Explanatory Notes to the Map of Major Active Faults of Iran

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ABSTRACT: *Active faulting in Iran is a direct indicator of active crustal deformation due to the convergence between Arabia and Eurasia which occurs at 2.1-2.5 cm/yr. In this paper active faults of Iran have been considered in some detail. Geometric characteristics, mechanisms and the trend of active fault zones in different areas of Iran have been discussed while considering their tectonic differences. Active faults in Zagros are blind and the focal mechanism solutions of the earthquakes of the region point to the presence of both thrust and transverse strike-slip faulting in its basement. Whereas in the rest of the country most active faults reach the surface. The earthquake mechanism solutions along active fault systems in eastern and central Iran imply dominance of strike-slip faulting in a transpression regime. Conversely, active faults in NW Iran are transtensive. The Alborz and Kopeh-Dagh fault zones are relatively vast active fault zones in which location of individual active faults is difficult. Aside from raised terraces in the shores of the Oman Sea, information on active faults in the Makran region is scarce.*

Keywords: Active fault; Earthquake; Iran; Seismotectonics

1. Introduction

Since movement on either side of the fault plane is in many cases accompanied by an earthquake, the study of active faults can be based on strong scrutiny of available earthquake data. However, this becomes difficult when studying structurally complex and inhomogeneous collision regions such as the Iranian Plateau in which seismicity is not the result of the activity of a few faults but is due to fault activity in zones one hundred kilometers wide [10, 40]. Due to the high density of active faults in Iran and the inaccuracy of the macroseismic data of the area, the source of some of the earthquakes have been related to more than one fault [9]. Additionally lack of accurate fault and epicentral maps result in the inability to correlate seismic data with the active faulting in the area. Obviously even the assumption of highly accurate seismic data, will not solely suffice to locate all existing active faults. This is mainly due to 1) the fact that many earthquakes are caused by blind faults such as earthquakes occurring in the Zagros region [8, 42], see Figure (1); 2) some damaging earthquakes with magnitude less than 6.5 may not leave ruptures on the ground surface and, 3) the gradual movement along many active faults over a long period of time is the result of a creep regime which does not result in a large earthquake [30, 62].

The map of Major Active Faults of Iran, as shown in Figure (2), overviews the distribution of major active faults of Iran and demonstrates the slip vectors and compressive axes, obtained from the solution of the focal mechanisms of the area's earthquakes, and *GPS* velocities in different areas of Iran.

Several items included in this map are explained in the following:

1.1. Active Faults

An active fault is defined as a fault which has moved repeatedly in recent geological time and has the potential for reactivation in the future. Virtually all major faults in Iran are active and thus have great seismic potential. Since study of active faults has not been detailed enough in Iran, we can not be certain that an area without active faults is completely free of earthquake risk. Active faults are classified as the following three types:

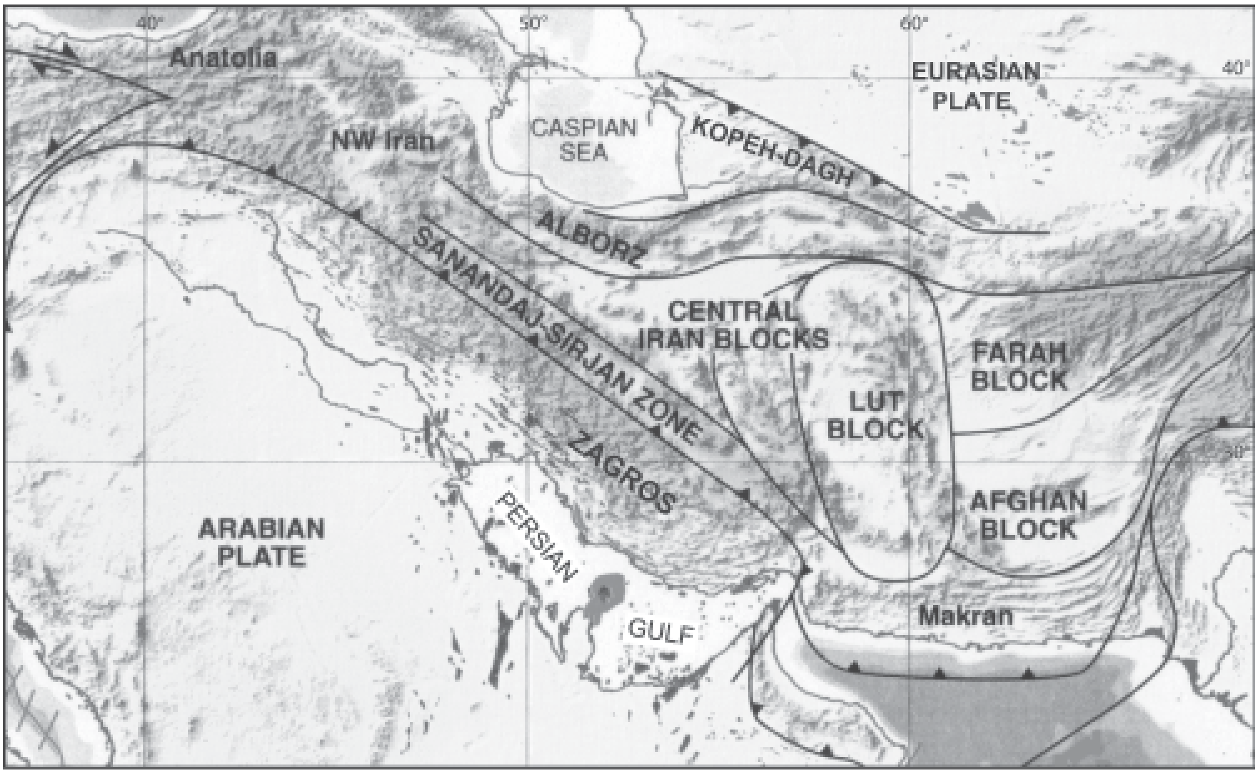

Figure 1. Tectonic setting of Iran and its subdivisions.

1.1.1. Earthquake Fault

During the last 500 years, surface ruptures associated with large earthquakes have appeared and documented in various places in Iran [2, 15]. Most of these ruptures occurred along the active faults which have moved repeatedly in the Quaternary, thus constituting evidence that these active faults have the potential of reactivating in the future.

1.1.2. Seismogenic Fault

An underground fault which generates an earthquake but does not leave ruptures on the ground surface can be called a seismogenic fault in order to distinguish it from an earthquake fault. This type is seismically identified.

1.1.3. Documented Quaternary Fault

This type is recognized to be active based on observation of offset Quaternary landforms, however, they are not known to be seismically active. This could be due to a very long recurrence interval along these faults or result from creeping, which continuously move slowly without necessarily causing earthquakes.

1.2. Earthquake Data

The earthquake data are compiled primarily from the catalogue of centroid moment tensor solutions (*CMT*) [27], which is nearly complete over the interval 1976-2002 for earthquakes greater than $Mw = 5.5$. All earthquakes with magnitude $mb = 5.8$ or greater that occurred during the period 1948 to 1976 in the area are taken from Chandra [26]. The solutions denoted by numerals are from Shirokova [54]; Jackson [38]; Shirokova [53] and Jackson and McKenzie [40].

1.2.1. Focal Mechanism Solutions

Focal mechanism solutions of the area's earthquakes have been displayed to reveal mechanisms of seismically active fault zones in Iran. These solutions indicate dominance of thrust and strike-slip faults in a compressive regime for vast majority of earthquakes of Iran.

1.2.2. Assignment of Fault Planes

Mechanism solutions for strike-slip faults indicate two steep nodal planes for all cases. The trend of the fault planes when earthquakes are associated with surface ruptures is known from the offset following recent earthquakes. However, it can also be known from distribution of aftershocks. Thus there is no ambiguity between the fault plane and the auxiliary plane in these cases. There is, however, inherent ambiguity between the fault plane and the auxiliary plane when earthquakes have mechanism solutions with a predominance of thrusting and when both nodal planes have nearly the same azimuth, such as most of the mechanism solutions of the earthquakes associated with the Zagros basement faults. For these cases the fault plane is known from geological structures observed in the region. For instance, in the Zagros the nodal plane with shallower dip is assumed to be the fault plane. This is in agreement with the northeast dipping structures observed in the Zagros Mountains.

1.2.3. Slip Vectors

The slip vector of mechanism solutions for which the fault planes are identified, generally indicate a broad convergent zone in Iran. This convergence is in many cases resulted in oblique motion of crustal material with respect to the trend of the seismogenic faults. However, slip vectors for some other recent earthquakes indicate that the convergence is partitioned into pure strike-slip motion and pure thrust faulting. Such partitioning can be seen along the Rudbar, Golbaf-Sirch and Main Kopeh-Dagh fault zones as well as in *NW* Zagros [57]. However, it was not possible to assign slip vectors to the mechanism solutions of earthquakes associated with the Zagros blind thrusts, as precise location of epicenters is not known with respect to the location of the seismogenic faults.

1.2.4. Compressive Axes

The direction of the horizontal projection of the maximum principal stress deduced from the focal mechanism solution of the area's earthquakes reveals a characteristic regional stress field along the colliding boundary. However, the distribution of horizontal compressive stress axes in different parts of Iran indicate that the local stress field is not everywhere consistent with the relative motion of the Iranian crust with respect to Eurasia. The compressive stress axes along the faults in central Iran are approximately *N-S*, parallel to relative motion of the two plates. However, they are *NE-SW* for the vast majority of earthquakes in Iran, which is not consistent with the direction of relative plate motion. For the earthquakes in the Zagros Mountains and the Kopet-Dagh region, the compressive axes have roughly a *N-NE* direction, and on the average, they are nearly perpendicular to the trend of the geological structures. The compressive axes for earthquakes in most southeastern parts of the Zagros deviate from *NE* to *NW* but remain perpendicular to the trend of the geological structures. The compressive axes determined for the earthquakes in the southwestern corner of the Caspian Sea, which all belong to the north-south trending seismic zone, have *E-W* trend.

2. Tectonic Setting

The Iranian plateau is situated between the Arabian plate to the south, and the Eurasian plate to the north. As a part of the active Alpine-Himalayan orogenic belt, it is composed of complex microcontinental blocks and ocean floored basins separated by major fracture zones. In this convergent zone, the overall northward motion of the Arabian plate is being compensated by, 1) folding and reverse faulting, resulting in a continuous thickening and shortening of the continental crust [10, 40], 2) strike slip faulting [24, 52, 67, 73], and 3) subduction of oceanic lithosphere of Oman Sea beneath Makran [25, 29].

GPS horizontal velocities show that Arabia moves at 2.1-2.5*cm/yr* due north relative to Eurasia [47, 67]. However, deformation is distributed differently over several active deforming zones. In eastern Iran shortening is distributed over the Makran subduction complex (up to 1.9*cm/yr*) and the Kopeh-Dagh Mts. (about 0.6*cm/yr*). To the west, shortening is distributed over the Zagros (about 0.8*cm/yr*) [33], and Alborz Mts. (about 0.5*cm/yr*) [68]. Right-lateral displacement takes place in western Iran mainly along the Main Recent Fault (about 0.3 ± 0.2*cm/yr*) and the North Tabriz Fault (up to 0.8*cm/yr*). The area located between Zagros and Alborz (Central Iran) moves due north at about 1.5*cm/yr* as a rigid block with respect to Eurasia while eastern Iran moves at slower rates (up to 9*mm/yr*). The contrast between the velocity vectors in west-central and eastern Iran takes the form of right-lateral strike slip motion along the north-south trending faults bounding the Lut block.

Since the type and trend of active faulting are diverse in different regions of Iran, an attempt is made to introduce the active faults of each region separately. To this end, the references are generally made to recent and historical earthquakes, and less often to geomorphic evidences.

3. Northern Iran

3.1. NW Iran

Northwest Iran is a region of intense deformation and seismicity situated between two thrust belts of the Caucasus to the north and the Zagros Mountains to the south. Earthquake focal mechanisms suggest that the convergence between Arabia and Eurasia has been accommodated mainly through *WNW*-trending right-lateral strike-slip faults in this region. These strike-slip faults appear to be the southeastern continuation into *NW* Iran of the North Anatolian fault and other right-lateral faults in *SE* Turkey. However, right-lateral faulting in the *SE* Turkey-*NW* Iran region is not continuous but consists of several discontinuous fault segments. Three of these segments ruptured during earthquakes in 1930, 1966 and 1976 [38, 40, 65, 74]. The North Tabriz fault segment, however, has been seismically inactive during the last two centuries. Among the many historical earthquakes that have occurred in the Tabriz region (e.g. the 858, 1042, 1273, 1304, 1550, 1641, 1717, 1721, 1780 and 1786 earthquakes), the destructive earthquakes of 1042 (*Ms* 7.3), 1721 (*Ms* 7.3) and 1780 (*Ms* 7.4) were accompanied by coseismic surface faulting [2, 15]. The 1721 and 1780 surface ruptures extended for at least 50 and 60*km* long, respectively [2] and occurred 60 years apart in time on adjacent fault sections suggesting that large earthquakes along the North Tabriz fault are clustered in time and are inter-related in space. The 1976 Chaldiran earthquake and its 55*km* long surface rupture in Turkey [65] suggests that there may be a typical surface rupture length for the most recent historical events in the Chaldiran-North Tabriz fault system. On the basis of offset drainages horizontal slip rates are found in the ranges of 3.1-6.4*mm/yr* along the northwestern segment of the North Tabriz fault [35]. The Khoy fault, the continuation of the Chaldiran fault, was associated with the 1977.5.26 earthquake. The focal mechanism solution of this event indicates a dominant right-lateral strike slip movement on the Khoy fault. Further south, an earthquake occurred on 1930.5.6 on the Salmas fault [23]. The resulting surface rupture was 30*km* long with signs of predominantly right-lateral strike slip faulting along with a normal component [2, 23]. The development of a normal faulting component, seen in the surface faulting at Salmas 1930, and possibly the 1981.07.23 and 1970.10.25 earthquakes imply that the active faults of this region are transtensive.

3.2. Alborz

The Alborz region is an active zone with a high density of active faults. Since many of the region's earthquakes were not associated with surface faulting and the mizoseismal areas of many of these earthquakes are relatively large, locating the active fault becomes complicated. The most important faults in the southern edge of Alborz, which their activity has been documented using both seismicity and field investigations are: The North Tehran fault, Mosha fault, North Qazvin fault, and Damghan fault [3, 5, 9, 10, 19, 21]. Seismic activity of Torud, Ipak and Abdarreh faults to the south of the Alborz mountains were followed by surface faulting [1, 2, 12, 69]. The focal mechanism solution of the 1962.9.1 Buin-Zahra and 2002.06.22 Changureh earthquakes which occurred on the southward-dipping Ipak and Abdarreh faults respectively, indicate predominance of thrust movements. However, field observations suggest that left-lateral movement dominates reverse movement along the Ipak fault [5]. The Khazar fault, a reverse fault with a southward dip direction, is the longest active fault in the Alborz, and is located in the northern edge of the Alborz mountains. This structure separates the Caspian depression to the north from the Alborz mountains in the south. The activity of some of the faults within the Alborz mountain range has been documented using historical and recent earthquakes. The Rudbar-Tarom Earthquake of 1990.6.20 was associated with 80*km* of discontinuous earthquake faulting [18]. The focal mechanism solution for this earthquake implies a left-lateral strike slip movement on a west-northwest fault plane. The surface faulting also indicates a small reverse component. The preliminary study found no convincing Holocene activity along the 1990 surface ruptures, and no active geomorphological features could be detected on the aerial photographs, or satellite imagery. Based on such evidences, it can be deduced that the earthquakes are not necessarily caused by the reactivating of old or recent faults; but in regions of distributed deformation such as the Iranian plateau, the possibility of formation of new faults in wide active fault zones is conceivable.

3.3. Kopeh-Dagh

In the Kopeh-Dagh, a region in northeast of Iran, strike slip faults form conjugate shear faults. The north-northwestern trending faults are dominant in the eastern Kopeh-Dagh. The 1929.5.1 Baghan-Germab earthquake is the only earthquake in Kopeh-Dagh which is associated with surface faulting [2, 62]. The surface rupture associated with the Baghan-Germab earthquake has a north-northwestern trend and a length of 50*km* [62] to 70*km* [2]. Ambraseys and Melville [2] report an oblique motion (right-lateral and reverse movement) on this fault. Movement on the faults with northeastern trends indicate a combination of left-lateral strike slip and normal components [62]. The focal mechanism solutions of the 1970.7.30 and 1974.3.7 earthquakes in western Kopeh-Dagh indicate domination of left-lateral strike slip movement with a small normal component on northeastern nodal planes [40]. The northeastern boundary of Kopeh-Dagh is marked by the Main Kopeh-Dagh fault. Although the measured displacement by Trifonov [66] suggests a right-lateral strike slip movement on this fault, the solution of the focal mechanism for the 1948.10.5 Ashkhabad earthquake on this fault zone indicates thrust faulting with a southwestern dip direction. On the southern margin of Kopeh-Dagh, activity of Esfarayen thrust has been documented by the 1969.1.3 earthquake. Recent activity of Kashafrud and Quchan faults within Kopeh-Dagh has also been documented [9-10].

4. Eastern and Central Iran

There are numerous active faults in Eastern and Central Iran whose seismic activity have been documented [2, 13, 14, 15, 16, 70, 71]. The fault systems in this region are different from other regions of Iran due to their orientations and geometric characteristics; namely, they are linear faults, lengthy and narrow in width.

The Doruneh active fault [12, 70, 73] is an arcuate structure with a length of about 650*km* which forms the longest active fault in eastern Iran. Seismic activity of this fault, both recent [40, 64] and historical [2], has not resulted in surface rupture. Geomorphic evidence indicates that the Doruneh fault has rotated clockwise about vertical axis as a result of concentration of shear along eastern margin of the Lut region [70]. This clockwise rotation which increases from west to east has resulted in left-lateral movement along the western segment of the fault while causing thrusting along its eastern segment.

In Dasht-e-Bayaz area, south of Doruneh fault, each of the 1968.8.31 and 1979.11.27 earthquakes were followed by surface faulting of approximately 80*km* and 60*km* respectively [2]. Field observations and solution of the focal mechanisms of the two earthquakes imply a predominant left-lateral strike slip movement along its east-west trend [2, 40, 70]. The correlation of the east-west trending faults which parallel and lie to the north and south of the Doruneh Fault with the region's earthquakes, implies their activity.

In south of the Dasht-e-Bayaz fault, there are several long linear faults striking north-south, visible on air photographs, satellite images and on the ground [70]. These extend south towards the Makran region, dominating the topography of eastern Iran and the borders of the Lut region and are known to be active [13, 70]. Occurrence of the 1941.2.16 and 1947.9.23 earthquakes was followed by north-south trending surface faulting [2]. The solution of the focal mechanism and the 20*km* surface faulting associated with the 1979.11.14 earthquake depicts domination of right-lateral strike slip movement along the north-south trending nodal plane [31, 40]. The 1997.5.10 Zirkuh earthquake on the Abiz fault is associated with a total of 125*km* of *NNW* trending surface faulting [16]. The focal mechanism solutions for this earthquake show a right-lateral strike slip movement with a small reverse component. Further south, the 1994.1.23 Sefidabeh earthquake was associated with a *NW* trending blind thrust system and involved bedding plane-slip on a growing anticline [14]. Recent studies used *SAR* interferogam to measure the amount of coseismic surface displacements associated with the Sefidabeh earthquake and *U*/*Th* dates of uplifted lake deposits to infer the slip rate (1.5*mm/yr*) along the Sefidabeh fault [50]. There is little modern seismicity on the other north-south structures in this region. These structures include the Nayband, West and East Neh, Zahedan, Shahdad, Jiroft and Sabzevaran faults. The offset geomorphologic features imply right-lateral strike slip motion at a rate of about 6*mm/yr* along the Jiroft-Sabzevaran fault system [51]. However, this rate decreases northward to about 2-3*mm/yr* along the Gowk-Nayband fault system [6, 72].

Seismic activity in northwest trending Rafsanjan, Ferdows and Tabas faults has been documented [9, 71]. The northwest trending Ferdows thrust fault was involved in the 1968.9.1 and 1968.9.4 earthquakes [10, 11]. The focal mechanism solution for the 1978.9.16 Tabas-e-Golshan earthquake which was accompanied by an approximately 85*km* surface faulting, implies a dominant thrust movement with a small right-lateral strike slip component [11, 71]. Surface deformations resulting from earthquake activity of active faults with north-south and northwest trends in this region, imply a combination of strike slip and thrust faulting. Along the north-south trending faults, the right-lateral strike slip component dominates the thrust component; whereas, in the northwest trending faults the opposite is true. Almost all of these active north-south and northwest trending faults, are frontal faults which separate mountain belts from compressional depressions [10].

5. Makran

The Makran ranges are formed due to subduction of oceanic crust of the Oman Sea, with a 6*km* thick sedimentary cover, beneath the Asian margin [29, 75]. The eastern limit of the Makran is marked by the Chaman and Ornach-Nal faults of Pakistan. The *NNW* trending Zendan-Minab-Palami fault zone marks the western limit of the Makran subduction zone and connects the western Makran to the eastern Zagros deformation domain. Recent *GPS* studies [6] as well as geomorphic investigation [51] suggest that the Minab-Zendan-Palami fault system is moving at a rate between 7-10*mm/yr*.

In contrast to the eastern Makran (in Pakistan) where historical and recent earthquakes occur [25, 49], there is little information on the active faults and seismicity of the western Makran (in Iran) subduction zone. The raised Holocene marine terraces in the Makran shores are the result of tectonic movements on thrust faults [43, 51]. The absence of plate boundary events in western Makran may suggest that the plate boundary is currently locked and experiences great earthquakes with long repeat times. Active faults however, are not limited to the Makran subduction zone. There is evidence of seismicity and recent activity of faults in the northern margin of Makran. Recent movement of these faults is composed of thrust and right-lateral strike slip faulting.

6. Sanandaj-Sirjan

In view of lack of data indicating occurrence of large recent and historical earthquakes, and insufficiency of evidences in the field and aerial photographs, no proof of existence of active faults in this zone has been found. Regardless, at the northeastern and southwestern boundaries, this zone has been confined by narrow fault zones within which fault activity has been documented.

The southwestern boundary of this zone is the northwest trending Main Zagros Reverse Fault [55] which joins the Main Recent Fault [63] due northwest. There is no documented surface evidence of historical rupturing or meizoseismal areas of large earthquakes along the *MZRF*, where the seismicity of the Zagros Mountains stops. The Main Recent Fault is an active wrench fault which is composed of several individual fault segments (i.e., Morvarid, Sahneh, Garun, Nahavand and Dorud [63]). The 1909.01.23 and 1957.12.13 earthquakes in this zone have been associated with surface faulting [8, 63]. Both the solution of focal mechanism of the events and offset of drainage pattern [57], depict dominant right-lateral strike slip movement on the northwest trending fault plane.

The northeastern boundary of Sanandaj-Sirjan, in most places, is marked by the elongation of depressions which are extended from the Rafsanjan fault in the southeast to the Kushk-e Nosrat fault in the northwest. There is little information on the seismic activity of this structure to the northwest. However, Geomorphic evidence indicates that some of these faults such as, the Deh Shir, Shahr-e Babak, Zephreh, Kashan, Tafresh and Indes faults have been active since late Pleistocene and responsible for repeated faulting events [12, 37, 45]. By contrast, the southeastern faults of this boundary have been seismically very active. Most of these faults consist of several segments arranged in a left stepping en-echelon pattern with some overlap. Three of these faults ruptured during six major earthquakes in the last 70 years: the Kuh-Banan fault in 1933 and 1977 [2, 11, 22], the Gowk fault zone in 1981, 1989 and 1998 [13, 17, 20, 72] and the Bam fault in 2003 [34, 59, 60, 61]. Field observations and earthquake focal mechanisms suggest that these earthquakes have been associated mainly with right-lateral strike-slip motion along faults that trend *NNW*.

7. Zagros

The Main Zagros Reverse and Main Recent faults separate two regions with utterly different seismicity and active faulting characteristics; namely, the Zagros mountains in the southwest and the Sanandaj-Sirjan zone in the northeast. Most focal mechanism solutions of earthquakes in the Zagros region indicate the presence of active reverse faults [8, 40, 48, 58]. 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 [7, 32, 41, 44, 46, 61]. These observations have led many workers to suggest *NE*-dipping reverse faults in the basement [8, 39, 40, 41, 46, 61]. Thus, the active Mountain Front Fault [8, 28] is considered to be a major seismogenic reverse fault in the Zagros basement [8].

The Kazerun Fault is a north-south trending strike-slip fault which crosses the Zagros belt at about longitude 51.5°. It has been described as the most significant strike-slip fault within the belt [4, 7, 8, 36, 56]. Lateral offset of Zagros fold axes and the Mountain Front Fault have frequently been invoked to confirm right-lateral displacement along this Fault [4, 8]. Focal mechanism solutions of the earthquakes along the Kazerun and other transverse faults within the Zagros region are interpreted as steeply-dipping strike-slip faults with minor components of normal-slip movement [7, 58]. Furthermore, the change in direction and magnitude of the *GPS* velocity vectors involve extension across the Kazerun fault [32]. NW of the Kazerun Fault, most moderate to large earthquakes occur near the Mountain Front Fault which follows the 1*km* high topographic contour [8]. To the *SE* of the Kazerun Fault, however, the same structure follows the 500*m* contour but has lower seismic activity. Active basement thrusting *SE* of the Kazerun Fault follows the 2*km* "topographic front" [32, 46].

8. Conclusions

Although many of the active fault zones of Iran have been determined, many of the individual active faults are yet to be studied. Due to the geological characteristics and scarcity of accurate seismic data in Iran, it is recommended to employ geodetic and geomorphologic methods in the study of active faulting. With the current level of information on the active faults of Iran, it is not possible to establish a dominant fault regime for the entire country. However, it can be generally stated that, in most cases a transpression regime governs the strike slip faulting in Iran.

Acknowledgments

We thank the four anonymous reviewers for their constructive criticisms. This work was supported by the International Institute of Earthquake Engineering and Seismology.

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