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Influence of the Basement Strike-Slip Fault on the 2005 and 2014 Earthquakes, Qeshm Island, Iran

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ABSTRACT

The Zagros belt in southern Iran is amongst the world's most seismically active mountain ranges that accommodates a significant portion of the convergence between Arabian and Eurasia Plates. Due to the larger earthquakes in Zagros, which have strike-slip focal mechanisms without any coseismic ruptures at the surface; it is important to identify the source of these earthquakes in the basement. The 2005 and 2014 earthquakes with Mw=5-6 in Qeshm Island are examples of them. The NE-trending Gachin fault zone is one of the main transverse faults that cross cut the major structures of Bandar Abbas zone and continues to the Persian Gulf; in which deformations of the fault are overprinted on the major structures. Based on the field, remote sensing and sismotectonic studies; the Gachin fault zone is the main cause of the recent deformations on the Quaternary sediments in Qeshm Island and its activities are continuing to present time; therefore, the above-mentioned earthquakes were caused by this fault. In other words, the convergence between Arabian and Eurasia Plates is in favour for the reactivation of Gachin fault zone in the basement as earthquakes.

Keywords:
Gachin Fault; Basement Strike-Slip Fault; Recent Deformation; Earthquakes; Qeshm Island

1. Introduction

Most of our findings of how continental crust accommodates plate tectonic motions comes from studies of the spatial distribution of seismicity in actively deforming mountain belts [e.g. 1-7]. The instrumental earthquake record offers a window in to the subsurface mechanics of the range, and has also been the focus of several previous studies [e.g. 1, 8, 9].

The Zagros belt in south-western Iran is one of the most rapidly deforming and seismically active fold and thrust belts in the Alpine-Himalayan belt, accommodating almost half of the present day shortening between Arabian and Eurasia Plates, which is ~25 mm yr^{-1} [10-11]. Though seismicity in Zagros is dominated by high-angle reverse faulting [12], strike-slip earthquakes have an important role in the Zagros range, where convergence is oblique. However, Zagros earthquakes only rarely rupture the surface [12]; because of the presence of Hormuz salt at the base of the ~10 km thick folded sedimentary cover [e.g. 13-15], together with the usually absent indication of coseismic ruptures at the surface, earlier studies concluded that the larger strike-slip earthquakes in Zagros involve faulting mostly within the basement [e.g. 1, 8, 9]. An increasing number of studies show that patterns of occurrence of earthquakes may bring relevant information on the location and time of occurrence of future major earthquakes [16-21].

There have been few documented studies about seismicity of Qeshm Island [5, 22, 23, 24]. In this article, active faults in the study area have been investigated and the main cause of the recent deformations as earthquakes was introduced. Here, we combine the surface geological information with seismology of main strike-slip earthquakes together with field observations to estimate the source of the earthquakes and investigate the result of recent deformations in Qeshm Island. The purpose of this paper is also to document deformations along the Gachin fault zone and recognition of the fault pattern on the surface. The manuscript is also aimed at determining geometric and kinematics variations of structures along the Gachin fault zone for better understanding of the effect of the fault zone on structural development of the Zagros fold-thrust belt.

2. Methods

In this paper, to realize the recent deformation, subsurface and surface data analyses are done. Subsurface data include the depth and focal mechanism of earthquakes, and the surface data is the geometry of structures such as fold and faults on the cover sediments. Remote sensing study of the satellite images was utilized for initial recognition of the exposed structures in Qeshm Island and around it. Surface patterns such as topography, drainage pattern, spectral reflection of rocks, bending of fold axes, and geometry of young folds with en-echelon pattern were used for recognition of the fault zone. Upon the results obtained from the remote sensing study, some areas on the Island were selected for detailed field studies. Seismological approaches such as earthquake hypocentral locations and focal mechanism studies play an important role in the understanding of present activities in the area. Therefore, a seismic map of the region has also been used. In Zagros mountains, there are no dense local seismic or geodetic networks and we must rely on catalogs of teleseismically determined earthquake locations as the on-line moment tensor catalogs, such as CMT (Centroid Moment Tensor), USGS (United States Geology Survey) and IIEES (International Institute of Earthquake Engineering and Seismology).

3. Tectonic Setting

The Zagros Fold-Thrust Belt is one of the youngest mountain belts, located in the middle part of the Alpine mountain system. The NW-SE trending belt developed during the collisional stage between Arabian Plate and Central Iranian block [25-26]. On the other hand, Following subduction of the Neotethys Ocean beneath Central Iran during the Mesozoic and early Cenozoic, the NE Arabian margin collided with the central Iranian continental block, and the Zagros belt represents the deformed north eastern edge of the Arabian plate and existed as a passive continental margin, Figure (1), [e.g. 26-27]. Estimates of the onset of continental collision range are from the late Eocene [e.g. 28-29] to the mid-late Miocene [e.g. 30-31].

To the NE of Zagros, the suture between deformed Arabian margin sediments and volcanic and metamorphic rocks of central Iran follows the

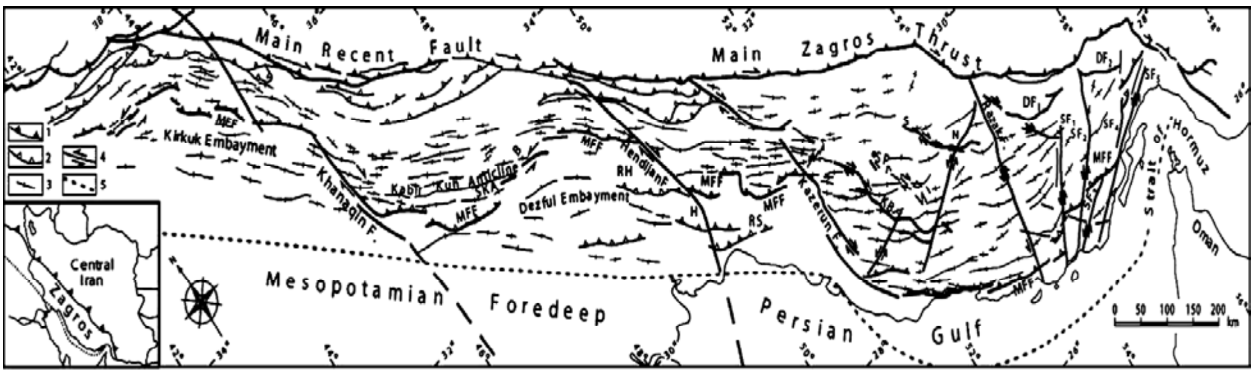

Figure 1. Structural map of the Zagros fold and thrust belt, showing major faults and anticline axes [39]. The numbers refer to high angle reverse fault, thrust fault, anticline axis, strike-slip fault and southern edge of the Zagros belt, respectively. MFF: Mountain Front Fault; SKA: Siah Kuh Anticline; B: Balarud Fault Zone; RH: Ramhormoz Fault; RS: Rag-e Sefid Fault; KB: Kareh Bas Fault; SP: Sabz Pushan Fault; S: Sarvestan Fault; SF1-SF5: left-lateral faults; DF1-DF2: right-lateral faults.

Main Zagros Reverse Fault or Main Zagros Thrust (MZRF in Figure 1), an important basement structure that marks the NE boundary of the range [e.g. 8, 32, 33, 34]. The NE of the MZRF, the Sanandaj-Sirjan zone contains metamorphosed rocks thought to belong to the Central Iranian continental block, although this area is sometimes included within Zagros itself [e.g. 35]. To the SW of the Zagros Mountains, the Mesopotamian foredeep basin (in the NW) and the Persian Gulf (in the SE) are foreland basins on Arabian Plate (Figure 1), lying at or near sea level with estimated crustal thicknesses of 40-50 km [e.g. 36-38].

The belt has been divided into two structural subzones including the High Zagros and the Zagros Simply Folded Belt from NE to SW that are distinct in their topography, geomorphology, exposed stratigraphy and seismicity. The High Zagros zone contains imbricate slices of Mesozoic and Palaeozoic sediments as well as ophiolites that were emplaced onto Arabian passive margin during the Late Cretaceous [26]. Its NW-trending thrust and reverse faults are well exposed at the surface, the most important ones being the Main Zagros Thrust and the High Zagros Fault in Figure (1). As mentioned before, this zone is separated from the Iranian plate along the Zagros orogeny suture zone (Main Zagros Thrust) (Figure 1), but GPS measurements suggest that it is no longer active except in the NW where it is coincident with the right-lateral Main Recent Fault [e.g. 40]. The HZF constitutes the boundary with the Zagros Simply Folded Belt.

The Zagros Simple Folded Belt, known as the Bandar Abbas zone in the study area [8], is very different from that of the High Zagros, having major structures parallel to the Zagros fold thrust belt. Thrust faults and related folds are the main structural elements of the belt that are transversely cross cut by two sets of subsurface fault zones developed during the late Alpine-Zagros orogeny [14, 39, 41-44]. The first set oriented NNW-SSE shows right-lateral strike-slip movement such as the Izeh, Kazerun, Sabzpushan and Sarvestan fault zones. The second set, NE-SW-oriented, has left-lateral strike-slip movement such as Balarud, Nezamabad, Firuzabad and Razak fault zones. The SE of the Zagros belt, Bandar Abbas zone, is dominated by the left-lateral strike-slip faults (Figure 1).

4. Geological Setting of Qeshm Island

Qeshm Island lies in the eastern Persian Gulf, ~10 km off the Iranian mainland, Figures (1) and (2). It is ~110 km in length and ~10 km in width, with ENE-trending, parallel to the mainland coast. Geologically, Qeshm Island bears many geological and structural similarities with the adjacent mainland; so it is part of the Zagros Simply Folded Belt and is dominated by folded Neogene marls and sandstones sediment at the surface [e.g. 45]. There are three major anticlines in the island that their fold axes do not follow parallel trends, EEN-WWS (Salakh anticline), NW-SE (Laft anticline) and NE-SW-trending (Suza anticline), Figure (2).

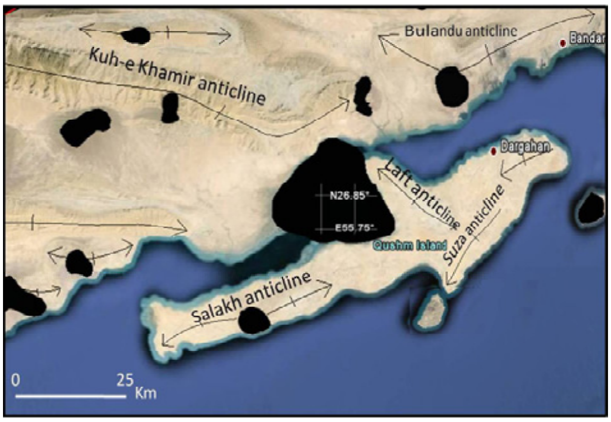

Figure 2. Major fold axes are marked with black lines on Qeshm Island satellite image. Black coloured polygons are salt domes.

Evaporites outcrop in the far western part of the island, where a salt dome (Kuh-e Namakdan) brings Cambrian Hormuz salt to the surface as a diaper in the core of Salakh anticline. Besides, we can see the big salt dome in the west of Laft anticline (Figure 2). These are two of many similar salt domes in the Simply Folded Belt. Hormuz salt outcrops in the cores of many anticlines in the Bandar Abbas zone. It is possible that Qeshm Island anticlines may also be cored with evaporites, although no salt is currently exposed at the surface [23].

The basement depth on the island is not known specifically. Spectral analysis of the aeromagnetic data [46-47] reveals a basement depth of ~16 km in the NW of Qeshm Island, on the mainland. While application of the half-slope method to individual magnetic anomalies yields depths of 10-17 km in the same area [48].

5. Recorded Earthquakes

Based on historical records, a few destructive earthquakes have inflicted damages on Qeshm Island in the past centuries. The location of earthquakes (of the twentieth century) in Iran shows that the island has been the locale of only a few background events, see Figures (3a) and (3b). As seen in Figure (3b), the island marks the southern edge of the Zagros fold system where seismicity of Zagros diffuses into the Persian Gulf. Nevertheless, from 2005 to 2015, the relative seismic quiescence of the island ended and a number of large and moderate earthquakes with depth>12 km shook the island during a ten-year period (Figure 3c and Table 1).

Here we focused on the two last main earthquakes in Qeshm Island; 27 November 2005 and 27 May 2014 with Mw=5.5-5.3 and depth=12-15.1 respectively (Table 1 and Figure 4). These earthquakes have strike-slip focal mechanisms (Table 1 and Figure 5). As the seismological approaches such as earthquake hypocentral locations and focal mechanism studies play an important role in the understanding of present activities of the area, the seismotectonic map of the region has been used in the following.

6. Structures along the Gachin Fault Zone

6.1. Major (Image Scale) Structures

The SE of Zagros belt (Bandar Abbas area) is dominated by the left-lateral strike-slip faults that are detected by Furst [41], 1-17 in Figure (4a). Generally, the trend of fold axes in the mainland Iran, north of the Qeshm Island that is part of Zagros, are mainly NW-SE, E-W, NE-SW which suggest a change in the trend of structures from west and central Zagros towards southeast where seismicity and mountain ranges disappear into Makran region (Figures 1 and 4a). Remote sensing studies of satellite images, show the presence of structures such as curvilinear geometry of the major

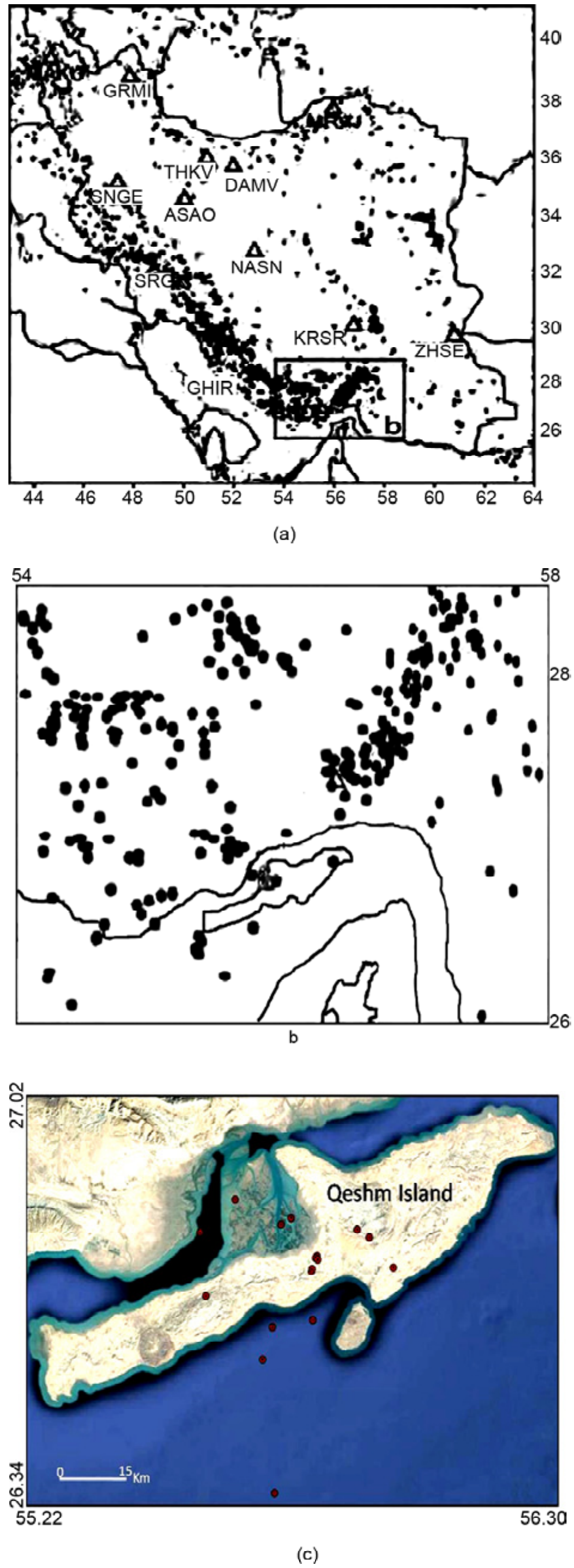

Figure 3. a) Seismicity of Iran from 1900 to the end of 2004 [22]. The study area has been marked by rectangle b on the map. b) Seismicity of Qeshm Island from 1900 to the end of 2004 [22]. c) Seismicity of Qeshm Island from 2005 to the end of 2015, only earthquakes with Mw>5, Table (1). Filled circles show the location of earthquakes.

Table 1. Date, location, magnitude and depth of Qeshm Island earthquakes from 2005 to the end of 2015. Data comes from CMT (Centroid Moment Tensor), USGS (United States Geology Survey) and IIEES (International Institute of Earthquake Engineering and Seismology). The strike-slip earthquakes studied in this research are highlighted.

Date	Latitude	Longitude	Strike 1	Dip 1	Rake 1	Strike 2	Dip 2	Rake 2	Mw	Depth Km
2005/11/27	26.66	55.8	257	39	83	86	51	96	5.9	12
2005/11/27	26.7	55.59	254	49	52	124	53	126	5	14.6
2005/11/27	26.65	55.89	218	87	2	308	88	177	5.5	12
2005/11/30	26.81	55.58	127	39	132	258	62	62	4.7	21.9
2006/06/03	26.72	55.83	111	45	112	260	49	69	5.1	12
2006/06/28	26.77	55.81	247	33	96	59	57	86	5.8	12
2008/09/10	26.65	55.72	234	33	76	71	58	99	6.1	12
2008/09/17	26.75	55.96	245	45	59	106	53	117	5.2	12
2008/12/07	26.82	55.74	69	41	115	217	53	69	5.4	12
2008/12/08	26.83	55.76	238	49	59	100	50	120	5.1	12
2008/12/09	26.75	55.8	241	33	73	81	59	101	5	14
2009/07/22	26.6	55.7	297	44	91	116	46	89	5.3	12
2012/01/09	26.86	55.65	242	45	36	125	66	129	4.9	17.2
2014/05/27	26.38	55.72	112	70	178	21	88	20	5.3	15.1

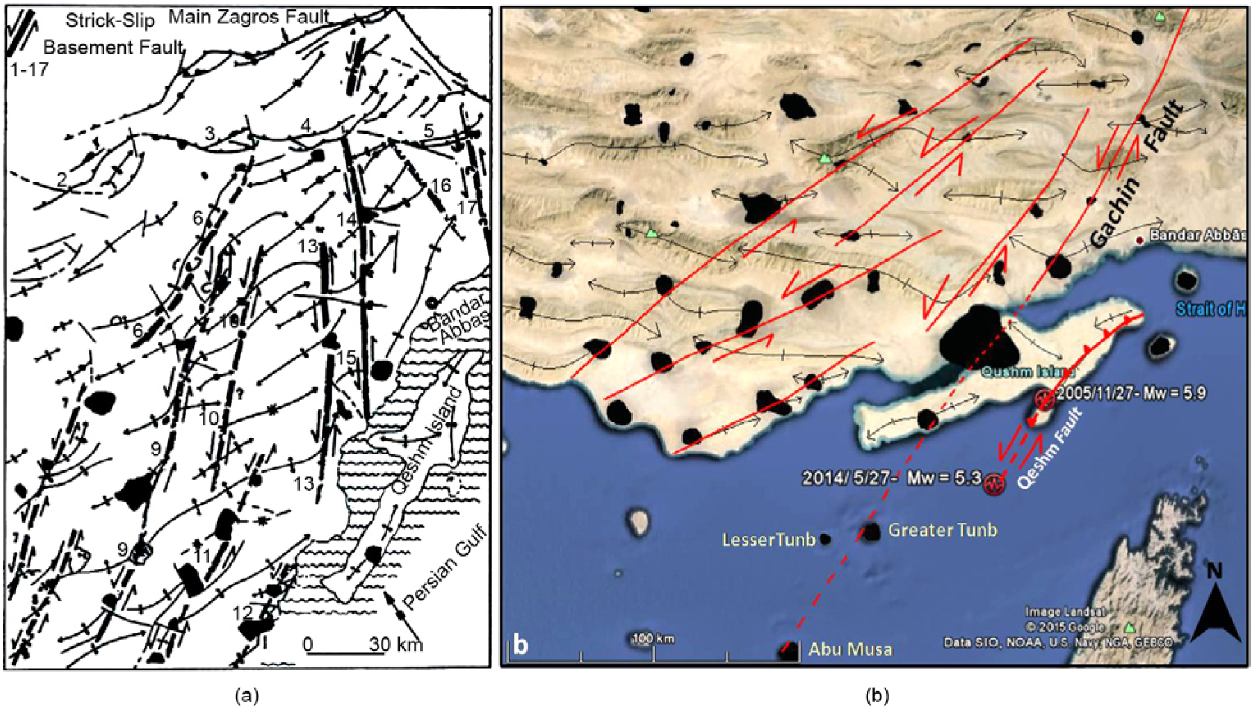

Figure 4. a) The left-lateral strike-slip faults in the Bandar Abbas area [41]. b) The satellite image of the study area shows left-lateral strike-slip faults and fold axial traces. The fault number 15 (a) is named Gachin fault in this article (b). Black coloured polygons are salt domes.

fold axial traces (Figure 4b), and bending of major reverse fault traces (HZF: High Zagros Fault; MFF: Zagros Mountain Front Fault and ZFF: Zagros Foredeep Fault), Figure (1), along the Gachin fault zone (the fault number 15 in Figure (4a) is named Gachin fault in this article). These signs can be seen along the other left-lateral strike-slip faults in Bandar Abbas zone [41] (Figure 4a). Due to the left-lateral deflection of Salakh anticline in Qeshm Island together with evaporates outcrop in the far western of the island where Kuh-e Namakdan (core of Salakh anticline), Lesser Tunb, Greater Tunb and Abu Musa salt domes are exposed as diapirs, it is suggested that the Gachin fault is continued toward Abu Musa Island, Figure (4b). Besides, as seen in Figures (4b) and (5), the Qeshm thrust fault has left-lateral bending as result of left-lateral reactivation of Gachin fault.

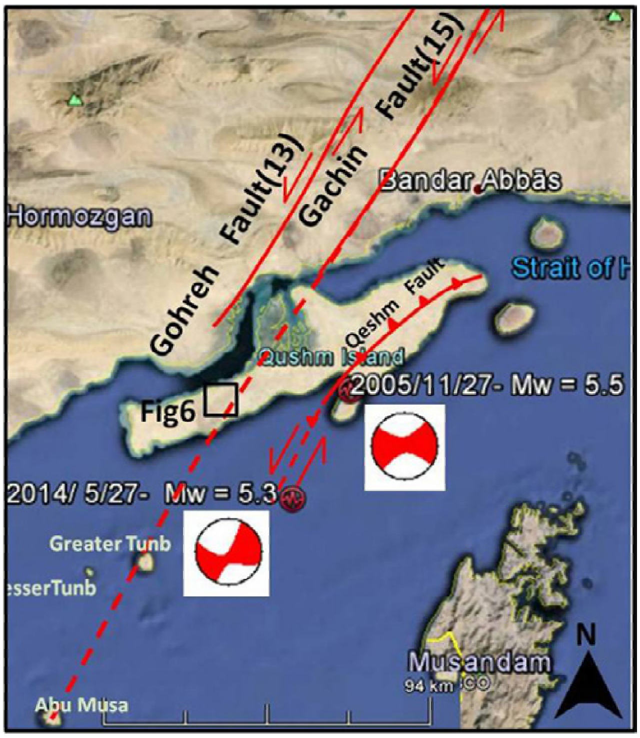

Figure 5. The satellite image of the study area shows Gachin and Qeshm faults. Location and focal mechanism of 2005/11/27 and 2014/5/27 earthquakes are illustrated. The position of Figure (6) is marked by black rectangle.

6.2. Minor (Field Observation) Structures

The NE-trending Gachin transverse fault zone has an influence on the structures of the entire cover sediment in the Bandar Abbas zone and Qeshm Island. Minor structures with different orientation than the behaviour of the belt major structures, which can only be recognized in the field, were studied along the Gachin fault zone. These structures, which are referred to as younger structures in this study were overprinted on the belt major structures. It should be noted that because of Gachsaran and Mishan formation special rheological behaviour during deformation, they were not included in the analysis. Field studies show that the frequency of minor folds in the folded belt is more than the faults, while in the High Zagros belt, faults are more abundant. Therefore, in this study area, minor folds are abundant. The minor structures along the Gachin fault zone were developed in both Tertiary (Pabdeh, Asmari and Aghajari formations) and Quaternary deposits. Such a distribution on the orientation and geometry of the minor structures in the zone reflect the presence of restraining zones across the Qeshm area along the Gachin fault zone. The structural map shows the location of minor fold structure and their stereograms related to the restraining zone (Figure 6).

Most of minor structures along the Gachin fault zone are developed on the alternation of soft marly siltstone and silty marl (Bakhtyari Formation equivalent) that usually covered by marine terraces with transitional bed that makes hard identification of small scale structures in this area. As the SW part of this fault zone, Qeshm Island, is covered by recent deposits, the minor folds and faults are observed difficulty. For example, some of the minor folds with SW-trending of fold axial traces are mapped in Qeshm Island, north of Kuh-e Namakdan salt dome (Figure 6). These folds are outcropped on the Quaternary sediments (Figures 7a and 7b). The geometry of the folds is gentle (Figure 7) with different orientations of the axes that are obviously clear, so that they change from parallel to the main fault zone to WSW toward the west of the fault zone (Figure 6c). Moreover, in this selected area, the streams are affected by some minor right-lateral strike-slip faults with en-echelon arrangement (Figure 7c), as P fractures (according to [49, 50]) within Gachin deformational fault zone (Figure 6). This geometry in a strike-slip fault system, generally produce either zones of restraining step-over regions or compression at restraining step-over regions [50].

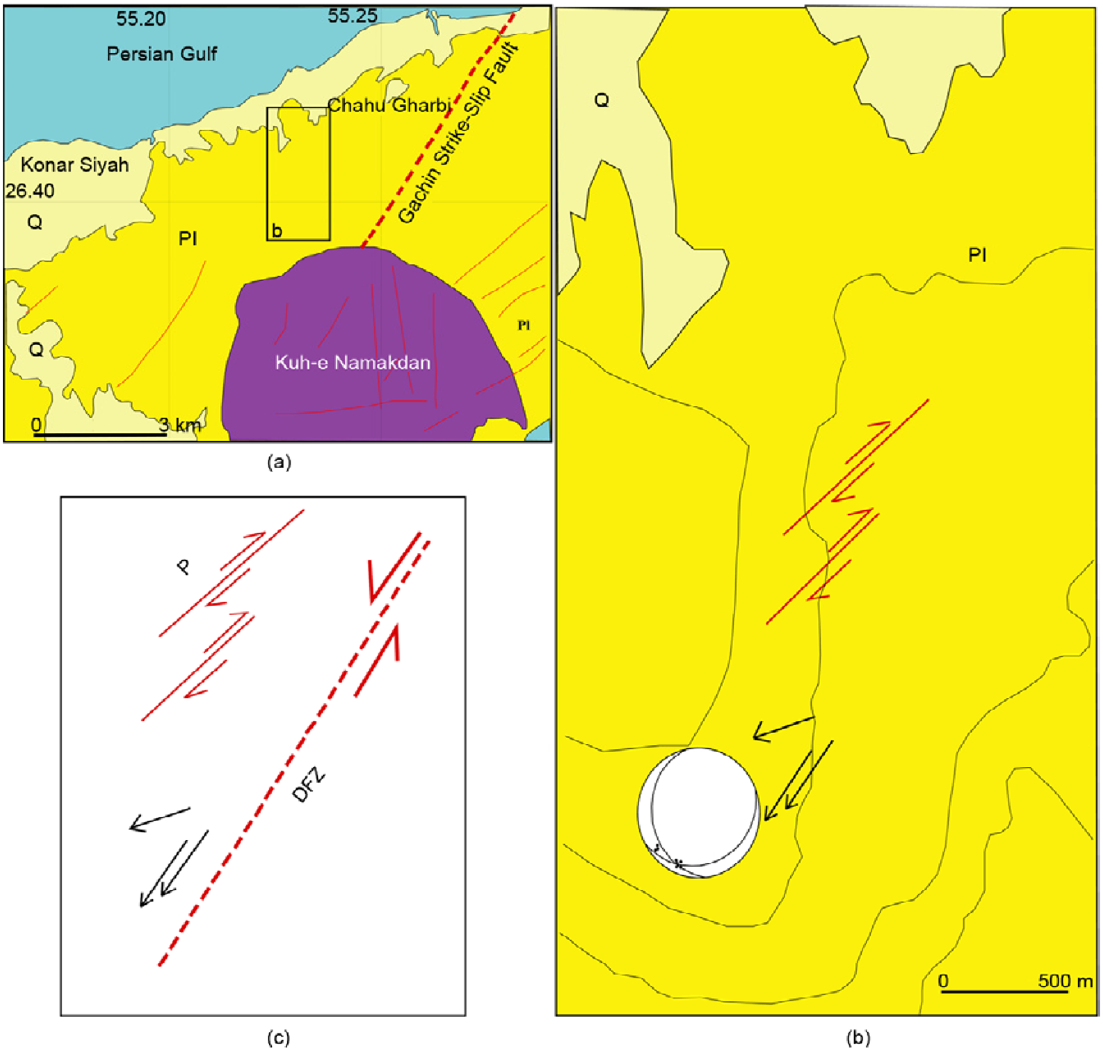

Figure 6. (a) and (b) The structural map of some minor folds and faults on the Quaternary sediments in the north of the Kuh-e Namakdan salt dome on the geological map of Qeshm, along the Gachin fault zone. The stereonets show limbs and fold axes. (c) Schematic model of the minor structures. The position of this Figure is marked in the Figure (5). DFZ: Gachin Deformation Fault Zone, Pl-Q: The Plio-Quaternary alternation of soft marly siltstone and silty marl (Bakhtyari Formation equivalent); Red line: Fault; Black arrow: Fold axis.

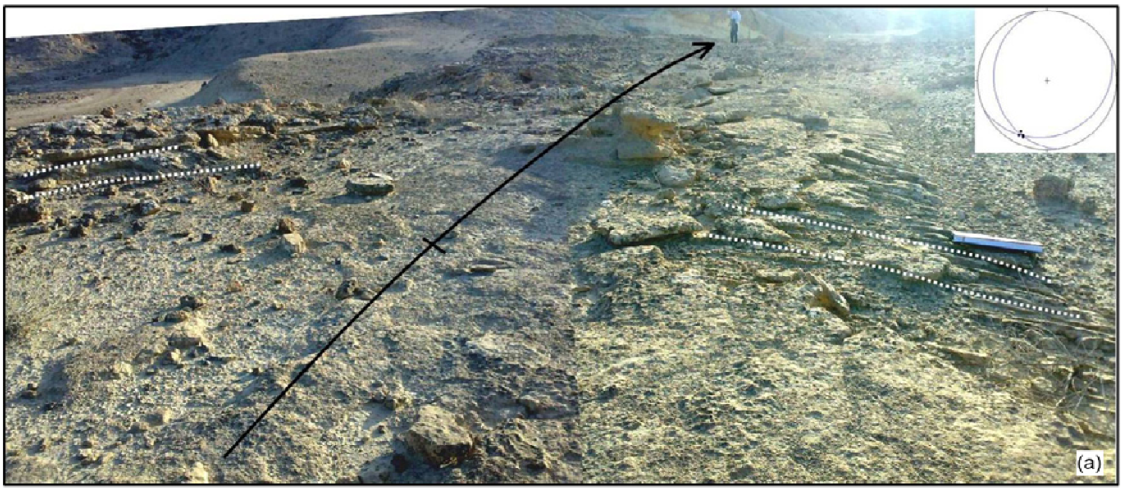

Figure 7. (a) and (b) Photos of minor folds on the Quaternary sediments of Qeshm Island. The stereonet shows fold axes (SW-trending). c. The offset of streams along right-lateral minor faults with SW-striking within the left-lateral Gachin fault zone in the island. Black line: Minor fold axis; White line: Bedding; Red line: Minor strike-slip fault; Blue line: Stream path. View of the photos: Toward south.

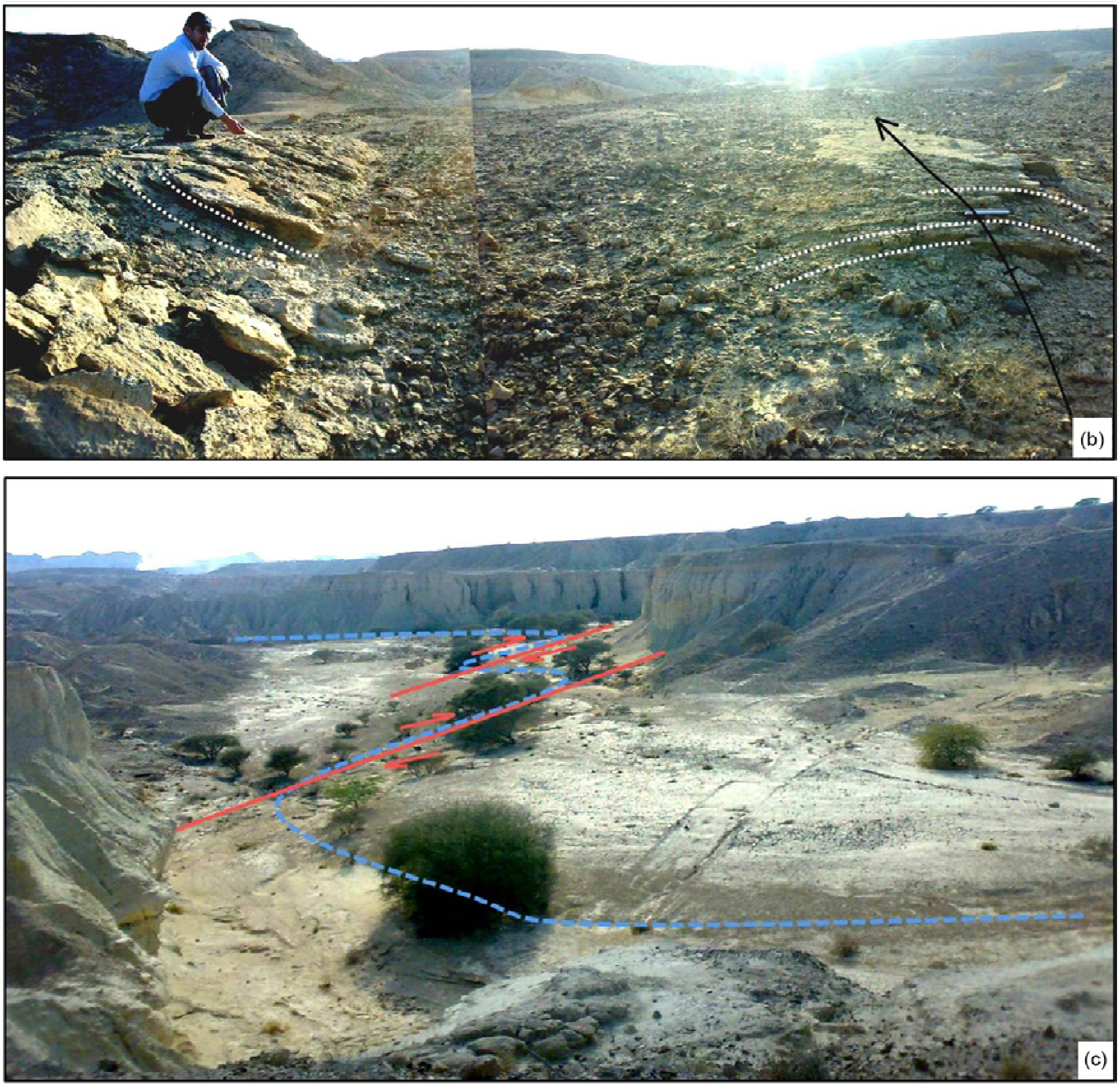

Figure 7. Continue.

7. Conclusion

The SE of Zagros belt (Bandar Abbas area) is dominated by the left-lateral strike-slip faults that are detected by Furst [41]. In this article, based on the field, remote sensing and sismotectonic studies; we believed that the NE-trending Gachin left-lateral strike-slip fault zone is the main cause of the recent deformations on the Quaternary sediments in Qeshm Island and surrounding areas.

The left-lateral strike-slip kinematics of the Gachin fault zone has interpreted using the curvilinear geometry of the major structures affected by the fault as well as the en-echelon pattern of minor structures developed within the fault zone. Remote sensing studies of the satellite images along the fault zone, show the presence of such structures as curvilinear geometry of faults and fold axial traces as well as Salt dome outcrops (Figure 4). The major structures of Zagros in this area are left-laterally deflected where they pass the Gachin fault zone (Figure 4). This happens only on the trace of the major structures the length of which is longer than the width of the fault zone. This interpretation is compatible with the field study [e.g. 51-52] and experimental modelling [53, 54] on similar strike-slip fault zones.

Other significant structures, such as minor folds and faults, can only be mapped by field studies. These minor structures can be recognized on Quaternary sediments in Qeshm Island and are related to reactivation of the Gachin fault zone (Figure 6). This geometry in a strike-slip fault system, generally produce either zones of compression at restraining step-over regions [50]. Detailed analyses of the minor folds and faults along the main fault zone indicate that they are spatially developed in restraining zones along the fault zone (Figure 6). Therefore, the Gachin fault zone along which these restraining zones have formed itself as a deep-seated principal deformation Fault zone.

The Gachin Strike-slip fault continues to the SW toward the Abu Musa salt dome. The epicentre locations of few strike-slip earthquakes, especially the November 27, 2005 and May 27, 2014 earthquakes, are along the Gachin fault and occurred with left-lateral focal mechanism (Figure 5). Therefore, it can be concluded that, the reactivation of Gachin fault zone is continuing to the present time and is the main cause of 2005/11/27 and 2014/5/27 earthquakes in Qeshm Island. Seismotectonic studies and migration of the earthquakes toward SW show that the SW tip of Gachin fault zone (in Qeshm Island) is more active than the middle part and the NE tip of it.

Comparing the presented models of the strike-slip faults origin in the orogenic belts by the surface deformations of Gachin fault zone reactivation, indicate that this fault zone is a basement fault. The basement origin of the Gachin fault can be confirmed by Hormuz salt formation extrusion and presence of earthquakes with the basement origin along the fault. Comparison between depth of the earthquakes and depth of the basement in Qeshm Island indicate this result of the basement origin of active Gachin fault zone.

The north-eastward movement of the Arabian Plate towards Central Iran is in favour for the reactivation of the fault. Therefore, it is proposed that such convergence can account for the reactivation of similar fault zones in the Zagros Fold-Thrust Belt like Izeh fault zone [55].

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References

1. Jackson, J. and Fitch, T. (1981) Basement faulting and the focal depths of the larger earthquakes in the Zagros Mountains (Iran). *Geophys. J. Int.*, **64**, 561-586.

2. Jackson, J. and McKenzie, D. (1988) The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East. *Geophys. J. Int.*, **93**, 45-73.

3. Maggi, A., Jackson, J.A., Priestley, K., and Baker, C. (2000) A re-assessment of focal depth distributions in southern Iran, the Tien Shan and northern India: do earthquakes really occur in the continental mantle? *Geophys. J. Int.*, **143**, 629-661.

4. Lohman, R.B. and Simons, M. (2005) Locations of selected small earthquakes in the Zagros mountains. Geochem. *Geophys. Geosyst.*, **6**, Q03001, doi:10.1029/2004GC000849.

5. Nissen, E., Yamini-Fard, F., Tatar, M., Gholamzadeh, A., Bergman, E., Elliott, J.R., Jackson, J.A., and Parsons, B. (2010) The vertical separation of mainshock rupture and microseismicity at Qeshm island in the Zagros Simply Folded Belt, Iran. *Earth planet. Sci. Lett.*, **296**, 181-194.

6. Nissen, E., Tatar, M., Jackson, J.A., and Allen, M.B. (2011) New views on earthquake faulting in the Zagros fold-and-thrust belt of Iran. *Geophys. J. Int.*, **186**, 928-944

7. Nissen, E., Jackson, J., Jahani, S., and Tatar, M. (2014) Zagros "phantom earthquakes" reassessed-The inter- play of seismicity and deep salt flow in the Simply Folded Belt? *J. Geophys. Res. Solid Earth*, **119**, doi:10.1002/2013JB010796.

8. Berberian, M. (1995) Master "blind" thrust faults hidden under the Zagros folds: active basement tectonics and surface morphotectonics. *Tectonophysics*, **241**, 193-224.

9. Talebian, M. and Jackson, J. (2004) A reappraisal of earthquake focal mechanisms and active shortening in the Zagros mountains of Iran. *Geophys. J. Int.*, **156**, 506-526.

10. Sella, G.F., Dixon, T.H., and Mao, A.L. (2002) REVEL: a model for recent plate velocities from space geodesy. *J. Geophys. Res.*, **107**(B4),

Art. No. 2081.

11. Vernant, Ph., Nilforoushan, F., Hatzfeld, D., Abbassi, M.R., Vigny, C., Masson, F., Nankali, H., Martinod, J., Ashtiani, A., Bayer, R., Tavakoli, F., and Chéry, J. (2004) Contemporary crustal deformtaion and plate kinematics in Middle East constrained by GPS measurements in Iran and northern Oman. *Geophys. J. Int.*, **157**, 381-398.

12. Walker, R.T., Andalibi, M.J., Gheitanchi, M.R., Jackson, J.A., Karegar, S., and Priestley, K. (2005) Seismological and field investigations from the 1990 November 6 Furg (Hormozgan) earthquake: a rare case of surface rupture in the Zagros Mountains of Iran. *Geophys. J. Int.*, **163**, 567-579.

13. Stocklin, J. (1968) Structural history and tectonics of Iran: a review. *Am. Assoc. Petrol. Geol. Bull.*, **52**, 1229-1258.

14. Falcon, L. (1969) 'Problems of the relationship between surface structure and deep displacements illustrated by the Zagros range'. In: *Time and Place Orogeny*. P. Kent, G. Satterthwaite and A. Spencer (Eds), Geol. Soc. London, 9-22.

15. Colman-Sadd, S.P. (1978) Fold development in Zagros simply folded belt, Southwest Iran. *AAPG Bulletin*, **62**, 984-1003.

16. Keilis-Borok, V.I. and Rotwain, I.M. (1990) Diagnosis of time of increased probability of strong earthquakes in different regions of the world: algorithm CN. *Phys Earth Planet Inter*, **61**, 57-72.

17. Jackson, D.D. and Kagan, Y.Y. (1999) Testable earthquake forecasts for 1999. *Seismol. Res. Lett.*, **70**, 393-403.

18. Kossobokov, V.G., Romashkova, L.L., Keilis-Borok, V.I., and Healy, J.H. (1999) Testing earthquake prediction algorithms: statistically significant advance prediction of the largest earthquakes in the Circum-Pacific, 1992-1997. *Phys Earth Planet Inter*, **111**, 187-196.

19. Kagan, Y.Y. and Jackson, D.D. (2000) Probabilistic forecasting of earthquakes. *Geophys. J. Int.*, **143**, 438-453.

20. Rhoades, D.A. and Evison, F.F. (2004) Long-range earthquake forecasting with every earthquake a precursor according to scale. *Pure Appl. Geophys.*, **161**, 47-71.

21. Tiampo, K.F., Assefa, D., Fernandez, J., Mansinha, L., and Rasmussen, H. (2008) Postseismic deformation following the 1994 Northridge earthquake identified using the localized Hartley Transform Filter. *Earth Sciences and Mathematics*, 1577-1602

22. Alinaghi, A. (2007) Moment Tensor inversion of some events of Qeshm Island earthquake sequences using INSN broadband data. *JSEE*, **9**(3), 153-157.

23. Nissen, E., Ghorashi, M., Jackson, J., Parsons, B., and Talebian, M. (2007) The 2005 Qeshm Island earthquake (Iran)-a link between buried reverse faulting and surface folding in the Zagros Simply Folded Belt? *Geophys. J. Int.*, **171**, 326-338.

24. Davoodi, Z. (2015) The Gachin fault zone as the main cause of the recent deformations on the sedimentary cover and the 2014 May 27 earthquake in the South of Qeshm Island. *SEE 7 Conference*, Tehran.

25. Ricou, L.E., Braud, J., and Brunn, J.H. (1977) Le Zagros. *Mémoire hors Série de la Société Géologique de France*, **8**, 33-52.

26. Stoneley, R. (1990) The Arabian continental margin in Iran during the Late Cretaceous. *Geol. Soc. Lond. Spec. Publ.*, **49**, 787-795.

27. Husseini, M.I. (1992) Upper Palaeozoic tectono-sedimentary evolution of the Arabian and adjoining plates. *J. Geol. Soc. Lond.*, 149, 419-429.

28. Hessami, K., Koyi, H.A., Talbot, C.J., Tabasi, H., and Shabanian, E. (2001) Progressive unconformities within an evolving foreland fold thrust belt, Zagros Mountains. *J. geol. Soc. Lond.*, **158**, 969-981.

29. Allen, M.B. and Armstrong, H.A. (2008) Arabia Eurasia collision and the forcing of mid-Cenozoic global cooling. Palaeogeog. *Palaeoclim. Palaeoecol.*, **265**, 52-58.

30. Stoneley, R. (1990) The Arabian continental margin in Iran during the Late Cretaceous. *Geol. Soc. Lond. Spec. Publ.*, **49**, 787-795.

31. McQuarrie, N., Stock, J.M., Verdel, C., and Wernicke, B.P. (2003) Cenozoic evolution of Neotethys and implications for the causes of plate motions. *Geophys. Res. Lett.*, **30**(20), 2036, doi:10.1029/2003GL017992.

32. Stocklin, J. (1974) 'Possible ancient continental margins in Iran'. In: *The Geology of Continental Margins*, 873-887, Springer-Verlag, New York, NY.

33. Falcon, N.L. (1974) Southern Iran: Zagros mountains. *Geol. Soc. Lond. Spec. Publ.*, **4**, 199-211.

34. Regard, V., Bellier, O., Thomas, J., Abbassi, M.R., Mercier, J., Shabanian, E., Feghhi, K., and Soleymani, S. (2004) Accommodation of Arabia-Eurasia convergence in the Zagros-Makran transfer zone, SE Iran: a transition between collision and subduction through a young deforming system. *Tectonics*, **23**, TC4007, doi:10.1029/2003TC001599.

35. Alavi, M. (2007) Structures of the Zagros fold-thrust belt in Iran. *Am. J. Sci.*, **307**, 1064-1095.

36. Al Amri, A.M. and Gharib, A.A. (2000) Lithospheric seismic structure of the eastern region of the Arabian Peninsula. *J. Geodyn.*, **29**, 125-139.

37. Al Damegh, K., Sandvol, E., and Barazangi, M. (2005) Crustal structure of the Arabian plate: new constraints from the analysis of teleseismic receiver functions. *Earth planet. Sci. Lett.*, **231**, 177-196.

38. Gok, R., Mahdi, H., Al Shukri, H., and Rodgers, A.J. (2008) Crustal structure of Iraq from receiver functions and surface wave dispersion: implications for understanding the deformation history of the Arabian-Eurasian collision. *Geophys. J. Int.*, **172**, 1179-1187.

39. Hessami, K., Koyi, H.A., and Talbot, C.J. (2001) The significance of strike slip faulting in the basement of the Zagros fold and thrust belt. *J. Petrol. Geol.*, **24**, 5-28.

40. Walpersdorf, A., Hatzfeld, D., Nankali, H., Tavakoli, F., Nilforoushan, F., Tatar, M., Vernant, P., Chéry, J., and Masson, F. (2006) Difference in the GPS deformation pattern of North and Central Zagros (Iran). *Geophys. J. Int.*, **167**, 1077-1088.

41. Furst, M. (1990) Strike-slip faults and diapirism of the South-Eastern Zagros ranges. *Proceedings in Symposium of Diapirism, Bandar Abbas, Hormozgan, Iran*, **2**, 149-181.

42. Ameen, M.S. (1992) Effect of basement tectonic on hydrocarbon generation, migration and accumulation in northern Iraq. *AAPG Bull.*, **76**, 356-370.

43. Barzegar, F. (1994) Basement fault mapping of E Zagros folded belt (SW Iran) based on space-born remotely sensed data. *Proceedings of the 10th Thematic Conference on Geologic Remote Sensing: Exploration, Environment and Engineering*. San Antonio, Texas, 455-466.

44. Yassaghi, A. (2006) Integration of landsat imagery interpretation and geomagnetic data on verification of deep-seated transverse fault lineaments in SE Zagros, Iran. *Int. J. Remote Sens.*, **27**(18-20), 4529-4544.

45. Molinaro, M., Leturmy, P., Guezou, J.-C., Frizon de Lamotte, D., and Eshraghi, S.A. (2005) The structure and kinematics of the southeastern Zagros foldthrust belt, Iran: from thin-skinned to thick-skinned tectonics. *Tectonics*, **24**, TC3007, doi:10.1029/2004TC001633.

46. Kugler, A. (1973) *An Interpretation of the Southwest Iran Aeromagnetic Survey*. Unpublished 1205, Oil Service Company of Iran.

47. Morris, P. (1977) B*asement Structure as Suggested by Aeromagnetic Surveys in SW Iran*. Internal Report, Oil Service Company of Iran.

48. Talebian, M. (2003) *Active Faulting in the Zagros Mountains of Iran*. Ph.D. Thesis, " University of Cambridge.

49. Woodcock, N.H. and Daly, M.C. (1986) The role of strike-slip fault systems at plate boundaries [and Discussion]. *Philosophical Transactions*, **317**(1539).

50. Sylvester, A.G. (1988) Strike-slip faults. *Geological Society of America Bulletin*, **100**(11), 1666-1703.

51. Lowell, J.D. (1972) Spitzbergen tertiary orogenic belt and the Spitzbergen fracture zone. *Geol. Soc. Am. Bull.*, **83**, 3091-3102.

52. Wilcox, R.E., Harding, T.P., and Seely, D.R. (1973) Basin wrench tectonics. *AAPG Bulletin*, **57**, 74-96.

53. Richard, P., Mocquet, B., and Cobbold, P.R. (1991) Experiments on simultaneous faulting and folding above a basement wrench fault. *Tectonophysics*, **188**(1-2), 133-141.

54. Odonne, F. and Costa, E. (1993) Relationships between strike-slip movement and fold trends in thin-skinned tectonics: analogue models. *Tectonophysics*, **228**, 383-391.

55. Davoodi, Z. and Yassaghi, A. (2009) Syn- to post-collision role of Izeh transverse fault zone in deformation of the Zagros fold-thrust belt. *Journal of Trabajos de Geologia*, **29**, 206-212.