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The June 22nd 2002 Changoureh-Avaj earthquake in Qazvin province, north central Iran

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Abstract

The Changoureh-Avaj earthquake of June 22nd 2002 is the largest shock since the occurrence of the 1962 Buyin-Zahra earthquake in Qazvin province. The source time function indicates that rupture, during the source process, was initiated with the main shock and was followed by a small aftershock. Therefore, the major amount of seismic energy was released during the first 10 seconds. Considering the field observation and the distribution of aftershocks, an average source dimension of about 20-30 km, a NW-SE strike and a SW dipping fault plane could be estimated. This result is in good agreement with the result of waveform analysis. The mechanism for the total source is obtained as (strike, dip, rake) = (267, 53, 71). The total seismic moment is calculated to be $M_0 = 5.35\times10^{25}$ dyne cm and the obtained moment magnitude in this analysis is $M_w = 6.4$. The average stress drop is about 40 bar. The static displacement is calculated to be about 35 cm. The Changoureh-Avaj earthquake is in some respects comparable with the 1962 Buyin-Zahra earthquake: they have similar mechanisms and occurred in similar fault systems. The Changoureh-Avaj earthquake is one of the rare events with a magnitude greater than 6 that has occurred in the vicinity of large densely populated cities. Therefore, the ground-motion characteristics during the main shock should be considered for the high safety design of structures in the region.

Key words: Changoureh-Avaj (southern Qazvin) earthquake, Source mechanism, Source parameters, Rupture process, Waveform modeling, Active faults

1 INTRODUCTION

On 22 June 2002 at 02:58:20.0 GMT, 08:28:20.0 local time, a shallow destructive earthquake (m_b=6.2; M_s=6.5; M_w=6.5; NEIC) without any felt foreshock occurred around the northwestern extension of the earlier shock of Buyin-Zahra that had caused extensive damage in 1962 (Tofigh-Reyhani, 2002). The early field observation reported that the epicenter of the main shock (35.67N; 48.93E; h=10 km; USGS) was located in Changoureh (Gheitanchi, 2003) in the southern part of Qazvin province, north central Iran. The main shock occurred in a region well known for its earlier shock that caused extensive destruction. It destroyed or severely damaged about 50 villages and completely demolished the villages of Changoureh and Ab-darreh (Moinfar, 2002). This earthquake is the largest shock since the occurrence of the 1st September, 1962 destructive earthquake with a magnitude 7.2 (Abdalian, 1963; Ambraseys, 1963; Berberian, 1976), in Qazvin province. The quake killed 230 people and injured 1466 and left many homeless in damaged areas (Farzanegan and Mirzaei-Alavijeh, 2002; Parhizkar et al., 2002). In this paper, the seismotectonic setting and the background seismicity of the affected area are reviewed. Then, the source parameters of the main shock are obtained by waveform inversion. Finally, the result of this study is compared and discussed with the facts revealed from the field observation and the recorded aftershock sequence.

2 SEISMOTECTIONICS SETTING

Iran is located in a very complex tectonic environment, where shortening takes place due to Arabi-Eurasia convergence and many destructive earthquakes have occurred in the past centuries. Deformation and seismicity in this region is mainly due to the continental shortening between the Eurasian and Arabian plates. Seismotectonics of Iran as a part of the Alpine-Himalayan orogenic belt has been the subject of several researchers (Nowroozi, 1972; McKenzie 1972; Jackson and McKenzie, 1984). The region, in this study, is enclosed between 48.5° and 51° east longitudes and 35° and 36° north latitudes. Geological evidences and fault plane solutions of earthquakes in the region indicate the existence of mainly thrust faulting (Jackson and McKenzie, 1984). Using the geological information and air-photos, an attempt has been made to provide a detailed fault map, including the observed local faults in this region. Figure 1 shows the detailed fault map of the region. As indicated in this figure, several major faults with almost northwest trends such as the Arab fault in the northwest, Avaj fault in the west, and Kushke-Nosrat fault in the southeast are examples of well known major faults in the region. In addition to these major faults, the region includes some minor faults, too. Several groups of faults with different trends suggest a complicated pattern of deformation in the region.

3 HISTORICAL EARTHQUAKES

Historical earthquakes of the Iranian plateau have been studied by several investigators (Ambraseys and Melville, 1982). Relying on very few data remaining from olden times, these studies suggest that north central Iran has experienced many destructive earthquakes in history. Here, a brief explanation of significant historical earthquakes, near to the epicentral area of Changoureh-Avaj, is given. In 956, Asadabad and Hamadan were seriously damaged by an earthquake, killing a large number of people. In November 1087, Hamadan and nearby regions were shaken by an earthquake and a number of people were killed. Strong aftershocks lasted a week. On 10 December 1119, a severe earthquake in Qazvin killed many people and caused extensive damage. The eastern Buyin-Zahra and the Karaj settlements were the worst affected. In 1191, a strong shock was felt in Hamadan without damage. In 1639, a destructive earthquake killed 12000 people in Qazvin. For further details one can still refer to Ambraseys and Melville (1982), a fonementioued.

4 INSTRUMENTALLY RECORDED EARTHQUAKES

Detailed and comprehensive seismicity studies require reliable data on the hypocentral parameters of earthquakes. Unfortunately, there were not enough data to evaluate seismic activity in north central Iran, mainly due to the lack of a seismological network operating full time of acceptable quality. Compared with historical

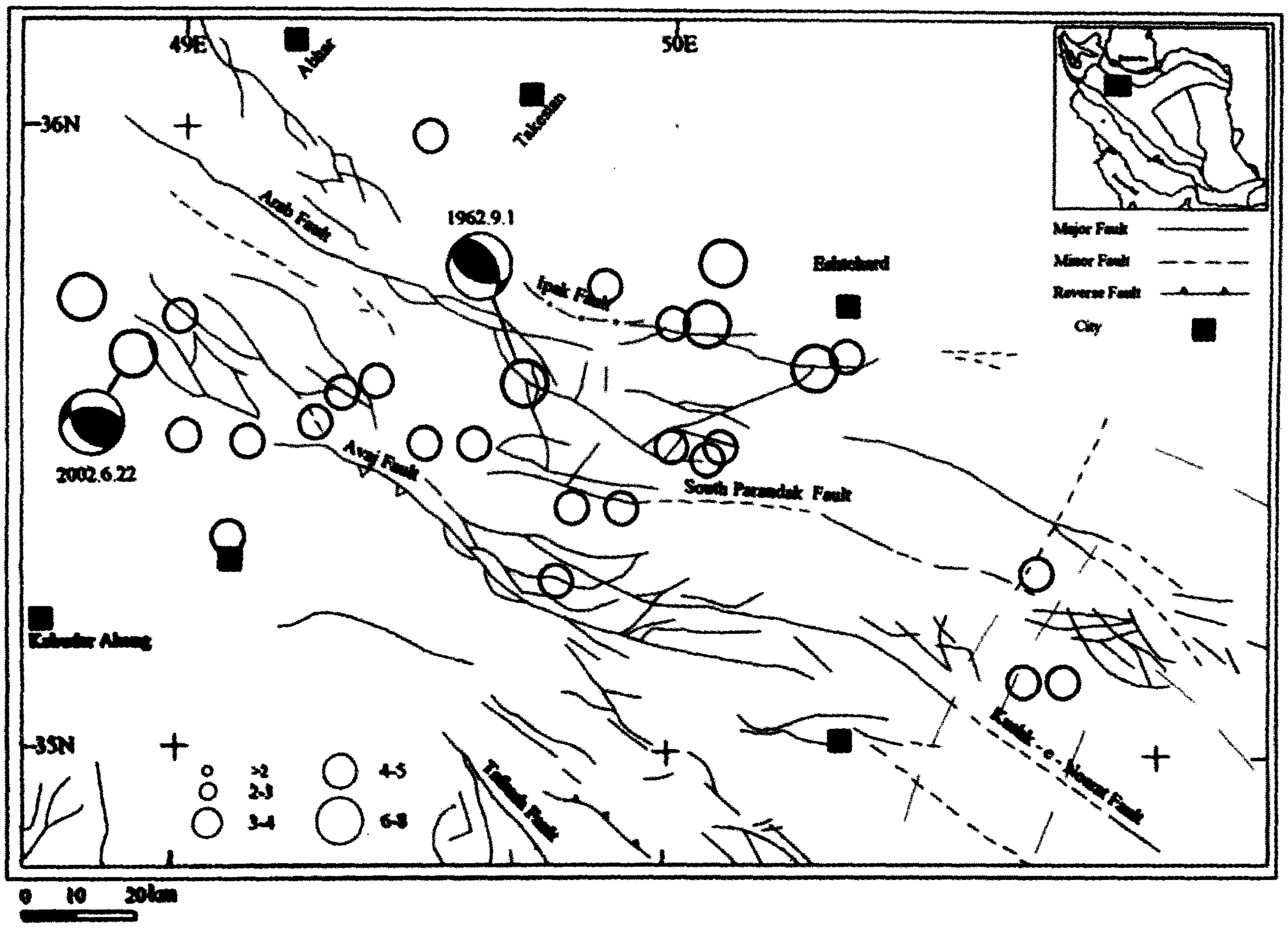

Figure 1. A simplified fault map of Avaj region based on the works done by Berberian (1976) and Jackson and McKenzie (1984) and the epicenters of strong earthquakes near the epicentral area, reported by ISC during 1950-2003 as well as the mechanism of two major earthquakes. Major towns are shown by solid squares. everal major faults with almost northwest trends such as Arab fault in northwest, Avaj fault in west, and Kushke-Nosrat fault in southeast are well known major faults in the region. In addition, the region includes several minor faults. Several groups of faults with different trends indicate a complicated pattern of deformation in the region. The epicentral distribution of earthquakes suggests that seismic activity was not significant in the past 100 years. A limited number of earthquakes occurred in the east part and no major earthquake is reported in the epicentral region of Changoureh-Avaj. (* Colour print on P. 54)

earthquakes, the present instrumentally recorded earthquakes of the region is much more understandable. During 1950-2003, source parameters of 32 instrumentally recorded earthquakes around the epicentral region of Avaj were reported by international seismological agencies. The reliability of source parameters depends on the quality and the quantity of seismic stations that have recorded these earthquakes. Recently, by a remarkable development in instrumentation and new techniques, the epicenteral determination of earthquakes has become much more reliable. The epicenters of these earthquakes are plotted on the fault map and indicated in figure 1. The epicentral distribution of earthquakes in this figure indicates that seismic activity in north central Iran was not remarkable in the past 100 years. Only limited earthquakes occurred in the east part of the region. No major earthquake is reported in the epicentral region of Changoureh-Avaj. The reported depth for all earthquakes in this region is shallow, though due to lack of seismic stations the depth determination cannot be reliable in this region.

5 MICROEARTHQUAKE ACTIVITY

In 1996, as a part of the national seismic network, the Institute of Geophysics of Tehran University deployed a telemetric seismic network in central Alborz to monitor the seismic activity. During 1996-2002 and before the occurrence of the Avaj mainshock, about 703 local earthquakes were recorded by the local seismic network. The epicentral distribution of the locally located earthquakes is indicated on the fault map in Figure 2. Although the distribution of remote seismic stations does not include the Avaj area, but the epicentral distribution of recorded earthquakes and the observed faults are in agreement. As it is shown in figure 2, the major seismically active area in the region, during 1996-2002 before the mainshock, is located in the vicinity of the epicenter of the 1962 destructive earthquake with a surface magnitude 7.2 in the area. The epicenters of local earthquakes are in agreement with the trends of major faults. To distinguish the seismic pattern of the region after the occurrence of the Avaj main shock, the

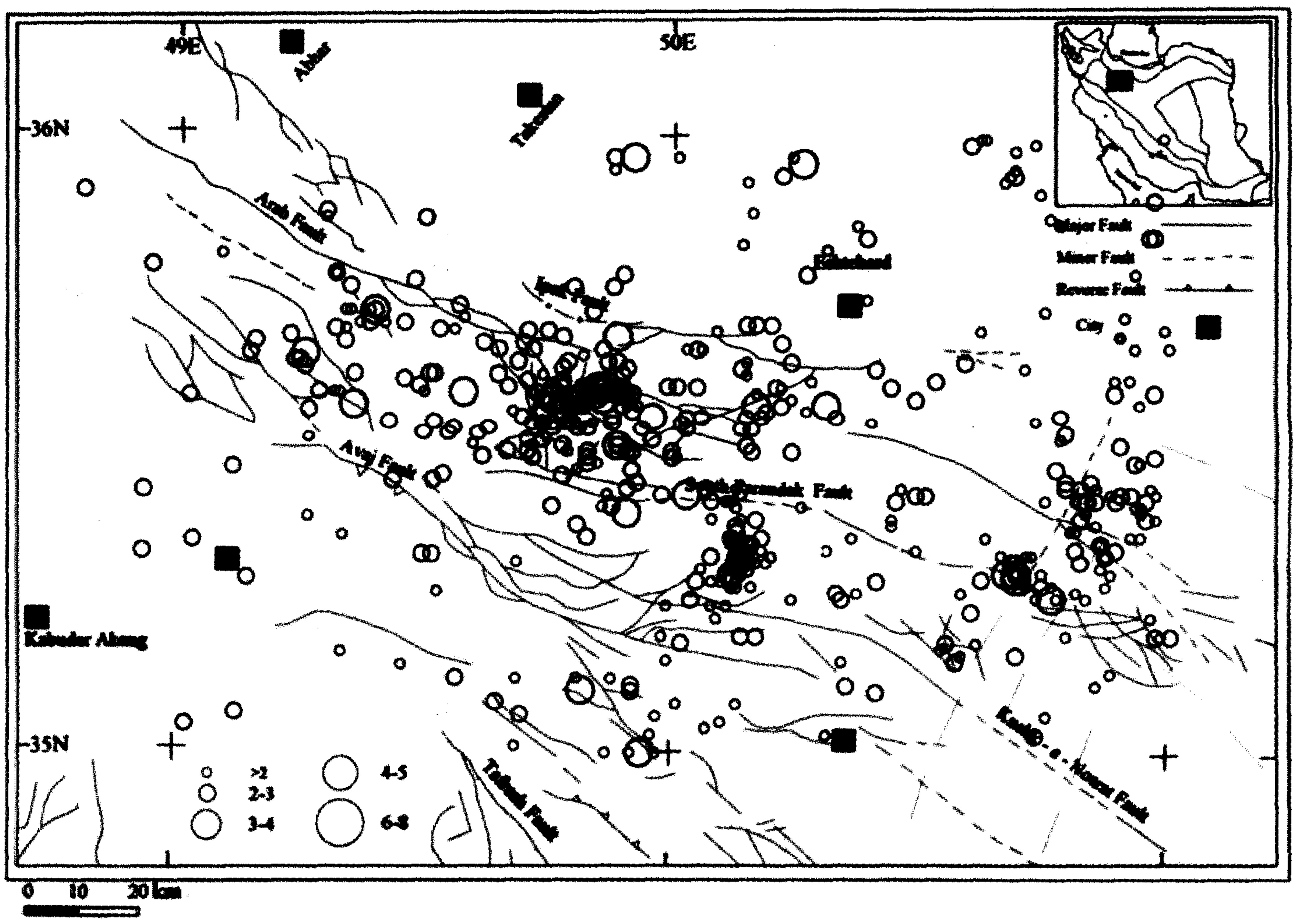

Figure 2. The epicenters of earthquakes around the epicentral area of Avaj reported by Tehran seismic Network before the mainshock and during 1996-2002. As shown, the major seismically active area is located in the vicinity of the epicenter of the 1962 destructive earthquake. The epicenters of local earthquakes are in agreement with the trends of major faults. Major towns are shown by solid squares. (* Colour print on P. 55)

epicenters of all recorded earthquakes including the main shock and aftershock sequence of Avaj, by the same local network during 2002-2003, are given on the fault map in figure 3. This figure indicates that a significant activity in the region with high concentration around the epicentral region of the main shock.

6 SOURCE PARAMETERS OF MAIN SHOCK

The 38 body waveforms recorded by Global Digital Seismic Network, GDSN, stations with epicentral distances between 30 and 100 degrees were inverted to their sources to investigate the source parameters of main shock. These records are well distributed in azimuth and allow a detailed study of the rupture process of the main shock. The station codes, azimuth, back azimuth, and the epicentral distance of stations are given in table 1. The P wave records with duration of 40 seconds and a sampling interval of 1.0 second were used for this analysis. Both the observed and synthetic Green's functions for all the stations are equalized to GDSN seismograms with the same outcome. To model the faulting, a multiple iterative deconvolution method was used (Gheitanchi et al., 1993). In this method, the observed seismograms were matched by synthetics computed for a sequence of point sources distributed on the fault plane. For the locations of subevents, we took 9 individual points along the fault trace at an equal spacing of 10 km and 5 individual depths, 2.5, 5.0, 7.5, 10.0 and 12.5 km. We assume a singlet and determine the pulse width of a source time function from the initial portion of the observed waveforms. The source time function of trapezoid shape having a rise time of 3 seconds and process time of 4 seconds is best fitted. Then, with the fixed source time function, the source depth and the crustal structure in the source region are determined in a trial and error manner. First with a fixed source time function we assume a crustal model and invert the waveforms for several source depths. The residual error is minimized for the depth of 10 kilometres.

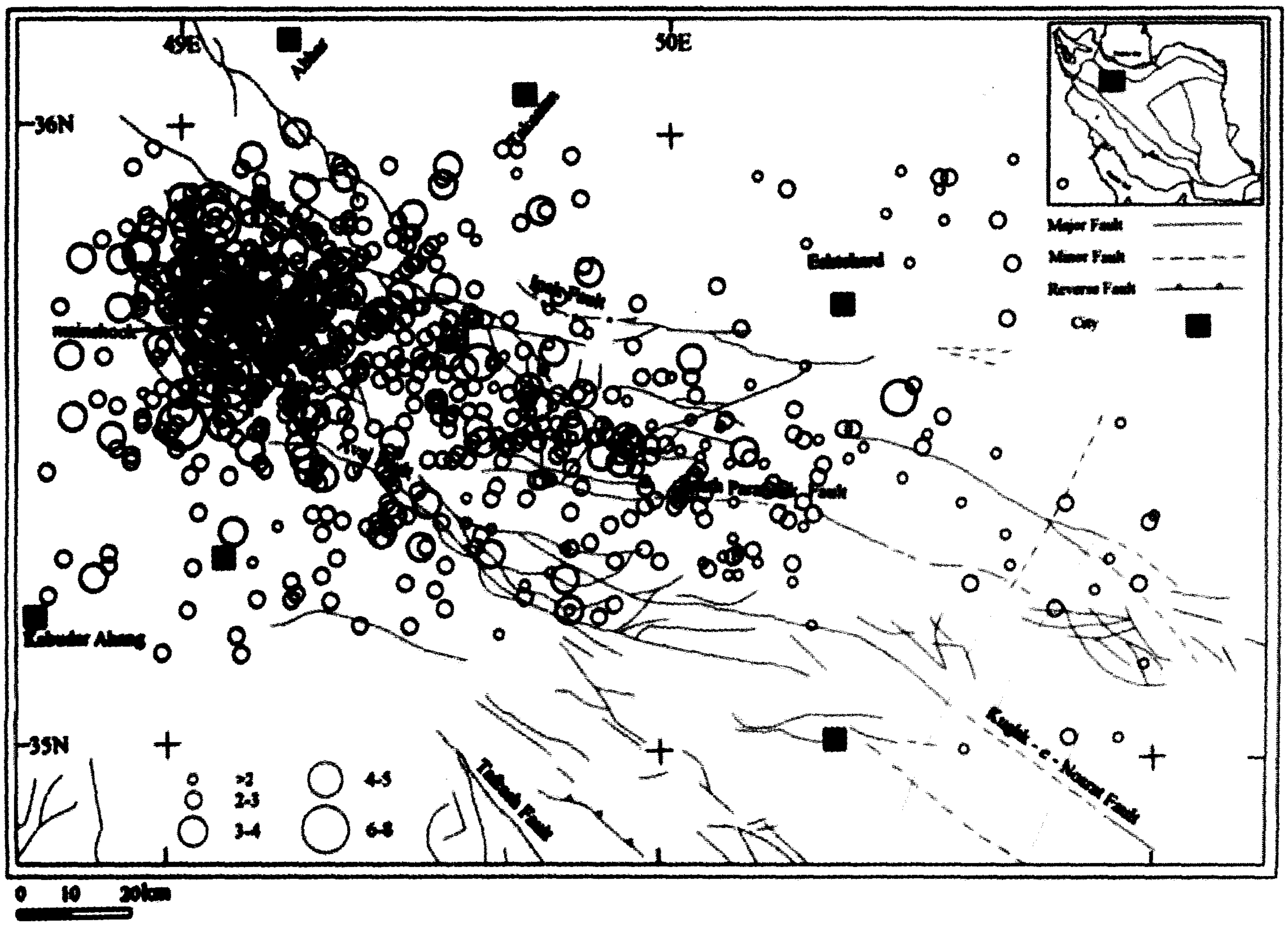

Figure 3. The epicenters of all recorded earthquakes including the mainshock and aftershock sequence of Avaj, reported by Tehran seismic Network during 2002-2003 are overlapped on the local fault map. A significant activity in the region with high concentration around the epicentral region of the mainshock could be understood. The epicenters of local earthquakes are in agreement with the trends of major faults. Major towns are shown by solid squares. (* Colour print on P. 55)

Table 1. Station code, azimuth, back azimuth, and epicentral distance of stations used in this study.

Stn	Az	B.Az	Del
COLA	7.2	-13.9	78.9
DAK	11.4	-17.5	85.2
BILL	21.2	-52.0	66.6
TIXI	22.8	-86.6	53.4
ADK	26.4	-35.8	84.1
MA2	33.1	-61.2	65.5
YAK	34.5	-79.0	55.0
PET	36.5	-53.4	72.7
YSS	47.7	-61.7	67.3
TLY	49.7	-90.7	41.6
MAJO	59.3	-60.4	69.3
GUMO	75.6	-54.1	86.8
DAV	92.1	-54.9	75.0
CHTO	97.3	-58.4	47.0
NWAO	128.7	-49.1	93.4
MSEY	170.2	-8.0	40.5
SUR	-155.3	23.7	72.7
LSZ	-155.1	20.8	54.3
SHEL	-124.8	44.0	72.9
RCBR	-97.7	54.1	89.3
PAB	-68.0	77.8	42.0
CMLA	-63.8	67.3	58.3
SJG	-60.4	48.0	98.7
BFO	-54.1	97.8	32.4
GRFO	-50.9	102.7	30.8
ESK	-44.0	96.9	40.5
HRV	-39.6	44.6	85.2
KONO	-34.1	115.6	35.0
WCI	-33.7	35.0	95.7
BORG	-31.7	89.9	50.1
CCM	-30.5	31.6	98.0
SFJ	-26.1	66.2	61.3
RSSD	-19.1	21.7	96.9
FFC	-16.3	23.2	86.6
KEV	-12.7	148.9	36.2
KBS	-9.3	136.9	46.0
ALE	-8.3	63.9	57.6
COR	-5.5	6.3	99.9

We select the source depth of 10 kilometres and using the standard crustal velocities (Jeffreys & Bullen, 1958), we perform the inversion for the crustal thicknesses of 36, 40 and 44 km. The residual error is not changed remarkably suggesting that the result of inversion is significant. We choose the thickness of 40 km and obtain the mechanism solution by a point source approximation. The observed and synthetic waveforms, the focal mechanism and the ray directions of the stations after the first iteration are given in Figure 4.

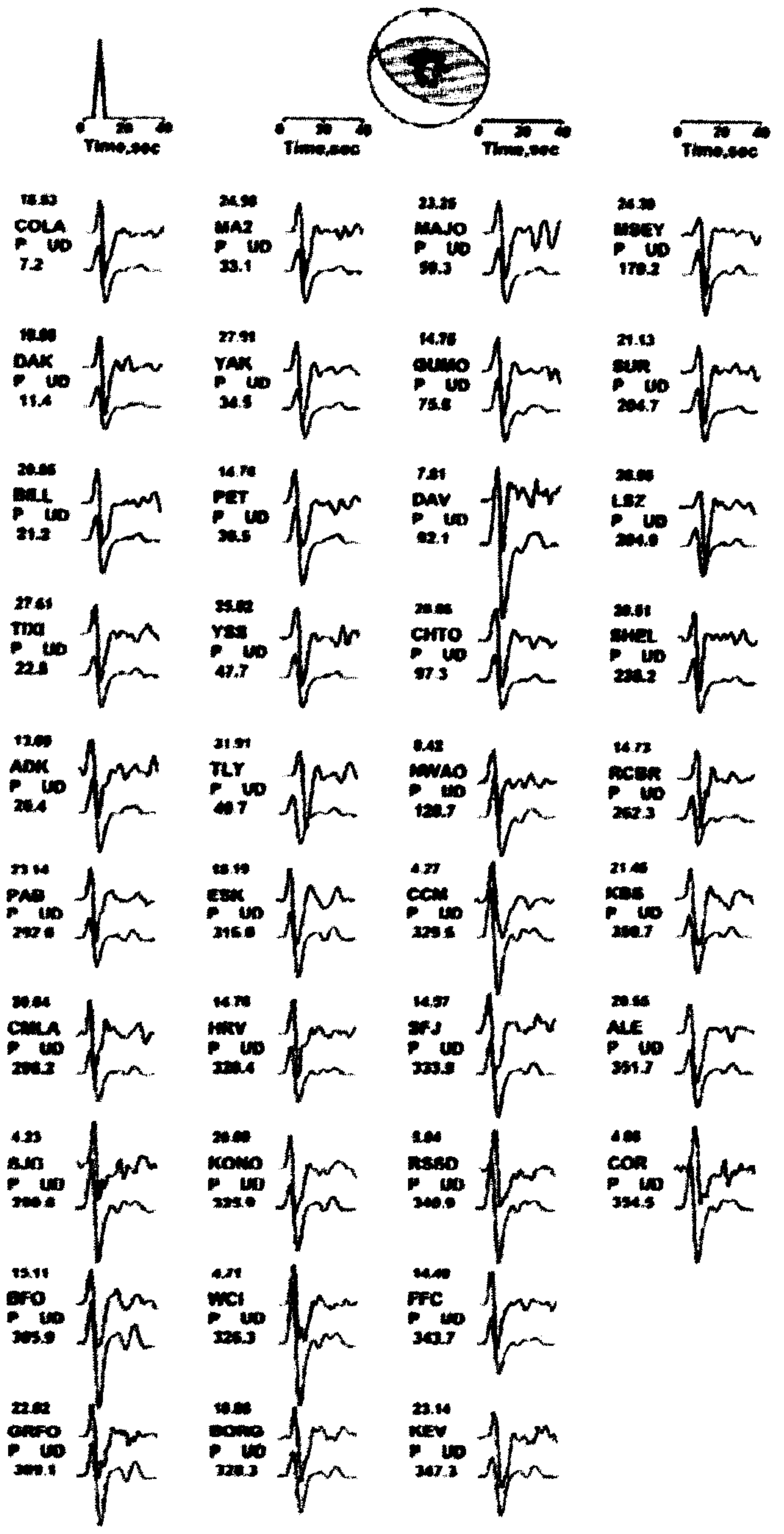

Figure 4. The source time function, the focal mechanism, and the ray directions of the stations used in this analysis as well as the comparison of the observed (top) and synthetic (bottom) waveforms after the first iteration for the 2002 Avaj earthquake. The correlation coefficient, the name, component and azimuth of station are given on the left side of each waveform. This figure shows that the mechanism is a pure dip-slip faulting and the correlation of observed and synthetic waveforms is acceptable.

This figure shows that the mechanism is a pure dip-slip faulting and the correlation of observed and synthetic waveforms is acceptable. In the next stage, for the fixed dip-slip fault plane, the spatio-temporal distribution of fault slip was determined by the waveform inversion procedure, in which, the slip direction was allowed to vary. The mechanism solution for the total source was obtained as (strike, dip, rake) = (267, 53, 71). The fault slip was consistent with the geological evidences. The total seismic moment was calculated to be $M_0 = 5.35\times10^{25}$ dyne cm and the obtained moment magnitude in this analysis was $M_w = 6.4$. Using the relation $\Delta\sigma = 2.5M_0/(S)^{3/2}$ (Gheitanchi et al., 1993) and approximating the rupture area, S, by $L\times(L/2)$ or $2(\upsilon\tau)^2$, where L=20 km is the fault length, $\tau = 7$ seconds is the rupture time and $\upsilon = 3.0$ km/s is the rupture velocity, the stress drop, $\Delta\sigma$, would be about 40 bar.

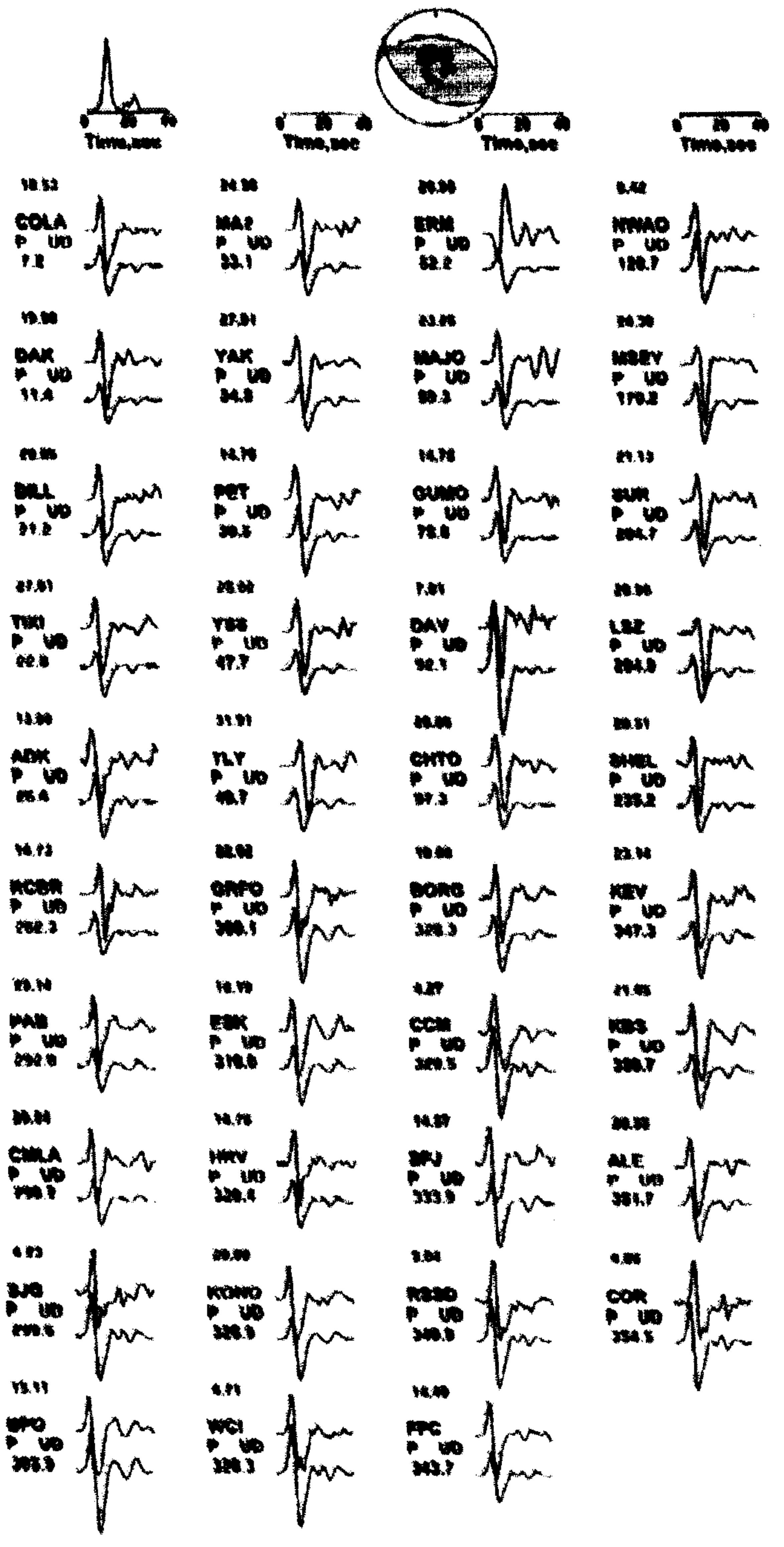

Figure 5. The source time function, the focal mechanism, and the ray directions of the stations used in this analysis as well as the comparison of the observed (top) and synthetic (bottom) waveforms for the final solutions of the 2002 Avaj earthquake. The correlation coefficient, the name, component and azimuth of station are given on the left side of each waveform.

Using the relation $M_0 = \mu DS$, where $\mu = 3\times10^{11}$ dyne cm^{-2} is the rigidity and S is the fault area, the average dislocation, D, is calculated to be 35 cm. The source time function, the focal mechanism, and the ray directions of the stations used in this analysis as well as the comparison of the observed and synthetic waveforms for the final solutions of the 2002 Avaj earthquake are given in figure 5. Contour lines of the correlation function obtained for the final solution are given in figure 6. The horizontal axis indicates time in seconds and the vertical axis shows distance in terms of kilometers. The extension of contours in vertical axis indicates a bilateral dislocation while the horizontal axis shows that the duration of dislocation was about 10 seconds.

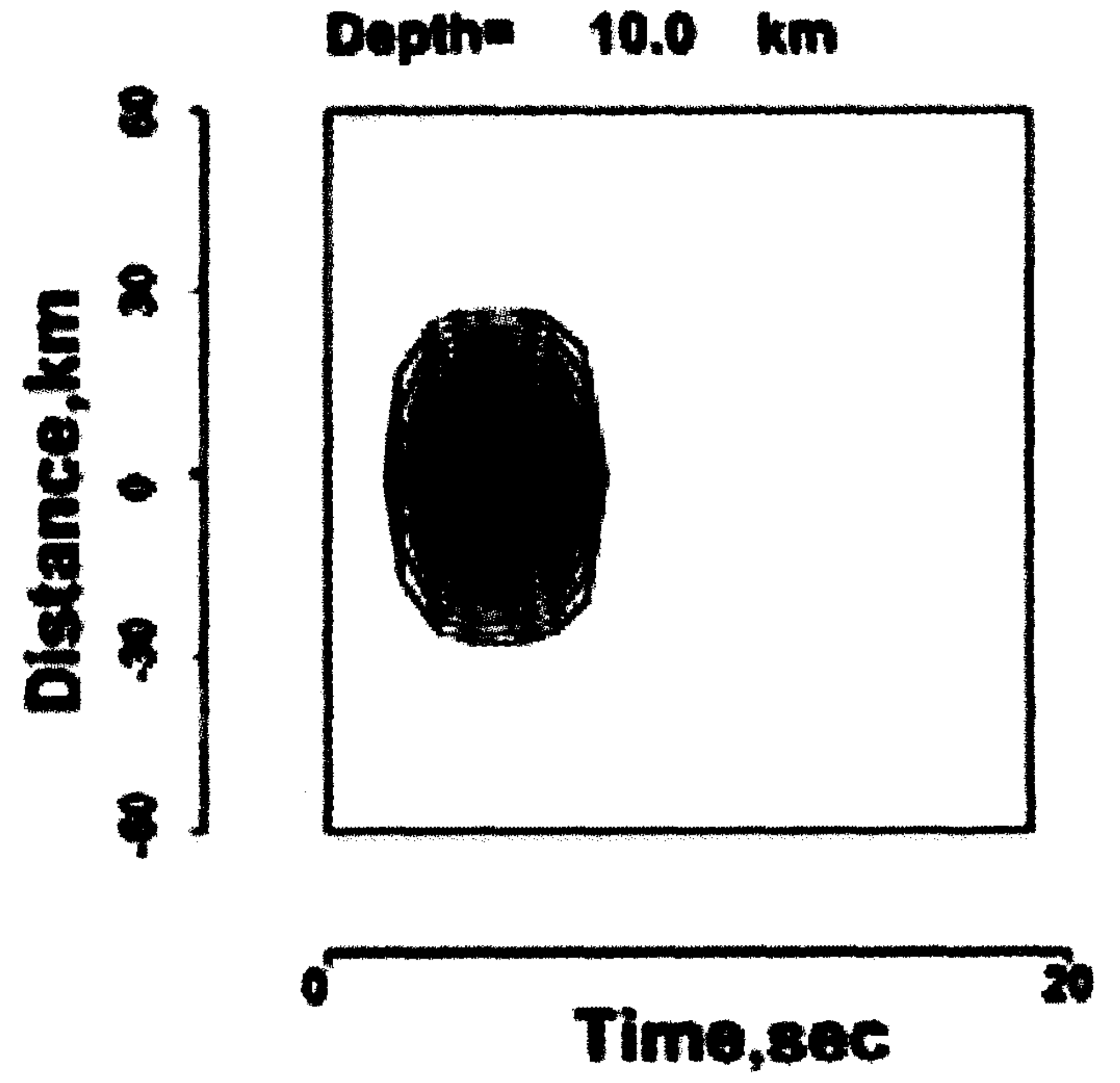

Figure 6. Contour lines of the correlation function obtained by the final solution. The horizontal axies indicates the duration of source time function. The vertical axies shows the extension of rupture along the fault. As indicated in the figure, the dislocation during the source process of main shock initiated in the in hypocenter and extended in a bilateral manner within the first 10 seconds.

7 DISCUSSIONS AND CONCLUSION

Regarding the field observation and the distribution of aftershocks, an average source dimension of about 20-30 km, a NW-SE strike and a SW dipping fault plane could be estimated.

Considering the epicenter of main shock as the initial break, the distribution of locally recorded aftershocks indicates that the rupture should be initiated in epicentral area and extended in a bilateral manner (Hosseini et al., 2002; Bozorgi, 2003). This fact is also understandable from the location of the main shock and the extension of surface rupture (Alavijeh and Nayyeri, 2002). The extent of aftershock activity indicates a range of 20-30 km source dimension, and is in agreement with the observed surface rapture (Bozorgi et al., 2003). The focal depth from modeling the bodywaves is 10-12 km. Based on these estimations, the size of the main fault should be at least 20×10 km^2. Hosseini et al.

(2002) by installing seismographs in four temporal stations around the damaged area, observed the after shocks one month after the occurrence of the main shock. Aanalyzing about 160 aftershocks, they suggested that most of the hypocenters distributed from 0 to 15 km depth and in a square with 25 km side in the damaged area. By the cross section of aftr shock normal to the fault strike they suggested that the dip direction and the dip angle of the main fault were S10W and 26 degree, respectively (Figure 7).

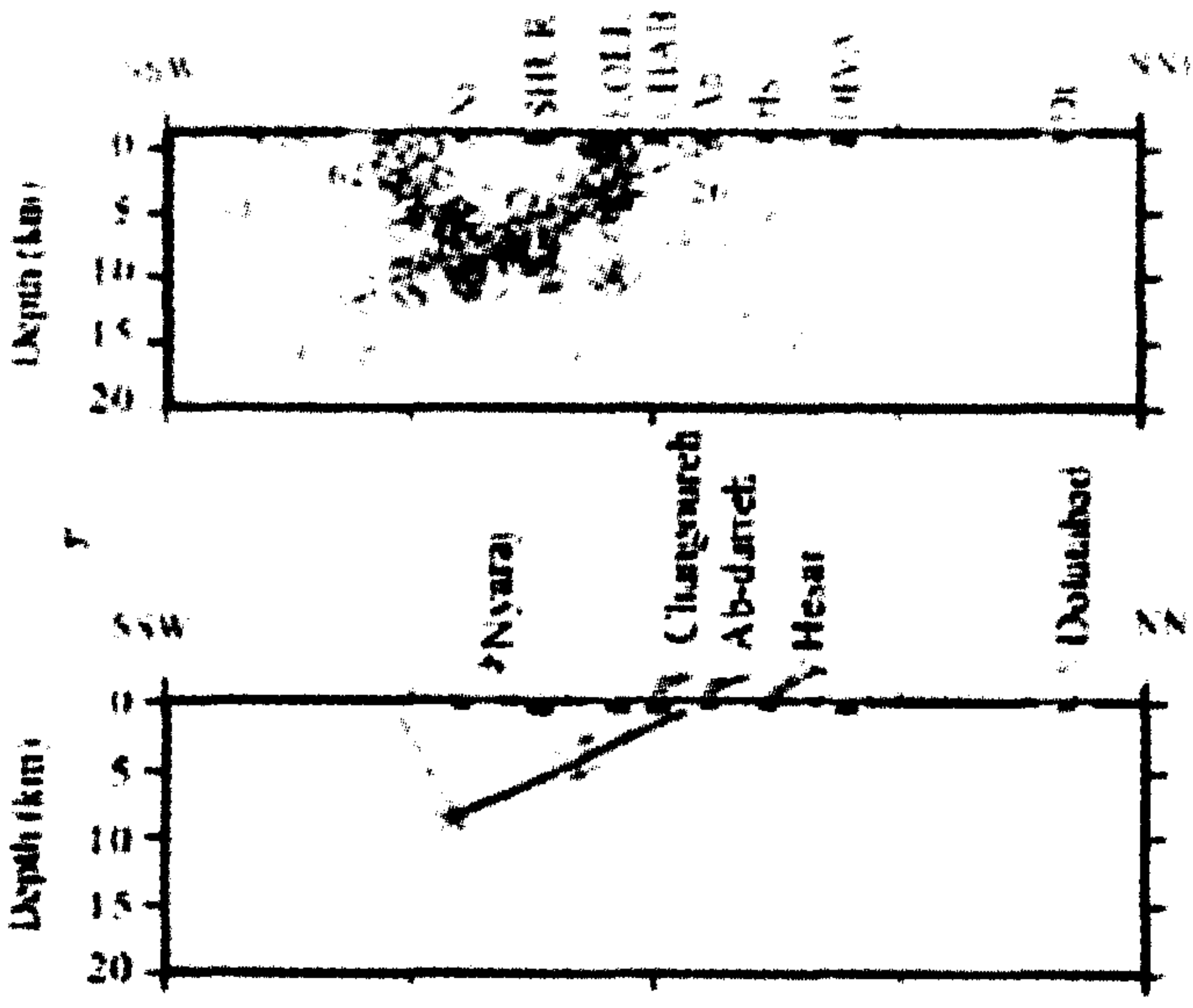

Figure 7. Cross section of aftershock hypocenters normal to the fault strike is shown in the top figure and the hypocenter of main shock (Star) and the extension of the main fault (Thick line) are given in the bottom (Reproduced from Hosseini et al., 2002). (* Colour print on P. 55)

In addition to the main fault, a conjugate sub-fault could be found in their vertical projection of the hypocenters in figure 7. The cross section also indicates that the majority of aftershocks are located on the western block, and the fault trace acted as a delimiting line. This suggests that the western block acted as a hanging wall during the source process of the main shock. More details are given by Hosseini et al. (2002). The centroid moment tensor solution for a best double couple point source given by USGS shows two nodal planes striking N290E (dipping 39 SW) and N117E (dipping 52 NE). A similar solution was given by Harvard University indicating predominantly trust type mechanisms and are in agreement with the mechanism obtained in this study. The seismic moment calculated by USGS (M_0=6.9 ×10^{25} dyne-cm) is smaller than evaluated by HRVD (M_0=7.0×10^{25} dyne-cm) but larger than the total seismic moment, 5.35×10^{25} dyne-cm, obtained in this study. The source parameters obtained by USGS and the University of Harvard as well as the result of this study are given in table 2. The results of the waveform analysis suggest that the rupturing was initiated in the epicentral region and was propagated in a bilateral manner towards northwest and southeast (Figure 6). The source time function indicates that rupture, during the source process, was initiated with main shock and was followed by a small aftershock. Therefore, the major amount of seismic energy was released during the first 10 seconds. The Changoureh-Avaj earthquake occurred on a NW-SE trending dip slip fault without any significant foreshock. The fault rupture that caused the Changoureh-Avaj earthquake is inferred to be at least 20 km on the basis of the main shock damage and the location of aftershocks. The fault rupture causing the Changoureh-Avaj earthquake apparently propagated bilaterally from the epicenter during the source process of main shock. However, the epicentral distribution of local earthquakes recorded by Tehran seismic network, after the main shock, indicates that by the occurrence of main shock not only the epicentral region of Avaj earthquake has a high seismic activity but also in the eastern extension, including the epicentral region of the 1962 destructive earthquake, the seismic activity has increased, significantly. This fact suggests that, by the occurence of the Avaj earthquake, the faults in the eastern extension were activated. The aftershocks had a depth range of 3-18 km (Bozorgi, 2003) indicating that the seismic activity was taking place within the upper crust and the seismogenic layer in this region had a thickness not greater than 20 km. The average stress drop was about 40 bar. The static displacement was calculated to be about 35 cm. Changoureh-Avaj earthquake is in some respects comparable with the 1 st September 1962 Buyin-Zahra earthquake (Petrescu & Purcaru, 1964; Wu & Ben-Menahem, 1965): they have similar mechanisms and occurred in similar fault systems. The Changoureh-Avaj earthquake is one of the rare events that occurred in the epicentral region

Table 2. The source parameters of main shock obtained by USGS and the University of Harvard as well as the result of this study.

Name	Strike	Dip	Rake	Strike	Dip	Rake	M_0 (dyne-cm)	M_w
USGS	280	39	76	117	52	101	6.9x10^{25}	6.5
HRVD	295	29	99	104	62	85	7.0x10^{25}	6.5
This study	267	53	71	117	41	113	5.3x10^{25}	6.4

with a magnitude greater than 6. Therefore, the ground-motion characteristics during the main shock should be considered for the high safety design of structures in the damaged area.

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