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Abstract: We analyzed in detail the seabed morphology of the seamounts and surroundings on the Djibouti Marginal Shelf (northern Alboran Sea) using high resolution (Sparker) and very high resolution (TOPAS) seismic reflection profiles and multibeam bathymetry. The aim of the study was to determine the recent geological processes, and in particular the contouritic processes associated with Mediterranean waters. Six groups of morphologic features were defined: structural features (seamount cap, tectonic depressions), fluid dynamics-related features (pockmarks), mass-movement features (gullies, slides), bottom-current features (moats, scour marks, terraces, elongated and separated drifts, plastered drifts, confined drifts, sheeted drifts), mixed features (ridges) and bioconstructions (carbonate mounds). The main processes controlling feature formation are Late Cenozoic tectonic activity and the interaction of Mediterranean waters with the seafloor topography. Seamounts act as topographic barriers that affect the pathway and velocity of Mediterranean water flows, which are subdivided into strands that interact with the surrounding seafloor. Sedimentary instability and fluid-dynamic processes play a minor role, and their occurrence is probably triggered by seismicity.

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We analyzed in detail the seabed morphology of the seamounts and surroundings on the Djibouti Marginal Shelf (northern Alboran Sea) using high resolution (Sparker) and very high resolution (TOPAS) seismic reflection profiles and multibeam bathymetry. The aim of the study was to determine the recent geological processes, and in particular the contouritic processes associated with Mediterranean waters. Six groups of morphologic features were defined: structural features (seamount cap, tectonic depressions), fluid dynamics–related features (pockmarks), mass-movement features (gullies, slides), bottom-current features (moats, scour marks, terraces, elongated and separated drifts, plastered drifts, confined drifts, sheeted drifts), mixed features (ridges) and bioconstructions (carbonate mounds). The main processes controlling feature formation are Late Cenozoic tectonic activity and the interaction of Mediterranean waters with the seafloor topography. Seamounts act as topographic barriers that affect the pathway and velocity of Mediterranean water flows, which are subdivided into strands that interact with the surrounding seafloor. Sedimentary instability and fluid-dynamic processes play a minor role, and their occurrence is probably triggered by seismicity.

Alboran seamounts, geomorphology, contourites, Mediterranean waters

Introduction

Varying definitions of the word “seamount” have been used in different geological contexts. Recently Staudigel et al. (2010) proposed that a seamount is any geographically isolated topographic feature on the seafloor taller than 100 m that is not located on continental shelves and is not part of other major landmasses. However, Kennett (1982) includes isolated mountains or chains of successive highs that rise at least 1000 m above the seafloor without a cortical origin. In the case of relief features that rise less than 1000 m above the seafloor, one can use the specific term hill or knoll (Kennett, 1982; OHI, 2008). The scientific aim of this paper is based on the view that seamounts are very significant features because they can interact with the hydrodynamic regime, changing the water circulation pathway (Owens and Hogg, 1980; Hernández-Molina et al. 2006; Howe et al. 2006) and affecting the sedimentary processes in the surrounding areas (Davies and Laughton, 1972; Roberts et al. 1974). Furthermore, seamounts are often regarded as areas of enhanced biodiversity and productivity in comparison with the surrounding ocean (Rogers, 1994, Genin, 2004).

The relationship between Mediterranean deep water masses and the seafloor morphology in the Alboran Sea was pointed out by Ercilla et al. (2002), who indicated the sedimentary importance of their influence on the western Moroccan slope, where they have controlled the development of a main contouritic system (the Ceuta Drift). The presence of erosional moats around seamounts of the Alboran Sea produced by bottom-current action has also been mentioned in other studies (Lo Iacono et al. 2008; Muñoz et al. 2008) but without a detailed analysis of the oceanographical and sedimentary processes that control them.

In this paper we characterize the geomorphology of several seamounts—Avempace, Herradura, Herradura Spur and Djibouti Ville (Al Idrisi)—located in the Djibouti Marginal Shelf region (northern Alboran Sea), paying special attention to the analysis of the contourite features and deposits developed under the influence of the circulation pathway of Mediterranean Water (MW) (Fig. 1). This detailed analysis will provide knowledge on the geologic processes, and especially on the shaping of the seafloor by MW on the Djibouti marginal shelf.

Geological settings

The Alboran Sea Basin is the westernmost physiographic unit of the Mediterranean Sea and is located at the western end of the Alpine Mediterranean orogenic belt, where it is bounded by the Gibraltar Arc. This orocline contraction was caused by the westward displacement of a continental block and collision against the South-Iberian and North-African continental margins during the Upper Oligocene and Miocene (Platt and Vissers, 1989; Comas et al. 1999; Platt, 2007). Contraction in the collision front was coeval with tectonic extension in the back-arc region from the Lower Miocene, which formed the Alboran Basin. The convergence direction between Africa and Eurasia has rotated from N-S to NW since the Upper Tortonian (Dewey et al. 1989). This change also implies an oblique tectonic regime in the region, with the development of contraction and strike-slip features in the basin that inverted the previous ones (Campos et al. 1992; Comas et al. 1992; Woodside and Maldonado, 1992; Watts et al. 1993; Vázquez and Vegas, 1996; Comas et al. 1999; Vázquez et al. 2008). At present,

the WNW convergence direction continues (McClusky et al. 2003; Fernández-Ibáñez et al. 2007; Vegas et al. 2008) and has led to active tectonics in the region.

The sedimentary cover has been deposited since the Lower Miocene and varies from 0 to 9 km (Chalouan et al. 1997; Comas et al. 1999). It displays the regional tectonic evolution as well as depositional processes, which are mainly controlled by variations in the location of straits and oceanographic characteristics. The analysis of seismic reflection profiles has made it possible to differentiate Miocene sedimentary units from Pliocene-Quaternary ones through the definition of a major Upper Messinian discontinuity in between (Campillo et al. 1992; Comas et al. 1992, 1999; Estrada et al. 1997; Hernandez-Molina et al. 2002). This discontinuity corresponds to the desiccation of the Mediterranean during the Messinian salinity crisis and the further erosion associated with the impact of flooding of Atlantic waters into the Alboran Basin at the end of this event (García-Castellanos et al. 2009; Estrada et al. 2010). This event marks the opening of the Strait of Gibraltar and the beginning of the modern oceanographic connection between Atlantic and Mediterranean waters.

As a response to this tecto-sedimentary evolution and cortical configuration, the Alboran Sea floor shows a complex physiography which has been classically described as three main domains: margins, basins, and structural highs (Olivet et al. 1973a y b; Auzende et al. 1975; Maldonado et al. 1992). The application of multibeam echosounder techniques has allowed the main geomorphologic characteristics of these domains to be studied (Muñoz et al. 2008). However, most studies have focused on tectonic geomorphology analysis (Ballesteros et al. 2008; Lo Iacono et al. 2008; Martínez-García et al. 2010), and less attention has been paid to the influence of water mass interaction on geomorphologic features.

Oceanographical settings

The water column structure of the Alboran Sea has been traditionally defined by three main water masses (Bryden and Stommel, 1982; Parrilla et al. 1986; Millot, 1999; Vargas-Yañez et al. 2002): Atlantic Water (AW), entering from the Strait of Gibraltar and flowing eastward from the surface to nearly 150–200 m depth, Levantine Intermediate Water (LIW), forming in the eastern Mediterranean and flowing westward between 200 and 600 m depth, and Western Mediterranean Deep Water (WMDW), which fills the deep basins and occurs mainly on the southern Moroccan margin.

A recent study of the Mediterranean outflow in the Strait of Gibraltar (Millot, 2009) indicates two other MWs: Winter Intermediate Water (WIW) at 150–200 m depth from the western basin lying above the LIW, and Tyrrhenian Dense Water (TDW) below 500 m from the eastern Mediterranean basin. In the Alboran Sea the intermediate MWs (WIW, LIW and upper-TDW) circulate mainly in the north and are lighter and less saline, while the dense and deep MWs (lower-TDW and WMDW) are uplifted and pushed away in the south. All these MWs circulate westward as density currents, alongslope and counterclockwise.

Measurements of water mass current velocities in the Alboran Sea are scarce and indicate only a few cm s^{-1} , $2.5\text{--}5 \text{ cm s}^{-1}$ for LIW and $5\text{--}12 \text{ cm s}^{-1}$ for WMDW (Pistek et al. 1985).

Methodology

The main body of datasets comprises multibeam echosounder and seismic profiles with degrees of resolution ranging from high (sparker) to very high (Topas) that were obtained by the Secretaría General del Mar (Spanish Ministry of the Environment and Rural and Marine Affairs), the Instituto Español de Oceanografía and the Instituto Geológico y Minero de España (both belonging to the Spanish Ministry of Science and Innovation) during several cruises (Fig. 2). These data were acquired using a KONGSBERG-SIMRAD EM300 multibeam echosounder and a parametric TOPAS PS 018 echosounder. The navigational data were acquired by DGPS. The multibeam echosounder data were processed by the Secretaría General del Mar using the SIMRAD NEPTUNE™ package, giving a bathymetric grid resolution of 35 meters with 100% coverage. The backscatter values were also obtained from the multibeam echosounder by means of CARAIBES™ software. For the morphological analysis we used the ArcGIS™ desktop v 9.3.1 software.

We also studied medium resolution seismic profiles from the database of the Instituto Geológico y Minero de España (http://www.igme.es/internet/sistemas_infor/BASESINTERNET/sigef.htm). All these seismic data were imported as SEG-Y files into KINGDOM SUITE™ software for interpretation.

Results: morphological features

The Djibouti Marginal Shelf develops between 850 and 900 m depth, on the slope margin between the Málaga and Adra provinces, and is characterized by a practically flat seafloor ($<0.5^\circ$) (Figs. 1 and 3). The slope displays a complex morphology affected by large linear faults (Vázquez, 2001), mass-movement deposits (Ercilla et al. 2009) and turbidite systems (Alonso and Ercilla, 2003). The seafloor of the Djibouti Marginal Shelf is interrupted by the presence of bank reliefs (Vázquez, 2005). These banks comprise several seamounts: Avempace Bank, Herradura Bank, Herradura Spur and Djibouti Ville Bank, also called Al Idrisi Bank. These seamounts show a cone-truncated geometry, except in the Herradura Spur, which displays a near-pyramidal geometry and some minor mounds with a cone geometry (Figs. 3, 4). The main seamounts show reliefs ranging from 500 m on the NE flanks to 1000 m on the SW flanks and their tops are at about 200 m water depth (See Table I). Average gradients of the seamounts are 0.8° , although locally values of 2° are measured at the top, and up to 40° on the flanks.

Six groups of morphological features (Fig. 4) were recognized in the seamounts and surrounding areas at the southwestern sector of the Djibouti Marginal Shelf, where the main seamounts are located. The features were classified as follows: structural features, fluid dynamics-related features, mass-movement features, bottom-current features, mixed features and biological-related features.

Structural features

i) Seamount caps correspond to relative low slope surfaces ($0\text{--}5^\circ$) that occupy the top of the main seamounts (Avempace Bank, Herradura Bank, Herradura Spur and Djibouti Ville Bank) (Fig. 4). On these banks, the seamount cap is at a depth of between 200 and 400 m depth, except on the Herradura spur, where it is at a

depth of between 440 and 500 m. These surfaces are characterized by a high to very high mean backscatter value ($>-20\text{dB}$) and the presence of alternating bands of different backscattering values that draw a complex pattern (Fig. 5a). These top surfaces are affected by outcropping ridges and bioconstructions, both described below.

ii) *Tectonic depressions* appear as linear depressions of NNE-SSW trends (Fig. 4). They have a mean length of 10 km and a mean width of 500 m but can reach lengths of 30 km and widths of 2 km. They are located between 650 and 1000 m water depth and have a relief of between 5 and 20 m. In the Sparker and TOPAS seismic profiles, they are associated with deeper faults (Fig. 5c, d, e), and depressions are their surface expression. These depressions are frequently controlled by the vertical movement of a single fault, but could also be related to an echelon array (Fig. 4) or defined by two different faults. Moreover, minor rhomb-shaped depressions can be defined as part of the main linear depressions that indicate a strike slip origin for these faults.

Fluid dynamics–related features

Pockmarks are circular depressions formed by the removal of sediment by escaping fluids (Judd and Hovland, 2007; Iglesias et al. 2010). In the study area they can be grouped into two clusters (Fig. 4) without any dominant orientation in the distribution pattern. The first cluster is located at the WSW of the Avempace seamount and is composed of 6 V-shaped pockmarks, which have a mean height of 19 m and a mean width of 200 m. In this field high resolution profiles differentiate truncated reflectors on the flanks of the depressions (Fig. 6a, b, c). The second cluster is located in the north part of the Avempace Bank and is formed by 4 pockmarks. These are similar in shape but bigger, with a mean height of 16 m high and a mean width of 400 m. In some cases they display higher reflectivity values than the surrounding areas.

Mass-movement features

i) *Gullies*. Two sets of gullies occur on different steep sectors (between 5° and 20°). One set of gullies is located on the steep seafloor of the Djibouti Marginal Shelf, at the south of the Herradura seamount. They have NE-SW linear pathways of about 1–1.5 km length and 15–20 m height, and a U-shaped symmetric profile (Fig. 7a, b). The second set of gullies is located on the flanks of the Herradura and Avempace seamounts, and has have a radial orientation with respect to the summit. These gullies are bigger than the first ones, with a length of 2 km and a width of 1.5 km.

ii) *Slides*. Only two minor sediment slides were located on the southern flank of the Herradura Bank seamount at 300–800 m water depth (Fig. 4), giving rise to mass movements with a SE and SW direction (Palomino et al. 2009). The SE slide covers 13 km^2 and extends to the SE for 4 km (Fig. 7c, d, e). The SW slide is smaller, with 2 km^2 extensions, a SW direction and a length of 1.5 km. The *scars* that correspond to lines of abrupt gradient located at the head of the Herradura Bank slides (Fig. 7f, g, h), between 300 and 450 m depth, are genetically related to slides. They usually show a curved geometry of 2–4 km length, reliefs that vary from 30 to 90 m, and a mean slope of 30° . Some other scar features have also been distinguished and usually affect the eastern and southern flanks of the Avempace Bank seamount (Fig. 4) between 300 and 500 m depth. These scars show lengths

ranging from 500 m to 2 km, reliefs of 20 to 40 m and a mean slope of 20°. In these cases, they are not related to sediment slides.

Bottom-current features

i) *Moats* are elongated morphologies that display different dimensions according to the flow that generates them. They are located at the foot of seamounts (700–950 m water depth) and are associated with the drift deposits (Fig. 4 and Fig. 8a, b, c). Moats usually have a relief of 40 m but can reach 85 m in the southeastern part of Avempace Bank. They show different orientations but E-W, SE-NW, N-S and NE-SW are predominant. The morphology is characterized by an asymmetric U-shaped profile with a steeper slope beside the seamount. They have a mean width of 1 km and a mean length of 5.5 km, but to the south of the Avempace seamount and to the east of the Herradura seamounts they are more than 2 km wide and 10 km long.

ii) *Scour marks* are negative reliefs of variable dimensions with a circular morphology. They are isolated in the northwestern part of Herradura Bank and clustered in the northeastern part of the study area, at the lee side of a small structural high located eastwards of Herradura Spur (Fig. 4). Scour marks are V- and U-shaped in cross section with a variable width ranging from 800 to 1000 m. These features have a relief of 5–25 m and a depth of 750–900 m. The V-shaped ones do not show clear erosion evidences, but the U-shaped ones have a flat bottom and show truncated reflectors on their walls (Fig. 8d, e, f).

iii) *Terraces* are low slope morphologies (between 0° and 5°) limited by small scarps (Fig. 8g, h, i) of 5–10 m height and a good lateral continuity. These features have been distinguished on the SW flanks of HR Bank (Fig. 8i), where they have developed at a water depth of between 280 and 450 m and have lengths of up to 6.5 km. Similar features of flat geometry have also been observed on Avempace Bank and Herradura Bank at around 300 m water depth.

iv) *Drifts*. Following the classification of Rebesco (2005), which is based on previous classifications (Faugères et al. 1993, 1999; Rebesco and Stow, 2001), four types of drift deposits (Fig. 4) were described in the study area:

- *Elongated mounded and separated drifts* are positive reliefs that are always associated with moats at the foot of seamount flanks, from 700 to 950 m depth (Fig. 9a). They show several trends (N-S, NE-SW, NW-SE and E-W) according to the seamount geometry. The drifts range from about 20 to 150 m high, tens to thousands of metres wide and 10 to 25 km in length, and show gradients of 0–2° though they can reach 35° at the moat edges. The thickness of these deposits is variable, from a few to hundreds of metres, and they have moderate to low backscatter values (-30 dB), increasing their intensity to the south where the values are -27 dB. Their seismic facies show a vertical cyclicity, with a more transparent zone at the base and high amplitude reflectors with a high lateral continuity at the top of the units.

- *Plastered drifts* appear mainly on the west side of the seamount flanks as elongated geometry (Fig. 4), and always as a sedimentary tail on the western flanks of seamounts. They are 5–20 km in length, tens of metres high and 5–10 km wide. The thickness of these drift deposits is variable, from a few to hundreds of metres (Fig. 9b) and they show an E-W main direction. They have low backscatter values, from -30 to -35 dB. They have subparallel reflectors and well-defined stratified seismic facies.

- *Confined drifts* are located between seamounts, being well developed in the southern part of the study area (Fig. 4), between the Herradura and Djibouti Ville

seamounts (NE-SW trending) and between the Djibouti Ville seamount and the unnamed southern high (E-W trending). They have a mounded shape (Fig. 9c) and an irregular geometry controlled by the high distribution. They can reach 20 km in length, 5 km in width, and a relief of more than 100 m. The thickness of these deposits can be as much as 300 m and they have moderate backscatter values, from -29 to -31 dB. Their seismic facies show the same cyclicity pattern and have high amplitude reflectors.

- *Sheeted drifts* occupy the flat seafloor sector of the Djibouti marginal shelf. They are located between the northern side of the margin, which is characterized in the lower part by the confluence of the Sacratif Turbidity System (Alonso and Ercilla, 2003), the deepest Baraza Slide lobes (Ercilla et al. 2009), and the southwestern seamount sector (Fig. 9a, 9d). Their surface is characterized by the presence of NNW-SSE-oriented positive reliefs with maximum level differences of about 15 m. The deposits show a wedge configuration northwards and a transition to the other three drift types differentiated in this area. They have medium to low backscatter values (Fig. 5a) and stratified seismic facies with continuous and subparallel reflectors of high amplitude.

Mixed features

i) *Ridges* are positive reliefs with steep slopes (from 5 to 10°) on both sides, and they are located at the summit of the structural highs (Fig. 10a, b, c). They have very variable dimensions, with heights of 1 to 100 m and lengths that can reach 10 km. They can be associated with the biogenic mounds at the top of the seamount although they can also be related to fault scarps and outcropping basement rocks. They appear at seamount summits from 200 to 350 m depth and on their flanks between 400 and 750 m depth.

Biological related features

i) *Biogenic mounds* are located at the top of the seamounts. They appear as an irregular floor made of carbonate-rich sediments (Fig. 10d, e, f). They were sampled on DEEPER cruises and are mostly composed of buried coral reefs and carbonate-shell benthic fauna (Gil et al. 2009). They have very high backscatter values (from -15 to -20 dB) and appear as mounds or ridges. These coral mounds are isolated bodies with an elongated shape at a depth of between 200 and 300 m. They are up to 5 km long and 2 km wide, 15 to almost 100 m high and very steep, with a gradient slope of 10–20°.

Discussion

Morphology origin and main geological processes

Although the seamounts on the Djibouti Marginal Shelf show recent tectonic activity (Vazquez et al. 2001, 2008), most of the mapped morphologic features are sedimentary in origin. The contouritic and tectonic processes are the most important, whereas the sedimentary instability and fluid dynamic processes have played a minor role. In the following paragraphs we explain the processes responsible for the formation of the above features. First, we discuss the origin of the most important features (bottom current features) and then the rest of the features (structural, biological, mixed, fluid-dynamic and mass-movement features).

Drift (mounded, plastered and sheeted) deposits and related bottom current features (*moats, scour marks and terraces*) are caused by the interference of MW masses with the seafloor topography and especially with the distribution of seamounts. Separated and mounded drifts appear at the base of the main seamounts on both sides, where the water current is divided. Plastered drifts are located behind the seamounts as tails on the lee side of the water mass direction; and sheeted drifts occupy the central sector of the Djibouti Marginal Shelf between the seamounts and the upper continental slope segment. The occurrence of different erosional bottom-current features must be observed as an indicator of water mass intensity of flow (Roberts et al. 1974; McCave and Carter 1997). When the MWs reach the Avempace seamount, Herradura seamount, Herradura Spur and Djibouti Ville seamount, they are divided into strands around them, adapting the trajectory according to the seamount geometry (Hernández-Molina et al. 2006). Moats mapped at their foots represent the path of the maximum current flow of the MWs that is intensified around the seamounts, producing non-deposition but erosion of the marginal shelf sediments. However, drifts are the result of a decrease in the bottom current flow of the MWs away from the base of the seamount, and this region is where the sedimentation increased (Howe et al. 2006). Scour marks are associated with the vorticity arising under the influence of a bottom-current flow around a seamount (Hernández-Molina et al. 2006). The scour marks that were mapped were considered as initial features in the origin of channels by means of depression coalescence, as is also suggested by Klauke et al. (2004).

The seamount cap is characterised by an irregular surface due to structure (ridges), water-mass currents (terraces) and biological-related processes (carbonated mounds). The summit of the seamounts is locally characterized by an abraded surface and terraces that could be related to the erosive action of water masses, probably both intermediate MW and AW in alternative action. We suggest that climate change can vary the water depth and/or velocity of the interface between the two water masses, so their coexistence would indicate variations in current velocities and positions of MW and AW over time. Similar variations have been suggested for the MW in the Gulf of Cadiz and on the Portugal margin (Llave et al. 2006; Voelker et al. 2006). This process could control the presence of different erosive terrace levels, which are relict features. Ridges on the seamount summit have a structural origin and could be related to deeper faults or to the outcropping of basement rocks, although they have also been associated with the presence of carbonate mounds. The very high reflective values in the ridges at the top of the seamounts could correspond to areas where carbonate coral mounds occur, as has been observed in several areas (De Mol et al. 2002; Masson et al. 2003; Kenyon et al. 2003; Lo Iacono et al. 2008). These mounds are made up of a large amount of dead cold-water coral, although there is evidence of living cold-water corals on the Djibouti Ville seamount (www.ma.ieo.es/deeper). The carbonate mounds in these seamounts are formed mainly of *Lophelia pertusa*, *Madrepora oculata* and *Desmophyllum*, *Caryophyllia* (Gil et al. 2009), the same species as those described previously in other seamounts in the Alboran Sea (Taviani et al. 2004; Hebbeln et al. 2009).

Aligned tectonic depressions are caused by the—usually normal—vertical displacement of a NNW-SSE fault system that affects the most superficial layers of sediments. However, their echelon geometry and the location of several rhombic depressions, such as minor pull-apart basins, allow us to characterize these fractures as right-lateral strike-slip faults. The presence of pockmarks has

1 been attributed to the seepage of gas and interstitial fluids from the underlying
2 sediments in fracture zones (Muñoz et al. 2008). Finally, slides are associated
3 with gravitational processes that favoured mass movements. The trigger
4 mechanics could be the erosion at the foot of the seamount that causes collapse
5 and sediment slides. Also, the high seismic activity in the zone (Bufo et al.
6 2004) could favour both seepage fluids and gravitational processes. Furthermore,
7 there is an interaction between turbidity and contour currents revealed by the
8 presence of slides on the flanks of the Avempace and Herradura seamounts:
9 turbidity currents drag the seafloor sediments to the southeast and southwest,
10 where they are quickly pirated by bottom currents.
11

12 **Contourite features and the oceanographic implications**

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14
15 The distribution of drift deposits in Alboran seamounts suggests that the
16 seafloor is under the influence of a bottom current that sweeps the zone to the
17 west. These deep MWs flow westwards (e.g. Parrilla et al. 1986; Millot, 2009),
18 but bottom current trends and their velocity could be affected by changes in slope
19 gradient, the occurrence of bathymetric highs and the overall morphology in the
20 zone. At the Avempace seamount the deep current flows to the west and moats are
21 described on the north and south sides of the seamount. Slight erosion on the east
22 side is also caused by the current when it meets the seamount. Moats are more
23 developed on their southern flank, and less on their northern one, where scours of
24 minor order also occur. This moat distribution indicates a westward flow (Roberts
25 et al. 1974, Owens and Hogg, 1980, Hernández-Molina et al. 2006). Mounded,
26 separated drifts are also associated with these moats (Fig. 4). Plastered drifts are
27 found on the lee side of the Avempace and Herradura seamounts, as a depositional
28 tail. These drift types are commonly found on the shadow zone downstream of
29 seamounts (Davies and Laughton, 1972; Masson et al. 2003; Hernández-Molina et
30 al. 2006).
31

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33
34 In the morphological high in the northeastern sector of the study area, the
35 process of formation of the drift-moat complex is very similar to that of the
36 Avempace seamount. However, in the zone opposite to the flow direction small
37 eddies increase the turbulence. This phenomenon generates circular depressions
38 (scour marks) created by whirls, and is also observed on the west side of the
39 Herradura seamount and the Herradura spur. The Herradura spur also acts as an
40 obstacle and reflects the current, as is suggested by the moat distribution.
41

42
43 The relative situation of the Herradura and Djibouti Ville seamounts and
44 the highs to the southeast generates depositional morphologies such as confined
45 drifts, generated by the bottom currents and are limited by moats. When the deep
46 water mass crosses between Djibouti Ville and the southeasternmost highs, it
47 causes erosion at the base of the highs, generating moats. When its velocity
48 decreases sufficiently, it produces not erosion but deposition of the sediments
49 beside the moat and on the opposite side of the highs. As a result of this
50 deposition, the mounded deposits appear as a patch between the structural highs
51 (confined drifts). The same process occurs between Herradura and Djibouti Ville.
52

53
54 The cap of the seamounts shows a different morphology and is influenced
55 mainly by the light intermediate MW. Bioconstructions could be related to an
56 enriched water uplifted when water masses intercept seamounts that favour the
57 growth of cold-water corals. Bottom-current features surrounding and over the
58 banks are the result of their interaction with light intermediate MW and deep MW.
59 Terraces are located at depths ranging from 280 to 450 m. Their formation could
60 have been affected by changes in water mass structure related to climate change.
61
62
63
64
65

Several water masses could be responsible for the morphology. Features at the seamount cap could be abraded by both the Atlantic inflow water mass and the intermediate MW, while the features of the Djibouti marginal shelf could be produced by the interaction of the seafloor topography with lighter intermediate MW or denser deep MW. Cacho et al. (2000) proposed a variability in the depth structure of water-mass stratigraphy as a response to the reduction in the thickness of WMDW (deep MW) in warm interstadials, which could allow a deeper circulation of LIW (light MW), which would play a role as bottom currents in the Djibouti Marginal Shelf.

Conclusions

Six groups of morphologic features have been defined on the Djibouti Marginal Shelf: structural features (seamount cap, tectonic depressions), fluid dynamics-related features (pockmarks), mass-movement features (gullies, slides), bottom-current features (moats, scour marks, terraces, elongated and separated drifts, plastered drifts, confined drifts, sheeted drifts), mixed features (ridges) and bioconstructions (carbonate mounds).

The main processes that control the features and deposits are the Late Cenozoic tectonic activity and the water mass dynamics, and especially their interaction with the seafloor topography.

Seamounts of the Djibouti Marginal Shelf act as morphological barriers that have conditioned the pathways and velocities of the Mediterranean bottom currents. The deep MW and light MW are subdivided into strands around the seamounts and their velocities are directly affected by physiographic irregularities along their course. These waters modified the existing morphologies, giving rise to new bottom current features.

We propose that a branch of the deep and denser MW masses circulates over the Djibouti Marginal Shelf on the northern slope of the Alboran margin under the lighter MW masses. This branch crosses between the seamounts of the Djibouti Marginal shelf, whereas traditionally this current has been defined only on the southern Moroccan continental margin.

The seamount cap could be eroded alternatively in this scheme by AW and intermediate MW. Furthermore, the presence of bioconstructions could be related to upwelling processes of lighter and denser MW and to the interface dynamics between AW and intermediate MW.

Some other structures present in the area, such as slides and pockmarks, must be related to secondary processes, such as sedimentary instabilities or seepage of subsurface fluids, probably with an important role of seismicity as a component of the trigger mechanism of both features. More thorough analyses are needed to determine their origin and evolution, as well as their interplay with the current-controlled sedimentary processes.

The mapping of the seabed of the Djibouti Marginal Shelf shows a fairly complex geomorphology and a great variety of oceanographically and geologically controlled sedimentary processes shaping the seafloor of regions with seamounts. This work also shows that the influence of seamounts in the physical processes is the main factor governing sedimentation and erosion in regions of this type. Bottom-current-controlled processes should therefore be taken into account in the long-term sedimentary evolution of similar regions.

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Figure legend

Fig 1 Distribution of the main physiographic domains in the Alboran Sea (Modified from Vazquez, 2001). Yellow rectangle represents the study area located around the marginal shelf of Djibouti, on the continental slope of the Alboran Sea. The bathymetric contour (blue lines) was obtained from GEBCO (General Bathymetry Chart of the Oceans). *Legend: 1: Avempace seamount; 2: Herradura seamount; 3: Herradura spur; 4: Djibouti Ville seamount (Al Idrisi seamount)*

Fig 2 Location of the data set for seismic profiles. Red and green lines for Topas seismic profiles and black lines for Sparker seismic profiles

Fig 3 Slope map in degrees around the seamount of the marginal shelf of Djibouti, showing the flat areas in blue and the steeper ones in red

Fig 4 Morphological map of the study area showing the structural, fluid dynamic-related, mass-movement, bottom current, mixed and biogenic features distinguished around the seamount of the marginal shelf of Djibouti

Fig 5 Maps illustrating the backscatter values in dB (a) and the slope variation in degrees at the seamount cap (b) based on multibeam bathymetric data, showing the flat and high reflective tops of the seamounts. Parametric Topas (d) and Sparker profiles (f) illustrating the structural features (tectonic depressions) described in the study area. Their morphological expression can be observed on the hill-shade multibeam bathymetric map (c), where Topas (red line) and Sparker profiles (black line) are also located

Fig 6 Parametric Topas (b) and Sparker (c) profiles illustrating the fluid dynamic-related features described in the study area. Their morphological expression can be observed on the hill-shade multibeam bathymetric map (a) where Topas (red line) and Sparker profiles (black line) are also located

Fig 7 Parametric Topas (d, g), Sparker (e, h) and bathymetric profiles (a) illustrating the mass-movement features described in the study area. Their morphological expression can be observed on the hill-shade multibeam bathymetric maps (b, c, f), where Topas profiles (red lines), Sparker profiles (black lines) and bathymetric profiles (green lines) are also located

Fig 8 Parametric Topas (b, e, h), Sparker (c, i) and bathymetric profiles (f) illustrating the bottom-currents features described on the study area. Their morphological expression can be observed on the hill-shade multibeam bathymetric maps (a, d, g), where Topas profiles (red lines), Sparker profiles (black lines) and bathymetric profiles (green lines) are also located

Fig 9 Selected examples of seismic Sparker profiles (a-d) illustrating the bottom current features (drifts deposits) described in the study area. Their morphological expression can be observed on the hill-shade multibeam bathymetric map, where black lines are the profile location

Fig 10 Parametric Topas (b, e) and Sparker profiles (c, f) illustrating the mixed and biological-related features described on the study area. Their morphological expression can be observed on the hill-shade multibeam bathymetric maps (a, d), where Topas profiles (red lines) and Sparker profiles (black lines) are also located

Table captions

Table I Main characteristic parameters measured in the seamounts.

Figure

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Bottom-currents features

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Table

<i>Seamount Name</i>	<i>Avempace</i>	<i>Herradura</i>	<i>Djibouti Ville</i>
<i>Location</i>	3°58'W / 36°22'N	3°45'W / 36°12'N	3°33'W / 36°08'N
<i>Max/Min depth (m)</i>	970 / 250	930 / 270	870 / 200
<i>Length/Width (m)</i>	12500 / 10000	17800 / 16000	9700 / 10500
<i>Height (m)</i>	700	660	670
<i>Area (km²)</i>	83	202	77
<i>Max/Min Slope (d)</i>	53.3 / 0.01	51.9 / 0.00	43.5 / 0.02