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High-resolution imagery of active faulting offshore Al Hoceima, Northern Morocco

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ABSTRACT

Two recent destructive earthquakes in 1994 and 2004 near Al Hoceima highlight that the northern Moroccan margin is one of the most seismically active regions of the Western Mediterranean area. Despite onshore geodetic, seismological and tectonic field studies, the onshore–offshore location and extent of the main active faults remain poorly constrained. Offshore Al Hoceima, high-resolution seismic reflection and swath-bathymetry have been recently acquired during the Marlboro-2 cruise. These data at shallow water depth, close to the coast, allow us to describe the location, continuity and geometry of three active faults bounding the offshore Nekor basin. The well-expressed normal-left-lateral onshore Trougout fault can be followed offshore during several kilometers with a N171°E ± 3° trend. Westward, the Bousekkour–Aghbal normal-left-lateral onshore fault is expressed offshore with a N020°E ± 4° trending fault. The N030°E ± 2° Bokkoya fault corresponds to the western boundary of the Plio-Quaternary offshore Nekor basin in the Al Hoceima bay and seems to define an *en échelon* tectonic pattern with the Bousekkour–Aghbal fault. We propose that these three faults are part of the complex transtensional system between the Nekor fault and the Al-Idrissi fault zone. Our characterization of the offshore expression of active faulting in the Al Hoceima region is consistent with the geometry and nature of the active fault planes deduced from onshore geomorphological and morphotectonic analyses, as well as seismological, geodetic and geodynamic data.

1. Introduction

The Alboran basin is located at the westernmost edge of the Mediterranean Sea and its structure is considered to be the result of the westward retreat of a subducting slab (Jolivet et al., 2008) during the Tertiary African–European convergence. The slab retreat started at the end of the Oligocene and seems still active today (Gutscher et al., 2002; Mauffret et al., 2007). The Alboran basin is underlain by thinned continental crust and volcanic arc rocks related to subduction and associated back-arc extension (Booth-Rea et al., 2007). It is bordered to the north and south by the thickened crust of the two westernmost Alpine fold-and-thrust belts, the Betic Cordillera in Spain and the Rif in Morocco (Fig. 1). Since the Tortonian, the external portions of the Alboran domain have undergone tectonic inversion particularly active along the Moroccan margin (Woodside and Maldonado, 1992). Large NW–SE dextral and NE–SW sinistral strike slip faults cross the Alboran basin and continue onshore (Fig. 1; *e.g.* Jebha, Nekor and Carboneras–Serrata faults; Ammar et al., 2007; Chalouan et al., 2008; Gracia et al., 2006; Martinez-Garcia et al., 2011; Mauffret et al., 2007). Here, we focus on the Al Hoceima region, the most seismically active region of the Alboran basin, south of the offshore Al-Idrissi fault zone (Fig. 1). The seismogenic character of the active faulting in the Al Hoceima region is demonstrated by the occurrence of destructive seismic events in historical and instrumental catalogs (El Mrabet, 2005). This region has been affected by strong seismic events such as the Mw 6.0 earthquake in May 26, 1994 and the Mw 6.4 earthquake in February 24, 2004 (*e.g.*El Alami et al., 1998; Stich et al., 2005; Fig. 2). The source faults

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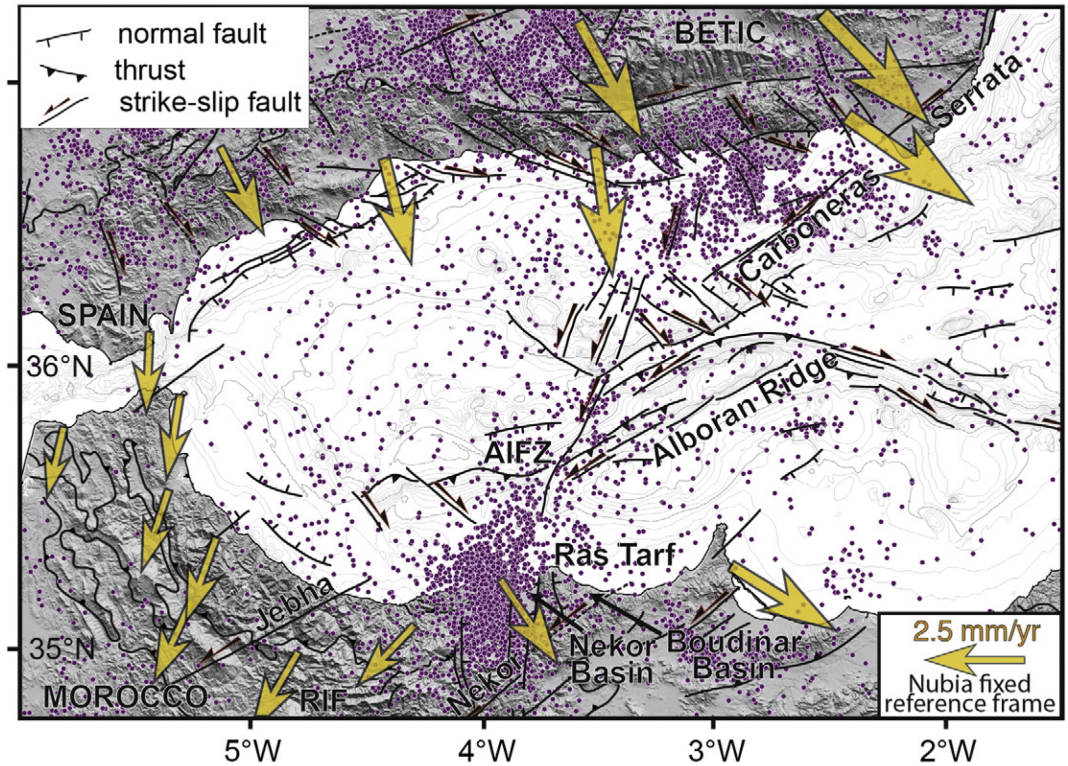

Fig. 1. Tectonic features of the Alboran basin. Onshore: satellite altimetry data from SRTM (http://topex.ucsd.edu/www_html/srtm30_plus.html). Offshore: GEBCO dataset (GEB 2008: http://www.gebco.net). Pink dots are epicenters of shallow seismicity (<50 km) between 1964 and 2012 (Instituto Geografico Nacional IGN database). Orange arrows: modeled GPS velocities with respect to Nubia (after Koulali et al., 2011). Tectonic features are from Crespo-Blanc and Frizon de Lamotte(2006)and Martinez-Garcia et al.(2011). Contour interval is 100 m. AIFZ: Al-Idrissi fault zone.

of these events are still debated: since neither of them produced noticeable primary surface rupture (Akoglu et al., 2006; Biggs et al., 2006). The present-day active faulting in the northeastern Rif has been relatively well studied onshore (*e.g.*Ait Brahim and Chotin, 1990; Meghraoui et al., 1996; Poujol et al., 2014) while only few offshore studies are available (Calvert et al., 1997; Gensous et al., 1986; Tesson et al., 1987). Detailed surveys in a shallow water environment are thus required to identify the connection between onshore and offshore structures. These data bring new insights on the present deformation in the seismically active Al Hoceima region.

2. The tectonic framework of the Al Hoceima region

The Al Hoceima region is located between the internal and external zones of the Rif whose primary structures consist of southward verging thrust sheets named the Bokkoya, the Tiziren and the Ketama Units represented by nappes of Palaeozoic terranes and their Mesozoic–Cenozoic cover (Fig. 2; Crespo-Blanc and Frizon de Lamotte, 2006). Volcanic rocks of the Tortonian–Messinian outcrop in Ras Tarf, east of Al Hoceima (El Azzouzi et al., 1999) and Plio-Quaternary sediments are confined in the Nekor and Boudinar basins (Fig. 2). In the Al Hoceima area, focal mechanisms show predominantly strike–slip fault solutions with a NNW–SSE P-axis and shallow depths (Hatzfeld et al., 1993; Stich et al., 2005; van der Woerd et al., 2014). Such an orientation is compatible with the present-day Africa–Eurasia plate convergence at a rate of 4.3 ± 0.5 mm/year from geodetic studies (Serpelloni et al., 2007).

The Al Hoceima region is affected by strong seismic events such as the Mw 6.0 earthquake in May 26, 1994 and the Mw 6.4 earthquake in February 24, 2004. For the 1994 earthquake the seismological data and analysis of InSAR interferograms suggest a blind or hidden NNE–SSW offshore–onshore left-lateral fault, striking about N20E, located about 9–10 km west of Al Hoceima City (Akoglu et al., 2006; Biggs et al., 2006; El Alami et al., 1998). For the 2004 earthquake, source time studies and seismic wave modeling suggest onshore sinistral rupture along NNE–SSW trending sinistral fault south of Al Hoceima (Stich et al., 2005; van der Woerd et al., 2014) or dextral rupture along WNW–ESE trending fault (*e.g.*van der Woerd et al., 2014). The analysis of InSAR interferograms led other authors to favor NW–SE dextral displacement (Akoglu et al., 2006; Biggs et al., 2006; Cakir et al., 2006) or conjugate dextral–sinistral displacements along NW–SE and NE–SW onshore strike–slip faults (Tahayt et al., 2009). For both events, the quality of interferograms is probably at the origin of the discrepancies.

Hence, while most studies concur on the presence of sinistral or dextral faulting, the precise fault plane activated during the 1994 and 2004 seismic events remains controversial. Apart from a 25 cm normal throw, identified on a NNE oriented fault strand in 2004 (Tahayt et al., 2009), moderate cracks linked to landslide events, and local tension cracks, no surface evidence of active faulting related to the 1994–2004 events has been observed (Ait Brahim et al., 2004; Galindo-Zaldívar et al., 2009; van der Woerd et al., 2014).

The present-day active faulting of the northeastern Rif is concentrated across the Nekor basin area. This basin is developed in a Plio-Quaternary fault system characterized by the NE–SW trending left-lateral strike–slip Nekor fault, the N–S trending Trougout–Bou Haddad and Imzouren–Ajdir-Boujibar normal-left-lateral faults (Ait Brahim et al., 1990; Meghraoui et al., 1996; Poujol et al., 2014). The continuity, location and geometry of these active faults offshore remain a challenging issue.

3. Methodology

In May 2012, during the Marlboro-2 survey aboard the R/V Téthys II, we acquired simultaneously shallow-water multibeam echo-sounder data using a Reson 8101 system and high-resolution seismic reflection data using a 250–500 J Sparker Source, a 6-channel SIG streamer and a numerical DELPH2 acquisition system. Bathymetry data have been acquired and pre-processed by using the Qinsy© software and processed

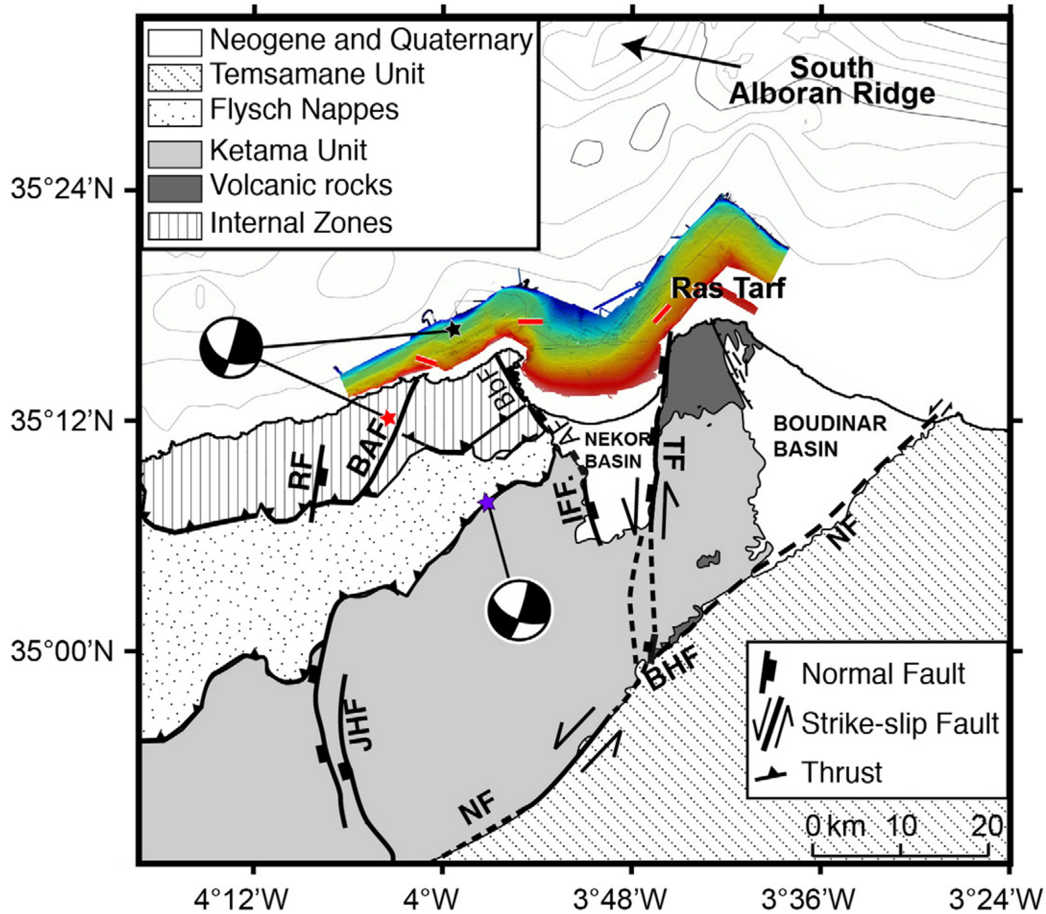

Fig. 2. Structural and geological onshore map of the Al Hoceima region. Offshore: Marlboro-2 multibeam bathymetry and contour lines from GEBCO dataset (2008: http://www.gebco.net). Major faults of the Al Hoceima region onshore based on compilation (El Alami et al., 1998; Medina and El Alami, 2006; Poujol et al., 2014). Focal mechanisms of the 1994 main shock (black star from El Alami et al., 1998; red star from Biggs et al., 2006) and of the 2004 main shock in violet from van der Woerd et al. (2014). Offshore red lines: locations of profiles presented in Fig. 3. AF: Ajdir fault; BAF: Bousekkour–Aghbal fault; BbF: Boujibar fault; BHF: Bou Haddad fault; IF: Imzouren fault; JHF: Jbel Hammam fault; NF: Nekor fault; RF: Rouadi fault; TF: Trougout fault. Dashed line: suspected fault.

with the Caraibes© software. Sound velocity was corrected using the Reson Sound Velocity Profiler (SVP 10/15). Seismic reflection data were processed using the CWP/SU software (Seismic Unix of the Center of Wave Phenomena, Colorado School of Mines, v.43R1). The data were stacked, filtered and migrated. The resolution for these two methods regarding the grid cell size and reflector size is less than 5 m for the bathymetry and 1 m for the seismic reflection data. Such a combination of high resolution, close to the shore, shallow water depths seismic and bathymetric surveys is suited to characterize blind or hidden active faults in a complex tectonic setting and to identify the connecting onshore–offshore structures.

4. Offshore evidence of active faulting

The high-resolution swath bathymetry reveals three main linear scarp-shape morphologies that affect and deform the seafloor of the continental shelf on the western and eastern side of the Nekor basin (Fig. 3). We interpret these traces as the surficial expressions of cumulative seafloor rupture on the continental shelf north of the Moroccan margin. The submarine fault scarps remain uncovered and show total vertical offsets of several meters of the seafloor. These up to 5-mhigh scarps may be traced from the coast until 7 km for the Trougout fault and 4 km northward for the Bousekkour–Aghbal and Bokkoya faults. The morphological expressions of the lattertwo faults show *en échelon* short segments of identical strike (Fig. 3). The strikes of the western Bousekkour–Aghbal and Bokkoya faults are N020°E $\pm$ 4° and N030°E $\pm$ 2°, respectively (Fig. 3a, b). The locally observed push-up structures (transpressional ridges) between fault segments are consistent with a sinistral sense of displacement. The strike of the Trougout fault is N171°E $\pm$ 3° (Fig. 3c). The high-resolution seismic reflection profiles that cross the faults reveal normal offsets along these 60 to 70° East and West dipping faults and distributed deformation in the Nekor inner basin (Fig. 3b, c). On the hanging wall block, typical half-graben with a fanning sequence indicate syn-tectonic sedimentation (Fig. 3a–c). On the footwall no growth sequence is observed. The acoustic basement is vertically offset by at least 60 m along the Bousekkour–Aghbal fault and by 50 m along the Bokkoya and Trougout fault.

5. Offshore–onshore link

The westernmost offshore newly mapped active fault (Fig. 3a) is remarkably continuous and aligned with the onshore sinistral Bousekkour–Aghbal strike–slip fault (Medina and El Alami, 2006; Mourier, 1982). Furthermore, the ground motion established from InSAR and the isoseismal map of the 1994 Al Hoceima main shock shows maximum damage centered along the trend of the Bousekkour–Aghbal fault (Akoglu et al., 2006; Biggs et al., 2006; El Alami et al., 1998), suggesting that this fault may have been active during the 1994 seismic crisis (El Alami et al., 1998). Biggs et al. (2006) and El Alami et al. (1998) locate the epicenter of the 1994 main shock along the NNE–SSW trend of the Bousekkour–Aghbal fault. The geophysical source inversions lead to solutions that favor a N20°E rupture plane localizes on the Bousekkour–Aghbal area (van der Woerd et al., 2014). We propose that the 1994 event re-activated the onshore–offshore Bousekkour–Aghbal fault (Figs. 3a, 4).

The offshore Bokkoya active fault is located directly north of Al Hoceima City about 10 km east of the Bousekkour–Aghbal fault (Fig. 3b). Our survey shows a continuous and detailed image of the

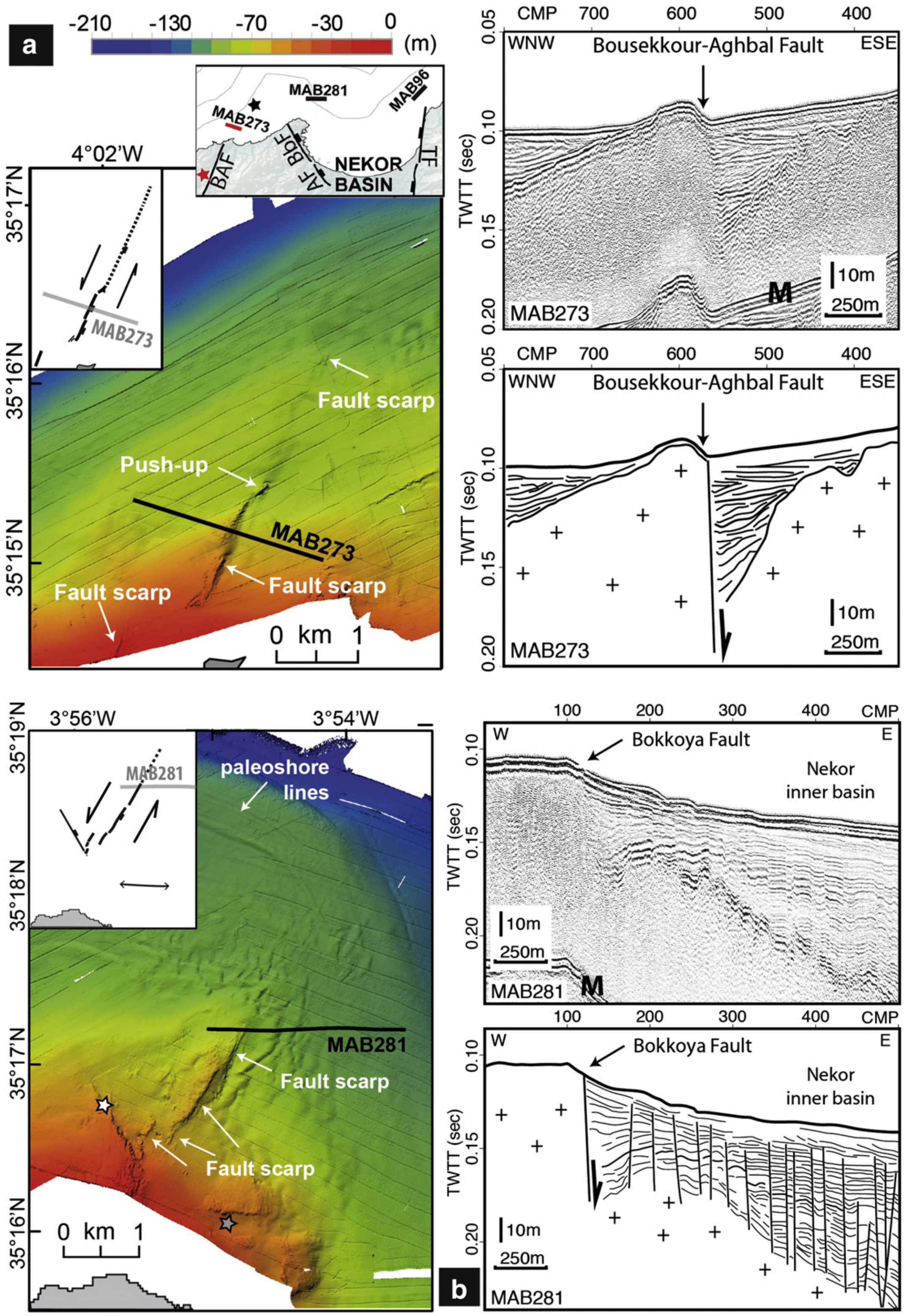

Fig. 3. Detailed swath-bathymetry of the fault scarps and high-resolution seismic reflection profiles across the active faults. a. Bousekkour–Aghbal fault. b. Bokkoya fault. White and gray stars: dextral strike–slip normal fault and eroded antiform respectively, compatible with the present-day Africa–Eurasia plate convergence. c. Trougout fault. White star: dextral strike–slip normal fault compatible with the present-day Africa–Eurasia plate convergence. See detailed onshore structural map with the localization of seismic lines as shown in inset a. For the bathymetric maps: see bathymetric map scale in a; black lines: locations of profiles; insets are schematic fault system; see legend in Fig. 2, double arrows represent an eroded antiform (b). For the seismic reflection lines and line drawings: vertical exaggeration (water) is 12; vertical scale assumes velocity of 1550 m/s; M: multiple; note that caution is necessary in geologic interpretations of the seafloor, because the sparker data are affected by the reverberatory nature of the source wavelet (bubble pulse).

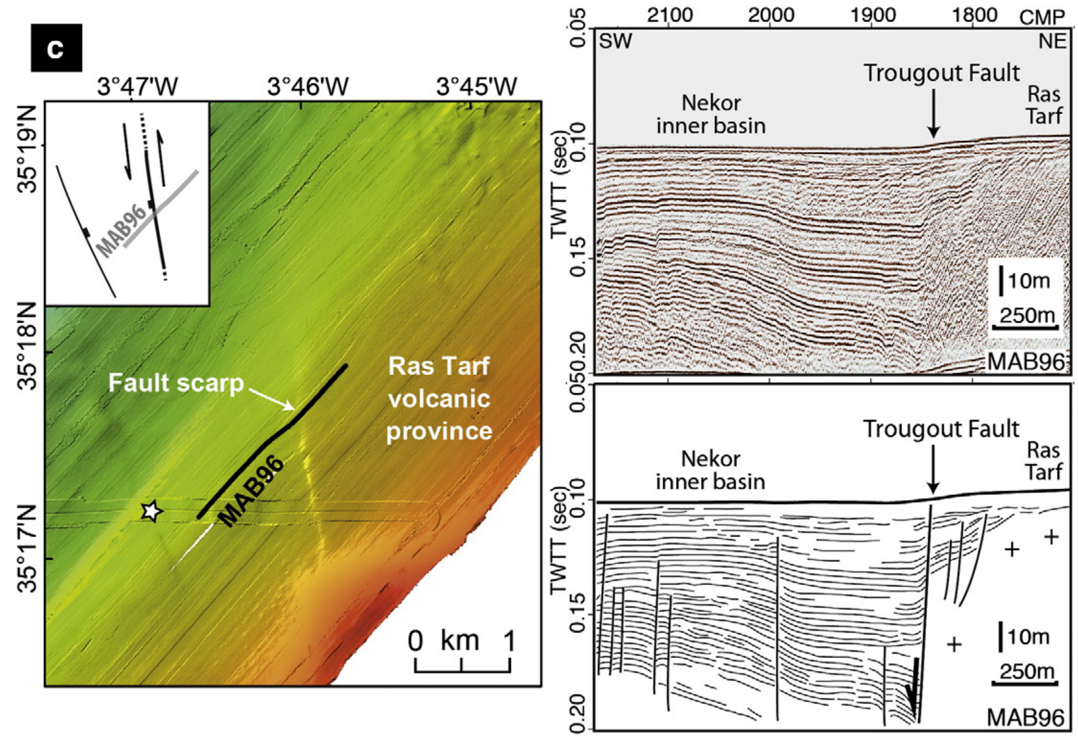

Fig. 3 (*continued*).

geometry of this fault, already suggested by Calvert et al. (1997) and Dillon et al. (1980) from medium resolution multichannel seismic line with a relatively large spacing. These new data show also that this fault was active recently. Onshore, in the Al Hoceima region, the most significant and recent faults do not match the location and trend of the Bokkoya offshore fault: the sinistral strike–slip Nekor and Trougout faults have a ENE–WSW and N–S trend respectively and the Imzouren–Ajdir-Boujibar normal faults trend NNW–SSE (Fig. 4). Most of the earthquakes from the 1994 and 2004 sequences are located west of the Nekor basin between the Imzouren–Ajdir-Boujibar and the Jbel Hammam–Bousekkour–Aghbal faults where no recent fault traces have been observed (Akoglu et al., 2006; Calvert et al., 1997; El Alami et al., 1998; Tahayt et al., 2009; van der Woerd et al., 2014). The onshore extent of the Bokkoya fault at that point is uncertain, although it could correspond to an on-land network of blind *en échelon* NNE–SSW transtensional faults.

Onshore, the Trougout fault shows a clear topographic signature with exposed fault planes suggesting recent activity (Meghraoui et al., 1996; Poujol et al., 2014). This onshore major normal-left lateral strike slip fault marks the contact between the Ras Tarf volcanic massif to the East and the Quaternary bay of Al Hoceima (*i.e.* Nekor basin) to the West, and clearly extends offshore to the north (Fig. 4).

These faults delineate the western and eastern boundaries of a regional structure, encompassing the Nekor basin *s.s.* that we interpret as the surface expression of a large-scale flower structure (Fig. 4b).

6. Discussion

We image three offshore NNE–SSW active faults that provide offshore evidence of surface ruptures related to the seismic activity of the Al Hoceima area. Without dating and direct field evidence, we cannot conclude when these faults were activated but the apparent seabed offset and recent syn-tectonic sediments attest their recent activity. Such morphological expressions of young faults on the seafloor have already been demonstrated for other seismically active transtensional regions like the Marmara sea basins (Armijo et al., 2005) and the Carboneras–Serrata fault (Gracia et al., 2006).

The described offshore extension of the Bousekkour–Aghbal fault fits reasonably well with InSAR and seismological-derived fault planes related to the 1994 event (Akoglu et al., 2006; Bezzeghoud and Buforn, 1999; Biggs et al., 2006; El Alami et al., 1998; van der Woerd et al., 2014). The trend of the Bokkoya fault coincides with the NNE–SSW co-seismic slip proposed in seismological source-time and InSAR studies for the 2004 event (Stich et al., 2005; Tahayt et al., 2009) and with the NNE–SSW-oriented cluster of the seismic events recorded in the region between 1970 and 2014. But most published studies show that the 2004 earthquake occurred on land. Moreover, Calvert et al. (1997) had previously identified the Bokkoya fault on industry seismic reflection profiles, thus attesting to its inception before the 2004 seismic event. For either earthquake, surface ruptures have not been detected from the onshore Moroccan margin. The offshore scarps show an up to 5-mhigh offset of the seafloor that could be generated by greater events. Without direct evidence of co-seismic rupture we cannot conclude that the Bousekkour–Aghbal and Bokkoya faults were activated during the 1994 and/or 2004 events. Nonetheless these faults certainly reflect cumulative effect of repeated co-seismic surface-faulting generated by the historical and instrumental seismic events in the Al Hoceima region.

The tectonic framework we propose, based on added information from the detailed bathymetry of these three offshore active structures, is consistent with (i) the NNE–SSW sources proposed in InSAR and seismological source-time studies (Akoglu et al., 2006; Stich et al., 2005; Tahayt et al., 2009), (ii) the large-scale distribution of seismicity in the Alboran basin and (iii) the regional displacement field indicated by GPS (Fadil et al., 2006; Koulali et al., 2011; Vernant et al., 2010), and that (iv) a distinct NNE–SSW trending fault is indicated by macroseismic studies showing that the locus of maximum shaking in 1994 was situated about 10 km west of Al Hoceima (Ait Brahim et al., 2004; El Alami et al., 1998; Hahou et al., 2004), matching our westernmost scarp. Furthermore, the macro-seismic intensity maps for the 1994 event show a predominant pattern of isoseismals "open to the sea",

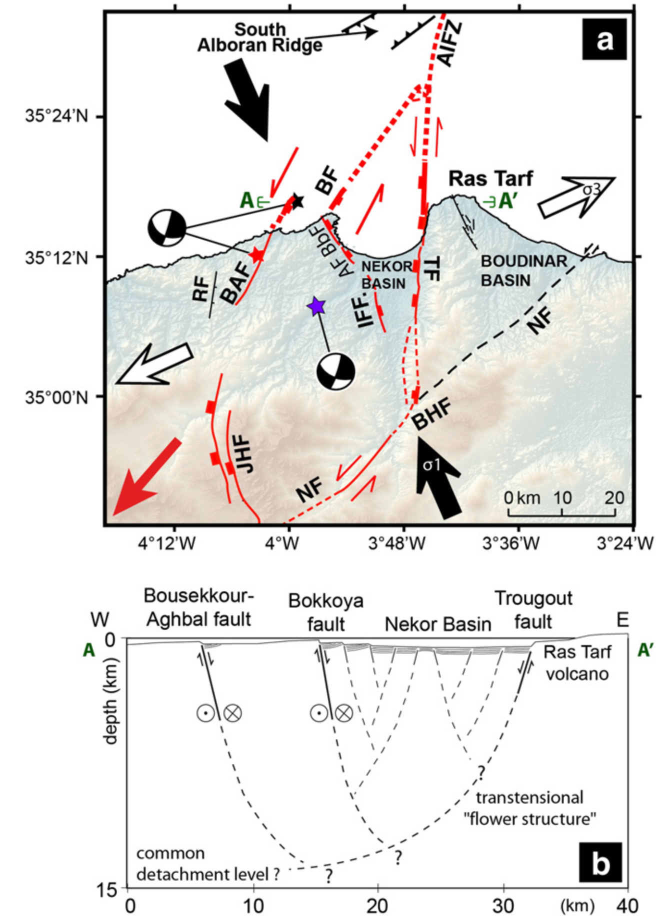

Fig. 4. a. Interpretative structural map of the onshore–offshore Al Hoceima active fault zone. Large arrows indicate present σ1 and σ3 directions (Medina and El Alami, 2006). The red arrow is compatible with the SSW movement of the independent Rif–Betic–Alboran block with respect to the African plate (Vernant et al., 2010). Trace of the fault onshore based on compilation (El Alami et al., 1998; Medina and El Alami, 2006; Poujol et al., 2014); offshore active faults based on this study. See legend in Fig. 2. b. Schematic E–W structural cross-section at 35°17′N (line track AA′, relief at the surface is exaggerated). Note the network of transtensional faults in the Nekor basin is simplified (the real number of faults is much higher as shown in Fig. 3b). AIFZ: Al-Idrissi fault zone. BF: Bokkoya fault.

suggesting that a significant portion of the rupture occurred along fault segments located offshore. (v) The three offshore active faults are in good accordance with the active tectonics and the sub-horizontal WSW–ENE minimum compressional stress axis deduced from earthquake focal mechanisms, previous seismic reflection study, and geomorphic data (Calvert et al., 1997; El Alami et al., 1998; Medina and El Alami, 2006; Poujol et al., 2014; Stich et al., 2005).

Kinematic data show an independent Rif–Betic–Alboran block moving SSW with respect to the African plate (*e.g.*Vernant et al., 2010). The local deformation pattern is mainly driven by the effect of this southward motion of the Central Rif block (Fig. 4a). The eastern boundary of this block coincides with the Al Hoceima seismogenic region. We suggest that the strike–slip related system defined by the active faults is part of the Central Rif block eastern boundary (Fig. 4a). The fault network in the Nekor basin does not show parallel overlapping strike–slip faults and normal faults that bound the basin. This asymmetric fault network leads us to interpret it as a strike–slip related basin and not a pull-apart basin *s.s.* (*e.g.*Ben Avraham, 1992) forming at the junction of the Al-Idrissi fault zone and Nekor fault (Fig. 3). In this proposed strike–slip related basin, the offshore–onshore Bousekkour–Aghbal NNE–SSW strike–slip fault connects to the N–S Jbel Hammam normal fault system, which itself connects to the active part of the NE–SW sinistral Nekor fault (Fig. 4). Previous deeper seismic reflection data show an offset of the basement (Calvert et al., 1997), demonstrating that the Bokkoya fault is a major eastward dipping fault that bounds the western Al Hoceima Bay. The onshore–offshore fault system eventually connects southward to the Nekor fault through a blind transtensional fault system onshore and northward to the Al-Idrissi fault zone. In the eastern part of the studied area, the onshore Trougout fault clearly extends offshore, branches further north with the Al-Idrissi fault zone, and connects southward to the Nekor fault through the Bou Haddad fault (Poujol et al., 2014). The northeastern part of the Nekor fault seems inactive according to the seismological data (Figs. 1, 4). We propose that the Trougout fault represents the active eastern major fault of the Nekor strike–slip related basin, while the Bousekkour–Aghbal and Bokkoya faults were recently active along its diffuse western boundary (Fig. 4). Between these structures, fanning of syn-tectonic sediments attests to normal fault activity. Small fault-bounded sub-basins connect at depth to a steep WSW dipping master fault, all together forming a large-scale transtensional "flower-structure" (Fig. 4b). The Trougout fault may be connected to a pre-existing detachment level at 9–12 km depth under the nappes (Galindo-Zaldívar et al., 2009; van der Woerd et al., 2014).

7. Conclusion

High-resolution bathymetric and sparker seismic data have revealed three fault scarps offshore the Al Hoceima coastline, reaching up to 5 m high, and showing evidence of recent cumulative transtensional deformation. We propose that recent seismic events activated the three mapped sinistral strike–slip normal faults within a complex transtensional system which shows signs of highly distributed active deformation.

The location of the observed faults matches the offshore prolongation of both the Bousekkour–Aghbal and Trougout onshore faults bounding the Plio-Quaternary Nekor basin. These new high-resolution data fill an important gap by expanding our knowledge of the location, continuity and geometry of the main offshore active faults close to shoreline in shallow water depth. These results have major implications for regional present-day tectonics, strain partitioning, tectonic stress studies and the role of structural inheritance of the Rif domain but also at larger scale for kinematics and dynamics of the Nubia–Eurasia plate boundary zone. Completing the inventory of offshore faults and determining the timing and frequency of seismic events here will be a significant challenge for future research.

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