# Imaging the Growth of Recent Faults: The Case of 2016-2017 Seismic Sequence Sea Bottom Deformation in the Alboran Sea (Western Mediterranean)

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**Imaging the growth of recent faults: the case of 2016-17 seismic sequence sea bottom deformation in the Alboran Sea (Western Mediterranean)**

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**Key Points:**

The 2016-17 seismic sequence is related to the wide NNE-SSW sinistral fault zone located in the central part of the Alboran Sea.

Epicentral seabottom deformations include mass transport deposits and recent faults.

Seismicity and seabottom deformations are located west of the main Al Idrisi Fault, supporting the westward widening of the fault zone.

## Abstract

The Eurasian-African NW-SE oblique plate convergence produces shortening and orthogonal extension in the Alboran Sea Basin (Westernmost Mediterranean), located between the Betic and Rif cordilleras. A NNE-SSW broad band of deformation and seismicity affects the Alboran central part. After the 1993-94 and 2004 seismic series, an earthquake sequence struck mainly its southern sector in 2016-17 (main event Mw=6.3, Jan 25, 2016). The near-surface deformation is investigated using seismic profiles, multibeam bathymetry, gravity and seismicity data. Epicentres can be grouped into two main alignments. The northern WSW-ENE alignment has reverse earthquake focal mechanisms and in its epicentral region recent mass-transport deposits occur. The southern alignment consists of a NNE-SSW vertical sinistral deformation zone, with early epicentres of higher magnitude earthquakes located along a narrow band 5 to 10 km offset westward of the Al Idrisi Fault. Here, near-surface deformation includes active NW-SE vertical and normal faults, unmapped until now. Later epicentres spread eastward, reaching the Al Idrisi Fault, characterized by discontinuous active NNE-SSW vertical fractures. Seismicity and tectonic structures suggest a westward propagation of deformation and the growth at depth of incipient faults, comprising a NNE-SSW sinistral fault zone in depth that is connected upwards with NW-SE vertical and normal faults. This recent fault zone is segmented and responsible for the seismicity in 1993-94 in the coastal area, in 2004 onshore and in 2016-17 offshore. Insights for seismic hazard assessment point to the growth of recent faults that could produce potentially higher magnitude earthquakes than the already formed faults.

**Key words:** Eurasian-African plate boundary; fault development; seismicity; mass transport deposits; active sea bottom deformations.

## 1. Introduction

Continuous plate motion has led to the activity of tectonic structures developed along plate boundaries, including faults with related seismicity. Seismic or creep behaviour of a fault is constrained by the rheology of the deformed rocks (Sibson, 1977). Brittle deformation is generally accommodated by previous fractures because the low cohesion with respect to the undeformed host rock causes them to be more easily reactivated (Anderson, 1951; Bott, 1959). When deformation propagates, the growth of fault zones is produced by stress concentrations at the boundaries of previous fault surfaces (Scholz, 1989) and the larger the fault, the higher the magnitude of the related earthquakes (Wells & Coppersmith, 1994). The activity of a fault requires the shear stress on its surface to exceed the values of cohesion and friction (Hajiabdolmajid et al., 2002). On a fault surface, the cohesion is low and needs lower shear stresses than on the new developing fault segments at the edge of the previous fault (Hajiabdolmajid et al., 2002). Thus, the propagation of a fault in unfractured resistant rocks can imply a high accumulation of elastic energy that may generate earthquakes of magnitudes higher than those triggered by a reactivation of previous fractures.

The Eurasian-African plate boundary in the Alboran Sea (westernmost Mediterranean) offers a unique research opportunity in a natural example that can provide insights as to the propagation of fault zones (Cowie & Scholz, 1992) (Fig. 1). The Alboran Basin is a Neogene-Quaternary extensional basin located within the Betic (Spain)-Rif (Morocco) alpine cordilleras, connected by the Gibraltar Arc (Andrieux et al., 1971). The major Trans-Alboran Shear zone (Larouzière et al., 1988; Frasca et al., 2015) accommodated the westward displacement of the Betic-Rif orogen during the development of the Gibraltar Arc. The Alboran Basin is floored by a thin continental crust made up of the alpine Internal Zone metamorphic complexes, with a Variscan basement located in the southeastern area (Ammar et al., 2007) resting above an anomalous mantle (Hatzfeld, 1976; Comas et al., 1992). The sedimentary infill consists of unconformable Miocene to Quaternary deposits (Comas et al., 1992; Juan et al., 2016). This sedimentary record is mostly deformed by two conjugated sets of dextral WNW-ESE and sinistral NE-SW faults, and folded by ENE-WSW oriented folds (Estrada et al., 2018; Martínez-García et al., 2017), the Alboran Ridge and Francesc Pagès seamount, pertaining to the main antiforms (Bourgeois et al., 1992). The growth of faults and folds takes place in the framework of recent NNW-SSE shortening, and regional Eurasian-African plate convergence (de Mets et al., 2015). The Eurasian-African plate boundary shows N-S to NW-SE convergence at present (Fadil et al., 2006; Koulali, 2011; Palano et al., 2015), at a rate of 4.93 mm/yr (Argus et al., 2010). Regional present-day ENE-WSW extensional stress is coeval with orthogonal compression and main stress axes are inclined (de Vicente et al., 2008; Stich et al., 2010).

The Betic-Rif Cordillera and Alboran Sea are affected by a 300 km broad and heterogeneous seismicity band related to the Eurasian-African plate boundary (Buforn et al., 1988). Seismicity generally occurs at shallow crustal levels (Buforn et al., 1995). Intermediate seismicity (40 to 120 km deep) is mainly located along a N-S elongated band in the western Alboran Basin that becomes NE-SW northwards (Morales et al., 1999; López-Casado et al., 2001; Buforn et al., 2017; Medina & Cherkaoui, 2017). Deep seismicity (600 to 640 km deep) is scarce but also occurs beneath the central Betic Cordilleras (Buforn et al., 1991, 2011). The area has heterogeneous local stresses probably due to fault interaction (Stich et al., 2010).

Several geodynamic models have been proposed for the region, including delamination (e.g. Seber et al., 1996; Lis Mancilla et al., 2013), or subduction with or without rollback (e.g. Pedrera et al., 2011; Ruiz-Constán et al., 2011; Gutscher et al., 2012; González-Castillo et al., 2015; Spakman et al., 2018), yet discussion remains alive. Moreover, in the central and eastern Alboran Sea, the recent fault system mainly composed by two conjugate WNW-ESE dextral and NNE-SSW sinistral fault sets evidences the activity of continental indentation tectonics (Estrada et al., 2018). Within this structural framework, a present-day zone of deformation with high seismic activity crossing the Alboran Sea —from Al Hoceima in the Rif to Adra and Cabo de Gata in the Betics— (Fig. 1) oblique to the previous Trans-Alboran Shear zone (Larouzière et al., 1988) has been proposed to be a main plate boundary (Fadil et al., 2006; Grevemeyer et al., 2015). However, relationships with the main tectonic structures observed in the seafloor have not yet been analysed in detail. The few available studies (Martínez-García et al., 2013; 2017 and references herein; Estrada et al., 2018) suggest that the NNE-SSW sinistral Al Idrisi Fault is the main structure with recent and present-day activity in the southern Alboran Sea (Fig. 1). This fault is connected onshore with the Trougout Fault in the Al Hoceima region (Morocco margin), which bounds the Nekor Basin (d'Acremont et al., 2014; Lafosse et al., 2017) and its propagation towards the Rif is discussed by Galindo-Zaldívar et al. (2009; 2015a) and Poujol et al. (2014). The Al Hoceima region is deformed mainly by faults that determine a succession of horsts and grabens, probably developed above crustal detachments (Galindo-Zaldívar et al., 2009; 2015a). In the northern Alboran Sea, the fault zone extends onshore toward the Campo de Dalías area, connecting with the Balanegra Fault in the boundary of the Betic Cordillera and Alboran Sea (Marín-Lechado et al., 2010).

January 25, 2016, marked the onset of a seismic sequence in the central-southern Alboran Sea (www.ign.es), with a main shock of Mw=6.3 (Figs. 1 and 2), and whose activity continues up to 2017. The area affected extends from the Francesc Pagès seamount and westernmost Alboran Ridge to the Nekor Basin. The main earthquake was felt in several coastal cities of northern Morocco and southern Spain, causing economic losses in both countries (http://www.ign.es/resources/noticias/Terremoto_Alboran.pdf). The earthquakes of this seismic sequence have been analysed in detail by the IGN (www.ign.es), Buforn et al. (2017), Medina and Cherkaoui (2017) and Kariche et al. (2018). They consider different velocity models for epicentre locations, suggesting that activity occurred in the area nearby Al Idrisi Fault; yet they do not compare their results with the more accurate position of this fault obtained by marine geophysical research (Martínez-García et al., 2013; 2017; Estrada et al., 2018; Lafosse et al., 2017). The comparison of seismological and marine geophysical researches clearly shows that the epicentres of the earliest stage of the sequence are located to the west of the Al Idrisi Fault.

This paper offers a multidisciplinary analysis of the recent and active near-surface tectonic deformations related to the 2016-17 seismic sequence within the greater context of the 1993-94 and 2004 sequences in the central Alboran Sea. Our contribution provides insights into the propagation of recent fault zones and how they are linked to seafloor deformations in addition to their relationships with the former Al Idrisi Fault.

## 2. Methodology and data

The combination of different geodetic and geophysical data made it possible to map the area affected by the 2016-17 seismic sequence, from the deep structure to near-surface morphology as well as the overall geodynamic setting.

### 2.1. Regional GPS data

Permanent GPS stations surrounding the central Alboran Sea served as the reference for present-day deformation in the region. MALA and ALME stations (respectively by Malaga and Almeria) along the Betic Cordillera coast, and MELI (by Melilla) on the African coast, time series were obtained from the EUREF permanent Network. Data were considered up to June 2017, and these stations were in operatation: ALME since 2001; MALA since 2005 and MELI since 2012. GNSS data were processed by means of Bernese Software to determine the displacement vectors.

## 2.2. Seismicity data

The seismicity database of the Spanish National Geographic Institute (IGN) (www.ign.es) registered the 2016-17 seismic sequence as well as the two previous main seismic series, in 1993-94 and 2004. The 2004 seismic sequence was carefully relocated by Van der Woerd et al. (2014). As the precise location of seismicity is sensitive to velocity models and to the distance of the seismic stations (Michelini & Lomax, 2004), literature (Buforn et al. 2017, Medina & Cherkaoui, 2017, Kariche et al. 2018) shows a non-coincident location for the 2016-17 seismic sequence´ epicentres. The 1993-94 and 2016-17 seismic sequences´ epicentre and hypocentre locations were calculated through a standard procedure considering the first arrivals of P and S waves and a standard velocity model (Carreño-Herrero & Valero-Zornoza, 2011). A careful relocation of the main events was provided by Buforn et al. (2017) and the IGN (IGN, 2016; www.ign.es) in light of the standard and recent velocity model (El Moudnib et al., 2015). Earthquake focal mechanisms were also obtained from the IGN database (www.ign.es), established from first arrival P-wave polarity. The present-day stress tensor was determined from seismicity using the method by Michael (1984), improved by Vavryčuk (2014).

## 2.3. Marine geophysics

The area affected by the 2016-17 seismic series was surveyed during the INCRISIS cruise on board the R/V Hesperides in May, 2016. A dense grid of 31 survey lines, with a total length of about 900 km, was designed taking into account the regional water depths and the general orientation of the morphological and structural features (Fig. 1b). Data positioning was determined via a Global Positioning System (GPS). The studied area was covered by a multibeam SIMRAD EM120 echosounder (frequency 12 kHz) that enabled us to record high resolution bathymetry. Vertical resolution was approximately 0.025% of water depth. CARIS Hips software was used for multibeam data processing. This bathymetry was integrated with previous datasets in the area (http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm) and gridded at 25 m.

Simultaneously with multibeam bathymetry, very high resolution seismic profiles were acquired with the SIMRAD TOPAS PS18 system (frequencies of 18 kHz - 1 to 6 kHz). In addition to this information, multi- and single-channel seismic records from the Instituto de Ciencias del Mar-CSIC database (http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm) were considered (Fig. 1c). All seismic profiles were integrated into a Kingdom Suite project (IHS Kingdom) for their correlation and interpretation. Likewise, gravity data were obtained during the INCRISIS cruise using a Lockheed Martin BMG3 marine gravimeter with a precision of 0.7 mGal. Gravity Free air and Complete Bouguer anomalies were determined considering a standard density of 2.67 g/cm$^3$. To extend the gravity anomalies to the shoreline we used the global free air dataset from Sandwell et al. (2014). Directional filters (horizontal gravity gradient) were applied in order to analyse the main tectonic structures.

## 3. Results

The area affected by the 2016-17 seismic sequence is located in the southern sector of the Alboran Sea central part (from 125 to 1450 m water depth), from the Nekor Basin to the vicinity of Alboran Ridge and Francesc Pagès seamount (Figs. 1 and 2). The northern steep side of the Alboran Ridge gives way abruptly to the Alboran Channel, whereas that of the Francesc Pagès seamount evolves to flat-lying seafloor of the deep basin through a terraced-shaped sector that parallels the seamount.

### 3.1. Present-day Alboran Sea shortening from GPS data and plate deformation

Deformation within the Alboran Sea is driven in part by the NW-SE regional convergence of the Eurasian and African plates (de Mets et al., 2015). The west to west-southwestward motion of the Betic-Rif Alboran block (Koulali et al., 2011; Palano et al., 2015) may also be the result of ongoing slab rollback towards the west (Pedrera et al., 2011; Ruiz-Constán et al., 2011; Gutscher et al., 2012; González-Castillo et al., 2015; Spakman et al., 2018), which would explain the E-W to ENE-WSW extensional focal mechanisms observed in the West Alboran Sea (Stich et al., 2010). At present, the GEODVEL plate model (Argus et al., 2010) indicates a N141ºE trend of convergence at a rate of 4.93 mm/yr in this region, supported by regional GPS data (Fadil et al., 2006). This regional deformation produces a NNW-SSE shortening which, in the central part of the Alboran Sea, may be constrained by the MALA and ALME stations in Spain, and by MELI station in Morocco (Fig. 1). The higher rates of MALA station with respect to ALME evidence ENE-WSW extension in the Betic Cordillera (Galindo-Zaldivar et al., 2015b). The southern displacement of ALME and MALA stations relative to the European plate contrasts with the northern displacement of MELI, supporting present-day shortening in the central Alboran Sea. The most intensely seismic area in 2016-17 is located in between MALA and MELI stations, with a relative NNW-SSE (N173ºE) shortening of 3.3 mm/yr.

### 3.2. Recentmost seismic sequence

A seismic zone of intense activity affects the central Alboran Sea, from the Campo de Dalias region in the north, to the Al Hoceima region in the south (Figs. 1 and 2), it being most intense at the southern end (Grevemeyer et al., 2015). The most recent seismic sequences were in 1993-94, 2004 and 2016-2017 (Fig. 2). The 1993-94 seismic sequence affected the coastal region nearby Al Hoceima, with a main earthquake of Mw=5.6 (May 26, 1994), after an earlier earthquake in the Campo de Dalías area, of Mw= 5.3 (Dec 23, 1993). In 2004, another seismic sequence with a devastating earthquake event of Mw= 6.4 (Feb 24) occurred onshore in the Al Hoceima region causing nearly 600 deaths and with aftershocks reaching the Alboran Sea (Van der Woerd et al., 2014). Earthquake focal mechanisms were very similar in all cases, pointing mainly to sinistral strike-slip along the NNE-SSW oriented deformation zone (El Alami et al., 1998; Stich et al., 2006, 2010), although also possible is the activity of WNW-ESE dextral faults in the 2004 sequence that affect Al Hoceima onshore areas (Akoglu et al., 2006; Van der Woerd et al., 2014).

The 2016-17 seismic sequence (Figs. 2 and 3) was initiated by a moderate earthquake (Jan 21, 2016, Mw=5.1) followed closely by a stronger event (Jan 25, Mw= 6.3) and by a long seismic series of decreasing activity during 2016-17 (Buforn et al., 2017; Medina & Cherkaoui, 2017; Kariche et al., 2018). The relatively long distances from hypocentres to seismic stations, generally greater than 50 km and in some cases reaching more than 80 km, decreases the quality of earthquake locations. Buforn et al. (2017) recognize average horizontal errors of 5 km and vertical errors of 10 km, comprised between 2 to 10 km horizontally and 3 to 17 km vertically. The location of 2016-17 seismic activity established by the IGN standard terrain velocity model (Carreño-Herrero & Valero-Zornoza, 2011) (Figs. 2a and 3) or El Moudnib et al. (2015) velocity model (Fig. 2b) shows a deformation band with two alignments, the main one, oriented NNE-SSW, changing sharply to a ENE-WSW trend. Considering the IGN standard terrain velocity model (Carreño-Herrero & Valero-Zornoza, 2011) (Figs. 2a and 3), the NNE-SSW alignment is about 40 km in length and 10-20 km wide, and includes shallow earthquakes (< 35 km depth) that affect the crust and upper mantle. It is parallel and significantly displaced westwards (up to 10 km) with respect to the Al Idrisi Fault (Fig. 2). The ENE-WSW alignment, about 20 km long and 10-15 km wide, is located along the northern side of the westernmost Alboran Ridge and the Francesc Pagès seamount, and is also characterized by a shallow seismicity (< 35 km). During month 1 (Jan 2016), the seismicity clearly defines the two alignments with widths of less than 10-20 km, the main southern one being displaced 5 to 10 km westwards with respect to the trace of the main Al Idrisi Fault (Figs. 2 and 3a). During month 2 (Feb 2016), seismic activity decreases and both alignments become wider (10-20 km) (Fig. 3b). Then, from month 3 (March 2016) to present, seismicity gradually decreased and affected a broader area, more than 15-25 km wide (Fig. 3c), in between the one clearly defined in month 1, and bounded eastward by the main trace of Al Idrisi Fault. Buforn et al. (2017) relocate the earthquakes considering El Moudnib et al. (2015) velocity model and also obtain the same pattern formed by two alignments, the NNE-SSW with a westward offset with respect to the Al Idrisi Fault seabottom location.

The earthquake focal mechanisms of the two seismicity alignments show different behaviours (Fig. 3d). The main NNE-SSW alignment is characterized by sinistral earthquake focal mechanisms related to NNE-SSW subvertical faults, roughly parallel to the elongation of the alignment. There is also heterogeneity of earthquake focal mechanisms with inclined P and T axes and normal faults, supporting ENE-WSW extension toward the southern deformation zone. In contrast, the ENE-WSW alignment is characterized by highly homogeneous reverse earthquake focal mechanisms associated with ENE-WSW faults. Present-day stress (Fig. 3) supports low NNW (N319ºE to N332ºE) inclined compression and orthogonal horizontal extension in both segments linked to prolate stress ellipsoids. Inclination is higher (47º) in the main alignment and its axial ratio is closer to triaxial stress.

### 3.3. Deep structure from gravity data

Bouguer complete gravity anomalies decrease in the Alboran Sea, from 110 mGal to 30 mGal, in a smooth transition from the east to the west up to 4.5ºW (Casas & Carbó, 1990). As the amplitude decreases, it narrows to the west, so that the greatest values are located in the central part.

The Bouguer complete anomaly map of the 2016-17 seismic sequence area and its surroundings shows values between 100 and 10 mGal. Despite some isolated highs, the values decrease progressively from north in the central Alboran to south in the Moroccan margin. Bouguer anomaly highs in the central Alboran (northern part of Fig. 4a) support the presence of a local thinning of the continental crust (Galindo-Zaldivar et al., 1998). The shaded relief of the complete Bouguer anomaly map with illumination from the east (Fig. 4b) is sensitive to N-S trends and tracks the extension of alignments coming out of Nekor Basin, at least as far as the Alboran Ridge. One alignment (labeled “B” in Fig. 4b) nearly parallels the Al Idrisi Fault, though displaced westward. The plots of the 2016-17 epicentres of earthquakes having magnitude over 3.9, once relocated, show that the southern sector lies over the alignment located in the middle.

## 3.4. Recent and active near-surface tectonic and sedimentary deformations

The morpho-bathymetric and seismic analysis of the near-surface sediments affected by the 2016-17 seismic sequence provides evidence of recent and active faults, as well as folds and mass transport deposits (MTDs) (Figs. 5, 6, 7, 8 and 9). MTDs are located on the northern side of the Francesc Pagès seamount and Alboran Ridge, along the ENE-WSW active seismicity alignment and the main earthquake (Figs. 5 and 6). Based on the thickness of remobilized sediment, small-scale MTDs (a few ms thick) and large-scale MTDs (tens of ms thick) were identified.

The small-scale MTDs occur mostly on the relatively steep slopes (~<5º) of the northern side of both seamounts, from >250 m to 1000 m water depth. They appear as vertically stacked subtabular units (a few tens of milliseconds) of unconsolidated deposits, and lenticular and irregular bodies of semi-transparent, contorted and discontinuous stratified facies, separated by relatively high reflectivity surfaces with local hyperbolic echoes. The strata pattern suggests the recurrent nature of gravity drive transport. These facies conform an irregular seafloor surface with gentle undulations (metric in scale). The large-scale MTDs mainly occur seaward with respect to the previous ones, and extend down to the deep basin (as much as 1450 m water depth). They are related to slide scars, most of them removing the small-scale MTDs. The slide scars display an amphitheatre shape (up to 1 km wide, 40 m relief) recognizable at seafloor, where they extend along a fringe at the foot of the Francesc Pagès seamount. Most of these MTDs are detached from the slide scars, and are acoustically defined by lenticular bodies (up to 55 ms thick) internally characterized by semitransparent and discontinuous stratified facies, and having a distinctive irregular seafloor surface recognized bathymetrically. Their acoustic character indicates disintegration of the removed mass, just after the initiation of mass flow-type movement. Seismic records also provide evidence of buried large-scale MTDs that interrupt and erode the surrounding basinal undeformed stratified facies, suggesting the episodic nature of such slope sedimentary instabilities, at least in recent geological times. Their stratigraphic position points to a simultaneous occurrence of some MTDs (Fig. 6).

With respect to the folds, the Alboran Ridge and Francesc Pagès seamount constitute the main antiformal structures deforming the region (Figs. 5 and 7). The ENE-WSW folds affect Miocene age deposits (Martínez-García et al., 2013). The fold geometry is irregular, with variable wavelengths (km in scale) and vergences (NNW or SSE). In addition, smaller-scale folds (hundreds of meters in scale) are identified in relation to the Al Idrisi Fault (Fig. 8), with axes oriented parallel to it.

The main fracture of morphological and seismic expression, deforming the most recent sediments, is the sinistral Al Idrisi Fault zone (Martínez-García et al., 2011, 2013, 2017) (Figs. 5 and 8). This fault has a 50 km-long northern segment with N35ºE trend. It develops a recent fault scarp of about 20 to 30 ms (15 to 23 m) at the northwestern edge of the Alboran Ridge that constitutes the upthrown block (Figs. 5 and 8). In the hanging wall, small-scale MTDs are recognized. The near-surface sediments in this sector are affected by folds. Al Idrisi Fault changes its direction suddenly to N15ºE in the area between the Francesc Pagès seamount and the westernmost end of the Alboran Ridge. Here, it is characterized by a sharp elongated depression covered by undeformed recent sediments. The main N15ºE southern segment is about 20 km long and extends discontinuously southward, towards the Nekor Basin in relay with the Trougout Fault, forming splay faults (Lafosse et al., 2017). The southern end of Al Idrisi Fault trace is located at a deformation zone with smaller faults reaching the seabottom (Fig. 5). Previous research of earthquake focal mechanisms (Grevemeyer et al., 2015; Martínez-García et al., 2011, 2013,

2017) suggests a sinistral slip on the Al Idrissi Fault NNE-SSW vertical fault plane, further confirmed by the short displacement, roughly 5 km, of the antiformal axis of Alboran Ridge with respect to the Francesc Pagès seamount (Martínez-García et al. 2011, 2013, 2017).

Our new geomorphological and tectonic map evidences, for the first time, a recent fault zone to the north of the Nekor Basin affected by the 2016-17 seismic sequence (Figs. 5 and 9). It is located approximately 5 to 10 km westward of the Al Idrisi Fault, south of Francesc Pagès seamount. Its bathymetric expression (a few meters of relief) correlates with the epicentral area. The faults have NW-SE orientation, with high northeastward or southwestward dips. The very high resolution seismic images of this recent fault zone suggest they are grouped in conjugate faults with a normal component affecting the most recent sediments, some of them reaching up to the seafloor (Fig. 9).

## 4. Discussion

This multidisciplinary focus on the 2016-17 seismic sequence in the Alboran Sea —in the wake of previous sequences in 1993-94 and 2004, and the former Al Idrisi Fault— sheds light on the seafloor deformation and relevant implications in terms of geological hazard. The results help to constrain the processes that occur during migration and propagation of active tectonic brittle deformations.

## 4.1. Constraining active tectonics: seismicity and seafloor deformations

Epicentres related to wrench faults are expected to be located along the fault zone trace. Vertical nodal planes of earthquake focal mechanisms from the main 2016 earthquake and most of the events in the southern Alboran Sea undoubtedly evidence the vertical dip of the seismic active faults (Fig. 3), in agreement with the seismological results of Buforn et al. (2017). Anyway, aftershock sequences can affect a wide zone (e.g. >10 km wide with respect to the main fault during the Landers 1992 seismic sequence, Hauksson et al., 1993) favoured by the structural complexity and pre-existing structures. In spite of Buforn et al. (2017) establish horizontal and vertical errors for the 2016-17 seismic sequence location, and Buforn et al. (2017) as well as Medina and Cherkaoui (2017) relate the seismicity with the Al Idrisi Fault, the careful analyses of epicentre locations for most of the NNE-SSW seismicity alignment (IGN, www.ign.es; Buforn et al., 2017; Medina & Cherkaoui, 2017; Kariche et al., 2018) points to they are displaced westwards with respect to the seafloor trace of the Al Idrisi Fault determined by marine geophysical data (Martínez-García et al., 2013, 2017; Estrada et al., 2018) (Figs. 2, 3 and 5). This displacement of the earthquakes is higher when the standard velocity model (Carreño-Herrero & Valero-Zornoza, 2011) is considered (IGN, www.ign.es; Medina and Cherkaoui, 2017; Kariche et al., 2018): roughly 10 km for the first stage earthquakes (Figs. 2a and 3a), as opposed to the roughly 5 km (Buforn et al., 2017) with the model by El Moudnib et al. (2015) (Fig. 2b). Although the mislocation of earthquakes by the poorly constrained velocity models and far seismic stations, may produce a westward shift of the seismicity with respect to the Al Idrisi Fault, all the available seismological studies (IGN, www.ign.es;

Buforn et al., 2017; Medina & Cherkaoui, 2017; Kariche et al., 2018) support the offset to the west of the seismicity and fault activity with respect to the former Al Idrisi Fault that roughly constitutes the eastern boundary of the fault zone. Our findings based on the marine geophysical dataset demonstrate the development of recent faults west of the former Al Idrisi Fault related to the westward propagation of the deformation (Figs. 2, 3, 8, 9 and 10).

The early earthquakes of the 2016-17 series are clearly grouped in the two relatively narrow (~10-20 km wide) NNE-SSW and ENE-WSW alignments, starting with the highest magnitude event (Mw= 6.3, Jan 25) where they join (Fig. 3a). The depth of seismicity is not well constrained because of the variability of crustal velocities and the few and far onshore stations; still, they correspond to crustal levels (<35 km depth), in agreement with Buforn et al. (2017), Medina and Cherkaoui (2017) and Kariche et al. (2018). New seismic faults started to develop at shallow crustal levels (roughly 5 to 10 km depth), as generally occurs in continental crust (Meissner & Strehlau, 1982). If an elliptical fault surface shape is considered (Watterson, 1986), the recent fault should extend in depth northward and southward into the seismogenic crustal layer. When deformation propagates upwards, the triggering fault is expected to reach the seafloor in the NNE-SSW epicentres alignment, due to the high dip of fault plane solutions in most of the earthquake focal mechanisms. According to empirical fault scaling relationships (Wells & Coppersmith, 1994), the main seismic event would be related to a surface rupture between 15 and 20 km and might deform the area. In the 2016-17 seismic series, a recent fault zone (10-20 km wide) reaching up to the seafloor was recognized in the main NNE-SSW seismicity alignment, south of Francesc Pagès seamount. This recent zone comprises NW-SE oriented conjugated normal faults coeval with the recent sedimentation, reaching different near-surface stratigraphic levels, probably rotating and connecting in depth with the major recent NNE-SSW vertical sinistral fault (Fig. 10). These shallow faults accommodate the NE-SW extension compatible with the activity of the main wrench fault, and are in agreement with crustal thinning in the Nekor Basin confirmed by Bouguer gravity anomalies (Fig. 4); they would be in line with the recent normal faults described by Lafosse et al. (2017) that demonstrate that the Nekor Basin is floored by a set of splay faults with normal slip component related to the southern prolongation of Al Idrisi Fault.

During later earthquakes, the 2016-17 seismic series deformation extended to a broad 10-20 km-wide fault zone in the NNE-SSW alignment, bounded westward by the recent faults and eastward by the Al Idrisi Fault and the Alboran Ridge. Al Idrisi Fault, in contrast, only deforms discontinuously near-surface sediments along the fault trace by recent or active faults and folds, suggesting the recentmost activity of some segments. Although the discontinuous evidences of activity may be the consequence of a seismic character of Al Idrisi Fault, with segments accumulating elastic deformation before the seismic rupture, alternatively they could indicate that the activity of those segments has been replaced by that of other recent faults offset to the west.

In the ENE-WSW alignment, the morphostructural pattern and deformation behaviour are different. The presence of MTDs (Figs. 5 and 6) and reverse earthquake focal mechanisms (Fig. 3d), and the absence of clear reverse faults affecting the near-surface, would suggest the presence of blind reverse faults at the core of the Alboran Ridge antiform (Fig. 10) (Martinez-Garcia et al., 2013).

Earthquakes may be assumed to be the main mechanism triggering the MTDs, deforming the near-surface sediment of the ENE-WSW alignment (Figs. 5 and 6) (Casas et al., 2011). The initiation of slope failure is due to cyclic loading applied on the sediment and a decreasing shear strength through the development of pore overpressure. Other factors, such as tectonic deformations resulting in seabed, may also contribute to increasing shear stress on the slope, or a decreasing sediment strength due to shearing, dilatancy and possible sediment creep (Locat & Lee, 2002).

### 4.2. Geodynamic implications and seismic hazard

The former NE-SW sinistral Trans Alboran Shear Zone (Larouzière et al., 1988) constituted a main tectonic structure during the Miocene, later becoming inactive and overprinted by the recent NNE-SSW deformation zone (Stich et al., 2006, 2010) between Campo de Dalías (Balanegra Fault) and the Al Hoceima region (Trougout Fault), including the Al Idrisi Fault (Fig. 10). This evolution reveals a progressive offset to the west and rotation of the central Alboran Sea active deformation zone. The recent shear zone has incipient low deformation. Al Idrisi Fault, which constitutes the longest fault in this deformation zone, has short strike-slip, however. It is expressed by low interaction at the edge where the Al Idrisi Fault orientation trace changes, and also by the short displacement between the Alboran Ridge and Francesc Pagès seamount antiform axes (Fig. 10).

At present, seismological and GPS studies hold the active seismic zone in the central Alboran Sea to be a main weak zone related to the Eurasian-African plate boundary (Fadil et al., 2006; Grevemeyer et al., 2015; Palano et al., 2015; Buforn et al., 2017; Medina & Cherkaoui, 2017). The fact that seismicity occurred near the African coastline in 1994, with maximum magnitude of Mw= 5.6 (May 26), and later propagated towards the continent in 2004 with a main event of Mw= 6.4 in February 24 (e.g. Akoglu et al., 2006; Van der Woerd et al., 2014 and references therein) would indicate that the 2016-17 seismicity (main event Mw= 6.3) is most likely located within the same regional deformation band (Figs. 2 and 10), at its northern edge. Accordingly, the recent fault zone exhibits a segmented behaviour with the progressive reactivation of 15-20 km length stretches demonstrated by the recent seismic series (1993-94, 2004, 2016-17) (Buforn et al., 2017; Medina & Cherkaoui, 2017; Kariche et al., 2018). In the Rif, seismic faults have rupture in depth but with no clear surface expression (Galindo-Zaldívar et al., 2009 and 2015a; Van der Woerd et al., 2014). Akoglu et al. (2006) and Van der Woerd et al. (2014) show that seismicity onshore Al Hoceima region has been produced by the activity of NNE-SSW but probably also WNW-ESE conjugated faults in NNW-SSE compression and ENE-WSW orthogonal extensional stresses.

Northwards, towards the Betic Cordillera, the deformation zone is connected with the Campo de Dalías and its seismicity during the 1993-94 series (Marín-Lechado et al., 2005) (Fig. 10).

The present day stresses determined from regional seismicity studies (de Vicente et al., 2008; Stich et al., 2010) agree with the data obtained in the context of the 2016-17 seismic sequence (Figs. 3 and 10). The NW-SE compression is prolate to triaxial, and inclined towards N319ºE in the NNE-SSW seismicity alignment, while N332ºE in the ENE-WSW alignment, with related orthogonal extension. Thus, compression is rotated in the two alignments, and is compatible with sinistral fault kinematics (Fig. 10). Whereas at the Earth´s surface, main stresses should be horizontal or vertical due to an absence of shear stress (Anderson, 1951; Bott, 1959), the inclination of main compression towards the NW at crustal depths suggests activity of northwestward thrusting to some extent. Moreover, this setting could be a consequence of the presence of a low-deformed resistant domain attached to the African plate, here corresponding to the external Rif units on the Variscan basement (Pedrera el al., 2011; Galindo-Zaldívar et al., 2015a; Estrada et al., 2018).

There is furthermore some disagreement between the maximum horizontal compression (between N139ºE and N152ºE) and maximum local shortening (N173ºE) (Fig. 10), estimated by the MALA and MELI GPS stations across the seismic active area. It may be that fault activity is not due to a simple strike-slip fault driven by a far field stress in the sense of Anderson (1951), but could accommodate crustal block displacement. The NE-SW extension that occurs towards the fault tips, at the northern edge of Campo de Dalías normal faults (Marín-Lechado et al., 2005; Galindo-Zaldívar et al., 2013), is transferred towards the southern edge, where normal faults splay at the Nekor Basin (Fig. 10) (Galindo-Zaldívar et al., 2009; Lafosse et al., 2017) and crustal thinning is confirmed by gravity results (Fig. 4a).

The epicentres of three seismic series are located west of the main faults recognized at surface, both in the Alboran Sea (Al Idrisi Fault) and in the northern Rif (Trougout Fault) (Figs. 2 and 10) (Galindo-Zaldívar et al., 2009, 2015a; d'Acremont et al., 2014). Hence, the development of the seismic active fault zone west of the well exposed Al Idrisi and Trougout faults might be attributed to the growth of recent faults owing to westward migration (Vitale et al., 2015) of the deformation during development of the Gibraltar Arc.

The westward migration of the Gibraltar Arc is well constrained by geological (Crespo-Blanc et al., 2016) and GPS data (Fadil et al., 2006; Koulali et al., 2011; Palano et al., 2015). However, the driving mechanism remains a matter of debate, with geodynamic models considering delamination (e.g. Seber et al., 1996; Lis Mancilla et al., 2013) and subduction (e.g. Pedrera et al., 2011; Ruiz-Constán et al., 2011; Gutscher et al., 2012; González-Castillo et al., 2015; Spakman et al., 2018), while roll-back is a suitable mechanism for Gibraltar Arc westward displacement and Alboran Sea development. The growth of this seismic NNE-SSW fault zone occurs in the area of weakest and most attenuated continental crust, corresponding to the central Alboran Sea, bounded by the thick continental crust of the Betic and Rif cordilleras. In this regional setting, the Eurasian-African convergence developed indentation tectonics (Estrada et al., 2018) accommodated by the Al Idrisi fault zone, which now extends to westward areas.

The development of active fault zones has vast implications for seismic hazard. The reactivation of an existing fracture calls for shear stress on the surface to attain the value of the friction and cohesion (Bott, 1959). Immediately previous to the formation of new fractures, shear stress would have to be above the values of friction in addition to cohesion —considerably higher (Anderson, 1951; Hajiabdolmajid et al., 2002). Given the same background setting, the development of a recent fault zone would allow for the accumulation of higher elastic deformation at the fault edges than along a well-developed previous fracture. These factors determine that the propagation of a recent fault, as occurs in the southern Alboran Sea, can produce earthquakes of higher magnitudes than pre-existing faults. The highest magnitude earthquakes of 2004 (Galindo-Zaldívar et al., 2009; d'Acremont et al., 2014) and 2016-17 occurred in areas of recently developed fault segments with scarce evidence of deformation at the surface (Fig. 10). Such faults tend to be particularly active in their initial stage of development, entailing high seismic hazard, and are moreover difficult to detect because of the low amount of accumulated deformation due to their recent age.

## 5. Conclusions

The Alboran Sea 2016-17 seismic sequence constitutes a unique opportunity to analyse the development of recent faults in conjunction with seismic hazard. This sequence occurred in the southern part of an active deformation zone crossing the central Alboran Sea and had a main event (Mw=6.3, Jan 25, 2016) located along the corner between the NNE-SSW and ENE-WSW deformation alignments, which are 10-20 km wide. The 40 km-long NNE-SSW alignment is located in the Nekor Basin and Francesc Pagès seamount, west of the seabottom Al Idrisi Fault trace, and the ENE-WSW one is along the northern side of Alboran Ridge and Francesc Pagès seamount. Data recorded during the INCRISIS cruise reveal that the ENE-WSW alignment is mainly characterized by recurrent MTDs that could be linked to earthquake and tectonic activity owing to uplift of the Alboran Ridge and Francesc Pagés antiforms. The NNE-SSW seismicity alignment is related to deep vertical sinistral faults, demonstrated by earthquake focal mechanisms, offset 5 to 10 km westwards from the former Al Idrisi Fault. The major NNE-SSW deep sinistral fault zone responsible for the 2016-17 main events would have activated fault segments up to 15 to 20 km in length for single events. The INCRISIS cruise reveals evidence for recent near-surface ruptures in NW-SE normal faults. These recent faults are related to the western boundary of the deformation zone, bounded eastward by the Al Idrisi Fault; although it is the main fault with seafloor expression, it has segments without recent activity. The present-day stress from earthquake focal mechanisms of 2016-17 constrains a maximum prolate to triaxial compression inclined towards N319ºE in the NNE-SSW alignment, and N332ºE in the ENE-WSW alignment, with related orthogonal extension. Stresses are oblique to the N173ºE shortening determined by GPS data that support sinistral slip behaviour, with some extent of northwestward thrusting.

These data reveal a westward migration and offset of active deformation with respect to the already developed Al Idrisi Fault (Fig. 10) that may be linked to the westward development of the Gibraltar Arc. Moreover, the NNE-SSW deformation zone is segmented and was progressively reactivated near the African coast in the 1993-94 seismic sequence, the southern onshore part being affected in 2004 and probably activating NNE-SSW sinistral and WNW-ESE dextral faults, with deformation later propagating offshore toward the northeast in 2016-17. The present-day NW-SE Eurasian-African plate convergence in the westernmost Mediterranean and the inherited heterogeneous rigid basement structures determine the location of deformation areas. At present, a main NNE-

SSW sinistral deformation fault zone, including the Al Idrisi Fault and recent developed faults offset to the west, connects the NW-SE extensional faults of the Campo de Dalias´s northern edge (Betic Cordillera) with the southern edge´s normal splay faults located at the Nekor Basin in the Rif (Fig. 10). This setting also contributes to the local crustal thinning of Nekor Basin supported by gravity data.

Geological hazard in the central Alboran Sea is closely related to the seismicity that constitutes a main triggering mechanism of MTDs and is moreover responsible for coseismic seafloor displacements. The development of recent faults that condition the westward widening of the fault zone compared with the already developed faults would imply the activity of the largest segments and the greatest accumulation of elastic energy, producing high magnitude earthquakes that increase seismic hazard. In any case, low accumulated deformation and recent activity are predominant features making it possible to recognize such faults, and therefore deserving further analysis through a multidisciplinary approach.

## Acknowledgements

We acknowledge the comments of Prof. N. Niemi, Prof. J. Bruce H. Shyu, Prof. M-A Gutscher and three anonymous reviewers which served to improve the quality of this paper. We also thank A. Mandarieta for his help with the figures. The geological data referenced in this paper are available in the text, the seismicity data are available on the IGN website at http://www.ign.es/web/ign/portal/sis-catalogo-terremotos and the marine geophysical data are available on the ICM-CSIC website at http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm . This study was supported by the Spanish projects INCRISIS (CGL2016-80687-R AEI/FEDER) DAMAGE Project FEDER, SARAS and FAUCES (CTM2015-65461-C2-1-R) and Marlboro cruises. French program Actions Marges, the EUROFLEETS program (FP7/2007-2013; n°228344). The participation of D. Palomino and J.T. Vazquez was funded by the IEO project RIGEL.

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## Figure captions

Fig. 1. Geological setting including regional faults and seismicity. a, Plate boundaries in the Azores-Gibraltar area (modified from Galindo-Zaldívar et al., 2003) and geological sketch of the main structural features and basins of the Alboran Sea (modified from Comas et al., 1999). Displacement of GPS stations around the Alboran Sea with respect to stable Eurasia are indicated (red arrows). The dotted area within the inset indicates the deformation area. b, Tracklines of multibeam, very high resolution seismics (TOPAS) and gravity surveyed simultaneously during the INCRISIS cruise. c, Tracklines of single- and multi-channel seismics (airguns) from the ICM database (http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm). Legend: AF, Al Idrisi Fault; AR, Alboran Ridge; AC, Alboran Channel; BF, Balanegra Fault; CD, Campo de Dalías; CG, Cabo de Gata; CF, Carboneras Fault; DB, Djibouti Bank; EAB, East Alboran Basin; FP, Francesc Pagès seamount; NB, Nekor Basin; NF, Nekor Fault; SAB, South Alboran Basin; TF, Trougout Fault; WAB, West Alboran Basin; YF, Yusuf Fault.

Fig. 2. Seismicity distribution during the 2016-17 seismic sequence and other recent seismicity (including 1993-94 and 2004 series) (2004 seismic sequence from Van der Woerd et al., 2014; other seismicity from www.ign.es database). a, Epicentres considering a standard velocity model. b, Relocated epicentres for the highest magnitude earthquakes of the 2016-17 seismic sequence according to El Moudnib et al. (2015). Legend: FP, Francesc Pagès seamount; NB, Nekor Basin.

Fig. 3. Seismicity during the 2016-17 seismic sequence. a, Epicentres month 1 (January 2016). b, Epicentres month 2 (Feburary 2016). c, Late epicentres (March 2016 to June 2017). d, Earthquake focal mechanisms from 2016-17 seismic crisis (data from I.G.N., www.ign.es). NNE-SSW alignment in blue, ENE-WSW alignment in red. The main earthquake, located at the edge of the two alignments, is shared by the two groups. Present-day stress is determined in the two main sectors of 2016-17 Alboran Sea seismic crisis area (by the methods of Michael, 1984; improved by Vavryčuk, 2014). e, cross sections of seismic activity orthogonal to the main alignments.

Fig. 4. Gravity anomaly maps and main tectonic features. a, Bathymetry map, contour lines every 100 m. b, Complete Bouguer gravity anomaly map at 2 km resolution. Contour lines every 5 mGal. c, A shaded relief map (illuminated from the East) of the complete Bouguer gravity anomaly. Black dashed lines denote offshore N-S alignments (labeled as A, B and C); white dots mark earthquakes with magnitude > 3.9; thin contour lines represent bathymetry.

Fig. 5. Recent sea bottom deformation affecting the 2016-17 Alboran Sea seismic active area: MTDs, faults and folds. a, INCRISIS bathymetry integrated with previous datasets in the area (http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm). Data is gridded at a resolution of 25 m. b, detailed view of recent fault scarps mapped during the INCRISIS multibeam bathymetry. The grey plain areas were not covered by the multibeam echosounder. c, geomorphological and tectonic map. The INCRISIS TOPAS seismic profiles were also integrated with the multi- and single-channel seismic records from the Instituto de Ciencias del Mar-CSIC database

(http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm). 2016 seismicity from www.ign.es database.

Fig. 6. Segments of TOPAS seismic records displaying the small- and large-scale MTDs mapped in the ENE-WSW seismicity alignment. Thin vertical discontinuous lines, noise.

Fig. 7. Segments of multi-channel seismic records displaying the Alboran Ridge (a) and Francesc Pagès seamount (b) folds.

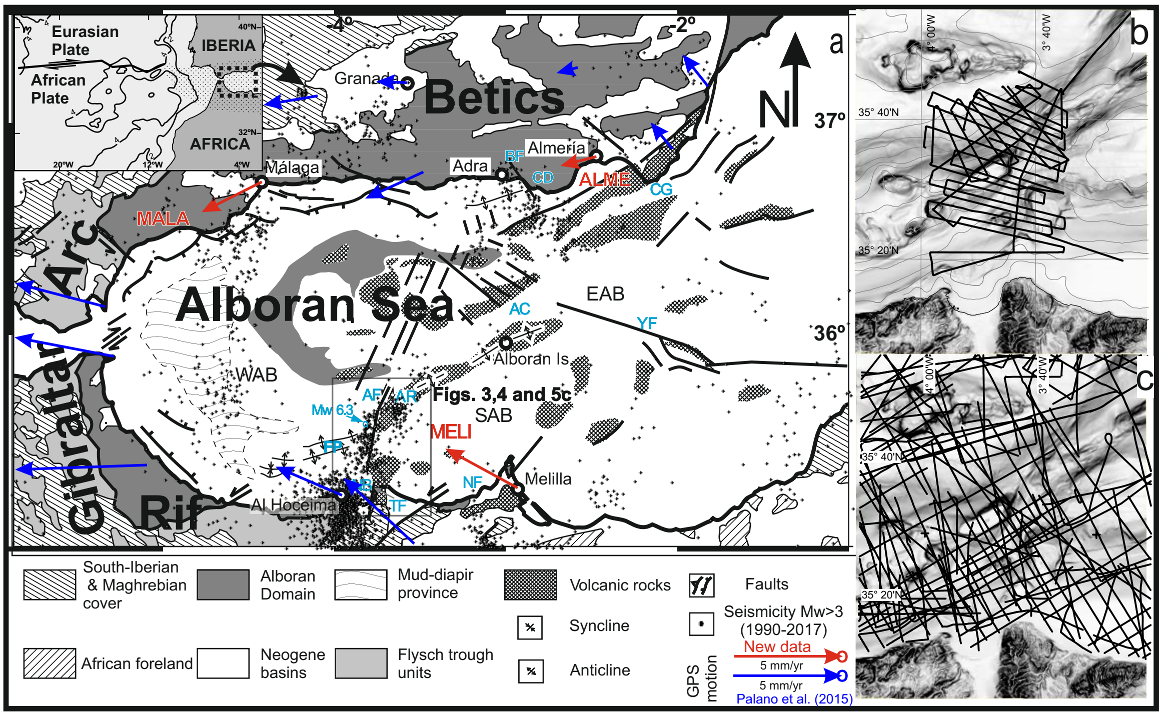
Fig. 8. Segments of TOPAS seismic records displaying the Al Idrisi Fault deformation along its trace. The fault generally affects recent sediments, although undeformed sediments cover the central part of the fault trace. Thin vertical discontinuous lines, noise.

Fig. 9. Segments of TOPAS seismic records displaying the recent fault zone identified in this study. This zone is located 5 to 10 km westwards of the Al Idrisi Fault (d). Thin vertical discontinuous lines, noise.

Fig. 10. Sketch illustrating the westward propagation of recent tectonic and seismic activity in the main NNE-SSW deformation zone crossing the Alboran Sea. a, Seismicity, main active structures, stress and shortening. 2004 seismic sequence from Van der Woerd et al. (2014); other seismicity from www.ign.es database. b, Sketch of main tectonic structures and westward migration of deformation from main Al Idrisi Fault trace. c, Interpretative cross sections and seismicity orthogonal to the main earthquake alignments. 1, sinistral fault (map and cross section). 2, normal fault. 3, recent normal fault. 4, epicentre of main event (Mw=6.3, Jan 25, 2016). 5, Active blind thrust. 6, Active NNE-SSW sinistral deep vertical crustal fault segment bounding westwards the NNE-SSW

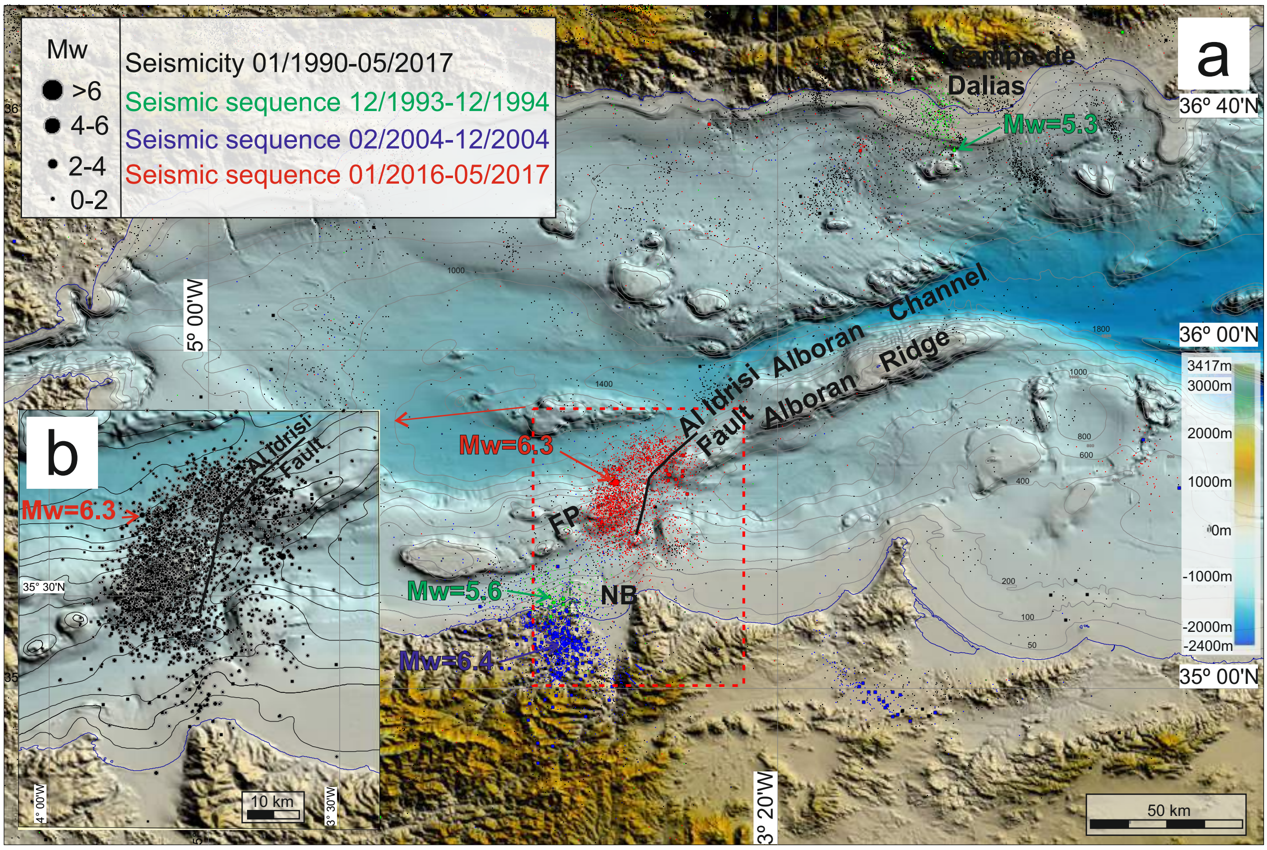
2016-17 seismicity alignment. 7, Active NNE-SSW vertical sinistral crustal fault segment related to the 1993-94 seismic crisis. 8, Active NNE-SSW vertical sinistral crustal fault segment related to the 2004 seismic crisis. 9, Offset to the west of recent deformation and seismicity in respect to Al Idrisi Fault. 10, Estimated convergence trend from GPS data. 11, Regional plate convergence trend. 12, Present-day trends of compression and extension determined from earthquake focal mechanisms. FP, Francesc Pagès seamount. MTD, Mass transport deposits.

**Fig. 1.**



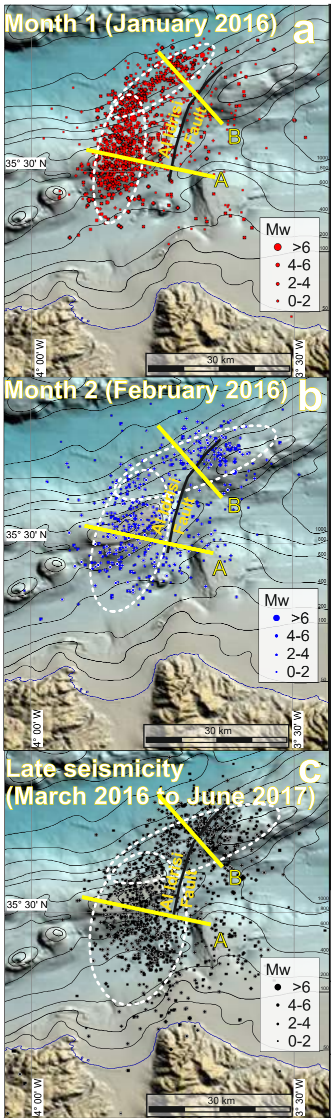
Eurasian Plate
African Plate
IBERIA
AFRICA
Betics
Granada
Málaga
Adra
Almeria
MALA
ALME
BF
CD
CG
N
37º
36º
4º
2º
a
b
c
Arc
Gibraltar
Alboran Sea
EAB
WAB
SAB
AC
YF
Alboran Is.
AF
AR
Figs. 3,4 and 5c
Mw 6.3
MELI
NF
TF
Melilla
Al Hoceima
Rif
35° 40'N
35° 20'N
3° 40'W
4° 00'W
South-Iberian & Maghrebian cover
Alboran Domain
Mud-diapir province
Volcanic rocks
Faults
Syncline
Seismicity Mw>3 (1990-2017)
Anticline
African foreland
Neogene basins
Flysch trough units
GPS motion
New data
5 mm/yr
5 mm/yr
Palano et al. (2015)

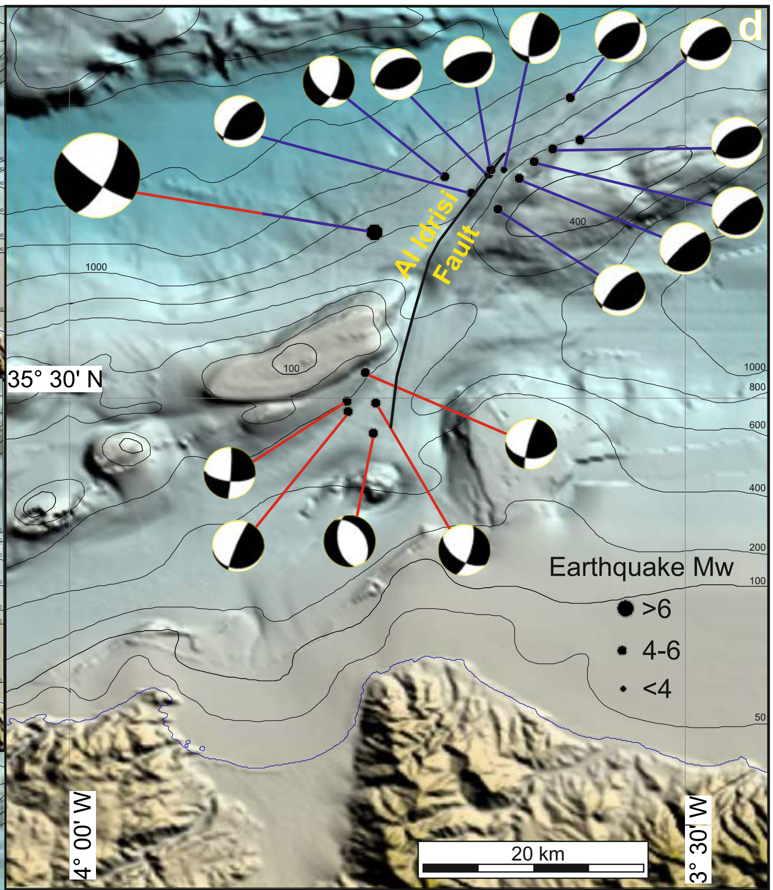
**Fig. 2.**



Mw
>6
4-6
2-4
0-2
Seismicity 01/1990-05/2017
Seismic sequence 12/1993-12/1994
Seismic sequence 02/2004-12/2004
Seismic sequence 01/2016-05/2017
a
Dalias
Mw=5.3
36° 40'N
Alboran Channel
36° 00'N
Al Idrisi Fault
Alboran Ridge
5° 00'W
b
Mw=6.3
Mw=6.3
FP
Mw=5.6
NB
Mw=6.4
35° 00'N
3° 20'W
35° 30'N
10 km
50 km
3417m
3000m
2000m
1000m
0m
-1000m
-2000m
-2400m

**Fig. 3.**




| Alignment | Events | $\sigma_1$ (tr/pl) | $\sigma_3$ (tr/pl) | Axial ratio $((\sigma_2-\sigma_3)/(\sigma_1-\sigma_3))$ |
|---|---|---|---|---|
| NNE-SSW | 6 | 320/47 | 61/10 | 0.14 |
| ENE-WSW | 12 | 332/24 | 241/3 | 0.38 |

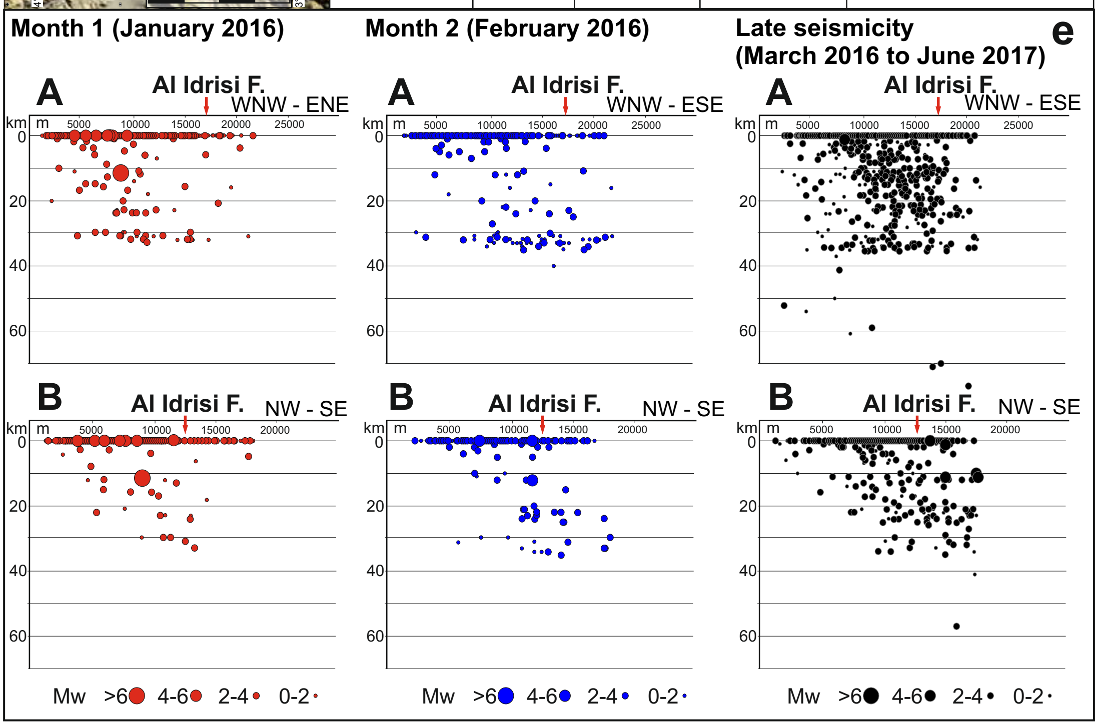
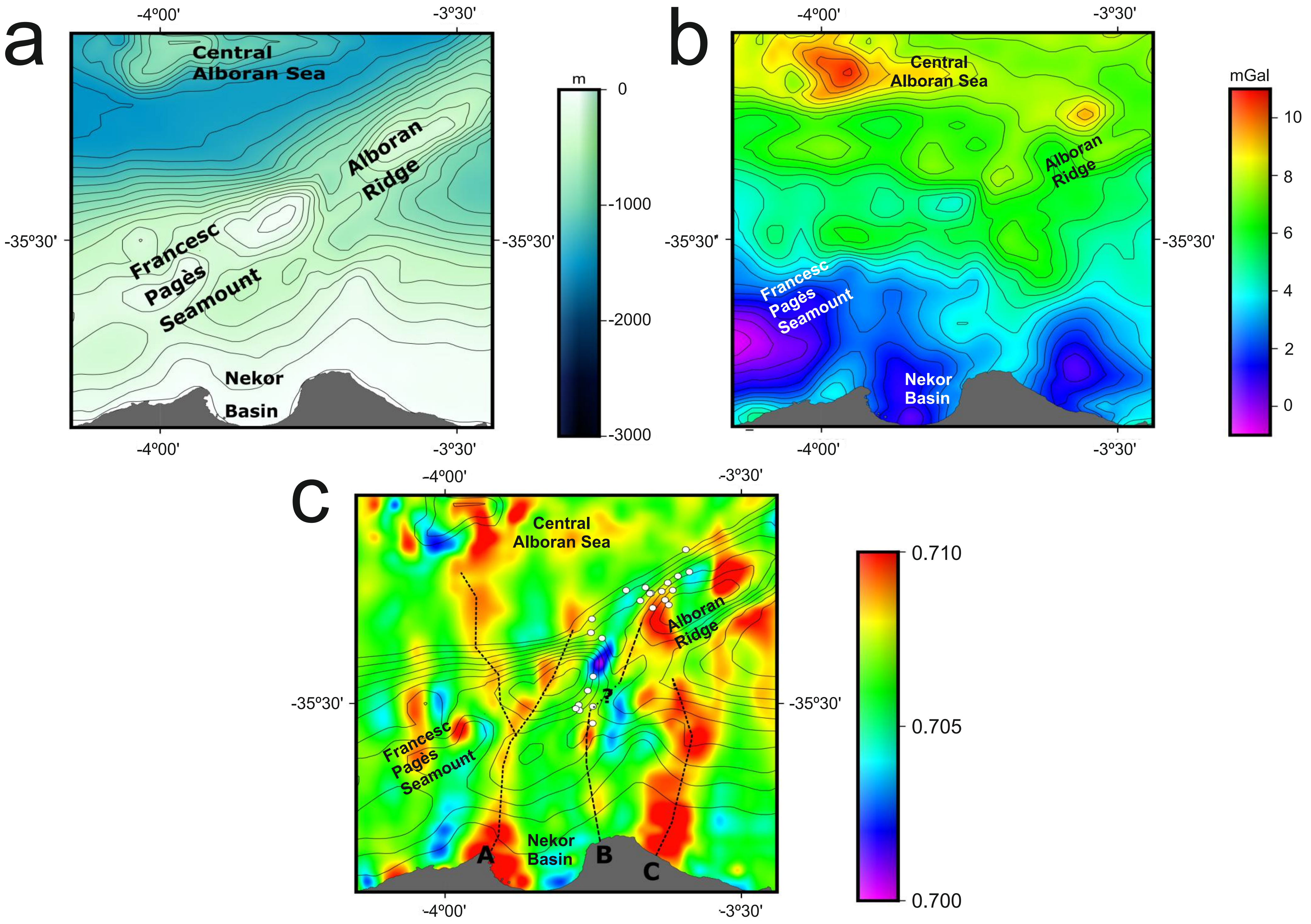
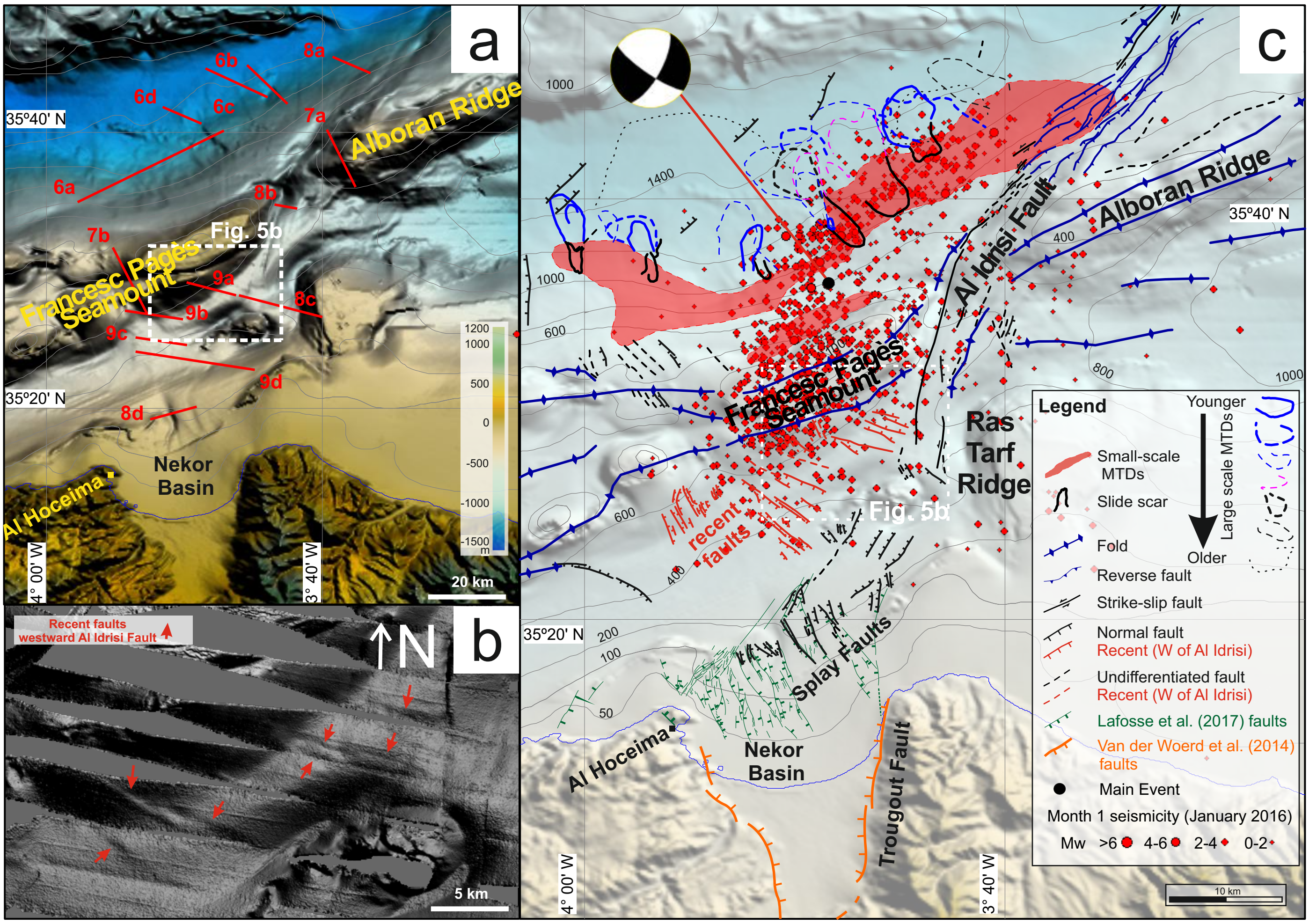


**Fig. 4.**



a
-4º00'
-3º30'
Central
Alboran Sea
Alboran
Ridge
Francesc
Pagès
Seamount
Nekor
Basin
-35º30'
m
0
-1000
-2000
-3000
b
Central
Alboran Sea
Alboran
Ridge
Francesc
Pagès
Seamount
Nekor
Basin
mGal
10
8
6
4
2
0
c
Central
Alboran Sea
Alboran
Ridge
Francesc
Pagès
Seamount
Nekor
Basin
A
B
C
?
0.710
0.705
0.700

**Fig. 5.**



a
b
c
Alboran Ridge
Francesc Pages Seamount
Fig. 5b
Nekor Basin
Al Hoceima
35°40' N
35°20' N
4° 00' W
3° 40' W
20 km
5 km
Recent faults westward Al Idrisi Fault
N
Al Idrisi Fault
Ras Tarf Ridge
recent faults
Splay Faults
Trougout Fault
Legend
Small-scale MTDs
Slide scar
Fold
Reverse fault
Strike-slip fault
Normal fault
Recent (W of Al Idrisi)
Undifferentiated fault
Recent (W of Al Idrisi)
Lafosse et al. (2017) faults
Van der Woerd et al. (2014) faults
Main Event
Month 1 seismicity (January 2016)
Mw >6 4-6 2-4 0-2
Younger
Older
Large scale MTDs
10 km

**Fig. 6.**

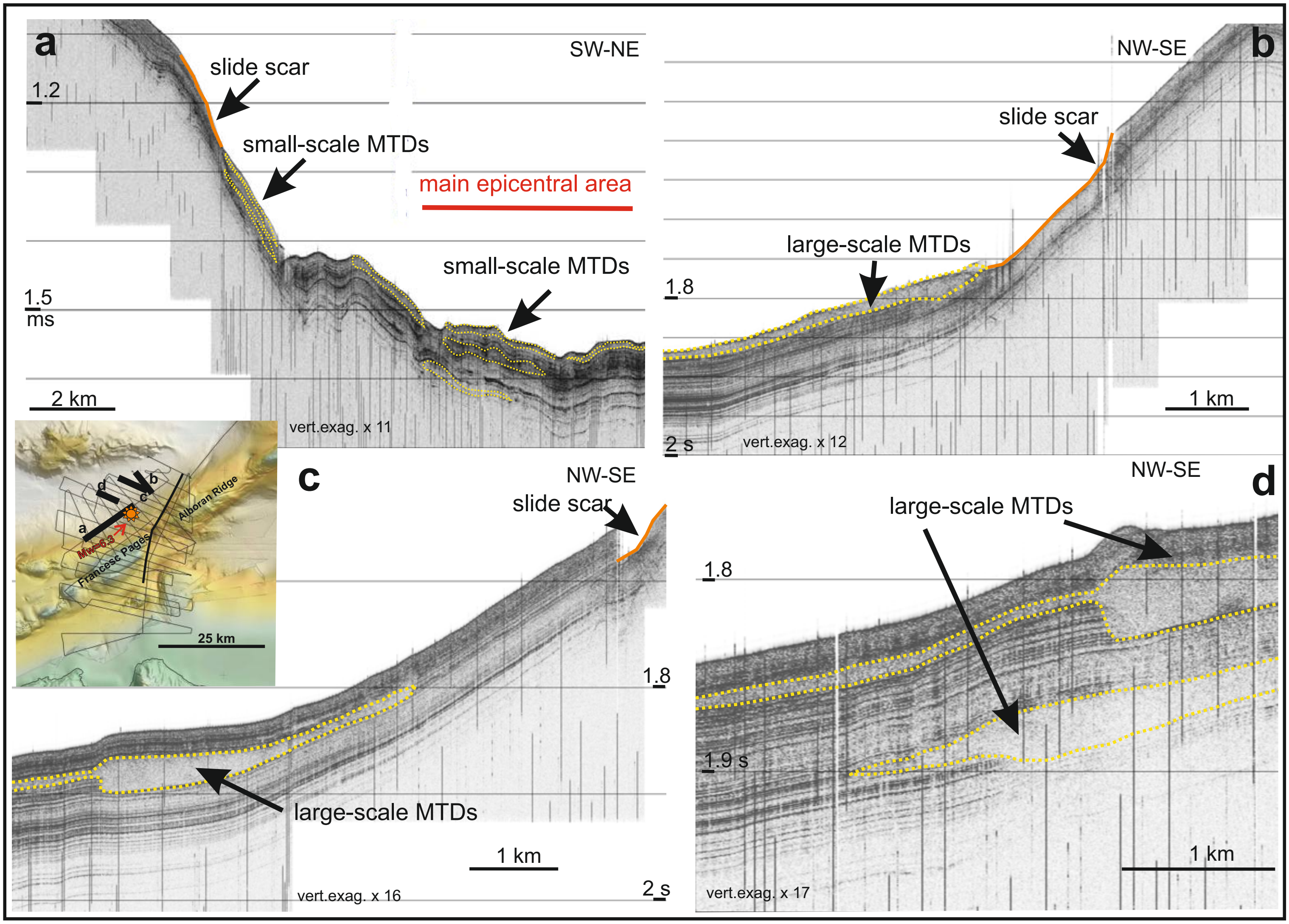

a
SW-NE
slide scar
1.2
small-scale MTDs
main epicentral area
small-scale MTDs
1.5
ms
2 km
vert.exag. x 11
b
NW-SE
slide scar
large-scale MTDs
1.8
1 km
2 s
vert.exag. x 12
c
NW-SE
slide scar
Alboran Ridge
Francesc Pages
Mw=6.3
25 km
1.8
large-scale MTDs
1 km
vert.exag. x 16
2 s
d
NW-SE
large-scale MTDs
1.8
1.9 s
1 km
vert.exag. x 17

**Fig. 7.**

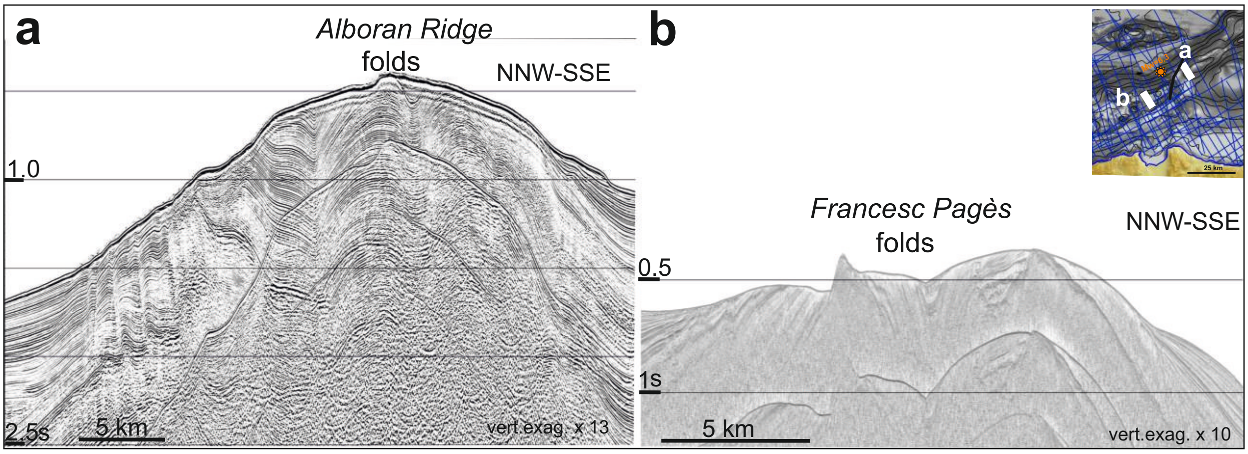

a
Alboran Ridge
folds
NNW-SSE
1.0
2.5s
5 km
vert.exag. x 13
b
a
b
Francesc Pagès
folds
NNW-SSE
0.5
1s
5 km
vert.exag. x 10

**Fig. 8.**

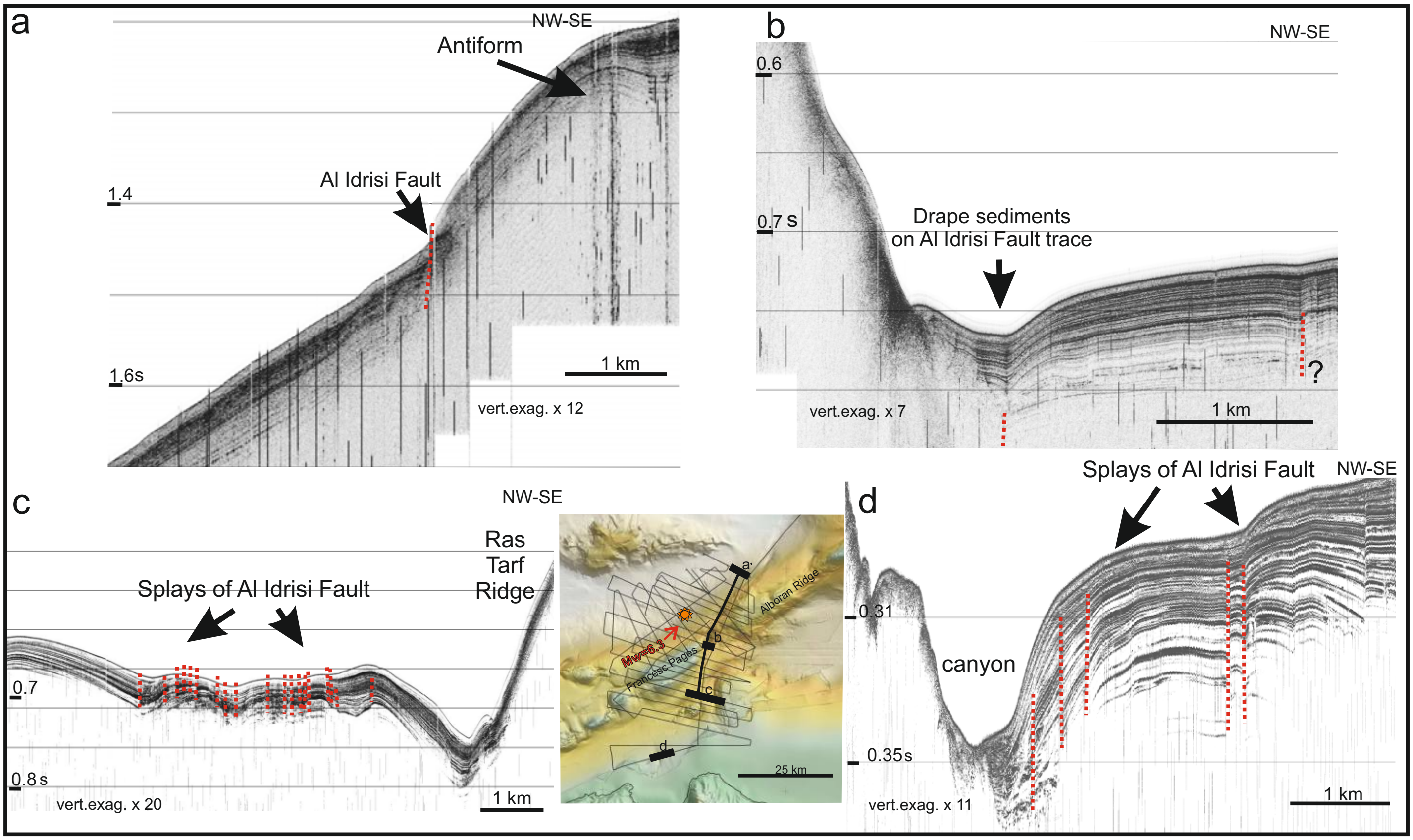

a
NW-SE
Antiform
Al Idrisi Fault
1.4
1.6s
1 km
vert.exag. x 12
b
NW-SE
0.6
0.7 s
Drape sediments
on Al Idrisi Fault trace
?
vert.exag. x 7
1 km
c
NW-SE
Ras
Tarf
Ridge
Splays of Al Idrisi Fault
0.7
0.8 s
vert.exag. x 20
1 km
a
b
c
d
Alboran Ridge
Francesc Pagès
Mw=6.3
25 km
d
Splays of Al Idrisi Fault
NW-SE
0.31
canyon
0.35s
vert.exag. x 11
1 km

**Fig. 9.**

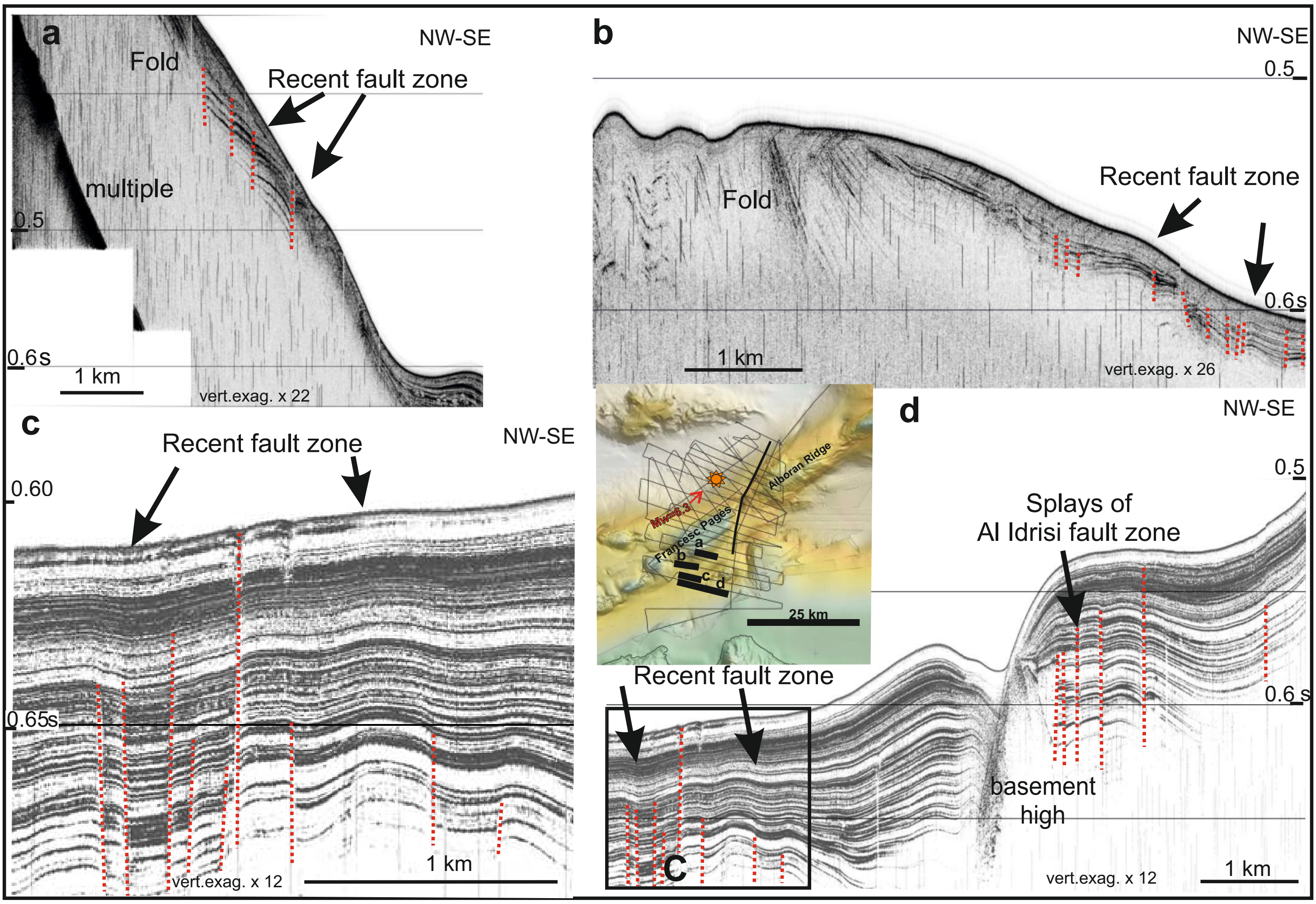
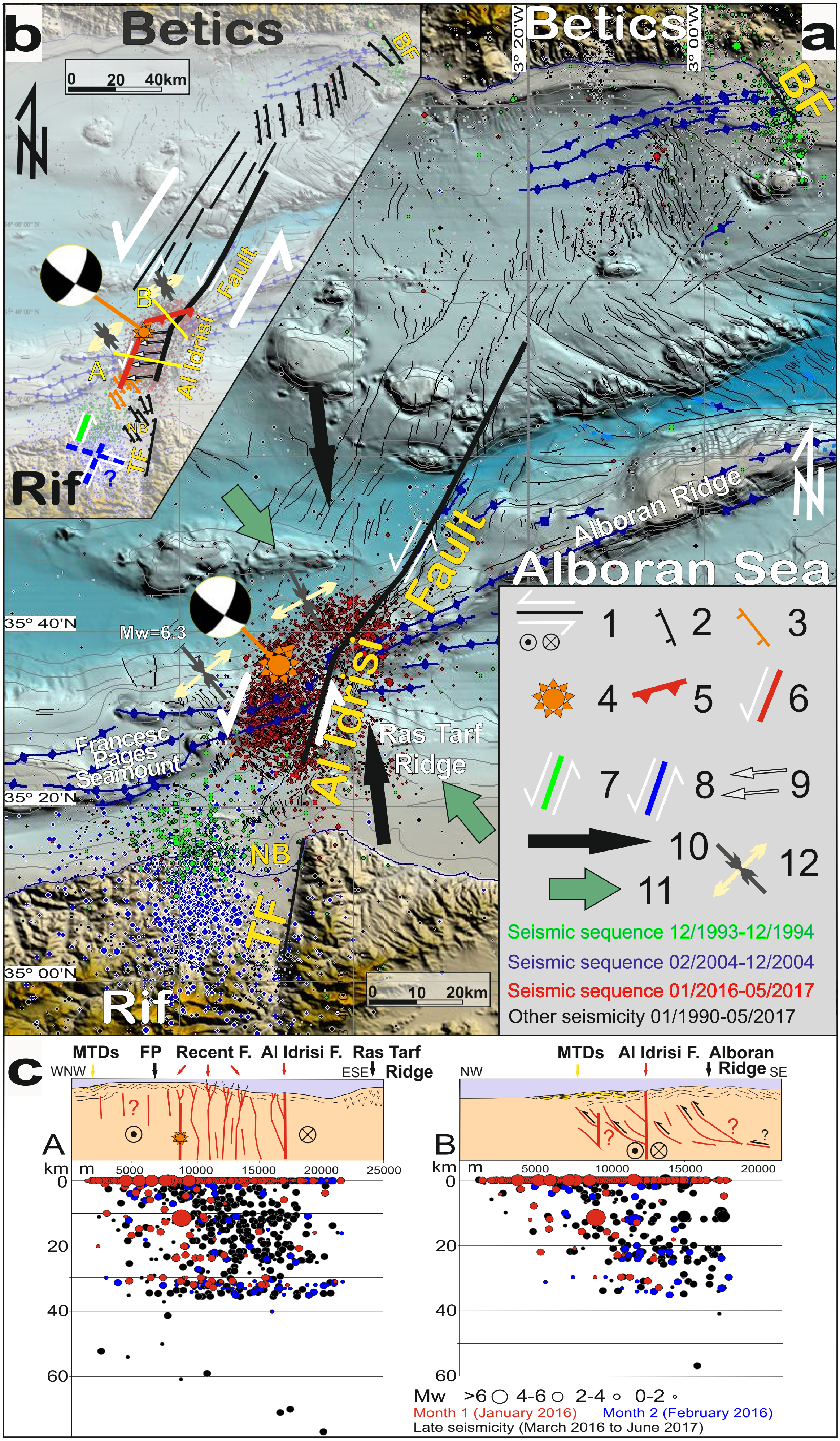

a
Fold
NW-SE
Recent fault zone
multiple
0.5
0.6s
1 km
vert.exag. x 22
b
NW-SE
0.5
Fold
Recent fault zone
0.6s
1 km
vert.exag. x 26
c
Recent fault zone
NW-SE
0.60
0.65s
vert.exag. x 12
1 km
Mw6.3
Alboran Ridge
Francesc Pages
25 km
d
NW-SE
0.5
Splays of
Al Idrisi fault zone
0.6 s
Recent fault zone
basement
high
C
vert.exag. x 12
1 km

**Fig. 10.**



b
Betics
0 20 40km
Al Idrisi Fault
A
B
NB
TF
Rif
a
Betics
3° 20'W
3° 00'W
BF
Alboran Ridge
Alboran Sea
Fault
Al Idrisi
Mw=6.3
35° 40'N
35° 20'N
35° 00'N
Francesc Pages Seamount
Ras Tarf Ridge
NB
TF
Rif
0 10 20km
1 2 3 4 5 6 7 8 9 10 11 12
Seismic sequence 12/1993-12/1994
Seismic sequence 02/2004-12/2004
Seismic sequence 01/2016-05/2017
Other seismicity 01/1990-05/2017
c
MTDs FP Recent F. Al Idrisi F. Ras Tarf Ridge
WNW ESE
A
km m 5000 10000 15000 20000 25000
0 20 40 60
MTDs Al Idrisi F. Alboran Ridge
NW SE
B
km m 5000 10000 15000 20000
0 20 40 60
Mw >6 4-6 2-4 0-2
Month 1 (January 2016) Month 2 (February 2016)
Late seismicity (March 2016 to June 2017)