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THE SEISMOTECTONICS OF THE WESTERN AND SOUTHERN MARGINS OF LUT BLOCK, CENTRAL IRAN

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ABSTRACT
The western and southwestern margins of the Lut Block in SE of Iran have experienced many historical and instrumental destructive earthquakes in which with 11 destructive earthquakes from 1977 to 2012, with about 195km surface rupturing in this area. In this study, we used different data sources by merging DEM terrain interpretation and satellite images (acquired from Quickbird, Aster and landsat and viewed in Google Earth) analysis with geomorphological surveys. We introduced a number of faults for the first time and also we investigated activity evidences for a group of the previous known faults. Our results have general applications in describing en-echelon faults, development of releasing and restraining bends and also in fault growth studies. According to earthquake distributions, we found that Nayband is almost aseismic in comparison with other systems, and also a diffuse pattern for Sabzevaran fault system.

INTRODUCTION
Tectonics of Iran is especially characterized by active faulting, large destructive earthquakes and Quaternary volcanism. About 189,640 human fatalities are reported due to 130 earthquakes in Iran in period of 1900 to 2016; on average 1459 persons in each year. 17 of these earthquakes resulted in more than 1000 victims each, and 11 of them were larger than magnitude 7 [National Geophysical Data Center, NOAA, 2016]. A substantial part of the earthquake fatalities is due to tectonic activities along the eastern and western margins of the Lut Block, which is considered as a rigid block with a thin crustal structure [Dehghani and Makris, 1984]. The eastern limit of the Lut block is Nehbandan fault system. The Nehbandan fault overprints the Sistan suture zone. Sistan suture zone represent an accretionary prism that was emplaced during of the N-S-trending Sistan ocean which once separated the Lut and Afghan block. The western limit of the Lut Block is separated from central Iran through a number of N-S to NNW-SSE striking right-lateral fault systems, including the Nayband, Gowk and Sabzevaran (Fig. 1). The study area is located at the W-SW Dasht-e Lut. The black box in fig (1c) indicates the location of this area.

Eleven destructive earthquakes, from 1977 to 2012, were accompanied by about 195 km of surface rupture in the S, SW of the Lut Block (Fig. 2; Rashidi et al., 2018). These earthquakes resulted in 44,700 human losses, 36,646 injured and more than 100,000 homeless. There are no reliable estimates of geometric-kinematic evolution of these strike-slip systems to be linked with their seismic activity; therefore, the estimated seismic hazard is not accurate enough. One of the main aims of the current study is to provide a framework for seismic hazard studies.

It is important that the seismicity of the area and its temporal and spatial variations be viewed as snapshots of the ongoing tectonic activities. Therefore, identification of the general tectonic/seismic patterns may provide complementary deductions for more realistic analysis and interpretation of observations.

The main active faults in the study area include: Nayband, Lakar Kuh, Ravar, Behabad, Kuhbanan, Jorjafk, Gowk, Bam, Mahan, Rayen, Lalehzar, Dalfard, Jabal-e-barez, Faryab, Chahmazrae, Sabzevaran and Shahdad (Fig. 1).

In provide a framework for seismic hazard studies, we introduced a number of faults for the first time and also we investigated activity evidences for a group of the previous known faults. Our results have general applications in describing en-echelon faults, development of releasing and restraining bends and also in fault growth studies. These results have important role in the hazard.

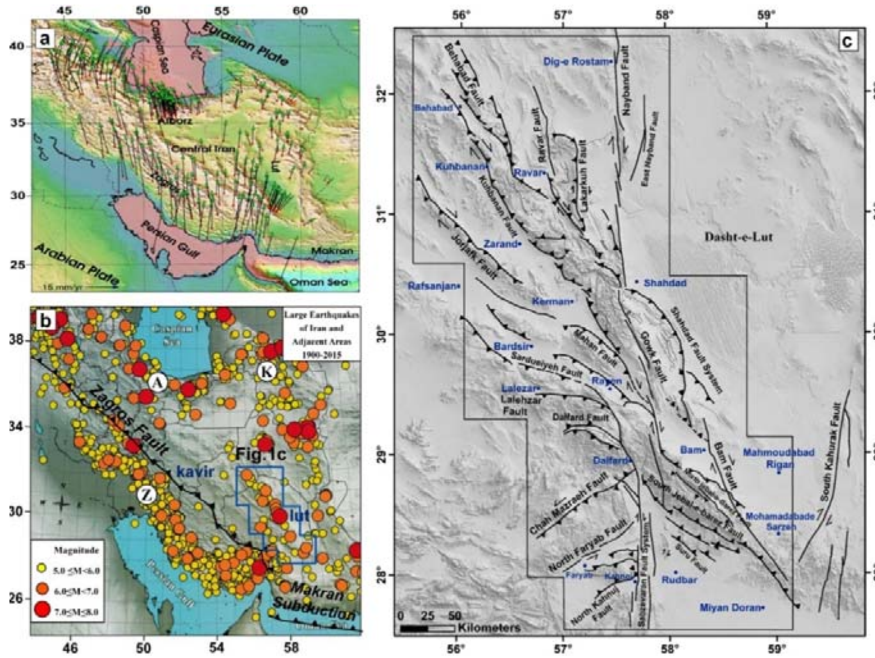

Fig. 1. (a) GPS velocity field relative to Eurasia in Iran [integrated from Zarifi et al. (2014) and Walpersdorf et al. (2014)]. (b) The filled circles show 5+ earthquakes taken from the ISC Catalogue (2015). Z, A, and K stand for Zagros, Alborz, and Kopeh Dagh respectively. (c) Shaded-relief topographic map of the west and south Lut region with active faults. Some of these faults are also mentioned for the first time.

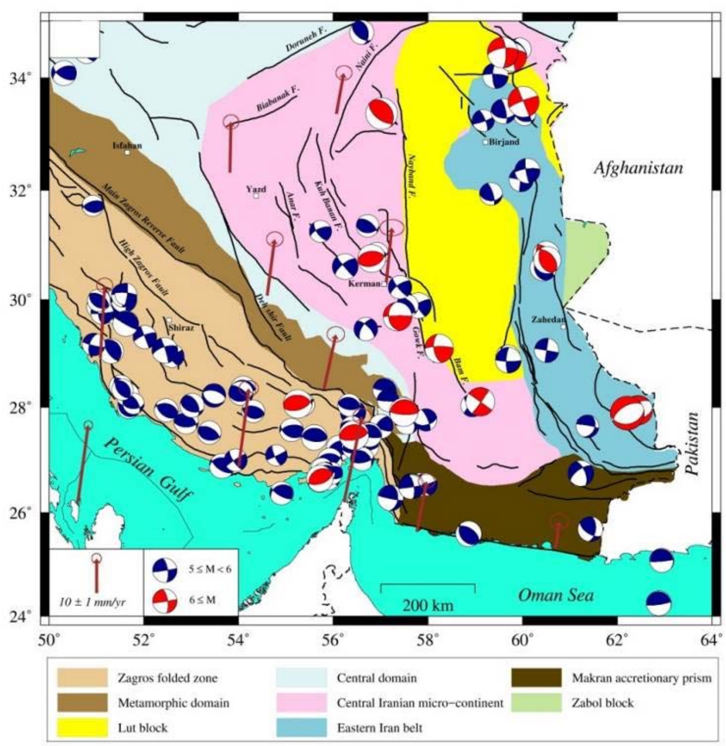

Figure 2. Tectonic setting of southern Iran with brown arrows as GPS velocities (Vernant et al., 2004) and CMT solutions of earthquake with magnitude more than 5 in the period of 1976 to 2018 (http://www.seismology.harvard.edu/CMTsearch.html).

MATERIAL AND METHODS

Active tectonic were determined using the Quaternary landforms, offset and tilting in the rock unites and the land scape response to cumulative displacement of the study area, by merging DEM terrain interpretation and satellite images (acquired from Quickbird, Aster and landsat and viewed in Google Earth) analysis with geomorphological field surveys.

In this study, we measured the offset, the upstream and downstream course of each river was projected onto the fault trace and we estimated the rivers gradients from SRTM data.

For some faults, kinematic measurements were recorded by slickenlines on the fault surface. For these faults, on the figures, position of P-and T-axes were determined, and P-and T-quadrants constructed to yield pseudo-fault plane solutions (using FaultKin Linked Bingham distribution, Allmendinger 2001).

STRIKE-SLIP FAULTS IN THE STUDY AREA

SABZEVARAN FAULT

The Sabzevaran fault with a NS strike consists of fresh steeps and scarps that bound the eastern flank of two narrow ophiolite horsts of Palaeozoic and Mesozoic ages [*Regard et al.*, 2004]. The Sabzevaran fault has 6 main en-echelon segments with right-step arrangement in the study area. Therefore, there are several pull-apart and releasing right stepover along the system (Fig.3a). The linearity of Sabzevaran fault suggests that it is nearly vertical and accommodates dominantly strike-slip displacements.

Despite the high slip rate of the Sabzevaran fault system, 5.7 ± 1.7 mm/yr in a direction N9±12°E [*Regard et al.*, 2005, 2006], no known destructive earthquake is associated with the fault. However, the tectonic evidences indicate high level of activity for the fault such that Neogene rock units show about 7.5 km offset. This offset is clearly visible on satellite images and topographic maps (Fig. 4a,b).

A large number of active faults, which cut through Quaternary units, are connected to the Sabzevaran system including Chahmazrae, North Faryab and North Kahnoj, all NE-SW- striking. Heydarabad and South Faryab. almost E-W- striking, and Halil Rud and Khatoun Abad, both NW-SE-striking (Fig. 7). The right-lateral strike-slip motion along the Sabzevaran fault has resulted in shearing and thrusting of the recent rock units and alluvial fans along these fault branches.

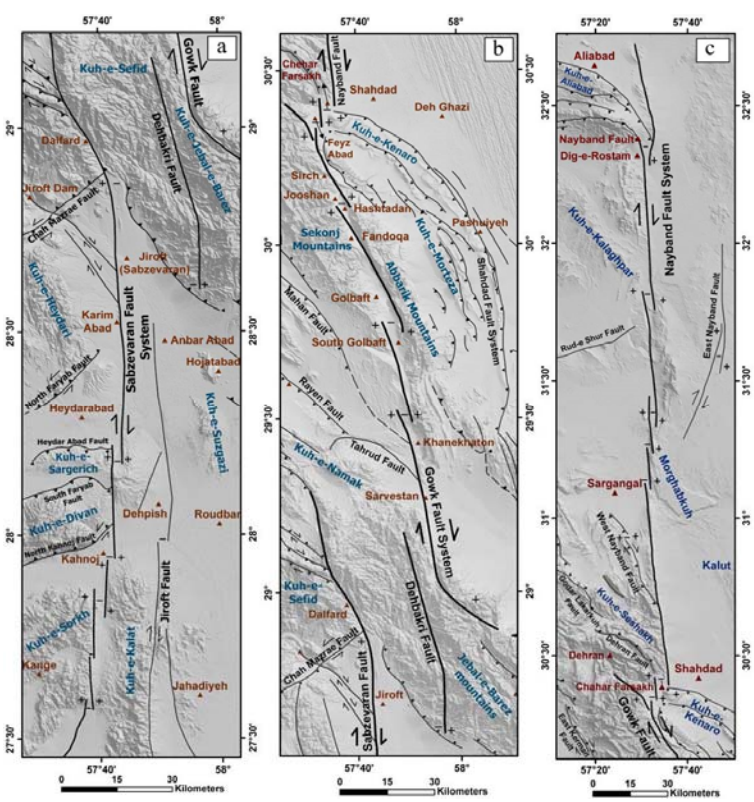

Fig. 3. Hillshaded DEM of the right-lateral faults striking N-S on the western side of the Lut Block, at longitude of about 57°45' E. (a) Sabzevaran fault (b) Gowk fault (c) Nayband Fault + and - signs indicate area of tension and compression.

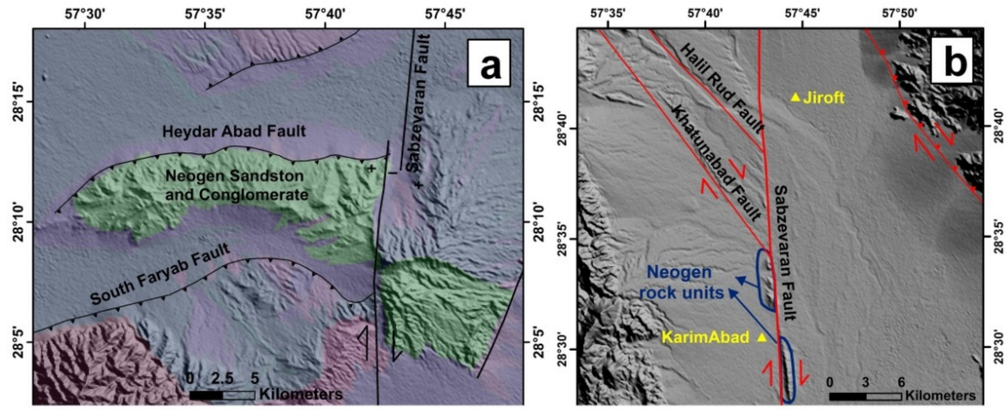

Fig. 4. (a), (b) show views of the about 7.5 km right-lateral offsets in Neogene sandstone and conglomerate rocks on segments of the Sabzevaran fault.

GOWK FAULT

The right-lateral Gowk fault (Fig. 1c) accommodates part of the total 15 mm/yr of the north-south, right-lateral shearing between Afghanistan and the interior of Iran [*Vernant et al.*, 2004; *Walker and Jackson*, 2004; *Meyer and Le Dortz*, 2007]. There are five main segments along the Gowk fault system, (Fig. 3b). Along these segments, releasing right stepovers and pullapart basins are observable, and they have extensively affected the drainage system. Due to the continuous activities of the fault, different offsets in structures with different age are observable (e.g. Fig. 5a,b). *Walker and Jackson* [2002] found a cumulative offset of 12 km along all segments of the system.

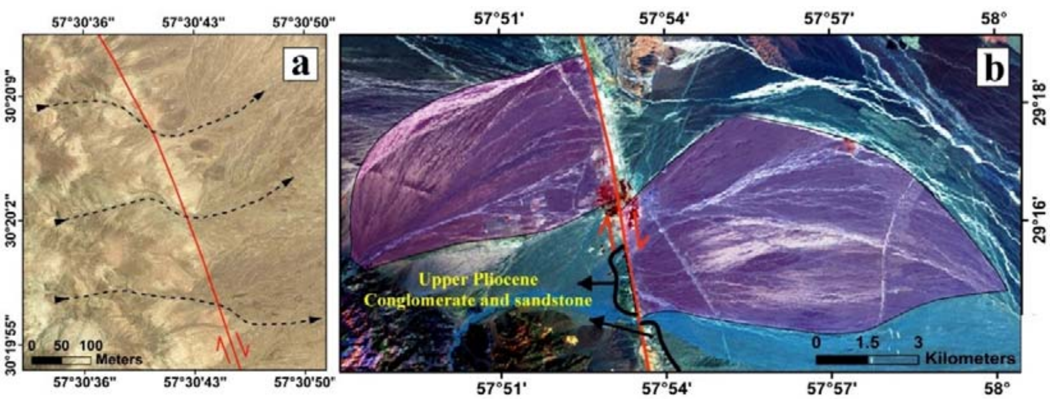

Fig. 5. (a) River offset (about 100 m) along the northern segment of the Gowk fault. (b) Offset of about 3.5 km of an alluvial fan and Upper Pliocene conglomerateand sandstone along the southern segment. (c), (d): Traces of Gowk fault in alluvial fan.

Walker et al. [2010] based on radiocarbon dating of two terrestrial wood fragments, estimated a minimum Holocene slip rate of 3.8±0.7 mm/yr on the Gowk fault. The slip rate on this fault seems to impart to the northern branches of Kuhbanan, Behabad, Ravar, Lakar Kuh, Nayband, and also impart to the southern branches of North Jabal-e-Barez, South Jabal-e-Barez, Hojat Abad and Suru. Of course some slip rate is consuming by rotating blocks along the Gowk fault. But we don't know its value. The relatively high slip rate of the Gowk fault infers the high seismic potential of the fault, which can be deduced also from the number of destructive earthquakes ascribed to the fault.

NAYBAND FAULT

The Nayband right-lateral fault runs for about 300 km (Fig. 3c) with a sharp linear trace (Fig. 6a). Several offsets along the fault are observed, including the largest river offset of about 1 km and also more than 7 km offset of Eocene rock units (Fig 6b). Six first-order segments can be identified along the Nayband fault based on main structural discontinuities such as bends and stepovers. These fault segments are arranged in right-stepping en-echelon pattern, which is recognizable in field, satellite images and topographic maps (Figs. 3c). Pullapart basins are developed along the fault due to the aforementioned geometric arrangement (e.g. Fig. 3c, - signs).

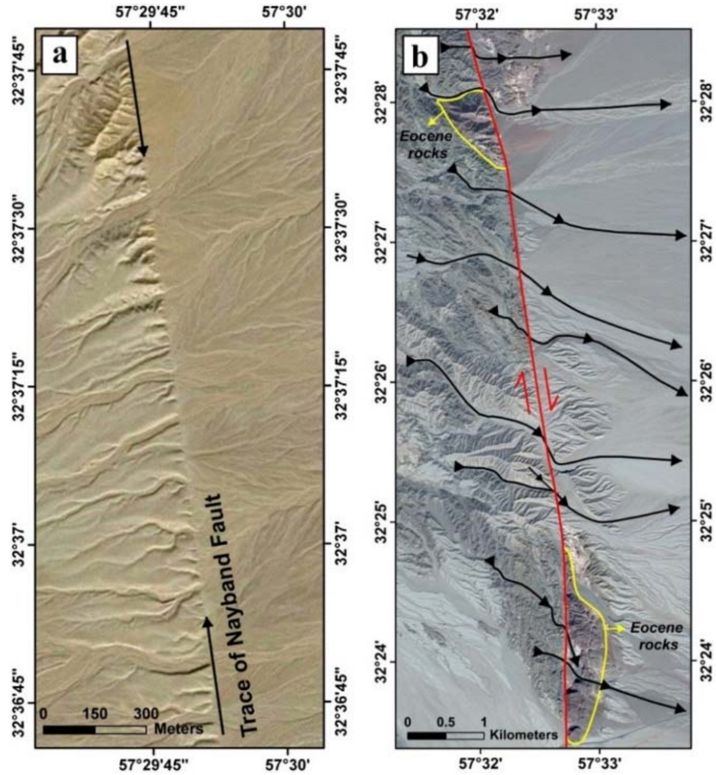

Fig. 6. (a) Quickbird image (from Google Earth) of the Nayband fault as it cuts across a series of alluvial fans. (b) Quickbird image of (from Google Earth) river offsets along the Nayband Fault. Offsets clearly show the position of the fault. The largest river offset is about 1 km long. The yellow units (Eocene rock units) make an offset of more than 7 km.

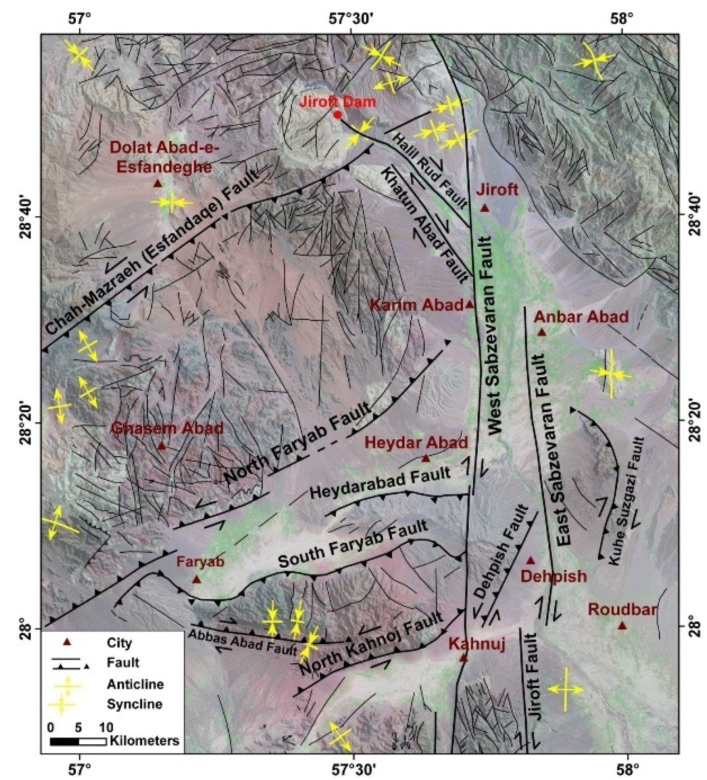

Figure 7. Sub branches of the Sabzvaran fault system in Jiroft-Kahnooj area.

MORPHOTECTONICS OF JIROFT-KAHNOOJ AREA

A large number of active faults, which cut through Quaternary units, are connected to the Sabzevaran system including Chahmazrae, North Faryab and North Kahnoj, all NE-SW- striking. Heydarabad and South Faryab. almost E-W- striking, and Halil Rud and Khatoun Abad, both NW-SE-striking (Fig.7). The right-lateral strike-slip motion along the Sabzevaran fault has resulted in shearing and thrusting of the recent rock units and alluvial fans along these fault branches.

MORPHOTECTONICS OF THE SOUTHERN MARGIN OF THE LUT BLOCK (BAM AND KAHORAK FAULTS)

In the southern margin of the Lut Block, along Bam and Kahorak faults, there are some evidences related to active faulting, such as river offset, folding, Quaternary faulting, and etc. These morphotectonic evidences young seismotectonic based on Bam and Kahorak activities in this area. According to the obtained results, these faults have strike-slip movements with a reverse component. Other faults in this area are Gohar, Giran-Rig, and the western segment of Jebal-Barez (Fig. 8). Along Gohar and Giran-Rig faults, we could find no morphotectonics evidences to define their mechanism, but with only some traces on satellite images.

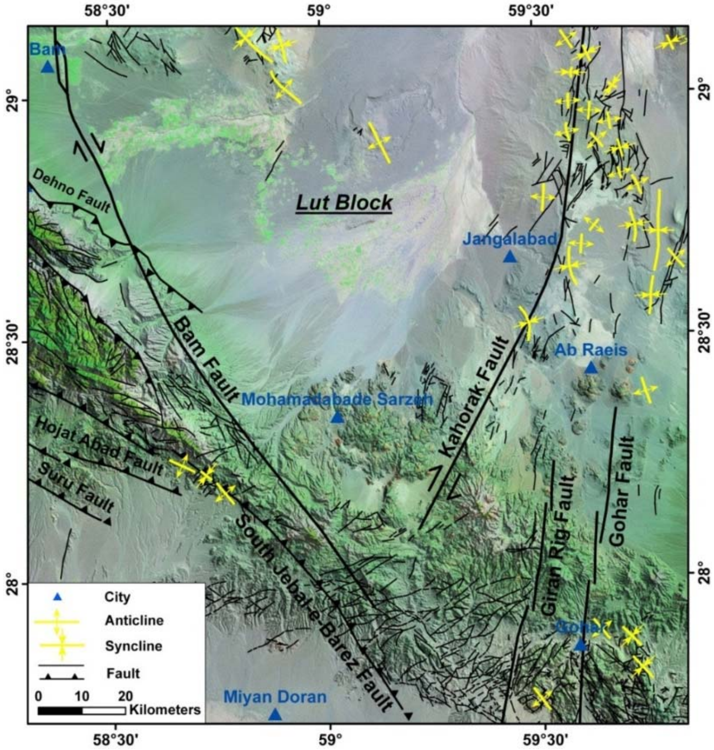

Figure 8. Structural map of the southern margin of the Lut block

SEISMICITY

The apparent lack of seismicity in the Lut block may be tentatively attributed to its relative rigidity (Berberian et al. 2001). The high level of seismicity along the western limits of this block is considered as a region of especially high seismic hazard (Fig. 9) (Ambraseys and Melville 1982; Berberian and Yeats 1999). Immediately westward of this high seismic hazard zone, the low level of seismicity corresponds with low GPS deformation rates (e. g. Vernant et al. 2004; Masson et al. 2007). Large earthquakes with different mechanisms (mostly strike-slip) occurred in the east and north-east part of the Lut block (Fig. 2). The pattern of seismicity in the east of the Lut block is diffuse and shows a higher level of seismicity relative to the western part of this block .

To further assess the correlation of the zone of high seismic activity along the western side of the Lut crustal block and the mapped major fault systems in the region, we computed 5 SW-NE cross sections striking about perpendicular to the main trend of seismicity (Fig. 9b). These cross sections (Fig. 9c) indicate that most of earthquakes occurred along known faults in depth range of 5 km to 20 km in the upper crust. For example, along profile-A a cluster dipping almost vertically can be observed which is connected at the surface to Golbaf-Sirch strike-slip fault system (GSF) that appears to play a significant role in transforming the remaining shortening from the South to the North (Berberian et al. 2001). The majority of the alignments in depth sections are near vertical, consistent with dominant strike-slip motion along Golbaf-Sirch, Kuhbanan and Posht-e Badam major faults in the Central Iran that accommodate additional N-S shortening by counterclockwise rotation in the horizontal plane (Walker and Jackson 2004; Mattei et al. 2012; Walperdorf et al. 2014).

The elongated zone of very high seismic hazard in the middle of Central Iran is following the NW oriented Kuhbanan fault (Fig. 9a).

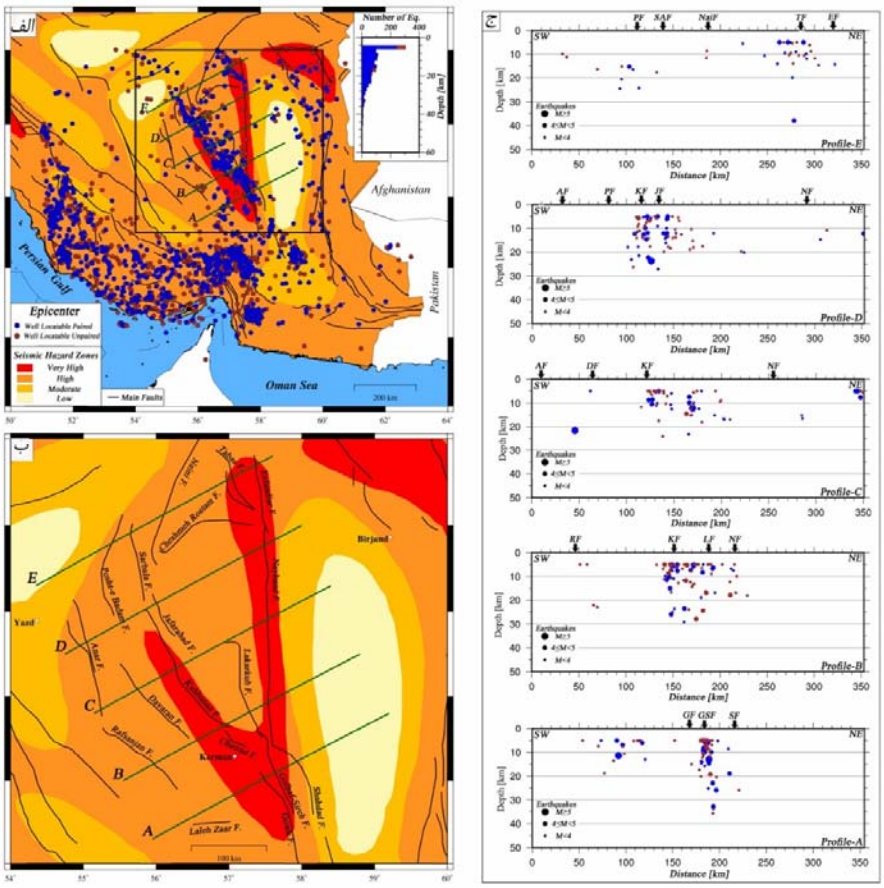

Figure 9. Hypocenter distribution of earthquakes in comparison with seismic hazard map (adapted from Moinfar et al., 2012). a: Seismicity map with hypocenter depth distribution shown by inset in upper right corner. b: Seismic hazard map with main fault systems in the western margin of the Lut block with location of different profiles. c: depth distribution of earthquakes along different profiles from bottom to top along profile A to E. GF: Gowk fault; GSF: Golbaf-Sirch fault; SF: Shahdad thrust fault; RF: Rafsanjan fault; KF: Kuhbanan fault; LF: Lakarkuh fault; NF: Nayband fault; AF: Anar fault; DF: Davaran fault; JF: Jafarabad fault; PF: Posht-e Badam fault; SAF: Sarbala fault; Naif: Naini fault; TF: Tabas fault; EF: Esfandiar fault.

CONCLUSIONS

In this study, we consider some fault systems including Nayband, Gowk, Sabzevaran, Bam, Kahorak as known ones and Gohar with Giran-Rig as unknown ones. A large number of active faults, which cut through Quaternary units, are connected to the Sabzevaran system including Chahmazrae, North Faryab and North Kahnoj, all NE-SW- striking. Heydarabad and South Faryab almost E-W- striking, and Halil Rud and Khatoun Abad, both NW-SE-striking. The right-lateral strike-slip motion along the Sabzevaran fault has resulted in shearing and thrusting of the recent rock units and alluvial fans along these fault branches.

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