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Jamshid AHMADIAN, Mamoru MURATA, Alireza NADIMI
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Jamshid AHMADIAN [a, b], Mamoru MURATA [c], Alireza NADIMI [d],
Hiroaki OZAWA [e] and Takeshi KOZAI [c]

[a-] Center for collaboration in community, Naruto University of Education, Naruto, Tokushima 772-8502, Japan
[b-] Department of Geology, Payame Noor University, P.O. Box 19395-3697, Tehran, IRAN
[c-] Natural Science Education (Science), Naruto University of Education, Naruto, Tokushima 772-8502, Japan
[d-] Department of Geology, Faculty of Science, University of Isfahan, P.O. Box 81746-73441, Isfahan, Iran
[e-] International Cooperation Center for the Teacher Education and Training, Naruto, Tokushima 772-8502, Japan

Abstract：Iran is an ideal natural laboratory for studying the kinematics and dynamics of plate interactions because of the various tectonic processes encountered, including continental collision, subduction of oceanic lithosphere (Makran) and a sharp transition between a young orogen (Zagros) and a subduction zone (Makran). In this research, tectonic evolution of Iranian Plateau during Cenozoic convergence between Arabian and Eurasian plates is reviewed and youngest tectonic activities in the plateau such as active faults, earthquakes, magmatism, and young volcanism and GPS velocities are described. Iran is one of the most seismically active countries in the world, being crossed by several major fault lines that cover at least 90% of the country. These earthquakes occurred along the active faults of Iran and show various mechanisms of fault movements.

Keywords：Iran, Earthquake, Active Tcetonics, Active Fault, Zagros Collision.

Ⅰ．Introduction

Iran is one of the world's best examples of a youthful stage of continent-continent collision, in which active faults, earthquake epicentres and young volcanos are mostly located within the political borders of the country. The continent-continent collision between the Arabian and Eurasian plates following the closure of the Neo-Tethys Ocean resulted in the development of the Zagros (Stöcklin, 1968; Falcon, 1974; Berberian and King, 1981). The collision appears to have commenced during the Late Eocene-Early Oligocene (e.g. Vincent *et al*., 2007; Agard *et al*., 2005, 2011). However, the most conspicuous manifestations of the collision, the Zagros and Alborz Mountains, have undergone their most significant deformation during the Middle Miocene-Holocene (Allen *et al*., 2004), and earlier deformation is largely confined to a much narrower belt between the Sanandaj-Sirjan zone and High Zagros (Agard *et al*., 2005).

The Zagros orogen extends from the Turkish-Iranian border to the NW, to the Makran area in the SE (where oceanic subduction is still active; Smit *et al*., 2010; Fig. 1A). The Zagros Orogen is sub-divided into several tectonic units and consists of the Zagros Simply Folded Belt (ZSFB), Zagros Imbricate Belt (High Zagros Belt or Crush Zone), Sanandaj-Sirjan Zone (SSZ) and Urumieh- Dokhtar Magmatic Arc (UDMA) (e.g. Stöcklin, 1968; Falcon, 1974; Alavi, 1994; Berberian and King, 1981; Agard *et al*., 2005). Other tectonic units of Iran are Central Iran, Eastern Iran, Alborz and Kopeh Dagh ranges (Fig. 1A).

In this research, we review tectonic evolution of Iran during Late Cenozoic- Quaternary and describe youngest tectonic activities in the Iran such as active faults, earthquakes and GPS velocities.

Ⅱ．Geotectonic setting

Zagros Orogenic Belt: The tectonic evolution of the Zagros Mountains was entirely due to plate tectonics and the converging of the Arabian and Eurasian continents (Fig. 1A). The timing of the collision of the Arabian and Eurasian plates is generally known to be in the Miocene. Study by Agard *et al*. (2005) in the High Zagros Mountains noted deposited Late Oligocene-Early Miocene conglomerates unconformably overlying the Eocene domain of the Iranian Plate and the 81.4-86.3 Ma obducted ophiolite of the Arabian Plate. This indicates that the timing of ocean closure and the inception of collision must have taken place between the mafic intrusions at 38 Ma and the 25-23 Ma Oligocene-Miocene deposits.

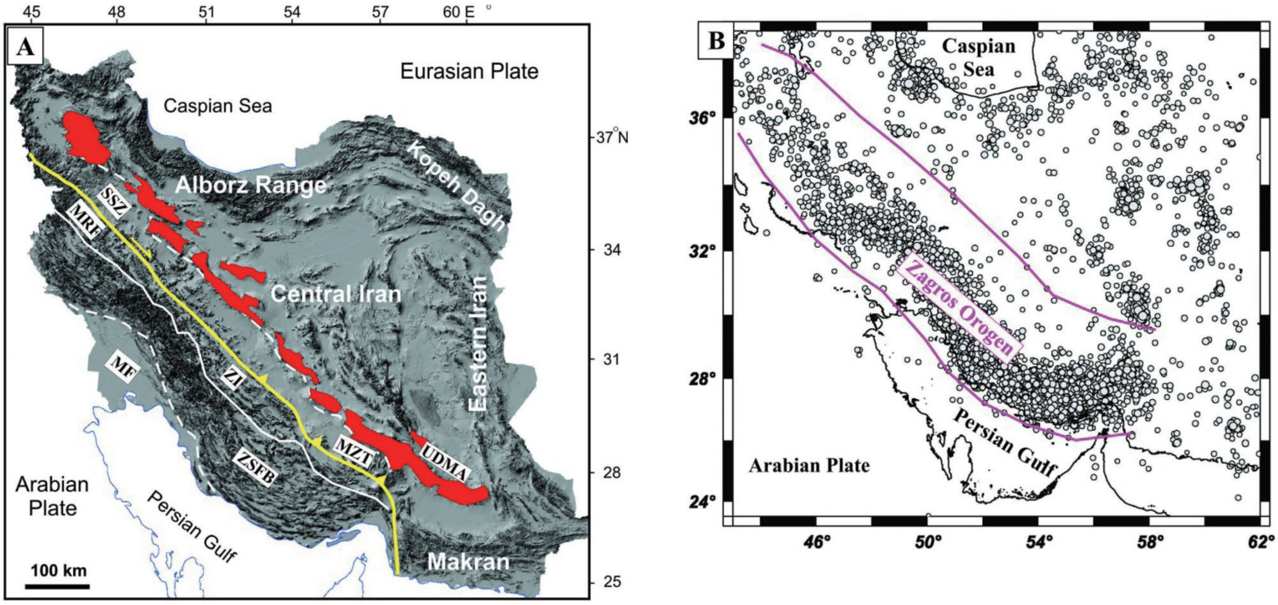

Figure 1. A) Structural units and tectonic features of the Arabia-Eurasia collision zone in Iran. MF- Mesopotamian Foredeep and Persian Gulf, ZSFB- Zagros Simply Folded Belt, ZI- Zagros Imbricate Belt, SSZ- Sanandaj-Sirjan Zone, UDMA- Urumieh-Dokhtar Magmatic Arc, MRF- Main Recent Fault and MZT- Main Zagros Thrust.
B) Distribution of earthquakes in Iran resulting from Arabia-Eurasia collision (Lacombe *et al*. 2006).
Open circles represent 4501 earthquakes (magnitude between 2.4 and 7.4) recorded from 1964 to 2002 (after the International Seismological Centre, online bulletin, Guest *et al*., 2006).

The Zagros Orogen has a complex history. During the Miocene, plate convergence underwent a change in direction from NE to NNE (McQuarrie *et al*., 2003) and was accompanied by folding and thrusting in the Zagros Imbricate Belt (see Molinaro *et al*., 2005). Lacombe *et al*. (2006) documented a Late Miocene to Early Pliocene pre- and syn-folding NE stress field in the ZSFB. Navabpour *et al*. (2007) identified various strike-slip, compressional and tensional stress regimes in the Zagros Imbricate Belt. Their investigations indicate that the main fold and thrust structure that developed during the Miocene in a generally compressional stress regime with an average 032° direction of the σ_1 stress axis. During three successive strike slip faulting stages developed strike-slip structures. The faults resulted from a different σ_1 direction in the Early Miocene (053°), Late Miocene-Early Pliocene (026°), and post-Pliocene (002°) times, evolving from pre-fold to post-fold faulting (Navabpour *et al*., 2007).

Sanandaj-Sirjan Zone: The SSZ remains a poorly documented part of the Zagros Orogen that is separated from the Zagros imbricate belt on the southwest by the Main Zagros thrust (MZT) (Fig. 1A). The northeastern boundary of SSZ is unclear because it is covered by Quaternary deposits, and contrary to its southern part, the northern part does not have any major faults. The SSZ may be separated from the Central Iran by steeply dipping faults (Stöcklin, 1974), and Morley *et al*. (2009) interpreted that the southern UDMA was uplifted and deformed along an important transpressional zone of deformation. Alavi (1994) even considered the boundary between UDMA and SSZ as the main Zagros Suture Zone.

Urumieh-Dokhtar Magmatic Arc: The UDMA situated between the SSZ and Central Iran, runs parallel to the Zagros Mountains and the SSZ (Fig. 1A). It forms a topographic ridge separating the SSZ from Central Iran, and bears huge volcano-sedimentary deposits, in places >10 km thick (Dimitrijevic, 1973). It is generally assumed that the UDMA was the magmatic arc overlying the slab of the Neo-Tethyan oceanic lithosphere which was subducted beneath the Iranian Plate (Berberian and Berberian, 1981; Alavi, 1994; Ahmadian *et al*., 2009, 2010). The UDMA is one of the most important belts of metalogeny in Iran (e.g. Haschke *et al*., 2010; Sarjoughian *et al*., 2012). Alkaline, post-collisional Pliocene-Quaternary volcanism are found in volumetrically large amounts in the latter area only, but small outcrops of (presumably Quaternary) alkaline basalt are found in many places, mainly along fault zones.

Central Iran: The Central Iran is surrounded by fold-and-thrust belts, within the Alpine-Himalayan orogenic system of western Asia. Being situated to the northeast of the Zagros-Makran Neo-Tethys suture and its sub-parallel Cenozoic magmatic arc (UDMA), the Central Iran is an area of continuous continental deformation in response to the ongoing convergence between the Arabian and Eurasian plates (Fig. 1A). The Central Iran consists, from east to west, of three major crustal domains: the Lut, Tabas and Yazd blocks (Alavi, 1991) separated by a series of intersecting regional-scale faults.

Although the stratified cover rocks can be correlated between the different blocks, locally significant facies and/or thickness variations occur across the domain boundaries. The eastern region of the Yazd Block, between the Yazd and Tabas blocks, provides remarkable exposures of the deeper sections of the Central Iranian platform strata, among which Late Neoproterozoic and Lower Paleozoic rocks are abundant (Nadimi, 2007).

Eastern Iran: The eastern limit of Arabia-Eurasia deformation occurs at roughly longitude 61°E, close to the political border between Iran and Afghanistan (Fig. 1A). Further east there is a sharp cut-off in seismicity, mountainous topography and active fault activity. The present-day right lateral strain across eastern Iran is measured by GPS at ~16 mm/yr (Vernant *et al*., 2004). Walker and Jackson (2002) used offset Quaternary basalts to estimate a slip rate of ~1.5 mm/yr on the Nayband fault, which suggests that the major part of the present-day strain is accommodated elsewhere. The southern part of the Eastern Iran consists of Makran Range that is an accretionary prism of an active subduction zone. In this area, oceanic crust of Oman Sea is subducting under continental crust of the Eastern Iran.

Alborz Range: The Alborz Range in northern Iran is roughly 600 km long and 100 km across, running along the southern side of the Caspian Sea (Fig. 1A). Alborz represent a good example of an intra-continental belt, with a stretched continental domain inverted during Late Triassic time (Zanchi *et al*., 2006) and the Tertiary (e.g. Guest *et al*., 2006; Ritz *et al*., 2006), as a result of both Palaeo-Tethyan and Neo-Tethyan closures. The Alborz is thus an integral part of the Arabia- Eurasia collision zone, and accommodates present-day convergence through orogen normal shortening and lateral escape of the South Caspian basin in the west, and more complex deformation partitioning, including right-lateral movements, to the east (Hollingsworth *et al*., 2006).

Kopeh Dagh Range: The Kopeh Dagh trends at 120°-300° for 700 km through northeast Iran and Turkmenistan between the Caspian Sea and the Afghanistan border (Fig. 1A). It separates the Turan region from central Iran, and so shows how plate convergence happens at the northern side of the collision zone. The range is up to 3000 m in altitude, some 2000 m higher than the Turkmen foreland to the north. North-south shortening across the west of the range may be ~75 km, based on a line balanced section by Lyberis and Manby (1999). This represents ~30% shortening of the 250 km wide western Kopeh Dagh region.

Ⅲ. Earthquakes in Iran

Iran is situated in a highly seismic part of the world, and has been frequently struck by catastrophic earthquake during recorded history. These earthquakes have resulted in great loss of life, and, in rendering large numbers of people homeless and disrupting the agricultural and individual basis of their lives, have been wasteful of national resources.

Iran is surrounded by tectonically active zones. Earthquakes are regularly felt on all sides of Iran (Fig. 1B). There are several huge earthquakes events during previous one hundred year ago. About 15,000 people died in 1976 as a result of an earthquake in western Iran. More than 20,000 people died in a 7.7 Richter scale earthquake in 1978 in Tabas, Central Iran. In 1981, more than 1000 people died in Kerman as a result of an earthquake. Around 40,000 people died in a 7.2 Richter scale earthquake in the northern Iranian province of Gilan. In June of 2002, more than 1100 people lost their lives in an earthquake in northwestern Iran. The casualties of the Bam earthquake of December 2003, Mw 6.6 will perhaps never be known exactly, but is thought to be between 26,000 (the official figure) and 40,000 (Berberian 2005). On February 22, 2005, a major earthquake (Mw 6.4) killed hundreds of residents in the town of Zarand and several nearby villages in north Kerman. The February 22 earthquake is 125 km northwest of the destructive earthquakes of June 11, 1981 (Mw6.6, ~3,000 deaths) and July 28, 1981 (Mw7.3, ~1,500 deaths) and about 250 km northwest of the devastating Bam earthquake of December 26, 2003. The 2005 Qeshm earthquake, Mw 6.0 was a powerful earthquake that occurred on November 27, 2005, in Qeshm Island, southern Iran.

Varzeghan Earthquake (Miyajima *et al*., 2012; http://www.iiees.ac.ir; http://irsc.ut.ac.ir): on the late afternoon of Saturday August 11, 2012 the northwest of Iran was shaken by two of the strong earthquakes in Iranian history (Fig. 2). First was hit by Mw 6.4 at 16:54 local time (12:23 GMT), and about 11 minutes later, a Mw 6.3 struck 10 km to the west. The deaths were more than 330 persons. Successively Varzeghan-Ahar earthquakes are the cluster ones or "earthquake sequence", and involved more than hundreds moderate and small temblors and are centered on Varzeghan area. After about three months from the main

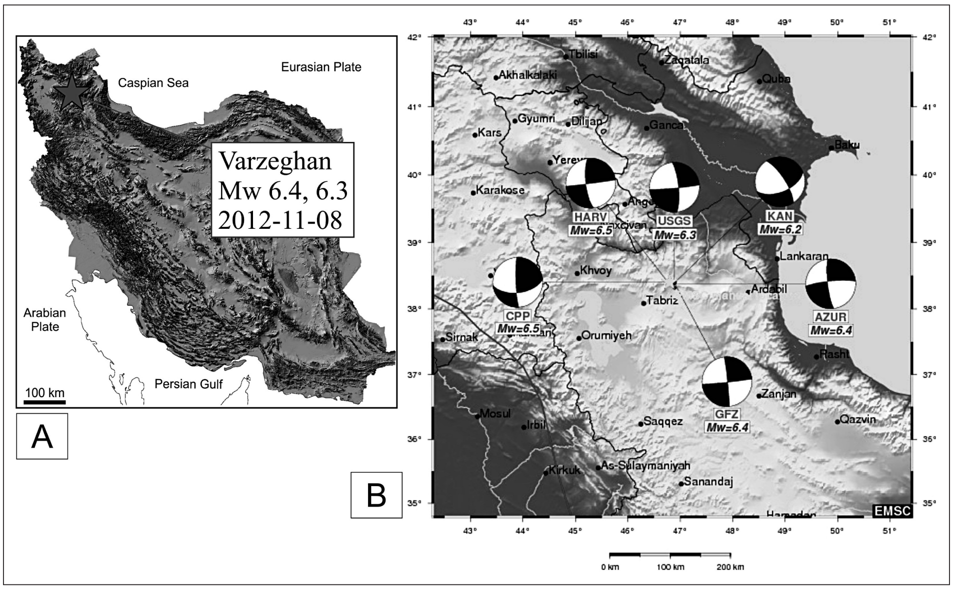

Figure 2.
A) Varzeghan Earthquake, Mw6.4 and 6.3, 2012-11-08 (from http://irsc.ut.ac.ir/index.php).
B) Focal mechanisms of Varzeghan Earthquake from various seismological centers. The focals show active strike-slip faulting of the earthquake.

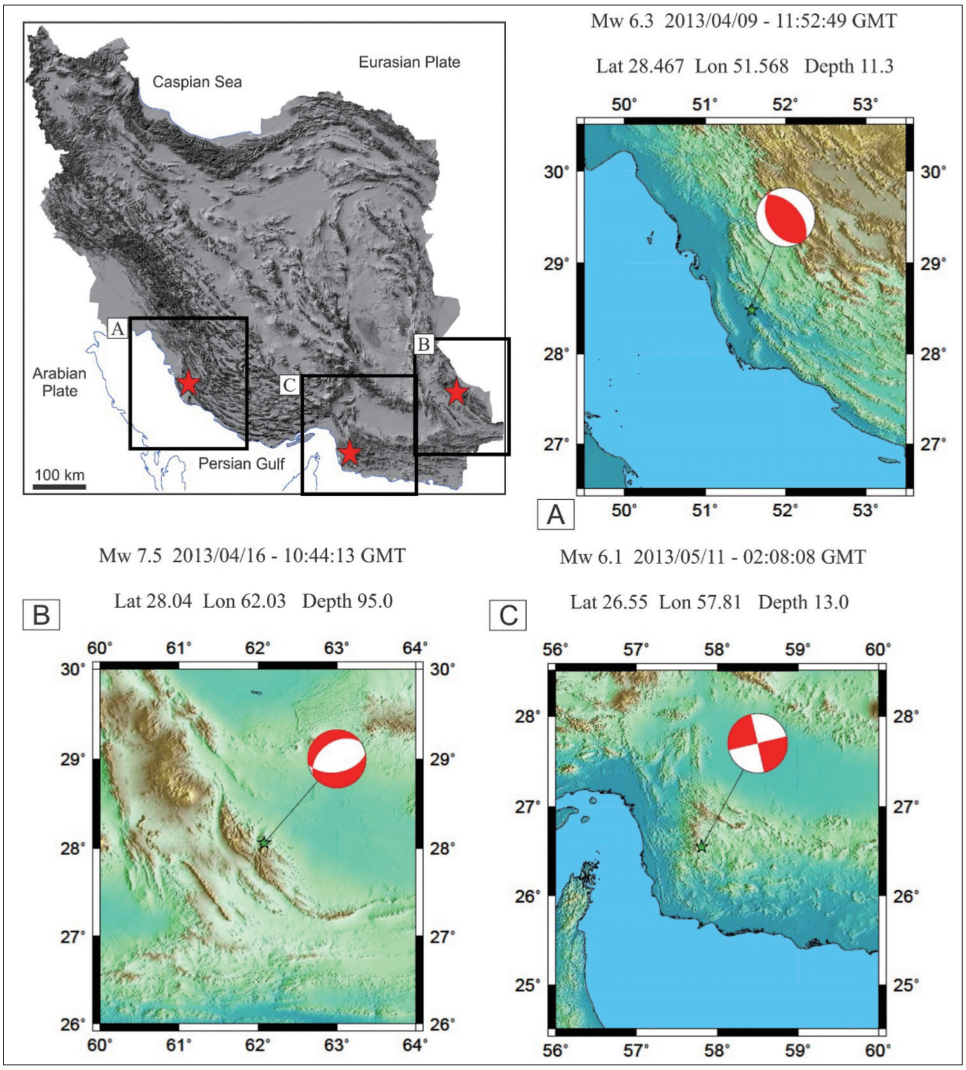

Figure 3.
Recent major earthquakes of Iran in 2013 (earthquake data from http://irsc.ut.ac.ir/index.php).
A) Boushehr Earthquake, Mw6.3, 2013-04-09.
B) Sistan Earthquake, Mw7.5, 2013-04-16.
C) Minab Earthquake, Mw6.1, 2013-05-11.

shock of earthquake, only during one day, on November 07, 2012, Seismological Center of Tehran University has recorded about 55 aftershocks with Mw 5.1 Richter and smaller.

In 2013, several huge earthquakes have been occurred in Iran (Fig. 3) (http://irsc.ut.ac.ir). The April 9, 2013 M6.3 (6.4: USGS: http://www.usgs.gov) earthquake in southern Iran, Boushehr occurred as result of NE-SW oriented thrust-type motion in the shallow crust of the Arabian plate (Fig. 3A). The depth and style of faulting in this event are

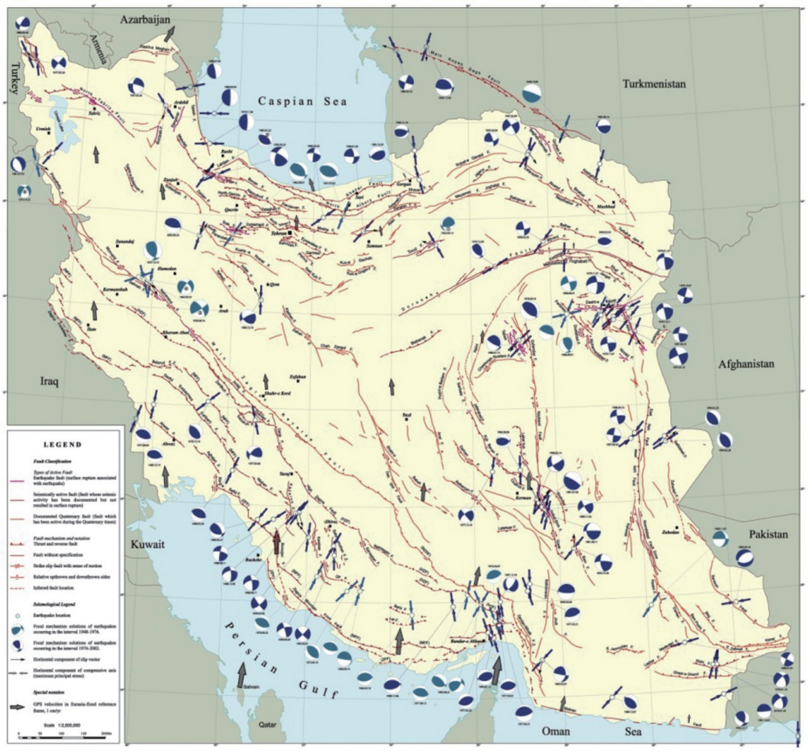

Figure 4. Map of active faults of Iran (Hessami *et al.*, 2003).

consistent with shortening of the shallow Arabian crust within the Zagros Mountains in response to active convergence between the Arabian and Eurasian plates (http://www.usgs.gov).

The April 16, 2013 M 7.5 (7.8: USGS) earthquake east of Sistan (Khash), occurred as a result of normal faulting at an intermediate depth in the Arabian plate lithosphere, approximately 80 km beneath the Earth's surface (Fig. 3B). Regional tectonics are dominated by the collisions of the Arabian and India plates with Eurasia; at the longitude of this event, the Arabian plate is converging towards the north-northeast at a rate of approximately 37 mm/yr with respect to the Eurasian plate (http://www.usgs.gov). Oman oceanic lithosphere is subducted beneath the Eurasian plate at the Makran coast of Iran and Pakistan, and becomes progressively deeper to the north.

The May 11, 2013 M 6.1 earthquake east of Minab, occurred as a result of strike-slip faulting (Fig. 3C). Regional tectonics are dominated by the collisions of the Arabian and Eurasian plates to the west and subduction of Oman oceanic lithosphere to the east.

Ⅳ. Active faults

1. Tectonic structure

The collision of two continental plates produces a zone of very complex tectonic structures. Many kinds of such tectonic structures formed also during Cenozoic times in the Zagros Orogen and other parts of Iranian Plateau, as a consequence of the collision between the Arabian and the Eurasian plates (Stöcklin, 1968; Falcon, 1974). Most of these structures are still active. Tectonic deformation in Iran during the last 3-5 Ma resulted mainly in the N-S-trending convergence and dextral strike-slip faulting (e.g. Berberian and King, 1981; Berberian, 1981) and partly in thrusting and accompanying folding.

There are many active faults in Iran that stretched with different trends in the structural zones of Iran (Fig. 4). In each zone, active faults have their special properties and formed in different tectonic scenario. Some of the active faults reactivated during the Zagros Orogen and later strike-slip movements in Iran. The major active faults in Iran are considered as tectonic boundary of the structural zones of Iran and smaller tectonic blocks (Fig. 4). In many places these faults dissect Pliocene to Quaternary rocks and sediments and have formed young sedimentary basins.

2. Active fault sets

Relative to the main NW-SE trend of tectonic structures in the Zagros Orogen, the fault pattern consists of major NW-trending longitudinal faults, NE-SW-trending transverse, N-S-trending oblique and E-W-trending oblique faults (Fig. 4). Longitudinal NW-SE-trending faults in Iran are parallel to the MZT. The fault set, developed in the Cenozoic times, is

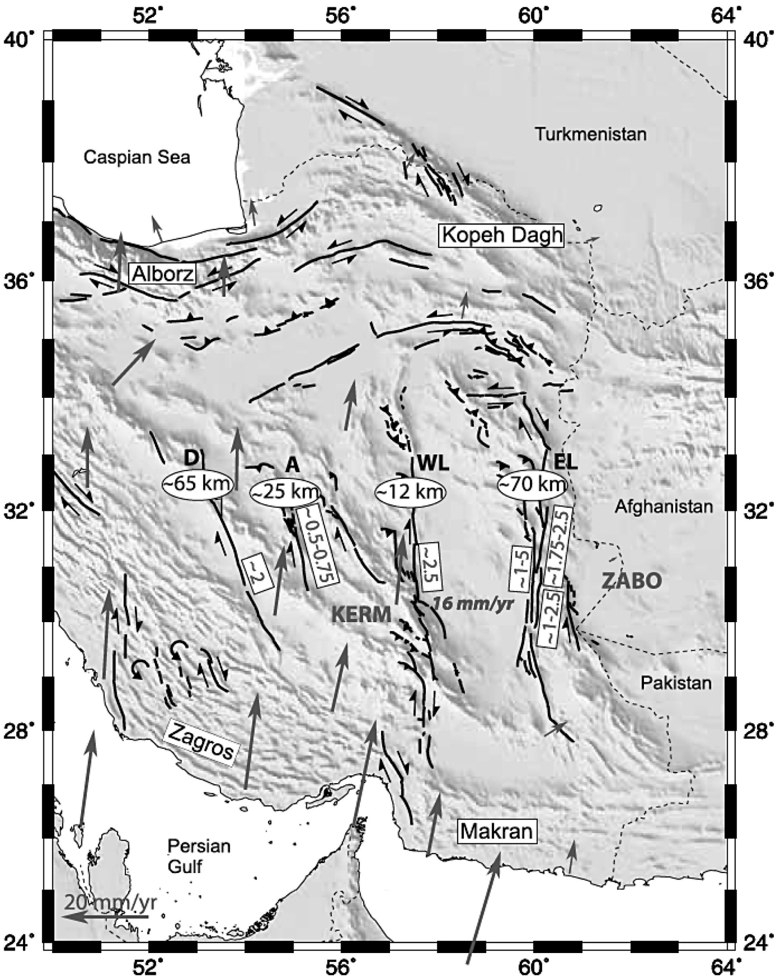

Figure 5.
Strike-slip faulting in the Central and Eastern Iran.
Modified from Walker and Jackson (2004). Total offsets across Dehshir (D), Anar (A), West Lut (WL, Nayband), and East Lut (EL, Nehbandan) faults are indicated in km. GPS velocities relative to stable Eurasia (red arrows, Vernant *et al*., 2004) indicate ~16 mm/yr of right-lateral shear across WL and EL fault systems. Slip-rate on individual faults (green numbers in mm/yr) is averaged over the Quaternary for West Lut (Walker and Jackson, 2002) and the Holocene for Dehshir (Meyer *et al*., 2006), Anar and East Lut (Meyer and Le Dortz, 2007).

part of a system NW-SE-trending dextral strike-slip faults that cut the upper continental crust of the Iranian Plateau (e.g. Berberian and King, 1981).

The MZT is the most important longitudinal fault in Iran. The fault is a tectonic boundary between the Iranian Plate to the north and the Zagros Fold-Thrust Belt to the south (Fig. 1A). The whole MZT is a c. 1350 km-long suture zone between the Arabian and Eurasian plates (e.g. Stöcklin, 1968; Agard *et al*., 2005). The northwestern part of the MZT that known as the Main Recent Fault is currently active and a dextral strike-slip sense is noted along its plane (e.g. Talebian and Jackson, 2002). Evidence of large earthquakes noted on the MRF plane e.g. Ms 7.4 in 1909 and Ms 6.7 in 1957 (Ambraseys and Moinfar, 1973) led several authors (e.g. Braud and Ricou, 1971; Talebian and Jackson, 2002) to consider the MRF and the North Anatolian Fault as an almost continuous active strike-slip zone along the northern Arabian Plate and Anatolian Microplate margins.

Transverse NE-SW-trending faults in Iran are perpendicular to the trend of MZT (Fig. 4). Some of these faults that are located near the Zagros orogenic belt have normal and sinistral components of movements and were formed during NE-SW shortening and NW-SE-trending lateral extensional movements. These faults are very small and are shorter than 100 km in length. Other NE-SW-trending faults that are located far from the orogenic belt, e.g. in the northeast Iran, were formed around the Central-East-Iran Microcontinent (Figs. 4 and 5). The faults have sinistral strike-slip component of movement. The Doruneh Fault with a length of ca 700 km is one of the longest and most prominent faults in Iran that is bordered northern boundary of Central Iranian Microcontinent. The fault trend changes from east to west and from NW-SE, E-W and NE-SW (Fig. 4). The western termination of the fault is considered a transverse fault. The Doruneh Fault performs an important role in the regional tectonics, by accommodating up to 15 mm/yr of north-south right-lateral shear between central Iran and Afghanistan (Vernant *et al*., 2004). The geomorphology of the western part of Doruneh fault contains numerous indications of cumulative left-lateral slip over various scales.

N-S-trending faults form one set of oblique sets in relation to the main NW-SE-trend of tectonic structures in the Zagros Orogen (Figs. 4 and 5). The major fault systems in the Central and Eastern Iran are oriented N-S, and are known to

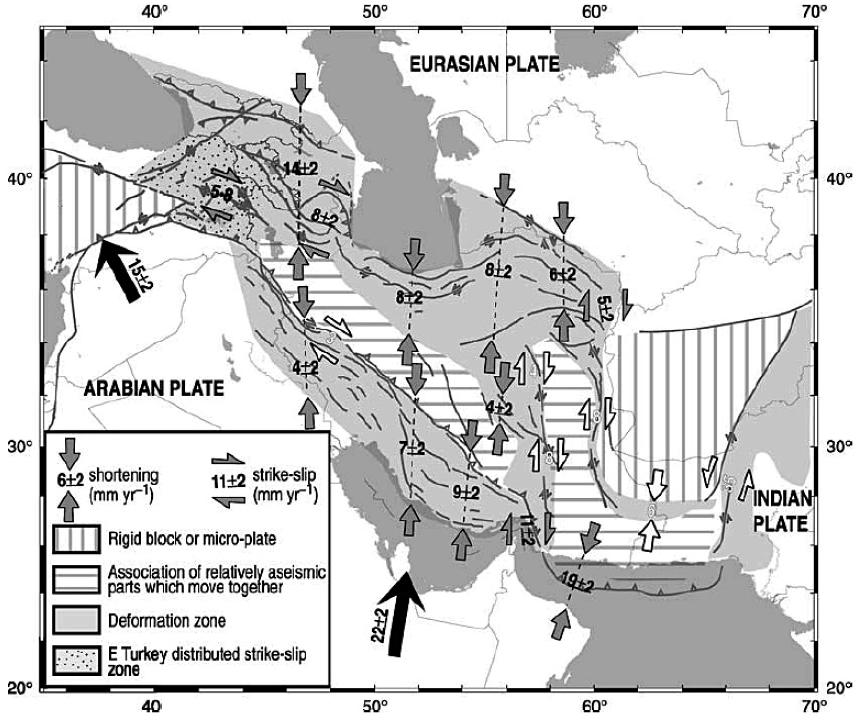

Figure 6.
Schematic illustration of the main results of GPS study of Vernant *et al.*, (2004).
Hatching shows areas of coherent motion, grey zones are actual deformation areas (see legend). Heavy arrows in black indicate the actual motion of the Arabian plate relative to the Eurasia. Grey arrows are deformation rates directly measured with GPS. Rates in eastern Turkey are deduced from McClusky *et al.*, (2000). White arrows are deduced rates from GPS, geological evidence and seismology, for motion along the Chaman Fault and the associated deformation zone the velocity is deduced from the REVEL model (Sella *et al.*, 2002). All the rates are given in mm/yr.

be right-lateral strike-slip faults from seismological and field investigations of earthquakes (e.g. Berberian and Yeats, 1999; Berberian *et al.*, 1999, 2001), from the right-lateral displacement of geomorphological features and rivers (e.g. Tirrul *et al.*, 1983), and from the role of the faults in accommodating right-lateral shear between Iran and Afghanistan (e.g. Jackson and McKenzie, 1984). There are numerous active faults in this set that from east to west are consist Nehbandan (east Lut Block), Nayband (west Lut Block), Anar and Dehshir faults. There are several huge earthquakes events along the faults such as Ms 7.7, 16 September 1978 Tabas (Berberian, 1979), Mw 7.1, 28 July 1981 Sirch (Berberian *et al.*, 1984), Mw 6.1, 23 February 1994 Sefidabeh (Berberian *et al.*, 2000), Mw 7.2, 10 May 1997 Zirkuh (Berberian *et al.*, 1999), Ms 6.6, 14 March 1998 Fandoqa (Berberian *et al.*, 2001), and Mw 6.6, 26 December 2003 Bam (Fu *et al.*, 2004) earthquakes.

E-W-trending faults form second set of oblique sets in relation to the main NW-SE-trend of tectonic structures in the Zagros Orogen (Figs. 4 and 5). These faults have formed along the northern boundary of Central Iranian Microcontinent and southern boundary of the South Caspian Block and during N-S-trending convergence of the Iranian tectonic blocks. This fault set has the lowest frequency in Iran. The Alborz faults in south Caspian, central part of the Doruneh and Dasht-e Bayaz faults are some examples of the set. The Dasht-e Bayaz earthquake (31 August 1968, M 7.2) was associated with E-W-trending sinistral fault zone more than 80 km long (Tchalenko and Ambraseys, 1970).

V. Discussion

This section focuses on the tectonic evolution of Iran, during Arabian-Eurasian convergence and later strike-slip movements in the Pliocene to Holocene.

1. GPS data and present day kinematics in Iran

Nilforoushan *et al.* (2003) and Vernant *et al.* (2004) provided GPS measurements and the first-order present-day kinematics of Iran (Fig. 6). GPS measurements suggest right-lateral displacements in northwestern Iran (Vernant *et al.*, 2004). GPS velocities along the northeastern boundary of the Arabian Plate relative to Eurasia are systematically smaller than the NUVEL-1A estimations. In the western part of Iran, distributed deformation occurs among several fold and thrust belts. In northwestern Iran large right-lateral motions are expected along the NW-SE Tabriz fault system and along a north-south fault bordering the western Caspian coast. The right-lateral deformation occurring between the western Caspian Sea and the Central Iranian Block could be distributed along NW-SE Iranian and Armenian fault systems.

Between the Central Iranian Block and the Arabian Plate, the central Zagros accommodates about 7±2 mm/yr of north-south shortening. The shortening rate decreases in northern Zagros, implying a right-lateral strike-slip rate along the MRF of 3±2 mm/yr, much smaller than geological estimates. North of the Central Iranian Block, the Alborz mountain range accommodates 8±2 mm/yr of north-south compression. Sites along the southern Caspian shore indicate roughly northward motion at 6.5±2 mm/yr relative to Eurasia.

In the eastern Iran, the western and eastern borders of the Lut Block are described as large right-lateral strike-slip faults (e.g. Tirrul *et al.*, 1983; Berberian and Yeats, 1999; Walker and Jackson, 2002; Vernant *et al.*, 2004). A dextral shear of 16 ±2 mm/yr occurs between Zabol in the east of Iran and the Central Iranian Block (Fig. 6) (Vernant *et al.*, 2004). Conrad *et al.* (1982) suggested, using palaeomagnetic data, that no significant rotation occurs during the Pliocene-Quaternary for the Lut Block. Therefore the velocity orientation of the Lut should be consistent with the surrounding orientations (Vernant *et al.*, 2004).

The tectonics of eastern Iran is mostly concentrated within the Makran subduction since the oceanic crust is subducting at 19.5±2 mm/yr roughly north-south under the Makran Wedge. Based on the GPS and geological information, the schematic kinematic pattern of the present-day Arabia-Eurasia convergence zone in Iran was prepared in Figure 6.

2. Arabia and Eurasia convergence and strike-slip movements

While distributed thickening in the Arabia/Eurasia collision zone is revealed to have played a dominant role in building the regional topography, the ways in which the Cenozoic convergence has been accommodated through strike-slip faulting in the Zagros (e.g. Authemayou *et al.*, 2009; Lacombe *et al.*, 2006; Talebian and Jackson, 2004) and central Iran is debated (e.g. Allen *et al.*, 2011; Meyer and Le Dortz, 2007; Walker and Jackson, 2004).

This have pointed out earlier that the kinematics of the Zagros collision is currently partitioning the N-S convergence, into a NW-SE orogen-parallel right-lateral strike-slip faulting along the MRF, and NE-SW orogen-normal shortening in the Zagros folds/thrusts (Authemayou *et al.*, 2009; Talebian and Jackson, 2004). The kinematic role of right-lateral strike-slip faulting in the Zagros is diversely interpreted (Mouthereau *et al.*, 2012). There are viewed as faults bounding, counterclockwise rotated blocks, which accommodate an arc parallel elongation between the partitioned domain of NW Zagros and no partitioned domain of the SE Zagros (Talebian and Jackson, 2004). This stretching, observed in the GPS data, is also emphasized by a component of belt-parallel extension, as recorded by fault slip data analysis, calcite twining and active/quaternary faulting (Mouthereau *et al.*, 2012).

Addition to the Zagros Mountains, the strike-slip faulting in occurred in other parts of the Arabia-Eurasia collision zone. There are several manners for deformation associated with strike-slip faulting to accommodate the plate convergence in continental interior (see Allen *et al.*, 2011). They can rotate about vertical axes to accommodate N-S shortening and arc-parallel lengthening, as proposed for the Zagros (Talebian and Jackson, 2004). Alternatively, they can accommodate relative motion between non rotating blocks such as between central and eastern Iran (Dehshir and Anar faults; Meyer and Le Dortz, 2007). These N-S right-lateral strike-slip faults absorb the differential displacement between the collision domain (central Iran) and the Makran subduction domain (eastern Iran) (Mouthereau *et al.*, 2012). A comparison between the long-term geological offsets and short-term geodetic displacement led Walker and Jackson (2004) to propose a cumulative N-S right-lateral shear in eastern Iran of 75-105 km. Assuming that the current kinematic configuration dates back to the inferred reorganization in the collision at 5-7 Ma (Allen *et al.*, 2004), these authors postulated that the strike slip faults of central Iran (e.g. Dehshir and Anar faults) accommodate a small amount of shortening (Mouthereau *et al.*, 2012). However, Meyer and Le Dortz (2007) pointed out that a long-term kinematic model based on extrapolation of GPS rates may not be valid. They inferred that strike-slip faults of central Iran have accommodated a cumulative right-lateral shear of 90 km (Dehshir and Anar faults) over the past 20 Myr. A paleoseismic study showed that the Dehshir fault has been capable of producing earthquake as big as M~7 (Nazari *et al.*, 2009). Therefore, there is evidence that right-lateral strike-slip faulting is not confined to the edges of the Lut block. Taking into account the lack of current internal deformation across central Iran (Vernant *et al.*, 2004) it has been suggested that deformation associated with strike-slip faulting slowed in the last few Myr and shifted progressively to the east of the collision (Meyer *et al.*, 2006; Allen *et al.*, 2011). The view that long-term N-S Arabia/Eurasia plate convergence in central Iran was partitioned by a combination of right-lateral strike slip faulting and thrusting has been emphasized by Allen *et al.* (2011), analogous to the situation in the Zagros (Talebian and Jackson, 2004).

As noted earlier and consistently with Allen *et al.* (2004, 2011), deformation (strike-slip faulting and thrusting) seems to have slowed in central Iran. This was possibly related to a change in boundary conditions in the east, associated with the onset of the Afghan-India collision at ~5-2 Ma that stopped the possibility for lateral extrusion/ escape (Mouthereau *et al.*, 2012). Here, in accord with the partitioning model of

Allen *et al*. (2011), in which orogen-parallel lengthening is limited, Mouthereau *et al*. (2012) propose that the transition was progressive since 15-10 Ma and related to arc-normal thickening, which led to the uplift of the Iranian plateau and to the cessation of active deformation in central Iran. The progressive thickening in the Iranian plateau (e.g. SSZ) possibly promoted the decline of activity along NNW-SSE strike-slip faults like the Dehshir or Anar faults (Mouthereau *et al*., 2012). The progressive arc-normal shortening was contemporaneous with a late stage of westward lateral extrusion that started after 10-11 Ma along the NAF in eastern Anatolia (e.g. Armijo *et al*., 1999) and in the Caspian Sea (Hollingsworth *et al*., 2006).

Mouthereau *et al*. (2012) concluded that the overall long-term distribution of deformation, a combination of partitioned strike-slip faulting and thrusting, in the Zagros collision region (they omit the yet subducting domain of eastern Iran) may be understood in the context of the N-S indentation of Arabia continent into Eurasia.

Ⅵ. Conclusions

The following conclusions can be drawn from the studies:

- Iran is subject to most types of tectonic activity, including active folding and faulting. Since 1900, more than 150,000 fatalities have resulted from earthquakes in Iran. These earthquakes occurred along the active faults of Iran and show various mechanisms of fault movements. The study of earthquake related faulting in Iran has shown the importance of the early Quaternary tectonic history as well as that of the pre-Quaternary geological record for the understanding of the present-day continental deformation during earthquakes.
- Distributed thickening in the Arabia/Eurasia collision zone is revealed to have played a dominant role in building the regional topography, the ways in which the Cenozoic convergence has been accommodated through strike-slip faulting in the structural units of Iran. The GPS velocities data confirmed north-south shortening between Arabian and Eurasian plates and showed that each tectonic block of Iran has moved and their boundaries made active faults of Iran.

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References

Agard, P., Omrani, J., Jolivet, L., and Mouthereau, F., 2005. Convergence history across Zagros (Iran): constraints from collisional and earlier deformation. International Journal of Earth Science, 94, 401-419.

Agard, P., Omrani, J., Jolivet, L., Whitechurch, H., Vrielynck, B., Spakman, W., Moniě, P., Meyer, B., Wortel, R., 2011. Zagros orogeny: a subduction-dominated process. In: Lacombe, O., Grasemann, B., Simpson, G. (Eds.), Geodynamic Evolution of the Zagros. Geological Magazine, 692-725.

Ahmadian, J., Haschke, M., McDonald, I., Regelous, M., Ghorbani, M., Emami, M., and Murata, M., 2009. High magmatic flux during Alpine-Himalayan collision: Constraints from the Kal-e-Kafi complex, central Iran. Geological Society of America Bulletin, 121, 857-868.

Ahmadian, J., Bahadoran, N., Torabi, Gh., and Murata M., 2010. Geochemistry and Petrogenesis of Volcanic Rocks from the Arousan-e- Kaboudan (NE of Anarak). Petrology, Research Bull. of Isfahan University, 1, 105-120.

Alavi, M., 1991. Tectonic map of the Middle East. Geological Survey of Iran.

Alavi, M., 1994. Tectonics of the Zagros orogenic belt of Iran; new data and interpretations. Tectonophysics, 229, 211-238.

Allen, M., Jackson, J., and Walker, R., 2004. Late Cenozoic reorganization of the Arabia-Eurasia collision and the comparison of short-term and long-term deformation rates. Tectonics, 23, TC2008, 1-16.

Allen, M.B., Kheirkhah, M., Emami, M.H., Jones, S.J., 2011. Right-lateral shear across Iran and kinematic change in the Arabia-Eurasia collision zone. Geophys. J. Int., 184, 555-574.

Ambraseys, N., and Moinfar, A., 1973. The seismicity of Iran: the Silakhor (Lurestan) earthquake of 23rd January 1909. Ann. Geophys., 26, 659-678.

Armijo, R., Meyer, B., Hubert, A., Barka, A., 1999.

Westward propagation of the North Anatolian fault into the northern Aegean: timing and kinematics. Geology 27 (3), 267-270.

Authemayou, C., Bellier, O., Chardon, D., Benedetti, L., Malekzade, Z., Claude, C., Angeletti, B., Shabanian, E., Abassi, M.R., 2009. Quaternary slip-rates of the Kazerun and the Main Recent Faults: active strike-slip partitioning in the Zagros fold-and-thrust belt. Geophysical Journal International 178, 524-540.

Berberian, M., 1979. Tabas-e-Golshan (Iran) catastrophic earthquakes of 16 September 1987: a preliminary field report. Disasters, 2, 207-219.

Berberian, M., 1981. Active faulting and tectonics of Iran. In: H.K. Gupta and F.M. Delany (Ed.), Zagros-Hindu Kush-Himalaya Geodynamic evolution. American Geophys. Union, Geodyn. Ser., 3, 33-69.

Berberian, M., 2005. The 2003 Bam urban earthquake: a predictable seismotectonic pattern along the western margin of the rigid Lut block, southeast Iran. Earthquake Spectra, 21, S35-S99.

Berberian, F., and Berberian, M., 1981. Tectono-Plutonic Episodes in Iran. Geological Survey of Iran, Rep. 52, 566-593.

Berberian, M., and King, G.C.P., 1981. Towards a paleogeography and tectonic evolution of Iran. Canadian Journal of Earth Sciences, 18, 210-265.

Berberian, M. and Yeats, R.S., 1999. Patterns of historical earthquake rupture in the Iranian Plateau. Bull. Seism. Soc. Am., 89, 120-139.

Berberian, M., Jackson, J.A., Qorashi, M. and Kadjar, M.H., 1984. Field and teleseismic observations of the 1981 Golbaf-Sirch earthquakes in SE Iran. Geophys. J. R. astr. Soc., 77, 809-838.

Berberian, M., Jackson J.A., Qorashi, M., *et al.*, 1999. The 1997 May 10 Zirkuh (Qa'enat) earthquake (M-w 7.2): faulting along the Sistan suture zone of eastern Iran. Geophys. J. Int., 136, 671-694.

Berberian, M., Jackson, J.A., Qorashi, M., Talebian, M., Khatib, M.M. and Priestley, K., 2000. The 1994 Sefidabeh earthquakes in eastern Iran: blind thrusting and bedding-plane slip on a growing anticline, and active tectonics of the Sistan suture zone. Geophys. J. Int., 142, 283- 299.

Berberian, M. *et al.*, 2001. The March 14, 1998 Fandoqa earthquake (Mw 6.6) inKerman province, SE Iran: re-rupture of the 1981 Sirch earthquake fault, triggering of slip on adjacent thrusts, and the active tectonics of the Gowk fault zone. Geophys. J. Int., 146, 371-398.

Braud, J., Ricou, L.E., 1971. L'accident du Zagros ou Main Thrust un charriage et un coulissement. Comptes Rendus de l'Académie des Sciences 272, 203-206.

Conrad, G., Montigny, R., Thuizat, R. and Westphal, M., 1982. Dynamique cénozöıque du bloc du Lout (Iran) diaprès les données paléomagnétiques, isotopiques, pétrologiques et structurales, Géol. Méditerranéenne, 9(1), 23-32.

Dimitrijevic, M.D. 1973. Geology of Kerman region. Geological Survey of Iran.

Falcon, N., 1974. Zagros Mountains, Mesozoic-Cenozoic orogenic belts (edited by Spencer, A.). Special Publication of Geological Society, London, 4, 199-211.

Fu, B., Yoshiki, N., Lei, X., Toda, S., and Awata, Y., 2004. Mapping active fault associated with the 2003 Mw 6.6 Bam (SE Iran) earthquake with ASTER 3D images. Remote Sensing of Environment, 92, 153-157.

Guest, B., Stockli, D.F., Grove, M., Axen, G.J., Lam, P., Hassanzadeh, J., 2006. Thermal histories fromthe central Alborz Mountains, northern Iran: implications for the spatial and temporal distribution of deformation in northern Iran. Geological Society of America Bulletin 118 (11/12), 1507-1521.

Haschke, M., Ahmadian, J., Murata, M., and McDonald, I., 2010. Copper mineralization prevented by arc-root delamination during Alpine-Himalayan collision in Central Iran. Economic Geology, 105, 855-865.

Hessami, K., Jamali, F., and Tabassi, H., 2003. Major active faults of Iran, scale 1: 2,500,000. International Institute of Earthquake Engineering and Seismology.

Hollingsworth, J., Jackson, J., Walker, R., Gheitanchi, M.R., Bolourchi, M.J., 2006. Strike slip faulting, rotation, and along-strike elongation in the Kopeh Dagh Mountains, NE Iran. Geophysical Journal International 166 (3), 1161-1177.

Jackson, J.A. and McKenzie, D.P., 1984. Active tectonics of the Alpine- Himalayan Belt between western Turkey and Pakistan. Geophys. J. R. Astr. Soc., 77, 185-246.

Lacombe, O., Mouthereau, F., Kargar, Sh., and Meyer, B., 2006. Late Cenozoic and modern stress fields in the western Fars (Iran): implications for the tectonic and kinematic evolution of central Zagros. Tectonics, 25, TC1003.

Lyberis, N., and Manby G., 1999. Oblique to orthogonal convergence across the Turan Block in the Post- Miocene. AAPG Bull., 83, 1135-1160.

McClusky, S., Balassanian, S., and Barka, A., *et al.*, 2000. Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus. J. Geophy. Res., 105, 5695-5719.

McQuarrie, N., Stock, J.M., Verdel, C., and Wernicke, B.P., 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions. Geophysical Research Letters, 30 (20), 2036, 6.1-6.6.

Meyer, B., and LeDortz, K., 2007. Strike-slip kinematics in Central and Eastern Iran: estimating fault slip-rates averaged over the Holocene. Tectonics 26 (5), Tc5009.

Meyer, B., Mouthereau, F., Lacombe, O., and Agard, P., 2006. Evidence of Quaternary activity along the Dehshir Fault: implication for the tertiary tectonics of Central Iran. Geophysical Journal International, 164, 192-201.

Miyajima, M., Fallahi, A., Sadeghi, A., Ghanbari, E., Soltan, H., Amiraslanzadeh, R., Vakilazadsarabi, A., Forouzandeh, F.J., and Sheikhalizadeh, R., 2012. Site investigation of the Ahar-Varzeghan earthquake in NW Iran of August 11, 2012. International Institute of Earthquake Engineering and Seismology, 1-16.

Molinaro, M., Leturmy, P., Guezou, J.C., Frizon de Lamotte, D., Eshraghi, S.A., 2005. The structure and kinematics of the south-eastern Zagros fold-thrust belt; Iran: from thin-skinned to thick-skinned tectonics. Tectonics 24, TC3007.

Morley, C.K., Kongwung, B., Julapour, A.A., Abdolghafourian, M., Hajian, M., Waples, D., Warren, J., Otterdoom, H., Srisuriyon, K., Kazemi, H., 2009. Structural development of a major late Cenozoic basin and transpressional belt in central Iran: the Central Basin in the Qom-Saveh area. Geosphere 5 (4), 325-362.

Mouthereau, F., Lacombe, O., and Vergés, J., 2012. Building the Zagros collisional orogen: timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence. Tectonophysics, 532-535, 27-60.

Nadimi, A., 2007. Evolution of the Central Iranian basement. Gondwana Research, 12, 324-333.

Navabpour, P., Angelier, J., and Barrier, E., 2007. Cenozoic post-collisional brittle tectonic history and stress reorientation in the High Zagros Belt (Iran, Fars province). Tectonophysics, 432, 101-131.

Nazari, H., Fattahi, M., Meyer, B., Sebrier, M., Talebian, M., Foroutan, M., LeDortz, K., Bateman, M.D., Ghorashi, M., 2009. First evidence for large earthquakes on the Dehshir Fault, Central Iran Plateau. Terra Nova 21, 417-426.

Nilforoushan, F., Masson, F., Vernant, P., Vigny, C., Martinod, J., Abbassi, M., Nankali, H., Hatzfeld, D., Bayer, R., Tavakoli, F., Ashtiani, A., Doerflinger, E., Daignières, M., Collard, P., Chèry, J., 2003. GPS networkmonitors the Arabia-Eurasia collision deformation in Iran. Journal of Geodesy 77, 411-422.

Ritz, J.F., Nazari, H., Ghassemi, A., Salamati, R., Shafei, A., Solaymani, S. and Vernant, P. 2006. Active transtension inside central Alborz: A new insight into Northern Iran-southern Caspian geodynamics. Geology 34, 477-80.

Sarjoughian, F., Kananian, A., Haschke, M., Ahmadian, J., Ling, W. and Zong, K. 2012. Magma mingling and hybridization in the Kuh-e Dom pluton, Central Iran. J. of Asian Earth Sciences, 54 (55), 49-63

Sella, G.F., Dixon, T.H. and Mao, A., 2002. REVEL: a model for recent plate velocities from space geodesy. J. Geophy. Res., 107, B4, ETG 11.1, 11.32.

Smit, J., Burrg, J.P., Dolati, A., and Sokoutis, D., 2010. Effects of mass waste events on thrust wedges: Analogue experiments and application to the Makran accretionary wedge. Tectonics 29, TC3003, 11p.

Stöcklin, J., 1968. Structural history and tectonics of Iran; a review. American Association of Petroleum Geologists Bulletin, 52 (7), 1229-1258.

Stöcklin, J., 1974. Possible ancient continental margin in Iran. in: Burk, C.A., Drake, C.L. (Eds.), The Geology of Continental Margins. Springer, Berlin, 873-887.

Talebian, M., and Jackson, J., 2002. Offset on the Main Recent Fault of NW Iran and implications for the Late Cenozoic tectonics of the Arabia-Eurasia collision zone. Geophysical Journal International, 150, 422-439.

Talebian, M., and Jackson, J., 2004. A reappraisal of earthquake focal mechanisms and active shortening in the Zagros Mountains of Iran. Geophysical Journal international, 156, 506-526.

Tchalenko, J.S. and Ambraseys, N.N., 1970. Structural analysis of the Dasht-e Bayaz (Iran) earthquake fractures. Geol. Soc. Am. Bull., 81, 41-60.

Tirrul, R., Bell, I. R., Griffis, R. J. and Camp, V. E. 1983. The Sistan suture zone of eastern Iran. Geological Society of America Bulletin 49, 134-50.

Vernant, P., Nilforoushan, F., Hatzfeld, D., Abbassi, M.R., Vigny, C., Masson, F., Nankali, H., Martinod, J., Ashtiani, A., Bayer, R., Tavakoli, F., and Chery, J., 2004. Present-day crustal deformation and plate kinematics in the Middle East constrained by GPS measurements in Iran and northern Oman. Geophysical Journal International, 157, 381-398.

Vincent, S.J., Morton, A.C., Carter, A., Gibbs, S., and Barabadze, T.G., 2007. Oligocene uplift of the Western Greater Caucasus: An effect of initial Arabia-Eurasia collision. Terra Nova, 19, 160-166.

Walker, R., and Jackson, J., 2002. Offset and evolution of the Gowk fault, S.E. Iran: a major intra-continental strikeslip system. J. Struc. Geology, 24, 1677-98.

Walker, R., and Jackson, J., 2004. Active tectonics and late Cenozoic strain distribution in central and eastern Iran. Tectonics, 23, TC5010.

Zanchi, A., Berra, F., Mattei, M. R., Ghassemi, M. and Sabouri, J. 2006. Inversion tectonics in central Alborz, Iran. Journal of Structural Geology 28, 2023-37.