CHARACTERIZATION OF THE NORTH-SOUTH FAULT SYSTEM IN THE ALBORAN SEA USING HIGH-RESOLUTION GEOPHYSICAL DATA: THE INITIATION OF A TRANSTENSIONAL FAULT SYSTEM

Caracterización del sistema de fallas Norte-Sur en el mar de Alborán mediante datos geofísicos de alta-resolución: el inicio de un sistema de fallas transtensional.

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Abstract: A key element in assessing the hazards associated with moderate to high seismic activity is the growth and connections of fault segments. The Alboran Sea is a Neogene basin located in the westernmost Mediterranean Sea and accomodate most of the convergence between the Eurasian and Nubian plates (4 – 5 mm/year) through different fault systems. This study shows the surface and depth characterization of the North-South Fault System in the northern Alboran Sea to understand better the region's kinematics using ultra-high-resolution geophysical data acquired in the area. The data analyses have revealed the presence of several fault scarps striking N-S, resulting in horst and graben systems and the presence of pockmarks in the area. The identified faults cut the post-Messinian seismostratigraphic units (last 5.3 Ma) up to the seafloor, which supports that the fault system is currently active. Moreover, results suggest that this fault system presents high segmentation and small accumulated displacements supporting that it is in its initial evolution stage of a transtensional system.

Keywords: active faults, ultra-high-resolution geophysical data, fault growth, transtensional fault system, Alboran Sea.

Resumen: *Un elemento clave a la hora de evaluar los riesgos asociados a una actividad sísmica de moderada a alta es el crecimiento y las conexiones de los segmentos de falla. El mar de Alborán es una cuenca Neógena, situada en el extremo occidental del Mediterráneo, y absorbe la mayor parte de la convergencia entre las placas Euroasiática y Nubia (4 - 5 mm/año) a través de diferentes sistemas de fallas. Este estudio muestra la caracterización en superficie y en profundidad del sistema de fallas Norte-Sur en el norte del Mar de Alborán para comprender mejor la cinemática de la región utilizando datos geofísicos de ultra alta resolución adquiridos en la zona. Los análisis de los datos han revelado la presencia de varias escarpas de fallas con dirección N-S, que dan lugar a sistemas de horst y graben y a la presencia de marcas de viruela en la zona. Las fallas identificadas cortan las unidades sismoestratigráficas post-mesinianas (últimos 5,3 Ma) hasta el fondo del mar, lo que apoya que el sistema de fallas está actualmente activo. Además, los resultados sugieren que este sistema de fallas presenta una alta segmentación y pequeños desplazamientos acumulados que apoyan que se encuentra en su etapa inicial de evolución de un sistema transtensional.*

Palabras clave: *fallas activas, datos geofísicos de ultra alta resolución, crecimiento de fallas, sistema de fallas transtensional, Mar de Alborán.*

Introduction

Earthquakes may affect populated areas and trigger tsunamis that threaten coastal areas and affect marine infrastructures. When assessing the hazards associated with moderate to high seismic activity, an important issue is the growth and connection of fault segments. Although tectonic deformation in the Alboran Sea is relatively slow (Vernant *et al*., 2010, Argus *et al.,* 2011), active fault systems have produced moderate and large earthquakes (Stich *et al.,* 2003; Calvert *et al.,* 1997; Alami *et al.,* 1998; Tahayt *et al.,* 2009; Gràcia *et al*., 2019).

In this work, we present a detailed characterization of the North-South Fault System (NSFS) located in the northern Alboran Sea (Fig. 1) based on a high- and ultra-high resolution geophysical dataset. These data were acquired during successive marine cruises within the framework of different Spanish National projects (IMPULS 2006, EVENT-SHELF 2009, EVENT-DEEP 2010, TOPOMED-GASSIS 2011 and SHAKE 2015). The aim of this study is to identify and characterize in detail seafloor morphologies using cutting-edge geomorphology analysis methods to link them with the shallow and deep structure by combining multi-scale seismic data.

Geological setting

The Alboran Sea is a Neogene basin located southeast of Iberia between the Euroasian and Nubian plates (Vernant *et al.,* 2010) (Fig. 1). The tectonic extension that dominated the area during the Miocene related to the roll-back of the Gibraltar Arc subduction slab (Lonergan and White, 1997) was followed by a compressional regime that has lasted from the Pliocene to the present (Comas *et al.,* 1999; Booth-Rea *et al*., 2007; Gómez de la Peña *et al.,* 2018, Martínez -Garcia *et al.,* 2017). The present-day deformation is controlled by the NW-SE to NNW-SSE

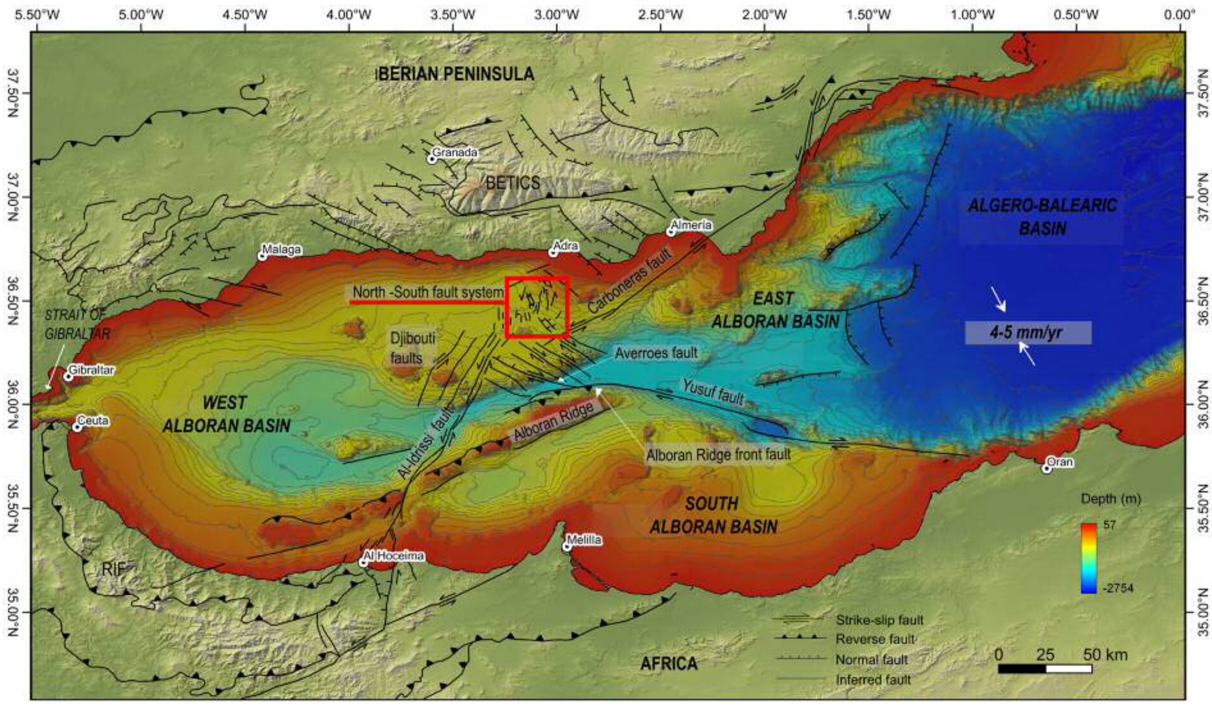

Fig. 1.- Tectonic setting of the Alboran Sea (GEBCO bathymetric data and SRTM-3 grid land topography). The red rectangle depicts the localization of the study area.
Fig. 1.- *Marco tectónico del Mar de Alborán (datos batimétricos GEBCO y topografía terrestre de la cuadrícula SRTM-3). El rectángulo rojo representa la localización de la zona de estudio.*

convergence (4 - 5 mm/yr) between both plates (Argus *et al.,* 2011). During the last period of deformation, Pliocene to nowadays, large strike-slip fault systems have developed, such as the Al-Idrissi, Carboneras and Yusuf fault systems (Gràcia *et al.,* 2006, 2019; Moreno *et al.,* 2016; Perea *et al.,* 2018). The seismicity in the region maybe described as low to moderate magnitude (Peláez *et al.,* 2007; Grevemeyer *et al.,* 2015); however, destructive events have occurred in historical and instrumental times, such as the Adra earthquakes of 1804 and 1910 (MSK Intensity > VIII) (Stich *et al.,* 2003), those of Al-Hoceima in May 1994 (Mw 6.0) (Calvert *et al.,* 1997; Alami *et al.,* 1998) and in February 2004 (Mw 6.3) (Tahayt *et al.,* 2009) or that of Al-Idrissi in January 2016 (Mw 6.4) (Gràcia *et al*., 2019).

Data and methods

The dataset used in this work was acquired during the SHAKE-2015 and EVENT-DEEP-2010 cruises and includes ultra-high-resolution bathymetry (1x1 m pixel resolution) acquired with autonomous underwater vehicles (AUV) (Fig. 2), TOPAS sub-bottom profiles, high-resolution sparker seismic profiles and deep multichannel seismic data.

In this study, we have performed different geomorphologic analyses on ultra-high-resolution bathymetric data, which are based on different quantitative relief-processing methods: bathymetric map; slope map; bathymetric differential openness map created by combining the differential openness map, the hillshade and the bathymetry; and one specific visualisation approach, the Red-Blue Relief map (RBRM), created by modifying the Red Relief image Maps (RRIM, Chiba *et al.,* 2008). We use all the relief visualizations for the characterization of the area but the most useful was the Red-Blue Relief map which allowed us to display the relief accurately and without lighting bias.

In addition, we carried out two more types of morphometric analyses: a) Perpendicular and parallel swath profiles of the identified scarps by using modified workflows from other authors (Pérez-Peña *et al.,* 2017), and b) Our semi-automated workflow to identify and characterize different types of pockmarks observed in

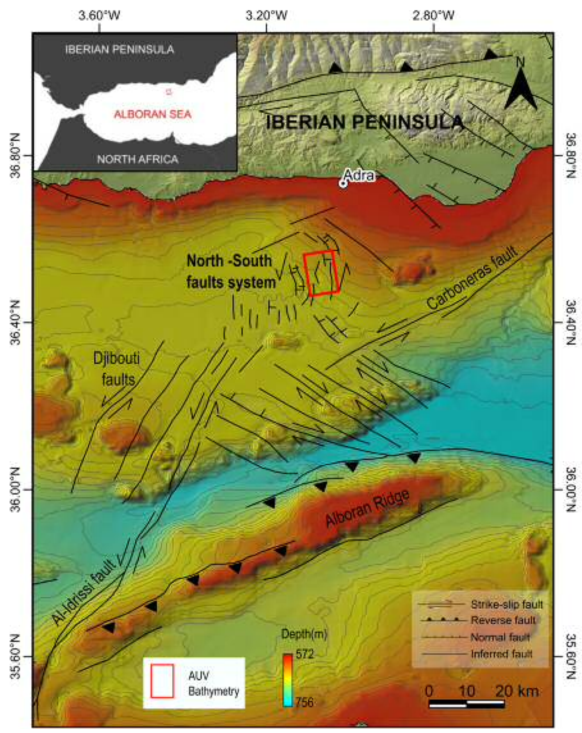

Fig. 2.- Location map of the ultra-high-resolution bathymetric data of our study (GEBCO bathymetric data and SRTM-3 grid land topography).
Fig. 2.- *Mapa de localización de los datos batimétricos de ultra alta resolución de nuestro estudio (datos batimétricos GEBCO y topografía terrestre de la cuadrícula SRTM-3).*

the area. Our analyses result in a high-resolution relief map with high precision that allows mapping with high resolution of the identified scarps, enhancing their continuity on the seafloor, quantifying their vertical and horizontal variability and their distribution to establish structural growth patterns.

After the geomorphological analysis, we have interpreted multi-scale seismic profiles to investigate the shallow and deep structure of the fault system.

First results

The high-resolution relief map highlights the presence of two main morphological features: N-S trending scarps and pockmarks.

The results of swath profiles across the scarps allow us to categorize them according to their vertical offset. Thus, we define secondary scarps as those with vertical offsets below 1 m, which are concentrated in the northern and southern terminations of the system. In contrast the main scarps reach heights larger than 20 m, with the maximum of 36 m, and are located southwest of the study area.

The high-resolution seismic profiles across the NSFS reveal that the scarps are related to different normal faults, resulting in a horst and graben configuration. These faults offset and displace the post - Messinian seismostratigraphic units (last 5.3 Ma) up to the seafloor, accounting for a sediment thickness between 0.4 and 0.6 s two-way travel time (300-450 m considering 1500 m/s as the sound speed in the water). This observation supports that the NSFS is currently active.

In the case of pockmarks, we identified two types: firstly, field pockmarks, in the shallower and 0-1 degree sloping areas of the zone and secondly, string pockmarks identified following the faults traces with a considerable vertical offset, from 10 meters.

Discussion and conclusions

The southwest location of the faults with the highest vertical offsets (vertical offsets > 20 meters), the secondary scarps characterized (vertical offsets < 1 meters) in the southern and northern termination areas and the morphology of the horst and graben system may suggest that the fault system is growing in a NE - SW direction, similarly to the observations done by other authors (Vázquez *et al.,* 2014). The NSFS's high segmentation and small cumulative vertical fault offsets lead us to consider it a transtensional system in its early stages of evolution. In addition, although the fault system shows normal kinematics in its surface structure, deep seismic profiles reveal a typical fault trace. According to Gràcia *et al.* (2019), it might correspond to the propagation towards the north of the Al-Idrissi fault.

Finally, the application of a semi-automated workflow to identify and characterize pockmarks allowed us to distinguish between two types: a) field pockmarks; and b) string pockmarks. The string pockmarks are aligned with the fault traces suggesting fault activity (past or present).

In summary, in this work, we show that an integrated, multi-scale approach, including very high-resolution geophysical data, allows to greatly improve the identification and characterization of active marine faults. A future research effort will focus on creating analogue and numerical models to understand better the present geodynamic evolution of the N-S fault system.

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