UNVEILING THE LARGEST STRIKE-SLIP FAULT SYSTEMS IN THE ALBORAN BASIN WITH UNPRECEDENTED RESOLUTION

Desvelando las principales fallas de desgarre de la Cuenca de Alboran con sistemas de muy alta resolución

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***Abstract**:* Here we present an overview of the three largest continental strike-slip fault systems in the Alboran Basin: Carboneras, Yusuf and Al-Idrissi. Our dataset results from an integration of different types of acoustic and seismic data acquired during five marine cruise during the past 10 years. A multiscale approach utilizing newly acquired AUV near-bottom bathymetry (1-m resolution), shipboard bathymetry, high-resolution seismics (Sparker) and deep penetration multichannel seismics (MCS) data is used. According to fault trend, geometry and time of activity, fault systems are divided in different segments. These large fault systems are able to generate M_w>6.0 to 7.4 earthquakes, which may represent a significant seismic hazard to the neighbouring areas

Key words: *strike-slip faulting, continental fault system, seismicity, micro-bathymetry, Alboran Sea*

Introduction

Present-day crustal deformation of the southeastern Iberian margin is mainly driven by the NW-SE convergence (4.5-5.6 mm/yr) between the African and Eurasian plates (e.g. DeMets et al., 2010) (Fig. 1). This convergence is accommodated over a wide deformation zone (Echeverria et al., 2013), with significant seismic activity south of the Iberian Peninsula (e.g. Buforn et al., 2004; Stich et al., 2006, 2010).

Located at the westernmost Mediterranean, the Alboran Sea is bounded by the Betic and Rif Cordilleras forming the Gibraltar Arc. The Alboran Basin was formed during the Miocene extensional process, probably related to westward roll-back of the Tethyan slab in a context of Africa-Iberia convergence (e.g. Booth-Rea et al., 2007, Martínez-Garcia et al., 2013, 2017; Gràcia et al., 2006, 2012). Successive extensional and compressional phases from the middle to late Miocene gave way to the present-day configuration with the development of large strike-slip and reverse fault systems (FS) (e.g. Morel and Meghraoui, 1996).

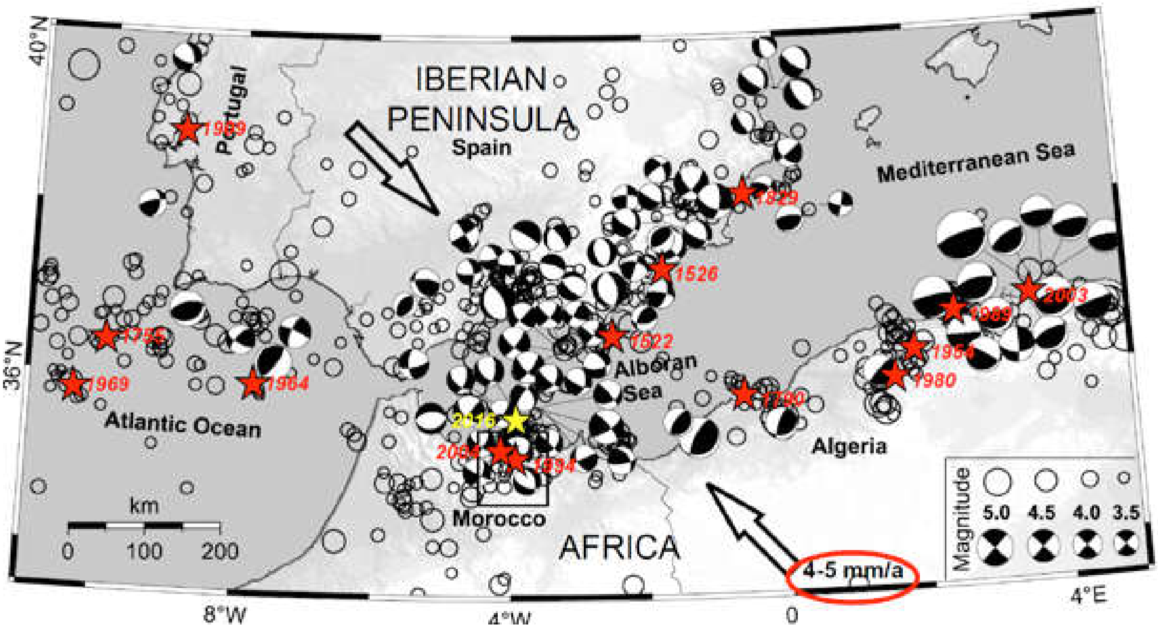

Figure 1: *Reverse and strike-slip focal mechanisms predominate in the south Iberian Margin (modified from Stich et al., 2003a). Large historical and instrumental earthquakes are depicted by a red star and year. Yellow star indicates the M_w6.4 event of 25^{th} January 2016 in the Alboran Sea.*

In the Alboran Sea, instrumental seismicity is characterized by shallow seismic events of low to moderate magnitude (Mw < 5.5) (Buforn et al., 2004; Stich et al., 2006, 2010). Nevertheless, large destructive earthquakes (MSK Intensity IX-X) some of them with submarine epicentres, have occurred in the Alboran region, as revealed by historical and instrumental records (Stich et al., 2003, Tahayt et al., 2004, Grevemeyer et al., 2015) (Fig. 1).

Dataset

Fault exploration of active regions offshore integrates the most advanced technologies covering different scales of resolution. Swath-bathymetry allows us to identify the geomorphological evidence of active faults, such as seafloor ruptures, fault scarps and fault traces (e.g. Gràcia et al., 2006). Seismic imaging methods, especially high-resolution, enable us to detect the stratigraphic evidence of past seismic activity, such as upward decreasingly displaced seismic horizons, folded and faulted reflectors, zones of shearing and discontinuities.

The present work results from an integration of different acoustic and seismic data acquired during the IMPULS (2006), EVENT-DEEP (2010), TOPOMED-GASSIS (2011), SHAKE (2015) and IDRISSI (2016) cruises on board the RV Hespérides and RV Sarmiento de Gamboa (Fig. 2). The bathymetric data used for this work corresponds to a multibeam compilation including data from different echosounders: AUVs (Autonomous Underwater Vehicles) near-bottom bathymetry (1-m resolution), and shipboard Simrad EM300, Simrad EM12S, SeaBeam 1050D and Atlas Hydrosweep DS (Fig. 2). Digital terrain models at 70 m, and locally, 20 m grid size were obtained. Regarding the AUV systems, AsterX and IdefX devices (Fig. 3) are autonomous underwater vehicles (AUV) dedicated to the scientific recognition on continental shelves and margins up to 2850 m deep. Their missions are devoted to study the seabed or the water column with multiple scientific objectives through various payloads: two EM2040 Kongsberg multibeam echosounder, Echors 10000 Ixea sediment sounder, CTD Seabird SBE49, ADCP, and magnetometer). During the SHAKE cruise (2015) we mapped using these vehicles different portions of the largest strike-slip faults: Carboneras FS, Yusuf FS and Al-Idrissi FS.

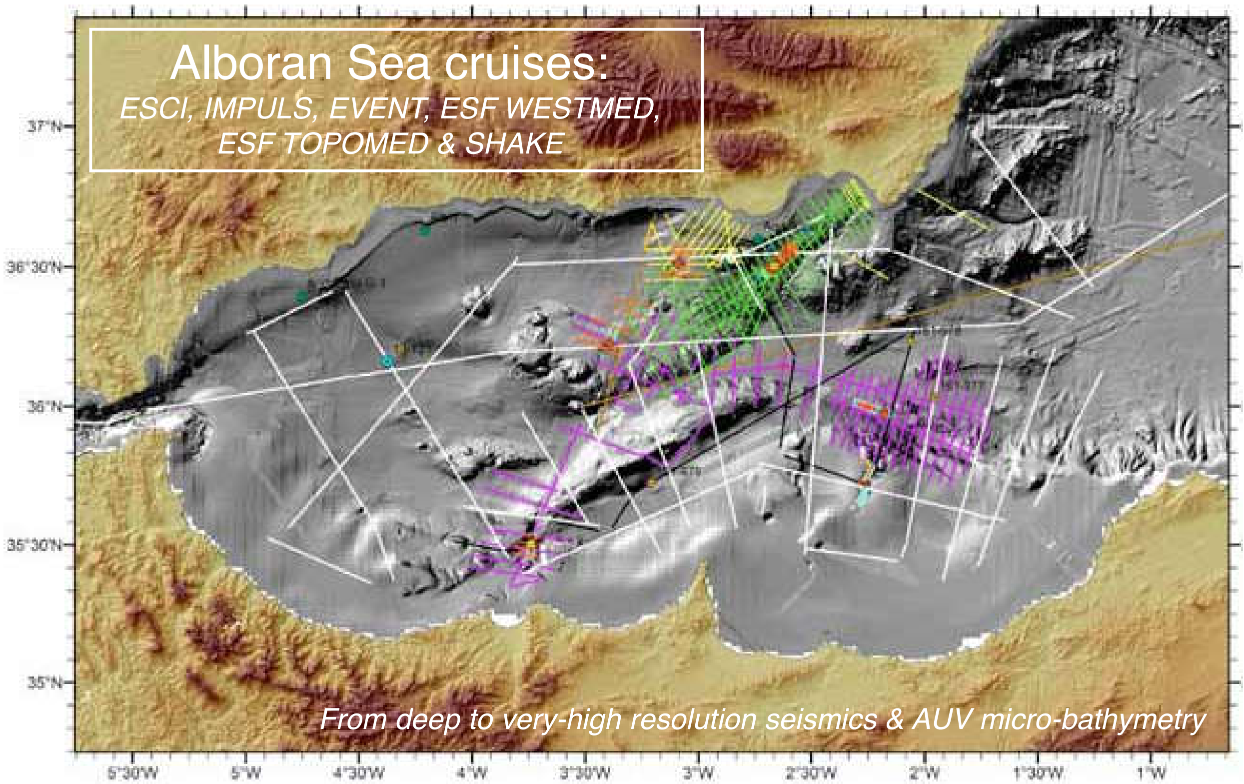

Figure 2*: Compilation of geological and geophysical dataset acquired in the Alboran Basin by the ICM-CSIC (Barcelona-CSI team). Brown: ESCI, yellow: EVENT-SHELF, Green: IMPULS, Purple: EVENT-DEEP Leg1, Black: EVENT-DEEP Leg2; White: TOPOMED. Alboran Sea with the location of high-resolution to deep penetration seismic cruises. DSDP, ODP and commercial wells are also located. In light blue: Location of AUV boxes.*

Figure 3: *The AUVs AsterX and IdefX (IFREMER, France) on board the RV "Sarmiento de Gamboa" during a transit in the Alboran Sea.*

The seismic data used is also multi-scale and includes the following systems: a) High-resolution sub-bottom profiler (parametric echosounder): TOPAS PS18 and Atlas Parasound P.35; b) Sparker GEO-SPARK SCS: source of 4 to 6kJ and 9 m long, 24-hydrophone single-channel streamer; c) High resolution MCS: source of 290 c.i. and 300 m long "GeoEel" Geometrics digital streamer with 48 channels (6.25 m channel interval); d) High to medium resolution MCS: 800 c.i. airgun source and 600 m long Sercel SEAL streamer with 96 channels (6.25 m channel interval); and e) Deep penetration MCS: 3060 ci air-gun source and 5100 m-long Sentinel Sercel streamer with 408 active sections (12.5 m channel interval) (Fig. 2).

Results and Discussion

In the Alboran Basin Quaternary faulting activity is dominated by a large left-lateral strike-slip system referred to as the Eastern Betic Shear Zone (e.g. Bousquet, 1979). This active fault system runs along more than 450 km and its southern termination, the Carboneras Fault, extends further into the Eastern Alboran Sea (Gràcia et al., 2006), including the Yusuf and Al-Idrissi fault systems. We now present each of the three systems:

The Carboneras FS is a NE–SW-trending upwarped zone of deformation defined by en echelon and parallel or sub-parallel fault traces, with a length of 90 km long and a width of 0.5 to 2 km. Two main segments are defined at sea: the northern is 48.5 km long, trends N047° and continues for 50 km onland in the same orientation; and the southern is 39 km long, trends N059 except the southernmost part that trends N050°. Based on left-laterally offset gullies, a strike-slip rate of 1.3 mm/a was obtained for the Quaternary sequence, in agreement with the rates obtained in trenches onshore and geodetic values (Echeverria et al., 2013). Assuming a surface rupture length of 70 km along the ~ N047 segment (offshore and onshore) and using empirical relationships, we found that Carboneras Fault is a potential source of large (M_w ~7.2) events (Gràcia et al., 2006; Moreno et al., 2016).

The 250 km long WNW-ESE trending dextral strike-slip Yusuf FS is the largest structure of the basin (Fig. 4). It is composed by two segments, each of them longer than 100 km, which meet at the Yusuf pull-apart basin. On the high-resolution MCS data, we observe active faulting within the pull-apart basin. On the deep MCS profiles, we find out that the Yusuf Fault represents a major lithospheric boundary between the continental crust of the Moroccan and Algerian Margin, and the magmatic arc crust of the Eastern Alboran Sea. On the basis of empirical relationships, the Yusuf FS has the potential to generate M_w 7.4 earthquakes.

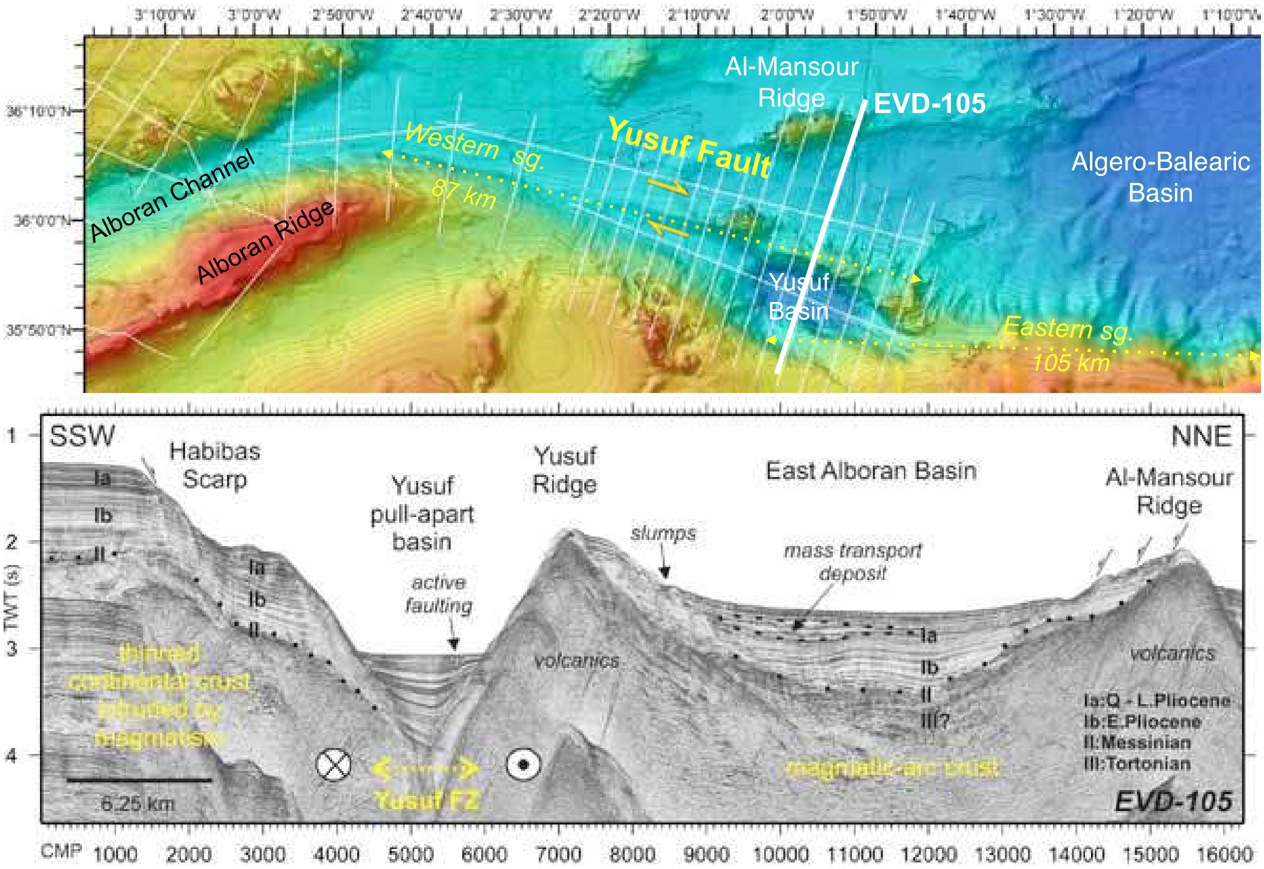

Figure 4: *Above: Bathymetric map of the Yusuf FS and seismic profiles. Fault segments are pull apart basin are depicted. Below: Seismic profile EVD-105 showing that the Yusuf FS is a lithospheric fault separating two different tectonic domains.*

The Al-Idrissi FS is a Late Pliocene to Quaternary structure, 1 to 4.8 km wide, 160 km long and NNE-SSW trending left-lateral composed by three main segments: north, central and south. On the MCS profiles, the north Al-Idrissi segment corresponds to a narrow, sub-vertical fault affecting all units and sharply cutting the western flank of the Alboran Ridge. Related nearby structures, such as the NS faults (Almeria margin) and the Bokkoya and Trougout faults (Moroccan margin) (Lafosse et al., 2017) are also part of this system. Large magnitude earthquakes have nucleated along this fault: the 1994 and 2004 Al-Hoceima earthquakes, and the recent 2016 Al-Idrissi earthquake (M_w 6.4).

In summary, we show that an integrated, multi-scale approach, from very high-resolution to deep penetration systems, helps to identify, characterize and built realistic marine fault source models. The large strike-slip fault systems in the Alboran Sea are able to generate M_w > 6.0 to 7.4 earthquakes (i.e. following empirical relationships, such as Wells & Coppersmith (1994)), which represent a significant seismic and tsunami hazard to the coasts of Spain and North Africa, and therefore should be considered in any hazard re-evaluation.

Acknowledgements: We acknowledge financial support from MINECO through Projects EVENT (CGL2006-12861-C02-02), SHAKE (CGL2011-30005-C02-02), ESF "TopoEurope" TOPOMED (CGL2008-03474-E/BTE), INSIGHT (CTM2015-70155-R).

References

Booth-Rea, G., Ranero, C.R. & Martínez, J.M. (2007). Crustal types and Tertiary tectonic evolution of the Alborán sea, western Mediterranean, G-cubed, 8, 1-25.

Bousquet, J.C. (1979) Quaternary strike-slip faults in southeastern Spain. Tectonophysics, 52, 277-286.

Buforn, E., Bezzeghoud, M., Udías, A. & Pro, C. (2004). Seismic sources on the Iberia-African Plate boundary and their Tectonic Implications. *Pure Appl. Geophys.*, 161, 623-646.

DeMets, C., Gordon, R.G. & Argus, D.F. (2010). Geologically current plate motions. *Geophys. J. Int.*, 181, 1–80.

Echeverria, A., Khazaradze, G., Asensio, A., Gárate, J., Dávila, J.M. & Suriñach, E. (2013). Crustal deformation in eastern Betics from CuaTeNeo GPS network. *Tectonophysics*, 608, 600-612.

Grevemeyer, I., Gràcia, E., Villaseñor, A., Leuchters, W. & Watts, A.B. (2015) .Seismicity and active tectonics in the Alboran Sea, Western Mediterranean: Constraints from an offshore-onshore seismological network and swath bathymetry data. J. Geophys. Res. 120, 8348–8365.

Gràcia, E., Pallàs, R., Soto, J.I., Comas, M., Moreno, X., Masana, E., Santanach, P., Diez, S., García, M. & Dañobeitia, J.J. (2006). Active faulting offshore SE Spain (Alboran Sea): Implications for earthquake hazard assessment in the Southern Iberian Margin. *Earth Planet. Sci. Lett.*, 241 (3-4), 734-749.

Gràcia, E., Bartolome, R., Lo Iacono, C., Moreno, X., Stich, D., Martínez-Diaz, J.J., Bozzano, G., Martínez-Loriente, S., Perea, H., Diez, S., Masana, E., Dañobeitia, J.J., Tello, O., Sanz, J.L., Carreño, E., & EVENT-SHELF Team (2012). Acoustic and seismic imaging of the Adra Fault (NE Alboran Sea): in search of the source of the 1910 Adra earthquake. *Natural Hazards and Earth System Sciences*, 12, 3255-3267.

Lafosse, M. et al. (2017). Evidence of Quaternary transtensional tectonics in the Nekor Basin (NE Morocco). *Basin Research*, 29, 470-489.

Martínez-García, P., Comas, M., Soto, J.I., Lonergan, L. & Watts, A.B. (2013). Strike-slip tectònics and basin inversion in the Western Mediterranean: The Post-Messinain evolution of the Alboran Sea. *Basin Research*, 25, 1-27

Martínez-García, P., Comas, Lonergan, L. & Watts, A.B. (2017). From extension to shortening: Tectonic inversion distributed in time and space in Alboran Sea, western Mediterranean. *Tectonics*, 36, 2777-2805.

Morel, J.L. & Meghraoui, M. (1996). Gorringe-Alboran-Tell tectonic zone: A transpression system along the Africa-Eurasia plate boundary. *Geology*, 24(8), 755-758.

Moreno, X., Gràcia, E., Bartolomé, R., et al. (2016). Seismostratigraphy and tectonic architecture of the Carboneras Fault offshore based on multiscale seismic imaging: Implications for the Neogene evolution of the NE Alboran Sea. *Tectonophysics*, 689, 115-132.

Stich, D., Ammon, C.J., Morales, J. (2003). Moment tensor solutions for small and moderate earthquakes in the Ibero_Maghtred region. J. Geophys. Res., 198, 2148-2168.

Stich, D., Serpelloni, E., Mancilla, F. & Morales, J (2006). Kinematics of the Iberia–Maghreb plate contact from seismic moment tensors and GPS observations. *Tectonophysics*, 426, 295-317.

Stich, D., Martín, R. & Morales, J. (2010). Moment tensor inversion for Iberia–Maghreb earthquakes 2005–2008. *Tectonophysics*, 483, 390-398.

Tahayt, A. Et a. The Al Hoceima eathquake of 24 February 2009, analysis and interpretation of data from ENVISAT ASAR and SPOT5 validated by ground-based obervations. *Rem Sens Env.*, 113, 306-316.

Wells, D.L. and Coppersmith, K.J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seism. Soc. Am*., 84, 974-1002.