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

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30 **Key Points:**

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

33 Epicentral seabottom deformations include mass transport deposits and recent
34 faults.

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

37

38 **Abstract**

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

63

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

66

67 **1. Introduction**

68 Continuous plate motion has led to the activity of tectonic structures
69 developed along plate boundaries, including faults with related seismicity.
70 Seismic or creep behaviour of a fault is constrained by the rheology of the
71 deformed rocks (Sibson, 1977). Brittle deformation is generally accommodated
72 by previous fractures because the low cohesion with respect to the undeformed
73 host rock causes them to be more easily reactivated (Anderson, 1951; Bott,
74 1959). When deformation propagates, the growth of fault zones is produced by
75 stress concentrations at the boundaries of previous fault surfaces (Scholz,
76 1989) and the larger the fault, the higher the magnitude of the related
77 earthquakes (Wells & Coppersmith, 1994). The activity of a fault requires the
78 shear stress on its surface to exceed the values of cohesion and friction
79 (Hajiabdolmajid et al., 2002). On a fault surface, the cohesion is low and needs
80 lower shear stresses than on the new developing fault segments at the edge of
81 the previous fault (Hajiabdolmajid et al., 2002). Thus, the propagation of a fault
82 in unfractured resistant rocks can imply a high accumulation of elastic energy
83 that may generate earthquakes of magnitudes higher than those triggered by a
84 reactivation of previous fractures.

85 The Eurasian-African plate boundary in the Alboran Sea (westernmost
86 Mediterranean) offers a unique research opportunity in a natural example that

87 can provide insights as to the propagation of fault zones (Cowie & Scholz,
88 1992) (Fig. 1). The Alboran Basin is a Neogene-Quaternary extensional basin
89 located within the Betic (Spain)-Rif (Morocco) alpine cordilleras, connected by
90 the Gibraltar Arc (Andrieux et al., 1971). The major Trans-Alboran Shear zone
91 (Larouzière et al., 1988; Frasca et al., 2015) accommodated the westward
92 displacement of the Betic-Rif orogen during the development of the Gibraltar
93 Arc. The Alboran Basin is floored by a thin continental crust made up of the
94 alpine Internal Zone metamorphic complexes, with a Variscan basement
95 located in the southeastern area (Ammar et al., 2007) resting above an
96 anomalous mantle (Hatzfeld, 1976; Comas et al., 1992). The sedimentary infill
97 consists of unconformable Miocene to Quaternary deposits (Comas et al., 1992;
98 Juan et al., 2016). This sedimentary record is mostly deformed by two
99 conjugated sets of dextral WNW-ESE and sinistral NE-SW faults, and folded by
100 ENE-WSW oriented folds (Estrada et al., 2018; Martínez-García et al., 2017),
101 the Alboran Ridge and Francisc Pagès seamount, pertaining to the main
102 antiforms (Bourgeois et al., 1992). The growth of faults and folds takes place in
103 the framework of recent NNW-SSE shortening, and regional Eurasian-African
104 plate convergence (de Mets et al., 2015). The Eurasian-African plate boundary
105 shows N-S to NW-SE convergence at present (Fadil et al., 2006; Koulali, 2011;
106 Palano et al., 2015), at a rate of 4.93 mm/yr (Argus et al., 2010). Regional
107 present-day ENE-WSW extensional stress is coeval with orthogonal
108 compression and main stress axes are inclined (de Vicente et al., 2008; Stich et
109 al., 2010).

110 The Betic-Rif Cordillera and Alboran Sea are affected by a 300 km broad
111 and heterogeneous seismicity band related to the Eurasian-African plate

112 boundary (Bufoin et al., 1988). Seismicity generally occurs at shallow crustal
113 levels (Bufoin et al., 1995). Intermediate seismicity (40 to 120 km deep) is
114 mainly located along a N-S elongated band in the western Alboran Basin that
115 becomes NE-SW northwards (Morales et al., 1999; López-Casado et al., 2001;
116 Bufoin et al., 2017; Medina & Cherkaoui, 2017). Deep seismicity (600 to 640 km
117 deep) is scarce but also occurs beneath the central Betic Cordilleras (Bufoin et
118 al., 1991, 2011). The area has heterogeneous local stresses probably due to
119 fault interaction (Stich et al., 2010).

120 Several geodynamic models have been proposed for the region,
121 including delamination (e.g. Seber et al., 1996; Lis Mancilla et al., 2013), or
122 subduction with or without rollback (e.g. Pedrera et al., 2011; Ruiz-Constán et
123 al., 2011; Gutscher et al., 2012; González-Castillo et al., 2015; Spakman et al.,
124 2018), yet discussion remains alive. Moreover, in the central and eastern
125 Alboran Sea, the recent fault system mainly composed by two conjugate WNW-
126 ESE dextral and NNE-SSW sinistral fault sets evidences the activity of
127 continental indentation tectonics (Estrada et al., 2018). Within this structural
128 framework, a present-day zone of deformation with high seismic activity
129 crossing the Alboran Sea —from Al Hoceïma in the Rif to Adra and Cabo de
130 Gata in the Betics— (Fig. 1) oblique to the previous Trans-Alboran Shear zone
131 (Larouzière et al., 1988) has been proposed to be a main plate boundary (Fadil
132 et al., 2006; Grevemeyer et al., 2015). However, relationships with the main
133 tectonic structures observed in the seafloor have not yet been analysed in
134 detail. The few available studies (Martínez-García et al., 2013; 2017 and
135 references herein; Estrada et al., 2018) suggest that the NNE-SSW sinistral Al
136 Idrisi Fault is the main structure with recent and present-day activity in the

137 southern Alboran Sea (Fig. 1). This fault is connected onshore with the
138 Trougout Fault in the Al Hoceima region (Morocco margin), which bounds the
139 Nekor Basin (d'Acremont et al., 2014; Lafosse et al., 2017) and its propagation
140 towards the Rif is discussed by Galindo-Zaldívar et al. (2009; 2015a) and Poujol
141 et al. (2014). The Al Hoceima region is deformed mainly by faults that determine
142 a succession of horsts and grabens, probably developed above crustal
143 detachments (Galindo-Zaldívar et al., 2009; 2015a). In the northern Alboran
144 Sea, the fault zone extends onshore toward the Campo de Dalías area,
145 connecting with the Balanegra Fault in the boundary of the Betic Cordillera and
146 Alboran Sea (Marín-Lechado et al., 2010).

147 January 25, 2016, marked the onset of a seismic sequence in the
148 central-southern Alboran Sea (www.ign.es), with a main shock of $M_w=6.3$ (Figs.
149 1 and 2), and whose activity continues up to 2017. The area affected extends
150 from the Francesc Pagès seamount and westernmost Alboran Ridge to the
151 Nekor Basin. The main earthquake was felt in several coastal cities of northern
152 Morocco and southern Spain, causing economic losses in both countries
153 (http://www.ign.es/resources/noticias/Terremoto_Alboran.pdf). The earthquakes
154 of this seismic sequence have been analysed in detail by the IGN (www.ign.es),
155 Bufo et al. (2017), Medina and Cherkaoui (2017) and Kariche et al. (2018).
156 They consider different velocity models for epicentre locations, suggesting that
157 activity occurred in the area nearby Al Idrisi Fault; yet they do not compare their
158 results with the more accurate position of this fault obtained by marine
159 geophysical research (Martínez-García et al., 2013; 2017; Estrada et al., 2018;
160 Lafosse et al., 2017). The comparison of seismological and marine geophysical

161 researches clearly shows that the epicentres of the earliest stage of the
162 sequence are located to the west of the Al Idrisi Fault.

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

169

170 **2. Methodology and data**

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

175

176 **2.1. Regional GPS data**

177 Permanent GPS stations surrounding the central Alboran Sea served as
178 the reference for present-day deformation in the region. MALA and ALME
179 stations (respectively by Malaga and Almeria) along the Betic Cordillera coast,
180 and MELI (by Melilla) on the African coast, time series were obtained from the
181 EUREF permanent Network. Data were considered up to June 2017, and these
182 stations were in operation: ALME since 2001; MALA since 2005 and MELI

183 since 2012. GNSS data were processed by means of Bernese Software to
184 determine the displacement vectors.

185

186 2.2. Seismicity data

187 The seismicity database of the Spanish National Geographic Institute
188 (IGN) (www.ign.es) registered the 2016-17 seismic sequence as well as the two
189 previous main seismic series, in 1993-94 and 2004. The 2004 seismic
190 sequence was carefully relocated by Van der Woerd et al. (2014). As the
191 precise location of seismicity is sensitive to velocity models and to the distance
192 of the seismic stations (Michelini & Lomax, 2004), literature (Buforn et al. 2017,
193 Medina & Cherkaoui, 2017, Kariche et al. 2018) shows a non-coincident
194 location for the 2016-17 seismic sequence' epicentres. The 1993-94 and 2016-
195 17 seismic sequences' epicentre and hypocentre locations were calculated
196 through a standard procedure considering the first arrivals of P and S waves
197 and a standard velocity model (Carreño-Herrero & Valero-Zornoza, 2011). A
198 careful relocation of the main events was provided by Buforn et al. (2017) and
199 the IGN (IGN, 2016; www.ign.es) in light of the standard and recent velocity
200 model (El Moudnib et al., 2015). Earthquake focal mechanisms were also
201 obtained from the IGN database (www.ign.es), established from first arrival P-
202 wave polarity. The present-day stress tensor was determined from seismicity
203 using the method by Michael (1984), improved by Vavryčuk (2014).

204

205 2.3. Marine geophysics

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

219 Simultaneously with multibeam bathymetry, very high resolution seismic
220 profiles were acquired with the SIMRAD TOPAS PS18 system (frequencies of
221 18 kHz - 1 to 6 kHz). In addition to this information, multi- and single-channel
222 seismic records from the Instituto de Ciencias del Mar-CSIC database
223 (<http://gma.icm.csic.es/sites/default/files/geoweb/OLsurveys/index.htm>) were
224 considered (Fig. 1c). All seismic profiles were integrated into a Kingdom Suite
225 project (IHS Kingdom) for their correlation and interpretation. Likewise, gravity
226 data were obtained during the INCRISIS cruise using a Lockheed Martin BMG3
227 marine gravimeter with a precision of 0.7 mGal. Gravity Free air and Complete
228 Bouguer anomalies were determined considering a standard density of 2.67
229 g/cm³. To extend the gravity anomalies to the shoreline we used the global free

230 air dataset from Sandwell et al. (2014). Directional filters (horizontal gravity
231 gradient) were applied in order to analyse the main tectonic structures.

232

233 **3. Results**

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

241

242 3.1. Present-day Alboran Sea shortening from GPS data and plate deformation

243 Deformation within the Alboran Sea is driven in part by the NW-SE
244 regional convergence of the Eurasian and African plates (de Mets et al., 2015).
245 The west to west-southwestward motion of the Betic-Rif Alboran block (Koulali
246 et al., 2011; Palano et al., 2015) may also be the result of ongoing slab rollback
247 towards the west (Pedrera et al., 2011; Ruiz-Constán et al., 2011; Gutscher et
248 al., 2012; González-Castillo et al., 2015; Spakman et al., 2018), which would
249 explain the E-W to ENE-WSW extensional focal mechanisms observed in the
250 West Alboran Sea (Stich et al., 2010). At present, the GEODVEL plate model
251 (Argus et al., 2010) indicates a N141°E trend of convergence at a rate of 4.93
252 mm/yr in this region, supported by regional GPS data (Fadil et al., 2006). This
253 regional deformation produces a NNW-SSE shortening which, in the central part

254 of the Alboran Sea, may be constrained by the MALA and ALME stations in
255 Spain, and by MELI station in Morocco (Fig. 1). The higher rates of MALA
256 station with respect to ALME evidence ENE-WSW extension in the Betic
257 Cordillera (Galindo-Zaldivar et al., 2015b). The southern displacement of ALME
258 and MALA stations relative to the European plate contrasts with the northern
259 displacement of MELI, supporting present-day shortening in the central Alboran
260 Sea. The most intensely seismic area in 2016-17 is located in between MALA
261 and MELI stations, with a relative NNW-SSE (N173°E) shortening of 3.3 mm/yr.

262

263 3.2. Recentmost seismic sequence

264 A seismic zone of intense activity affects the central Alboran Sea, from
265 the Campo de Dalías region in the north, to the Al Hoceima region in the south
266 (Figs. 1 and 2), it being most intense at the southern end (Grevemeyer et al.,
267 2015). The most recent seismic sequences were in 1993-94, 2004 and 2016-
268 2017 (Fig. 2). The 1993-94 seismic sequence affected the coastal region
269 nearby Al Hoceima, with a main earthquake of $M_w=5.6$ (May 26, 1994), after an
270 earlier earthquake in the Campo de Dalías area, of $M_w= 5.3$ (Dec 23, 1993). In
271 2004, another seismic sequence with a devastating earthquake event of $M_w=$
272 6.4 (Feb 24) occurred onshore in the Al Hoceima region causing nearly 600
273 deaths and with aftershocks reaching the Alboran Sea (Van der Woerd et al.,
274 2014). Earthquake focal mechanisms were very similar in all cases, pointing
275 mainly to sinistral strike-slip along the NNE-SSW oriented deformation zone (El
276 Alami et al., 1998; Stich et al., 2006, 2010), although also possible is the activity

277 of WNW-ESE dextral faults in the 2004 sequence that affect Al Hoceima
278 onshore areas (Akoglu et al., 2006; Van der Woerd et al., 2014).

279 The 2016-17 seismic sequence (Figs. 2 and 3) was initiated by a
280 moderate earthquake (Jan 21, 2016, Mw=5.1) followed closely by a stronger
281 event (Jan 25, Mw= 6.3) and by a long seismic series of decreasing activity
282 during 2016-17 (Buforn et al., 2017; Medina & Cherkaoui, 2017; Kariche et al.,
283 2018). The relatively long distances from hypocentres to seismic stations,
284 generally greater than 50 km and in some cases reaching more than 80 km,
285 decreases the quality of earthquake locations. Buforn et al. (2017) recognize
286 average horizontal errors of 5 km and vertical errors of 10 km, comprised
287 between 2 to 10 km horizontally and 3 to 17 km vertically. The location of 2016-
288 17 seismic activity established by the IGN standard terrain velocity model
289 (Carreño-Herrero & Valero-Zornoza, 2011) (Figs. 2a and 3) or El Moudnib et al.
290 (2015) velocity model (Fig. 2b) shows a deformation band with two alignments,
291 the main one, oriented NNE-SSW, changing sharply to a ENE-WSW trend.
292 Considering the IGN standard terrain velocity model (Carreño-Herrero & Valero-
293 Zornoza, 2011) (Figs. 2a and 3), the NNE-SSW alignment is about 40 km in
294 length and 10-20 km wide, and includes shallow earthquakes (< 35 km depth)
295 that affect the crust and upper mantle. It is parallel and significantly displaced
296 westwards (up to 10 km) with respect to the Al Idrisi Fault (Fig. 2). The ENE-
297 WSW alignment, about 20 km long and 10-15 km wide, is located along the
298 northern side of the westernmost Alboran Ridge and the Francesc Pagès
299 seamount, and is also characterized by a shallow seismicity (< 35 km). During
300 month 1 (Jan 2016), the seismicity clearly defines the two alignments with
301 widths of less than 10-20 km, the main southern one being displaced 5 to 10 km

302 westwards with respect to the trace of the main Al Idrisi Fault (Figs. 2 and 3a).
303 During month 2 (Feb 2016), seismic activity decreases and both alignments
304 become wider (10-20 km) (Fig. 3b). Then, from month 3 (March 2016) to
305 present, seismicity gradually decreased and affected a broader area, more than
306 15-25 km wide (Fig. 3c), in between the one clearly defined in month 1, and
307 bounded eastward by the main trace of Al Idrisi Fault. Bufo et al. (2017)
308 relocate the earthquakes considering El Moudnib et al. (2015) velocity model
309 and also obtain the same pattern formed by two alignments, the NNE-SSW with
310 a westward offset with respect to the Al Idrisi Fault seafloor location.

311 The earthquake focal mechanisms of the two seismicity alignments show
312 different behaviours (Fig. 3d). The main NNE-SSW alignment is characterized
313 by sinistral earthquake focal mechanisms related to NNE-SSW subvertical
314 faults, roughly parallel to the elongation of the alignment. There is also
315 heterogeneity of earthquake focal mechanisms with inclined P and T axes and
316 normal faults, supporting ENE-WSW extension toward the southern deformation
317 zone. In contrast, the ENE-WSW alignment is characterized by highly
318 homogeneous reverse earthquake focal mechanisms associated with ENE-
319 WSW faults. Present-day stress (Fig. 3) supports low NNW (N319°E to N332°E)
320 inclined compression and orthogonal horizontal extension in both segments
321 linked to prolate stress ellipsoids. Inclination is higher (47°) in the main
322 alignment and its axial ratio is closer to triaxial stress.

323

324 3.3. Deep structure from gravity data

325 Bouguer complete gravity anomalies decrease in the Alboran Sea, from
326 110 mGal to 30 mGal, in a smooth transition from the east to the west up to
327 4.5°W (Casas & Carbó, 1990). As the amplitude decreases, it narrows to the
328 west, so that the greatest values are located in the central part.

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

342

343 3.4. Recent and active near-surface tectonic and sedimentary deformations

344 The morpho-bathymetric and seismic analysis of the near-surface
345 sediments affected by the 2016-17 seismic sequence provides evidence of
346 recent and active faults, as well as folds and mass transport deposits (MTDs)
347 (Figs. 5, 6, 7, 8 and 9). MTDs are located on the northern side of the Francesc
348 Pagès seamount and Alboran Ridge, along the ENE-WSW active seismicity

349 alignment and the main earthquake (Figs. 5 and 6). Based on the thickness of
350 remobilized sediment, small-scale MTDs (a few ms thick) and large-scale MTDs
351 (tens of ms thick) were identified.

352

353 The small-scale MTDs occur mostly on the relatively steep slopes ($\sim < 5^\circ$)
354 of the northern side of both seamounts, from > 250 m to 1000 m water depth.
355 They appear as vertically stacked subtabular units (a few tens of milliseconds)
356 of unconsolidated deposits, and lenticular and irregular bodies of semi-
357 transparent, contorted and discontinuous stratified facies, separated by
358 relatively high reflectivity surfaces with local hyperbolic echoes. The strata
359 pattern suggests the recurrent nature of gravity drive transport. These facies
360 conform an irregular seafloor surface with gentle undulations (metric in scale).
361 The large-scale MTDs mainly occur seaward with respect to the previous ones,
362 and extend down to the deep basin (as much as 1450 m water depth). They are
363 related to slide scars, most of them removing the small-scale MTDs. The slide
364 scars display an amphitheatre shape (up to 1 km wide, 40 m relief) recognizable
365 at seafloor, where they extend along a fringe at the foot of the Francesc Pagès
366 seamount. Most of these MTDs are detached from the slide scars, and are
367 acoustically defined by lenticular bodies (up to 55 ms thick) internally
368 characterized by semitransparent and discontinuous stratified facies, and
369 having a distinctive irregular seafloor surface recognized bathymetrically. Their
370 acoustic character indicates disintegration of the removed mass, just after the
371 initiation of mass flow-type movement. Seismic records also provide evidence of
372 buried large-scale MTDs that interrupt and erode the surrounding basinal
373 undeformed stratified facies, suggesting the episodic nature of such slope

374 sedimentary instabilities, at least in recent geological times. Their stratigraphic
375 position points to a simultaneous occurrence of some MTDs (Fig. 6).

376 With respect to the folds, the Alboran Ridge and Francesc Pagès
377 seamount constitute the main antiformal structures deforming the region (Figs.
378 5 and 7). The ENE-WSW folds affect Miocene age deposits (Martínez-García et
379 al., 2013). The fold geometry is irregular, with variable wavelengths (km in
380 scale) and vergences (NNW or SSE). In addition, smaller-scale folds (hundreds
381 of meters in scale) are identified in relation to the Al Idrisi Fault (Fig. 8), with
382 axes oriented parallel to it.

383 The main fracture of morphological and seismic expression, deforming
384 the most recent sediments, is the sinistral Al Idrisi Fault zone (Martínez-García
385 et al., 2011, 2013, 2017) (Figs. 5 and 8). This fault has a 50 km-long northern
386 segment with N35°E trend. It develops a recent fault scarp of about 20 to 30
387 ms (15 to 23 m) at the northwestern edge of the Alboran Ridge that constitutes
388 the upthrown block (Figs. 5 and 8). In the hanging wall, small-scale MTDs are
389 recognized. The near-surface sediments in this sector are affected by folds. Al
390 Idrisi Fault changes its direction suddenly to N15°E in the area between the
391 Francesc Pagès seamount and the westernmost end of the Alboran Ridge.
392 Here, it is characterized by a sharp elongated depression covered by
393 undeformed recent sediments. The main N15°E southern segment is about 20
394 km long and extends discontinuously southward, towards the Nekor Basin in
395 relay with the Trougout Fault, forming splay faults (Lafosse et al., 2017). The
396 southern end of Al Idrisi Fault trace is located at a deformation zone with
397 smaller faults reaching the seabottom (Fig. 5). Previous research of earthquake
398 focal mechanisms (Grevemeyer et al., 2015; Martínez-García et al., 2011, 2013,

399 2017) suggests a sinistral slip on the Al Idrissi Fault NNE-SSW vertical fault
400 plane, further confirmed by the short displacement, roughly 5 km, of the
401 antiformal axis of Alboran Ridge with respect to the Francesc Pagès seamount
402 (Martínez-García et al. 2011, 2013, 2017).

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

413

414 **4. Discussion**

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

421

422 4.1. Constraining active tectonics: seismicity and seafloor deformations

423 Epicentres related to wrench faults are expected to be located along the fault
424 zone trace. Vertical nodal planes of earthquake focal mechanisms from the
425 main 2016 earthquake and most of the events in the southern Alboran Sea
426 undoubtedly evidence the vertical dip of the seismic active faults (Fig. 3), in
427 agreement with the seismological results of Buform et al. (2017). Anyway,
428 aftershock sequences can affect a wide zone (e.g. >10 km wide with respect to
429 the main fault during the Landers 1992 seismic sequence, Hauksson et al.,
430 1993) favoured by the structural complexity and pre-existing structures. In spite
431 of Buform et al. (2017) establish horizontal and vertical errors for the 2016-17
432 seismic sequence location, and Buform et al. (2017) as well as Medina and
433 Cherkaoui (2017) relate the seismicity with the Al Idrisi Fault, the careful
434 analyses of epicentre locations for most of the NNE-SSW seismicity alignment
435 (IGN, www.ign.es; Buform et al., 2017; Medina & Cherkaoui, 2017; Kariche et
436 al., 2018) points to they are displaced westwards with respect to the seafloor
437 trace of the Al Idrisi Fault determined by marine geophysical data (Martínez-
438 García et al., 2013, 2017; Estrada et al., 2018) (Figs. 2, 3 and 5). This
439 displacement of the earthquakes is higher when the standard velocity model
440 (Carreño-Herrero & Valero-Zornoza, 2011) is considered (IGN, www.ign.es;
441 Medina and Cherkaoui, 2017; Kariche et al., 2018): roughly 10 km for the first
442 stage earthquakes (Figs. 2a and 3a), as opposed to the roughly 5 km (Buform et
443 al., 2017) with the model by El Moudnib et al. (2015) (Fig. 2b). Although the
444 mislocation of earthquakes by the poorly constrained velocity models and far
445 seismic stations, may produce a westward shift of the seismicity with respect to
446 the Al Idrisi Fault, all the available seismological studies (IGN, www.ign.es;

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

453 The early earthquakes of the 2016-17 series are clearly grouped in the
454 two relatively narrow (~10-20 km wide) NNE-SSW and ENE-WSW alignments,
455 starting with the highest magnitude event ($M_w = 6.3$, Jan 25) where they join
456 (Fig. 3a). The depth of seismicity is not well constrained because of the
457 variability of crustal velocities and the few and far onshore stations; still, they
458 correspond to crustal levels (<35 km depth), in agreement with Bufo et al.
459 (2017), Medina and Cherkaoui (2017) and Kariche et al. (2018). New seismic
460 faults started to develop at shallow crustal levels (roughly 5 to 10 km depth), as
461 generally occurs in continental crust (Meissner & Strehlau, 1982). If an elliptical
462 fault surface shape is considered (Watterson, 1986), the recent fault should
463 extend in depth northward and southward into the seismogenic crustal layer.
464 When deformation propagates upwards, the triggering fault is expected to reach
465 the seafloor in the NNE-SSW epicentres alignment, due to the high dip of fault
466 plane solutions in most of the earthquake focal mechanisms. According to
467 empirical fault scaling relationships (Wells & Coppersmith, 1994), the main
468 seismic event would be related to a surface rupture between 15 and 20 km and
469 might deform the area. In the 2016-17 seismic series, a recent fault zone (10-20
470 km wide) reaching up to the seafloor was recognized in the main NNE-SSW
471 seismicity alignment, south of Francesc Pagès seamount. This recent zone

472 comprises NW-SE oriented conjugated normal faults coeval with the recent
473 sedimentation, reaching different near-surface stratigraphic levels, probably
474 rotating and connecting in depth with the major recent NNE-SSW vertical
475 sinistral fault (Fig. 10). These shallow faults accommodate the NE-SW
476 extension compatible with the activity of the main wrench fault, and are in
477 agreement with crustal thinning in the Nekor Basin confirmed by Bouguer
478 gravity anomalies (Fig. 4); they would be in line with the recent normal faults
479 described by Lafosse et al. (2017) that demonstrate that the Nekor Basin is
480 floored by a set of splay faults with normal slip component related to the
481 southern prolongation of Al Idrisi Fault.

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

493 In the ENE-WSW alignment, the morphostructural pattern and
494 deformation behaviour are different. The presence of MTDs (Figs. 5 and 6) and
495 reverse earthquake focal mechanisms (Fig. 3d), and the absence of clear
496 reverse faults affecting the near-surface, would suggest the presence of blind

497 reverse faults at the core of the Alboran Ridge antiform (Fig. 10) (Martinez-
498 Garcia et al., 2013).

499 Earthquakes may be assumed to be the main mechanism triggering the
500 MTDs, deforming the near-surface sediment of the ENE-WSW alignment (Figs.
501 5 and 6) (Casas et al., 2011). The initiation of slope failure is due to cyclic
502 loading applied on the sediment and a decreasing shear strength through the
503 development of pore overpressure. Other factors, such as tectonic deformations
504 resulting in seabed, may also contribute to increasing shear stress on the slope,
505 or a decreasing sediment strength due to shearing, dilatancy and possible
506 sediment creep (Locat & Lee, 2002).

507

508 4.2. Geodynamic implications and seismic hazard

509 The former NE-SW sinistral Trans Alboran Shear Zone (Larouzière et al.,
510 1988) constituted a main tectonic structure during the Miocene, later becoming
511 inactive and overprinted by the recent NNE-SSW deformation zone (Stich et al.,
512 2006, 2010) between Campo de Dalfas (Balanegra Fault) and the Al Hoceima
513 region (Troughout Fault), including the Al Idrisi Fault (Fig. 10). This evolution
514 reveals a progressive offset to the west and rotation of the central Alboran Sea
515 active deformation zone. The recent shear zone has incipient low deformation.
516 Al Idrisi Fault, which constitutes the longest fault in this deformation zone, has
517 short strike-slip, however. It is expressed by low interaction at the edge where
518 the Al Idrisi Fault orientation trace changes, and also by the short displacement
519 between the Alboran Ridge and Francesc Pagès seamount antiform axes (Fig.
520 10).

521 At present, seismological and GPS studies hold the active seismic zone
522 in the central Alboran Sea to be a main weak zone related to the Eurasian-
523 African plate boundary (Fadil et al., 2006; Grevemeyer et al., 2015; Palano et
524 al., 2015; Buforn et al., 2017; Medina & Cherkaoui, 2017). The fact that
525 seismicity occurred near the African coastline in 1994, with maximum
526 magnitude of $M_w = 5.6$ (May 26), and later propagated towards the continent in
527 2004 with a main event of $M_w = 6.4$ in February 24 (e.g. Akoglu et al., 2006; Van
528 der Woerd et al., 2014 and references therein) would indicate that the 2016-17
529 seismicity (main event $M_w = 6.3$) is most likely located within the same regional
530 deformation band (Figs. 2 and 10), at its northern edge. Accordingly, the recent
531 fault zone exhibits a segmented behaviour with the progressive reactivation of
532 15-20 km length stretches demonstrated by the recent seismic series (1993-94,
533 2004, 2016-17) (Buforn et al., 2017; Medina & Cherkaoui, 2017; Kariche et al.,
534 2018). In the Rif, seismic faults have rupture in depth but with no clear surface
535 expression (Galindo-Zaldívar et al., 2009 and 2015a; Van der Woerd et al.,
536 2014). Akoglu et al. (2006) and Van der Woerd et al. (2014) show that
537 seismicity onshore Al Hoceima region has been produced by the activity of
538 NNE-SSW but probably also WNW-ESE conjugated faults in NNW-SSE
539 compression and ENE-WSW orthogonal extensional stresses.

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

543 The present day stresses determined from regional seismicity studies (de
544 Vicente et al., 2008; Stich et al., 2010) agree with the data obtained in the
545 context of the 2016-17 seismic sequence (Figs. 3 and 10). The NW-SE

546 compression is prolate to triaxial, and inclined towards N319°E in the NNE-SSW
547 seismicity alignment, while N332°E in the ENE-WSW alignment, with related
548 orthogonal extension. Thus, compression is rotated in the two alignments, and
549 is compatible with sinistral fault kinematics (Fig. 10). Whereas at the Earth's
550 surface, main stresses should be horizontal or vertical due to an absence of
551 shear stress (Anderson, 1951; Bott, 1959), the inclination of main compression
552 towards the NW at crustal depths suggests activity of northwestward thrusting
553 to some extent. Moreover, this setting could be a consequence of the presence
554 of a low-deformed resistant domain attached to the African plate, here
555 corresponding to the external Rif units on the Variscan basement (Pedrera et
556 al., 2011; Galindo-Zaldívar et al., 2015a; Estrada et al., 2018).

557 There is furthermore some disagreement between the maximum
558 horizontal compression (between N139°E and N152°E) and maximum local
559 shortening (N173°E) (Fig. 10), estimated by the MALA and MELI GPS stations
560 across the seismic active area. It may be that fault activity is not due to a simple
561 strike-slip fault driven by a far field stress in the sense of Anderson (1951), but
562 could accommodate crustal block displacement. The NE-SW extension that
563 occurs towards the fault tips, at the northern edge of Campo de Dalías normal
564 faults (Marín-Lechado et al., 2005; Galindo-Zaldívar et al., 2013), is transferred
565 towards the southern edge, where normal faults splay at the Nekor Basin (Fig.
566 10) (Galindo-Zaldívar et al., 2009; Lafosse et al., 2017) and crustal thinning is
567 confirmed by gravity results (Fig. 4a).

568 The epicentres of three seismic series are located west of the main faults
569 recognized at surface, both in the Alboran Sea (Al Idrisi Fault) and in the
570 northern Rif (Troughout Fault) (Figs. 2 and 10) (Galindo-Zaldívar et al., 2009,

571 2015a; d’Acremont et al., 2014). Hence, the development of the seismic active
572 fault zone west of the well exposed Al Idrisi and Trougout faults might be
573 attributed to the growth of recent faults owing to westward migration (Vitale et
574 al., 2015) of the deformation during development of the Gibraltar Arc.

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

589 The development of active fault zones has vast implications for seismic
590 hazard. The reactivation of an existing fracture calls for shear stress on the
591 surface to attain the value of the friction and cohesion (Bott, 1959). Immediately
592 previous to the formation of new fractures, shear stress would have to be above
593 the values of friction in addition to cohesion —considerably higher (Anderson,
594 1951; Hajiabdolmajid et al., 2002). Given the same background setting, the
595 development of a recent fault zone would allow for the accumulation of higher

596 elastic deformation at the fault edges than along a well-developed previous
597 fracture. These factors determine that the propagation of a recent fault, as
598 occurs in the southern Alboran Sea, can produce earthquakes of higher
599 magnitudes than pre-existing faults. The highest magnitude earthquakes of
600 2004 (Galindo-Zaldívar et al., 2009; d'Acremont et al., 2014) and 2016-17
601 occurred in areas of recently developed fault segments with scarce evidence of
602 deformation at the surface (Fig. 10). Such faults tend to be particularly active in
603 their initial stage of development, entailing high seismic hazard, and are
604 moreover difficult to detect because of the low amount of accumulated
605 deformation due to their recent age.

606

607 **5. Conclusions**

608 The Alboran Sea 2016-17 seismic sequence constitutes a unique
609 opportunity to analyse the development of recent faults in conjunction with
610 seismic hazard. This sequence occurred in the southern part of an active
611 deformation zone crossing the central Alboran Sea and had a main event
612 ($M_w=6.3$, Jan 25, 2016) located along the corner between the NNE-SSW and
613 ENE-WSW deformation alignments, which are 10-20 km wide. The 40 km-long
614 NNE-SSW alignment is located in the Nekor Basin and Francesc Pagès
615 seamount, west of the seabottom Al Idrisi Fault trace, and the ENE-WSW one is
616 along the northern side of Alboran Ridge and Francesc Pagès seamount. Data
617 recorded during the INCRISIS cruise reveal that the ENE-WSW alignment is
618 mainly characterized by recurrent MTDs that could be linked to earthquake and
619 tectonic activity owing to uplift of the Alboran Ridge and Francesc Pagès

620 antiforms. The NNE-SSW seismicity alignment is related to deep vertical
621 sinistral faults, demonstrated by earthquake focal mechanisms, offset 5 to 10
622 km westwards from the former Al Idrisi Fault. The major NNE-SSW deep
623 sinistral fault zone responsible for the 2016-17 main events would have
624 activated fault segments up to 15 to 20 km in length for single events. The
625 INCRISIS cruise reveals evidence for recent near-surface ruptures in NW-SE
626 normal faults. These recent faults are related to the western boundary of the
627 deformation zone, bounded eastward by the Al Idrisi Fault; although it is the
628 main fault with seafloor expression, it has segments without recent activity. The
629 present-day stress from earthquake focal mechanisms of 2016-17 constrains a
630 maximum prolate to triaxial compression inclined towards N319°E in the NNE-
631 SSW alignment, and N332°E in the ENE-WSW alignment, with related
632 orthogonal extension. Stresses are oblique to the N173°E shortening
633 determined by GPS data that support sinistral slip behaviour, with some extent
634 of northwestward thrusting.

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

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

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

661

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676

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919

920 **Figure captions**

921 Fig. 1. Geological setting including regional faults and seismicity. a, Plate
922 boundaries in the Azores-Gibraltar area (modified from Galindo-Zaldívar et al.,
923 2003) and geological sketch of the main structural features and basins of the
924 Alboran Sea (modified from Comas et al., 1999). Displacement of GPS stations
925 around the Alboran Sea with respect to stable Eurasia are indicated (red
926 arrows). The dotted area within the inset indicates the deformation area. b,
927 Tracklines of multibeam, very high resolution seismics (TOPAS) and gravity
928 surveyed simultaneously during the INCRISIS cruise. c, Tracklines of single-
929 and multi-channel seismics (airguns) from the ICM database
930 (<http://gma.icm.csic.es/sites/default/files/geowebs/OLsurveys/index.htm>).

931 Legend: AF, Al Idrisi Fault; AR, Alboran Ridge; AC, Alboran Channel; BF,
932 Balanegra Fault; CD, Campo de Dalías; CG, Cabo de Gata; CF, Carboneras
933 Fault; DB, Djibouti Bank; EAB, East Alboran Basin; FP, Francesc Pagès
934 seamount; NB, Nekor Basin; NF, Nekor Fault; SAB, South Alboran Basin; TF,
935 Trougout Fault; WAB, West Alboran Basin; YF, Yusuf Fault.

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

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

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

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

968 (<http://gma.icm.csic.es/sites/default/files/geoweb/OLsurveys/index.htm>). 2016
969 seismicity from www.ign.es database.

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

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

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

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

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

992 2016-17 seismicity alignment. 7, Active NNE-SSW vertical sinistral crustal fault
993 segment related to the 1993-94 seismic crisis. 8, Active NNE-SSW vertical
994 sinistral crustal fault segment related to the 2004 seismic crisis. 9, Offset to the
995 west of recent deformation and seismicity in respect to Al Idrisi Fault. 10,
996 Estimated convergence trend from GPS data. 11, Regional plate convergence
997 trend. 12, Present-day trends of compression and extension determined from
998 earthquake focal mechanisms. FP, Francesc Pagès seamount. MTD, Mass
999 transport deposits.

1000

Fig. 1.

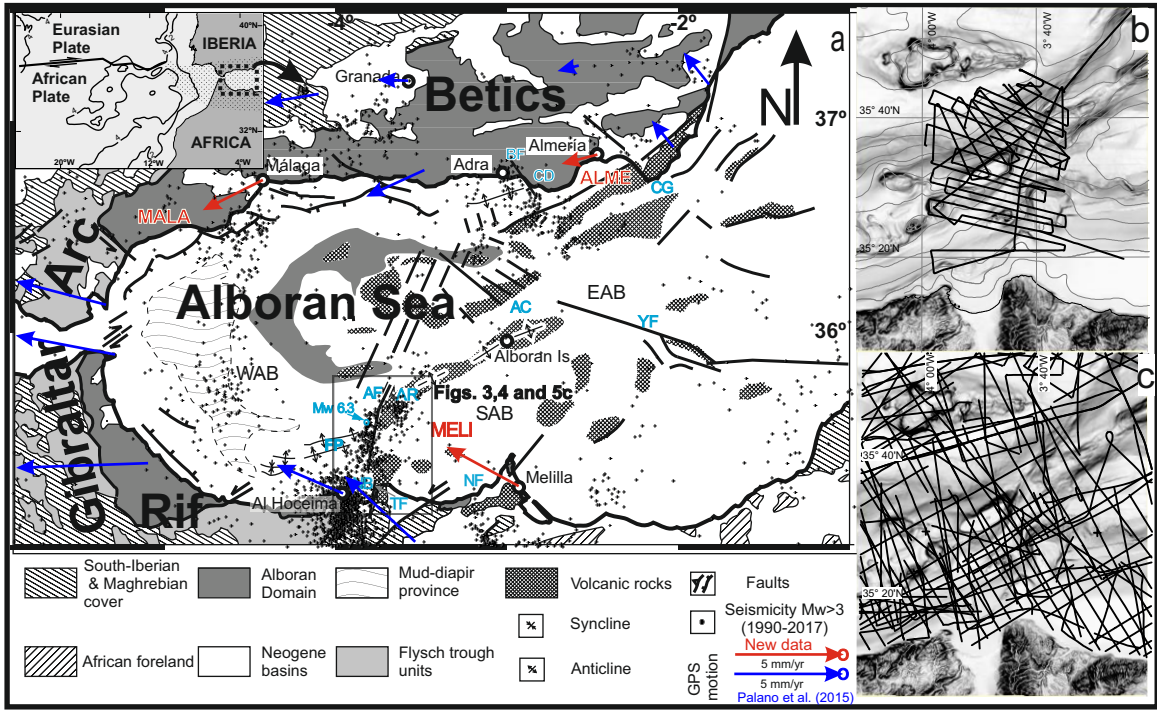


Fig. 2.

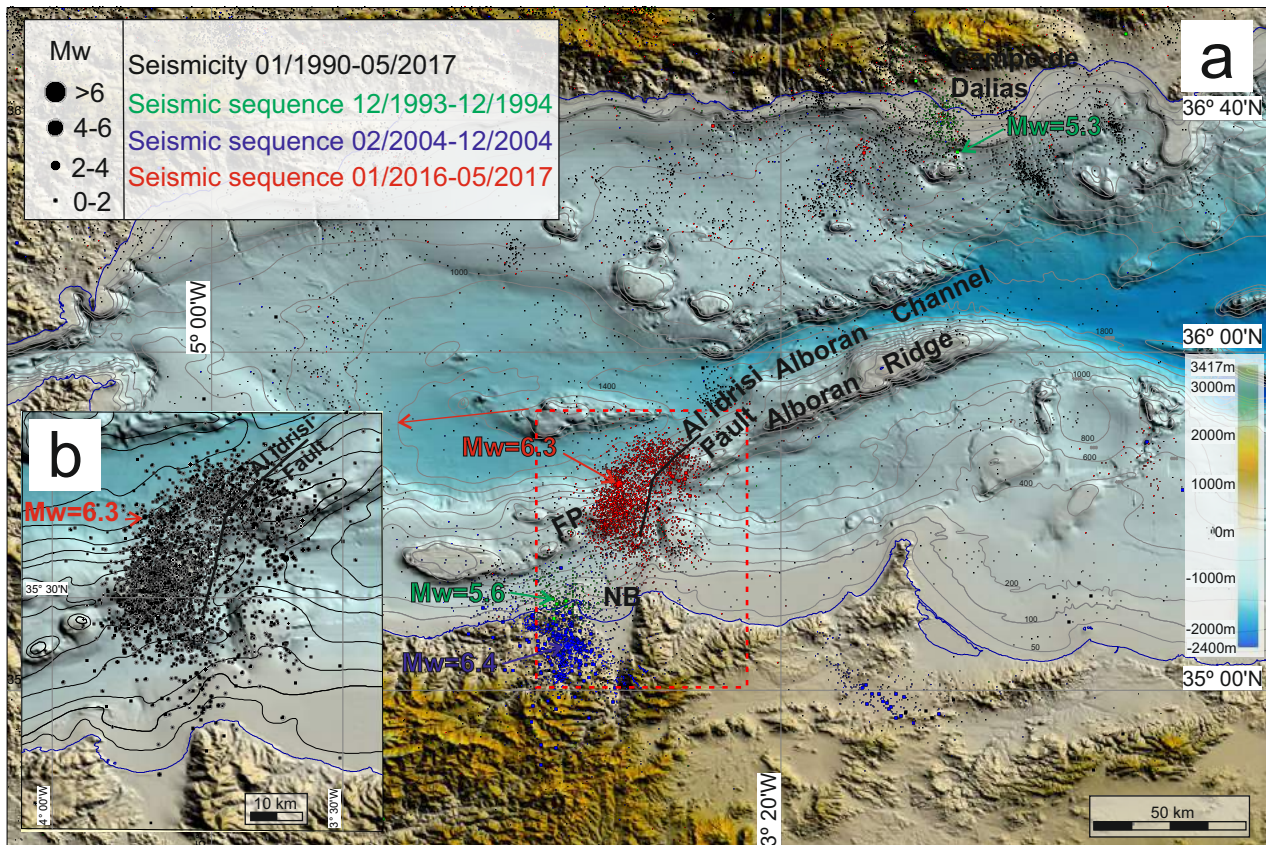


Fig. 3.

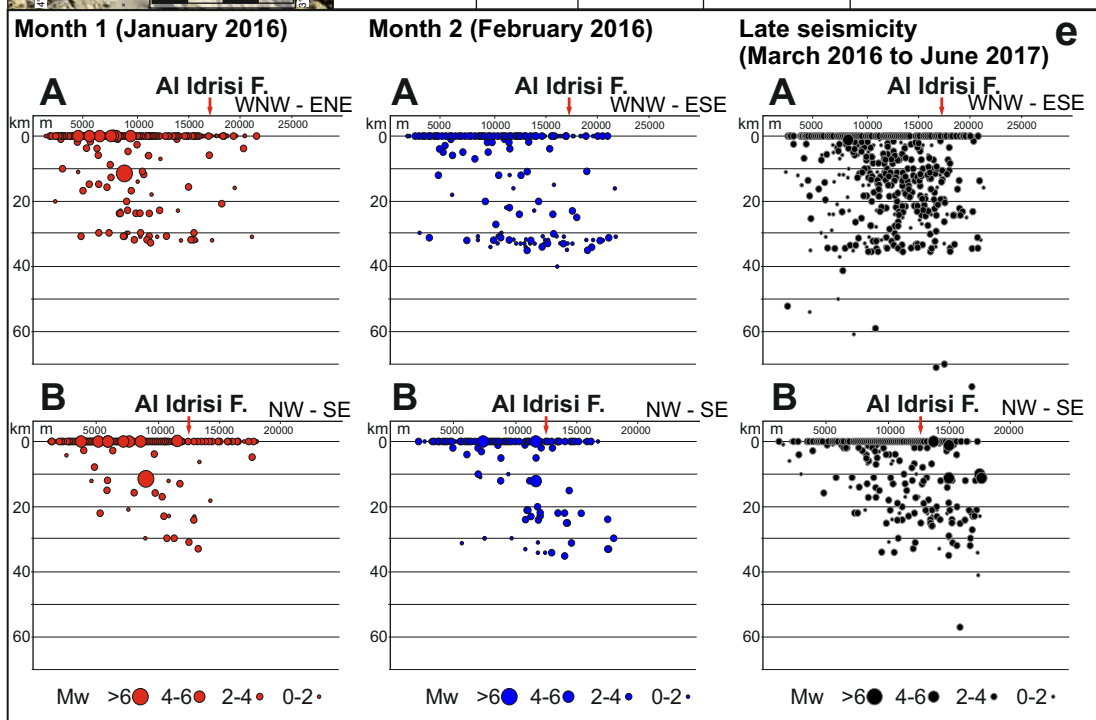
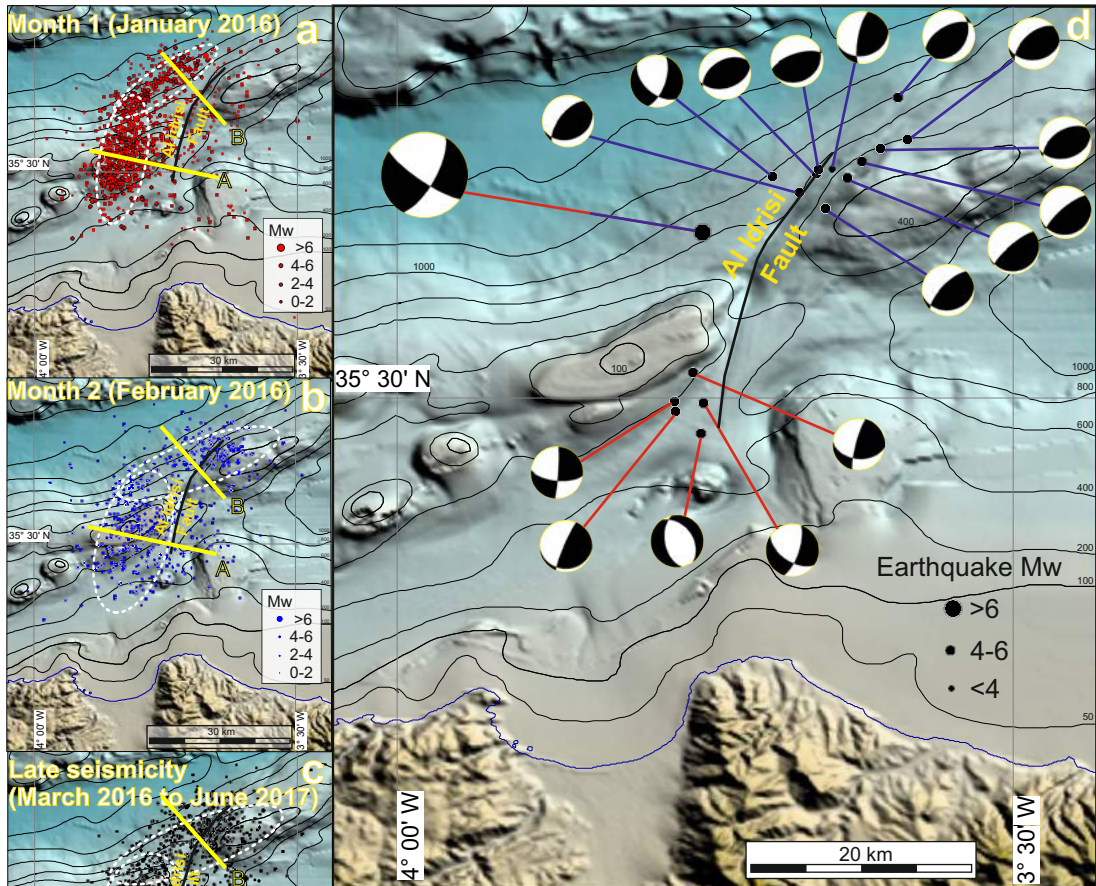


Fig. 4.

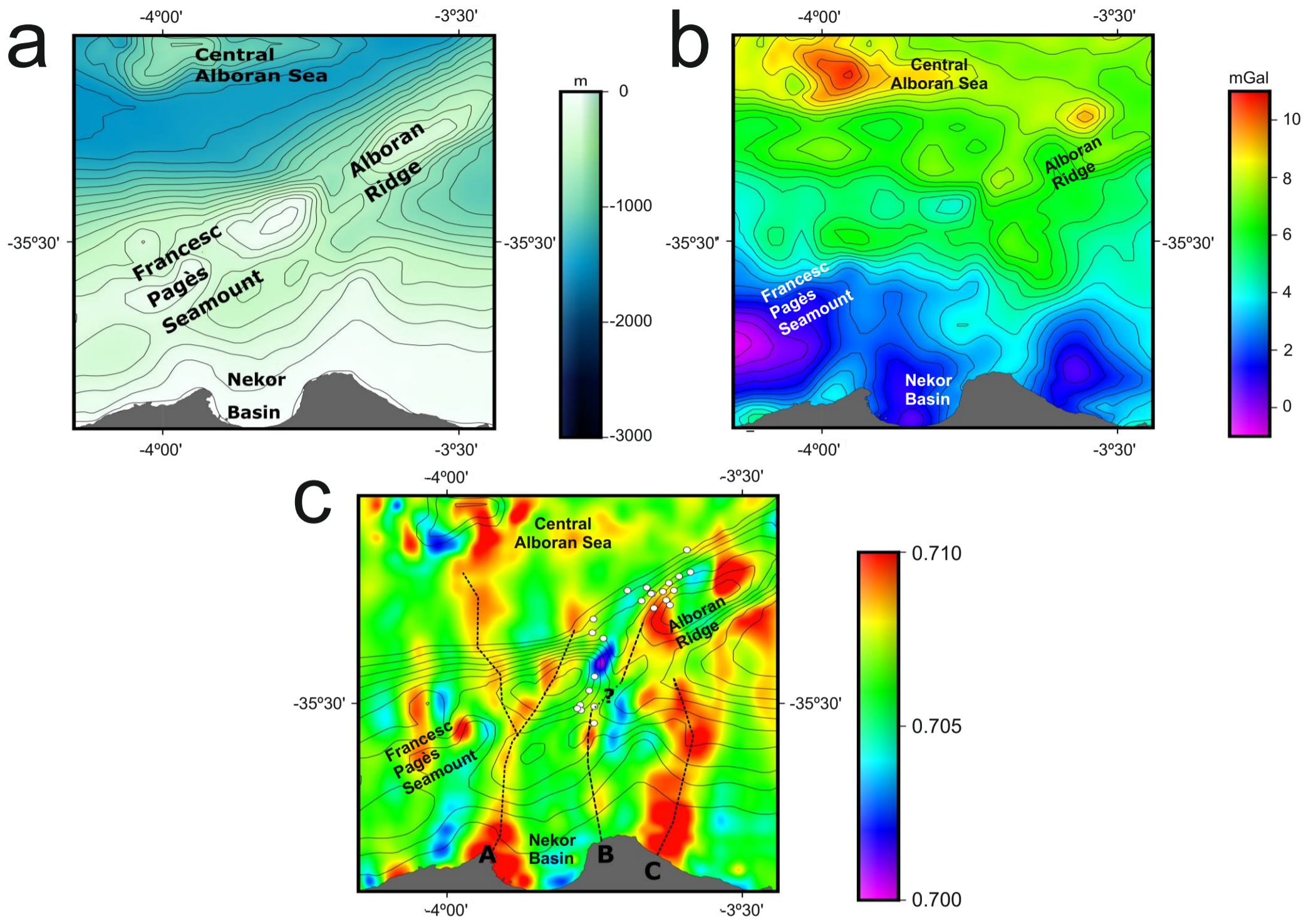


Fig. 5.

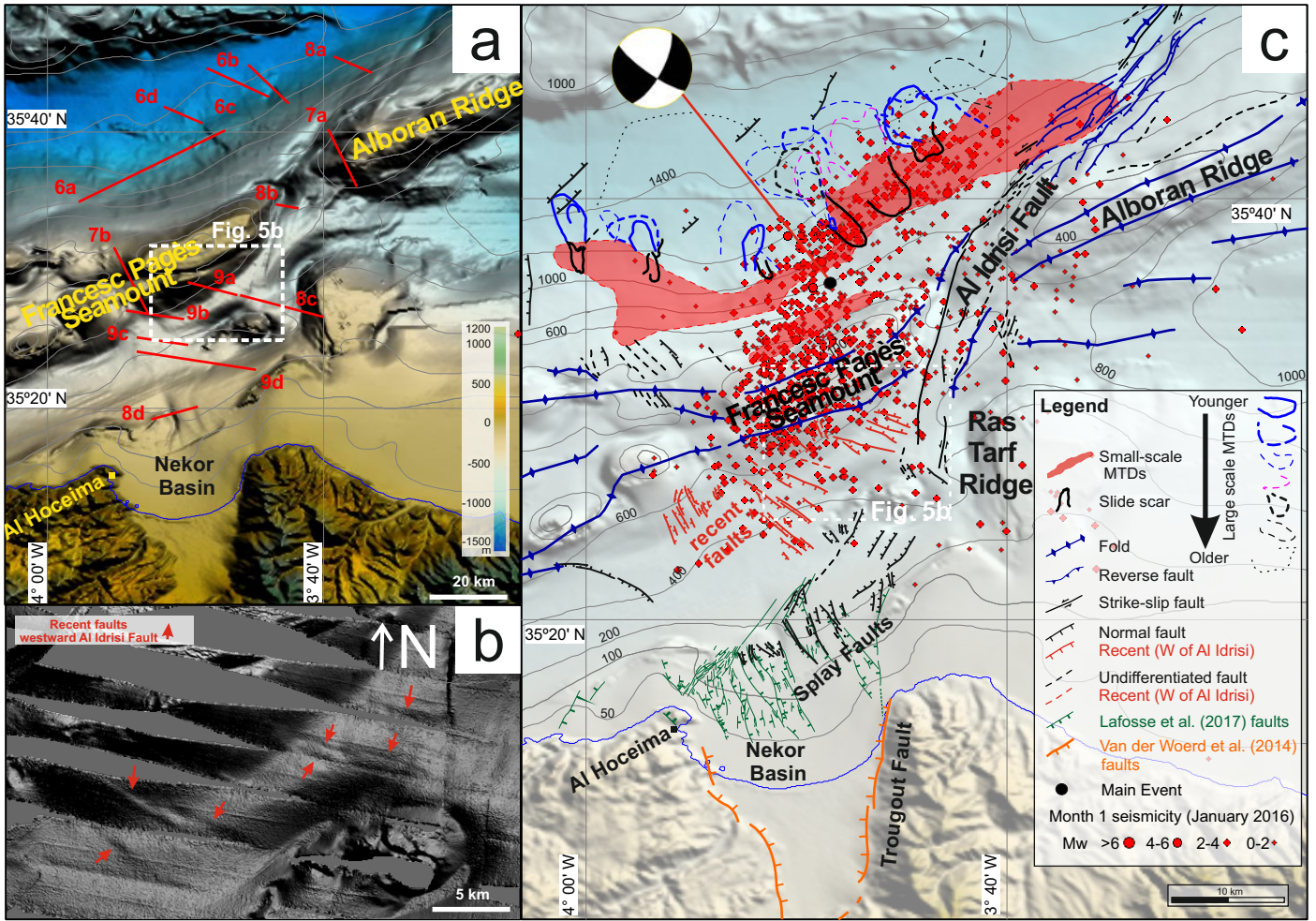


Fig. 6.

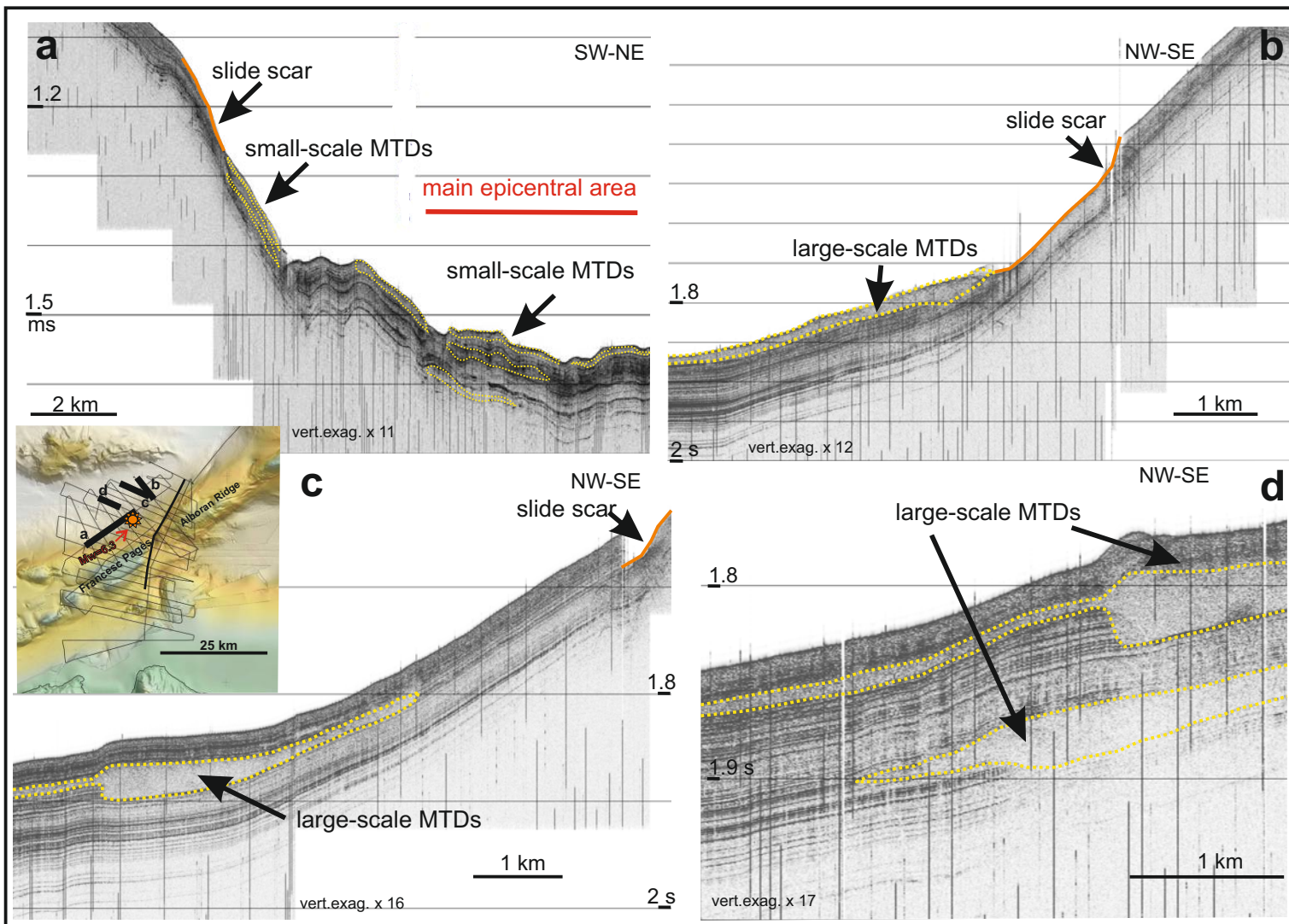


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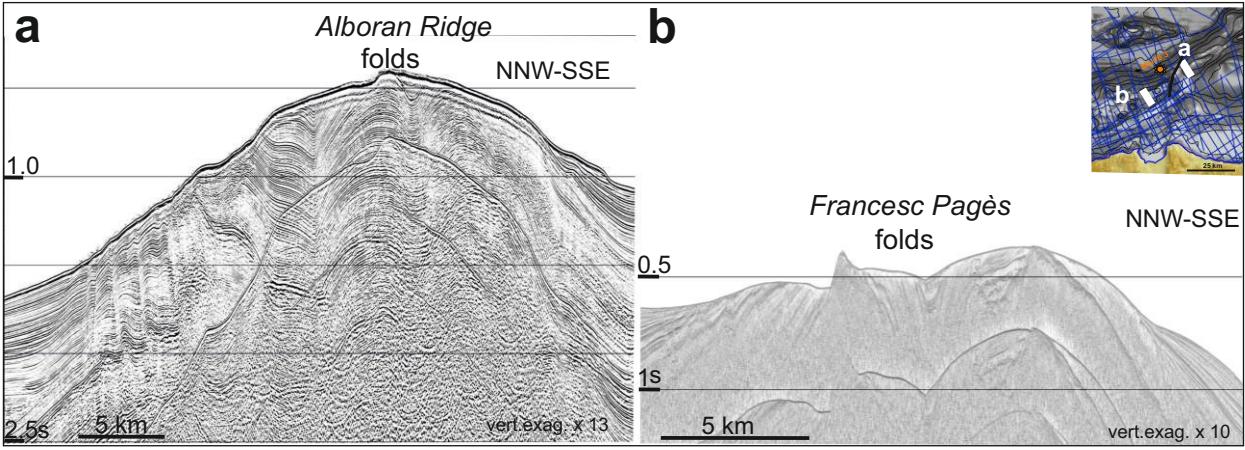


Fig. 8.

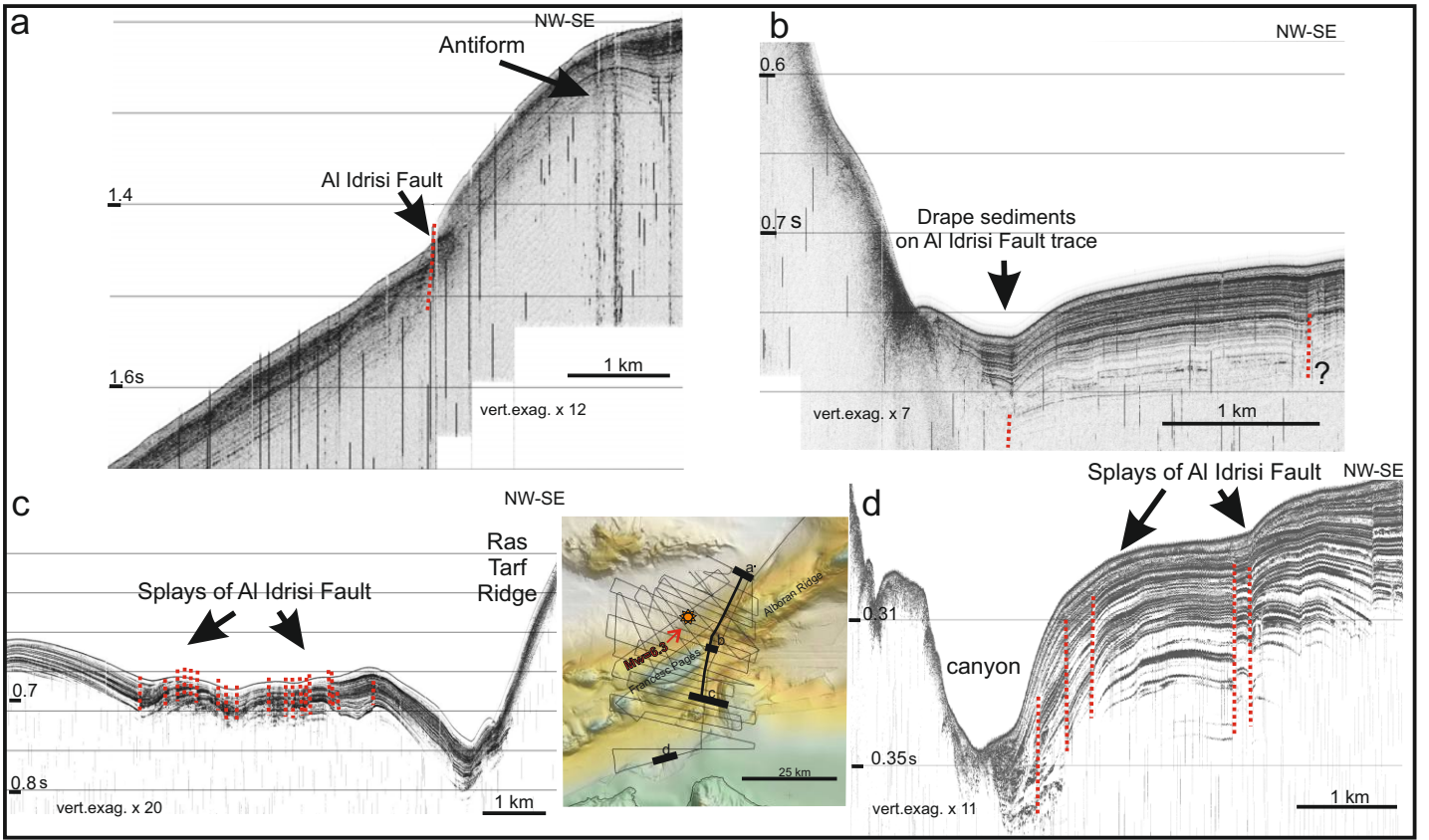


Fig. 9.

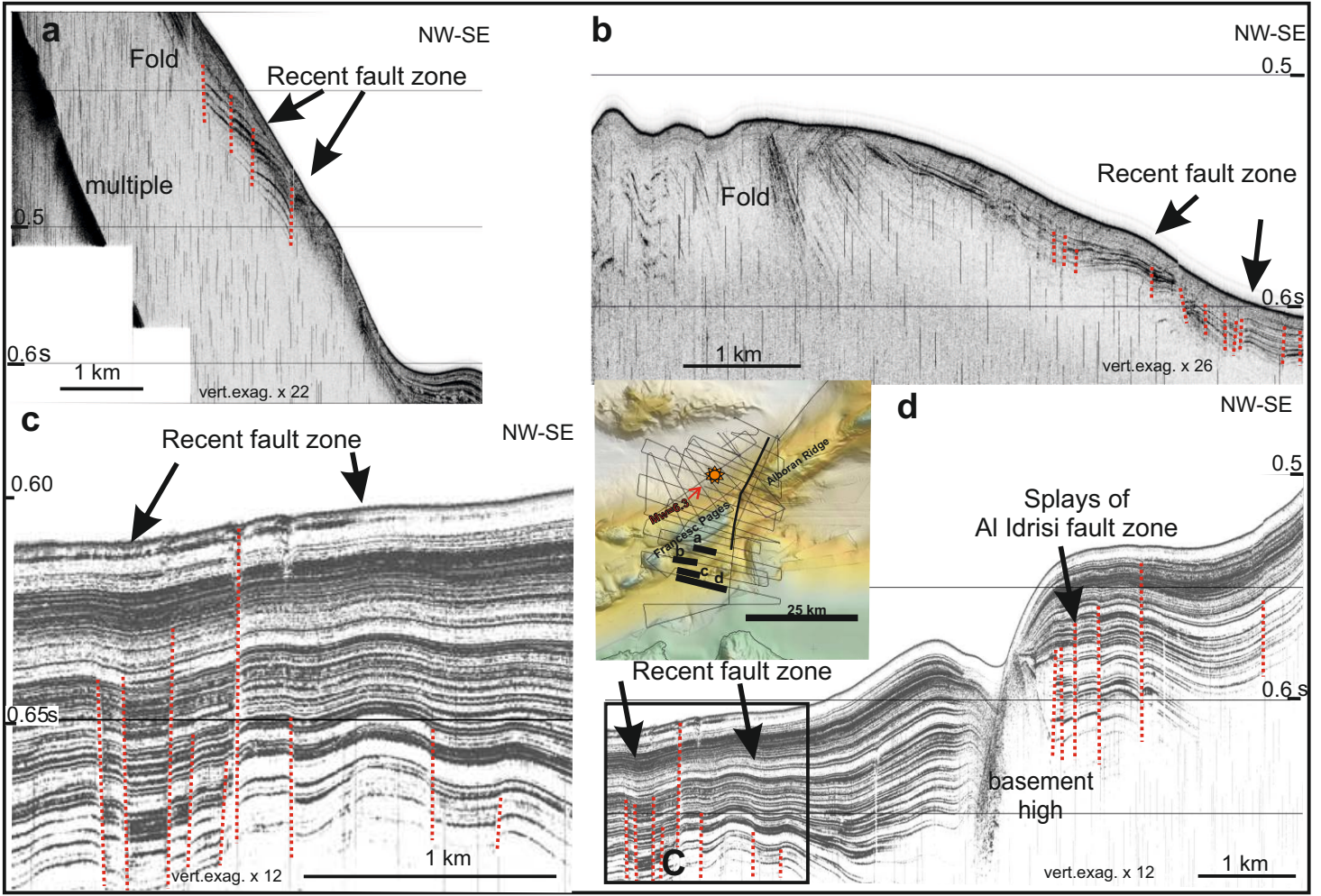


Fig. 10.

