Kinematic analysis of secondary faults within a distributed shear-zone reveals fault linkage and increased seismic hazard

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Abstract

Complex multifault earthquake ruptures involving secondary faults emphasize the necessity to characterize their seismogenic potential better and study their relationship with major faults to improve the seismic hazard assessment of a region. High-resolution geophysical data were interpreted to make a detailed characterization of the Averroes Fault and the North Averroes Faults, which are poorly known secondary right-lateral strike-slip faults located in the central part of the Alboran Sea (western Mediterranean). These faults appear to have evolved since the Pliocene as part of a distributed dextral strike-slip shear zone in response to local strain engendered by the diverging movement of the Carboneras Fault to the north, and the Yusuf and Alboran Ridge faults to the south. In addition, the architecture of these faults suggests that the Averroes Fault may eventually link with the Yusuf fault, thus leading to a higher seismogenic potential. Therefore, these secondary faults represent a hitherto unrecognized seismogenic hazard since they could produce earthquakes up to moment magnitude (M_w) 7.6. Our results highlight the importance of the role played by secondary faults in a specific kinematic framework. Their reciprocal linkage and their mechanical relationship with the main faults could lead to future complex fault ruptures. This information could improve fault source and earthquake models used in seismic and tsunami hazard assessment in this and similar regions.

Keywords

Active faults; strike-slip faults; fault linkage; distributed shear zones; earthquakes; Alboran Sea; western Mediterranean

1 Introduction

Detailed structural mapping, as well as kinematic and seismogenic characterization of active submarine fault systems, is essential for determining possible fault linkages for potential rupture scenarios and, consequently, for improving the assessment of the seismic and tsunami hazard in densely populated coastal areas. Recent advances in seafloor and subsurface imaging have made it possible to obtain high-resolution seismic and bathymetric data, which can be used to accurately characterize the kinematic patterns and tectonic architecture of submarine faults with unprecedented detail (Armijo et al., 2005; Barnes, 2009; Bartolome et al., 2012; Brothers et al., 2015; Escartín et al., 2016; Gasperini et al., 2011a,b; Gràcia et al., 2012, 2006; Martínez-Loriente et al., 2013; McNeill et al., 2007; McNeill and Henstock, 2014; Moreno et al., 2016; Perea et al., 2012; Polonia et al., 2012; Sahakian et al., 2017). In addition, methods have been developed to determine the seismogenic potential and earthquake history of single faults based on on-fault marine paleoseismology (e.g. Barnes and Pondard, 2010; Brothers et al., 2011, 2009). These studies have generally focused on large continental fault systems. Nevertheless, surface rupture mapping of recent large magnitude earthquakes shows complex multifault ruptures involving unknown or poorly known secondary faults (e.g., Elliott et al., 2012; Hamling et al., 2017; Quigley et al., 2012). These observations highlight the need to characterize onshore and offshore secondary fault systems as well as their relationship to major faults to improve seismic hazard assessment (e.g., Field et al., 2014; Perea and Atakan, 2007; Stirling et al., 2012). Here we present an example of a previously unknown secondary active fault system located in the central Alboran Sea (western Mediterranean), which is related to the largest faults controlling the regional geodynamics.

The Alboran Sea is a Neogene basin formed by crustal extension related to the subduction system in the Gibraltar Arc (e.g., Booth-Rea et al., 2007; Comas et al., 1999; van Hinsbergen et al., 2014). At present, left-lateral and right-lateral strike-slip faults trending NE-SW and WNW-ESE, respectively, accommodate part of the strain related to the NW-SE convergence (4-5.5 mm/yr) between the African and Eurasian plates (e.g., DeMets et al., 2010; Palano et al., 2015; Vernant et al., 2010). Consequently, the Alboran Sea shows a remarkable seismic activity, mainly concentrated along what is known as the Trans-Alboran Shear Zone (De Larouzière et al., 1988). Although this seismicity is mainly characterized by low to moderate magnitude events (Bufo et al., 1995; Stich et al., 2006), large and destructive earthquakes have occurred in the region, such as the 1522 Almería (IEMS98 IX; Spain), the 1790 Oran (IMSK IX-X; Algeria), the 1910 Adra (IEMS98 VIII and M_w 6.1; Spain), the 1994 and 2004 Al-Hoceima (M_w 6.0 and 6.4, respectively; Morocco), and the 2016 Al-Idrissi (M_w 6.4; Morocco) events (e.g., Biggs et al., 2006; Bufo et al., 2017; Calvert et al., 1997; Gràcia et al., 2012; Martínez Solares and Mezcu, 2002; Stich et al., 2003; Tahayt et al., 2009; van der Woerd et al., 2014) (Fig.1).

The main active faults in the Alboran Sea are the left-lateral Carboneras and Al-Idrissi strike-slip faults, the right-lateral Yusuf strike-slip fault and the Alboran Ridge thrust fault (Gràcia et al., 2006; Martínez-García et al., 2013; Medaouri et al., 2014; Moreno et al., 2016) (Fig. 1). These faults converge at the center of the Alboran Sea between the East and West Alboran basins. Their structural relationship, however, is still under debate. In between these main faults there is a secondary fault-system, the Averroes Fault (AF) and North Averroes Faults (NAFs) with a WNW-ESE trend (Fig. 1). Understanding the tectonic evolution of these secondary faults and their relationship and potential linkage with the large fault systems will help to characterize the present kinematics of the area and define potential fault rupture scenarios.

Accordingly, the overarching goals of this work are: (a) to characterize the WNW-ESE trending AF and NAFs based on newly acquired swath-bathymetry, sub-bottom acoustic profiles, and high-resolution multichannel seismic data; (b) to determine the role of these secondary faults to further understand the kinematic pattern and style of deformation in the central part of the Alboran Sea; and (c) to evaluate the contribution and relevance of secondary faults to the seismogenic potential of the western Mediterranean region.

2 Data and methods

Our dataset comprises swath-bathymetry and recently acquired high-resolution seismic reflection profiles, including sub-bottom (SBP) and multichannel (HR-MCS) data (Fig. 2). The integration of these datasets makes it possible to accurately map fault traces for offshore areas and estimate vertical and horizontal displacements.

During the EVENT (2010) and SHAKE (2015) cruises, 30 m grid size swath-bathymetry was acquired with the ATLAS Hydrosweep DS multibeam echosounder, hull mounted system of the RV Sarmiento de Gamboa. This dataset has been included in the existing bathymetric compilation covering most of the Alboran Sea with a grid size of 50 m (e.g., Gràcia et al., 2012, 2006; Ballesteros et al., 2008) (Figs. 2, 3). The different datasets were processed and integrated using the CARIS software.

The HR-MCS profiles were acquired during the IMPULS (2006) and EVENT (2010) cruises on board the RV Hesperides and RV Sarmiento de Gamboa, respectively. Multichannel seismic data were collected in the IMPULS cruise using a 300-m long GeoEel Geometrics digital streamer with 48 channels, towed at 2 m water depth. The streamer was composed by 6 active sections of 50 meters, and each section contained 8 channels with 6.25 m spacing. The seismic

source consisted of an 8-airgun array with a total volume of 4.75 l. In the EVENT cruise, a 600-m long Sercel SEAL 96 multichannel seismic streamer with channel spacing of 6.25 m was used and towed at 2.5 m water depth. The source array was composed of 10 airguns, with a total volume of 13.1 l. Data acquired during the two surveys were quality controlled on board and processed, time-migrated and interpreted at the seismic laboratory of the Institut de Ciències del Mar-CSIC using the ProMAX, Globe ClaritasTM, and IHS Kingdom softwares, respectively. The applied processing seismic flow included: statics correction; trace editing (deleting noisy channels in terms of RMS quality control); 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 SEG-Y export format.

The SBP profiles were acquired at the same time as the HR-MCS profiles during the IMPULS survey, using the Simrad TOPAS PS18 hull mounted system of the RV Hesperides. The collected profiles show the detailed sedimentary architecture of the uppermost tens of meters below the seafloor (up to 100 m), mainly Plio-Quaternary sedimentary units, and evidence recent fault activity.

3 Seismostratigraphy of the central part of the Alboran Sea

During the last decades, the seismostratigraphic units in the central part of the Alboran Sea have been successively re-defined due to the availability of high-quality and high-resolution seismic datasets (e.g., Booth-Rea et al., 2007; Comas et al., 1999; Gomez de la Peña, 2017 Juan et al., 2016; Martínez-García et al., 2013; Moreno et al., 2016). In addition, the combination of the seismic data with radiometric dating and biostratigraphic analyses of sediments and rocks collected in sediment cores and commercial and scientific boreholes (e.g. Ocean Drilling

Program sites; Comas et al., 1999) has made it possible to establish accurate ages for the seismostratigraphic units (Fig. 4).

In our HR-MCS profiles, five seismostratigraphic units (Ia1, Ia2, Ia3, Ib1, and Ib2) are identified above the regional Messinian reflector (top of unit II) (Figs. 5, 6). These units were previously characterized and described by Moreno et al. (2016) (Fig. 4) and their ages are, from youngest to oldest: Ia1 - upper Quaternary (present day to 0.78 Ma); Ia2 - lower Quaternary (0.78 to 2.45 Ma); Ia3 - Upper Pliocene (2.45 to 3.28 Ma); Ib1 - upper Lower Pliocene (3.28 to 4.57 Ma); Ib2 - low Lower Pliocene (4.57 to 5.33 Ma); and II - Upper Miocene (> 5.33 Ma).

4 A secondary fault system in the central Alboran Sea: The Averroes and North Averroes Faults

In the central part of the Alboran Sea, the seafloor morphology of the Djibouti Plateau shows the presence of an elongated and narrow trough, striking N115° to N125°, which corresponds to the surface expression of the AF (Fig. 2). Over time, its vertical and horizontal displacement has generated a 2-km wide and 13.2-km long basin, referred to as the Averroes Basin (AB in Figs. 2, 5, 6), which becomes progressively narrower as it crosses the Adra Ridge. To the southeast, across the Alboran Channel and up to the Alboran Ridge, there is an escarpment aligned with the AF that bends slightly to the WNW-ESE and uplifts the seafloor locally at the center of the channel, forming an elongated ridge (Figs. 2, 3a). Considering that the AF extends from the Djibouti Plateau to the base of the Alboran Ridge, its total length is 46.6 km (Table 1). The bathymetric map (Figs. 2, 3a, 3b) shows a geomorphologic step-over where the AF intersects the northwestern edge of the Alboran Channel, in which the block north of the fault has been displaced towards the southeast. To estimate the lateral offset on the AF, we identified piercing points on both sides of the fault, geomorphologic similarities on the seafloor and the fit

with the bathymetric contours. Accordingly, this fault scarp has a right-lateral cumulative offset of about 4181 m (Fig. 3b; Table 2).

The HR-MCS profiles reveal that the AF is a right-lateral sub-vertical fault with a vertical component, dipping $\sim 70^\circ$ to 90° , offsetting all seismostratigraphic units from the Miocene to the Quaternary, and showing seafloor expression (Figs. 5, 6). The seismic profiles show that the AF splits into two branches when it crosses the Adra Ridge South, and that bounding to the northeast, the Averroes Basin has numerous secondary faults that may link in depth with the AF (Fig. 5a). The average vertical offset, measured on different HR-MCS profiles crossing the Averroes Basin, is 0.61 s two-way travel time (TWTT) at the base of unit Ib1, which is depth converted to a range between 473 and 488 m (Fig. 5a). However, this should be considered as a minimum offset range since the time-depth conversion is based on a nominal interval velocity of 1550-1600 m/s in the uppermost sediments, as precise seismic velocities are not available in this area.

Across the Djibouti Plateau and Adra Ridge North, there are several escarpments, small sub-basins and lineaments parallel to the AF (Figs. 2, 3a). These features correspond to the surface expression of the NAFs, which are labeled NAF1 to NAF4. Broadly, these fault systems are characterized by a main escarpment with much smaller vertical throws than in the AF. An anastomosed and/or sigmoidal geometry fault system can be observed where the different minor escarpments link (Fig. 3a). The main faults of each NAF system cut across the Djibouti Plateau, the Adra Ridge North and reach the Alboran Channel and East Alboran Basin. Their lengths range between 16.9 km (NAF2b) and 36.5 km (NAF2) (Table 1). Moreover, they have different morphological features that exhibit lateral offsets across the faults, indicating that they all have a right-lateral movement (e.g., offset linear ridges on the Adra Ridge North or scarps in the

northwestern margin of the Alboran Channel) (Figs. 3a, 3d-f). Considering the offsets between the identified piercing points projected into the NAFs, it is possible to estimate a right-lateral movement ranging between 1185 m (NAF2) and 656 m (NAF3) (Figs. 3d-f; Table 2).

The HR-MCS and SBP profiles show that there is pervasive faulting corresponding to the NAFs, which offsets all the sedimentary units and the basement at the Djibouti Plateau and Adra Ridge North (Fig. 6). These faults are sub-vertical (dipping 70°-90°), have small vertical throws, and some of them branch at depth. Usually, two faults bound each NAF system, which laterally join and dip in opposite directions towards the center of the faulted zone and clearly offset the Quaternary units and deform the seafloor (e.g., NAF 1 and NAF2 in Figs. 3a, 6). Between these bounding faults, there are minor faults that merge laterally at depth and most of them offset Pliocene units. The activity of the different NAFs has produced small, elongated depressions in the seafloor (Figs. 2, 3a) and some exhibit subdued negative flower structure geometry (e.g., NAF1 and NAF3 in Fig. 6), indicating the accommodation of transtensive deformation.

Regarding the activity of the AF and NAFs, the interpretation of the HR-MCS profiles suggests different tectonic phases based on changes in thickness of the sedimentary units within the Averroes Basin and Djibouti Plateau (Fig. 7). The first phase is preceded by the deposition of unit Ib2 (low Lower Pliocene) infilling local depressions related to the Messinian unconformity (Figs. 7b, 7c). Although the activity of the faults may have started during the deposition of unit Ib2, the most intensive and significant transtensive deformation is observed in unit Ib1 (upper Lower Pliocene). This activity resulted in the creation of the Averroes Basin and some minor local basins related to the activity in the NAFs (Fig. 7d). These observations disagree with previous studies that suggest that the Djibouti Plateau was not affected by significant deformation prior to the Quaternary (Martínez-García et al., 2013). The previous tectonic phase

is followed by the deposition of unit Ia3 (Upper Pliocene; Fig 7e), which shows an almost constant sedimentary thickness throughout the entire area. This suggests a period of tectonic quiescence or, alternatively, pure strike-slip deformation without vertical displacement along the AF and NAFs. The presence of a small local depocenter located in the northwestern termination of the AF, together with the observation that the AF and NAFs are almost parallel to the WNW-ESE regional stress field at that time (MartínezGarcía et al., 2013), might support pure strike-slip displacement along the faults. Finally, during the Quaternary, the tectonic activity may have increased or changed from strike-slip to transtensional, as recorded by the presence of local depocenters associated with the northwestern termination of the AF and NAF faults (Fig. 7f). However, the deformation rates might have been quite moderate considering the relatively constant thickness of the Quaternary units over the area. In agreement with these observations, the measured lateral offsets on the AF and NAFs (Fig. 3; Tables 2) may correspond to the cumulative fault displacement since the upper Lower Pliocene (4.57 Ma).

5 Discussion: kinematics, fault linkage and seismic potential

The analysis of the bathymetric and HR-MCS data reveals that the AF and NAFs are right-lateral strike-slip faults, with transtensive and transpressive deformation patterns in the Djibouti Plateau and the Alboran Channel, respectively. The following points are the evidence for this kinematic interpretation: (a) right-lateral offsets observed on the northwestern margin of the Alboran Channel and across the Adra Ridge North; (b) vertical to sub-vertical fault dip; (c) changes in the dip-slip component of the AF (extension in the Averroes Basin to compression in the Alboran Channel), coinciding with variations in the strike of the fault and resulting in releasing and restraining bends; (d) anastomosed to sigmoidal geometry of the NAFs, which may indicate fault segment linkage and lateral growth of the systems (Aydin and Berryman, 2010;

Schreurs, 2003); and (e) subdued negative flower-structure geometries and formation of small elongated depressions along some of the NAFs (Figs. 2, 3, 5, 6).

The right-lateral strike-slip AF and NAFs are related to the Neogene-Quaternary thinning of continental crust intruded by arc magmatism (e.g., Booth-Rea et al., 2007; Mancilla et al., 2015), and are bounded by the largest active faults in the Alboran Sea, the Carboneras left-lateral strike-slip fault to the northwest, and the Alboran Ridge thrust and Yusuf right-lateral strike-slip faults to the south (Figs. 1, 8). These two facts most likely determine the style of deformation in this area. Generally, strike-slip deformation in the continental lithosphere is distributed over a wide shear-zone instead of accumulating in a single fault (e.g., McKenzie and Jackson, 1983). In addition, analogue models of fault development and interaction in distributed strike-slip shear zones (e.g., Dooley and Schreurs, 2012; Schreurs, 2003) exhibit similar features and geometries at the surface and in-depth as those observed for the AF and NAFs (Figs. 2, 3, 5, 6, 8). Although the present NW-SE trending convergence rate controls the regional deformation in the Alboran Sea, the motion towards the NE of the southeastern block of the Carboneras Fault and to the E/ESE of the northern block of the Alboran Ridge and Yusuf faults may result in the development of a local stress field between these main structures. In agreement with the fault strike, the resulting local field may trend approximately E-W (Fig. 8b). Since the regional stress-field affects the continental crust, we propose that the central Alboran region may have evolved as a distributed right-lateral strike-slip shear zone, forming a WNW-ESE pervasive fault system (i.e., AF and NAFs) to accommodate local deformation. Analogue models applied to similar settings predict that sub-vertical parallel strike-slip faults developed in a distributed shear zone may strike between 28° and 35° relative to the direction of the bulk shear (Dooley and Schreurs, 2012; Schreurs, 2003). Considering that the strike of the AF and NAFs ranges between N115°

and N125°, the local right-lateral bulk shear may strike approximately N90°, in agreement with the assumed local stress field (Fig. 8b).

Understanding and assessing fault linkage to characterize the maximum earthquake rupture length is critical for estimating the expected maximum magnitudes, and thus, improving seismic hazard studies that include active faults as earthquake sources (e.g., Field et al., 2014; Perea and Atakan, 2007; Stirling et al., 2012). In the study area, the structural connection between the AF and the Yusuf Fault is under debate. Martínez-García et al. (2013) proposed that the Yusuf fault terminates at the northern side of the Alboran Ridge where it links with the Alboran Ridge thrust fault, although without any connection to the AF. The geomorphologic analysis of the bathymetry along the southern margin of the Alboran channel shows that there is no large discontinuities or step-overs between the Yusuf and Alboran Ridge faults, suggesting that both are part of the same fault system. In addition, we observed that: (a) the AF offsets the seafloor, generating an elongated ridge across the Alboran Channel (Figs. 2, 3a-c); (b) there is a right-lateral step-over at the base of the NW margin of the Alboran Ridge aligned with the AF and showing a similar strike (Figs. 2, 3c); and (c) there is a minor ENE-WSW escarpment across the Alboran Ridge slope (Figs. 2, 3c). Our observations suggest that the AF cuts across the Alboran Channel and connects to the Yusuf fault system. Moreover, the increased deformation (larger offset and elongated basin) along the AF than in the other NAFs could result from the AF accommodating part of the deformation transmitted by the Yusuf fault. Analogue models that consider interferences between thrust and strike-slip faults, with similar geometries to those observed across the Alboran Ridge and Yusuf faults, reveal the formation of outer faults when a velocity discontinuity is placed in front of the thrust domain (Rosas et al., 2015). The outer faults have a similar direction as the main strike-slip faults and cut across previously formed thrust

faults. The resulting structural geometries resemble the AF, Yusuf, and Alboran Ridge faults, and therefore are consistent with a connection between the AF and Yusuf Fault to form a continuous right-lateral strike-slip system. Hence, considering the link between the AF and the Yusuf Fault, the maximum fault rupture length of the main fault increases from 175 km to at least 221 km, with evident implications regarding seismic hazard.

Despite the current relatively low seismic activity in this area, our observations demonstrate that the AF and NAFs are active since they offset the Quaternary units and deform the seafloor (Figs. 2, 3, 5, 6). In 2009 and 2010 a network of ocean bottom seismometers was deployed in the Alboran Sea and land seismometers were used in the neighboring coastal areas (Grevemeyer et al., 2015). A total of 229 local earthquakes were recorded, most of them of low magnitude (M_w 1.2 to 2.8), and the largest event recorded in the East Alboran Basin was M_w 3.5. The locations of the earthquakes show a cluster of seismicity at the intersection between the Alboran Channel and the AF while other events nucleate near the NAFs (Figs. 2, 3a, 8a). This microseismicity may highlight the present-day activity of the AF and NAFs. In addition, the crustal models obtained in this area reveal that the maximum thickness of the seismogenic zone is 15 km (Grevemeyer et al., 2015), which limits the earthquake nucleation on the faults to this depth.

The seismic potential of a given fault is determined by its slip-rate and by the maximum magnitude of the earthquake it can generate. To estimate the long-term slip-rate of the AF and the NAFs we measured the right-lateral offsets recorded for different morphological features, and the vertical offset on the AF (Fig. 3; Table 2). Assuming that these offsets are the result of the fault activity since their formation in the upper Lower Pliocene (4.57 Ma), the Plio-Quaternary lateral slip-rate for the AF is estimated to be 0.91 mm/yr and range between 0.14 and

0.26 mm/yr for the NAFs (Table 2). In addition, the AF has produced a minimum vertical offset of about 473-488 m at the base of Unit Ib1 (4.57 Ma), resulting in a minimum vertical slip-rate of about 0.1 mm/yr for the same time interval. Assuming that the lateral slip-rate of the AF has been constant over time and considering that the offset at the base of the Alboran Ridge (1011 m; Fig. 3c) is produced by displacement along the AF, it can be postulated that this fault most likely connected to the Yusuf fault system during the Calabrian (about 1.1 Ma). The higher slip-rate for the AF suggests that this fault is accommodating more deformation than the NAFs, probably due to its connection with the Yusuf fault. However, considering that the two faults may have been linked during the Quaternary and that the AF has been more active than the NAFs since their formation in the upper Lower Pliocene (Fig. 7), we can conclude that the AF has always been the main fault of the distributed shear zone. Although there are large uncertainties in the lateral and vertical slip-rate estimates, they appear consistent with those of the bounding faults determined by GPS block kinematic modeling (e.g., Vernant et al., 2010), and with the AF and NAFs representing secondary faults in the regional tectonic framework.

To estimate the maximum magnitude earthquake that the AF and NAFs could generate, we considered the mapped fault length and the empirical relationship proposed by Wesnousky (2008) (see Table S1 in supplementary materials for M_w obtained using other relationships). Accordingly, the AF has the potential of generating earthquakes of M_w as large as 7.0, and the NAFs between 6.6 and 6.9 (Table 1). However, considering a scenario in which the AF and the Yusuf fault may be linked and that both could rupture at the same time, the related earthquake reaches a maximum M_w of 7.6 (Table 1). Recent large earthquakes, such as the Kaikoura event (Hamling et al., 2017), have resulted in complex multifault surface ruptures, involving a number of unknown or poorly known secondary faults in the rupture process. In addition, recent studies

based on the analysis of several surface ruptures (Biasi and Wesnousky, 2016) have shown that earthquake ruptures are equally likely to propagate over fault steps of 3 km. Considering that the distance from the southeastern tip of NAF 1 and NAF2 to the Yusuf fault or the AF is shorter than 3 km (Fig. 3a) a complex multifault rupture could be possible, and even larger magnitude earthquakes cannot be ruled out. Earthquakes with a magnitude equal to or larger than 7.6 and generated in the first 15 km of the upper crust (Grevemeyer et al., 2015) may produce surface rupture, with vertical offsets in certain zones of the fault system (e.g., Averroes Basin and Alboran Ridge). Eventually, they might trigger submarine mass movements on the slopes of surrounding ridges. These landslides could be tsunamigenic depending on their acceleration (Driscoll et al., 2000) and represent an additional threat to nearby coastal areas.

6 Conclusions

This study identifies and characterizes the seismic potential of previously unknown secondary active fault systems, the AF and NAFs, which displace the Quaternary sedimentary units and deform the seafloor in the Alboran Sea producing microseismicity. We propose that these faults may have developed in a distributed E-W right-lateral strike-slip shear zone during the last 4.57 Ma to accommodate the local stress field resulting from the different kinematics along the Carboneras and Yusuf fault systems. The seismogenic characterization of the AF and NAFs reveals that these structures are characterized by low slip-rates (<1 mm/yr) but have the potential for generating moderate to large earthquakes ($6.6 < M_w < 7.0$) in an area presently characterized by low seismic activity. In addition, the data demonstrate a likely linkage between the AF and the Yusuf fault, which would lead to increased earthquake magnitudes that can reach up to M_w 7.6.

These results demonstrate that, in the offshore, high-resolution geophysical methods are fundamental for identifying, accurately mapping and characterizing secondary fault systems, and thus, they are critical to the understanding of the main active fault systems. In addition, we also demonstrate that specific studies aimed at understanding the role that the secondary faults play in a specific kinematic framework and their relationships with main fault systems, are essential for defining fault interaction and linkage and determining their seismogenic potential more accurately. This information should be included in seismic hazard studies of complex fault linkages and future fault rupture scenarios to improve the characterization of large earthquakes. In addition, this would contribute to producing more realistic fault sources and fault earthquake models, which would improve the assessment of the offshore seismic and tsunami hazards.

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Figure 1. Topographic and bathymetric map of the central part of the Alboran Sea. Epicenters of historical (I_0 MSK) and instrumental (M_w) earthquakes were obtained from the IGN (Spanish seismic catalog) and focal mechanisms from Stich et al. (2010), except for the Al-Idrissi 2016 event, provided by the IGN. White arrows indicate the present-day convergence between the African and Eurasian plates (DeMets et al., 2010). AF: Averroes Fault; AIF: Al-Idrissi Fault; ARF: Alboran Ridge Fault; CF: Carboneras Fault; NAFs: North Averroes Faults; YF: Yusuf Fault. Dashed white rectangle localizes Fig. 2. Isobaths every 100 m. Inset: General map of the region showing the Eurasia and Africa plate boundary.

Figure 2. High-resolution bathymetric map of the central part of the Alboran Sea. Colored circles are earthquakes coded by depth and sized by magnitude (M_w) (Grevemeyer et al., 2015). Thin light orange and red lines locate the high-resolution multichannel seismic (HR-MCS) profiles acquired during the IMPULS and EVENT cruises, respectively. Black and red arrows indicate the trace of the Averroes Fault (thicker) and the main North Averroes Faults (NAF; thinner). AB stands for Averroes Basin. Thick white lines show the location of the interpreted HR-MCS profiles presented in this work: EVD-125 (Fig. 5a), EVD-123 (Fig. 5b), and IM-23 (Fig. 6d). Dashed white rectangle localizes Fig. 3a.

Figure 3. (a) Slope-enhanced shade relief map of the central part of the Alboran Sea with the location of the Averroes Fault (AF) and North Averroes Faults (NAFs) (white zones correspond to flat areas and dark grey to black to steep areas). Triangles with the same color indicate homologous piercing points to calculate the faults' right-lateral offsets. Black dashed line rectangles localize Figures b to f. Yellow circles correspond to earthquake epicenters (Grevemeyer et al., 2015). (b to f) Detailed shaded relief maps with the location of the piercing points used to calculate the lateral fault offsets for the Averroes Fault and NAF Faults. The

projection of the piercing points towards the fault plane follows the trend of the identified geomorphic features. Isobaths are every 100 m. The relief maps without interpretation are in the supplementary material Fig. S1.

Figure 4. Ages and seismostratigraphic units identified in the central part of the Alboran Sea and their correlation with previous studies focused on the post-Messinian evolution of the Alboran Sea. Limits between units are displayed with the same color as the respective horizon in the seismic profiles. Red wavy lines are indicative of erosive unconformities. TS: This study; M2016: Moreno et al. (2016); MG2013: Martínez-García et al (2013); J2016: Juan et al. (2016).

Figure 5. Interpreted HR-MCS seismic profiles EVD-125 (a) and EVD-123 (b). AB: Averroes Basin. In the HR-MCS profiles, thick black lines represent the main faults. Horizon's (H1 to H5) ages provided in Fig. 4. Vertical exaggeration (V:H) x5. Location of the seismic profiles is in Fig. 2. The seismic profiles without interpretation are in supplementary material Fig. S2.

Figure 6. (a, b, c) Interpreted sections (vertical exaggeration x20) of the sub-bottom parametric profile acquired simultaneously with the HR-MCS profile IM-23. (d) Interpreted HR-MCS seismic profile IM-23, where thick black lines represent the main faults. AB: Averroes Basin; NAF: North Averroes Fault. Horizon's (H1 to H5) ages provided in Fig. 4. Vertical exaggeration (V:H) x5. Location of the profile IM-23 is in Fig. 2. The seismic profiles without interpretation are in supplementary material Fig. S3.

Figure 7. (a) Map showing the present-day bathymetry of the central part of the Alboran Sea. Red lines show the position of the newly mapped faults in the area. Dark gray dotted lines localize the high-resolution multichannel seismic profiles used in the seismic mapping, and the white polygon shows the area of interpolation. AB: Averroes Basin; NAF #: North Averroes

Faults. (b) Map of the interpolated topography of Unit II (Upper Miocene - Messinian erosion surface) in milliseconds (TWTT). (c–f) Interpolated isochore maps in milliseconds (TWTT) of units Ib2 (low Lower Pliocene), Ib1 (upper Lower Pliocene), Ia3 (Upper Pliocene) and Ia1+Ia2 (Lower and Upper Quaternary). Contour interval indicated on each map. Gray lines indicate the faults. For the interpolation, we used the Flex Gridding algorithm in the IHS Kingdom® software, defining a cell size of 150 m and a distance interpolation of 5 km.

Figure 8. (a) High-resolution gray-shaded relief map of the central part of the Alboran Sea showing the main active faults as well as the newly mapped Averroes Fault (AF) and North Averroes Faults (NAF), their kinematic and the interpreted style of deformation. White arrows indicate the present-day convergence between the African and Eurasian plates (DeMets et al., 2010). Yellow circles correspond to earthquake epicenters (Grevemeyer et al., 2015). (b) Schematic sketch showing the location of the distributed E-W right-lateral strike-slip shear zone in relation to the main fault systems and the average strike of each system. ARF: Alboran Ridge Fault; CF: Carboneras Fault; YF: Yusuf Fault.

Table 1. Characterization of the lateral offset and slip-rate of the Averroes Fault (AF) and North Averroes Faults (NAFs).

Table 2. Calculation of the maximum magnitude earthquake for the Averroes Fault (AF) and North Averroes Faults (NAFs).

Fig.1_Perea et al.

Fig.2_Perea et al.

Fig.3_Perea et al.

Fig.4_Perea et al.

Fig.5_Perea et al.

Fig.6_Perea et al.

Fig. 7_Perea et al.

Fig.8_Perea et al.

Table 1. Calculation of the maximum magnitude earthquake for the Averroes Fault (AF) and North Averroes Faults (NAFs).

Fault	Fault length (km)	Wesnousky et al [2008] ^a $M_w=5.56+0.87\log L$
AF	46.6	7.0
NAF1	36	6.9
NAF2	36.5	6.9
NAF2a	28	6.8
NAF2b	16.9	6.6
NAF3	33	6.9
NAF4	21.5	6.7
Yusuf+AF	221.6	7.6

a. L: surface rupture length in km. Rang M_w 5.9-7.9. $L \geq 15$ km. **Application:** All regions for the relevant slip types but acknowledging that the regression dataset will be dominated by plate boundary earthquakes. The author indicates the relationship is most relevant to strike-slip sources.

Table 1_Perea et al.

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Table 2. Characterization of the lateral offset and slip-rate of the Averroes Fault (AF) and North Averroes Faults (NAFs).

Fault	Length (km)	Lateral offset (m) ^a	Lateral slip-rate (mm/yr)	Start of activity (Ma)
AF	46.6	4181 (a-a')	0.91	4.57
NAF 1	36	721 (b-b')	0.16	4.57
NAF2	36.5	1185 (c-c')	0.26	4.57
NAF2a	28	950 (d-d')	0.21	4.57
NAF2b	16.9	-	-	4.57
NAF3	33	656 (e-e')	0.14	4.57
NAF4	21.5	892 (f-f')	0.24	4.57

a. Letters in between brackets indicate the measured offsets. See figure 3 to localize the places.

Table 2_Perea et al.

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