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Seismotectonics of Sahneh fault, middle segment of main recent fault, Zagros mountains, western Iran

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Abstract

A detailed mapping and short-term microearthquake survey in a small region covering the Sahneh fault segment of the Main Recent Fault of the Zagros Mountains, in western Iran, is conducted to study the seismotectonics of the Sahneh fault. It is found that the Sahneh fault is an active second order structure of the transpression (positive flower structure) type with temporarily low level of seismic activity.

Meizoseismal regions of historical earthquakes, macroseismic epicenters of pre-instrumental (1900~1963) earthquakes, as well as the location of microearthquakes together with the structural geology of the region, strongly suggest that the study region should be considered as a localizing structure, so that the seismic activity of the region cannot reliably be correlated to any known active faults. Present microseismic activity is concentrated in the area bounded by the southern part of the Sahneh fault and the northern elongation of the Nahavand fault, that covers the meizoseismal regions of the Farsinaj earthquake of 13 December 1957 (M_s=6.7).

Focal mechanism of earthquakes and structural analysis confirms the prominent right-lateral strike-slip deformation along the Sahneh fault. This is consistent with relative motion between the Arabian Plate and the Central Iran Microcontinent. Hypocenters of earthquakes recorded from August to September 1998, by the local seismic network, show that earthquakes in this region originate mainly in depths of about 10 km.

Key words: main recent fault, microseismicity, Zagros, Sahneh fault, seismotectonics

1. Introduction

The convergence of two continents can be accommodated by crustal thickening and by lateral transport of the crust out of the path of the converging continents (e.g., England and Molnar, 1990). The principal features suggesting thickening and lateral transports are reverse and strike-slip faults respectively.

The Zagros fold-thrust belt as a part of the Alpine-Himalayan orogenic belt, is one of the youngest and most active continental collision zones on the earth (Snyder and Barazangi, 1986). Two major faults dominate the tectonics of the northeastern boundary of the Zagros; the Main Zagros Reverse Fault and the Main Recent Fault (Tchalenko and Braud, 1974; Berberian, 1995; Figure 1). The Main Zagros Reverse Fault has NW-SE strike from western Iran to north of Bandar Abbas and the Main Recent Fault is a major right-lateral strike-slip seismogenic structure, broadly parallel but younger than the Main Zagros Reverse Fault which transects it in several places.

The Sahneh fault, the middle segment of the Main Recent Fault, is studied based on structural analysis, investigation of the historical and instrumental seismicity and short-term microearthquake survey during August and September 1998. Meizoseismal regions of historical earthquakes, macroseismic epicenters of pre-instrumental earthquakes, as well as the location of microearthquakes together with the structural geology of the region, strongly suggest that the study region should be considered as a localizing structure, so that in investigation of seismic activity of the region it is not possible to reliably correlate an earthquake to one of the known faults in the active fault zone. Present microseismic activity is concentrated in the area bounded by the southeastern part of the Sahneh fault and the northern elongation of the Nahavand fault, that covers the meizoseismal region of the Farsinaj earthquake of 13 December 1957, M_s=6.7 (Figure 2).

2. Tectonic setting

The Zagros fold-thrust belt as a part of the Alpine-Himalayan orogenic belt, is one of the youngest and most active continental collision zones on the earth (Snyder and Barazangi, 1986), which extends for about 1500 km from the Taurus mountains in southeastern Turkey to the Minab Fault to the east of the Strait of Hormoz in southern Iran (Figure 1). The belt is a broad zone of continuing compressional deformation that experiences horizontal shortening of the basement (and not a simple underthrusting of the Arabian plate beneath the Iranian plateau) on reactivated normal faults which stretched and thinned the basement of a continental

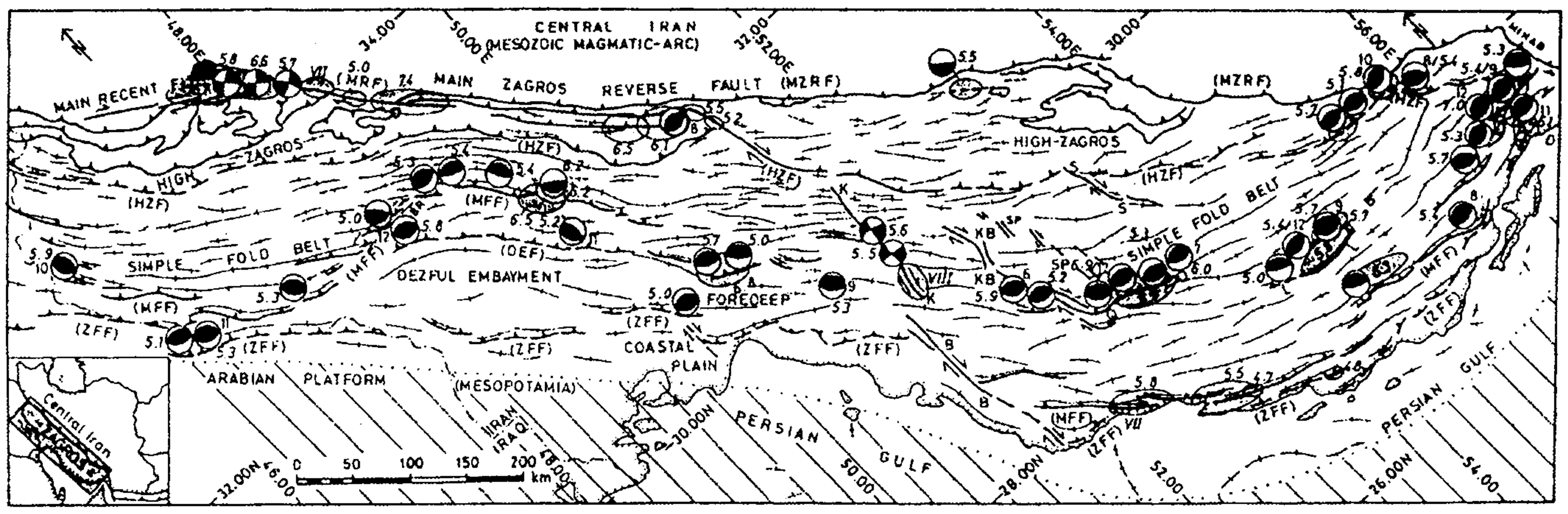

Figure 1. Map of active faults, selected focal mechanism solutions and meizoseismal regions of moderate and major earthquakes in Zagros (after Berberian, 1995).

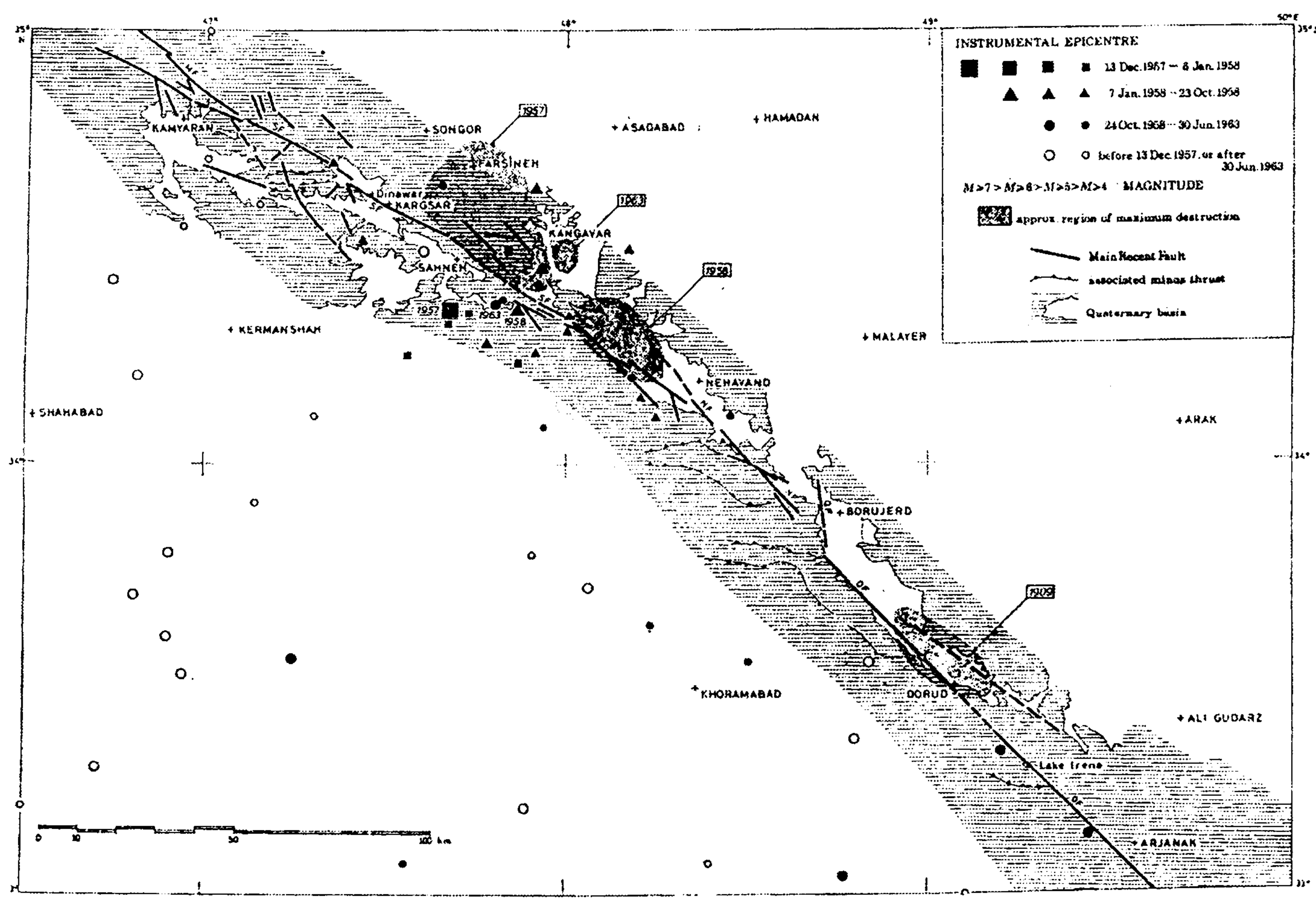

Figure 2. Macroseismic regions of earthquakes on the Main Recent Fault (after Tchalenko and Braud, 1974).

margin on which the Mesozoic sedimentary cover was deposited (Jackson, 1980; Jackson *et al.*, 1981; Jackson and Fitch, 1981; Berberian, 1981, 1995; Molnar and Chen, 1982). Two major faults dominate the tectonics of the northeastern boundary of the Zagros: the Main Zagros Reverse Fault and the Main Recent Fault (Figure 1). The Main Zagros Reverse Fault has NW-SE strike from western Iran to north of Bandar Abbas. To the northwest, the boundary feature consists of a series of right-lateral strike-slip faults called the Main Recent Fault. The Main Recent Fault is a prominent right-lateral strike-slip fault system with a northwest-southeast trend, in the northeast Zagros border zone, which is broadly parallel to, and younger than, the Main Zagros Reverse Fault. It is a major seismogenic structure constituted of several segments (namely: Dorud, Nahavand, Garun, Sahneh, Morvarid and Piranshahr faults) with different levels of seismicity. More intense seismic activity in the Zagros is concentrated along the Main Recent Fault, between 33°~35° N on the Dorud, Nahavand and Sahneh segments, while the Morvarid and Piranshahr segments, to the north, show relative seismic quiescence (Tchalenko and Braud, 1974; Berberian, 1995).

Many authors believe that the Main Recent Fault dies out southward at about 31° N (e.g., Jackson and McKenzi, 1984; Jackson *et al.,* 1995; Berberian, 1995), but there are some indications that it may extend southeastward (e.g., Baker, 1993). The Sahneh fault, which connects the Garun and Nahavand faults in the southeast to the Morvarid fault in the northwest, is about 100 km long and strikes between N295° and N300°. Direction of the Sahneh fault is exceptional compared to the other segments of the Main Recent Fault, which are characteristically at about N315°. The Sahneh fault may be divided into three sections of approximately equal length (Tchalenko and Braud, 1974).

3. Seismic activity of the region

Although earthquakes are distributed across the entire Zagros, earthquakes of larger magnitudes are mostly nucleated along different segments of the Main Recent Fault. For example, the Silakhor earthquake of 23 January 1909, $M_s=7.4$, on the Dorud fault segment, is the largest event recorded in the Zagros. The Sahneh and Nahavand faults are responsible for several documented destructive earthquakes in historical and instrumental time periods (e.g., Tchalenko and Braud, 1974; Berberian, 1994). Moreover, archeological excavations provide some indications of much earlier destructive earthquakes in the region (Tchalenko and Braud, 1974; Ambraseys, 1974; Moinfar, 1976).

A destructive earthquake on 27 April 1008 devastated the important city of Dinavar. The city was completely destroyed with the loss of more than 16,000 people. The magnitude of this earthquake is estimated to be $M_s=7.0$ (Ambraseys and Melville, 1982). It is one of the most intense earthquakes in the Zagros. The number of fatalities and existence of a considerably large fault scarp in the region (Figure 3), that most possibly formed during this earthquake, implies that the magnitude of this earthquake is underestimated. According to experience in earthquake regions, the most possible epicenter for this earthquake is 33.62°N 47.64°E, where the Main Recent Fault intersects the Main Zagros Reverse Fault (Figure 4). A large earthquake of $M_s=6.5$, strongly shocked the same region in September 1107 (Ambraseys and Melville, 1982). Additional information on this earthquake is not available.

The Farsinaj (Farsineh) earthquake of 13 December 1957, $m_b=6.5$, $M_s=6.7$, occurred close to the northeastern boundary of the Zagros. This event is attributed to the Sahneh segment of the Main Recent Fault by some authors. More than fifty kilometers of fault breaks on the Sahneh fault during Farsinaj earthquake is pointed out by Berberian (1981). Indeed, the Farsinaj earthquake fault did not break the surface

Figure 3. A view of the fault scarp along the Sahneh fault adjacent to the village of Dastjerdeh-e-Sofla, looking south.

(e.g., Tchalenko and Braud, 1974). Field investigations and interviews with local people show that the earthquake occurred on a buried fault, probably a continuation of the Nahavand fault.

About eight months after the catastrophic earthquake in Farsinaj, a destructive earthquake of magnitude $m_b=6.2$, $M_s=6.6$, occurred in the Firuzabad district of Nahavand on 16 August 1958 (Figure 4). It was associated with ground rupture, consisting of a wide zone of cracks running in a general northwest-southeast direction, at least 20 kilometers long (Ambraseys and Moinfar, 1974a). The Firuzabad earthquake was preceded by a relatively large foreshock of $M_s=5.7$, on 14 August 1958.

On 21 September 1958, a violent shock of magnitude 5.2 ruined seven villages in the region of Dinavar. The evidences of ground deformation, probably of tectonic origin, between the villages of Kargasar and Karaj, most probably occurred during this shock is reported (Ambraseys and Moinfar, 1974b).

Following a period of relative quiescence after the Firuzabad earthquake, the region of Karkhaneh in Kangavar, was damaged by an earthquake of $M_s=5.8$, on 24 March 1963. The meizoseismal area of this earthquake lies between and overlaps the meizoseismal area of the earthquakes of Farsinaj to the northwest and Firuzabad in the southeast. The Karkhaneh earthquake was not preceded by any identifiable foreshock, but was followed by strong aftershocks that continued for about a month. It caused considerable ground deformation along the Kangavar valley running for at least 8 km (Ambraseys and Moinfar, 1974b).

Since writing this paper, on 24 April 2002, a sequence of earthquakes, the largest one with magnitude $m_b=5.2$, $Ms=5.2$ (USGS/NEIC QED Earthquake Bulletin), killed

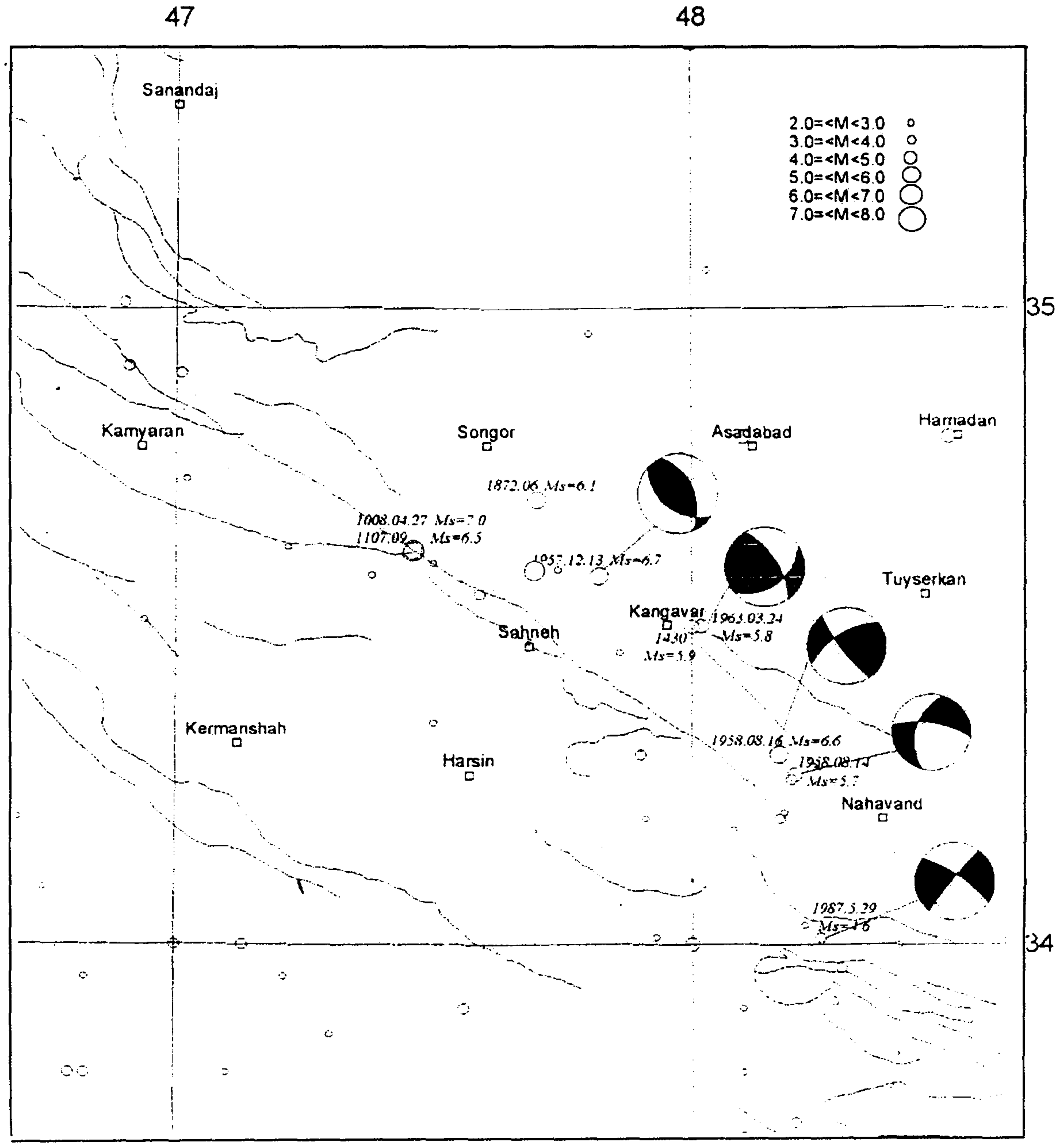

Figure 4. Fault map, earthquake epicenters (1008~1997 AD) and selected focal mechanism solutions of earthquakes in Sahneh and surrounding regions.

one person, injured 56 in the Dinavar region and destroyed 60 villages, of which 10 suffered complete destruction.

4. Field investigations

Detailed mapping of the Sahneh fault and 36 days of special earthquake survey were conducted during August and September 1998. the existence of an exceptional fault scarp coincident with the Sahneh fault plane, in the vicinity of the village of Dastjerdeh-e-Sofla has provided a distinct geomorphic structure of tectonic origin (Figure 3). The fault scarp is convex in shape with curvature to the north. The fault strikes ~N300^o in the study site, quite similar to the strike of the Sahneh fault that is visible on the Landsat imagery and air-photos. This structure clearly shows a positive flower (palm-tree) structure that is formed during Quaternary (Recent) tectonic movements. In the vicinity of this fault scarp, especially from the village of Mir-Taheri in the west to the village of Doab in the east, uplifted Quaternary alluviums exist lying under the large volume of severely brecciatted crystallized Jurassic limestone constituting the fault scarp. It is very possible that the intense seismic activity of the region, such as the catastrophic earthquake of 27 April 1008 in Dinavar, that caused 16000 casualties with large ground deformations, has been a consequence of the activity of this fault segment. Based on drainage patterns, geological markers and geomorphological features, Talebian and Jackson (2002) have determined a right-lateral offset of ~50 km on the Sahneh fault. If slip would have begun at 3-5 Ma, it would yields a horizontal slip rate of 10~17 mm/yr. (Talebian and Jackson, 2002).

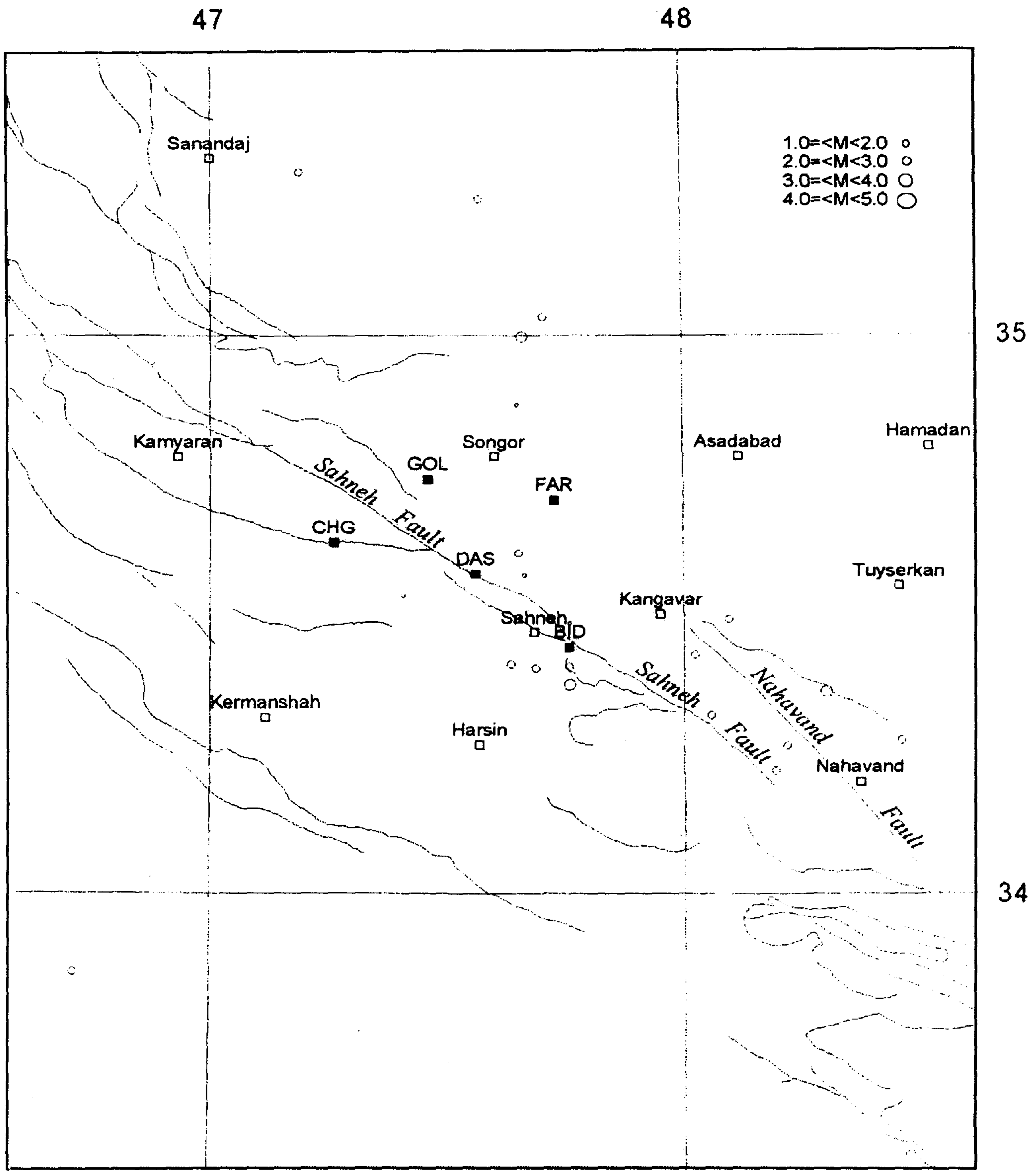

Figure 5. Fault map and epicenters of earthquakes recorded by the temporary seismic network (the network operated for 36 day in August and September, 1998). Recording stations are marked by quadrangles.

A sequence of earthquakes, the largest one with magnitude m_b=5.2, *Ms=5.2* (USGS/NEIC QED Earthquake Bulletin) on 24 April 2002, resulted in considerable damage in the Dinavar region. The first author visited the affected region and found that the earthquake was nucleated from the reactivation of the Sahneh fault, creating very clear Riedel shears of left stepping arrangement. This is a very classic manifestation of shear fractures in a simple shear zone of right-lateral strike-slip mechanism (a paper including details of fracturing during these earthquakes is in preparation).

A local seismographic station network consisting of five portable analog seismographs was installed on and around the Sahneh fault from August to September 1998 (Figure 5 and Table 1). Four of the instruments were PS2 seismographs and the fifth was a Sprengenther MEQ800 seismograph. Stations were arranged in a trapezoid array, so that four PS2 seismographs were located in the corners and the MEQ800 seismograph in the center of the trapezoid (on the Sahneh fault).

Table 1. Seismographic stations and their equipment.

Instrument Type	Elevation (m)	Latitude (°)	Longirude (°)	Station Code
PS2	1700	34.74	47.46	GOL
PS2	1493	34.63	47.26	CHG
MEQ – 800	1435	34.57	47.56	DSG
PS2	1495	34.44	47.76	BID
PS2	1825	34.71	47.73	FAR

During 36 days of seismic survey, the local network recorded 23 reliable earthquakes. The majority of the events are located close to the Sahneh fault and near to the Nahavand fault (Figure 5). The accuracy of instruments is one half-second. The upper limit of Residual Mean Square (RMS) is considered as 0.3 s that results in location accuracy of ± 2.5 km in the worst case. Daily timing of the instruments were controlled by radio frequency of one pulse per second (1 PPS). As the velocity structure of the crust in Zagros is so little known, the three layer model (Table 2), given by Niazi *et al.* (1978), for Kermanshah region, is acceptable for our purpose.

Table 2. The crustal model of Kermanshah region (Nazi et al., 1978).

Thickness (km)	V_S (km/s)	V_P (km/s)	Layer
4.00	2.10	3.80	1
16.00	3.30	5.70	2
?	4.10	7.10	3

Earthquake parameters are determined using HYPO71 PC software, which is appropriate for locating local events. Due to a relatively_good array deployment and continuous timing control, we believe that the locally recorded earthquake parameters are reliable.

Hypocenters of earthquakes recorded during the August and September 1998, by a relatively dense seismic network, show that earthquakes in the study region originate mainly in depths of about 10 km, and earthquake activity in depths of more than 15 km is not recorded.

5. Focal mechanism solution of earthquakes

Whenever a sufficient number of seismographic stations are arranged in a good station distribution around the causative fault of an earthquake, it is possible to define focal mechanism of the earthquake accurately. In this study, because of an insufficient number of seismographic stations, we used polarities of first P motions recorded during 36 days of seismic survey in different stations around the Sahneh fault to define composite focal mechanism of earthquakes. In the best solution, the first nodal plane strikes N294° and dips NE at 66° and the second nodal plane strikes N31° and dips SE at 76° (Figure 6). The strike of first nodal plane agrees quite well with the strike of the Sahneh fault. Considering the first nodal plane as the fault plane and regarding the location of P and T axes, the solution shows prominent right-lateral strike-slip mechanism with a component of reverse faulting. This is in accord with the characteristics of the Sahneh fault deduced from structural geology.

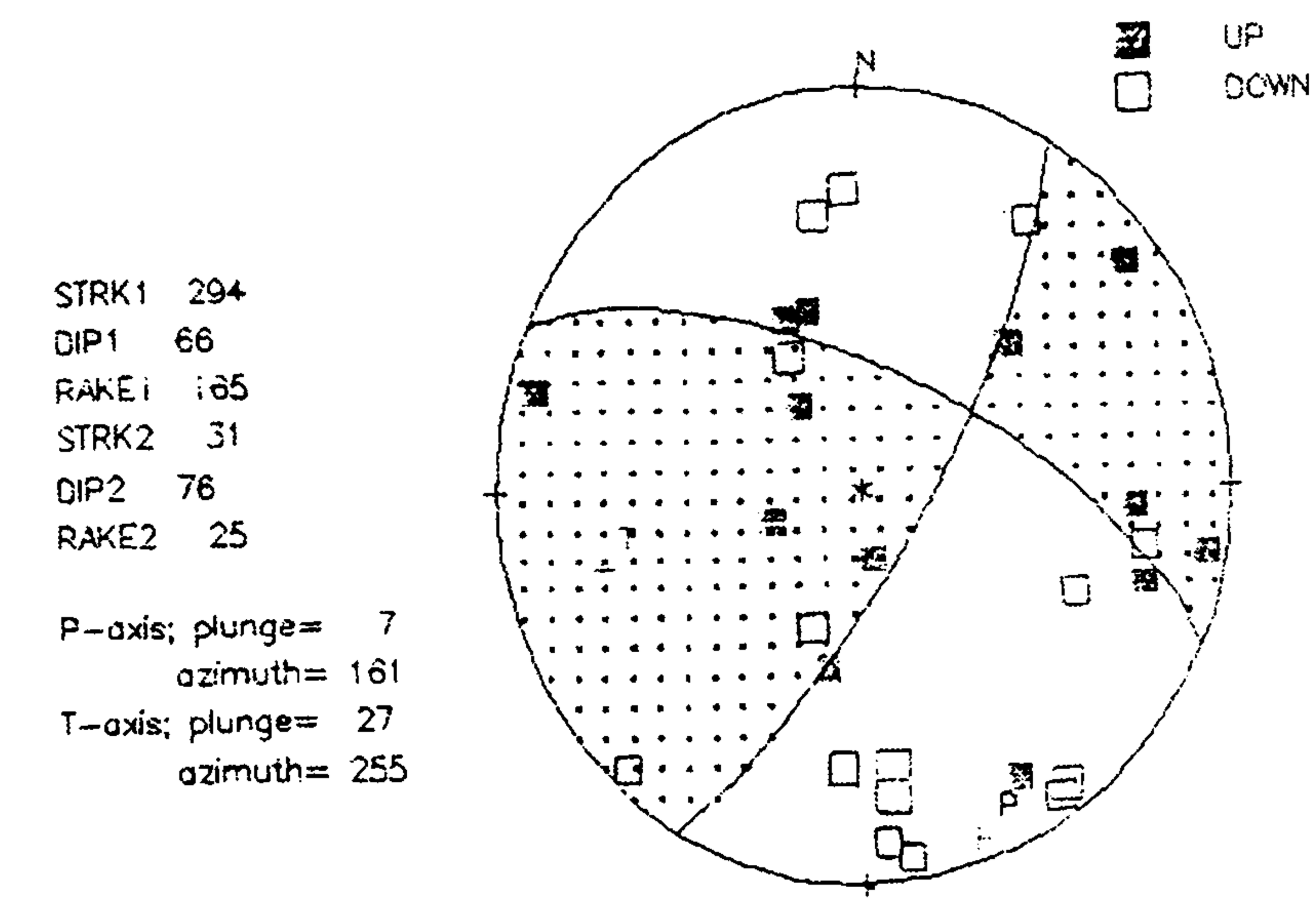

Figure 6. Composite focal mechanism solutions of earthquakes recorded by the temporary seismic network.

Although the focal mechanism solutions often do not provide the required resolution in focal depth and fault plane solution for detailed seismotectonic studies, this solution can be proved by the mechanism of movements on the Main Recent Fault. Fault plane solutions of earthquakes on 14 and 16 August 1958 (Shirokova, 1967), based on the first P motion polarities (Figure 4), show prominent right-lateral strike-slip motion on a NW trending fault. Ni and Barazangi (1986), using a waveform modeling technique, determined right-lateral strike-slip solution for the Karkhaneh earthquake on 1963.3.24, which was nucleated from the movement of the Nahavand fault. Jackson and McKenzi (1984), based on the first P motions suggest the same mechanism for this event. The CMT solution of an earthquake on 1987.05.29, M_s= 4.6, also shows right-lateral strike-slip faulting in this zone. These consistencies show that the occurrence of large-, small- and microearthquakes are related to the same stress field, which is not complicated from a tectonic point of view.

6. Conclusions

Meizoseismal regions of historical earthquakes in Dinavar, macroseismic epicenters of pre-instrumental earthquakes, as well as the location of microearthquakes together with structural geology of the region, strongly suggest that the Sahneh fault is an active secondary Riedel (P shear) structure of transpression (positive flower structure) type with a temporarily low level of seismic activity.

Present microseismic activity is concentrated in the area bounded by the southern part of the Sahneh fault and the northern elongation of the Nahavand fault, that covers the meizoseismal regions of the Farsinaj earthquake of 13 December 1957 (M_s=6.7).

The Farsinaj earthquake of 13 December 1957, $m_b=6.5$, $M_s=6.7$ is attributed to the Sahneh segment of the Main Recent Fault by some authors. More than fifty kilometers of fault breaks on the Sahneh fault during the Farsinaj earthquake are pointed out in some articles. Indeed, the Farsinaj earthquake fault did not break the surface. Field investigations and interviews with local people show that the earthquake occurred on a buried fault, most probably a continuation of the Nahavand segment of the Main Recent Fault. The large number of fatalities, intense ground deformations and existence of a considerably large fault scarp in the vicinity of the village of Dastjerdeh-e-Sofla, most possibly formed during the 27 April 1008, $M_s=7.0$, earthquake, implies that the magnitude of this earthquake is underestimated.

Hypocenters of earthquakes recorded during August and September 1998, by a relatively dense seismic network, show that earthquakes in this region nucleate mainly in depths of about 10 km, and an earthquake deeper than 15 km is not recorded.

Focal mechanism of large earthquakes on the Main Recent Fault, deduced from first P motions as well as from waveform modeling technique, show prominent right-lateral strike-slip displacements. Composite focal mechanism solution of microearthquakes shows prominent right-lateral strike-slip mechanism with a component of reverse faulting, which accord with the characteristics of the Sahneh fault deduced from structural geology. Geometry of an exceptional fault scarp along the Sahneh fault exhibits a positive flower structure formed during compressional strike-slip (transpression) motions. Right-lateral offset of ~50 km on the Sahneh fault, based on drainage patterns and geological markers is documented by Talebian and Jackson (2002). A right-lateral strike-slip motion on the Dinavar segment of the Sahneh fault can be deduced by the creation of a typical set of shear fractures during the most recent earthquake on 24 April 2002, $M_s=5.2$ (USGS/NEIC).

The consistency of the results of structural geology, focal mechanism solutions of earthquakes, offset of geological markers together with the most recent ground ruptures (forming typical left stepping Riedel shears) indicate prominent right-lateral strike-slip motions with a component of reverse faulting, resulting in a transpression system of ground deformation.

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Reference

Ambraseys, N. N., 1974, The historical seismicity of north-central Iran: Geol. Surv. Iran, Rep. 29, 47-96.

Ambraseys, N. N. and Melville, C. P., 1982, A History of Persian Earthquakes: Cambridge University Press, Cambridge, 219.

Ambraseys, N. N. and Moinfar, A., 1974a, The seismicity of Iran; The Firozabad earthquake of 16th August 1958: Annali. di Geofisica., **27**, 1-21.

Ambraseys, N. N. and Moinfar, A., 1974b, The seismicity of Iran; The Karkhaneh, Kangavar, earthquake of 24th March 1963: Annal. di Geofis., **27**, 23-36.

Baker, C., Jackson, J. and Priestley, K., 1993, Earthquakes on the Kazerun line in the Zagros mountains of Iran; strike-slip faulting within a fold and- thrust belt: Geophys. Jour. Int., **115**, 41-61.

Berberian, M., 1981, Active faulting and tectonics of Iran: *in* Gupta, H. K. and Delany, F. M. Ed., Zagros-Hindukush-Himalaya Geodynamic Evolution, Am. Geophys. Union and Geol. Soc. Am., Geodynamic Series, **3**, 33-69.

Berberian, M., 1994, Natural Hazards and the first earthquake catalog of Iran, Vol. 1; historical hazards in Iran prior to 1900: IIEES, Tehran, Iran.

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

England, P. and Molnar, P., 1990, Right-lateral shear and rotation as the explanation for strike-slip faulting in eastern Tibet: Nature, **344**, 140-142.

Jackson, J. A., 1980, Reactivation of basement faults and crustal shortening in orogenic belts: Nature, **283**, 343-346.

Jackson, J. A. and Fitch, T. J., 1981, Basement faulting and the focal depth of the large earthquakes in the Zagros mountains (Iran): Geophys. J. R. astr. Soc., **64**, 561-586.

Jackson, J. A., Fitch, T. J., and McKenzi, D. P., 1981, Active thrusting and the evolution of the Zagros fold belt: in McClay, K. R. and Price, N. J., Ed., Thrust and Nappe Tectonics, Geol. Soc. Spec. Pub., **9**, 371-379.

Jackson, J. A. and McKenzi, D. P., 1984, Active tectonics of the Alpine-Himalayan belt between Western Turkey and Pakistan: Geophys. J. R. astr. Soc., **77**, 185-264.

Jackson, J., Haines, J. and Holt, W., 1995, The accommodation of Arabia-Eurasia plate convergence in Iran: Jour. Geophys. Res., **100**, 15205-15219.

Moinfar, A., 1976, The importance of macroseismic studies of past earthquakes: *in*, Proc. CENTO Semin. Recent Advances in Earthq. Hazard Minimization, Tehran, Iran, 65-69.

Molnar, P. and Chen, W. P., 1982, Seismicity and mountain building: *in*, Hsued, K. J., Ed., Mountain Building Processes, Academic Press, London, 41-57.

Ni, J. and Barazangi, M., 1986, Seismotectonics of the Zagros continental collision zone and a comparison with the Himalayas: Jour. Geophys. Res., **91**, 8205-8218.

Niazi, M., Asudeh, I., Ballard, J., Jackson, J., King, J. and McKenzi, D., 1978, The depth of seismicity in the Kermanshah region of the Zagros mountains Iran: Earth Planet. Sci. Lett., **40**, 270-274.

Shirokova, E. I., 1967, General features in the orientation of principal stresses in earthquake foci in the Mediterranian-Asia seismic belt: Izv. Acad. Nauk. USSR, Ser. Geophiz., **1**, 12-22.

Snyder, D. B. and Barazangi, M., 1986, Deep crustal structure and flexure of the Arabian plate beneath the Zagros collisional mountain belt as inferred from gravity observation: Tectonics, **5**, 361-373.

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: Submitted to Geophys. Jour. Int.

Tchalenko, J. S. and Braud, J., 1974, Seismicity and structure of the Zagros (Iran); the Main Recent Fault between 33° and 35° N: Phil. Trans. R. Soc. Lond., A **227**, 1-25.