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Characterizing two basement strike-slip faults in the Zagros Mountains; Razak and West Mand faults

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Abstract

The north-south trending strike-slip faults within the basement of the Zagros fold and thrust belt, which are inherited from the Pan-African construction phase, were reactivated during the suturing and convergence of Arabia and Central Iran since the Late Cretaceous and influenced the NW-SE trending structures of the Zagros belt. Among most of these transverse faults, the Kazerun fault which delineates the western boundary of the salt plugs in the Zagros belt near longitude 51.5°E is described in detail as the most significant transverse strike-slip fault recognized in the belt. Here, during the course of our investigations we found new evidence indicating that the north-south trending Kazerun fault system can be extended southwards to the coast of the Persian Gulf as evidenced by a prominent escarpment marking the west side of the Mand anticline as well as the observations of surface faulting associated with the right-lateral motion of recent geomorphic features. However, the north-south trending Razak fault has also been recognized as one of the major transverse faults in the Zagros basement. Right-lateral strike-slip motion along the Razak fault strands can be inferred from the associated lateral offset of stream beds observed on satellite images, aerial photos and on the field. Unlike what have been previously suggested, this study concludes that the southern ends of some of the north-south trending strike-slip faults which cross the NW-SE structures of the Zagros belt are not turned into thrusts striking ESE, sub-parallel to the fold axes, but instead the southern continuation of the north-south trending faults can be extended southwards to the coast of the Persian Gulf and Saudi Arabia.

Keywords: Strike-slip fault, Kazerun fault, Razak fault, Zagros mountains, active faulting

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1 Introduction

Many north-south trending lineaments and transverse strike-slip faults which cross the NW-SE structures of the Zagros fold-thrust belt have been developed during the latest Proterozoic and early Cambrian in the Arabian basement (see, e.g., Falcon, 1974; Haynes and McQuillan, 1991; Berberian, 1995; Hessami et al., 2001). During the Mesozoic, and especially in the Triassic and Late Cretaceous, the N-S uplifts and basins related to this group of basement faults were intermittently reactivated (Edgell, 1996; Sherkati and Letouzey, 2004; Sepehr and Cosgrove, 2005). The transverse basement faults which segment the Zagros seismic zone (Hessami et al., 2001) have a number of characteristic features in common. They are steep to vertical and strike-slip motion along them can be inferred from the associated lateral offset of geomorphic features (Bachmanov et al., 2004; Authemayou et al., 2005) and fold axes observed on geological maps and satellite images. Current seismicity indicates that the N-S trending basement strike-slip faults are still active (Hessami et al., 2001; Talebian and Jackson, 2004; Tatar et al., 2004).

In the NE of the Zagros Mountains, these strike-slip faults bend to the NW before terminating at the Main Zagros Reverse Fault or its continuation, the Main Recent Fault. The southern ends of most of the north-south trending strike-slip faults in the cover appear to turn into thrusts striking ESE, sub-parallel to the fold axes. However, in the basement, the southern continuation of the north-south trending faults can be traced through the NE portion of Arabia by both the structural trend of the oil fields attributed to movement along basement faults (National Iranian Oil Company, 1975, 1976; McQuillan, 1991) and gravity highs associated with the initial basement stretch (Stern and Johnson, 2010). Thus, it is likely that these N–S trending structures are related to structures with the same trend in Saudi Arabia, and which are known to have acted as normal faults in Palaeozoic times (Ziegler, 2001).

This study uses the observations of faulting recognized on satellite images and aerial photos, in conjunction with field investigations, to detect southernmost segment of the Kazerun fault system and to infer its fault activity. Moreover, based on the recent observation of offset stream beds along the southernmost section of the Razak fault which is clearly exposed at the ground surface, we revise its mechanism and describe the geomorphic features associated with its recent activity.

2 Tectonic setting

The NW-SE trending Zagros fold and thrust belt (Figure 1) extends for about 1,600 km from a location some 300 km southeast of the East Anatolian Fault in northeast Turkey (which is in Taurus Mountains) through northern Iraq and southeast Iran, to the Strait of Hormuz where the north-northwest trending Zendan-Minab fault system (Regard et al., 2005) separates the Zagros belt from the Makran accretionary prism.

The NE limit of the Zagros belt is marked by the Main Zagros Reverse Fault (MZRF), also named as Main Zagros Thrust (MZT), which is rotated about a horizontal axis to form a steeply NE-dipping to sub-vertical reverse fault (Stöcklin, 1974; Berberian, 1995). The extension of the Main Zagros Reverse Fault to the NW of latitude ~33°N is referred to as the Main Recent Fault (Tchalenko and Braud, 1974) which is a right-lateral strike-slip fault as indicated by offset geomorphic features and earthquake focal mechanism solutions (Talebian and Jackson, 2002).

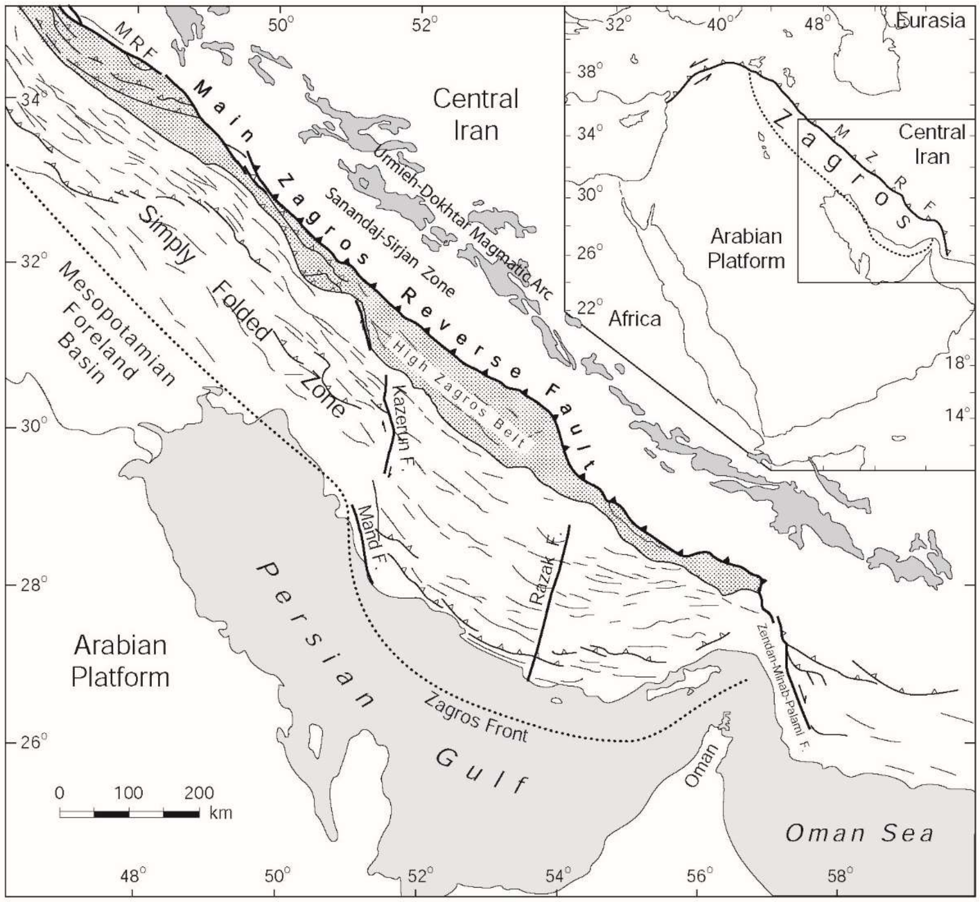

Figure 1. Location map and Zagros Mountains (southwest Iran).

There is no clear surface boundary to the frontal edge of the Zagros fold and thrust belt where folding is gentle both on land and beneath the Persian Gulf. However, the southern edge of the Zagros deformation front can be defined at different levels by the shape in map view of the oil- and gas fields (Talbot and Alavi, 1996).

The only exposed basement rocks within the Zagros fold and thrust belt are a few blocks of igneous and metamorphic rocks brought to the surface in salt diapirs (Haynes and McQuillan, 1991; Jahani et al., 2009). The role of tectonic events, in particular extensional faulting, has been suggested as the main cause for initial salt movements in SE Zagros during Early Paleozoic rifting. However, current extrusion of the salt diapirs may be controlled by transverse faults in the Zagros basement (McQuillan, 1991; Talbot and Alavi, 1996; Hessami et al., 2001; Koyi et al., 2008). All the transverse strike-slip faults in the Zagros basement have inherited their roughly north-south strikes from "the old grain of Arabia", which can be traced from the Central and Southern Red Sea (Ziegler, 2001; Stern and Johnson, 2010). These faults are known to be the surface manifestations of old Pan-African structures which have controlled the facies and thickness of sediments deposited since at least the Jurassic-Cretaceous, and which have influenced the styles of their subsequent deformation (Sepehr and Cosgrove, 2005).

The thickness of sedimentary cover deposited on the shelf along the northern margin of the Arabian Plate ranges between 5 and 13 km but is not known in detail (Falcon, 1974; Alavi, 2004). The sedimentary cover of the Zagros fold and thrust belt is decoupled from its underlying basement along the Lower Paleozoic shales or the Late Precambrian Hormuz Salt Formation (Jahani et al., 2009). The cover contains two other evaporite sequences of Late Jurassic (Hith Formation) and Early Miocene (Gachsaran Formation) ages. The latter plays a significant role in the deformation of the cover locally (Sherkati and Letouzey, 2004; Casciello et al., 2009).

Plate reconstructions show that deformation within the Zagros fold and thrust belt is due to the relative convergence between Arabia and Asia (Central Iran) since late Early Cretaceous, i.e., Late Aptian (Farahpour and Hessami, 2012). This convergence which is attributed to subduction of the NE margin of Neotethys beneath Central Iran (Agard et al., 2005) in Turonian-Coniacian time led to the emplacement of ophiolites onto the northern edge of the Arabian Plate and the Oman Peninsula (Sherkati and Letouzey, 2004) and to the development of a tectonically controlled foreland basin system to the southwest of this orogen (Farahpour and Hessami, 2012). This emplacement predated the final closure of Neotethys and the suturing of Arabia with Central Iran, which was completed in the late Oligocene-Miocen time (Barrier and Vrielynck, 2008; Agard et al., 2005).

Most focal mechanism solutions of earthquakes in the Zagros region indicate the presence of active reverse faults (Berberian, 1995). The most recently determined focal depths (8-14 km) imply that moderate to large earthquakes occur in the uppermost part of the Arabian basement, beneath the Hormuz Salt Formation (Talebian and Jackson, 2004; Tatar et al., 2004). These observations have led many workers to suggest NE-dipping reverse faults in the basement. Although the focal depths of the small earthquakes are not well known, they are likely to mark thrust faults in the cover sediments (Koyi et al., 2000) that sole out in both/either the deep Hormuz and/or the shallow Gachsaran salt layers.

Focal mechanism solutions of the earthquakes along the transverse faults within the Zagros region are interpreted as steeply-dipping strike-slip faults with minor components of dip-slip movement. Most of these solutions are consistent with right-lateral movement on nodal planes parallel to NNW-trending faults.

The present crustal shortening associated with the convergence between Arabia and Eurasia is clearly shown in recent Global Positioning System (GPS) results spanning Iran (Khorrami et al., 2019). These velocity estimates show that Arabia moves at 21–25 mm/yr due north relative to Eurasia. However, deformation is distributed differently over several active deforming zones. In eastern Iran shortening is distributed over the Makran subduction complex (up to 19 mm/yr) and the Kope-Dagh Mountains (about 6 mm/yr). To the west, shortening is distributed over the Zagros (about 7 mm/yr), and Alborz Mountains (about 5 mm/yr). Right-lateral displacement takes place in western Iran mainly along the Main Recent Fault (about 3 ± 2 mm/yr) and the North Tabriz fault (up to 8 mm/yr). The area located between Zagros and Alborz moves due north at about 14 mm/yr as a rigid block with respect to Eurasia, while eastern Iran moves at slower rates and the eastern most station does not move at all. The contrast between the velocity vectors in west-central Iran and eastern Iran takes the form of right-lateral strike-slip motion along the north-south trending faults bounding the Lut block.

3 Observations and discussion

3-1 Razak fault

Barzegar (1994) used remotely-sensed data to detect a number of strike-slip faults in the SE Zagros. Most of these faults had been already identified as structural anomalies on geological maps (National Iranian Oil Company, 1975, 1976) and are consistent with the alignments of salt plugs (McQuillan, 1991; Koyi et al., 2008). The Razak fault was detected on an image from the Gemini spacecraft (Barzegar, 1989) (Figure 2), but could not be clearly identified on Landsat images (Figure 3) because the north-south descending orbit of the Landsat almost parallels its trend (Barzegar, 1994). Based on distortion of fold axes in the sedimentary cover and displacement of seismic zones in the basement, Hessami et al. (2001) suggested that the Razak fault is a left lateral strike-slip fault. However, no seismological evidence could be seen to support the existence of left lateral faults in the SE Zagros belt (Talebian and Jackson, 2004).

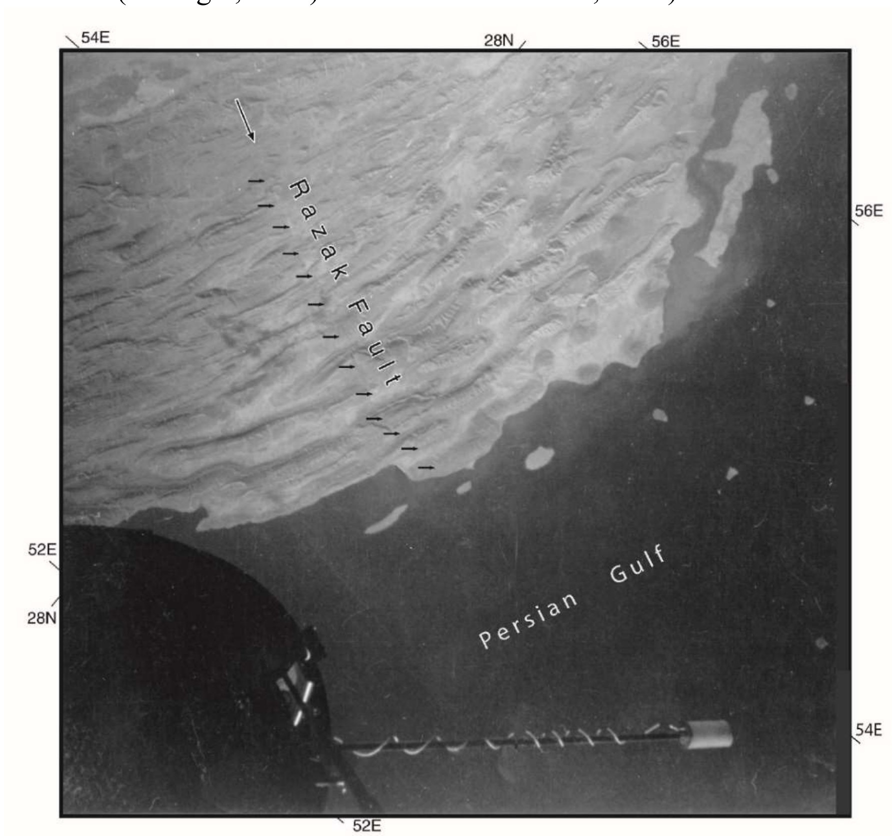

Figure 2. Gemini satellite image of the Razak fault (arrowed) (after Hessami et al., 2001).

The Razak fault is a NNE trending fault situated ~47 km east of Jahrom, with a total length of about 200 km. During the course of our present investigations we found new evidence along the southernmost end of the Razak fault indicating some prominent escarpments marking the west side of the Chiru anticline (Figure 4). We also made observations of surface faulting associated with strike-slip motion of recent geomorphic features; streambeds have been offset in a right-lateral sense along several parallel fault strands at this locality (Figure 5). Due to strike-slip motion along these segments, small gullies incised within the young alluvial fan are displaced right-laterally for about 10-15 m and vertical displacements are measured for about 2-3 m (Figure 6). Moreover, topographic profile across the fault zone shows that the eastern block is downthrown with respect to western block suggesting that the strike-slip motions are associated with vertical displacements (Figure 7).

Figure 3. Landsat satellite image (Google Earth) of the Razak fault (arrowed).

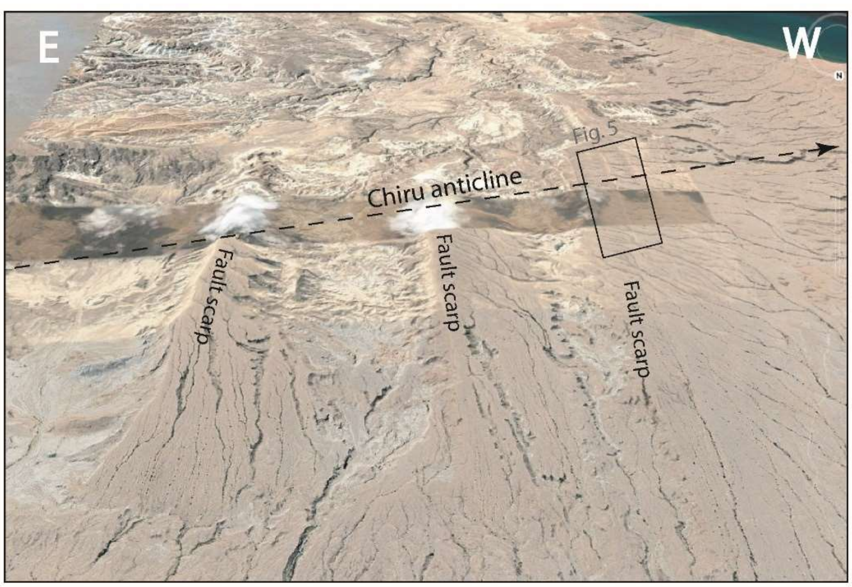

Figure 4. Satellite image (Google Earth) shows N-S trending fault scarps marking the west side of Chiru anticline. Rectangle encloses Figure 5. See Figure 3 for location

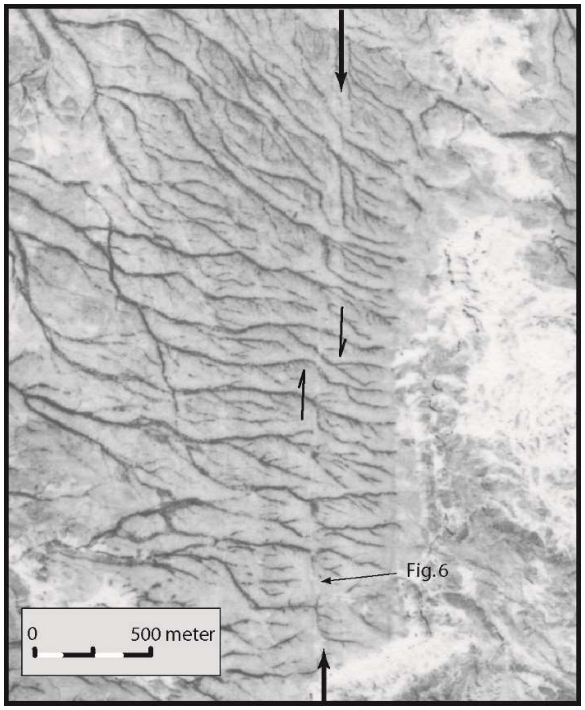

Figure 5. Arial photograph shows N-S trending surface faulting associated with strike-slip motion. Gullies have been offset in a right-lateral sense along one of the fault strands at this locality. See Figure 4 for location.

Although we did not succeed to observe the fault plane directly in the field, slip vectors deduced from focal mechanism solutions of the area's earthquakes along other right-lateral strike-slip faults in the SE Zagros (Talebian and Jackson, 2004) suggest that the vertical displacements might be resulted from a normal component of motion. However, since the absolute age of the offset fan is not known, slip rate along the Razak fault remains unknown.

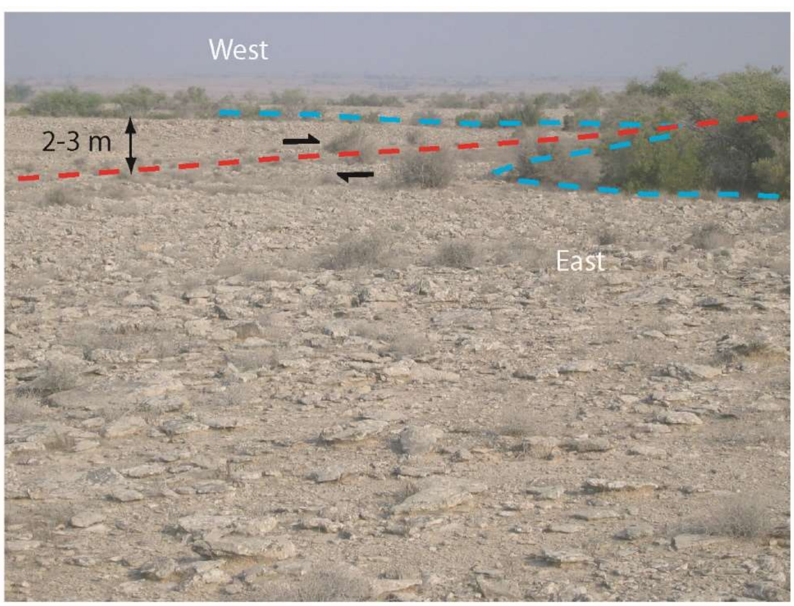

Figure 6. Fault trace (red dashed line) showing vertical component, down to the east. Right-lateral offset is clear in the river delineated by blue dashed line. See Figure 5 for location.

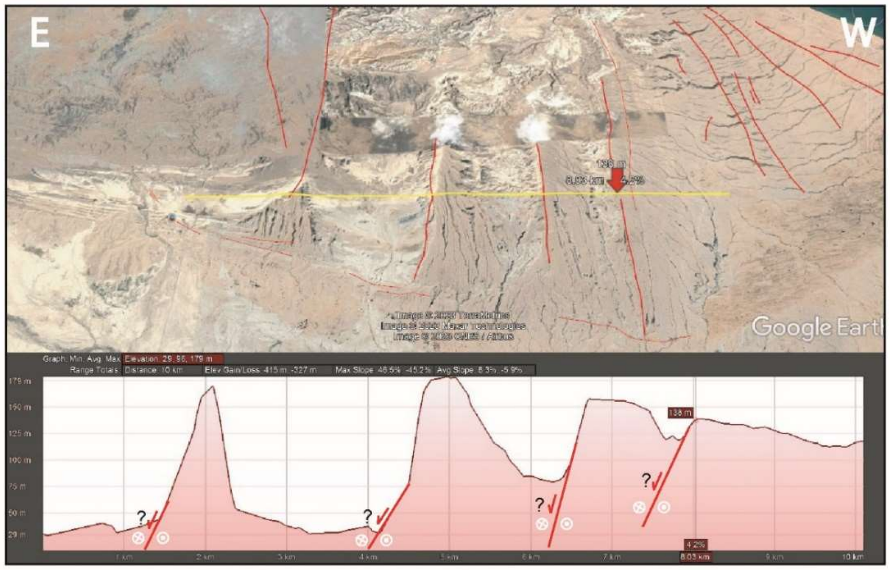

Figure 7. Topographic profile across the Razak fault strands. The eastern blocks are downthrown with respect to the western blocks. The strike-slip fault segments may be associated with a normal component of motion (see text for explanation). Topo section is plotted at ×20 vertical exaggeration.

3-2 West Mand fault

Here we present structural and geomorphic evidence to introduce the north-south trending west Mand (also known as Mond) fault lying to the south of the Kazerun fault, as the southernmost segment of the Kazerun fault system. The Kazerun fault system is a north-south trending strike-slip fault zone, which crosses the Zagros belt at about longitude 51.5˚E and separates the northwestern and southeastern Zagros regions (Figure 1). It has been described as the most prominent of a number of north-south lineaments that cross the Simple Folded Belt in Central Zagros (Baker et al., 1993; Berberian, 1995; Talbot and Alavi, 1996; Sepehr and Cosgrove, 2005).

The Kazerun fault limited the distribution of the Late Precambrian Hormoz salt (i.e., the major decollement horizon that separates the Precambrian basement from the overlying sedimentary cover) to the west. Lateral offset of Zagros fold axes and stream beds have frequently been invoked to confirm right-lateral displacement along this fault. Cumulative right-lateral displacement of 140 and 150 km of the Mountain Front Fault (MFF) and the Zagros Foredeep Fault (ZFF) can be measured respectively along the Kazerun fault (Berberian, 1995). Furthermore, focal mechanism solutions of earthquakes imply current right-lateral motion on nodal planes parallel with the Kazerun fault (Baker et al., 1993; Talebian and Jackson, 2004).

Sepehr and Cosgrove (2005) presented a new interpretation for the evolution of the Kazerun fault zone and argued that at the surface, the fault zone can be delineated by four north-south trending segments including, from north to south, the Sisakht, Yasuj, Kamarij and Borazjan segments. However, according to Authemayou et al. (2005), the Kazerun fault system is made of three north-trending fault segments of equivalent length (~100 km long), i.e., the northern (Dena), the central (Kazerun) and the southern (Borazjan) segments. Both these studies agree that the same Borazjan fault forms the most southerly segment of the Kazerun fault system. However, based on geometrical characteristics recognized during the course of this study, we detected four main segment boundaries which led us to define two sets of fault

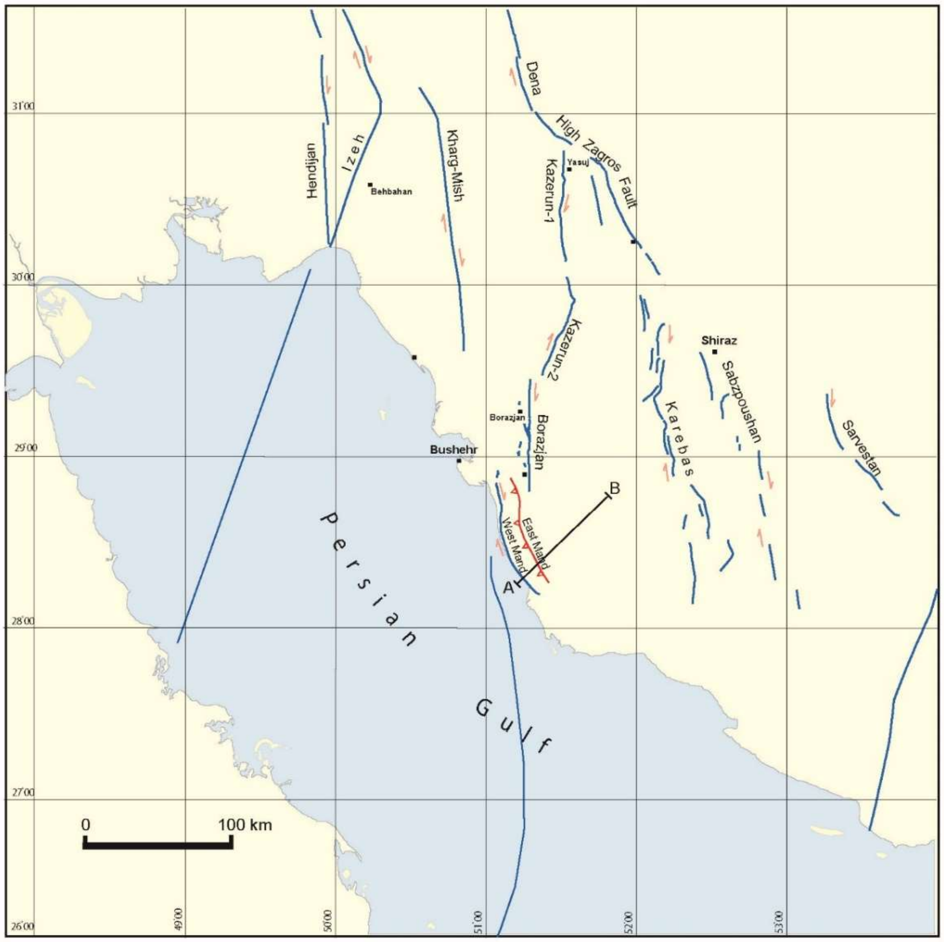

Figure 8. Main N-S trending strike-slip faults in the Central Zagros. Fault traces in the Persian Gulf are adapted from Stern and Johnson (2010) and National Iranian Oil Company (1976).

segments along the Kazerun fault system; the northern set and the southern set (Figure 8). A sharp bend along the Kazerun segment marks the segment boundary of the two sets. The northern set consists of two left-stepping segments of Dena (in the north) and Northern Kazerun (denoted as Kazerun-1) with a gap of about 15 km in between. The southern set consists of three right-stepping segments of Southern Kazerun (denoted as Kazerun-2), Borazjan (center) and West Mand (in the south).

Therefore, here, we consider the NNW trending West Mand fault as the southernmost segment of the Kazerun fault system (West Mand on Figure 8). The West Mand fault segment, with a length of about 87 km, lies southwest of the Borazjan segment with a right-stepping gap. The West Mand fault had been previously identified as the Zagros foredeep reverse fault by Berberian (1995). There are two convincing lines of evidence that movement on the West Mand strike-slip fault in the basement has resulted in folding of the Mand anticline. The first comes from observation of one N-S trending fault scarp which is clearly visible on satellite images and in the field (Figure 9, north of Mand anticline, 2.7 km east of Chah Talkh). Due to strike-slip motion along the West Mand segment, small gullies are displaced right-laterally for about 12 m and vertical displacements

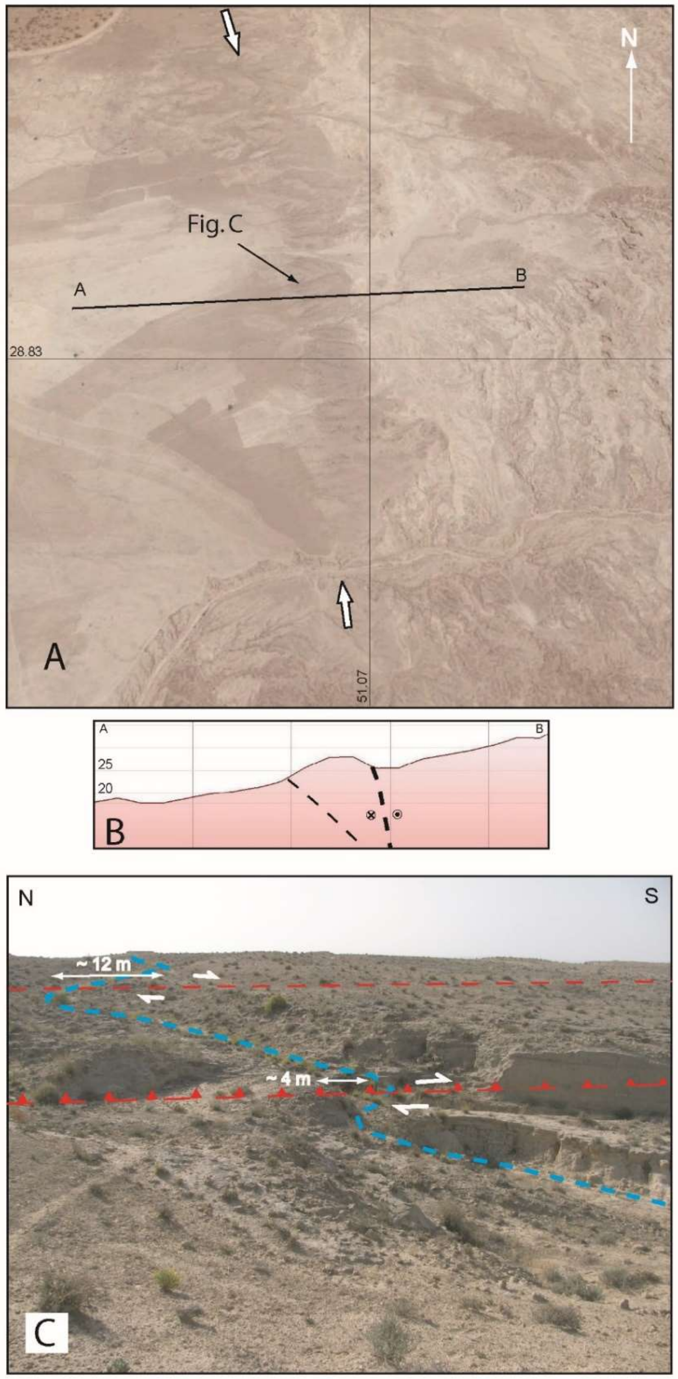

Figure 9. Satellite image (Google Earth) and field photo of West Mand fault scarp associated with right-lateral motion of recent geomorphic features. Location of the photo (C) is shown on (A).

are measured for about 5-8 m.

Focal mechanism solution of the 02/03/2004 earthquake (Mw 5.1) located in the close vicinity of this fault scarp involves right-lateral movement on the NNE trending nodal plane (Figure 10). The 01/04/1981 (Mw 5.2) earthquake also seems to be associated with reactivation of the West Mand fault segment. CMT solution of this event indicates right-lateral movements with a reverse component on a NNW trending nodal plane parallel with the West Mand fault segment.

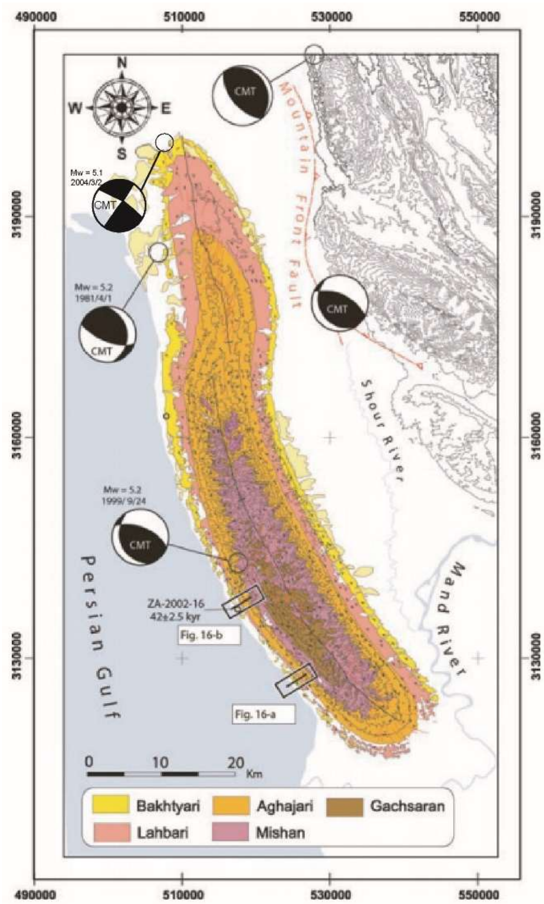

Figure 10. Topographic and geological map of the Mand anticline with elevation contour lines every 100 m. Focal mechanism solutions for large earthquakes from the Harvard CMT database are also indicated (Modified after Oveisi et al., 2008).

The second line of evidence comes from experimental works on analogue models designed to study the effect of basement strike-slip faults on cover rock sequences (see, e.g., Richard and Krantz, 1991). The analogue models show that buckle folds can be formed in the cover rocks as a result of strike-slip movements in the basement. These types of buckle folds form with an aspect ratio (half wavelength to axial length ratio) of between 1:5 and 1:10.

Based on the above-mentioned discussion, we suggest that the Mand detachment anticline (as inferred by Sherkati et al., 2006 and Oveisi et al., 2008) may be produced because of movement on the West Mand basement strike-slip fault. Nevertheless, as it can be seen from the geological cross section (Figure 11), the east-northeastern side (back limb) of the Mand anticline is bounded by a seismically active back-thrust (East Mand on Figure 8). The East Mand reverse fault is associated with the 24/09/1999 (Mw 5.2) earthquake.

4 Concluding remarks

In this study, we detected the southern extension of the Kazerun fault and used observations of faulting recognized on satellite images, in conjunction with field investigations, as well as focal mechanism solutions of earthquakes to infer fault activity along the West Mand right-lateral strike-slip fault. We also described the

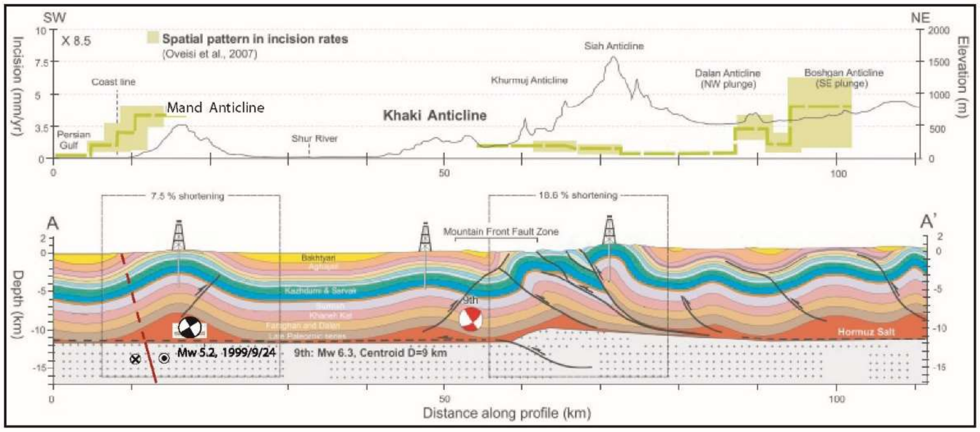

Figure 11. Topography and geological sections across the Mand and Khaki anticlines. CMT solutions of 24 September 1999, Mw 5.2 and 9 April 2013, Mw 6.2 events are plotted onto section. Note that a back-thrust has developed on the back-limb of the Mand anticline. Focal mechanism of the 1999 earthquake and distribution of micro-seismicity confirm the existence of the back-thrust. Field observations and fault plane solutions of earthquakes suggest existence of a right-lateral strike-slip fault beneath the Mand anticline in the basement (Modified after Elliott et al., 2015). See Figure 8 for location.

introduced Razak srike-slip fault that has been relatively obscured by the dominant younger NW-SE trending structural features of the Zagros fold-thrust belt (Figure 1). Right-lateral strike-slip motion along this structure can be inferred from the associated lateral offset of stream beds observed on satellite images and in the field. However, topographic profile across the Razak fault zone shows vertical component of displacement in recent deposits varying from place to place, but in any case, the dip slip component is subsidiary to the main right-lateral strike-slip movement.

Many early studies have emphasized that the southern ends of most of the north-south trending strike-slip faults, which cross the NW-SE structures of the Zagros belt, are turned into thrusts striking ESE, sub-parallel to the fold axes. However, here we showed that the southern continuation of at least some of the north-south trending faults can be extended southwards to the coast of the Persian Gulf. This conclusion confirms the previous postulation suggesting the north-south trending structures in the Zagros belt are related to structures with the same trend in Saudi Arabia.

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