsula comprises three main water masses (Millot 1999, 2009; Candela 2001). (1) The deepest parts of the basin are filled by the *Western Mediterranean Deep Water* (WMDW; Fig. 3), generated in the Gulf of Lion where convective processes are known to reach depths of 2,000 m. In general, the WMDW flows below 500 m, following the contour of the lower slope, continental rise and abyssal plain around the Iberian Peninsula and Balearic Islands although, in the West Alboran Basin, this water mass flows mainly along the Moroccan margin (Figs. 3, 4 and 5). (2) Between 500 and 150 m water depth, the basin is occupied by the *Levantine Intermediate Water* (LIW; Fig. 4), formed by convection in the Eastern Mediterranean and having passed through the Sicilian Strait. Around Iberia, the LIW flows mainly along the upper and middle continental slope (Figs. 3, 4 and 5). (3) The upper water layer (<150 m) is formed by the inflow of Atlantic water through the Strait of Gibraltar (*Modified Atlantic Water*, MAW; Fig. 5). Although these aforementioned water masses are generally recognized, Millot (2009) has very recently considered a more complex structure and dynamics of five water masses in the Western Mediterranean, including low- versus high-density water masses.

Around the Atlantic Iberian margin, five main water masses have been more clearly identified (Figs. 3, 4 and 5, Table 1; e.g. Iorga and Lozier 1999; González-Pola 2006; Serra et al. 2010b). These are, from bottom to top: (1) the

Table 1 Main water masses in the Western Mediterranean and North Atlantic around Iberia

| Main water masses around Iberia | Regional water depth of lower interface |
|--|---|
| Mediterranean Sea | |
| Modified Atlantic Water (MAW) | ~0.15 km |
| Levantine Intermediate Water (LIW) | ~0.5 km |
| Western Mediterranean Deep Water (WMDW) | |
| Northeast Atlantic | |
| North Atlantic Central Water (NACW) | ~0.6 km |
| Mediterranean Outflow Water (MOW) | ~1.5 km |
| Labrador Sea Water (LSW) | ~2.2 km |
| North Atlantic Deep Water (NADW) | >4 km |
| Lower Deep Water (LDW), composed mainly of Antarctic Bottom Water (AABW) and Labrador Deep Water (LDW) | |
| Central North Atlantic | |
| North Atlantic Central Water (NACW) | ~0.5/0.6 km |
| Mediterranean Outflow Water (MOW) | ~1.4 km |
| North Atlantic Deep Water (NADW) | >4 km |
| Lower Deep Water (LDW), composed mainly of Antarctic Bottom Water (AABW) | |

Lower Deep Water (LDW), composed mainly of Antarctic Bottom Water (AABW; Fig. 3) and flowing regionally below 4,000 m mainly across the abyssal plains; (2) the *North Atlantic Deep Water* (NADW; Fig. 3), flowing in various directions between 4,000 and 2,200 m depth; (3) the *Labrador Sea Water* (LSW; Fig. 4), circulating regionally towards the southwest between 2,200 and 1,500 m depth (main core at ~1,800 m); (4) the *Mediterranean Outflow Water* (Fig. 4), located between 1,500 and 600 m depth, with the main core at ~1,200 m flowing to the north and west along the middle slope around the Iberian margin into the Bay of Biscay; and (5) the *North Atlantic Central Water* (NACW; Fig. 5), characterized by a complex circulation pattern involving different currents and directions between 600 m and the surface (main core at ~350 m).

The MOW is the most important in terms of along-slope processes and CDS development. After its exit through the Gibraltar gateway, the MOW comprises an intermediate water mass, warm and very saline and which flows to the northwest along the middle slope (Fig. 4) under the *Atlantic inflow* and above the NADW (Thorpe 1975; Zenk 1975; Gardner and Kidd 1983; Ochoa and Bray 1991; Baringer and Price 1999). It has a flux of about 1.78 Sv through the Strait of Gibraltar, composed of both LIW and WMDW (Bryden and Stommel 1984; Bryden et al. 1994), and generates important along-slope processes along the Atlantic margin (Serra et al.

2010b). In the Gulf of Cadiz, it flows between 500 and 1,400 m depth with a velocity close to 300 cm/s at the strait (Ambar and Howe 1979) and around 80–100 cm/s at the Cape San Vicente latitude (Cherubin et al. 2000). Its distribution is conditioned by the complex morphology of the continental slope, which generates two main cores, one between 500–700 m depth (upper core or *Mediterranean Upper Water*, MU) and another between 800 and 1,400 m depth (lower core or *Mediterranean Lower Water*, ML). The ML is further subdivided into three branches (Fig. 4; Madelain 1970; Zenk 1975; Ambar and Howe 1979; Johnson and Stevens 2000; Borenäs et al. 2002). In the western sectors, the interaction of the two cores with the seafloor generates large Meddies (Richardson et al. 2000).

After exiting the Gulf of Cadiz, the MOW shows three principal branches (Fig. 4): the main one flows to the north, another to the west, and yet another to the south reaching the Canary Islands and then veering towards the west (Iorga and Lozier 1999; Slater 2003). The northern branch flows along the middle slope of the Portuguese margin, and is subdivided by the influence of the Galicia Bank. These two branches then converge and circulate to the east in the Gulf of Biscay, following the continental slope contour (Fig. 4). The MOW continues to the Porcupine Bank and circulates partly to the north along the Rockall Trough, before eventually reaching the Norwegian Sea (Iorga and Lozier 1999; Slater 2003).

Simulated bottom velocities

Assessing the mean bottom velocities (cm/s) resulting from numerical simulations over the 3-year study period, as well as the corresponding standard deviations (Figs. 6 and 7), one key observation is that the regional circulation of the aforementioned water masses has a great impact at the seafloor in specific parts of both the Western Mediterranean Sea and Atlantic Ocean margins and abyssal plains. In the discussion below, the following categorization of mean bottom-current velocities has been adopted, although recognizing that maximum values may periodically reach two or three times the average:

- low velocity: 0–10 cm/s. Little effect on seafloor, inhibits deposition, smooth surfaces, lineation
- medium velocity: 11–20 cm/s. Transports clay and silt, fine sand rippled surfaces, lineation
- high velocity: 21–40 cm/s. Transports fine–medium sand, larger ripples, grooves/ridges
- very high velocity: >40 cm/s. Transports sand, severe winnowing, variety of bedforms and erosion.

In the Western Mediterranean Sea, the higher velocities are found mainly on the shelves and the abyssal plains

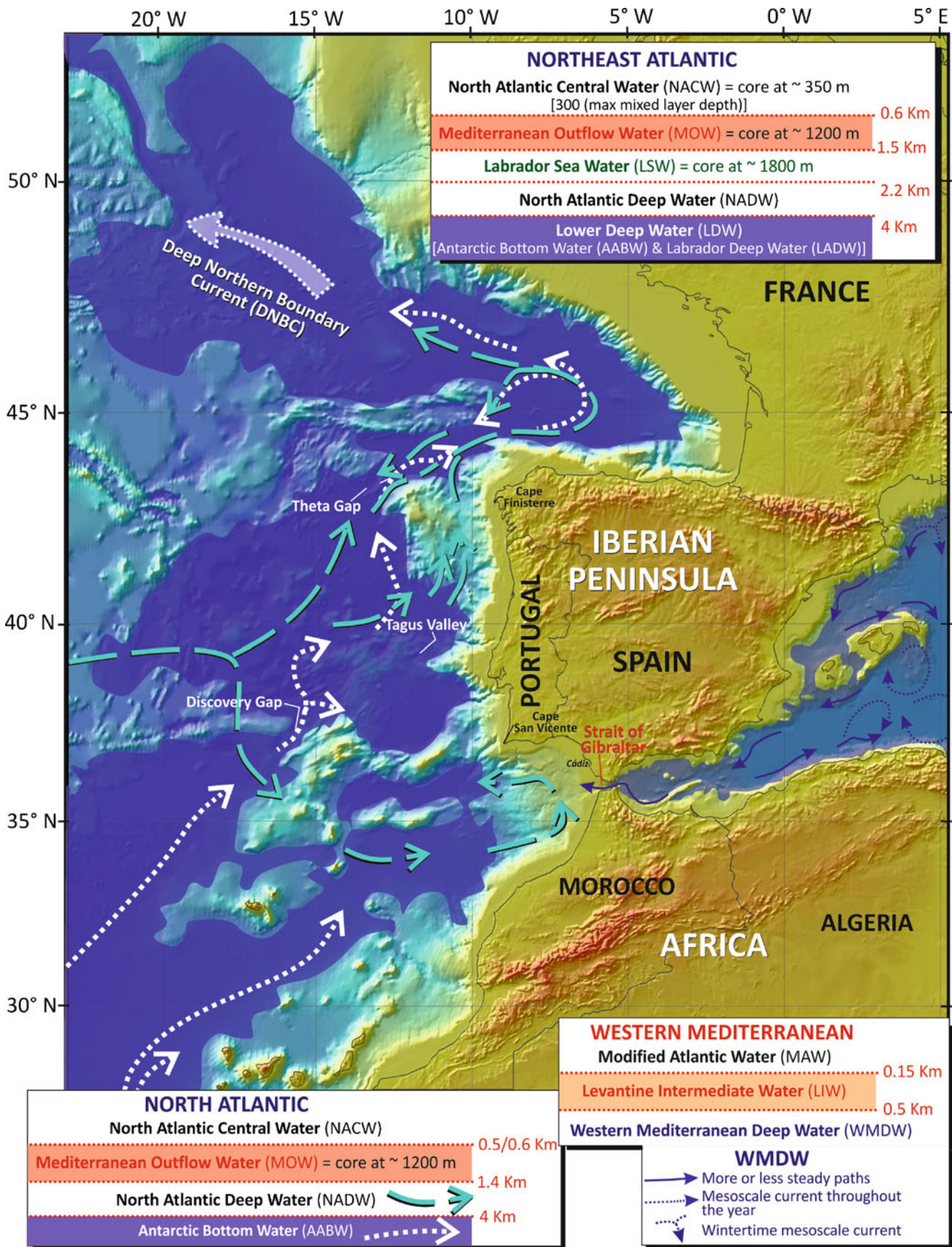


Fig. 3 Deep-water circulation in the Western Mediterranean and North Atlantic (for bibliographic sources, see Appendix; for further explanation, see text)

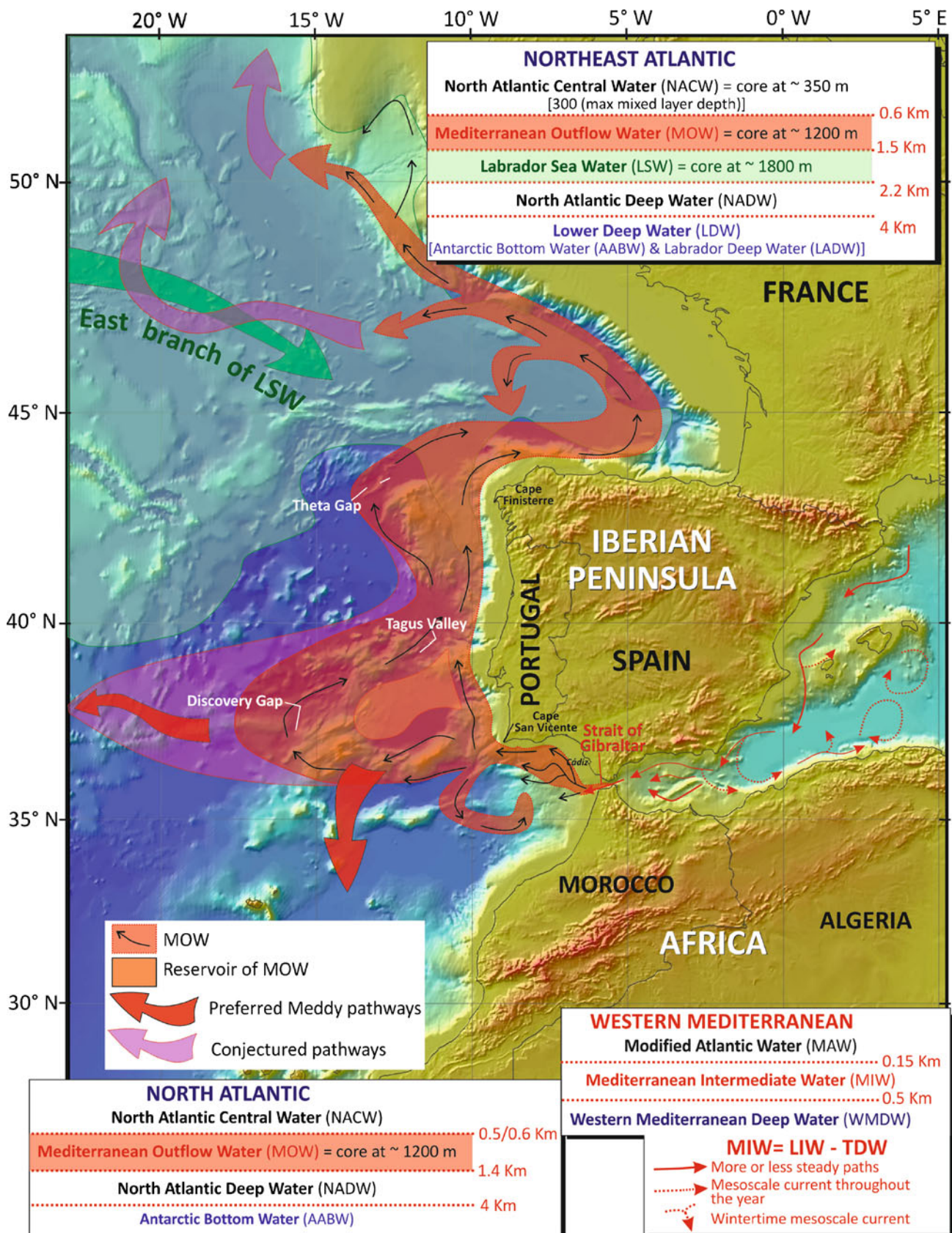


Fig. 4 Intermediate water circulation in the Western Mediterranean and North Atlantic (for bibliographic sources, see Appendix; for further explanation, see text). *LIW* Levantine Intermediate Water, *TDW* Tyrrhenian Deep Water

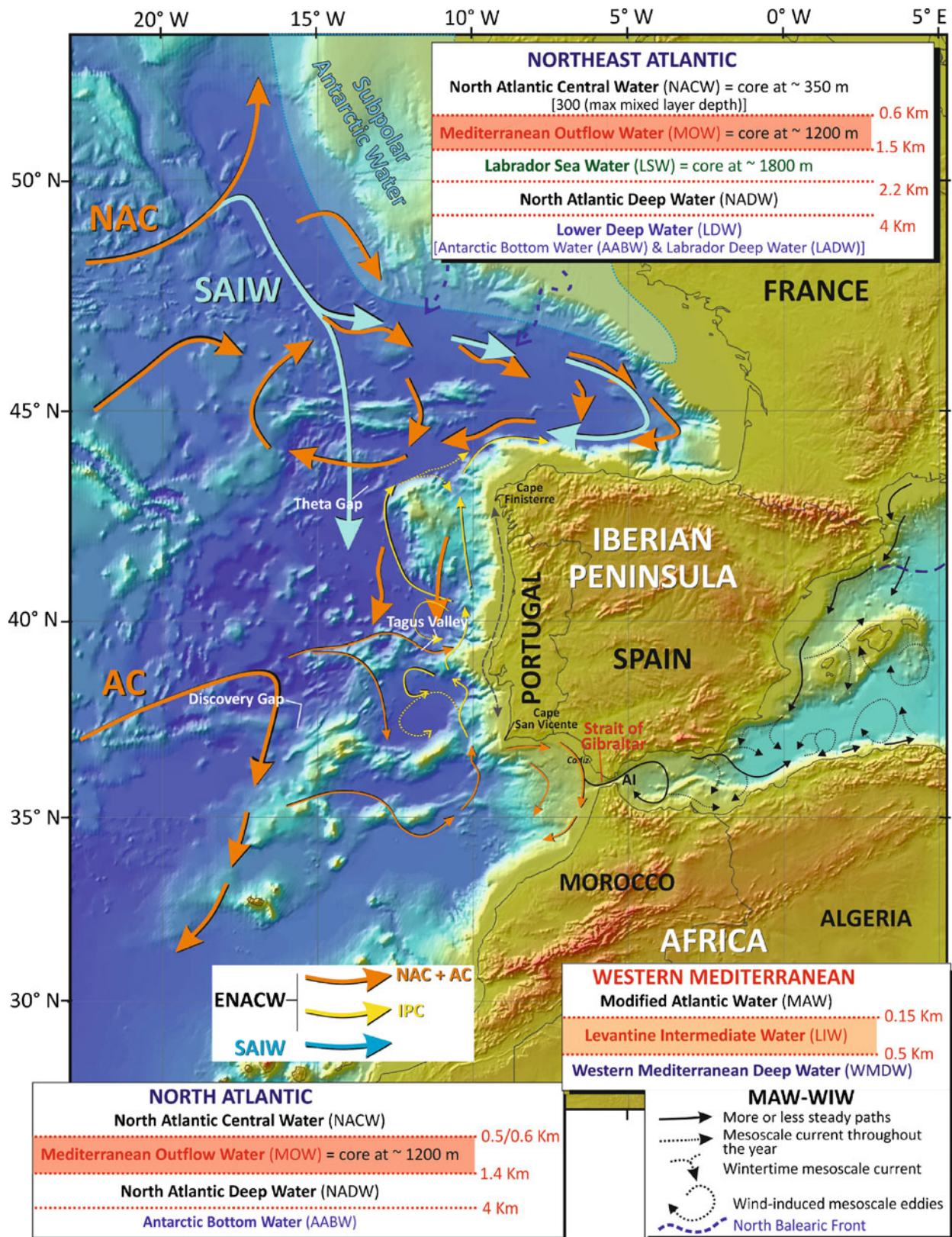


Fig. 5 Surficial water circulation in the Western Mediterranean and North Atlantic (for bibliographic sources, see Appendix; for further explanation, see text). AC Atlantic Current, AI Atlantic inflow, ENACW East North Atlantic Current Water, IPC Iberian Polar Current, NAC North Atlantic

Current, SAIW Subarctic Intermediate Water, WIW Western Mediterranean Intermediate Water (formerly Winter Intermediate Water, in the western basin)

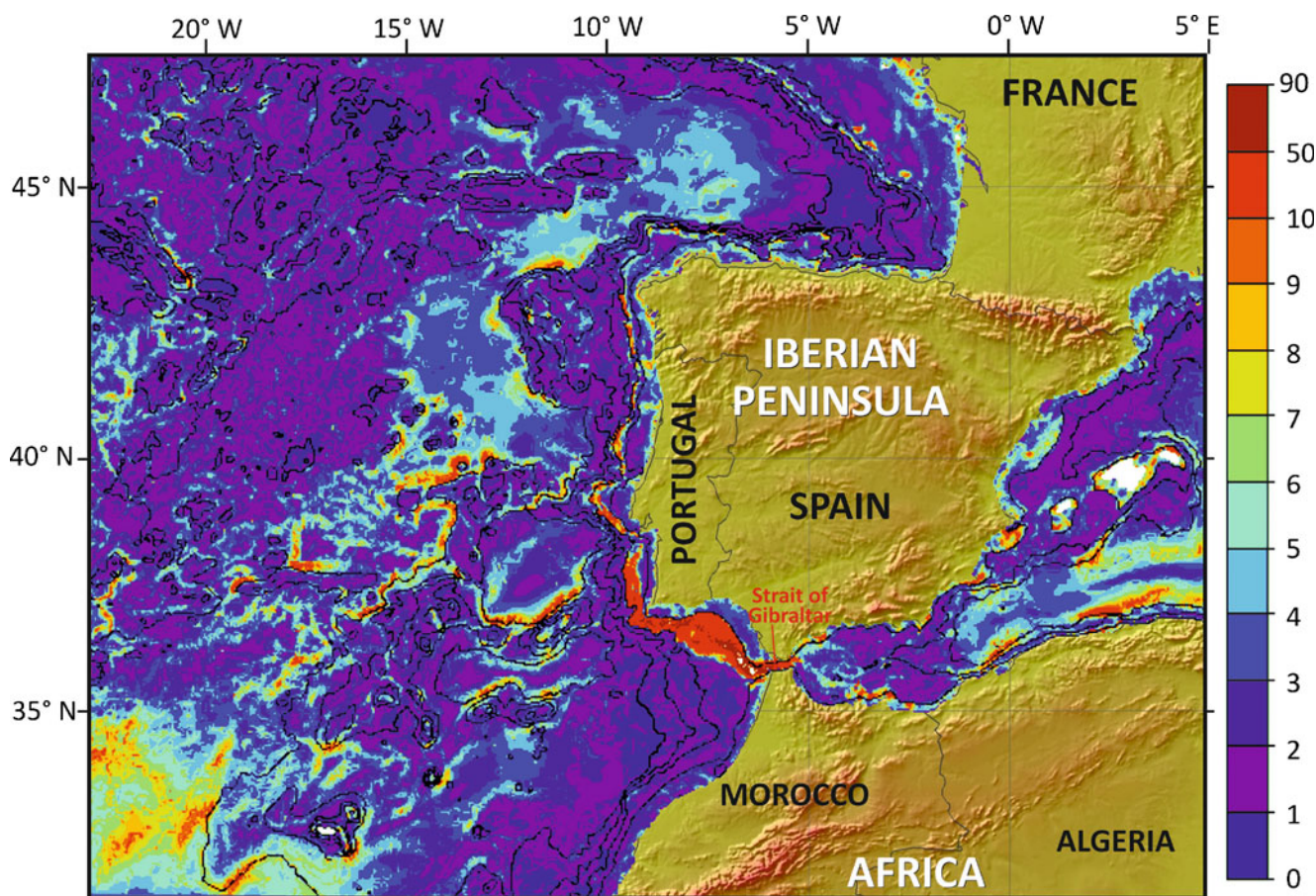


Fig. 6 Mean bottom velocities (cm/s) around Iberia, based on numerical simulations over a 3-year period. Sites of stronger bottom currents are clearly visible

(Figs. 6 and 7), whereas most of the slope domains are swept by water masses with low velocities (<4–5 cm/s). Nevertheless, in this general context the continental slopes which bound the Alboran Sea are an exception. Here the WMDW and LIW have slightly higher velocities associated with submarine scarps, seamounts, and both the slopes and abyssal plains of the western basin. Along the Moroccan slope, higher velocities are identified along the middle slope, whereas the lower slope has rather low velocities (>6 cm/s for the former; Figs. 6 and 7), due to the LIW and WMDW circulation respectively. Along the northern Spanish slope, the higher velocities are located mainly on the upper slope associated with the circulation of the inflow of Atlantic water through the Strait of Gibraltar.

On the continental shelves of the Western Mediterranean Sea, simulated bottom-current velocity values are generally just over 5 cm/s (but locally exceed 10 cm/s). This is not only around the continent but also on the continental shelf in the vicinity of the Balearic Islands (Figs. 6 and 7).

Simulated mean bottom-current velocities on the abyssal plains are generally lower, especially at depths exceeding 2,000 m due to WMDW circulation. Mean values are 3–4 cm/s, with the higher velocities located mainly on the

lower slope around the Balearic Promontory and also at the border of the Algero-Provençal abyssal plain. Here, the bottom-current velocities reach 10 cm/s, especially along the African margin. Again, in this general context the abyssal plain of the West Alboran Basin has several areas with relatively high bottom-current velocity values of up to 5 cm/s. These are possibly related to eddies from WMDW circulation (Figs. 6 and 7).

The Strait of Gibraltar itself has very high bottom-current velocities related to MOW overflow, the maximum recorded velocity being 2.8 m/s. Overall, simulated mean velocities exceed 10 cm/s and range from >90 cm/s near the exit of the strait to >50 cm/s several hundred kilometres downstream in the Gulf of Cadiz (Figs. 6 and 7).

Along the Atlantic Iberia margin, the highest simulated mean bottom-current velocities are identified as occurring over the western and northern shelves, especially along the middle slope (Figs. 6 and 7). Along-slope processes are therefore dominant on the middle slope of the Gulf of Cadiz, related to circulation of both the upper (MU) and lower (ML) strands of the MOW. Here, simulated velocities exceed 10 cm/s, commonly reaching 50–90 cm/s. Also in other sectors of

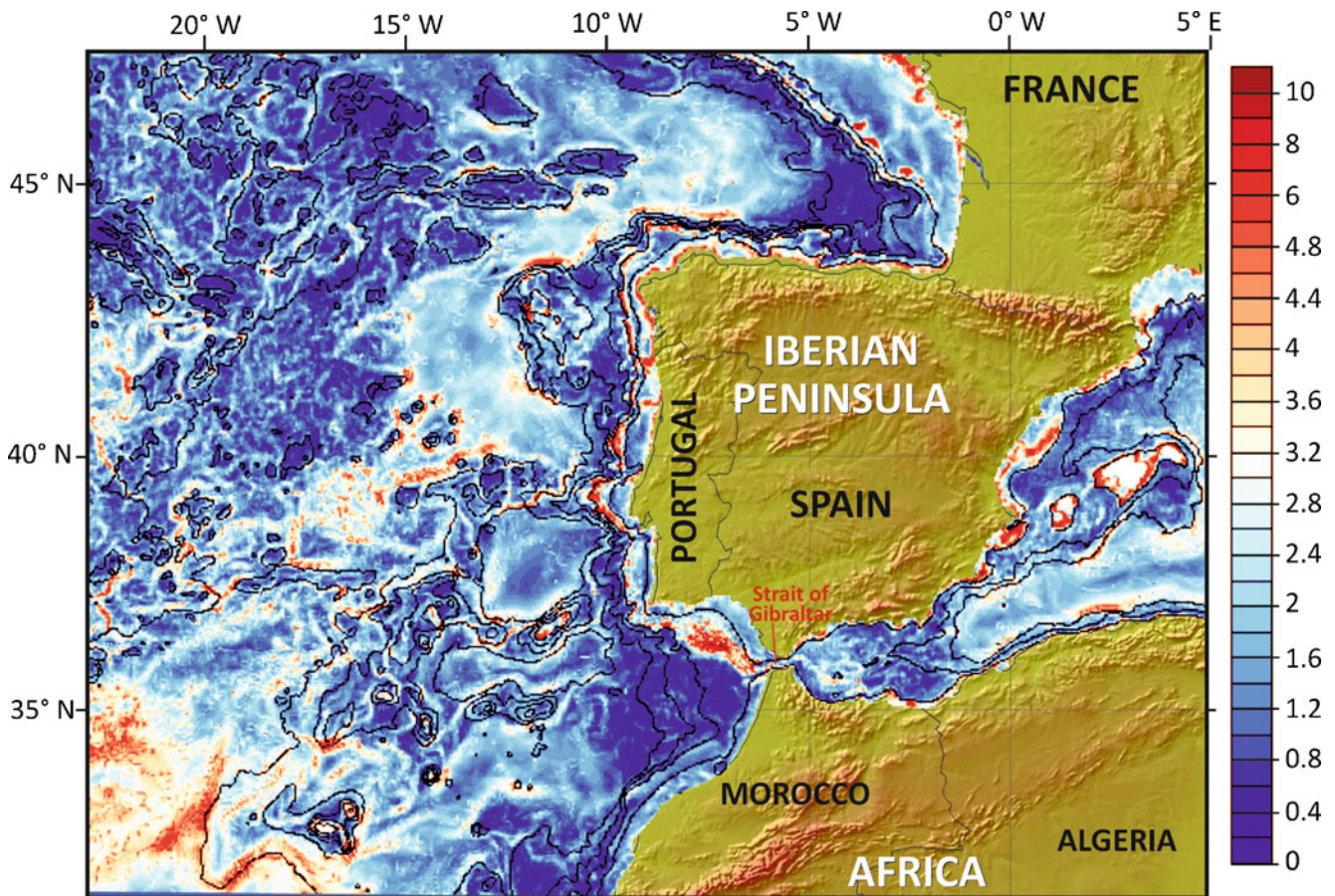


Fig. 7 Standard deviations of simulated bottom velocities (cm/s) around Iberia, highlighting sites where bottom currents are more variable

the Atlantic Iberian slope, the highest velocities occur on the middle slope (Fig. 6), with values commonly exceeding 10 cm/s (and locally >50 cm/s) associated with the northern MOW branch in the Portuguese, Galician and Cantabrian slope sectors. The upper and lower slope generally have lower velocities of about <4–5 cm/s; where associated with large seamounts and banks (such as the Extremadura Spur, the Oporto, Vigo and Vasco de Gama seamounts, and the Galicia Bank), however, velocities of >9–10 cm/s can be found.

Bottom-current velocities on the Atlantic abyssal plains are quite variable and can be high to very high. On the Madeira, Horseshoe, Tagus and Iberia abyssal plains, the highest velocities are found mainly along the eastern boundaries (e.g. at the base of the Madeira-Tore Rise or of the Galicia Bank), often reaching 10 cm/s and locally >50 cm/s. Less frequently, locally high values occur along their western boundaries (Figs. 6 and 7) or, in the Union Basin, along its northern flank. Bottom-current processes at this scale on these abyssal plains are associated with the LDW north-eastern circulation. Contrasting with these aforementioned abyssal plains, bottom-current velocities on the Agadir, Sena, Biscay and Porcupine abyssal plains are generally much lower (<5–8 cm/s) to extremely low (2–4 cm/s).

Deep gateways such as the Discovery Gap, Tagus Valley and Theta Gap are essential in controlling circulation and water-mass exchange in the abyssal regions (Figs. 6 and 7). Relatively high bottom-current velocities occur in these areas.

In the oceanic domain beyond the abyssal plains, the simulated mean bottom-current velocities are usually low (<3 cm/s) but, in this part of the North Atlantic, there are numerous seamounts which represent important obstacles for water-mass circulation; high bottom-current velocities (10–20 times the mean velocities) occur around their flanks, locally reaching >50 cm/s (Figs. 6 and 7). In fact, the locations of highest bottom-current velocities differ between flanks of various seamounts. The Ampere and Coral Patch seamounts have highest velocities along their northern flanks; the island of Madeira, as well as the Dragon, Unicorn and Sea seamounts have highest velocities on their SE flanks; generally low simulated bottom-current velocities occur in the vicinity of the Atalante and Charcot seamounts but the highest values are identified on their northern flanks. In the NW sector of Figs. 6 and 7 south of the King's Trough, the highest velocities occur on the western and south-western flanks of oceanic highs. North of this trough, no analogous pattern can be recognized.

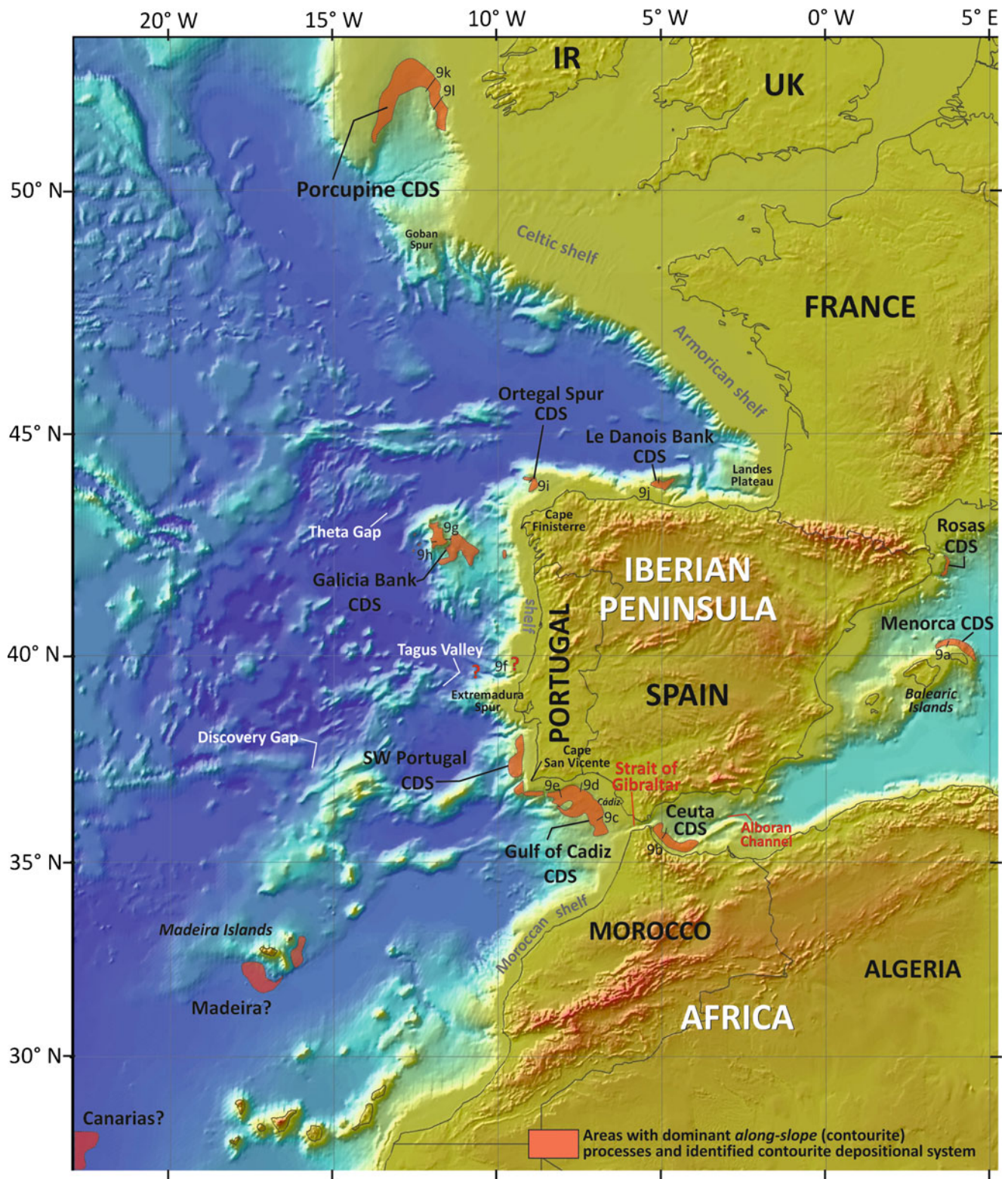


Fig. 8 Main locations of dominate along-slope (contourite) processes and identified contourite depositional systems (CDS) along the continental margins and abyssal plains around Iberia

Circulation of water masses: products

In both the Mediterranean Sea and the Atlantic Ocean sectors, circulation of water masses around the Iberia margin has produced numerous individual contourite drifts as well as several distinct contourite depositional systems, each involving two or more drifts and associated erosional elements (Fig. 8). In the Western Mediterranean, there are three systems under the influence of the LIW and WMDW (Figs. 8 and 9).

1. Along the NE Catalanian slope (Fig. 8), Canals (1985) defined the possible occurrence of contourite features at Rosas between 1,200 and 2,300 m water depth, and between the Cap de Creus and slightly south of the La Fonera canyons. Here, one or two distinct drifts are evident, each prograding upslope.
2. Northwest of Menorca on the lower slope at depths reaching 2,000 m (Fig. 8), there is a broad, low-relief but distinct plastered drift about 150 km long and 25 km wide, with a contourite moat along its seaward margin (Mauffret 1979; Velasco et al. 1996; Fig. 9). The drift is mud-dominated and has about 100 m of relief. This contourite drift was generated by deep bottom currents of the southward branch of the WMDW, which borders the Valencia Trough from north to south following a cyclonic pattern at depths of 2,000 m (Frigola et al. 2007, 2008).
3. The Ceuta contourite drift is located in the southwestern Alboran Sea (SW Mediterranean), close to the Strait of Gibraltar (Fig. 8) and running parallel to the Moroccan middle slope at water depths of 200–700 m (Ercilla et al. 2002). This is probably the best-known drift in the Western Mediterranean to date, characterized as an elongated plastered drift deposited on a slope terrace and of broad lenticular geometry. It is about 100 km long and 28 km wide, with a relief of up to 400 m (up to 700 ms two-way travel time, TWT; Fig. 9). This drift has been formed under the influence of a westward-flowing, simple tabular deep-water mass, producing deposition on the middle slope and erosion at the toe of the slope (Ercilla et al. 2002). The Ceuta drift is composed of Pliocene and Quaternary deposits over the basal surface. The Quaternary sedimentary record has been subdivided into five seaward-prograding units, with seismically stratified facies showing reflections of high lateral continuity and amplitude, converging both seawards and landwards (Fig. 9). The drift is composed mainly of muds intercalated with 40–50 cm thick layers of sandy muds bounded by sharp surfaces and thinner (10 cm thick) silty clay layers with gradual contacts.

In the Strait of Gibraltar the major processes defined are erosive, since the bottom current is high enough to prevent

deposition (Kelling and Stanley 1972; Stanley et al. 1975; Serrano et al. 2005). Although this area has been surveyed repeatedly during several cruises, no distinctive contourite features have been reported thus far, apart from several large depressions and channels which may be associated with MOW circulation (Esteras et al. 2000). Along the Atlantic Iberian margin, the following drifts and CDSs have been identified to date.

1. MOW interaction with the middle slope of the Gulf of Cadiz margin has developed one of the most extensive and complex CDS ever described, extending around the western Iberian margin (Fig. 8) and long a focus of research (e.g. Madelain 1970; Kenyon and Belderson 1973; Gonthier et al. 1984; Nelson et al. 1993, 1999; Llave et al. 2001, 2006, 2007, 2010; Stow et al. 2002c; Alves et al. 2003; Habgood et al. 2003; Hernández-Molina et al. 2003, 2006; Mulder et al. 2003, 2006; Hanquiez et al. 2007; Marchès et al. 2007). This CDS comprises both large depositional and erosional features (Fig. 9) generated by a strong current with speeds highest close to the Strait of Gibraltar (<300 cm/s) and decreasing at Cape St. Vincent (~80 cm/s; Kenyon and Belderson 1973; Ambar and Howe 1979; Cherubin et al. 2000). The main depositional features are sedimentary wave fields, sedimentary lobes, mixed drifts, plastered drifts, elongated mounded and separated drifts, and sheeted drifts. The main erosional features are contourite channels, furrows, marginal valleys and moats. Along the margin, their specific locations define five morphosedimentary sectors within the CDS (for details, see Hernández-Molina et al. 2003, 2006 and Llave et al. 2007). The development of each sector at a given point in time is related to the systematic deceleration of the MOW as it flows westwards from the strait, due to interaction with margin bathymetry, and to the effects of the Coriolis force. In general, the drifts are composed mainly of muddy, silty and sandy sediments of mixed terrigenous (dominant component) and biogenic composition (Gonthier et al. 1984; Stow et al. 1986, 2002c). Within the large contourite channels, by contrast, sand and gravel are found (Nelson et al. 1993, 1999) as well as many erosional features (Hernández-Molina et al. 2006; García et al. 2009). In the proximal sector close to the Strait of Gibraltar, an exceptionally thick sandy-sheeted drift (~815 m thick) is located, with sand layers averaging 12–15 m in thickness (minimum 1.5 m, maximum 40 m; Buitrago et al. 2001; Llave et al. 2007).
2. Along the western Portuguese margin, Alves et al. (2003) described the occurrence of contourite features (Fig. 8) on both the middle slope and continental rise. Middle slope drifts are associated with MOW interaction with

different sectors of the Atlantic Iberian margin (Fig. 9). By contrast, drifts located on the rise have been interpreted as reflecting the local influence of AABW (LDW) north-eastern circulation (Alves et al. 2003).

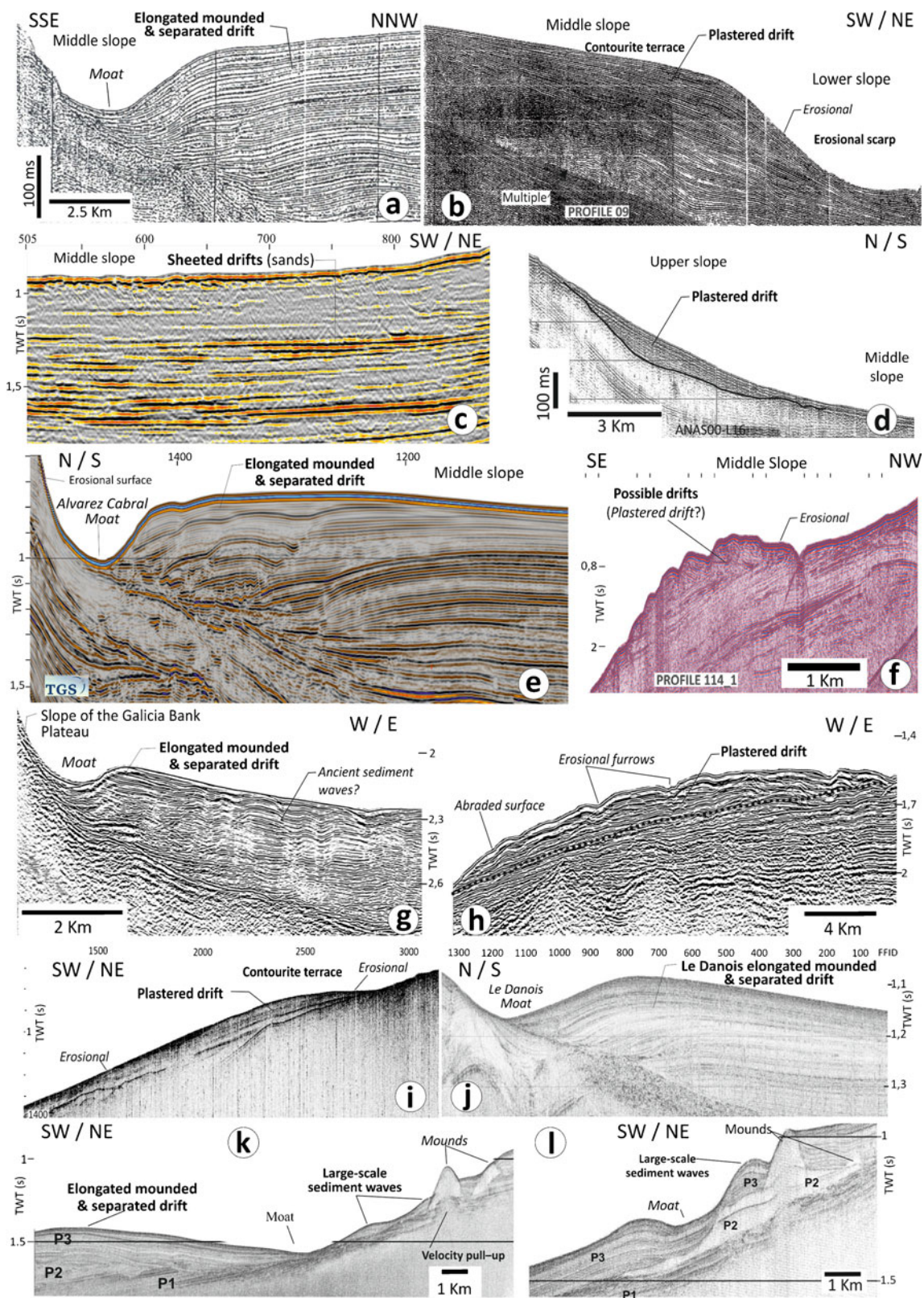
3. Contourite features have been recently defined in the vicinity of the Galicia Bank (Fig. 8), and around highs and topographic irregularities of the transitional zone, the Deep Galicia Margin and the north-western flank of the Galicia Bank (Ercilla et al. 2009, 2010). The main features described to date include moats, erosional and constructional furrows, abraded surfaces, large drifts (mainly elongated separated and plastered) and sediment waves (Fig. 9). They are genetically associated with several water masses: MOW, LSW, NADW and LDW, flowing at different depths and velocities and in different directions (Ercilla et al. 2010). In addition, along the Galicia slope between 1,700 and 2,300 m water depth (Fig. 8), elongated separated drifts composed mainly of muddy sediments have been recently described (Bender et al. 2010; Mena et al. 2010). Their genesis has been attributed to the local slope morphology interacting with the Deep Intermediate Water mass (DIW) which flows parallel to the slope, as well as to their proximity to shelf export pathways.
4. At the Ortegal Spur, a CDS has been recently identified as being related to along-slope MOW circulation (Fig. 8) between 500 and 600 m and about 1,500–1,600 m (Hernández-Molina et al. 2009b). The interaction of the impinging MOW from the west with the Ortegal Spur has generated a contourite depositional system composed of erosional and depositional features (Fig. 9). The erosional features comprise terraces of tens of metres of relief and several hundreds of metres long, and moats of tens of metres of relief and hundreds of metres wide. The main depositional features (drifts) include plastered to mounded, elongated types tens of metres thick. Near-surface sediment samples contained fine sands to muddy sands (Hernández-Molina et al. 2009b), as well as planktonic foraminiferal tests as part of a biogenic sandy contourite.
5. The northernmost large CDS identified around the Iberian margin is located in the Cantabrian sector (Fig. 9), at the Le Danois Bank or “Cachucho” (Ercilla et al. 2008a, b; Iglesias 2009; Van Rooij et al. 2010a). It is unique with respect to the known sedimentary systems along the upper slope of the Biscay margin. Whereas the steep Biscay slopes are dominated by downslope processes, the Le Danois CDS has been generated by along-slope processes due to MOW circulation, conditioned by seafloor irregularities and two topographic highs, the Le Danois Bank and the smaller Vizco High. This has enabled the development of present-day depositional and erosional features such

Fig. 9 Examples of contourite features (depositional and erosional) in identified contourite depositional systems (CDS; for approximate locations of profiles, see Fig. 8): **a** airgun seismic profile, Menorca CDS (extracted from Velasco et al. 1996); **b** airgun seismic profile oblique to Ceuta plastered drift (central sector; extracted from Ercilla et al. 2002); **c** uninterpreted multichannel seismic reflection (MCS) profile, sandy drifts near Strait of Gibraltar, and middle slope of Gulf of Cadiz CDS (line S-81A, courtesy REPSOL); **d** sparker seismic profile, plastered drift along upper and middle slope of Gulf of Cadiz CDS (based on Hernández-Molina et al. 2006; Llave et al. 2007, 2010); **e** uninterpreted MCS profile, Faro-Albufeira mounded elongated and separated drift, and Alvarez Cabral Moat on middle slope of Gulf of Cadiz CDS (courtesy TGS-NOPEC; cf. Hernández-Molina et al. 2006; Llave et al. 2007, 2010; Marchès 2008); **f** uninterpreted MCS profile, possible plastered drift deposits defined by Alves et al. (2003) on Portuguese middle slope (Luis Pinheiro, personal communication); **g, h** uninterpreted airgun seismic profiles, Galicia Bank CDS, elongated mounded and separated drift at base of slope of Galicia Bank Plateau (**g**), and plastered drift deposits on top of that bank (**h**); **i** high-resolution sparker profile, Ortegal Spur CDS; **j** high-resolution sparker profile, Le Danois elongated mounded and separated drift at base of Le Danois Bank (extracted from Van Rooij et al. 2010a); **k, l** sparker seismic profiles, Porcupine Bank, illustrating seismic features and unit geometry on eastern slope of Porcupine Seabight (extracted from Van Rooij et al. 2003)

as elongated mounded and separated drifts, plastered drifts, moats and slide scars (Van Rooij et al. 2010a).

Discussion and conclusions

The circulation of water masses around Iberia leads to the development of along-slope currents and to the generation of contourite erosional and depositional features, in some places forming complex CDSs of large dimensions and sediment thickness (Hernández-Molina 2009; Hernández-Molina et al. 2010b). The general links between bottom currents and deposits are well established and, although they are not well known in detail, their sedimentary records yield important information regarding their geological evolution and palaeoclimatic variation. Most of the drifts and CDSs described thus far are located on slopes. In the Mediterranean Sea they occur on the middle (Rosas and Alboran CDSs) and lower (Menorca and Alboran CDSs) slope sectors, due to the influence of the WMDW and LIW. Along the Iberian Atlantic margin, they are found mostly on the middle slope, associated with MOW influence. This is the case for the CDSs of the Gulf of Cadiz, Portuguese slope, Galician margin, Ortegal Spur and Le Danois Bank. The influence of MOW extends far beyond the present study area to the north, to the Porcupine Seabight and other parts of the NW European margin. Very few examples of contourite features are associated along the Iberian Atlantic margin with other water masses, only locally along the Portuguese margin (Alves et al. 2003) and the vicinity of the Galicia Bank (Ercilla et al. 2009, 2010).



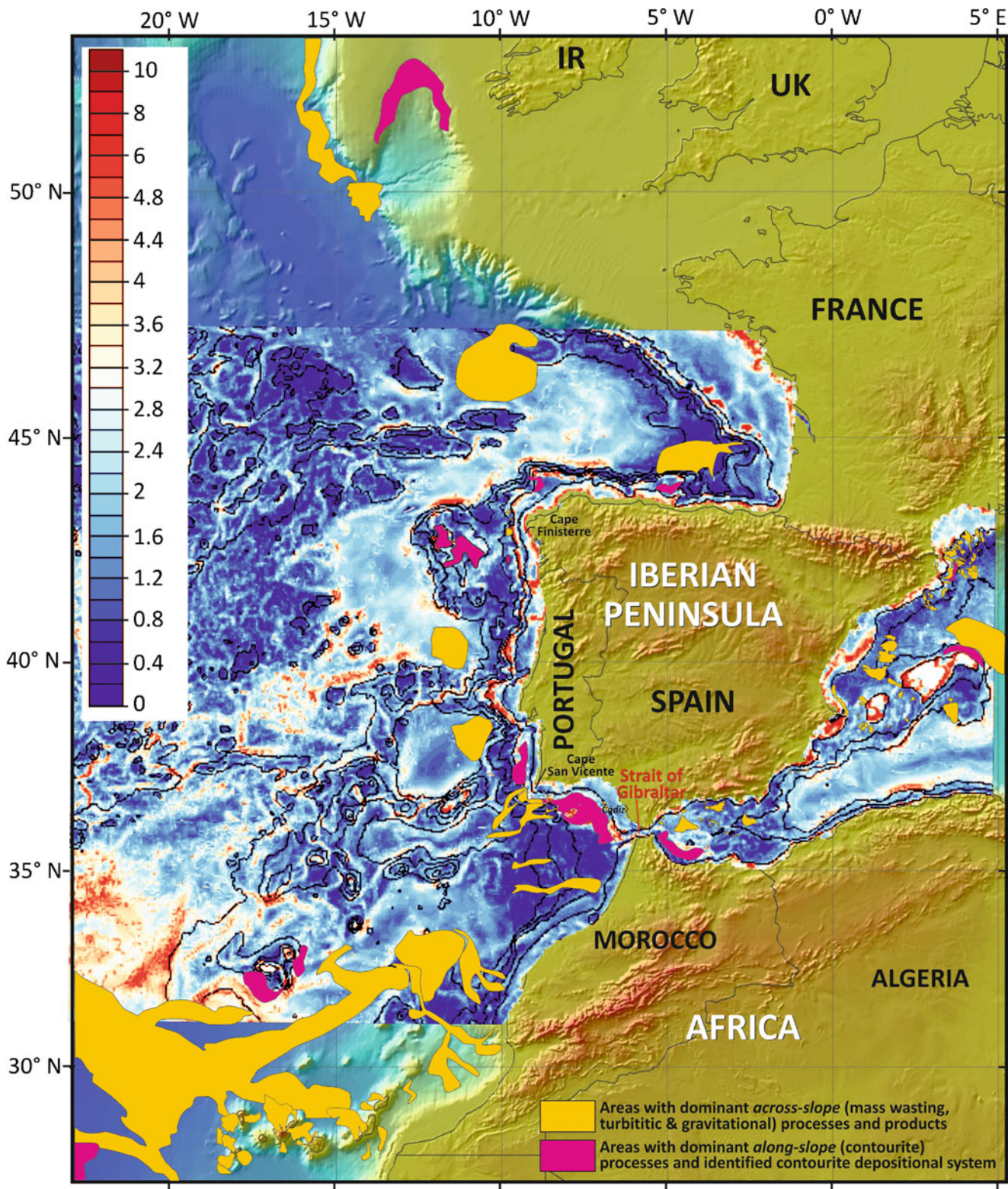


Fig. 10 Combining numerically simulated bottom currents with existing regional knowledge of the main locations of dominant along-slope (contourite) and across-slope (mass wasting, turbiditic, gravitational) processes identified along the continental margins and

abyssal plains around Iberia. Compilation of across-slope processes and associated products is based mainly on data and interpretations from Weaver et al. (2000) and Serrano et al. (2005)

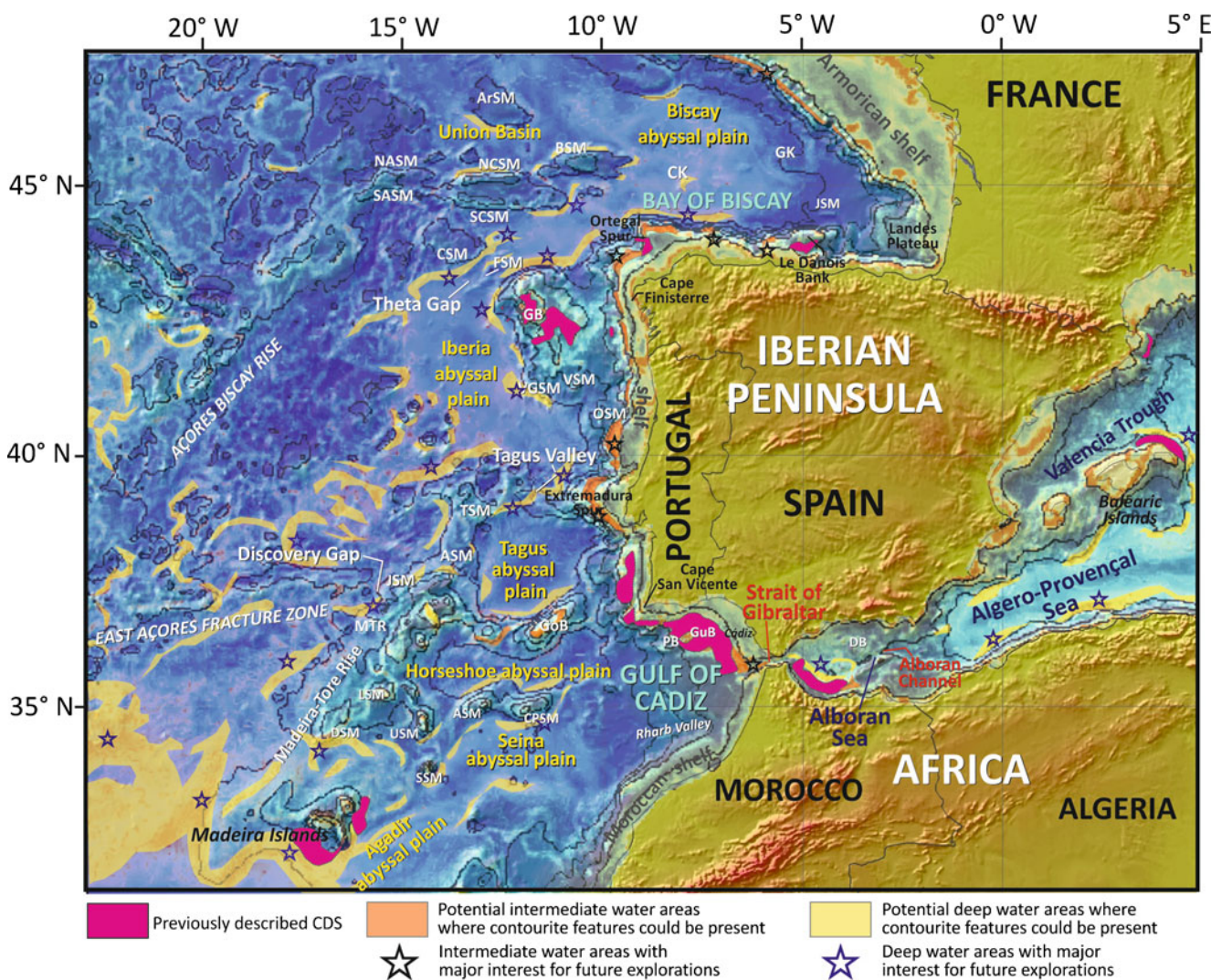


Fig. 11 Potential areas where new contourite features (depositional and erosional) could be present along the continental margins and abyssal plains around Iberia, together with selected deep and intermediate water areas of major interest for future exploration

Numerical simulation of bottom currents

This paper presents the first attempt to combine numerically simulated bottom currents with existing data on contourite features along the Iberian margin. Even a cursory glance at the data reveals that the strongest simulated bottom currents are closely associated with the distribution of contourite drifts and CDSs (Fig. 10). In addition, there are other areas with high simulated bottom-current velocities but where no CDSs have been reported to date. Nevertheless, some large features related to bottom-current circulation have been identified, such as around the southern and southeast flanks of the island of Madeira (Wynn et al. 2000).

Numerically simulated bottom currents facilitate the identification of areas where contourite-related processes could potentially be found in the study region, associated not only with the MOW but also with other water masses.

These include (1) the continental slopes of the Alboran Sea and Atlantic Iberian margins and (2) the abyssal plains (Fig. 10). On the Algero-Provençal abyssal plain, bottom-current velocities reach 10 cm/s, especially at the southern boundary along the African margin. Strong bottom-current velocities on the Atlantic abyssal plains can be identified in, for example, the Madeira, Tagus and Iberian sectors where higher velocities are found at the eastern boundaries, reaching 10 cm/s and locally >50 cm/s. Along-slope processes at this scale are associated mainly with the WMDW and LIW in the Alboran Sea, and with both the MOW and LDW in the Atlantic. In all these areas, there is good potential for the recognition of contourite features in the future.

Margin topography exerts a strong influence on bottom-current velocities. Oceanic gateways are essential in controlling water-mass exchange between the abyssal plains, and thereby bottom-current velocities and pathways.

The Discovery Gap, Tagus Valley and Theta Gap are all important gateways for deep-water circulation in the region, each being associated with higher than normal bottom-current velocities favouring the occurrence of contourite features (Fig. 10). The Strait of Gibraltar has a very special role in Mediterranean–Atlantic water-mass exchange, associated with the highest bottom-current velocities known anywhere in the study region (nearly 300 cm/s). This is also one of the most important oceanic gateways worldwide, enabling the overflow and circulation of MOW to the Atlantic Ocean (e.g. Serra 2004; Legg et al. 2009). Oceanic gateways with high velocities are typical of erosional bottom-current systems characterized by mainly linear bedforms displaying moderate to high seafloor relief resulting from scouring and incision, as well as by irregular scour hollows, sub-circular to circular holes, sand/gravel pavements and bare rock surfaces (Stow et al. 2009).

Slopes, banks and promontories are all instrumental in forcing higher than normal bottom-current velocities. The highest velocities observed around Iberia are found where the impinging flow increases its velocity due to the increased slope angles of prominent banks (e.g. Galicia, Guadalquivir and Le Danois), promontories (e.g. Balearic and Extremadura) and spurs (e.g. Ortegá).

Seamounts also represent important obstacles for water-mass circulation, and high bottom-current velocities (up to 10–20 times the mean velocities) can be identified around their flanks (Fig. 10), reaching values of >50 cm/s. This explains the occurrence of notable contourite features in the vicinity of both small and large seamounts in the Alboran Sea (Palomino et al. 2010), along the Iberia Atlantic margin of the Gulf of Cadiz (Hernández-Molina et al. 2006; García et al. 2009) and along the Galicia margin (Ercilla et al. 2009, 2010).

The collation and study of numerically simulated bottom currents can therefore be instrumental in identifying otherwise unexplored areas where along-slope processes may be important and as yet unknown contourite depositional systems may have developed. There are four principal reasons why these may have been overlooked: (1) they are often confused with hemipelagic deposits; (2) they are masked by deposits resulting from dominant downslope processes, especially at the base of slopes, on the continental rise or in proximal areas of abyssal plains (Fig. 10); (3) contourite deposition is inhibited or the deposits removed by the frequent and/or erosive action of downslope processes; and (4) good descriptive knowledge of contourites has only fairly recently been established in marine studies, and they have not been considered in traditional work. There are certainly more contourite systems to be found along the Iberian margin, so that their importance within the deep-sea context will be even greater than today. The new maps of simulated bottom currents presented here will help define where new drifts and CDSs

may be found, even within the camouflage of major downslope systems (Fig. 11).

Although the present study has shown that the numerically simulated bottom-current data are overall consistent with observed bottom-current and sediment patterns in the region, one should be cautious by recognizing the constraints of these findings. In some areas, the simulated velocities do not match the data collected by current meter or inferred in terms of bedforms. For example, this is the case on the slope north and northeast of the island of Menorca, where there are independent observations of relatively strong bottom currents (Mauffret et al. 1982; Maldonado et al. 1985; Palanques et al. 1995; Velasco et al. 1996; Acosta 2005). Indeed, near-bottom current measurements at 1,800 m water depth on the Gulf of Lion deep margin, where WMDW formation takes place (Millot and Monaco 1984), gave mean values of 20 cm/s (maximum of 50 cm/s), contrasting strongly with the much lower simulated mean bottom velocities for this area. Another example is the middle slope of the Gulf of Cadiz, where the simulated values probably considerably underestimate the real values, because MOW flow reaches nearly 300 cm/s close to the Strait of Gibraltar, slowing regionally to ~80 cm/s at Cape St. Vincent (Kenyon and Belderson 1973; Ambar and Howe 1979; Cherubin et al. 2000) but remaining highly variable locally (Serra 2004; Serra et al. 2010b) and increasing substantially due to seafloor irregularities (Hernández-Molina et al. 2006; García et al. 2009; Stow et al. 2009). Tidal variability would largely explain this disagreement between simulated and observed velocities. Within these constraints, the simulations constitute an important first-stage estimate for the margin as a whole.

Thus, the numerically simulated bottom-current data provided here represent average velocity values, by definition not automatically accounting for site-specific natural variability. In fact, bottom-current velocities and, for that matter, instantaneous direction can vary considerably over a wide range of spatiotemporal scales (e.g. Gross and Williams 1991; Rebesco and Camerlenghi 2008). This may be as short as 24 h, due to the influence of deep-water tidal dynamics, internal waves or solitons (Rebesco and Camerlenghi 2008; Stow et al. 2009), a few weeks due to eddies, vortices and episodic benthic storm events (Hollister 1993; Stow et al. 2009; Serra et al. 2010b), seasonally as a result of winter convection (Canals et al. 2006), and tens to thousands of years due to other key factors modulating bottom-current generation and transport pathways (Rebesco and Camerlenghi 2008; Stow et al. 2009). The fact remains that the data presented in this work (Fig. 7) identify several key areas where highest mean bottom-current velocities occur, forming a solid basis for future regional modelling exercises and predictions for other areas.

Processes, products and their implications

Large contourite depositional and erosional features such as found along the Iberia margin are generated by relatively stable hydrological conditions leading to long-term bottom-water flows (Rebesco and Camerlenghi 2008). The present model of water-mass circulation and its dynamics around Iberia was initiated after the opening of the Gibraltar gateway at the end of the Miocene (5.4–5.6 Ma; Berggren and Hollister 1974; Mulder and Parry 1977; Maldonado et al. 1999; García-Castellanos et al. 2009), when the isolation of the Mediterranean Sea and the global effects of the Messinian salinity crisis ended (Ryan et al. 1973; Hsü et al. 1978; Duggen et al. 2003). However, major effects of MOW circulation were probably delayed until the gateway had deepened sufficiently to enable its major outflow about 4.0–4.2 Ma ago (Hernández-Molina et al. 2009c). The most recent hydrodynamic situation was fully established later but not before the beginning of the Quaternary (~2.4–2.6 Ma), contemporaneously to the global cooling which initiated the glacial–interglacial cyclicality of the Pleistocene (e.g. Thunell et al. 1991). Work on the Alboran Sea, Gulf of Cadiz and Le Danois CDSs has identified their evolution to be similar in terms of coeval palaeoceanographic changes in water masses (Llave et al. 2001, 2006; Ercilla et al. 2002; Hernández-Molina et al. 2002, 2006; Stow et al. 2002c; Van Rooij et al. 2010a). There was a further change in the nature of contourite depositional and erosional features coeval with the mid-Pleistocene revolution (0.9 Ma), due to the switch to a “full glacial” mode with 100 ka cyclicality (Llave 2003; Llave et al. 2007; Van Rooij et al. 2010a). Changes in water-mass circulation and associated marine sedimentation patterns occurring since then due to climatic and eustatic influences are partially known (e.g. Grousset et al. 1988; Vergnaud-Grazzini et al. 1989; Nelson et al. 1993; Zahn et al. 1999; Schönfeld and Zahn 2000; Cacho et al. 2000; Shackleton et al. 2000; Schönfeld et al. 2003; Llave et al. 2006, 2007; Voelker et al. 2006; Frigola et al. 2007, 2008; Lebreiro et al. 2009; Lebreiro 2010; Voelker and Lebreiro 2010; Bender et al. 2010; Gonthier et al. 2010; Mena et al. 2010).

The establishment of present-day along-slope oceanographic processes has some important implications which are examined below based on the combination of numerically simulated bottom currents with existing knowledge of contourite features (also see Fig. 11).

Continental margin studies

Weaver et al. (2000), Mienert and Weaver (2003) and Benetti (2006) have characterized the Atlantic continental margin based on sedimentary processes. As in earlier work, however, their model significantly underplays the role of along-slope processes in margin evolution. It is largely for

this reason that the present data for the Iberian margin are not consistent with the models proposed by those authors. Along-slope processes around Iberia are generated mainly by MOW circulation in specific areas (e.g. Gulf of Cadiz, Portuguese margin, Galician margin and Cantabrian margin), leading to the formation of extensive contourite drifts and CDSs, especially during the Quaternary.

Sedimentary controls

The development of both depositional and erosional contourite features depends not only on bottom-current velocity (cf. above) but also on several other important control factors, including (1) local margin morphology: particular inherited geological features which shape the morphology of the margin, and various slope irregularities (cf. above), facilitating local water-mass interaction with the seabed; (2) sediment supply: for example, downslope supply from submarine canyons, slides and debris flows; suspended sediments from the shelf break or pirated by water masses and deposited along-slope; sand spillover from adjacent shelves and hinterland; local and more distal erosion by impinging water masses; (3) local MOW oceanographic behaviour: some slope irregularities represent specific obstacles for water-mass circulation, and this can generate increased velocities resulting in local turbulence, eddies, cores, filaments, secondary flows, etc., all of which affect local erosional and depositional contourite features; (4) sea-level and climate change: arguably the most challenging area of future work on along-slope processes and products.

Geohazards

Combination of simulated bottom velocities around Iberia and seafloor mapping of bottom-current bedforms along the margin can be of great significance in potential hazard mapping. Furthermore, there is a direct link between bottom-current velocities and bedforms based on the bedform-velocity matrix of Stow et al. (2009). Together, these data can provide information on likely seafloor current velocities and, hence, their possible threat to seafloor structures, submarine cables and pipelines. Furthermore, there is a growing awareness of the link between bottom-current activity and slope instabilities leading to major downslope slumping and sliding.

Water-mass structure

Two specific elements of water-mass structure have important implications for along-slope systems:

1. The development and maintenance of large gyres (eddies or Meddies) which, although very variable,

serve to concentrate the highest bottom-current energy in time and space (Serra 2004; Serra et al. 2010b). This can lead to periodic benthic storm events.

2. The fact that some of the water masses circulating around the Iberia margin have remarkable density contrasts. This in turn leads to the development of internal waves and/or solitons along the interface between these water masses (Cacchione et al. 2002; Apel 2004).

Any disturbance penetrating the pycnocline is capable of generating internal waves but their generation usually is conditioned by tidal influence (Apel 2000, 2004). Energy associated with these internal waves is locally important around the Iberia margin, which could explain why simulated velocities are higher than in surrounding areas, as in the West Alboran Basin. In the Strait of Gibraltar, the Camarinal and Spartel sills produce solitons with amplitudes of 50 to 100 m and wavelengths of 2 to 4 km (Armi and Farmer 1988; Farmer and Armi 1988; Brandt et al. 1996; Jackson 2004), reaching at least 200 km into the Western Mediterranean and persisting for more than 2 days before decaying to background levels (Apel 2000; Jackson 2004). This is also the case along the north-western coast of the Iberian Peninsula and around the Galicia Bank where large internal wave occurrences have been reported (Correia 2003; Jackson 2004). The interaction of internal waves or solitons with the sea bottom affects depositional and erosional processes. In particular, the density interface associated with internal waves has been postulated as a major mechanism in the production and maintenance of intermediate and bottom nepheloid layers (McCave 1986; Dickson and McCave 1986; Cacchione et al. 2002; Puig et al. 2004).

Biota and bottom currents

There are strong relationships between specific deep-water biotic communities, bottom-water flow, sediment substrate type, and local geological processes (e.g. Howe et al. 2004; OSPAR 2006; Reveillaud et al. 2008; Van Rooij et al. 2010b). This is evidenced by, for example, the occurrence of chemosynthetic communities associated with carbonate mounds and mud volcanoes, and of cold-water coral (CWC) ecosystems along the paths of bottom currents. Indeed, the discovery of CWC mounds along the Galicia Bank (Ercilla et al. 2009, 2010), the Bay of Biscay and Cantabrian margin, and the Porcupine Seabight (Van Rooij et al. 2003, 2010b; Huvenne et al. 2009) has been clearly associated with MOW dynamics. Additionally, MOW density seems to be highly beneficial for benthic ecosystems by maintaining nutrients in suspension, and possibly by providing a “connectivity” link for the dispersal of CWC

larvae (Dullo et al. 2008). Strong bottom currents are required to deliver re-suspended nutrients to cold-water coral ecosystems (Roberts et al. 2006). Therefore, bottom currents are a key environmental factor influencing the growth and maintenance of deep-water biotic communities, as well as an important risk factor possibly leading to substratum erosion and collapse, and ecosystem silting up (Van Rooij et al. 2010b).

Mineral and energy resources

Contourite systems are recognized as having a mainly unexplored potential for both mineral and energy resources (e.g. Teleki et al. 1987; Earney 1990; Seibold and Berger 1993; Shanmugam 2007; Viana and Rebesco 2007; Viana 2008, 2010; Rebesco and Camerlenghi 2008). For example, the development of specific mineral resources such as ferromanganese nodule fields depends directly on the seafloor being swept by strong bottom currents (Van Andel et al. 1977; Kennett 1982; Cronan 2003). It was for this reason that Faugères and Stow (1993) suggested *manganiferrous contourites* as a typical marine contourite facies. These are associated mainly with contourite channels and moats (Faugères and Stow 1993; Faugères et al. 1993) or banks and seamounts (Kennett 1982; Cronan 2003) where higher bottom-current velocities usually exist, as has been described for the Gulf of Cadiz (Mélières et al. 1970; González et al. 2009, 2010a, b). The highest-velocity bottom currents have been demonstrated as being fully capable of winnowing of finer-grained material and also of coarser-grain transport, resulting in the building of extensive sandy sheeted drifts such as that in the proximal Gulf of Cadiz. Where buried in the subsurface, these provide a potential reservoir target for oil and gas resources.

In conclusion, the findings and arguments of the present study convincingly demonstrate that simulated bottom-current velocities around Iberia are very useful for a better understanding of the detailed nature of bottom currents and of how they erode, transport and deposit sediments. It is clear that the role of bottom currents in shaping continental margins has been generally significantly underestimated, and that other parts of most margins will have still unknown and unexplored contourite systems, with challenging implications for future research, resource exploration and ecosystem management.

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Appendix

Water-mass compilation for both the Western Mediterranean and North Atlantic: Fig. 3, deep-water circulation; Fig. 4, intermediate water circulation; Fig. 5, surficial water circulation, based on data and arguments from the following authors: Wüst (1936, 1961), Madelain (1970), Kelling and Stanley (1972), Kenyon and Belderson (1973), Mélières (1974), Thorpe (1975), Zenk (1975), Stanley et al. (1975), Ambar and Howe (1979), McCartney and Talley (1982), Gardner and Kidd (1983, 1987), Fiúza (1984), Bryden and Stommel (1984), Gascard and Richez (1985), Pollard and Pu (1985), Dickson et al. (1985), Parrilla and Kinder (1987), Caralp (1988, 1992), Haynes and Barton (1990), Herburn and La Violette (1990), Pingree and Le Cann (1990), Zenk and Armi (1990), Garrett et al. (1990), Perkins et al. (1990), Cano and García (1991), Ochoa and Bray (1991), McCartney (1992), Nelson et al. (1993, 1999), Reid (1994), Ambar and Fiúza (1994), Arhan et al. (1994), Bryden et al. (1994), Daniault et al. (1994), Pollard et al. (1996), Paillet and Mercier (1997), Mazé et al. (1997), Díaz del Río et al. (1998), Fiúza et al. (1998), Paillet et al. (1998, 1999), Millot (1999), Baringer and Price (1999), Iorga and Lozier (1999), OSPAR (2000), van Aken (2000, 2002), Johnson and Stevens (2000), Cherubin et al. (2000), Richardson et al. (2000), Samthein et al. (2000), Weaver et al. (2000), Candela (2001), Mauritzen et al. (2001), Borenäs et al. (2002), Hernández-Molina et al. (2002, 2006), Huthnance et al. (2002), Slater (2003), Serra (2004), Valencia et al. (2004), Díaz del Río (2006), González-Pola (2006), Sánchez et al. (2006), García Lafuente et al. (2008), García et al. (2009), Legg et al. (2009), Serra et al. (2010b), Van Rooij et al. (2010a), Stow et al. (unpublished data).

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