Source parameters of the 1998 Fandoqa earthquake in Kerman Province, south-east Iran

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Abstract
In this study, the source parameters of the 1998 Fandoqa earthquake were investigated. The observed teleseismic, bodywaves of mainshock were modeled in order to obtain the source process. The information from field investigations and the result of locally recorded aftershock activity were considered as supplementary data. The source process fitted with a single source model having a strike-slip mechanism very similar to the result of CMT solution. Rupture during this earthquake initiated in the epicentral area and extended in a bilateral manner. The seismic moment from bodywaves was calculated to be $M_0=7.1 \times 10^{37}$ dyne-cm and its effective stress drop was about 86 bar while its related dislocation was estimated to be 1.46 m.

Key words: Fandoqa earthquake, Seismicity of Kerman Province, Source parameters, Waveform modeling, Focal mechanism, Seismotectonics, Active Faults, Aftershock activity, Source Process

1. Introduction
On the 14th March 1998 at 19h 40m 31.8s GMT, 23h 16m 31.8s local time, a strong earthquake occurred in the Fandoqa area not far from the epicenters of the recent destructive earthquakes that occurred in 1981 and 1989 in Kerman province southeast of Iran. The epicenter of the earthquake was computed as 30.05 N-57.5E by ISC. The magnitude of the mainshock given by ISC, was mb=5.9, Ms=6.9 and the focal depth determination indicated a shallow depth of 9 kilometers. The earthquake killed five people and injured fifty others. It destroyed 2000 homes and left 10,000 homeless in the epicentral area (Mirzaei et al., 1998). Shortly after the occurrence of the mainshock the Geophysics Institute of Tehran University deployed a temporary seismic network in the damaged area and monitored the aftershock activity for six weeks (Soltzman et al., 1998). This paper uses the results of the field and seismological investigations as well as the outcome of aftershock activity to analyze the source parameters. First the active fault system and the seismicity background are reviewed. Then, the source parameters of the mainshock and the result of aftershock activity are explained. In the last part, information from the field investigations and from the locally recorded aftershock activity is used to model the teleseismic bodywaves observed in GDSN stations. Finally, the results of this study are compared and discussed with the results of other studies.

2. Active fault system
The Kerman region is surrounded by the depressions of the Great Kavir desert in the north and Lut in the east, and the Zagros mountain ranges in the south and west. The major Quaternary faults in the area are the Kuhbandan fault with northwest-southeast direction and the Nayband fault with a length of 400 km and a north-south trend. In contrast to the Zagros regions where no apparent surface fault trace is observable following even a powerful earth-quake, in this region strong earthquakes are often associated with well recognizable surface faulting. The main activated fault during the 1998 Fandoqa earthquake followed the existing traces of the Gowk fault system recognizable on satellite and aerial photographs and on the ground and joins several deep depressions from north to south with a total length of about 160 km (Berberian et al., 1984). The Gowk fault system roughly follows the Dasht-e-Lut boundary while at the northern and southern ends the reverse component is remarkable. Dominant right-lateral ground displacements that accompanied the mainshock coincided precisely with the pre-existing geological fault trace of high-angle reverse character (Ghorashi and Talebian, 1998). The mainshock produced 23 km of surface faulting with up to 3 m right-lateral strike-slip and 1 m vertical offsets (Berberian et al., 2001). The active faults as well as the instrumentally located epicenters of the destructive earthquakes in the Kerman region are given in figure 1.

3. Seismicity background
Our knowledge of the historical background of seismic activity in the Kerman region is very limited partially due to the low density of population (Ambraseys and Melville, 1982), and partially because of the low rate of
seismic activity in the past centuries. On the other hand, the instrumentally recorded earthquakes and the existence of several active faults all indicate that the region has a high potential for seismic activity. Both the historical background and the instrumentally recorded earthquakes indicate that the seismicity of central Iran including Kerman province, does not follow a linear pattern. During 1977-1998, alone five strong earthquakes caused extensive damage and many human casualties in this region (Gheitanchi, 1999a). All earthquakes were associated with complicated surface ruptures showing a combination of dip-slip and strike-slip motions. The March 14th, 1998 earthquake occurred along a short segment of the Gowk Fault System, where the longer part had moved during the Golbaf-Sirch earthquake of 28, July 1981 (Berberian et al., 1984). The epicenters, the focal mechanisms and the causative faults of recent strong earthquakes in Kerman are given in figure 2.

4. Source parameters of mainshock

The magnitude, origin time and the hypocentral location
were given by several agencies for the mainshock. This information is summarized in Table 1. Among these agencies, USGS and Harvard University as their routine work published the source mechanism immediately after the occurrence of the mainshock. The centroid moment tensor solution for a best double couple point source given by USGS shows two nodal planes striking N56E (dipping 89 SE) and N146E (dipping 58). Another solution was given by Harvard University indicating two nodal planes striking N61E (dipping 85 SE) and N154E (dipping 57). Both solutions indicate predominantly strike-slip mechanisms and are in agreement with the mechanism of other earthquakes in this region. The seismic moment calculated by USGS ($M_0 = 7.7 \times 10^{35}$ dyne-cm) is smaller than evaluated by HRVD ($M_0 = 9.4 \times 10^{35}$ dyne-cm). To provide better constraints on the source parameters of the mainshock, we analyzed the combined body and surface waves from 18 GDSN stations which are in a good azimuthal coverage and used a modified version of the centroid moment tensor solution (Kawakatsu, 1995). The best double couple for final solution showed two nodal planes striking N61.8E (dipping 63.28 SE) and N 158.9E (dipping 76.2 SW). The seismic moment was calculated to be $M_0 = 1.02 \times 10^{36}$ dyne-cm and the moment magnitude was $M_w = 6$. The source parameters obtained by USGS, the University of Harvard and Berberian et al (2001) as well as the result of this study are given in Table 2.

The mainshock was followed by several moderate aftershocks which caused minor damage in the affected area. The strongest of them, with $M_b = 5.2$, occurred on the 18th November 1998 and damaged houses at Chahar Farsakh, 45 km north of the mainshock region and was associated with surface cracking near the north end of the Gowk fault system (Berberian et al., 2001). In order to study the aftershock activity, a temporary seismic network was deployed within the meizoseismic area one week after the occurrence of the mainshock by the Institute of Geophysics in Tehran University and the seismic activity was monitored for forty-five days. The network included five portable digital system PDAS and four analog PS2. More details such as the location of seismic stations and the process of data as well as the source parameters of aftershocks were given in a preliminary report (Soltanian et al., 1998). About 1595 aftershocks were recorded by the local seismic network during forty-five days. Out of this number, 680 were located. The analysis of these aftershocks indicated that the seismicity appears to be more scattered than along a fault zone. Aftershocks extended over an approximately 40 km long zone with a general NW-ES elongation following the trend of main fault system. The depth of aftershocks extended down to 20 km but the high concentration seemed to be down to 15 km. The epicentral distribution and the cross sections of aftershocks along and across the main fault are given in figure 3 and figure 4.

5. Teleseismic bodywave modeling

To obtain more details of the source process of the mainshock we modeled the P and S digital waveforms observed at thirty GDSN stations within the epicentral distance from 30 to 90 degrees. The S-waves were rotated in order to obtain the transverse component for the SH analysis. The records with a duration of 60

Table 1. The magnitude, origin time and the hypocentral location given by several agencies for the mainshock.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Origin time</th>
<th>Lat.</th>
<th>Lon.</th>
<th>Dep.</th>
<th>$M_b$</th>
<th>$M_s$</th>
<th>$M_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOS</td>
<td>1998 03 14</td>
<td>19h 40m 30.4s</td>
<td>30.117</td>
<td>57.618</td>
<td>33.0</td>
<td>6.6</td>
<td>6.5</td>
<td>--</td>
</tr>
<tr>
<td>EID</td>
<td>1998 03 14</td>
<td>19h 40m 28.0s</td>
<td>30.101</td>
<td>57.503</td>
<td>00.0</td>
<td>5.3</td>
<td>6.8</td>
<td>--</td>
</tr>
<tr>
<td>BHI</td>
<td>1998 03 14</td>
<td>19h 40m 27.1s</td>
<td>30.320</td>
<td>57.520</td>
<td>10.0</td>
<td>5.7</td>
<td>7.3</td>
<td>--</td>
</tr>
<tr>
<td>NEI</td>
<td>1998 03 14</td>
<td>19h 40m 27.0s</td>
<td>30.154</td>
<td>57.605</td>
<td>09.0</td>
<td>5.9</td>
<td>6.9</td>
<td>6.6</td>
</tr>
<tr>
<td>ISC</td>
<td>1998 03 14</td>
<td>19h 40m 31.8s</td>
<td>30.161</td>
<td>57.612</td>
<td>43.5</td>
<td>5.8</td>
<td>6.7</td>
<td>--</td>
</tr>
<tr>
<td>HRV</td>
<td>1998 03 14</td>
<td>19h 40m 34.2s</td>
<td>30.950</td>
<td>57.600</td>
<td>15.0</td>
<td>--</td>
<td>--</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Table 2. The source parameters obtained by USGS, the University of Harvard and Berberian et al (2001) as well as the result of this study.

<table>
<thead>
<tr>
<th>Name</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake</th>
<th>$M_0$ (dyne-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS</td>
<td>149</td>
<td>-66</td>
<td>-179.0</td>
<td>58.0</td>
<td>89</td>
<td>-24.0</td>
<td>$7.7 \times 10^{25}$</td>
</tr>
<tr>
<td>HRV</td>
<td>153</td>
<td>65</td>
<td>-176.0</td>
<td>61.0</td>
<td>86.0</td>
<td>-25.0</td>
<td>$9.6 \times 10^{25}$</td>
</tr>
<tr>
<td>Berberian et al</td>
<td>156</td>
<td>54</td>
<td>-165.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>$9.1 \times 10^{25}$</td>
</tr>
<tr>
<td>This study</td>
<td>158.9</td>
<td>76.2</td>
<td>-152.4</td>
<td>61.8</td>
<td>63.2</td>
<td>-15.5</td>
<td>$1.02 \times 10^{26}$</td>
</tr>
</tbody>
</table>

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sP phase as well as the P and pP phases were included in producing synthetic waveforms. We performed one iteration because the residual error did not decrease remarkably for more than one iteration and a single source model could describe the initial 60 seconds of recorded waveforms. By examining several crustal models, a three layer structure with crustal thickness of 42 km was found to have a minimum approximation error and best fit. The seismic moment was calculated to be $M_0 = 7.1 \times 10^{23}$ dyne-cm. Rupture during this earthquake initiated in the epicentral area and extended in a bilateral manner. This result could be understood from the contour lines of the correlation function for the final solution which is shown in figure 5. The selected examples of

![Contour lines of the correlation function for the final solution.](image)

6. Discussions and Conclusion
The waveform modeling indicated that the 1998 Fandooq earthquake was a single source with a right-lateral strike-slip mechanism having a small normal component very similar to the result of the CMT solution. This mechanism is consistent with the geological and seismological observations and the investigation carried out by Berberian et al (2001). In our previous study of the two destructive earthquakes, which occurred within 47 day in 1981 devastating the towns of Golbaf, Sirch and Chaharfarsak, we calculated the shear strains produced by the first earthquake around its activated fault and indicated that significant accumulation of shear strain (or earthquake-generating stress) preceded the occurrence of the second
earthquake. It was concluded that this fact should have had an appreciable effect on the mechanical state in the focal region and played some role in the occurrence of the following earthquakes. Now, the 1998 March 14 Fandoqa earthquake occurred in the area where the stress field was increased by the previous earthquakes. Moreover, as inferred from our waveform modeling in the previous study, the 1981 July 27 Sircor earthquake was a multiple source having two major subevents. The first subevent had a pure reverse mechanism but the second subevent had a large strike-slip component which was consistent with observed severe destruction as well as maximum displacements and could explain the sense of rupture (Gheitanchi, 1999b). The mechanism of the second subevent of the 1981 Sircor earthquake is very similar to the 1998 Fandoqa earthquake suggesting that these two events should correspond to the same fault system. This was confirmed by the field report indicating that the 1998 ruptures closely followed the trace of the surface faulting in the 1981 July 27 Sircor earthquake (Berberian et al., 2001). The triangular source time function having a rise and process time of 6 seconds, which was best fitted for this study, agrees well with the results given by Berberian et al. (2001) who indicated that about 80 per cent of the moment was released in the first 6 seconds. The seismic moment obtained from bodywaves, in this study, was $M_0 = 7.1 \times 10^{22}$ dyne-cm at a depth of 10 km for the centroid. Berberian et al. (2001) got the seismic moment $9.1 \times 10^{23}$ dyne-cm at a depth of 5 km for the centroid. This tradeoff is entirely expected as at a shallower depth greater moment is needed.

The distribution of locally recorded aftershocks generally followed the trend of the fault system but had a diffused pattern suggesting that the nearby faults were activated so as to readjust the stress field around the epicentral area that had been perturbed by the occurrence of the mainshock. This phenomena was observed in the case of the 1981 earthquakes in this region by computation of the shear strains produced by the first earthquake in 1981 around its activated fault (Gheitanchi, 1999b).

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