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

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Abstract

The present contribution represents the first attempt to comprehensively describe regional along-slope processes and their sedimentary impacts around the Iberian margin, combining numerically simulated bottom currents with existing knowledge of contourite depositional and erosive features. The obtained correlation links the circulation of water masses with the main contourite depositional systems (CDS) and estimates other potential areas where new CDS could be found. Their study should be of great interest not only because of the stratigraphic, sedimentological, palaeoceanographic and palaeoclimatological significance, but also because of their relation with possible specific deep marine geohabitats and/or mineral and energy resources.

Key words: *Water-mass circulation, simulated bottom current velocities, along-slope processes, contourites, Iberian margin.*

Introduction

Along-slope oceanographic processes related to near-bottom currents generate large erosive and depositional features (drifts), which together shape Contourite Depositional Systems (CDS) or mixed contourite-turbidite systems, where bottom currents have interacted with down-slope processes (Faugères *et al*., 1999; Stow *et al*., 2002a; Viana and Rebesco*,* 2007; Hernández-Molina *et al.*, 2008a,b; Rebesco and Camerlenghi, 2008). However, when the water masses flowing along the continental slope are energetic enough, they can mask the effects of down-slope processes and generate complex CDS's of huge dimensions (10^3-10^6 km^2) and sedimentary thicknesses (> 2000 m) comparable in extent with large Turbidite Depositional Systems (Zhenzhong *et al.,* 1998; Faugères *et al*., 1999; Stow *et al.*, 2002a). Some of the better-known cases are those located along-slope of the Gulf of Cadiz (Nelson et al., 1993, 1999; Llave *et al*., 2001, 2007; Hernández-Molina *et al.*, 2003, 2006; Mulder *et al.,* 2003, 2006; Habgood et al., 2003), Porcupine Seabight (Van Rooij *et al*., 2003; Øvrebø *et al*., 2006); offshore southern Greenland (Hunter et al., 2007); offshore Brazil (Viana *et al*., 2002a, b; Viana and Rebesco, 2007) and along the Argentine margin (Hernández-Molina et al., 2009a).

The study of along-slope processes and their deposits in general, and the CDS's in particular, has represented one of the most active lines of research in Marine Geology during the last decade, mainly because of their very great stratigraphic, sedimentological, palaeoceanographic, and palaeoclimatological significance; their close link with sediment instability on continental slopes; and because of their direct relation with possible mineral and energy resources (Pickering *et al*., 1989; Stow *et al*., 2002b; Rebesco, 2005; Viana and Rebesco*,* 2007; Rebesco and Camerlenghi, 2008; Hernández-Molina et al., 2010a).

International projects, such as the oceanic drilling programmes **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 ocean basins. 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 and 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, 1987; Derégnaucourt and Boillot, 1982; Comas and Maldonado, 1988; Boillot 1979; Nelson y Maldonado, 1990; Maldonado and Nelson, 1988, 1999, Maldonado and Comas, 1992; Estrada et al., 1997; Pérez-Belzuz et al., 1997; Pérez-Belzuz, 1999; Maldonado et al., 1999; Vazquez, 2001; Iglesias, 2009, among many others). The circulation of water masses around Iberia leads to the development of along-slope currents generating, in turn, contourite erosive and depositional features that form extensive, complex and often poorly known CDS's of large dimensions and sediment thickness in different geologic contexts. These have a valuable sedimentary record of their geological evolution, since the Iberian margins lie under the influence of several different water masses, some of which impinge upon the seafloor with relatively high velocity and interact along the middle and upper continental slope.

Although, there are many scattered bottom current measurements along the margin, there is still a major lack of long-term records as well as areas with very few or no measurements. Whereas mean velocities are commonly relatively low (5-15 cm/s), these are greatly exceeded in some places, reaching normal values > 80 cm/s and rarely almost 300 cm/s, as at the exit of the Strait of Gibraltar (Ambar and Howe, 1979; Iorga and Lozier, 1999; Candela, 2001). Clearly, therefore, bottom currents are a major controlling factor on along-slope sedimentation and in shaping the deep seafloor (Stow et al., 2009). They are semi-permanent features of deep ocean circulation, which vary in location and velocity over a range of timescales. They operate at a range of 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, moat, and furrows (Hernández-Molina et al., 2008b). Stow et al. (2009) published recently 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 the likely contourite features under a particular bottom current velocity regime.

As part of this special volume of the Baiona International Congress on "*Deep-Water Circulation: Processes and Products*" (Baiona, Spain, 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: (a) to combine previous work and new regional data on along-slope processes and their sedimentary impacts around Iberia; (b) to combine for the first time numerically simulated bottom currents with existing knowledge of contourite depositional and erosive features; and (c) to use these data to better link the circulation of water masses with the main CDS's, both known and as yet unexplored, and to consider their future implications.

Methods and data base

This work synthesizes a large amount of both our own and published data from the Iberian margin in the following broad areas.

a) Characterization of water masses and their dynamics.

A compilation of data and results about the water masses around the Iberian margins and their dynamics, both in the Mediterranean Sea and in the Atlantic Ocean, has been realised and simplified for this contribution. Physical oceanographic compilation was gathered from bibliographic sources, based on data and ideas from many authors (Fig. 2 and 3). A compilation of water masses like the one presented here is extremely difficult and complex since there is a great heterogeneity in both data coverage and terminology. Therefore, our compilation should be considered as a preliminary sketch for evaluating the along-slope processes around Iberia and further improvements will undoubtedly be necessary to update and improve this first compilation. A special emphasis have been realized related the Mediterranean water masses, especially to the Mediterranean Outflow Water (MOW), since many along-slope processes are related to its circulation.

b) Numerical bottom current circulation

The numerical ocean simulations were performed with the MIT general circulation model (Marshall et al., 1997), which is a primitive-equation z-coordinate ocean model. The computational domain included the Northeast Atlantic and Western Mediterranean regions and extended 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 and 140 levels were used in the vertical, with resolutions varying from 5m in the upper ocean to 100m 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 used to force the ocean model 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 m^4 s^{-1} and 5×10^8 m^4 s^{-1} for diffusion and viscosity, respectively. The model was integrated for the 6-year period 1990-

1995 and the analysed daily-averaged results correspond to the 3-year period 1993-1995. The present simulations were previously analyzed in Serra et al. (2010b) with focus on the vertical structure of the model generated Mediterranean Water eddies and their interaction with the 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.

c) Along- slope (contourite) sea bottom feature characterization

We have compiled a broad database and from separate publications, noting details around Iberia of contourite depositional and erosive features, bedforms, substrate and current velocity as available. These data have enabled us to: a) identify where known CDS's are located, b) determine the major common features and their differences, outlining their role in the recent slope evolution; c) combine along-slope (contourite) sea bottom feature characterization with numerically simulated bottom currents.

Characterization of contourite features on sea-bottom has been executed including data from the Western Mediterranean Sea (Canals, 1985; Velasco *et al*., 1996; Frigola et al., 2007; 2008. Esteras et al., 2000; Ercilla et al., 2002), and the Atlantic Iberian margins (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, 2009b, 2010; Mulder *et al*., 2003, 2006; Van Rooij *et al*., 2003, 2010a; Øvrebø *et al.,* 2006; Hanquiez *et al*., 2007; Ercilla et al., 2008a and b; 2009, 2010; Marchès *et al*., 2007; Garcia et al., 2009; Iglesias, 2009; Bender et al., 2010; Mena et al., 2010). These data include: a) *Bathymetric data*, mainly regional bathymetric data from mono- and multi beam echosounders; b) *Sidescan sonar data*, available from some areas and providing useful backscatter imagery of the sea bottom; c) S*eismic reflection data*, including low-resolution reflection Multichannel seismic (MCS) reflection profiles; medium/high-resolution seismic profiles (from Sparker & Airgun systems); very high-resolution seismic profiles using mainly 3.5-kHz system and TOpographic PArametric Sounder (TOPAS); d) *Core and borehole data* from different surveys, incorporated into the study of some areas, for groundtruthing seismic facies patterns, and in order to analyze the timing of the processes responsible for the development of the depositional units and to establish the chronology of the units; e) *Submarine photographs* as locally available (mainly in the Gulf of Cadiz); f) *Physical oceanographic data* taken on several of our own cruises comprising CTD and XBT profiles, which yield temperature and salinity information. Compilation and interpretation of this oceanographic data and its correlation with the morphologic features have already been published for some areas (García, 2002; Mulder et al., 2003; 2006; Hernández-Molina et al., 2006; 2009c).

Terminology

There is a growing consensus within the marine science community about the terminology to use for these along-slope sedimentary systems. We follow this terminology as far as possible. The term *bottom current* is preferred as the general term for those semi-permanent deep-water currents capable of eroding, transporting, and depositing sediments on the sea-floor (Rebesco and Camerlenghi, 2008). Bottom currents are the result of both THC and the major wind-driven circulation pattern of the oceans. Generally, these currents are semi-permanent in nature with a net flow along-slope, but can be extremely variable in direction and velocity, plus exhibit giant eddies, and local downslope, upslope or oblique-to-slope flow, especially near the basin's entrance or exit gateways (Rebesco and Camerlenghi, 2008).

The term *contourite* is now generally accepted as the term for those sediments deposited or substantially reworked by bottom currents and contour currents *sensu stricto.* The major accumulations of contourite deposits are referred to as *drifts* or *contourite drifts*, for which several classifications have been proposed mainly based on their morphologic, sedimentological and seismic characteristics (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 has been termed a *contourite depositional system* (CDS), by analogy with and of equal importance to *turbidite depositional systems* (Stow et al., 1986, 2002b; Hernández-Molina et al., 2003; 2006, 2008a). In the same way, where different CDS's are connected laterally (and vertically) and associated with the same water mass in the same or adjacent basins, we can consider this as a *contourite depositional complex* (CDC, Hernández-Molina et al., 2008a).

Circulation of water masses around Iberia: oceanographic processes

a) Water masses and dynamics around Iberia.

Around the Iberian margins, both in the Mediterranean Sea and in the Atlantic Ocean, there are several water masses flowing at different depths and in the same or opposite directions, which generate important along-slope sedimentary processes at the seafloor.

In the Mediterranean Sea, there are several places where dense water masses are generated (Fig. 2), such that the Western Mediterranean Sea 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 A), generated in the *Gulf of Lion* where convective processes are known to reach depths up to 2000 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 Western Basin of the Alboran Sea, this water mass mainly flows along the Moroccan margin (Fig. 3). 2) Between 500 and 150 m water depth, the basin is occupied by *Levantine Intermediate Water* (LIW, Fig. 3 B), formed by convection in the Eastern Mediterranean and having passed through the *Sicilian Strait*. Around Iberia, the LIW preferably flows along the upper and middle continental slope (Fig. 3). 3) The upper layer (< 150 m) is formed by the inflow of Atlantic Water through the Gibraltar Strait (*Modified Atlantic Water,* MAW. Fig. 3 C). Although these aforementioned water masses are generally recognised, Millot (2009) very recently has considered a more complex structure and dynamics of five water masses along the western Mediterranean, including light versus dense Mediterranean water masses.

On the other hand, around the Atlantic Iberian margin, five main water masses have been more clearly identified (Fig. 3A, B and C) (e.g. Iorga & Lozier, 1999; González-Pola, 2006; Serra et al., 2010b, among others). These are, from bottom to top: 1) the Lower Deep Water (LDW) (mainly composed of Antarctic Bottom Water, AABW, Fig. 3 A), flowing regionally below 4000 m mainly across the abyssal plains; 2) the North Atlantic Deep Water (NADW, Fig. 3 A), flowing in different directions between 4000 and 2200 m depth; 3) the Labrador Sea Water (LSW, Fig. 3 B), circulating regionally towards the SW between 2200 and 1500 m depth (main core at ~1800 m); 4) the Mediterranean Outflow Water (MOW, Fig. 3 B), located between 1500 and 600 m depth, with the main core at ~1200 m flowing to the N and W along the middle slope around the Iberian margin into the Bay of Biscay; and 5) the North Atlantic Central Water (NACW, Fig. 3 C) flowing in a complex circulation pattern with different currents and directions between 600 m and the surface (main core at ~350 m).

Amongst these, the MOW is the most important in terms of along-slope processes and CDS development. After its exit through the Gibraltar Gateway, the MOW represents an intermediate water mass, warm and very saline which flows to the NW along the middle slope (Fig. 3B) under the *Atlantic Inflow* (AI) and above the NADW (Zenk, 1975; Thorpe, 1975; Gardner and Kidd, 1983; Ochoa and Bray, 1991; Baringer and Price, 1999). It represents a flux of around 1.78 Sv through the Gibraltar Gateway, composed of both LIW and WMDW (Bryden and Stommel, 1984; Bryden *et al*., 1994), and generates important along-slope sedimentary processes along the Atlantic margin (Serra et al., 2010b). In the Gulf of Cadiz, it flows between 500 and 1400 m depth with a velocity close to 300 cm/s at the Strait (Ambar and Howe, 1979) and around 80-100 cm/s at 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, between 500-700 m depth (Upper core or *Mediterranean Upper Water,* MU), and between 800 and 1400 m depth (Lower Core or *Mediterranean Lower Water,* ML). The ML is further subdivided into three branches (Fig. 3B) (Madelain, 1970; Zenk, 1975; Ambar and Howe, 1979; Johnson and Stevens, 2000; Borenäs *et al*., 2002). In the western sectors, the interaction of these branches with the seafloor generates big *meddies* (Richardson *et al*., 2000).

After exiting the Gulf of Cadiz, the MOW shows three principal branches (Fig. 3B): the main one flows to the North, the second to the W, and the third to the S reaching the Canary Islands, and then veering towards the W (Iorga and Lozier, 1999a; Slater, 2003). The northern branch flows along the middle slope of the Portuguese margin, being divided in two by the influence of the Galicia Bank (Fig. 3B). These two branches return to converge and subsequently circulate to the E in the Gulf of Biscay following the continental slope contour (Fig. 3B). The MOW reaches the *Porcupine Bank* and partly circulates to the N along the *Rockall Trough* until reaching the Norwegian Sea (Iorga and Lozier, 1999a; Slater, 2003).

b) Simulated bottom velocities around Iberia.

Analysing the simulated average bottom velocity (cm/s) and standard bottom velocity (cm/s) from Figures 4 and 5, one of the principal observations 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 around Iberia. In our discussion below, we adopt the following notation for mean bottom current velocities, while recognising 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 and 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.

Within the Western Mediterranean Sea the greater velocities are found mainly on shelves and over the abyssal plains (Fig. 4 and 5), whereas most of the slope domains are swept by waters masses with low velocities (<4-5 cm /s). Nevertheless, in this general context the continental slopes that bound the Alboran Sea are an exception. Here the WMDW and LIW have slightly higher velocities associated with submarine scarps, local seamounts, and both slopes and abyssal plains of the western basin (Fig. 4 and 5). Along the Moroccan slope major velocities are along the middle and lower slope remain quite low (> 6 cm/s, Fig. 4 and 5), due to the LIW and WMDW circulation respectively. Along the northern Spanish slope, the higher velocities are also of similar low magnitudes and mainly located on the upper slope associated with the inflow of Atlantic Water through the Gibraltar Strait.

On the continental shelves of the Western Mediterranean Sea bottom simulated current velocities values are generally just over 5 cm/s (but locally over 10 cm/s), not only around the continent, but also on the continental shelf around the Balearic Islands (Fig. 4 and 5).

Simulated bottom current velocities on the abyssal plains are generally lower, especially under the 2000 m water depth due to the circulation of the WDMW. Average values are 3-4 cm/s, with relatively higher velocities mainly located on the lower slope around the Balearic Promontory and also in borders around the Algero-Provençal abyssal plain. Here the bottom-current velocities reach 10 cm/s, especially along the African margin (Fig. 4 and 5). Again, in this general context, the abyssal plain of Western Alboran Basins has several areas with bottom current velocities values up to 5 cm/s. These areas look like circular and are possibly related to eddies from the WMDW circulation (Fig. 4 and 5).

The Strait of Gibraltar itself has very high bottom current velocities related to the overflow of the MOW, up to a maximum recorded velocity of 2.8 m/s near the seafloor. Throughout the Gateway region velocities are everywhere over 10 cm/s, and range from > 90 cm/s near the exit of the Straits to > 50 cm/s several hundred kilometres downstream in the Gulf of Cadiz (Fig. 4 and 5).

Along the Atlantic Ocean margin around Iberia, the highest simulated bottom current velocities are identified over the western and northern shelves, and especially along the middle slope (Fig. 4 and 5). Along-slope processes are therefore dominant along the middle slope of Gulf of Cadiz related to circulation of both the Upper (MU) and Lower (ML) strands. Here, simulated bottom current velocities are over 10 cm/s, and commonly with values of 50-90 cm/s. Over the rest of the Atlantic Iberian slope, the highest velocities are also identified along the middle slope (Fig. 4), with common values > 10 cm/s (and locally > 50 cm/s) associated with the northern branch of the MOW along the Portuguese, Galicia and Cantabrian slope. The upper and lower slope, in general, has simulated bottom current velocities with lower velocities of about < 4-5 cm /s, although where associated with large seamounts and banks (such as the Extremadura Spur; Oporto, Vigo and Vasco de Gama seamounts; and the Galicia Bank), velocities > 9-10 cm/s can be found.

Bottom-current velocities across the Atlantic abyssal plains are quite variable and can be high to very high. In the Madeira, the Horseshoe, the Tagus, and the Iberia abyssal plains, the highest velocities are mainly located along their eastern boundaries (e.g. at the base of the Madeira-Tore Rise or base of the Galicia Bank) often reaching 10 cm/s, and locally > 50 cm/s. More rarely, locally high values are found along their western boundaries (Fig. 4 and 5) or, within the Union basin, along its northern flank. Bottom current processes at this scale in these abyssal plains are associated with the LDW north-eastern circulation. Compared with these aforementioned abyssal plains, bottom current velocities over the Agadir, Sena, Biscay and Porcupine abyssal plains (Fig. 4 and 5) 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 (Fig. 4 and 5), and relatively higher bottom current velocities are also identified within them.

In the oceanic domain, away from the abyssal plains, the simulated 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 the water-mass circulation and high bottom current velocities (10-20 times in magnitude their average velocity) are also identified around their flanks, reaching locally values > 50 cm/s (Fig. 4 and 5). In fact, one important observation is that, depending of the seamount location the position of the highest bottom current velocities is different. In this sense, the Ampere and Coral Patch Seamounts have the highest velocities along their northern flanks; the Madeira Island, DSM, USM and SSM seamounts have the highest velocities on their SE flanks; and although around the Atalante and Charcot Seamounts there are generally low bottom current velocities, the highest values are identified on their northern flanks. Over irregularities in oceanic crust located in the NW sector of Figures 4 and 5, south from the King´s

Trough, the highest bottom current velocities are related to the western and south-western flanks of oceanic highs. North from the King´s Trough the distribution of the highest simulated bottom-current velocities is less clear.

Circulation of water masses around Iberia: products

Circulation of water-masses around the Iberia margin, in both the Mediterranean Sea and Atlantic Ocean, has produced a number of individual contourite drifts, and several different contourite depositional systems (CDS), each involving two or more drifts and associated erosional elements (Fig. 6). Within the Western Mediterranean Sea, three systems are documented under the influence of the LIW and WMDW (Fig. 6 and 7).

1) Along the NE Catalonian slope (Fig. 6), Canals (1985) defined the possible occurrence of contourite features at Rosas between 1200 and 2300 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 (Canals, 1985).

2) NW of Menorca, on the lower slope at depths up to 2000 m (Fig. 6), there is a broad, low-relief but distinct contourite drift. It is a plastered drift about 150 km in length and 25 km wide with a contourite moat along its seaward margin (Maufret, 1979; Velasco *et al*., 1996) (Fig. 7). The drift is mud dominated and has about 100 m of relief above the adjacent sea floor. This contourite drift was generated by deep bottom currents belonging to the southward branch of the WMDW flow, which borders the Valencia Trough from north to south following a cyclonic pattern at depths of 2000m (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. 6), running parallel to the Moroccan middle slope at a water depth of 200–700 m (Ercilla et al., 2002). This drift is probably the best known drift in the Western Mediterranean to date. It is mainly characterized as an elongated plastered drift deposited over a slope terrace, with a broad lenticular geometry. It is around 100 km long, 28 km wide, with a relief of up to 400 m above from the surrounding sea-floor (up to 700 milliseconds two-way travel time, Fig. 7). It is formed under 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 divided into five prograding seaward units, with seismically stratified facies that produce reflections with high lateral continuity and amplitude, converging both seaward and landward (Fig. 7). 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.

Within the Strait of Gibraltar the major defined processes 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 in several cruises, no distinctive contourite features have been published thus far, apart from several large depressions and large channels that might be associated with the MOW circulation (Esteras et al., 2000).

Along the Atlantic Iberian margins the following drifts and CDS's are known to have been generated (Fig. 6 and 7):

1) The interaction of the MOW 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 west Iberian margin (Fig. 6). Many authors have highlighted this interaction and have characterized its erosive and depositional features along the middle slope (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. 7), conditioned by a strong current with speeds reaching nearly 300 cm s^{-1} close to the Strait of Gibraltar, slowing to ~80 cm s^{-1} at Cape St. Vincent (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. All of them have a specific location along the margin, and their distribution defines five morphosedimentary sectors within the CDS (details are to be found in Hernández-Molina et al. 2003, 2006 and Llave et al., 2007). The development of each of these five sectors at any time is related to a systematic deceleration of the MOW as it flows westwards from the Strait, due to its interaction with margin bathymetry, and to the effects of Coriolis force. In general, the drifts are mainly composed of muddy, silty and sandy sediments, with a mixed terrigenous (the dominant component) and biogenic composition (Gonthier et al., 1984; Stow et al., 1986, 2002c). By contrast, within the large contourite channels, sand and gravel are found (Nelson et al., 1993, 1999) as well as many erosional features (Hernández-Molina et al., 2006; Garcia 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 that average 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) have described the occurrence of contourite features (Fig. 6), both along the middle slope as well as the continental rise. Middle slope drifts are associated with the interaction of the MOW with different sectors of the middle slope of the Atlantic Iberian margin (Fig. 7), but, on the contrary, drifts located on the rise have been attributed to the local influence of AABW (LDW) north-eastern circulation (Alves *et al.,* 2003).

3) Contourite features have been recently defined around the Galicia Bank (Fig. 6), and those around the highs and topographic irregularities of the Transitional Zone, Deep Galicia Margin, and Northwestern Flank of the Galicia Bank (Ercilla et al., 2006, 2009, 2010). The main features described include moats, erosive and constructional furrows, abraded surfaces, large drifts (mainly elongated separated, and plastered) and sediment waves (Fig. 7). 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 1700 and 2300 m water depth (Fig. 6), elongated separated drifts mainly composed of muddy sediments have been described recently (Bender et al., 2010; Mena et al., 2010). Their genesis is attributed to the local slope morphology interacting with the Deep Intermediate Water mass (DIW), which flows parallel to the slope, as well as their proximity to shelf export pathways (Bender et al., 2010; Mena et al., 2010).

4) At Ortegal Spur, a CDS has been identified very recently, related to the MOW circulation along slope (Fig. 6) between 500-600 m and about 1500-1600 m (Hernández-Molina et al., 2009c). The interaction of the impinging MOW from west with the Ortegal Spur has generated a contourite depositional system (CDS) composed of erosive and depositional features (Fig. 7). The erosive features comprise terraces of tens of meters of relief and several hundreds of meters long, and moats of tens of meters of relief and of hundreds meters wide. The main depositional features (drifts) include plastered to mounded, elongated types (tens of meters thick). Sediment samples collected from the near surface of these drifts contain fine sands to muddy sandy (Hernández-Molina et al., 2009c), 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 on the Cantabrian margin (Fig. 7), at the Le Danois Bank or "Cachucho" (Ercilla *et al*., 2008a and 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 the MOW circulation, conditioned by seafloor irregularities and two topographic highs; the large Le Danois Bank and the smaller Vizco High. This has allowed the development of the present-day depositional and erosive features, such as respectively elongated mounded and separated drifts, plastered drifts, moats and slide scars (Van Rooij et al., 2010a).

Discussion

Numerical simulation of bottom currents

The circulation of water masses around Iberia leads to the development of along-slope currents and to the generation of contourite erosive and depositional features, in some places forming complex CDS's of large dimensions and sediment thickness (Hernández-Molina et al., 2009b, 2010b). The general link between bottom current and deposits are well established and, although they are not well known in detail, their sedimentary record will yield important information regarding their geological evolution and palaeoclimate variation. Most of the drifts and CDS's described thus far are located on the slope. In the Mediterranean Sea they are located on the middle (Rosas and Alboran CDS) and lower (Menorca and Alboran CDS) slope due to the influence of the WMDW and LIW. Whereas on the Iberia Atlantic margin they are mostly located on the middle slope associated with the remarkable influence of the MOW. This is the case of the CDS´s located in the Gulf of Cadiz, Portuguese slope, Galicia Margin, Ortegal Spur, and Le Danois Bank. The influence of MOW stretches far outside the present study area to the N, to the Porcupine Seabight and other parts of the NW European margin. Very few examples of contourite features are associated in the Iberia Atlantic margin with other water masses, only locally in the Portuguese margin (Alves et al., 2003) and the surrounding areas of the Galicia Bank (Ercilla et al., 2009, 2010).

This paper represents the first attempt to combine numerically simulated bottom currents with existing data on contourite features. Immediately it can be demonstrated that the highest simulated bottom currents are very coincident with the distribution of contourite drifts and CDS's (Fig. 8). In addition, there are other areas with high simulated bottom current velocities but no previous description of any CDS. Nevertheless, some large features related to the effect of bottom-current circulation have been published, such as around the southern and southern east flanks of the Madeira Island and within the Agadir slope, where large sedimentary wave fields were noted (Wynn et al., 2000).

Furthermore, numerically simulated bottom currents allow the identification of other areas where contourite processes can also be found, not only associated to the MOW but also to other water masses. For example, two major areas in deeper water can be identified (Fig. 8): a) the continental slopes of the Alboran Sea and Atlantic Iberian margins; and b) the abyssal plains. In the Algero-Provençal abyssal plain, bottom-current velocities are up of 10 cm/s, especially in its southern boundary along the African margin. Strong bottom-current velocities in the Atlantic abyssal plains can also be identified. In the Madeira, the Tagus, and the Iberia abyssal plains, higher velocities are located in their eastern boundaries, reaching 10 cm/s, and locally > 50 cm/s. Along-slope processes at this scale are mainly associated with the WMDW and LIW along the Alboran Sea, and with both the MOW and the LDW in the Atlantic. In all these areas, there is good potential for the recognition of contourite features in the future.

We recognise several important controls exerted by margin topography on bottom current velocities:

(a) *Oceanic gateways* are essential in controlling water-mass exchange and also the bottom-current velocities and pathways between the abyssal plains. The Discovery gap, Tagus valley and Theta Gap are each important deep gateways for deep-water circulation and each are associated with higher than normal bottom current velocities, favouring the occurrence of contourite features (Fig. 8). The Gibraltar Gateway has a very special role on the Mediterranean-Atlantic water-mass exchange and results in the highest bottom current velocities known anywhere (nearly 300 cm/s). It also constitutes one of the most important oceanic gateways in the world allowing the overflow and circulation of MOW to the Atlantic Ocean (Serra, 2004; Legg et al., 2009).

(b) *Oceanic gateways* with high velocities are typical of erosional bottom-current systems, characterized by mainly linear bedforms displaying moderate to large seafloor relief resulting from scour 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).

(c) *Slopes, banks and promontories* are all instrumental in forcing higher than normal bottom current velocities. The highest velocities observed around Iberia are found when the impinging flow increases its velocity related to increased slope angles of prominent banks (such as the Galicia, Guadalquivir, or Le Danois Banks), individual promontories (such as the Balearic or the Extremadura promontories), and spurs (such as Ortegal Spur).

(d) *Seamounts* also represent important obstacles for water-mass circulation and high bottom current velocities (up to 10-20 times the average velocity) can be identified around their flanks (Fig. 8), reaching values > 50 cm/s. For this reason, notable contourite features are found enhanced around small and large seamounts in the Alboran Sea (Palomino et al., 2010), along the Iberia Atlantic margin in 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 determine new areas where along-processes may be important and new large contourite depositional systems could be developed. There are three principal reasons why they have not so far been identified: (i) they are masked by the deposits of dominant down-slope processes, especially in some areas at the base of the slope, continental rise or proximal areas of abyssal plains (Fig. 8); (ii) contourite deposition is inhibited or removed by the frequent and/or erosive action of downslope processes; and (iii) good descriptive knowledge of contourites in marine studies has only fairly recently been established, and much earlier traditional work did not consider them. Certainly, there are more contourite systems to be found along the Iberian margins so that their importance in the deep-sea context will be even greater than now. The new maps of simulated bottom currents presented here will help define where new drifts and CDS's may be found, even within the camouflage of major downslope systems (Fig. 9).

Although we have shown that the numerically simulated bottom current data are relatively coincident with existing bottom current and sediment data, we should be cautious in its use and applications. In some areas, for example, the simulated velocities do not coincide with present data collected by current meter or inferred by bedforms. For example, this is the case on the slope north and northeast of Menorca Island, where high bottom-currents were previously estimated (Mauffret et al., 1982; Maldonado et al., 1985; Palanques et al., 1995; Velasco et al., 1996; Acosta, 2005). Here, near-bottom current measurements at 1800 m water depth in the Gulf of Lion deep margin where WMDW formation takes place (Millot and

Monaco, 1984), gave mean values of 20 cm s^1 (maximum of 50 cm s^1), although the simulated velocities are very low indeed. A second example is in the middle slope of the Gulf of Cadiz, where the numerically simulated bottom currents probably underestimate considerably the real values, because MOW reaches nearly 300 cm s^{-1} close to the Strait of Gibraltar, slowing regionally to ~80 cm s^{-1} at Cape St. Vincent (Kenyon and Belderson, 1973; Ambar and Howe, 1979; Cherubin et al., 2000), but having a great variability (Serra, 2004; Serra et al., 2010b), and increasing locally considerably due to seafloor irregularities (Hernández-Molina et al., 2006; Gracía et al., 2009; Stow et al., 2009). In spite of these inconsistencies, the numerically simulated bottom currents remain a very important first stage estimate for the margin as a whole.

We further note that the numerically simulated bottom current data provided here gives an average value for the velocity, which takes into account some of the natural variability that occurs in nature. In fact, bottom current velocities vary considerably over a range of timescales (Gross and Williams, 1991), whereas other processes can model the speed and the instantaneous direction (Rebesco y Camerlenghi, 2008). This natural variability may occur on a scale of 24 h due to deepwater tidal, internal wave or soliton influence (Rebesco y Camerlenghi, 2008; Stow et al., 2009), a few weeks due to eddies, vortices, episodic benthic storm events (Hollister, 1993; Stow et al., 2009; Serra et al., 2010), seasonally by winter convection (Canals et al., 2006), and from tens to thousands of years due to other natural variations in bottom current generation and transport (Rebesco y Camerlenghi, 2008; Stow et al., 2009). Nevertheless, the bottom current velocity presented in this work (Fig. 5) estimates the areas where highest mean bottom current velocities are located considering all this possible variability, and therefore is fully informative of the regional view of where highest mean bottom current velocities should be located.

Processes, products and their implications.

Large contourite depositional and erosional features, as described here 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 masses circulation and its dynamics around Iberia started to be developed 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 complete isolation of the Mediterranean Sea and global effects of the Messinian salinity crisis ended (Ryan *et al*., 1973; Hsü *et al.,* 1978; Duggen *et al.,* 2003). However, the major effects of MOW were probably not felt until the Gateway had deepened sufficiently to allow its major outflow around 4.0-4.2 Ma (Hernández-Molina et al., 2009d; Llave *et al.,* this volume). According to several authors, the most recent hydrodynamic model was fully established later still at the base of the Quaternary (~ 2.4-2.6 Ma) contemporary to the global cooling that initiates the glacial-interglacial cyclicity characteristic of the Pleistocene (Thunell *et al*., 1991). So far, the studies carried out on the CDS´s of Mar de Alboran, Gulf of Cadiz, and Le Danois has allowed to identify a similar evolution between them, determining coeval palaeoceanographic changes in water masses in the past (Ercilla et al., 2002; Llave *et al.,* 2001, 2006; Hernández-Molina *et al*., 2002, 2006; Stow *et al*., 2002c; Van Rooij et al., 2010a). Based on these works, there was a further change in the nature of contourite depositional and erosive features coeval with the Middle Pleistocene Revolution (MPR, 0.9 Ma) due to the switch to a “full glacial” mode with 100 ka cyclicity (Llave, 2003; Llave et al., 2007; Van Rooij et al., 2010a). Since then, the influence of the environmental changes (climatic and eustatic) in water masses circulation and their influence in the marine sedimentation is partially known (e.g. Grousset *et al*., 1988; Vergnaud-Grazzini *et al*., 1989; Nelson *et al.*, 1993; Zanh et al., 1999; Cacho *et al.*, 2000; Shackleton et al., 2000; Schönfeld and Zahn, 2000; Schönfeld et al., 2003; Llave *et al*., 2006, 2007; Voelker *et al*., 2006; Frigola et al., 2007; 2008; Lebreiro et al., 2009, 2010; Voelker and Lebreiro, 2010; Bender et al., 2010; Mena et al., 2010, among others).

Once the present along-slope oceanographic processes were established we point out below some important implications based on the combination of numerically simulated bottom current with existing knowledge of contourite features.

1. *Continental Margin studies.* Recently, Weaver *et al*. (2000), Mienert and Weaver (2003) and Benetti (2006) have characterized the Atlantic continental margins based on their sedimentary processes. However, their model in common with earlier work, significantly underplays the role of along-slope processes on margin evolution. It is largely for this reason that our data for the Iberian margins do not conform well to the models that these authors suggest. The along-slope processes around Iberia are generated mainly by the MOW circulation in certain areas (e.g. *Gulf of Cadiz, Portuguese margin, Galicia margin* and *Cantabrian margin*). The interaction of these water masses has generated extensive contourite drifts and CDS’s, especially during the Quaternary.

2. *Depositional controls.* The development of both depositional and erosional contourite features not only depends of the bottom-current velocity (as above) but also on several other important controls including: (a) *Local morphology of the margin.* The particular inherited geological features that shape the margin morphology and the various slope irregularities (as noted above), providing the best place for local water mass interaction with the seabed. (b) *Sediment supply.* There are a great variety of sediment inputs to drift generation – downslope supply from submarine canyons, slides and debris flows; suspended sediments stirred up at the shelf break or pirated by the water masses and deposited along slope; sand spillover from the adjacent shelf and hinterland; local and more distal erosion of the impinging water mass along its path flow. (c) *Local oceanographic behaviour of the MOW*. Some slope irregularities represent specific obstacles for the water mass circulation. The presence of such features can generate increased velocity and produce local turbulence, eddies, cores, filaments, secondary flows, etc, all of which affect local erosive and depositional contourite features (Hernández-Molina et al., 2008b; García et al., 2009). (d) *Sea-level and climate change.* One area of further work we are presently

following is to better elucidate the role of sea-level and climate change in controlling along-slope processes and products.

3. *Geohazards.* A 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. In addition to the simulated bottom velocities, there is a direct link between bottom current velocity and bedform based on the bedform-velocity matrix recently published by Stow et al. (2009). Together these data can provide information on likely seafloor current velocities and hence their impact on erosion and chaffing of 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.

4. *Water mass structure.* There are two specific elements of water mass structure that have important implications for along-slope systems. (a) The development and maintenance of large gyres (eddies of 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 interspersed with normal flow conditions. (b) 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 and can explain the reason why the simulated velocities are higher than in surrounding areas, as in the case of the Western Alboran basin. The Camarinal and Spartel Sills produce within the Strait of Gibraltar solitons with amplitudes of 50 to 100 m, wavelengths of 2 to 4 km (Farmer and Armi, 1988; Armi and Farmer, 1988; Brandt et al., 1996; Jackson, 2004) and can reach at least 200 km into the western Mediterranean Sea and exist for more than two days before decaying toward background level (Apel, 2000; Jackson, 2004). This is also the case along the northwestern coast of the Iberian Peninsula and around the Galicia Bank where large internal wave occurrences take place (Correia, 2003; Jackson, 2004). The interaction of internal waves or solitons with the sea-bottom affects depositional and erosion processes. In particular, the density interface associated with internal waves has been postulated as one of the major mechanisms 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).

5. *Biota and bottom currents.* There is a relationship between specific biotic communities in deepwater, the nature of bottom-water flow, the substrate sediment type, and any localized geological processes (Howe et al., 2004; OSPAR, 2006; Reveillaud et al., 2008; Van Rooij et al., 2010b). This is evidenced, for example, by the finding of chemosynthetic communities associated with carbonate mounds and mud

volcanoes; and cold-water coral (CWC) ecosystems under the path of bottom currents. For example, the discovery of cold-water coral mounds along the Galicia Bank (Ercilla et al., 2009; 2010); the Bay of Biscay and the Cantabrian margins, and the Porcupine Seabight (Van Rooij et al., 2003; Huvenne et al., 2009; Van Rooij et al., 2010b) has been clearly associated with the dynamics of MOW. Additionally, the density of the MOW seems to be most beneficial for benthic ecosystems in order to keep nutrients in suspension and may provide a "connectivity" link for the dispersal and distribution of CWC larvae (Dullo et al., 2008). Strong bottom currents are required in order to deliver re-suspended nutrients to the cold-water coral ecosystems (Roberts et al., 2006). Therefore, bottom currents are one of the environmental factors that influence both the growth and maintenance of deepwater biotic communities. They are also one of the risk factors leading to substratum erosion and collapse, and to ecosystem silting up (Van Rooij et al., 2010b).

6. *Mineral and energy resources.* Contourite systems are recognized as having a mainly unexplored potential for both mineral and energy resources (Teleki *et al*., 1987; Earney, 1990; Seibol y Berger, 1993; Viana and Rebesco, 2007; Shanmugam, 2007; Rebesco and Camerlenghi, 2008; Viana, 2008; 2010). For example, there are some specific mineral resources, such as ferromanganese nodules fields, which depend directly on the sea-floor being swept by strong bottom currents (Van Andel et al., 1973; Kennet, 1982; Cronan, 2003). It was for this reason that Faugères and Stow (1993) suggested *manganiferrous contourites* as a typical marine contourite facies. They are mainly associated with contourite channels and moats (Faugères and Stow, 1993; Faugères *et al*., 1993); or around Banks and seamounts (Kennet, 1982; Cronan, 2003), where higher bottom current velocities usually exist, as has been described for the Gulf of Cadiz (Melières, et al., 1070; González et al., 2009a,b; 2010). The highest velocity bottom currents have been demonstrated as fully capable of winnowing, cleaning and transporting sandy material and of building 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.

Conclusions

The circulation of water masses around Iberia leads to the development of along-slope currents generating, in turn, contourite erosive and depositional features that form individual contourite drifts, erosional elements and complex CDS's of large dimensions and sediment thickness in a range of different geologic contexts. These have a valuable sedimentary record of their geological evolution linked to palaeoceanographic, paleoclimate and sea-level changes through time.

The regional simulated bottom current velocities of the water mass circulation around Iberia have strong impact on the seafloor. Two principal areas of influence are noted: (a) the continental slopes of the Alboran Sea and of the Atlantic Iberian margins; and (b) the abyssal plains in the Western Mediterranean and eastern Atlantic. In the Algero-Provençal abyssal plain, bottom-current velocities are up of 10 cm/s, especially on its southern boundary along the African margin. Strong bottom-current velocities in the Atlantic abyssal plains can also be identified. In the Madeira, the Tagus, and the Iberia abyssal plains, higher velocities are located in their eastern boundaries, reaching 10 cm/s, and locally > 50 cm/s. Along-slope processes at this scale are mainly associated with the WMDW and LIW in the Alboran Sea, and with both the MOW and the LDW in the Atlantic. Deep gateways are essential in controlling water-mass exchange and also the bottom-current velocities and pathways between the abyssal plains. In addition, seamounts represent important obstacles for the water-mass circulation and high bottom current velocities (10-20 times the normal velocity) are also identified around their flanks, reaching values > 50 cm/s.

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 sediment. From this study it is clear that the role of bottom currents in shaping continental margins is generally significantly underestimated, and that other parts of most margins will have still unknown and unexplored contourite systems. Controls on along-slope sedimentary systems include the bottom current structure and velocity, seafloor morphology and irregularities, sediment supply, sea-level and climate change. The combination of simulated bottom velocities with seafloor mapping of bedforms and the bedform-velocity matrix recently published by Stow et al. (2009) yields important information for geohazard mapping with respect to slope instability and for the location of seafloor installations, cables and pipelines. It is also of great significance because of their direct relation with specific deep marine geohabitats and mineral and energy resources.

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Figures

Figure captions

Figure 1. Area Location and bathymetric map with continental margins and abyssal plains around Iberia [*Base bathymetric map from* R. Leon (Pers. Comm.), realised from satellite data from Smith and Sandwell, 1997]. *Legend of the main physiographic reference points, in alphabetical order*: ASM = Ampere Seamount; ArSM= Armorican Semount; 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= Gorringe Bank; JoSM= Jovellanos Seamount; JSM = Josephine Seamount; HSM = Hirondelle Seamount; LCSM= La Coruña Seamount; LSM = Lion Seamount; NASM= North Atlante Seamount; NCSM= North Charcot Seamount; OSM= Oporto Seamont; SASM= South Atlante Seamount; SCSM= South Charcot Seamount; SSM = Sea Seamount; TSM= Tore Seamount; USM = Unicorn Seamount; VGSM= Vasco de Gama Seamount; VSM= Vigo Seamount.

Figure 2. Mediterranean Sea sketch with the general superficial water mass circulation, the winter convection areas, and the main water mass formation zones (*Adapted from* Arnone *et al.*, 1990 and Candela, 2001).

Figure 3. Figure 3. Water masses compilation both the Western Mediterranean and North Atlantic Sea gathered from bibliographic sources: A) Deep water circulation; B) Intermediate water Circulation and C) Superficial water circulation (see the text for further explication). This compilation is based on data and ideas from all the following authors: Wüst, 1936, 1961; Madelain, 1970; Kelling and Stanley, 1972; Kenyon and Belderson, 1973; Melières, 1974; Stanley et al., 1975; Thorpe, 1975; Zenk, 1975; Ambar and Howe, 1979; McCartney and Talley, 1982; Gardner and Kidd, 1983, 1987; Bryden and Stommel, 1984; Gascard and Richez, 1984; Fiúza, 1984; Dickson et al., 1985; Pollard and Pu, 1985; Parrilla and Kinder, 1987; Caralp, 1988, 1992; Garrett *et al.*, 1990; Haynes and Barton, 1990; Herburn and La Violette, 1990; Perkins *et al.*, 1990; Pingree and Le Cann, 1990; Zenk and Armi, 1990; Arham *et al.*, 1994; Cano and García, 1991; Ochoa and Bray, 1991; McCartney, 1992; Nelson *et al.*, 1993, 1999; Ambar and Fiúza, 1994; Bryden *et al.*, 1994; Daniault et al., 1994; Reid, 1994; Pollard et al., 1996; Mazé *et al.*, 1997; Paillet and Mercier, 1997; Díaz del Río et al., 1998; Fiuza *et al.*, 1998; Paillet *et al.*, 1998, 1999; 2001; Baringer and Price, 1999; Ioga and Lozier, 1999; Millot, 1999; Cherubin *et al.*, 2000; Johnson and Stevens, 2000; OSPAR 2000; Richardson *et al.*, 2000; Sarnthein *et al.*, 2000; Weaver *et al.*, 2000; Candela, 2001; Van Aken, 2000, 2002; 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., in preparation). *Legend of the main water masses, in alphabetical order*: AABW= Antarctic Bottom Water; AC= Atlantic Current; AI= Atlantic Inflow; LDW= Lower Deep Water; LADW= Labrador Deep Water; LIW= Levantine Intermediate Water; LSW= Labrador Sea Water; IPC= Iberian Polar Current; MAW= Modified Atlantic Water; MOW= Mediterranean Outflow Water; NAC= North Atlantic Current; NACW/ENACW= North Atlantic Central Water; NADW= North Atlantic Deep Water; SAIW = Subarctic Intermediate Water; and WMDW= Western Mediterranean Deep Water.

Figure 4. Simulated bottom velocities (cm/s) around Iberia.

Figure 5. Time average of simulated bottom velocities (cm/s) around Iberia.

Figure 6. Main area locations with dominate *along-slope* (contourite) processes and identified Contourite Depositional Systems (CDS) within the continental margins and abyssal plains around Iberia.

Figure 7. Examples of contourite features (depositional & erosive) generated within the identified Contourite Depositional Systems (CDS): A) Airgun seismic profile across the Menorca CDS (Velasco et al., 1996); B) Airgun seismic profile oblique to the Ceuta plastered drift across its central sector (Ercilla et al., 2002); C) Uninterpreted multichannel seismic-reflection (MCS) profile across the sandy drifts closer to the Strait of Gibraltar and along the middle slope of the Gulf of Cadiz CDS (line S-81A, provided by REPSOL-YPF Oil Company); D) Sparker seismic profiles showing examples of a plastered drift along the upper and middle slope of the Gulf of Cadiz CDS (Hernández-Molina et al., 2006; Llave et al., 2007, 2010); E) Uninterpreted MCS profile across the Faro-Albufeira mounded elongated and separated drift and the Alvarez Cabral moat on the middle slope of the Gulf of Cadiz CDS (data courtesy of TGS-NOPEC Geophysical Company ASA). It represents a classic example of middle-slope contourite deposition (Hernández-Molina et al., 2006; Llave et al., 2007, 2010); F) Uninterpreted MCS profile across the possible plastered drifts deposits defined by Alves et al. (2003) on the Portuguesse middle slope (data courtesy of Luis Pinheiro, Pers. Comm.); G) & H) Uninterpreted Airgun seismic profiles at Galicia Bank CDS, showin examples of elongated mounded & separated drift at the base of the sslope of the Galicia Bank Plateau (G) and a plasterd drift deposits on top of that Bank (H); I) High-resolution sparker profile across the Ortegal Spur CDS; J) High-resolution sparker profile across the Le Danois elongated mounded & separated drift at the base of the Le Danois Bank (Van Rooij et al., 2010); K) & L) Sparker seismic profiles on the Porcupine Bank indicating the seismic features and unit geometry on the eastern slope of the Porcupine Seabight (Van Rooij et al., 2003). For the aproximate location of the profiles, see Fig. 6.

Figure 8. Combining numerically simulated bottom currents with existing knowledge of contourite features around Iberia and major gravitational areas.

Combining numerically simulated bottom currents with existing regional knowledge of the main areas locations with dominant *along-slope* (contourite) and *across-slope* (mass wasting, turbiditic, & gravitational) processes identified within the continental margins and abyssal plains around Iberia. Across-slope processes and associated products compilation is mainly based on data and ideas from Weaver et al. (2000) and Serrano et al. (2005).

Figure 9. Potential areas where in theory new contourites features (depositional & erosive) could be presented, within the continental margins and abyssal plains around Iberia. Also the best deep and intermediate water areas with major interest for future explorations are selected.

Figure

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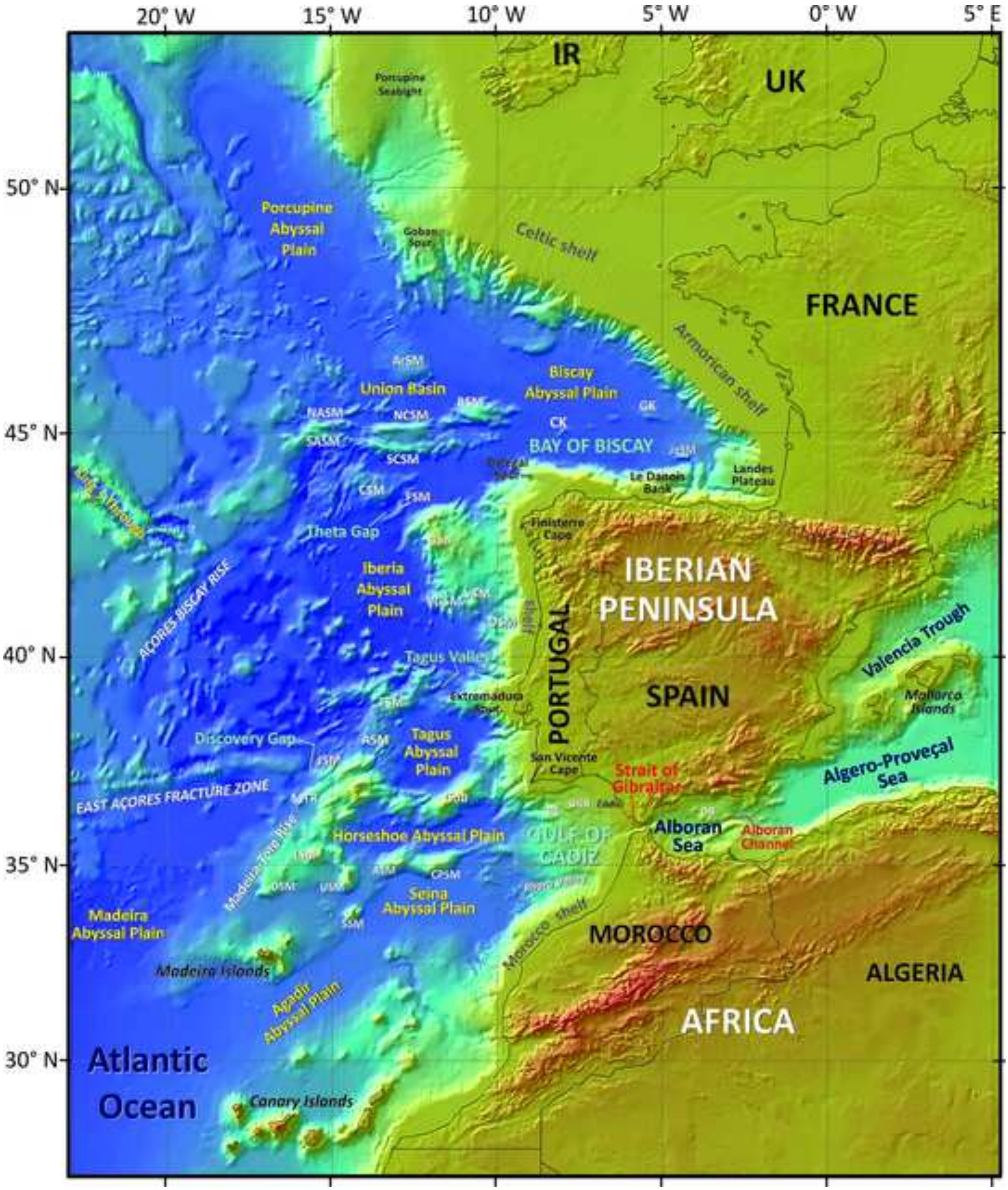

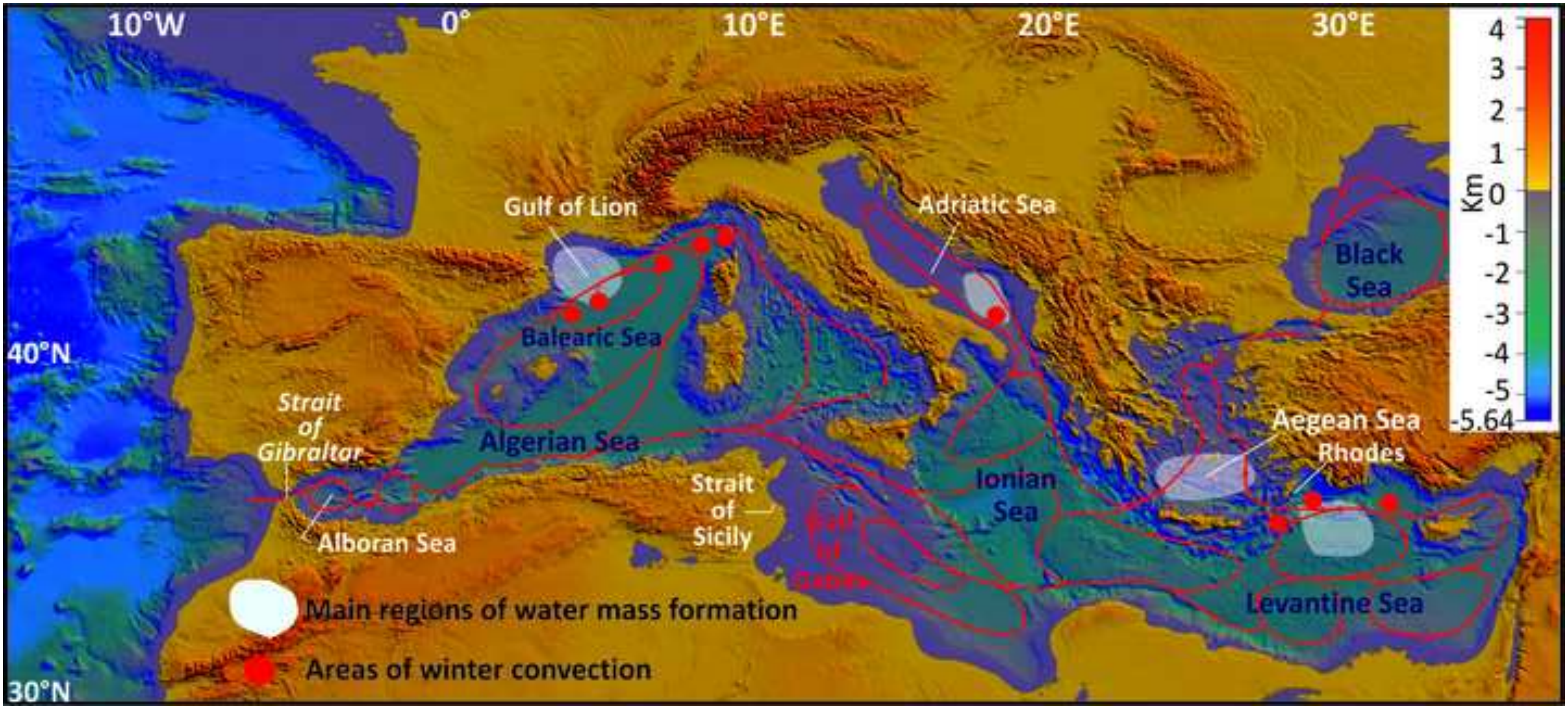
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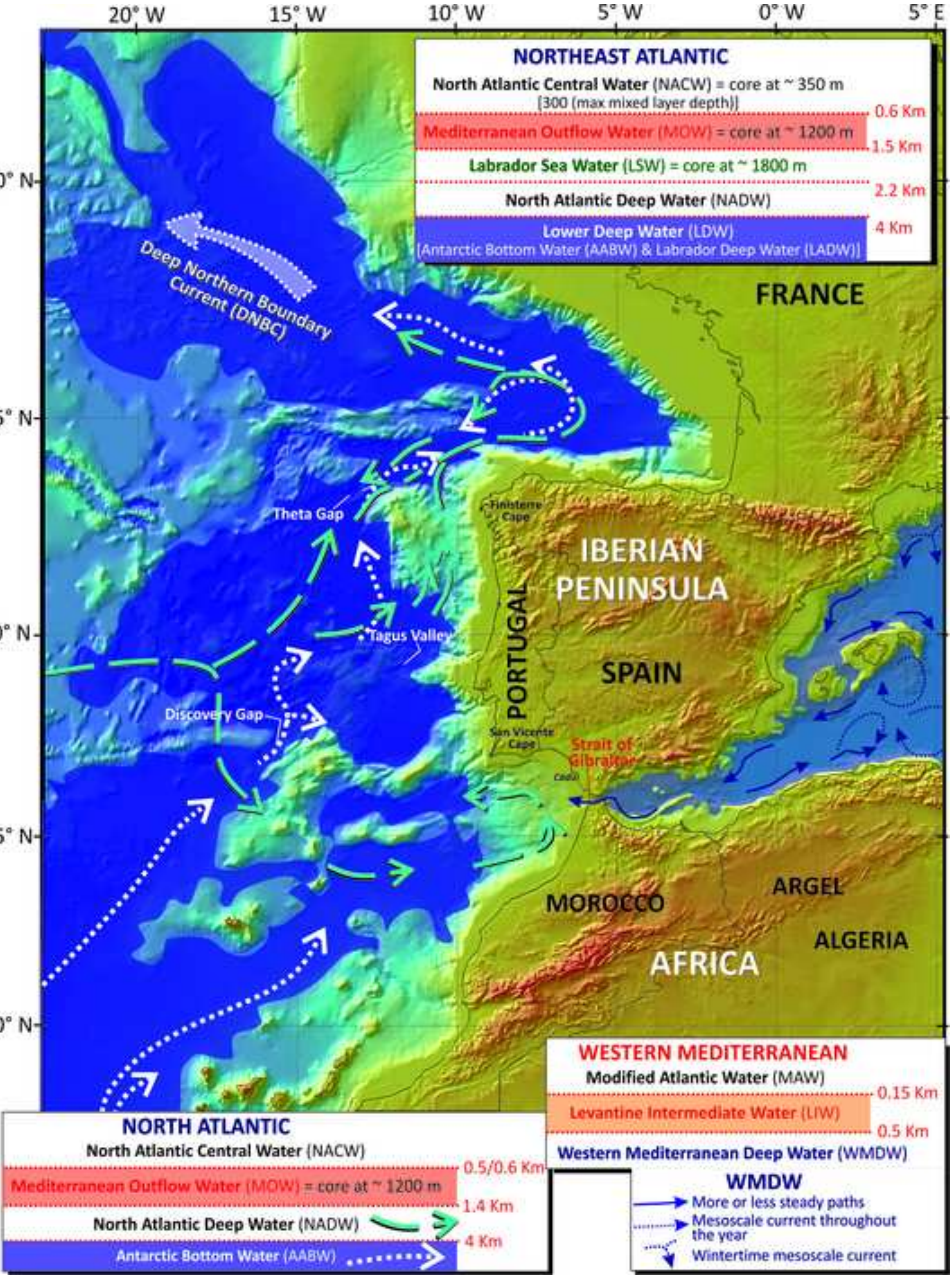
Black Sea
Balearic Sea
Strait of Gibraltar
Algerian Sea
Alboran Sea
Strait of Sicily
Gulf of Gabes
Ionian Sea
Aegean Sea
Rhodes
Levantine Sea
Main regions of water mass formation
Areas of winter convection

Figure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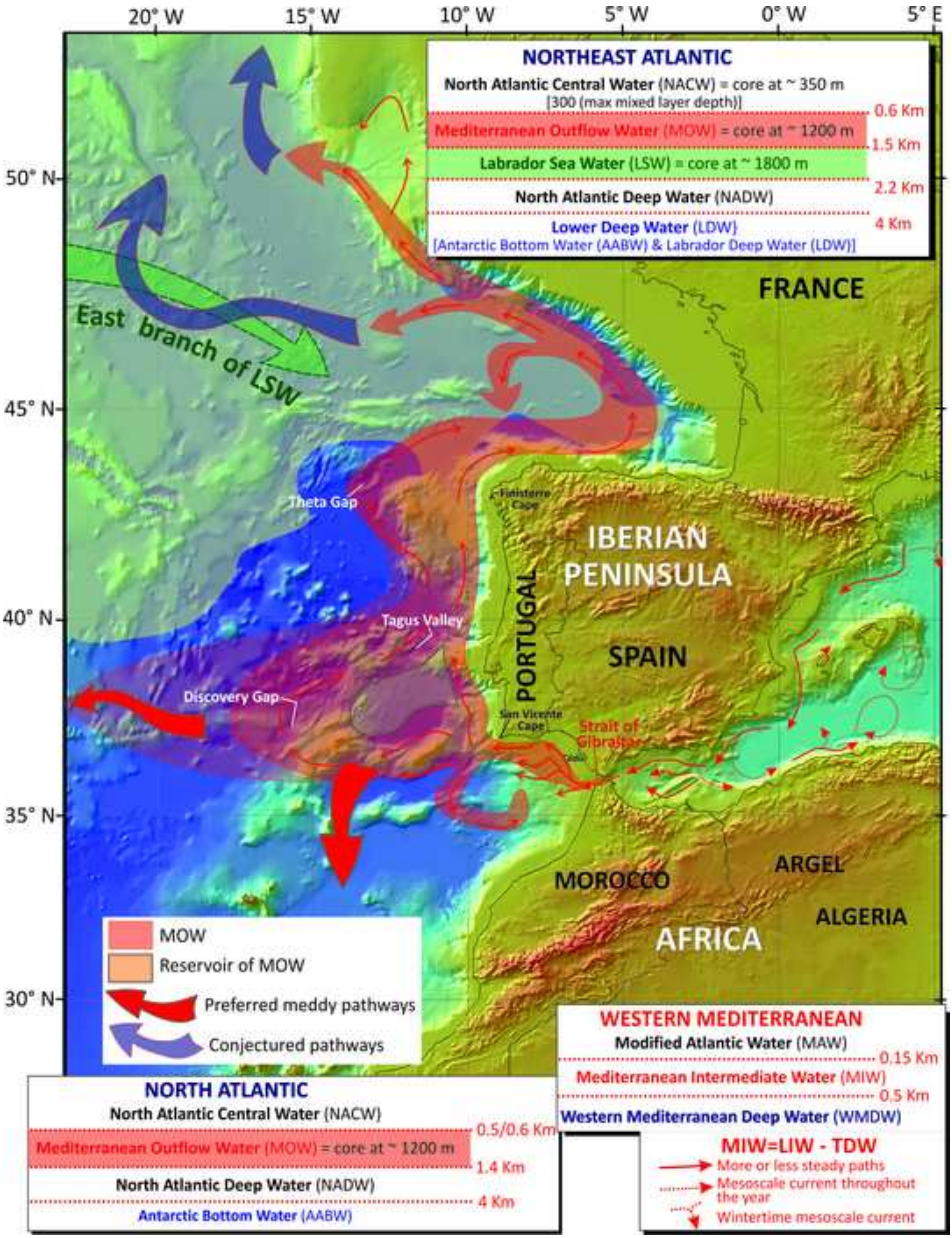
NORTHEAST ATLANTIC
North Atlantic Central Water (NACW) = core at ~ 350 m
[300 (max mixed layer depth)]
0.6 Km
Mediterranean Outflow Water (MOW) = core at ~ 1200 m
1.5 Km
Labrador Sea Water (LSW) = core at ~ 1800 m
2.2 Km
North Atlantic Deep Water (NADW)
4 Km
Lower Deep Water (LDW)
[Antarctic Bottom Water (AABW) & Labrador Deep Water (LADW)]
Deep Northern Boundary Current (DNBC)
FRANCE
Finisterre Cape
Theta Gap
IBERIAN PENINSULA
PORTUGAL
SPAIN
Tagus Valley
Discovery Gap
San Vicente Cape
Strait of Gibraltar
Cadiz
MOROCCO
ARGEL
ALGERIA
AFRICA
WESTERN MEDITERRANEAN
Modified Atlantic Water (MAW)
0.15 Km
Levantine Intermediate Water (LIW)
0.5 Km
Western Mediterranean Deep Water (WMDW)
WMDW
More or less steady paths
Mesoscale current throughout the year
Wintertime mesoscale current
NORTH ATLANTIC
North Atlantic Central Water (NACW)
0.5/0.6 Km
Mediterranean Outflow Water (MOW) = core at ~ 1200 m
1.4 Km
North Atlantic Deep Water (NADW)
4 Km
Antarctic Bottom Water (AABW)

Figure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2.2 Km
North Atlantic Deep Water (NADW)
4 Km
Lower Deep Water (LDW)
[Antarctic Bottom Water (AABW) & Labrador Deep Water (LDW)]
East branch of LSW
FRANCE
Theta Gap
Finisterre Cape
IBERIAN PENINSULA
PORTUGAL
SPAIN
Tagus Valley
Discovery Gap
San Vicente Cape
Strait of Gibraltar
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ARGEL
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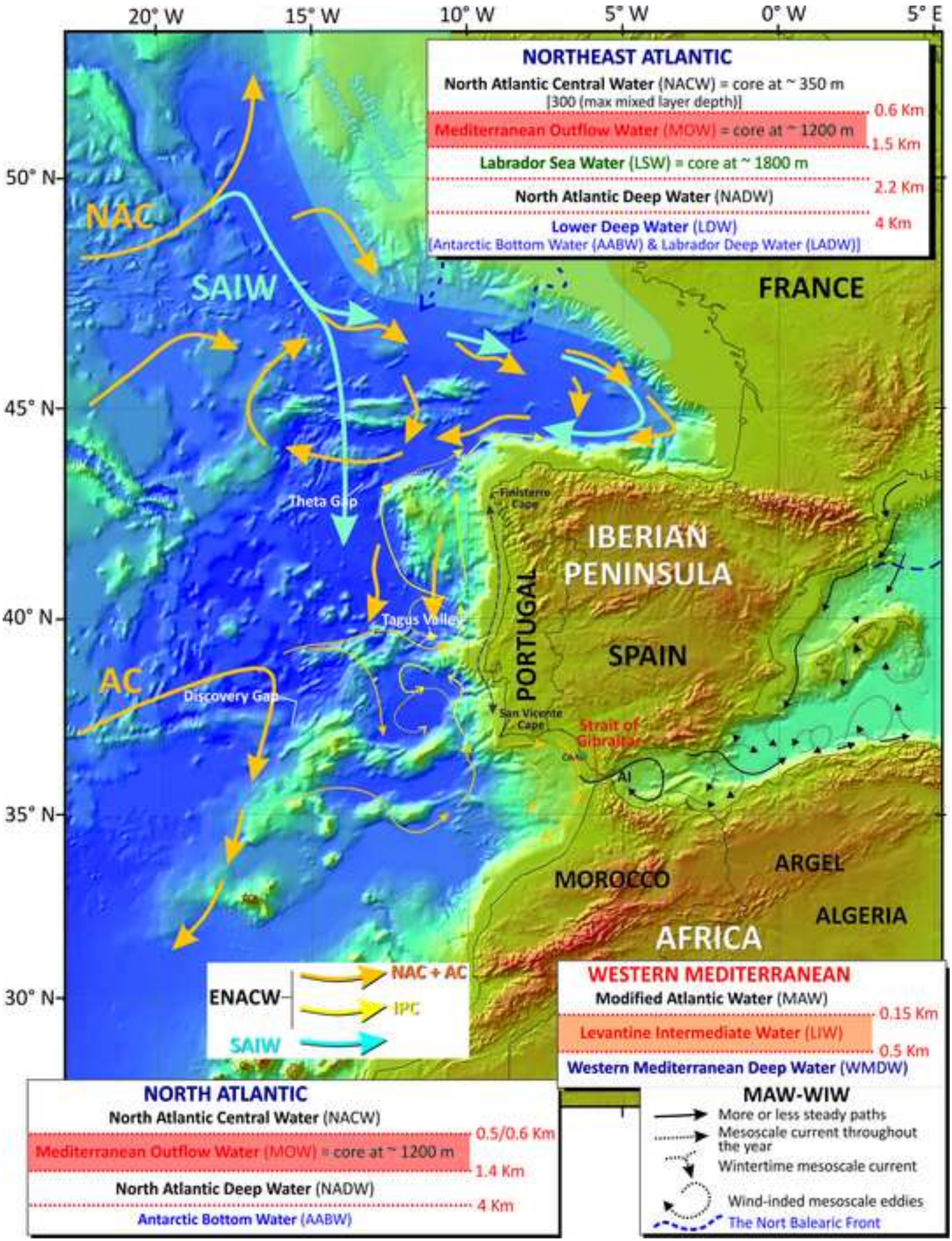
AFRICA
MOW
Reservoir of MOW
Preferred meddy pathways
Conjectured pathways
NORTH ATLANTIC
North Atlantic Central Water (NACW)
0.5/0.6 Km
Mediterranean Outflow Water (MOW) = core at ~ 1200 m
1.4 Km
North Atlantic Deep Water (NADW)
4 Km
Antarctic Bottom Water (AABW)
WESTERN MEDITERRANEAN
Modified Atlantic Water (MAW)
0.15 Km
Mediterranean Intermediate Water (MIW)
0.5 Km
Western Mediterranean Deep Water (WMDW)
MIW=LIW - TDW
More or less steady paths
Mesoscale current throughout the year
Wintertime mesoscale current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2.2 Km
North Atlantic Deep Water (NADW)
4 Km
Lower Deep Water (LDW)
(Antarctic Bottom Water (AABW) & Labrador Deep Water (LADW))
NAC
SAIW
FRANCE
Theta Gap
Finisterre Cape
IBERIAN PENINSULA
PORTUGAL
SPAIN
Tagus Valley
AC
Discovery Gap
San Vicente Cape
Strait of Gibraltar
AI
MOROCCO
ARGEL
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ENACW
NAC + AC
IPC
SAIW
WESTERN MEDITERRANEAN
Modified Atlantic Water (MAW)
0.15 Km
Levantine Intermediate Water (LIW)
0.5 Km
Western Mediterranean Deep Water (WMDW)
NORTH ATLANTIC
North Atlantic Central Water (NACW)
0.5/0.6 Km
Mediterranean Outflow Water (MOW) = core at ~ 1200 m
1.4 Km
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Antarctic Bottom Water (AABW)
MAW-WIW
More or less steady paths
Mesoscale current throughout the year
Wintertime mesoscale current
Wind-inded mesoscale eddies
The Nort Balearic Front

Figure

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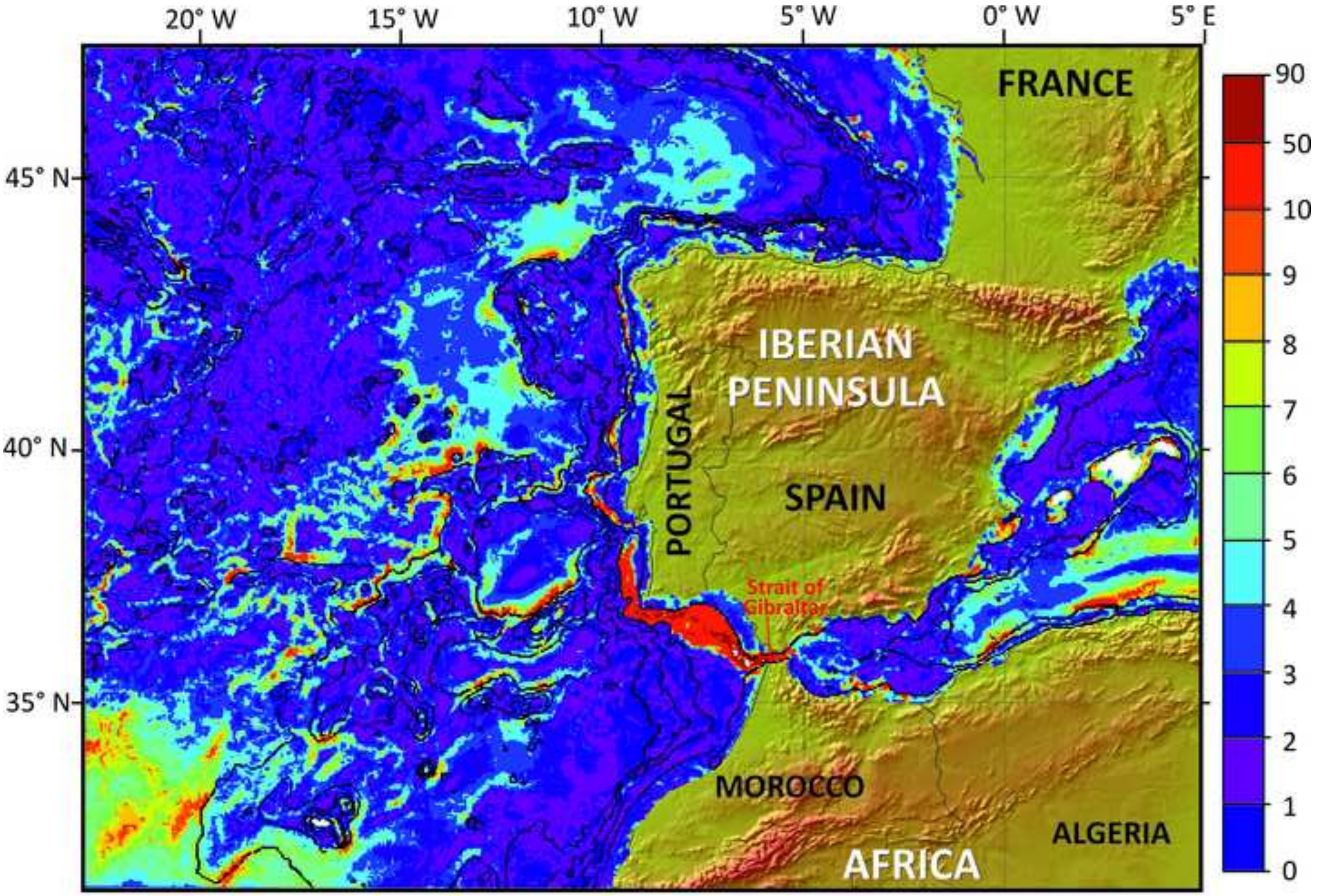
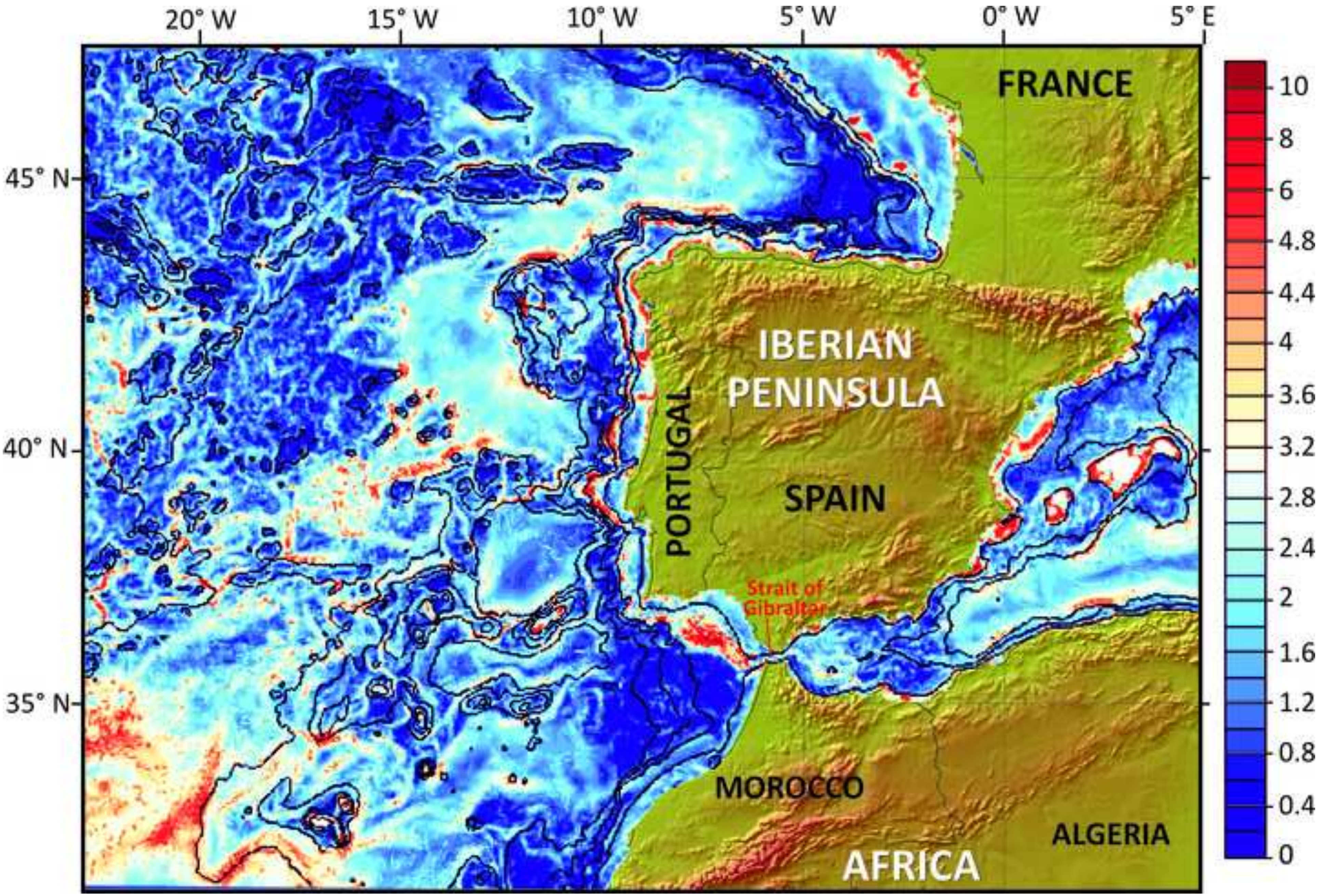


Figure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10
8
6
4.8
4.4
4
3.6
3.2
2.8
2.4
2
1.6
1.2
0.8
0.4
0

Figure

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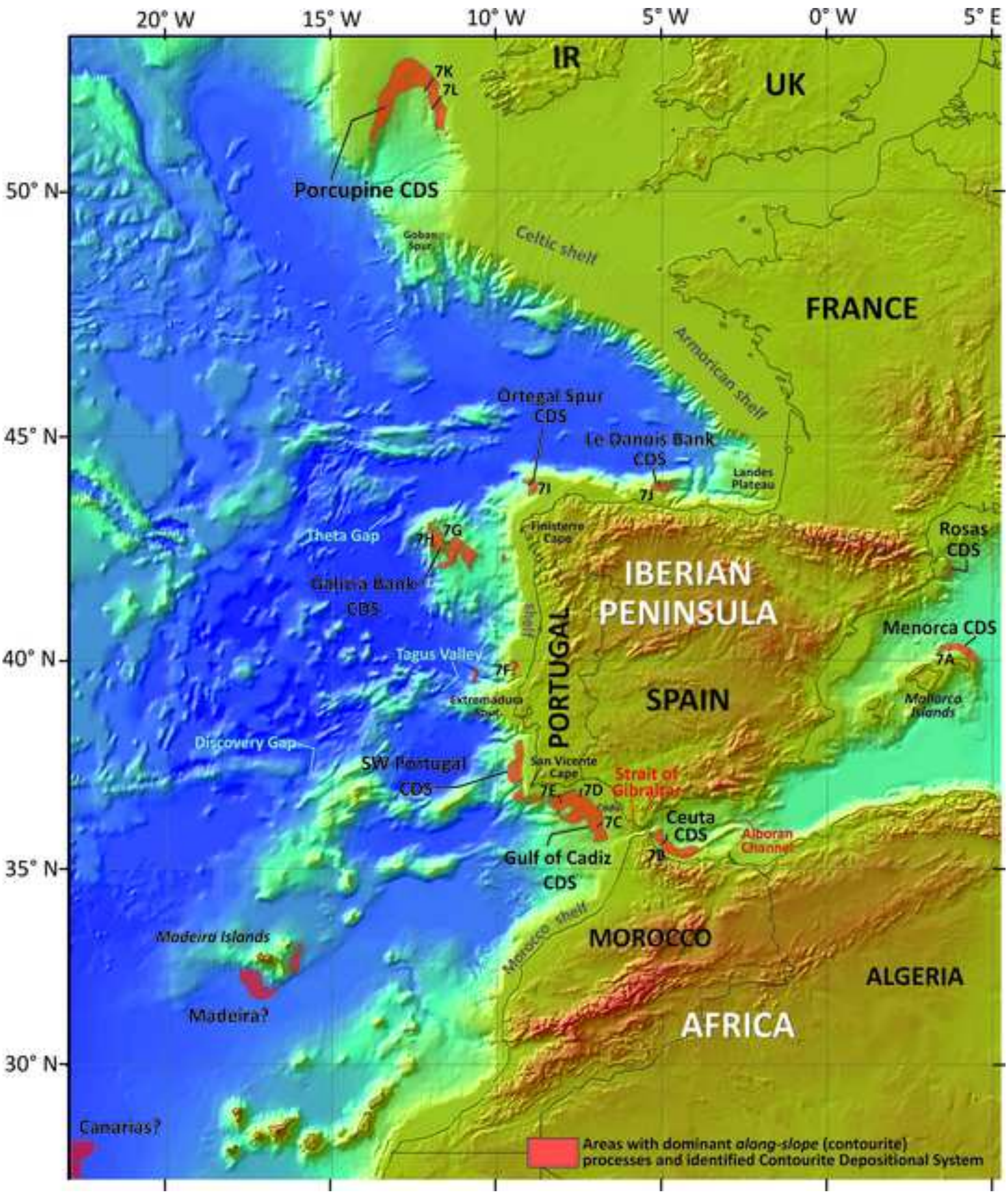

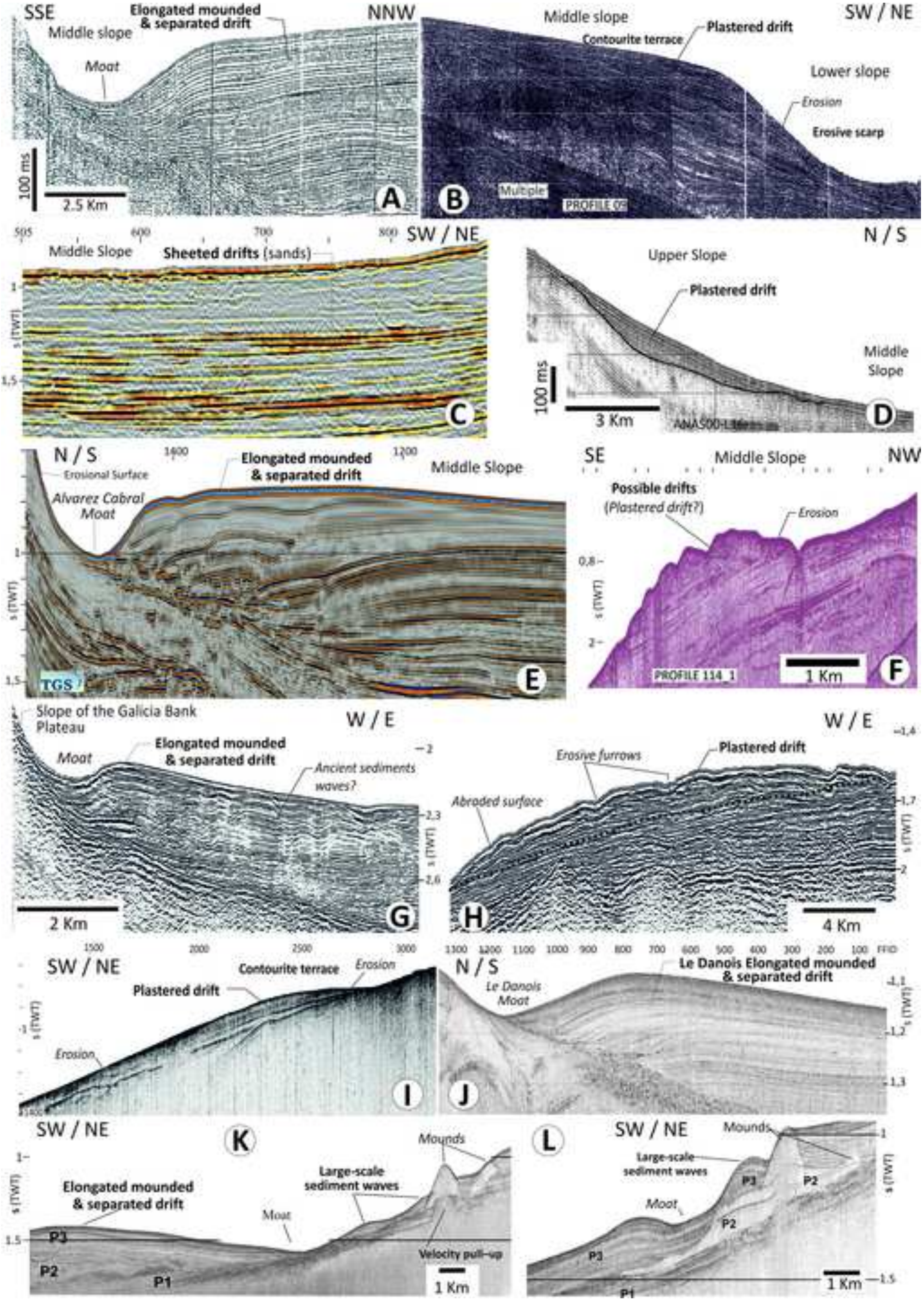
SSE
Elongated mounded & separated drift
NNW
Middle slope
Moat
100 ms
2.5 Km
A
Middle slope
SW / NE
Plastered drift
Contourite terrace
Lower slope
Erosion
Erosive scarp
Multiple
PROFILE 09
B
505
600
700
800
SW / NE
Middle Slope
Sheeted drifts (sands)
1
s (TWT)
1,5
C
N / S
Upper Slope
Plastered drift
Middle Slope
100 ms
3 Km
ANAS00-L3
D
N / S
1400
1200
Erosional Surface
Elongated mounded & separated drift
Middle Slope
Alvarez Cabral Moat
1
s (TWT)
1,5
TGS
E
SE
Middle Slope
NW
Possible drifts (Plastered drift?)
Erosion
0,8
s (TWT)
2
PROFILE 114_1
1 Km
F
Slope of the Galicia Bank Plateau
W / E
Moat
Elongated mounded & separated drift
2
Ancient sediments waves?
2,3
s (TWT)
2,6
2 Km
G
W / E
1,4
Erosive furrows
Plastered drift
Abraded surface
1,7
s (TWT)
2
4 Km
H
1500
2000
2500
3000
SW / NE
Contourite terrace
Erosion
Plastered drift
s (TWT)
1
Erosion
1400
I
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
FFID
N / S
Le Danois Elongated mounded & separated drift
Le Danois Moat
1,1
s (TWT)
1,2
1,3
J
SW / NE
K
Mounds
1
s (TWT)
Elongated mounded & separated drift
Large-scale sediment waves
Moat
1.5
P3
P2
P1
Velocity pull-up
1 Km
L
SW / NE
Mounds
1
Large-scale sediment waves
P3
P2
s (TWT)
Moat
P2
P3
1 Km
1.5
P1

Figure

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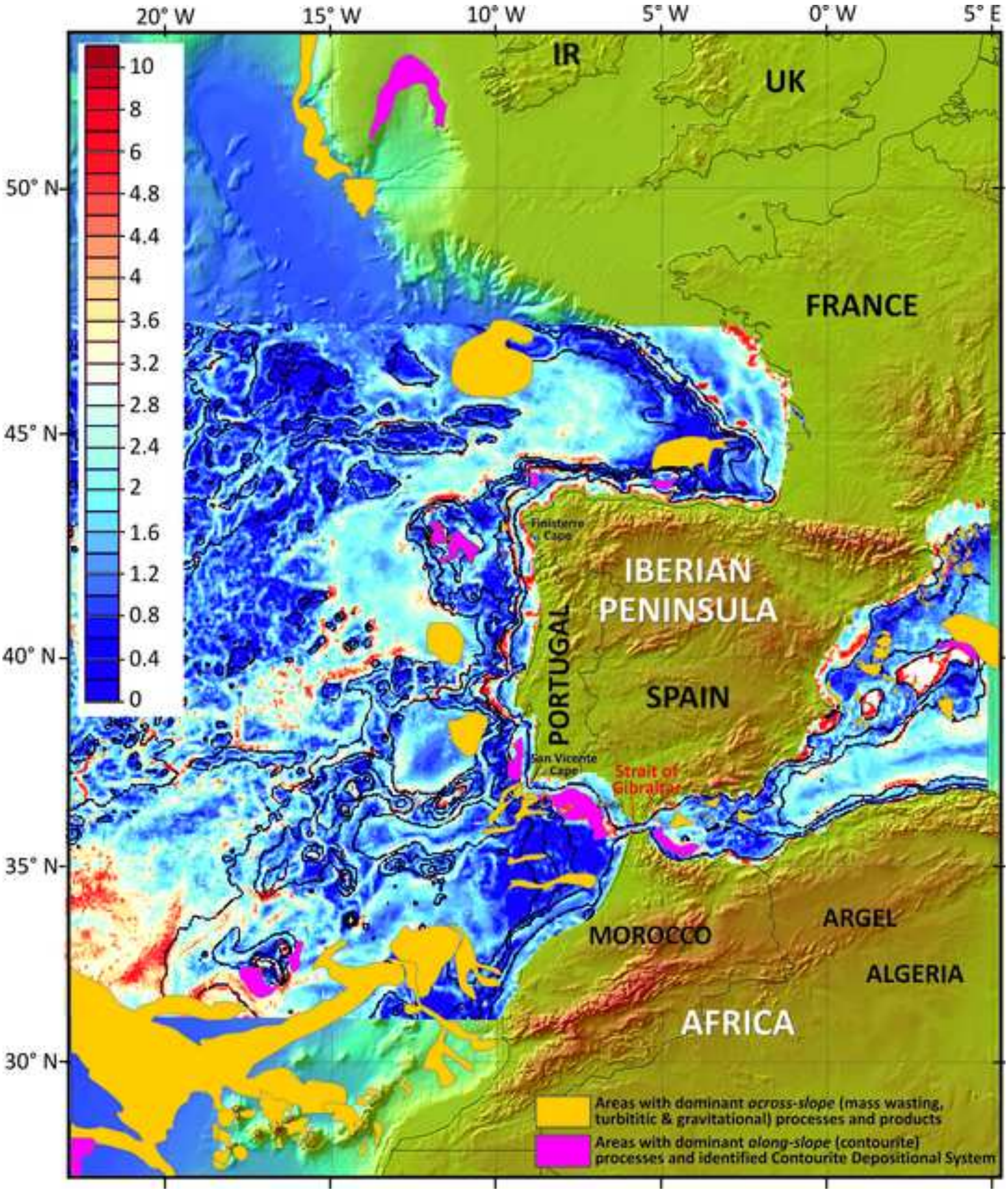
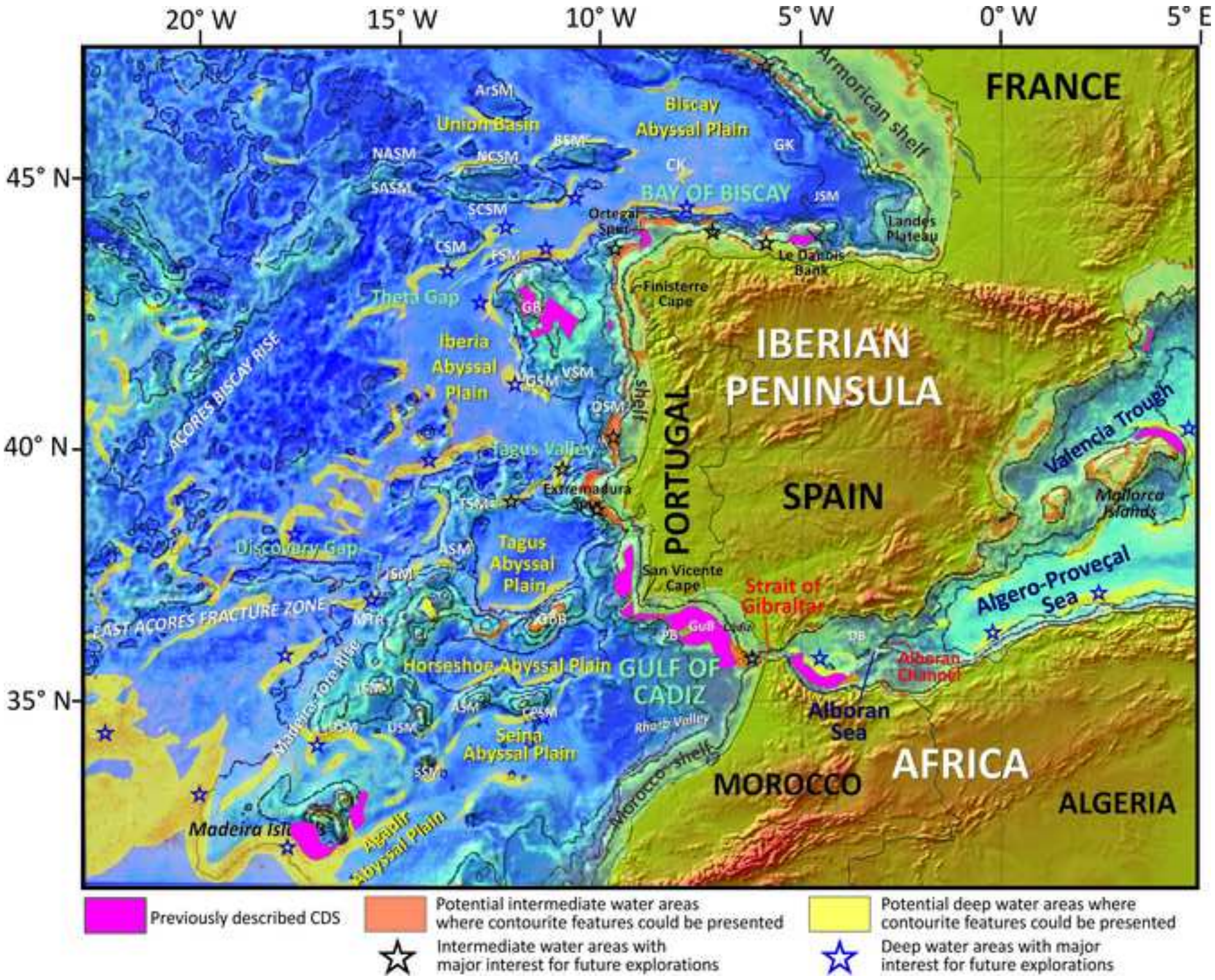


Figure


20° W
15° W
10° W
5° W
0° W
5° E
45° N
40° N
35° N
FRANCE
Armorican shelf
ArSM
Union Basin
Biscay Abyssal Plain
BSM
GK
NASM
NCSM
CK
SASM
BAY OF BISCAY
JSM
SCSM
Ortegal Spur
Landes Plateau
CSM
FSM
Le Danois Bank
Finisterre Cape
Theta Gap
GB
IBERIAN PENINSULA
ACORES BISCAY RISE
Iberia Abyssal Plain
VSM
GSM
shelf
OSM
PORTUGAL
Valencia Trough
Tagus Valley
Extremadura Spur
SPAIN
TSM
Mallorca Islands
Discovery Gap
ASM
Tagus Abyssal Plain
San Vicente Cape
Algero-Proveçal Sea
JSM
Strait of Gibraltar
EAST ACORES FRACTURE ZONE
MTR
GDB
Gulf Cadiz
PB
DB
Horseshoe Abyssal Plain
GULF OF CADIZ
Alboran Channel
Madeira-Tore Rise
ASM
CPSM
Alboran Sea
USM
Rharb Valley
Seine Abyssal Plain
AFRICA
SSM
Morocco shelf
MOROCCO
ALGERIA
Madeira Isl.
Agadir Abyssal Plain
Previously described CDS
Potential intermediate water areas where contourite features could be presented
Potential deep water areas where contourite features could be presented
Intermediate water areas with major interest for future explorations
Deep water areas with major interest for future explorations