NEW INSIGHTS OF THE IBERIAN-AFRICAN PLATE BOUNDARY ALONG THE ALBORAN BASIN (WESTERN MEDITERRANEAN) BASED ON DEEP SEISMIC IMAGES.

Una nueva visión del límite entre las placas Iberia y África en la Cuenca de Alborán (Mediterráneo Occidental) basada en imágenes de sísmica profunda.

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***Abstract**: Although several geodetic studies reveal motion across the Alboran Basin, the low seismicity derived of the slowness of the structures has put the seismic and tsunamigenic potential of the faults on a second order problem. Due to the recent earthquakes recorded in the region (e.g. January 2016 Mw= 6.4), with magnitudes high enough to cause considerable damage in the nearby cities and to be felt in all the coastal cities surrounding the basin, this concept is rapidly changing. Moreover, despite the low slip rate estimated for the faults at this region, their seismic potential resides on their large dimensions. Most of them coincide with crustal scale boundaries, are well oriented to the present-day stress regime and show a seafloor morphological expression that points out to their present (upper Quaternary) activity. Considering that the location of these faults seems to be controlled by the lithospheric configuration of the basin, a suitable characterization to the crustal domain is fundamental to define these tectonic boundaries and to estimate its seismic and associated tsunamigenic hazard. Within this study we propose to identify the active tectonic structures and to estimate their seismogenic potential by advancing in the deep structure characterization.*

Key words: *active tectonics, deep structure, slip estimation, seismogenic potential*

***Resumen:** Aunque los estudios geodésicos revelan movimiento en la cuenca de Alborán, la baja sismicidad registrada ha puesto el potencial sísmico y tsunamigénico de estas estructuras en un segundo plano. Debido a los recientes terremotos registrados en la zona (ej. enero 2016, Mw=6,4), con magnitud suficiente para afectar a las ciudades costeras adyacentes y causar daños, este concepto está cambiando. A pesar de la baja sismicidad registrada instrumentalmente, causada por la baja velocidad en el movimiento de estas fallas, el potencial sísmico de estas estructuras reside en sus grandes dimensiones. Muchas de estas fallas actúan como límites a escala cortical, bien orientadas en el sistema de esfuerzos actual y por lo tanto, activas. Su localización parece estar controlada por la configuración litosférica de la zona, por lo que una correcta caracterización de la estructura profunda es fundamental para definir estas fallas de grandes dimensiones y su potencial sísmico asociado.*

***Palabras clave:** tectónica activa, estructura profunda, estimación del desplazamiento, potencial sísmico.*

The Alboran Basin (Western Mediterranean) (Fig. 1) hosts the plate boundary between the Iberian and African tectonic plates. Here, the deformation is distributed over a wide zone in which few well-defined tectonic structures are accommodating the convergence between these two plates. Due to the long recurrence interval of the active faults (estimated in more than 1000 years for onland faults, Gràcia et al., 2006), these structures have been usually ignored in the seismic hazard assessment. However, kinematic modelling shows relative displacements along the basin (Koulali et al., 2011). The occurrence of recent earthquakes with large magnitude (e.g. January 2016, Mw=6.4, Al-Idrissi Fault), implies that these faults may suppose a risk for the adjacent coastal areas.

The extensional processes that led to the Alboran Basin formation took place from the Early to the Late Miocene, led by slab roll-back and slab tearing on the Gibraltar Arc subduction system (Wortel and Spackman, 2000). Afterwards, during the Plio-Quaternary, the basin has been deformed due to the convergence between the Iberia and Africa plates, producing the contractive reorganization of some structures at the basin. However, the expected inversion is not affecting the entire basin. Tectonic activity is instead focused on a few first order faults (e.g. Alboran Ridge, Yusuf, Al-Idrissi and Carboneras faults), in which location seems to be conditioned by the lithospheric structure inherited from the basin opening, considering that they are engendered at the edges between different crustal domains (Gómez de la Peña et al., submitted). Thus, an accurate characterization of the crustal domains of the Alboran Basin and the transition between them is key to improve our understanding of the seismogenic potential of the faults in this complex area.

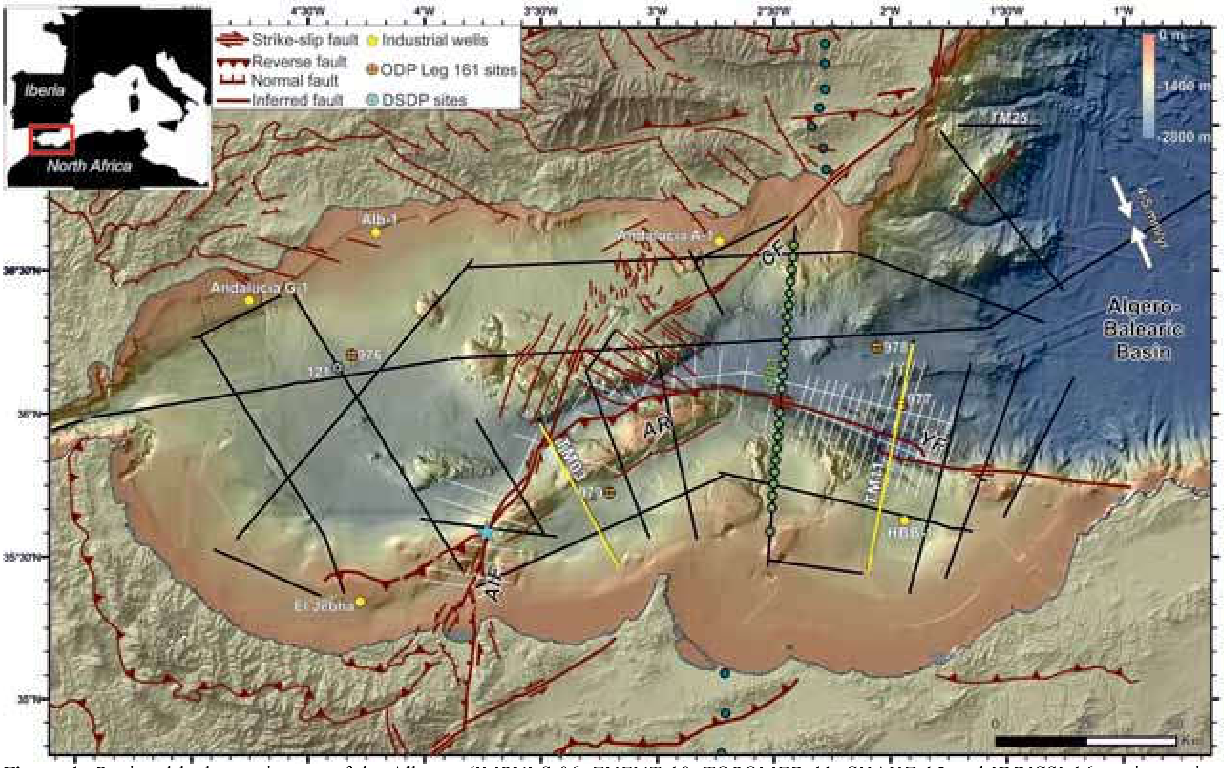

Figure 1: Regional bathymetric map of the Alboran (IMPULS-06, EVENT-10, TOPOMED-11, SHAKE-15 and IDRISSI-16 marine cruises (Gràcia et al., 2006) and a compilation of existing datasets from IEO and GEBCO). Main tectonic structures and the epicentre of the January 2016 earthquake (blue star) are displayed (Gràcia et al., submitted). TOPOMED (black lines) and EVENT-DEEP (white lines) multichannel seismic reflection profiles are depicted, as well as the OBH/OBS and on-land stations (green dots) from P01 WESTMED profile. Yellow lines point out the available PSDM profiles. Inset: Location of the shown area (red rectangle). AIF: Al-Idrissi Fault, AR: Alboran Ridge, CF: Carboneras Fault, YF: Yusuf Fault.

The Alboran Basin is a seismically active zone, characterized by shallow to intermediate and low to moderate magnitude (maximum Mw ≤ 6.4) instrumental earthquakes. In addition, historical records evidence that large earthquakes (MSK Intensity X-XI) have also been generated in the past (Gràcia et al., 2006; Grevemeyer et al., 2015). These events involve a seismic and tsunamigenic hazard for the region that cannot be characterized only with the instrumental records (< 100 years). Thus, to analyse the seismic hazard of this area is necessary to also study the active faults.

The crustal structure of the Alboran Basin has been under debate since the first surveys in the late 1980's (e.g. Platt et al., 2013). Although the regional crustal and upper mantle structure have been extensively studied recently (i.e. global tomography (Chertova et al., 2014), receiver function analysis (Mancilla and Diaz., 2015) or full-waveform inversion (Fichter and Villaseñor, 2015) the lithosphere underneath the Alboran Basin remains inadequately imaged, as the resolution of the crustal model is limited due to sparse data, inhibiting a precise characterization of the crust underneath the basin.

Based on multichannel seismic reflection studies (i.e. TOPOMED project), with seafloor and basement ground-truthing through available borehole and dredge samples, four different crustal domains have been defined for the area: (i) a thin continental domain (West Alboran and Malaga basins), (ii) the magmatic arc domain (East Alboran Basin), (iii) the North-African continental domain (South Alboran, Pytheas and Habibas basins) and (iv) oceanic crust (Algero-Balearic Basin) (Gómez de la Peña et al., submitted).

Unfortunately, basement dredges and borehole data are scarce, and, to a better understand of the deep structure of the Alboran Basin, wide-angle seismic deep-penetrating data are needed. In this study, we fulfil the characterization of the Alboran Basin crustal domains through the interpretation and analysis of a Wide Angle Seismic profile, deep-penetration multichannel (DP-MCS) and high-resolution multichannel (HR-MCS) seismic sections. These data are used (1) to identify the crust type under the basin, (2) to characterize the entire dimension of the faults, delineating the crustal domain boundaries, (3) to estimate the total slip accommodated by the main structures in the area, and (4) to estimate their seismogenic potential. Here, we focus our study in two of the most prominent active structures in the region: the Yusuf Fault and the Alboran Ridge (Fig. 1).

The Wide Angle Seismic (WAS) data used in this study was acquired in the frame of the WESTMED project (cruise M69/2, 2006) on board the german RV "Meteor". A 32-litres BOLT air-guns array at 140 bar, fired every 60 s were used. To carry out the survey, 20 ocean bottom hydrophones (OBH) and 5 ocean botton seismometers (OBS) from GEOMAR (Kiel, Germany) were deployed on the offshore areas, and land stations were also placed (Fig. 1). In this study we have inverted and analyzed profile P01, which runs from the south of Iberia (Almeria) to the north African margin (east of Nador) crossing the East Alboran basin, the Yusuf fault ang the Pytheas basin (Fig. 1). In this profile were used 24 OBH and OBS spaced <2.5 km, and 13 onshore geophones located on both margins. Velocity modelling has been carried out using the Korenaga inversion method. The result resolves the crustal structure and the Moho depths across the Alboran Basin. This profile runs coincident with a crustal-scale multichannel seismic reflection profile, allowing the association of the velocity variations and anomalies with their geologic origin. Further, the comparison between 1D vertical Vp structure and density models with empirical Vp and density relationships sheds light on the petrological nature of the basement, fulfilling the crustal domain characterization.

As mentioned, in this study we have used two types of MCS data, a regional covering grid of DP-MCS profiles acquired during the TOPOMED-GASSIS (2011), nested with a closer spacing grid of HR-MCS profiles collected during the EVENT-DEEP Leg 1 (2010) (Fig. 1). The DP-MCS profiles were acquired on board of the Spanish RV "Sarmiento de Gamboa", using a 5100 meters long active section of a solid state Sentinel SERCEL streamer with 408 active sections (12.5 m channel interval), towed at 10 m depth, and using a 50.15 l (3060 c.i.) air-gun source. The source array was composed of 8 G-GUN II air-guns deployed at 7.5 m depth, in a single cluster distribution. The air-guns were fired every 30 m (TM01, TM02), 40 m (TM03-TM05) and 50 m (TM06 to TM25) at a pressure of 2000 psi. The total record length was 14 s (Two Way Travel Time, TWTT) with a sample rate of 2 ms. These profiles have been processed using "GLOBE Claritas" software. The processing flow was designed to obtain a crustal scale image, preserving the resolution in the sedimentary basins but also imaging the deeper parts of the crust and the upper mantle. Processing steps in time domain include minimum-phase conversion, real geometry definition accounting for streamer feathering, spherical divergence correction, predictive deconvolution in Tau-P domain (to eliminate the bubble and short periods multiple reverberations), surface consistent deconvolution, Surface Related multiple elimination (SRME) demultiple, Radon filter demultiple, normal-move-out correction based on velocity semblance analysis, Dip Move Out (DMO) correction, stretching mute, amplitude recovery, time migration and a time and spatial variant band-pass filter. In order to obtain the real geometry of the structures in depth, we have performed a Pre-stack Depth Migration (PSDM) to profiles TM03 (across the Alboran Ridge) and TM11 (across Yusuf Fault) (Fig. 1). This PSDM has been performed using the Echos software. The HR-MCS were acquired on board the RV "Sarmiento de Gamboa". The objective was to image shallow structures and seismostratigraphic units and to this was used a multichannel SEAL seismic streamer with 96 active sections, channel spacing of 6.25 m and towed at 2.5 m water depth. The source array was composed by 10 air-guns with a total volume of 13.1 l, fired every 12.5 / 18.95 m, depending on the location of the lines. The record length was of 8 s TWTT with a sample rate of 2 ms. These profiles have been processed using ProMAX and GLOBE Claritas software, with the aim of obtaining a high-resolution image of the sedimentary cover. The main processing steps applied for these profiles include statics correction, trace editing, top mute from 0 time to seabed, bandpass filter, FK filtering for a specific dip noise, true amplitude recovering due to spherical divergence loss energy, Common Depth Point (CDP) sorting, Normal Move Out after picking a velocity model, CDP stack, trace equalization, time migration, and SEGY export format.

On the basis of all these new information, we have been able to fulfill the fault characterization by analyzing the deep structure of the basin, fundamental to estimate the real dimensions of the faults and to understand how the deep estructure is conditioning the location of the nowadays active faults. On the seismic data, the Carboneras, Yusuf, Alboran Ridge front and Al-Idrissi faults are imaged as crustal scale faults, cutting the entire crust and putting together different crustal domains. Accordingly, we have obtained a mean fault depth ranging between 10 and 15 km. In addition, based on the earthquake depht obtained by microseismicity studies, the faults in the area seem to be seismogenic till ~15 km (Grevemeyer et al., 2015). Consequantly, to estimate the seismic potential of this structures it is fundamental to consider the entire fault trace till at least ~15 km depth.

Segment	Length (km) ~SRL (km)	Width (Km)	Area (km²)	Estimated Mw			
				Wells and Coppersmith	*Wesnousky*	*Stirling*	*Stirling (plate boundary)*
West Yusuf F.	87	3.5	870	7.3±0.1	7.3±0.1	**7.1**±0.1	**7.0**±0.2
East Yusuf F.	105	4.5	1050	7.4±0.1	7.3±0.1	**7.3**±0.1	**7.1**±0.2
W+E Yusuf F.	150	18	1500	7.6±0.1	7.5±0.1	**7.9**±0.1	**7.3**±0.2
Alboran Ridge	113	2	1130	7.5±0.1	**7.3**±0.1	7.1±0.1	7.2±0.2

Wells and Coppersmith (1994): $Mw = 5.16 + 1.12\ Log\ (SRL)$

Wesnousky et al., (2008): $Mw = 5.56 + 0.87 \log L$

Stirling et al., (2008): $Mw = 4.18 + (2/3) \log W + (4/3) \log L$

Stirling et al., (2008) (strike-slip plate boundary): $Mw = 3.09 + 4/3 \log A$

Table 1: Estimated maximum earthquake for the Yusuf Fault and the Alboran Ridge systems, taking as input parameters the length and width of the segment and following the empirical relationship proposed by Wells and coppersmith (1994), Stirling et al., 2008 and Wesnousky et al., 2008. Mw: Moment magnitude, L: Length, SRL: Surface Rupture Length, W: Width, A: area. Estimation is based in the fault dimensions measured on the bathymetric maps (lengh) and on the seismic profiles (depth). The most suitable results for each area, chose in base of the tectonic setting, have been depicted in bold. The error is estimated on base of ~10% uncertainty in the input measurements.

Using the PSDM sections, we estimate the total slip accommodated by the most prominent tectonic structures in the area since the Earliest Pliocene. The PSDM sections of the crustal structure allow us to analyzed the real geometry of these structures at depth and to measure slip. We use the deformation-related geometry of strata and faults to estimate slip on the main faults, applying the exceed-area method and relationships obtained through numerical modelling of strike-slip systems (e.g. Rodgers, 1980; Epard & Groshong, 1993). Results reveal that the total slip accomodated by both fault systems is ~16-30 km since the Early Pliocene.

To estimate the maximum magnitude that the Yusuf and Alboran Ridge faults could produce we have use different empirical relationships (Wells & Coppersmith, 1994; Stirling et al., 2008; Wesnousky, 2008) that consider the type of crust, the tectonic setting and the dimensions of the faults (Table 1). The maximum earthquake value, together with the slip-rate of a fault, determine its seismic potential. Thus, the maximum earthquake is needed to estimate the seismic potential of a fault and then, its associated seismic hazard. The calculated maximum earthquake values for both faults imply a much larger seismic hazard than the expected.

Main conclusions of our study suggest that:

(1) The location of the active faults is controlled by the deep structure. In the current contractive tectonic setting, initiated in the Pliocene (<5.3 Ma), strain is mainly accommodated in few prominent tectonic structures, such as the Alboran Ridge Front fault and the Yusuf Fault. These faults nucleated at the transitions between the different lithospheric domains, as these areas represent the weakest rheological zones of the basin.

(2) Estimated total slip accommodated by the main fault system may be similar (with error bounds) to the estimated plate convergence value since the Messinian time (~24 km). Thus, slip on that faults may have accommodated most of the Iberian – African plate convergence during the Plio-Quaternary, revealing that the contractive reorganization of the Alboran basin is focused on a few first-order structures that act as lithospheric boundaries, rather than widespread and diffuse along the entire basin.

(3) Based on empirical relationships, the maximum earthquake for the main structures of the area is Mw>7 for the Yusuf and Alboran Ridge front faults. Thus, they should be take into account in earthquake hazard maps and seismic hazards prevention plans of the coastal areas.

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