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Submarine canyon dynamics in the Mediterranean and tributary seas - An integrated geological, oceanographic and biological perspective

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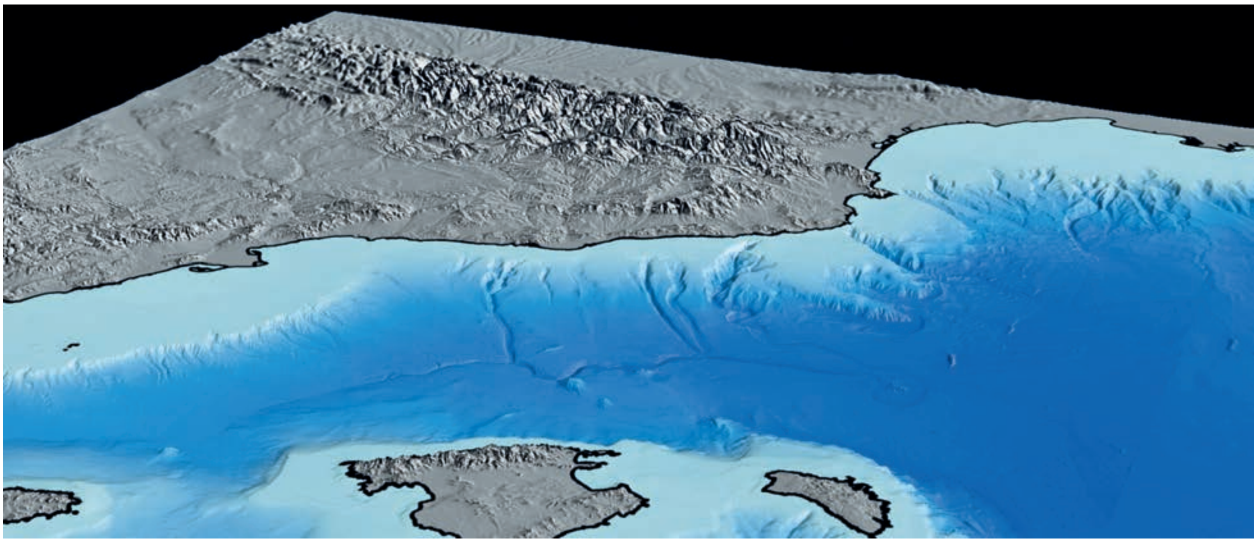

CIESM - The Mediterranean Science Commission

Submarine canyons and related features in the Alboran Sea: continental margins and major isolated reliefs

Juan T. Vázquez[1], Gemma Ercilla[2], Belén Alonso[2], Carmen Juan[2,3], José L. Rueda[1], Desirée Palomino[1], Luis M. Fernández-Salas[4], Patricia Bárcenas[5], David Casas[6], Víctor Díaz-del-Río[1], Ferrán Estrada[2], Marcel.li Farran[2], Marga García[3,7], Emilio González[1], Nieves López-González[1], Bouchta El Moumni[8] Contouriber, Montera and Mower Teams

[1] *Instituto Español de Oceanografía, C.O. de Málaga, Fuengirola, Spain*
[2] *Instituto de Ciencias del Mar, CSIC, Barcelona, Spain*
[3] *Renard Centre of Marine Geology, Dept. of Geology and Soil Science, Gent University, Belgium*
[4] *Instituto Español de Oceanografía, C.O. de Cádiz, Spain*
[5] *Departamento de Análisis Matemático, Facultad de Ciencias, Universidad de Málaga, Spain*
[6] *Instituto Geológico Minero de España, Madrid, Spain*
[7] *Instituto Andaluz de Ciencias de la Tierra, CSIC, Granda, Spain*
[8] *Université Abdelmalek ESSAADI, Larache, Morocco*

Abstract

The analysis of a data set of multibeam bathymetry plus high resolution seismic and parametric profiles allow us to characterize the geomorphologic units on the Alboran Sea-floor as well as the evolution of morpho-sedimentary systems along the Pliocene and Quaternary, later than the main erosive Messinian event. Since the opening of the Gibraltar Straits, the sedimentary evolution of this basin has been controlled by the interchange of water masses between the Atlantic Ocean and the Mediterranean Sea. Basin physiography is also a consequence of the Pliocene-Quaternary compression which has progressively uplifted the sourrounding reliefs and deforms the interior and the margins of the basin. On this scenario, several submarine canyons and gullies have been developed in this basin which traverse especially the northern margin and the flanks of the Northern Alboran Ridge, without affecting the African margins. This fact must be related to the action of bottom contour currents which constitute the main morpho-sedimentary process. The influence of water masses distributed the sedimentary input carried by rivers and coming from the erosion of surrounding ranges. In the southern margin of this basin this influence is stronger and inhibits the development of transversal submarine canyons.

INTRODUCTION

The Alboran Sea constitutes the westernmost physiographic unit of the Mediterranean Sea. It is a semi-enclosed basin bordered by the Iberian and African margins and it is divided in two main basins (Eastern Alboran and Western Alboran) connected by a narrow corridor (Alboran Through) and two main intra-slope basins (Southern Alboran and Motril). Its physiography is characterised by narrow continental shelves, pseudo-concentric continental slopes, two wide marginal plateaus (MP): the Moulouya MP on the south-eastern continental slope and the Djibouti-Motril MP on the northern one, and several morphologic traits (structural and volcanic highs and ridges) (Fig. 1).

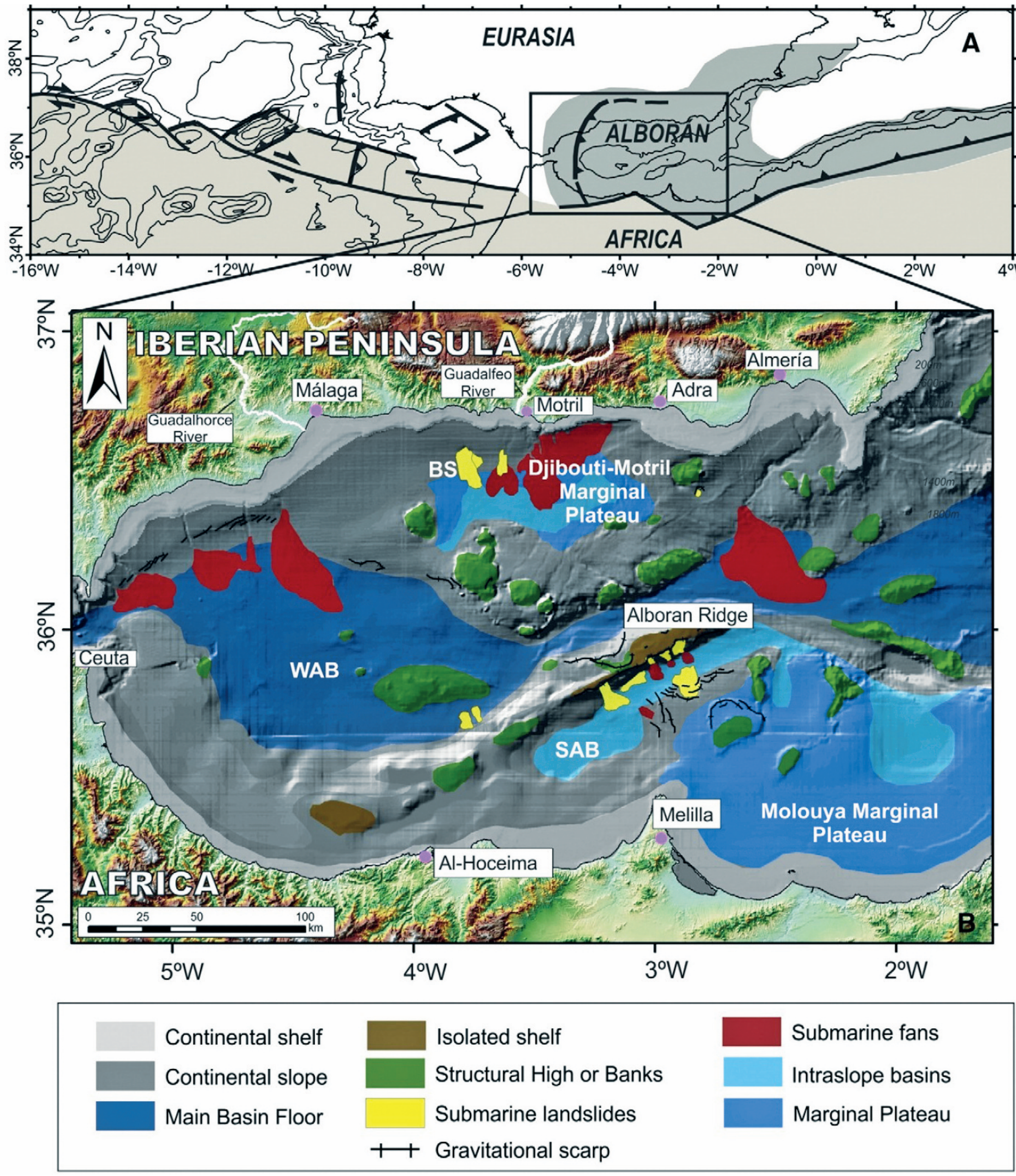

Figure 1. (A) Plate-tectonic scheme of the Ibero–Maghrebian region (modified from Vázquez and Vegas, 2000). WAS: Western Alboran Subduction Zone. (B) Physiographic Map of the Alboran Sea basin plotted on a hillshade model. A compilation of multibeam bathymetry (50 × 50 m) has been used for the construction of this model and has been plotted on a general hillshade model based on ETOPO bathymetry (1000 × 1000m). On land, a DTMmodel has been used based on the 1° × 1° files available from the 2000 Shuttle Radar Topography Mission, the resolution is about 90 m. BS: Baraza slide. SAB: South Alboran Basin, WAB: West Alboran basin. (Modified from Macías *et al.,* 2015).

Atlantic and Mediterranean water masses are connected through the Strait of Gibraltar and they meet and interact in the Alboran Sea. This oceanographic gateway controls the water masses changes and the complex physiography of the Alboran Sea Basin conditions the dynamics of these masses. In this regard the distribution of ridges, seamounts and marginal plateaus acts as obstacles to the intermediate and deep flows. The present-day circulation is defined by three major water masses: 1) the surficial Atlantic Water (AW) characterized by <36–36.5 psu salinity, average temperature of 16ºC, extended down to 150-250 m water depth that describes two anticyclonic gyres, Western and Eastern; 2) low density (LD) Mediterranean water, formed by the Western Intermediate Water (WIW, 37–37.7 psu salinity, temperature of 12.9–13ºC, extended down 300 m water depth) and Levantine Intermediate Water (LIW, salinity of 38.5 psu, temperature of 13.1–13.2ºC), which on the Spanish continental slope only extends down to 600m water depth; and 3) the underlying high density (HD) Mediterranean water, formed by the Western Mediterranean Deep Water (WMDW, 38.40–38.52 psu salinity, temperatures of <12.7–12ºC) which is largely restricted to the Moroccan margin (below 180m water depth, deep basins and the Spanish base-of-slope below 600m water depth) (Millot, 2009 and references therein) (Fig. 2).

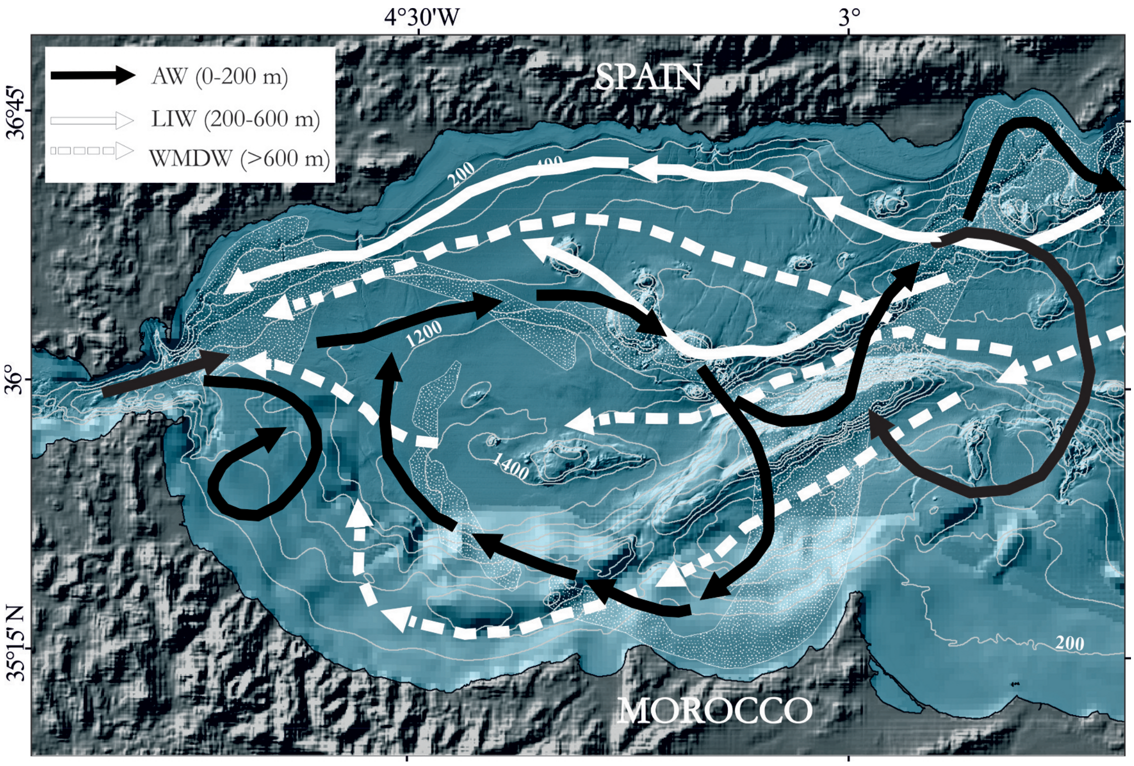

Figure 2. Bathymetric map of the Alboran Sea with the present-day regional circulation model. Legend: AW, Atlantic Water; WIW, Western Intermediate Water; LIW, Levantine Intermediate Water; WMDW, Western Mediterranean Deep Water; and ShW, Shelf Water (a mixture of AW and WMDW).

The Alboran Sea Basin has been formed in the context of the Western Mediterranean back-arc during the Upper Oligocene-Miocene rifting (Comas *et al.*, 1999; Jolivet and Faccena, 2000), in the interior of the Gibraltar Arc (Betics-Rif orogen) during the westward migration of the Alboran Crustal Domain (Platt *et al.*, 2003). Stretching and normal faulting in the extensional phase produced continental crust thinning accompanied by several andesitic volcanic episodes (Duggen *et al.*, 2004). This region has been under compression from the Late Miocene to the present (Martínez-García *et al.*, 2013). It is characterized by the generation of a broad deformation area and strain partitioning (de Vicente *et al.*, 2008). The great variety of focal earthquake mechanisms ranging from pure thrust to strike slip and normal faulting (Stich *et al.*, 2010 and references therein) and the presence of penetrative linear structures on the seafloor evidence the intense and varied active tectonics in this region (Gràcia *et al.*, 2006; Ballesteros *et al.*, 2008; Vázquez *et al.*, 2008).

The basement of the Alboran Domain has been deforled from the Tortonian to the present simultaneously the tilting of the Iberian and African continental margins and the uplift of the Betic and Rif cordilleras around the Alboran basin – Betics and Rif Ranges. Cordilleras uplift and the reduction and deepening of the Tortonian basin must be considered as part of the same deformation process related to the overall convergence between Africa and Eurasia and the blocking of the Alboran Domain westward migration. The Betics Cordillera uplift is evidenced by the presence of Tortonian carbonate reefs at 1,000 m in elevation (Braga *et al.*, 2003) and by current GPS measurements series (Giménez *et al.*, 2000). As a result, the Messinian saw the closure of the rifean and north betics straits which constituted the connection between the Atlantic Ocean and the Mediterranean Sea. This closure resulted in partial desiccation of the Mediterranean Sea and intense erosion of their margins (CIESM, 2007; Estrada *et al.*, 2011). Later, Pliocene and Quaternary tectonics would drive the formation of the new Gibraltar connection.

Pliocene to present sedimentary regimen of the Alboran Sea Basin is controlled basically by the interplay of three processes: i) sedimentary inputs from the interlands controlled by uplift of surrounding cordilleras, ii) glacioeustatic sea level changes, iii) and water masses dynamics and their related bottom motion modulated by long term climatic oscillations and short term seasonal variations.

In recent years the interpretation of sedimentary systems throughout the Pliocene-Quaternary and current sedimentary dynamics has undergone a major change: the new sedimentary models are based on the importance of the erosion and deposition processes related to water masses dynamics and sea level changes at regional scales and to tectonically controlled morphological features at local scale (Palomino *et al.*, 2011; Ercilla *et al.*, 2012a,b; Juan *et al.*, 2012a,b; Juan *et al.*, 2014; Ercilla *et al.*, 2015). The continental slopes mostly comprise alongslope plastered drifts with striking terraces formed under the action of the LD (Iberian margin) and HD water masses (African margin). The plastered drifts connect to a deeper plastered drift on the Western Spanish base of slope and to sheeted drifts in the basins, all formed under the action of the HD waters.

In this scenario, submarine canyons are the feeding element of the sedimentary model, as they cross the continental slope eroding the terraces and the alongslope plastered drifts and mouth directly into fan lobes on the base of the slope and in adjacent basins, with aggrading and migrating leveed channels interrupting the lateral continuity of the plastered and sheeted drifts. The canyon-fanlobe abrupt transition is always coincident with features sculpted by contour currents. Several incisive submarine canyons systems have been developed along the Pliocene-Quaternary (Estrada *et al.*, 1997; Fernández-Puga *et al.*, 1999; Estrada *et al.*, 2011) and some of them nowadays cut the Iberian margin of the Alboran Sea (Alonso and Ercilla, 2002; García *et al.*, 2006) and both flanks of the Alboran Ridge (Bárcenas *et al.*, 2004), while only one well developed submarine canyon occurs on the African margins (Ercilla *et al.*, 2002). This distribution points to a more important development of turbidity flows in the northern margins of the Alborán Sea. This work, presents a comparative morphosedimentary study of the canyons in this region.

METHODOLOGY

This paper is based on the study of combined data obtained by means of multibeam sounders (Kongsberg-Simrad EM-12S, EM-120, EM300, EM710 and ATLAS Hydrosweep DS), ultra-high (parametric TOPAS PS 018 echo sounder and ATLAS Parasound P-35) and high reflection seismic systems (EG&G sparker and 3-channel Airgun) and SIGEOF databases. All the seismic profiles were integrated into a Kingdom Suite project, comprising single and multichannel seismic records with different resolutions.

A systematic analysis has been done related to the morphography of submarine canyons using geographic information systems (ArcGis software). Their location and a series of geometric parameters were considered: head and mouth depths, average and thalweg lengths, width, incision, sinuosity and slope gradients. Where the thalweg length is measured along the current canyon axis, the average length is measured as the straight line between the head and the mouth of the canyon, sinuosity is calculated as the ratio between the thalweg and the average lengths, the width is the distance between the two main walls of the canyon, and the incision is the maximum height difference between the walls and the thalweg of the canyon.

Sampling by gravity cores and/or surficial dredges has been carried out on several canyons and a benthic TV camera (IEO VOR APHIA) was used to observe sea floor on the canyons of La Linea and Guadiaro by means of several video-transects.

Modern Submarine Canyons and Gullies Systems

The distribution of submarine canyons in the Alboran Sea shows an important difference from a morpho-sedimentary point of view: the uneven development of canyon-fan systems along the margins of this basin. Ten canyons and two gullies systems are defined in the Iberian margin (Alonso and Ercilla, 2002; Baro *et al.*, 2012), and numerous gullies with at least two canyons are described in the flanks of the Northern Alboran Ridge (Vázquez *et al.*, 2015). In contrast no main canyons and turbidite systems develop in the Moroccan margin, where the Ceuta canyon is the only submarine feature incising the slope, eroding the contourite deposits and mouthing into the entrance floor of the Strait of Gibraltar (Ercilla *et al.*, 2002) (Fig. 3). Canyons and channels define nine turbidite systems showing two main types of sedimentary models: i) submarine fan type (La Linea, Guadiaro, Baños, Torre Nueva, Fuengirola, Sacratif, Almeria) and ii) submarine ramp (Salobreña and Calahonda) type (Ercilla *et al.*, 2014; Macías *et al.*, 2015). The uneven development of Canyon-fan systems on the two margins and the variable architecture of the fans are a result of the unequal interaction between alongslope and downslope processes.

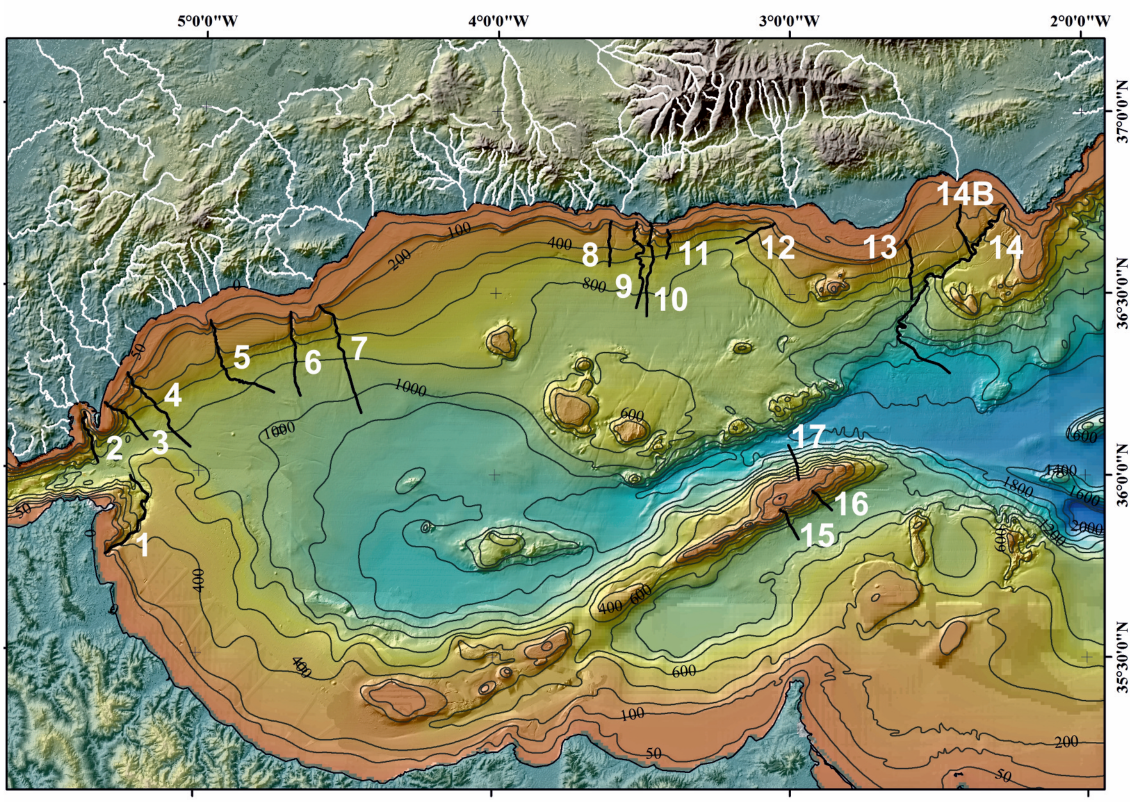

Figure 3. Location of Submarine Canyons and Gullies on the Alboran Sea margins and Northern Alboran Ridge. The fluvial drainage pattern is represented by white lines on the south-iberian onshore. 1, Ceuta Canyon; 2, Algeciras Canyon; 3, La Linea Canyon-Fan; 4, Guadiaro Canyon-Fan; 5, Baños Canyon-Fan (also called Placer de las Bovedas Canyon); 6, Torrenueva Canyon-Fan (also called Calahonda Canyon); 7, Fuengirola Canyon-Fan; 8, Salobreña turbiditic ramp system; 9, Motril Canyon; 10, Carchuna Canyon; 11, Calahonda turbiditic system; 12, Adra Valley; 13, Campo de Dalias gullies; 14, Almeria turbiditic system; 15, Al-Borani Canyon-Fan System; 16, Piedra Escuela Canyon; 17, Castor gullies area.

The sedimentary model of the fans is similar for all, being characterized by a single feeder canyon that usually crosses the terraced plastered drift of the continental slope and directly mouths into a fanlobe that develops from the lower scarp on the base of slope and basin transition. However a double canyon system feeds the Sacratif fan deposits (Alonso and Ercilla, 2002) and the Almería Canyon is characterized by a complex feeder system and a structural control (Cronin, 1995). The fanlobes comprise a single linear to low sinuosity feeder channel, which evolves to higher sinuousity channel. The fan turbidite model also comprises gullies mouthing onto a non-channel lobe. The ramp shape model comprises few to several input points represented by canyons and gullies that evolve downslope to a fan lobe with multiple leveed channels and distributary channels.

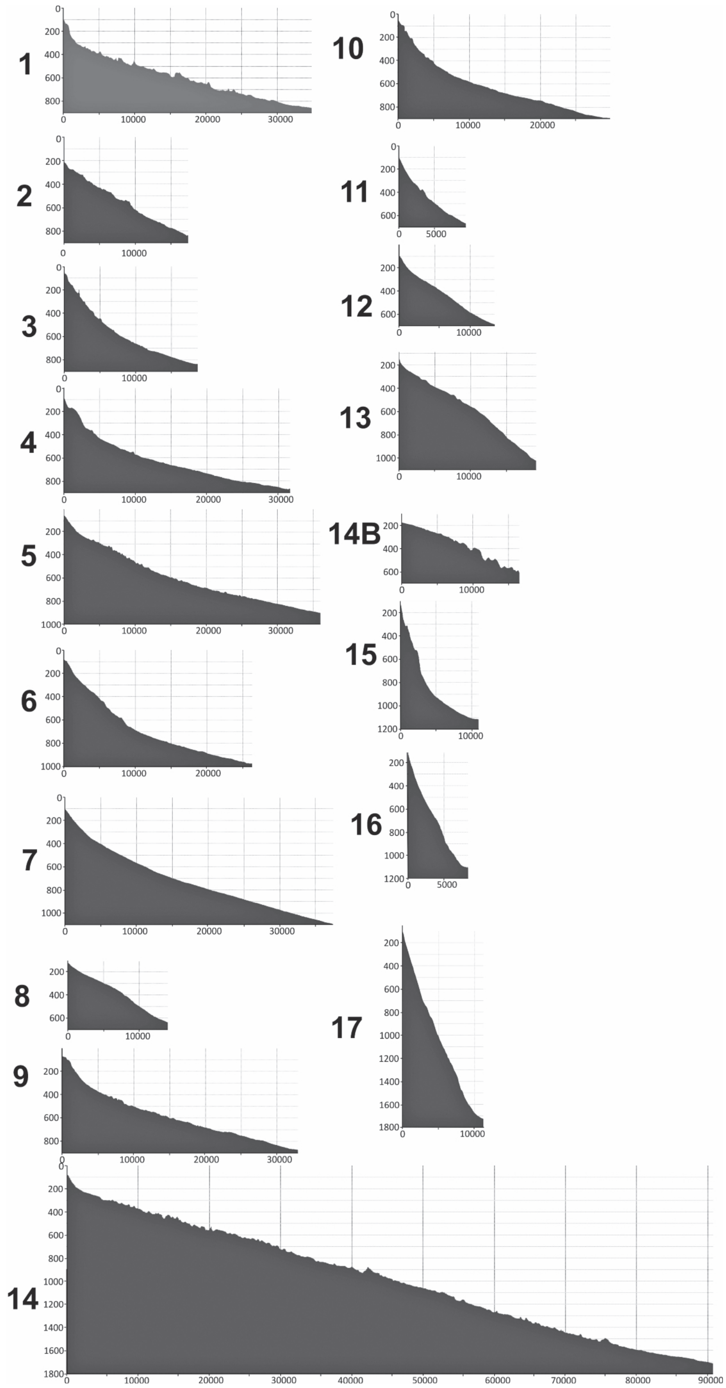

Figure 4. Longitudinal profiles of submarine canyons and gullies studied on the Alboran Sea. The profiles are located in Fig. 3.

Canyons Morphology

The following paragraphs describe the morphological features of these canyons, and the related turbidite fan (Fig. 3).

1) The Ceuta Canyon (1 in Figs. 3 and 4) is the only canyon present in the north African continental margin. It has been excavated on contourite deposits that form the Ceuta plastered Drift (Ercilla *et al.*, 2002). It has a length exceeding 40 km, a width between 3 and 6 km and a marked pathway. It extends from 55 m water depth at the head to 900 m water depth, mouthing on to the floor of the Strait of Gibraltar where accumulation of related deposit has been mapped.

2) The Algeciras Canyon (2 in Figs. 3 and 4) is located in the axis of the Algeciras Bay. It has a length greater than 20 km and a winding track. Its width varies between 1 and 4 km, and it extends from 24 m water depth at the head and 864 m water depth at the mouth, also located on the floor of the Strait of Gibraltar without related deposits. Its head is close to the coast (< 1 km) that is off the mouth of three rivers in the central part of the bay: Palmones, Guadacortes, and Guadarranque rivers.

3) La Linea Canyon-Fan (3 in Figs. 3 and 4) is the smallest of these systems located on the Alboran Sea (< 20 km long, < 8 km wide). It is fed by a main canyon and a secondary tributary canyon that merges at the foot of the lower slope. The eastern secondary canyon is about 7 km long, its head is located at the upper slope related and corresponds to a landsline scar whereas the western main canyon (9 km long) incises into 2 km the outer shelf and has a width between 1.4 and 1.9 km. Its head is characterized by two gullies that together have a horseshoe geometry whose branches are opened towards the coast and join to the canyon thalweg. These gullies begin their development at 15 m water depth, no more than 1 km distant from the coast, without apparent connection with any river mouth, and are 1.5 and 2 km long. Canyons mouth onto a fan shape lobe which is incised by rectilinear channels (< 5 km long).

4) The *Guadiaro Canyon-Fan* (4 in Figs. 3 and 4) is about 25 km long and 16 km wide. It is defined by a 14 km long feeder submarine canyon, and 1.7-2.5 rim width, whose head incises 3.5 km onto the outer shelf and is controlled by a rock outcrop. It is located 3 km from shore characterized by the mouth of the Guadiaro river. The canyon evolves to a lobe incised by a unique 13 km long leveed channel whose dimensions decrease downslope. The lobe has a fan shape 14 km long and 16 km wide; its seafloor morphology reveals the presence of old channels in the distal domains. A pockmark like feature field has been located on these deposits.

5) The *Baños Canyon-Fan* (5 in Figs. 3 and 4) is about 35 km long and 13 km wide. It comprises a 17 km long submarine canyon with 0.6-1.8 rim width (also called Placer de las Bovedas Canyon) whose head incises onto the outer shelf about 2 km. The head is located to the east of a rocky outcrop and the distance to the shore is about 6 km, where some rivers mouth as Guadalmina o Verde are found, without a direct relationship. The canyon evolves to a 6 km long leveed channel with a sinuous pathway. This leveed channel evolves to a channeled lobe that bifurcates into smaller distributary channels. The fan lobe displays a lobate shape area 16 km long and 12 km wide.

6) The *Torrenueva Canyon-Fan* (6 in Figs. 3 and 4) is 37 km long and 6 km wide. It is characterized by a canyon (also called Calahonda Canyon) about 15 km long and 0.5-2 km of rim width. The head incises 2 km onto the outer shelf and is located at 5.5 km from the shore where no main river mouth is found. At the depth of 600 m it is characterized by a strong linear geometry. This canyon evolves to a rectilinear leveed channel of 11 km long, it changes at about 1000 m water depth to a less incised and amalgamated type channel down to 1185 m water depth. There, it passes downslope to a 12 km long and 7km wide lobe. The surface of this lobe is characterized by longitudinal straight lineations that resemble small-scale rectilinear channel incisions.

7) The *Fuengirola Canyon-Fan* (7 in Figs. 3 and 4) is about 40 km long and 20 km wide. It is defined by a 14 km long and narrow (0.7 km wide) canyon, whose head enters onto the shelf about 1 km. It is located 6 km away from the coast and the river Fuengirola of the mouth. It evolves to a 8 km long, sinuous main leveed channel that mouths into a lobe with rectilinear distributary leveed channels. The fan lobe deposits have dimension of about 25 x 19 km.

8) The *Salobreña turbiditic ramp system* (8 in Figs. 3 and 4) is defined by two major gullies (about 14 km long), and three more between these (3 to 8 km long), with the head located on the upper slope around 180-190 m water depth. However they must be related with a group of very straight and small-scale gullies, at least twenty, that cross the outer shelf and the shelf break and have lengths between 0.5 and 2 km, directly related to the submarine deltaic deposits of the Guadalfeo river. Feeding gullies mouth into a lobe with an unchanneled apron shape about 17 x 11 km.

9) The *Sacratif turbiditic system* is fed by two canyons, eastern or *Motril Canyon* (9 in Figs. 3 and 4) of 9 km long and 2.4-3.5 km rim wide, and western or *Carchuna Canyon* (10 in Fig. 3A) of 11 km long and 2-3.2 km rim wide. The head of the Motril Canyon enters 1.5 km in the outer shelf and one additional km corresponding to a narrow gully which has 15 m of incision and extends toward the coast close to the submarine deltaic deposits of the Guadalfeo river. The head of the Carchuna Canyon incises 3.3 km onto the inner shelf, and it reaches 15 m water depth. It is located very close to the coast (< 0.5 km) without any rivers mouth. Both canyons evolve to leveed channels < 7 km long that mouth into channeled lobes with distributary channels that have variable pathways, from sinuous to reclinear. The lobe has dimensions of 24 x 14 km.

10) The *Calahonda turbiditic ramp system* (11 in Figs. 3 and 4) is composed of at least four relatively short (1 to 6 km long; 0.6-0.8 km wide) canyons plus gullies, their incision and length decrease to the east. These canyons evolved to leveed channels up to 11 km long, with trajectories from rectilinear to low sinuous. All together define a channeled lobe with an apron shape of 15 x15 km.

11) The *Adra Valley* (12 in Figs. 3 and 4) is a smooth valley channelized in the thalweg. It is 11 km long and 0.4-0.8 km wide. It has a slightly curved geometry and is extended from 85 m water depth in the head, at 6 km of distance from the Adra river mouth, until 650 m water depth where the canyon mouth on the Motril basin floor without related deposits. Its path is conditioned by a NE-SW active Quaternary anticlinal (Vázquez *et al.*, 2014).

12) The *Almeria turbiditic system* (14 in Figs. 3 and 4) is the largest turbiditic system of the Alboran Sea. The course of the Almeria Canyon is affected by the Serrata and Cape of Gata faults and by the interaction with NNE–SSW structures at several points along its longitudinal extension (Estrada *et al.*, 1997; Lo Iacono *et al.*, 2008). The canyon head is NE-SW oriented, it is located 3.5 km from the shore, close to the Cape of Gata, and entering about 4 km onto the shelf. The canyon is fed by three additional tributary systems (García *et al.*, 2006): the first is named Campo de Dalias which corresponds to a set of NNW-SSE to N-S oriented gullies (13 in Figs. 3 and 4) of 9 to 22 km, long occasionally with NNE-SSW oriented segments related to the action of main faults; the second is the Andarax system that is NNW-SSE oriented and shows two well differentiated sectors dissected by the La Serrata fault, northwards corresponding to a set of gullies related to the submarine deltaic deposits of the Andarax river mouth and soutwards corresponding to a major canyon; and the third, named Gata, corresponds to a NNE-SSW oriented channel generated by binding of the gullies that are eroding the shelf break and upper slope of the western part of the Cabo de Gata shelf. The Almeria Canyon at 1200 m water depth evolves to the fan lobe formed by the Almeria leveed Channel that runs southward for 26 km describing a curve trajectory down to about 1650 m. When this channel enters the eastern Alboran basin (about 1500 m water depth) the overbank area widens and from 1650 m the main leveed channel branches into distributary channels that make up the lobe deposits that extend down to the seafloor at 1800 m water depth. The fanlobe has the biggest lobular shape, 45 km long and 30 km wide.

13) The *Al-Borani Canyon-Fan System* (15 in Figs. 3 and 4) is located on the southern flank of the Northern Alboran Ridge. The Al-Borani canyon extends from the shelf (65–120 m water depth) downslope to 800m water depth (lower slope), with an average gradient of 12°, 3 km long and 2-2.5 km wide. The head zone is located around 65-70 m water depth and is characterized by several scars that produce a horseshoe geometry open to the canyon and affect the insular shelf of the Alboran Island. This canyon largely corresponds (1.8 km) to the proper incision on the Alboran island shelf. The upper canyon sector (110–350m depth) trends WNW–ESE and contains most of the tributary gullies. The lower canyon (350–800 m depth) is oriented NNE–SSW and becomes steeper (up to 19°) around 700 m water depth. Depositional features are located at the base of the slope-basin floor, where the Al-Borani Fan occurs. This fan is lobate, with a maximum width of 7 km and a length of about 7.7 km, and extends from 800 to 1,100 m water depth with a gentler gradient (1°–4°). It has two main NNW–SSE turbidite channels, small distributary channels, overbank deposits, and lobe deposits (Macías *et al.*, 2015).

14) The *Piedra Escuela Canyon* (16 in Figs. 3 and 4) is located on the southern flank of the Northern Alboran Ridge. It extends from 106 to 935 m water depth, is 5.7 km long and 0.5-0.9 km wide, and incises 0.9 km onto the Alboran island shelf. A mass flow deposits extends to 1115 m water depth from its mouth on the Southern Alboran Basin, it has 4.5 km long and 4 km wide, but no channels have been differentiated.

15) The *Castor gullies area* (17 in Figs. 3 and 4) is located on the northern flank of the Northern Alboran Ridge. It is composed by the Castor Canyon (10 km long, 0.4-0.6 km wide) that incises 1 km onto the outer shelf of the Alboran Island and connects the top of the North Alboran Ridge with the floor of the Alboran Trough, and over gullies (3-4.5 km long). No recognized deposits are associated with this system.

The distribution of submarine canyons in the Alboran Sea shows an important difference from a morpho-sedimentary point of view: the uneven development of canyon-fan systems along the margins of this basin. Twelve submarine canyons, gullies sets or canyon-fan systems (15 to 99 km long) have been identified in the Iberian margin and three minor canyon-fan system (4-8 km long) or gullies set have been localized in the flanks of the Northern Alboran Ridge (Fig. 3). In contrast, Canyon-fan systems do not develop in the Moroccan margin, where the Ceuta canyon is the only submarine feature incising the slope. The uneven development of Canyon-fan systems on the two margins and the variable architecture of the fans are a result of the unequal interaction between alongslope and downslope processes.

Modern habitats and sediments

At present no systematic study of bottom types and habitats has been carried along the Alboran Sea submarine canyons and gullies (Würtz, 2013), except for a multidisciplinary oceanographic survey realized in the frame of the VIATAR Project (Díaz-del-Río *et al.*, 2014) to characterize the sediments and habitats along two canyons-fan systems in the northwestern area of the Alboran Sea, the La Linea and Guadiaro canyons and fan deposits (Fig. 5).

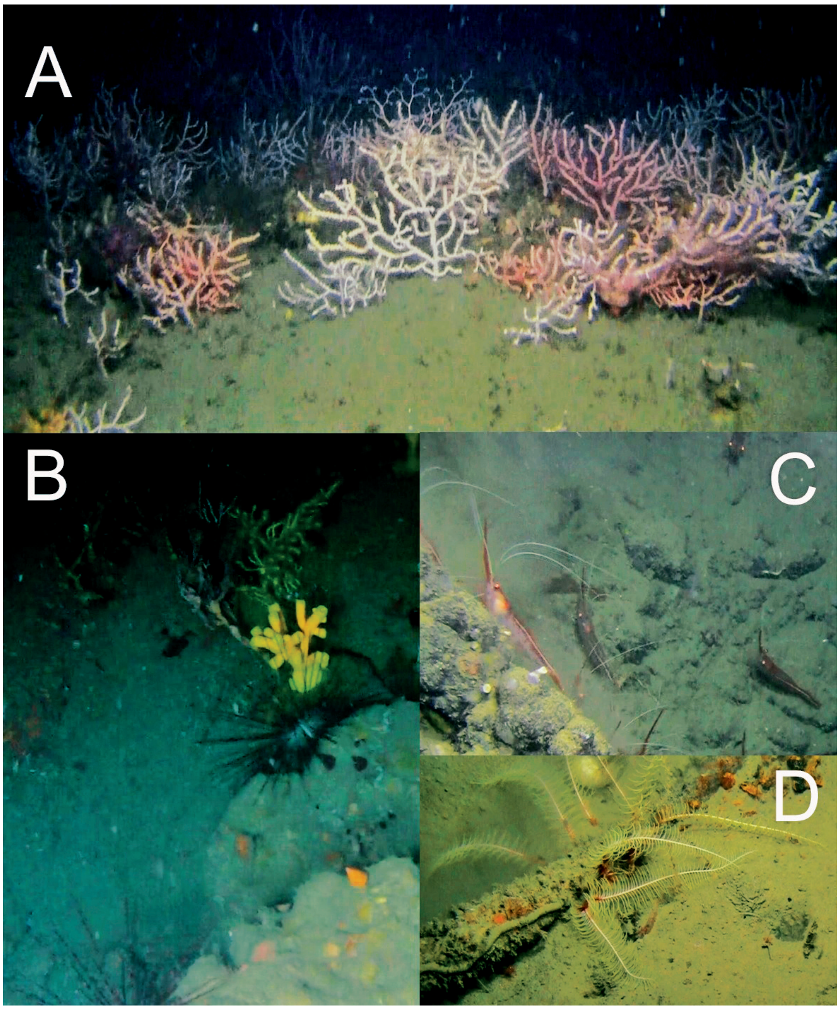

Figure 5. Different habitats and species found in La Linea and Guadiaro submarine canyons (Northwestern sector of the Alboran Sea). (a): Aggregation of gorgonians (*Eunicella verrucosa*); (b): Detail of two threatened species the sea urchin *Centrostephanus longispinus* and the cold-water coral *Dendrophyllia cornigera* (yellow); (c): Crustacean decapods of the genus *Plesionika*; (d): The ophiuroid *Ophiothrix* sp.

A) La Línea Submarine canyon

The seafloor of the head canyon (100-140 m depth) is characterized by muddy fine sand sediment, with abundant detritus, and a benthic community dominated by filter and deposit feeders, including sea-pens, sedentary polychaetes (Onuphidae, *Spiochaetopterus* sp.), molluscs (*Tellina compressa, Euspira fusca,* etc.) and decapods such as *Goneplax rhomboides* and pagurids (*Pagurus* spp.). This type of benthic community is somehow similar to the so called "Biocoenose des vases terrigenes cotieres" by Pérès and Picard (1964), included in the EUNIS habitat type "Circalittoral sandy mud" (A5.34). At this depth, there are also hard bottoms at the walls of the head, especially at the central part of the two tributaries where abundant remains of cold-water corals (mainly *Madrepora oculata*) occur as well as some echinoderms inhabiting the crevices among them (mainly *Ophiothrix* cf. *fragilis*). Live coral of the genera *Caryophyllia* and *Coenocyathus* colonize the vertical sides of the rocks. These formations with hard bottoms colonized by cold-water corals are included in the EU Habitat Directive (Reefs 1170), in the OSPAR convention ("*Coral gardens*") and also in EUNIS ("*Circalittoral coral reefs*", A5.63).

At 200 m depth, the thalweg sediment contains a higher amount of bioclasts (mainly remains of bivalves and of *M. oculata*) and the associated species include some decapods such as *Plesionika* *martia* and pagurids (*Pagurus* sp.), as well as sedentary polychaetes (*Spiochaetopteridae, Cirratulidae*) and macrourid fishes (*Malacocephalus laevis*). At the margins of the channel, the hard bottoms contain a higher density of ophiuroids (mainly *Ophiotrix* cf. *fragilis*) as well as solitary (*Caryophyllia* sp.,) and colonial cold-water corals (*M. oculata, Dendrophyllia cornigera*), constituting a habitat that is also in the Habitat Directive (*Reefs* 1770) and similar to the listed OSPAR and EUNIS habitats constituted by cold-water corals. Other species with a protected status included in the Annex II of the Barcelona Convention such as the gastropod *Charonia lampas* subsp. *lampas* also occur in this area.

At the thalweg of the canyon from 300 to 400 m water depth the sediment is composed of muddy fine sand. At 300 m water depth the thalweg is colonized by ceriantiids (*Cerianthus* sp.), decapods (*Pagurus* spp. and *Munida* spp.) and echinoderms (*Cidaris cidaris*) with a higher amount of cold-water coral remains (*M. oculata*) in those areas located close to the sides of the channel. At 400 m depth, sediments have a higher percentage of recent bioclasts of typical infralittoral mollucs (*C. gallina, Glycymeris nummaria*) as a consequence of the downward transport. The benthic community is dominated by different polychaete groups (mainly Eunicidae, Glyceridae and Capitellidae), molluscs species (*T. compressa, Nassarius ovoideus* and *E. fusca*) and the sea-cucumber *Leptosynapta* cf. *inhaerens*. Some of these species are very common in shallower circalittoral bottoms with muddy fine sand, and their presence could also be linked to the transport from the shelf down the canyon. This hypothesis is supported by the finding of large remains of leaves of the Mediterranean endemic seagrass *Posidonia oceanica*, which constitutes meadows in infralittoral bottoms located nearby (e.g. Manilva) (Luque and Templado, 2004). At greater depth (425m), the sediment is muddy with abundant detritus and remains of typical shelf species, such as the bivalves *Saccella commutata* and *Myrtea spinifera* as well as the gastropod *N. ovoideus*. The benthic community has a lower biodiversity than that at the upper parts of the canyon and is dominated by small capitellid polychaetes. At the eastern side of the thalweg, between 310-440 m, the sediment is muddy and colonized by cerianthiids, with the presence of the decapods *Munida* sp. and *Plesionika* sp. and a higher amount of cold-water coral remains close to hard bottoms on the side of the thalweg. In this area the two main types of habitats are the “Deep-sea biogenic gravels” (EUNIS A6.22) and the “Deep-sea mud” (EUNIS A6.5). At greater depths (800 m), the sediment is similar as well as the habitat type, which is dominated by cerianthiids, with the presence of disperse echinoids (mainly *Cidaris cidaris*).

B) Guadiaro submarine canyon

At the head of the canyon (~ 70-90m), the sediment is composed of pebbles, and microgravels coarse sand and mud, and the benthic community contains species typical of these sediment types on the continental shelf of the Alboran sea, such as the bivalve *Astarte fusca* or the echinoid *Echinus acutus*. This type of community usually appears in the EUNIS habitat “Circalittoral mixed sediments” (A5.44). At greater depths the sediment is also characterized by bioclasts (remains of corals, shells) as well as rocks of different sizes. The gorgonian *Eunicella verrucosa* is very common on these bottoms, along with species such as the echiuran *Bonellia viridis* or echinoderms *Echinus acutus* and *Centrostephanus longispinus*. The last species is protected under the Habitats Directive 92/43/CE (Annex IV) and is listed in the annex II of the list of endangered and threatened species of the Barcelona Convention. This type of habitat is included in the Habitat Directive (1170, “Reefs”), in OSPAR convention (“*Coral gardens”*) and represents the EUNIS habitat type “Mediterranean coralligenous communities moderately exposed to hydrodynamic action” (A4.26).

At the middle-upper part of the canyon (233 m depth), the sediment has a lower content of pebbles, and bioclasting gravels and a higher presence of compact mud. The benthic community is composed of polychaetes such as *Spiochaetopterus* sp. and molluscs such as *Anadara polii* and *Clelandella miliaris*. The benthic community is composed of *Plesionika* cf *edwarsii*, galatheid crabs (mainly *Munida* sp.), echinoderms (*Echinus acutus*), gorgonians (mainly *Callogorgia verticillata*) and large colonies of the cold-water coral *Madrepora oculata*, with larger densities than those found at La Linea submarine canyon. The cold-water coral habitats are included in the EU Habitat Directive (Reefs 1170), in the OSPAR convention (“*Coral gardens”*) and also in EUNIS (Circalittoral coral reefs, A5.63). At greater depths (293 m) sediments are composed of fine sand with sparse rocks of different sizes and medium levels of bioturbation. This area displays a lower biodiversity, with the presence of the decapod *Plesionika* sp., the crinoid *Neocomatella europaea,* and the ophiuroid *Ophiotrix* sp, among the rocks. At greater depths along the thalweg (397m) muddy bottoms are dominant and colonized by polychaetes of different families (Capitellidae, Terebellidae, Spionidae, Polynoinae) and typical shelf bivalve molluscs such as *S. commutata* or *M. spinifera*. The habitat would correspond to "Deep-sea mud" (EUNIS A6.5); it also contains benthic components that would normally occur at shallower depths but could have colonized these bottoms due to the vertical transport of sediment and fauna along the canyon.

Geohazards

Two main processes related to canyon occurrence have been detected as probable hazards in the Iberian margin of the Alboran Sea:

i) The development of landslides along the canyon leading to tsunami triggering in the basin. Landslides have been located on the upper slope sector of the La Linea and Motril canyons, and at the canyon head of the Alborani canyon (see Macías *et al.*, 2015).

ii) Retrogressive erosion at the canyon head have been detected in several canyons; the most important is related to the Carchuna canyon (Ortega *et al.*, 2014) the highest economic impact could be produced at the Algeciras canyon head where substantial human infrastructures are located. Other areas affect by gullies erosion are the head of the Motril and La Linea canyons.

Canyon-fan systems evolution

The architectural elements of the canyon-fan systems show different seismic facies. The canyon fill deposits display complex facies pattern with chaotic fill, prograding fill, divergent fill and mounded fill facies. Canyon facies are better developed in the Fuengriola and Almeria canyons. Some canyons (Baños/Calahonda and Torrenueva) do not show canyon floor deposits and their seismic expression is only recognized by the V-shape valley incision with truncation of reflections in their walls and floors. The canyons facies appear as irregular bodies with a well-defined distribution related to the linear canyon feature. The channel fill deposits, that are similar to the canyon ones, are defined because of their association to the levee deposits and are mostly defined by chaotic facies. They are identified in all the turbiditic systems. The chaotic facies presents two subtypes: i) wavy and disrupted reflections of medium amplitude that appear as mound or lens-shaped bodies, bounded by irregular erosional surfaces; and ii) strong, contorted reflections of high acoustic amplitude with hyperbolic and hummocky reflectors, sometimes showing traces of the original parallel bedding. Their overbank deposits are formed by downlapping continuous conformable to wedging reflections. The lobes display facies that vary laterally, being mostly chaotic and/or transparent for the distributary channels, and stratified, continuous and discontinuous, for the overbank, non-channeled and lobe fringe.

Discussion and conclusions

The Alboran Sea is characterized by at least fifteen erosive systems, between submarine canyons, valleys, gullies and channels, which are the main feeder system of at least nine turbiditic fans in the Iberian margins and two in the Northern Alboran Ridge but none in the African margins.

Main controls of submarine canyons evolution and distribution are related to regional tectonics, water mass dynamics and sea level fluctuations linked to climate oscillations. Recent findings indicate that most of the canyons described here originate from at least the Messinian salinity crisis. Formation and/or location of Alboran canyons have been related to connection of river mouths (e.g., La Linea, Guadiaro), retrogradational local slope failures (e.g., Baños, Torrenueva). Sediment source has been mainly controlled by the Pliocene-Quaternary compressive tectonics that produces the uplift of the surrounding Betic-Rif cordilleras and basin inversion (Martínez-García et al., 2013). Deformation controls the continental sediment input provided by river transport as well as the accommodation of the sedimentary units. When sediment arrives to the sea, water masses circulation redistributed it throughout basin or formed dense gravitative flows that are funneled down through the canyons . There suspended sediment interferes with contemporaneous secondary circulation through the canyons (Allen and Durrie de Madron, 2009; Allen and Hickey, 2010). Likewise, reworking shelf sediment by storms and carving canyons walls and floor can also supply additional sediment to the flows running along canyon (Ercilla *et al.*, 1994; Alonso and Ercilla, 2002; Fernández-Salas, 2007). In the northwestern canyons, a well differentiated alonslope influence is noted along the entire canyon-fan system: the eastward AW influences the canyon head, the westward Mediterranean LW interferes along the main canyon course and the Mediterranean HW affect the fan deposit. A similar pattern is observed in the northeastern area.

Finally, the influence of climatic oscillations has a twofold dimension on the dynamics of submarine canyons. On the long term, the Pliocene-Quaternary glaciations episodes, have been commonly used to explain the episodes of canyons enlargement, excavation and incision of the continental shelves during events of sea level falls (Ercilla *et al.*, 1992, 1994; Hernández-Molina *et al.*, 1994; Ercilla and Alonso, 1996; Hernández-Molina *et al.*, 2002; Ortega *et al.*, 2014). The pattern of this incision is slightly regular, usually reaching the head between 55 and 90 m water depth, at distances less than 1 km from the coast. With respect to short-term variations, we suggest fluvial flooding events and / or to rapid increases in rivers flow as a main factor controlling sedimentary and evolutive dynamics. These processes can generate hyperpycnal flows at the rivers mouth that sink due to its higher density, and can cross the continental shelf and reach the canyons head, producing both erosive and sedimentary effects on the continental shelf (gullies and sedimentary waves) and along the canyons (gullies and turbiditic events). These processes have been observed mainly in the central and eastern sectors of the margin related to the mouth of Guadalfeo, Adra (Fernández-Salas *et al.*, 2007; Lobo *et al.*, 2006; Lobo *et al.*, 2014; Bárcenas *et al.*, 2015) and Andarax rivers.

The sedimentary development of these canyons-fans systems suggests that the spatial and temporal distributions of the turbidite deposits making up these fanlobes involve lateral and longitudinal migrations of the main turbidity flows and related flows coming from the canyons. The relocation of flows pathways have been analysed in detail for the Sacratif system. Likewise, the development of these canyons-fans systems interrupts the lateral continuity of terraced plastered and sheeted drifts. The depositional architecture, dimensions, and plan-view morphology of the canyon-fan elements indicates that the sedimentary composition of the fans ranges from sandy to mixed sand-mud, becoming sandier towards the Strait of Gibraltar.

The oceanographic gateway context of interaction between Atlantic and Mediterranean waters that characterizes the Alboran Sea and its related bottom contouritic processes, is also a main factor responsible for the architecture model of these canyon-fan systems as well as their absence in the Moroccan margin (Ercilla *et al.*, 2014). When fine sediment arrives to the sea, it is taken by the Atlantic water mass (0 to 250 m depth) and distributed by the two anticyclone gyres that define its circulation. Fine sediment becomes part of a complex system of circulation mainly formed by three underlying water masses, the Winter Intermediate Water (100 to 300 m), the Levantine Intermediate Water (200 to 600 m) in the Spanish margin, and the Western Mediterranean Deep Water (> 275 m) mainly in the Moroccan margin. Their contouritic processes contribute to the outbuilding of the margin and infilling of the basins.

Based on the oceanographic and sedimentary contexts, as well as the overall architecture and geometry of the canyon-turbidite systems, it is possible to distinguish two scenarios where there is interaction between alongslope and downslope processes, occurring at different intensities. These scenarios help us understand the potential mechanisms that may have been conditioning the uneven development of canyon-fan systems in the Alboran Sea basin (Ercilla *et al.*, 2014).

1) *The Spanish margin scenario, where the interaction has conditioned the fan architecture and its variability.* In this scenario when sediment arrives to the sea, the finest fraction is capted by the AW. The dynamics of the two anticyclone gyres and the well-developed isopycnal and related processes (e.g., internal waves) between the Atlantic and Mediterranean waters represent potential mechanisms for maintaining the fine sediment in suspension and dispersing it in the nepheloid layer throughout the Alboran Sea. Caption would result in fine sediment deprivation in the downslope flows feeding the fans, explaining the lack of defined levees in the canyon margins and the sandier fans towards the Straits of Gibraltar, where the currents are faster. Thus, the interplay between the unequal activity of the AW (its eastwards velocity decrease) and its two

anticyclonic gyres (Eastern-permanent versus Western-semipermanent), as well as the LD and HD accelerating toward the Strait of Gibraltar, would favour significant captation from the gravity flows outbuilding the fan lobes in the west.

2) *The Moroccan margin scenario, where the interaction is stronger and has conditioned the lack of canyon-fan systems.* In this scenario, the interplay between the captation by the Atlantic anticyclonic gyres, more sediment in suspension, and dispersion due to the enhanced density contrast between the AW and HD Mediterranean waters, together with the waters of the HD core impinging and accelerating along the Moroccan margin due to being forced to flow upslope, all favour intense alongslope sediment transport. This intense transport avoids the convergence of sediment along the Moroccan margin, inhibiting the local occurrence of potential erosive gravity flows and leading to the formation of canyons and/or their related fan lobes.

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