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Estimating the macroseismic parameters of earthquakes in eastern Iran

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ABSTRACT

Macroseismic intensity values allow assessing the macroseismic parameters of earthquakes such as location, magnitude, and fault orientation. This information is particularly useful for historical earthquakes whose parameters were estimated with low accuracy.

Eastern Iran (56°–62°E, 29.5°-35.5°N), which is characterized by several active faults, was selected for this study. Among all earthquakes occurred in this region, only 29 have some macroseismic information. Their intensity values were reported in various intensity scales. After collecting the descriptions, their intensity values were re-estimated in a uniform intensity scale. Thereafter, Boxer method was applied to estimate their corresponding macroseismic parameters.

Boxer estimates of macroseismic parameters for instrumental earthquakes (after 1964) were found to be consistent with those published by Global Centroid Moment Tensor Catalog (GCMT). Therefore, this method was applied to estimate location, magnitude, source dimension, and orientation of these earthquakes with macroseismic description in the period 1066–2012. Macroseismic parameters seem to be more reliable than instrumental ones not only for historical earthquakes but also for instrumental earthquakes especially for the ones occurred before 1960. Therefore, as final results of this study we propose to use the macroseismically determined parameters in preparing a catalog for earthquakes before 1960.

1. Introduction

Detailed and accurate information of earthquakes can be used to understand the seismicity and also to assess seismic hazard of a region. Macroseismic Data Points (MDPs) with or without complete descriptions could be one of the best sources of information to estimate the earthquake parameters especially when instrumental records are lacking.

There are several documents with descriptions of MDPs for some Iranian earthquakes. The intensity values were reported in four types of intensity scales; one 5° scale (Ambraseys and Melville Scale: AMS) (Ambraseys and Melville, 1982) and three 12° scales: the Modified Mercalli (Wood and Neumann, 1931; Richter, 1958), the Medvedev-Sponheuer-Karnik (MM; MMI) (Medvedev et al., 1964) (MSK), and the European Macroseismic Scale (EMS) (Grünthal, 1992, 1998). In this study, descriptions of some of these earthquakes were collected using a large set of available documents (books, reports, and articles) [e.g. Zare and Memarian (2003), Ambraseys and Melville (1982), and Berberian (1976, 1977, 1981)].

In order to be used for estimating earthquake parameters, the intensity values have to be provided in a uniform intensity scale. In this study, the intensity values were re-estimated for MDPs and earthquakes with descriptions, based on EMS intensity scale nthal (1992, 1998); nthal (1992, 1998). This scale is the newest and more complete macroseismic scale including details on damage for different types of buildings. Moreover, to even consider all reported environmental effects, the Environmental Seismic Intensity (ESI) scale (Michetti et al., 2004, 2007; Guerrieri et al., 2015) was also used in re-estimating some intensity values, especially in sparsely populated areas where information on damage is lacking.

In the current literature, there are mainly three methods that can be used to determine the earthquake parameters using macroseismic datasets. The first one, developed by Bakun and Wentworth (1997), uses a grid search to find the best results. The results of this method are sensitive to the spatial distribution of intensity data; so, with poor data, it sometimes locates the macroseismic epicenter away from the area with maximum intensities. Epicentral uncertainties are modelled as contour lines of different confidence levels of the residuals of the calculated

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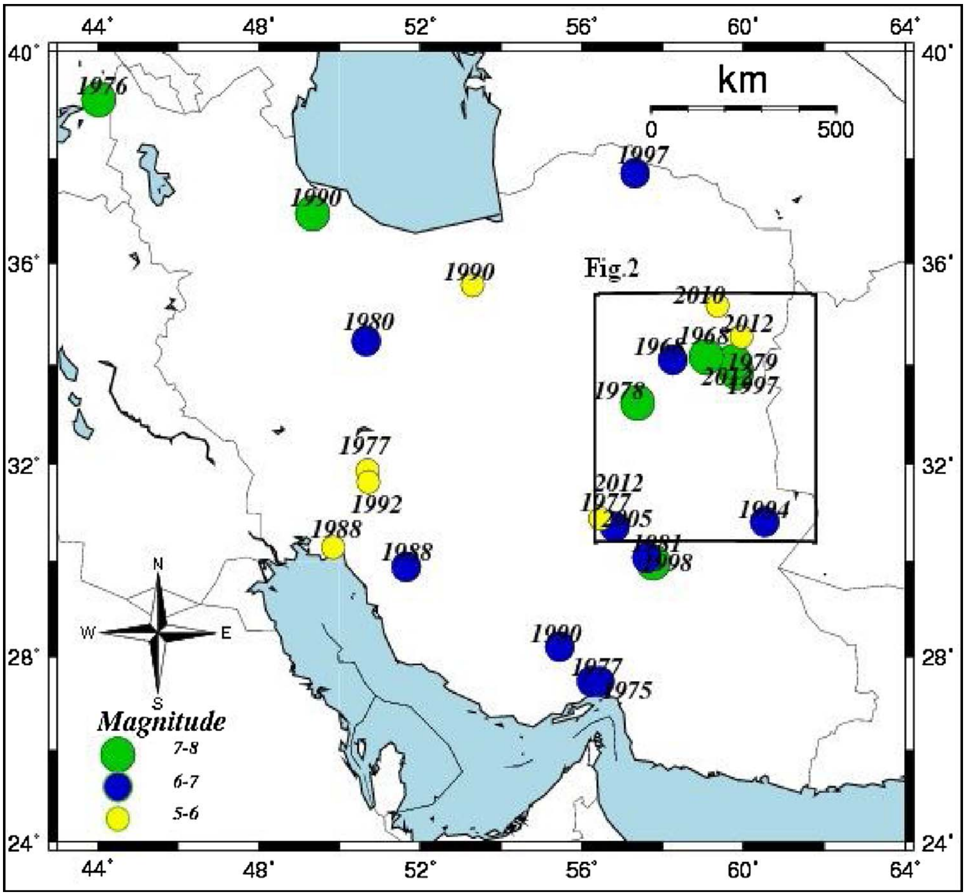

Fig. 1. Map of Iranian instrumental earthquakes used in this study. Rectangle indicates the area (Eastern Iran) which macroseismic parameters are computed in this study.

magnitudes; this information could not be easily included in a parametric catalog (Gomez-Capera et al., 2014). The second one (Boxer method) developed by Gasperini et al. (1999, 2010) computes the epicenter as the barycenter of the distributions of sites with the highest intensity value and is scarcely sensitive to irregular distribution of intensities. Even with few MDPs, its calculated epicenter is relatively stable and the method provides consistent uncertainties for all parameters (Gomez-Capera et al., 2014). The third one (MEEP method) introduced by Musson and Jiménez (2008) does not provide stable results, especially for moderate to high magnitudes (Gomez-Capera et al., 2014).

As the number and distribution of MDPs of Iranian earthquakes are usually poor, Boxer "Method 0" (see Gasperini et al., 2010) was selected in this study to determine the earthquake parameters.

2. Methodology

Boxer method was proposed by Gasperini et al. (1999) as an evolution of the algorithm initially developed by Gasperini and Ferrari (1995). Boxer was originally proposed for Italy; but, starting with the 4.0 release, it can even be used in other areas of the world because a calibration procedure is included in such version. Among the others, "Method 0" of Boxer requires less information for each earthquake and uses "robust" estimators (like the trimmed mean) that are scarcely sensitive to outliers. The strategy of this method involves five steps: 1) locating the earthquake, 2) assessing the earthquake moment magnitude (Mw), 3) computing the source dimensions (length and width), 4) estimating the source orientation (azimuth), and finally 5) representing the source.

The algorithm described by Gasperini and Ferrari (1995, 2000) computes the epicentral intensities (I_0) as the largest observed intensity if there are 2 or more MDPs with such highest intensity. In other cases, I_0 is set to I_{max}-1. The location coordinates are computed as the trimmed means (that is, the arithmetic average of the data that falls between the twentieth and eightieth percentiles) of the coordinates of MDPs with the highest intensity values (Gasperini et al., 1999). The magnitudes are computed based on Sibol et al. (1987) relationship for each isoseismal. Then, the magnitude of each earthquake is computed as the weighted trimmed mean of the magnitudes obtained from different isoseismals.

The earthquake seismogenic source could also be computed as a rectangular region or a "box" (from which comes the name Boxer). This box is centered in the calculated epicenter and the orientation is computed as the weighted axial mean of the distribution of the axial orientations (Gasperini et al., 2010). Empirical relationships of Wells and Coppersmith (1994) for all kind of focal mechanisms are used to calculate the subsurface rupture length (RLD) and the down dip rupture width (DW) based on the moment magnitude. The box is finally represented graphically as the surface projection of the fault by assuming a dip angle of 45° which is about the average value for dip-slip faults.

The uncertainties of the parameters are estimated using formal method and bootstrap simulations (Efron and Tbishirani, 1986; Hall, 1992). Formal uncertainties of epicentral coordinates are calculated as

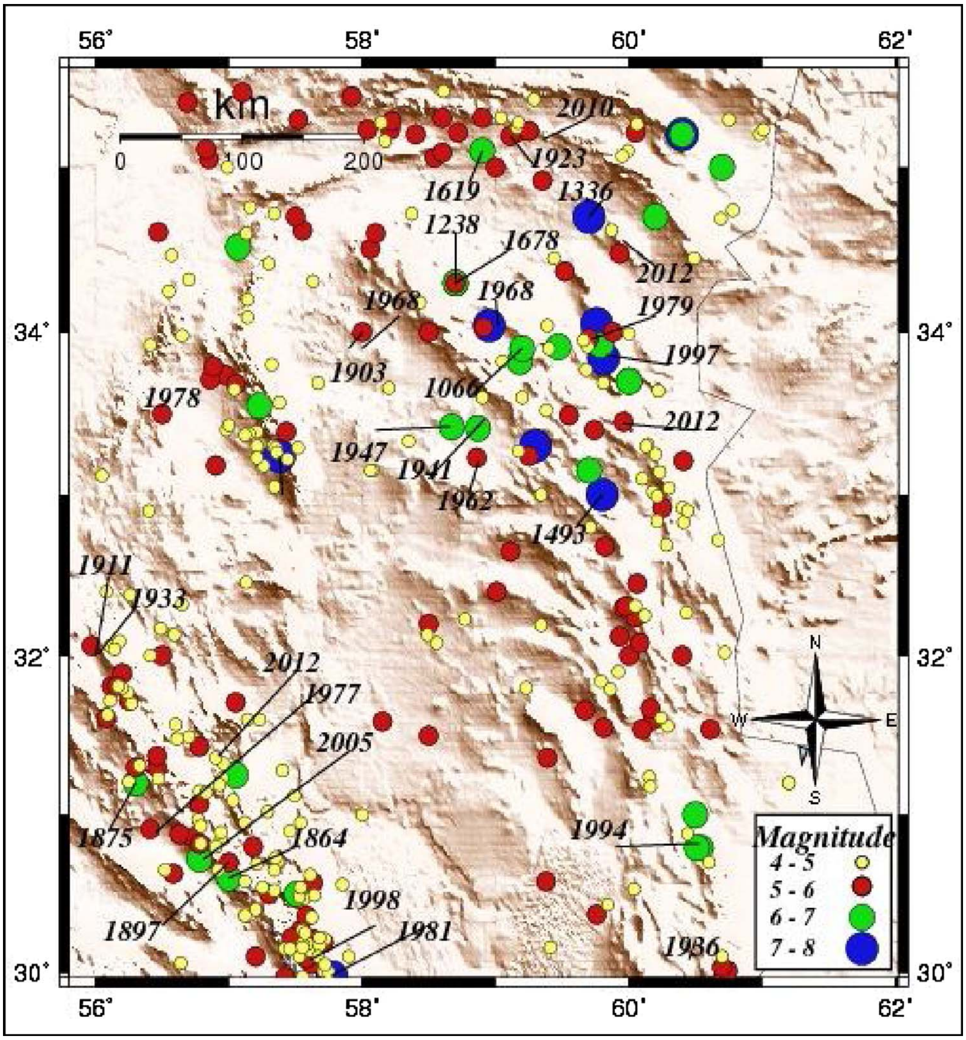

Fig. 2. Location of earthquakes with magnitude larger than 4 in eastern Iran; Earthquakes with macroseismic information are shown with their dates.

the standard deviation of the mean of the coordinates used in computing the trimmed mean, while for magnitudes, it is estimated as the inverse of the square root of the sum of the weights of each isoseismal used in the trimmed means (Gasperini et al., 2010). More details on the Boxer methodology can be found on the original papers.

3. Dataset

3.1. Preparing dataset

Most of the used instrumental earthquakes of this study were concentrated in eastern part of Iran. This is a region with several active faults where no large earthquakes occurred in very recent years. Moreover, these earthquakes have the largest magnitudes among the other used earthquakes. Therefore, this area (56.0–62.0°E, 29.5–35.5°N) was selected as the first part of Iran in which earthquake parameters were estimated using their macroseismic datasets and the Boxer method (Fig. 1).

In earthquake catalog of Iran published by Shahvar et al. (2013) and Zare et al. (2014), 352 earthquakes with magnitude 4 or more were reported up to the end of 2012 in the selected area (Fig. 2). From them, only 74 earthquakes have some information on intensity values (Appendix A in Supplementary materials) and only 29 earthquakes have the reports of some MDPs (Table 1). Information on the historical and instrumental earthquakes with their description reports was collected from available references. The list of such references is reported in Appendix (B in Supplementary materials). A dataset of 29 earthquakes occurred between years 1066 and 2012 with about 600 MDPs was prepared for the selected area. The maximum number of MDPs (128) concerns the Ardekul-Ghaen (1997.05.10) earthquake while some earthquakes [Qahestan (1066) and Gonabad (1238 and 1678)] have only one MDP.

Latitudes and longitudes of MDPs were taken from the dataset of the Statistical Centre of Iran (2006) if present; if not, especially for historical earthquakes of which some settlements were totally destroyed and do not exist anymore, the books of cities and villages coordinates published by Papeli Yazdi (1989) and Mofakham Payan (1960) were also used. MDPs without coordinates or good information were removed.

3.2. Estimating intensity values

Different published reports, books, and articles reported the intensity values of Iranian earthquakes in four scales. Most of these

Table 1
List of earthquakes with macroseismic information in eastern Iran; (Region: location of occurred earthquake; Y: Year; M: Month; D: Day; Lat: Latitude; Lon: Longitude; H: hypocentral depth; Mw: instrumental moment magnitude; Unc_{Mw}: instrumental uncertainty of magnitude based on Shahvar et al. (2013); N_{MDPs}: Number of MDPs).

Region	Y	M	D	Lat	Lon	Mw	Unc_{Mw}	N_{MDPs}
Qahestan	1066	05	–	33.90	59.20	6.5	–	1
Gonabad	1238	–	–	34.30	58.70	5.3	–	1
Khaf	1336	10	21	34.70	59.70	7.6	–	2
Momen Abad	1493	01	10	33.00	59.80	7.0	–	4
Dogh Abad	1619	–	–	35.10	58.90	6.5	–	2
Gonabad	1678	–	–	34.30	58.70	6.5	–	1
Kerman	1864	01	17	30.60	57.00	6.0	–	2
Kuhbanan	1875	05	01	31.20	56.30	6.0	–	5
Kerman	1897	05	27	30.70	57.00	5.7	–	4
Torshiz	1903	09	25	34.00	58.00	5.9	–	5
Ravar	1911	04	18	32.00	56.00	6.2	–	8
Kaj Drakht	1923	05	25	35.19	59.11	6.0	–	6
Laleh Zar	1923	09	22	29.20	56.90	6.7	–	20
Mohammad Abad	1941	02	16	33.48	58.79	6.1	–	13
Dolat Abad	1947	09	23	33.62	58.64	6.8	–	13
Musaviyeh	1962	04	01	33.21	58.87	5.7	–	13
Dash-e-Bayaz	1968	08	31	34.16	59.08	7.4	0.2	62
Gisk	1977	12	19	30.89	56.45	5.9	0.1	65
Tabas	1978	09	16	33.24	57.38	7.3	0.1	70
Koli-BonyAbad	1979	11	27	34.06	59.76	7.0	0.1	34
Sirch	1981	07	28	29.98	57.77	7.2	0.2	21
Sefidabeh	1994	02	24	30.82	60.53	6.3	0.1	29
Ardekul-Ghaen	1997	05	10	33.86	59.83	7.2	0.2	128
Fandogha	1998	03	14	30.08	57.61	6.7	0.1	13
Zarand	2005	02	22	30.72	56.81	6.4	0.1	17
Someh	2010	07	30	35.17	59.36	5.5	0.2	16
Ravar	2012	02	27	31.37	56.92	5.5	0.1	3
Khaf	2012	07	01	34.56	59.95	5.3	0.1	11
Zahan	2012	09	02	33.44	59.95	5.1	0.1	5

intensity values were determined by Berberian (1976, 1977) in the MMI intensity scale, by Ambraseys and Melville (1982) in AMS intensity scale, by Ambraseys (2001) in the MSK intensity scale, and by Zare and Memarian (2003) in the EMS intensity scale.

To prepare a dataset of earthquakes in a uniform intensity scale, the earthquake descriptions are the most important and preferable source. Therefore, when available, descriptions were directly considered to re-estimate the intensity values in both EMS and ESI scale. The comparison of the intensity values estimated by the two scales showed that in most cases, they are consistent with each other and the differences between them are about one degree at most (Fig. 3). According to Michetti et al. (2007), when we have descriptions for estimating intensities in both EMS and ESI scale the final intensity is the maximum between these two scales. In the following, we will refer applying two scales as the EMS-ESI scale. As half degrees (*e.g.* 6.5 and 5.5) are not explicitly defined in various intensity scales, only integer values were estimated for this study.

For some MDPs without descriptions but with intensity values estimated by other authors using different scales, we convert them to the EMS-ESI scale using the tables of correspondence reported in Table 2 that were determined in another work by Amini et al. (2017) as the averages of the intensities estimated by the EMS and/or ESI scales over the degrees of other scales for a dataset MDPs for which there were both descriptions and intensities.

4. Calibration and attenuation relationship

According to Gasperini et al. (2010), the first task with Boxer method is calibration. The procedure should be performed using MDPs of instrumental earthquakes (occurred after 1964). The number of these earthquakes in Iran and eastern part of Iran are 22 and 13, respectively. The list of these instrumental earthquakes with their MDPs information is reported in Appendix (C in Supplementary materials).

Regression coefficients of the Sibol et al. (1987) formula for each isoseismal were estimated (using Boxer code in COMPCOEFF mode) by considering earthquakes with more than four MDPs for that isoseismal and also using suitable weighting described by Gasperini et al. (2010). Regressions coefficients estimated for both Iran and eastern part of Iran are reported in Tables 3 and 4, respectively. 22 Iranian instrumental earthquakes (from 1964 to 2012) were selected to estimate the coefficients of the Pasolini et al. (2008) attenuation equation of Iran:

$$I = I_E - (0.0004 \pm 0.0004)(D - h) - (1.0676 \pm 0.0677)[\ln(D) - \ln(h)] \quad (1)$$

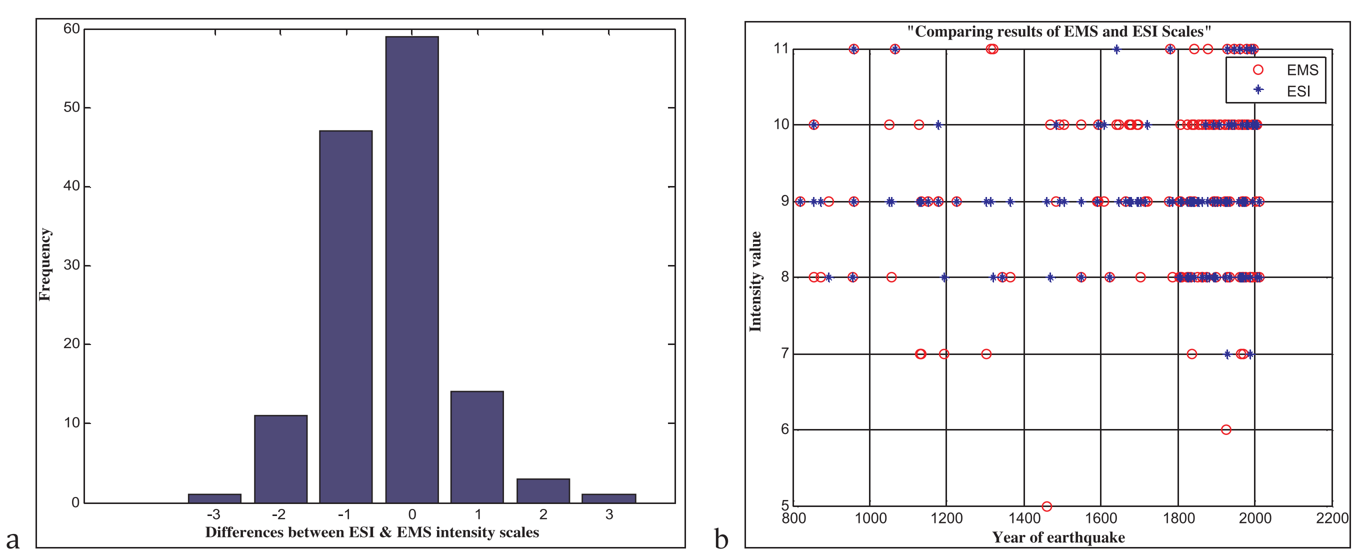

Fig. 3. Comparison of EMS and ESI intensity values for 138 Iranian earthquakes which have descriptions to separately estimate their intensity values in both scales; a) Frequency distribution of differences between EMS and ESI scales, b) Comparison between intensity values estimated by the two intensity scales, separately.

Table 2
Tables of correspondence from intensities in MMI (a), EMS (b), MSK (c), and AMS (d) scales to EMS-ESI scale; Av: Average of intensity in EMS-ESI scale for each degree of other intensity scale; I: rounded integer degree used for conversion; Std: standard deviation of intensity in EMS-ESI scale for each degree of other intensity scales).

a

MMI	Av	I	Std
3	4.200	4	-
4	4.473	4	0.70
5	5.410	5	0.79
6	6.562	7	0.79
7	7.988	8	0.79
8	8.877	9	0.74
9	9.810	10	0.70
10	10.33	10	0.70

b

EMS	Av	I	Std
4	5.214	5	-
5	4.931	5	0.70
6	6.296	6	0.74
7	7.500	7	0.70
8	8.088	8	0.79
9	9.466	9	0.70
10	11.000	11	-

c

MSK	Av	I	Std
4	4.055	4	0.70
5	5.090	5	0.70
6	6.714	7	0.70
7	7.685	8	0.70
8	8.944	9	0.74
9	9.800	10	0.74
10	10.285	10	0.70

d

AMS	Av	I	Std
1	10	10	0.70
2	9.454	9	0.79
3	8.032	8	0.79
4	6.366	6	0.74
5	4.188	4	0.70

Table 3
Calibrated coefficients of Boxer for all of Iran instrumental earthquakes with MDPs in this study; (N_{EQ}: Number of earthquakes with that intensity; N_{MDPs}: Number of MDPs of that intensity; σ: Standard deviation of the model; R^2 (%): Percentage of the coefficient of variation).

Intensity	N_{EQ}	N_{MDP}	a	b	c	σ	R^2 (%)
6	12	208	5.5387 ± 1.3166	0.1586 ± 0.0169	–	0.2636	89.82
7	10	146	3.4961 ± 0.6878	0.0627 ± 0.0395	0.0182 ± 0.0073	0.3229	81.12
8	11	205	4.1069 ± 0.4629	−0.0284 ± 0.0421	0.0349 ± 0.0100	0.2821	80.93
9	5	106	4.2568 ± 0.2338	0.1331 ± 0.1121	–	0.3288	31.96

Table 4
Calibrated coefficients of Boxer for Eastern Iran instrumental earthquakes with MDPs in this study; (N_{EQ}: Number of earthquakes with that intensity; N_{MDPs}: Number of MDPs of that intensity; σ: Standard deviation of the model; R^2 (%): Percentage of the coefficient of variation).

Intensity	N_{EQ}	N_{MDP}	a	b	c	σ	R^2 (%)
5	5	29	5.3898 ± 1.0391	0.0368 ± 0.0537	–	0.6248	13.50
6	5	89	3.4319 ± 0.2448	0.2218 ± 0.0175	–	0.1264	98.17
7	6	79	3.5063 ± 0.4519	0.1227 ± 0.0314	0.0172 ± 0.0052	0.2150	94.05
8	6	95	4.8036 ± 0.5525	0.1966 ± 0.0497	–	0.2824	79.60

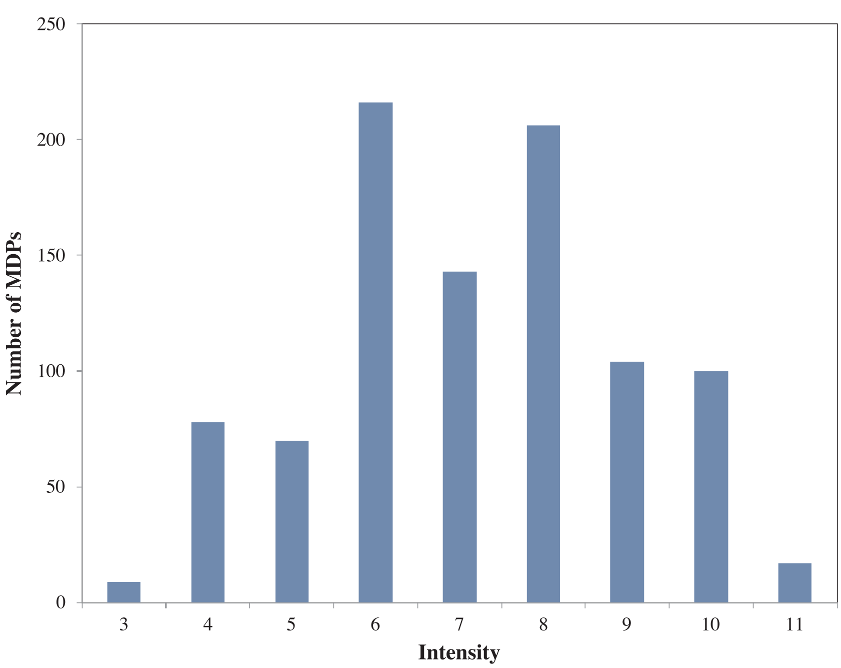

Fig. 4. Frequency distribution of the macroseismic intensity of the 22 events used for calibration (about 1000 MDPs).

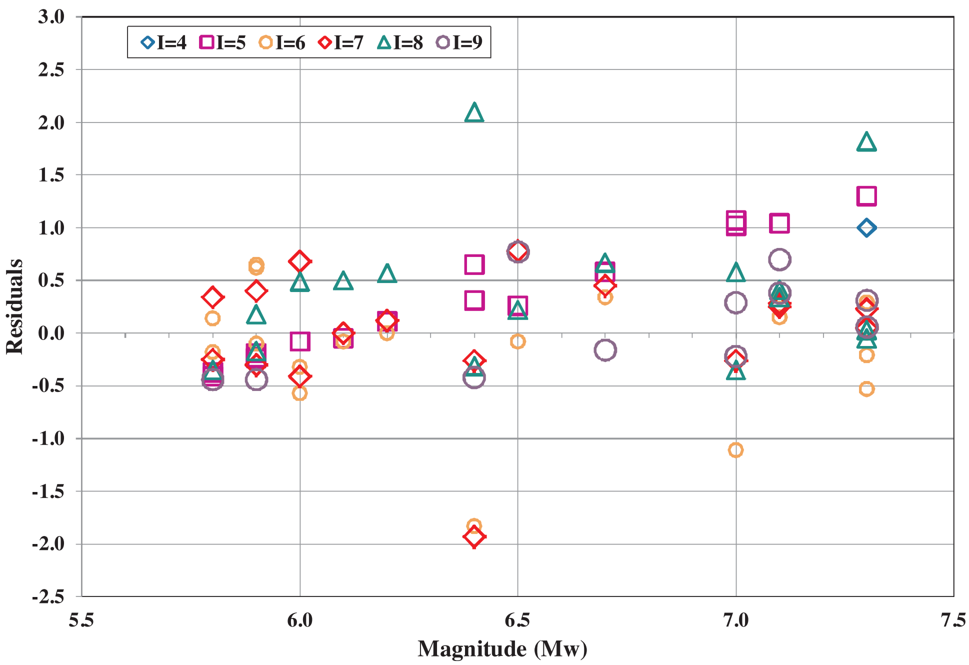

Fig. 5. Mw residuals [Mw-Mi (ith earthquake)] for different intensity classes in the calibration set.

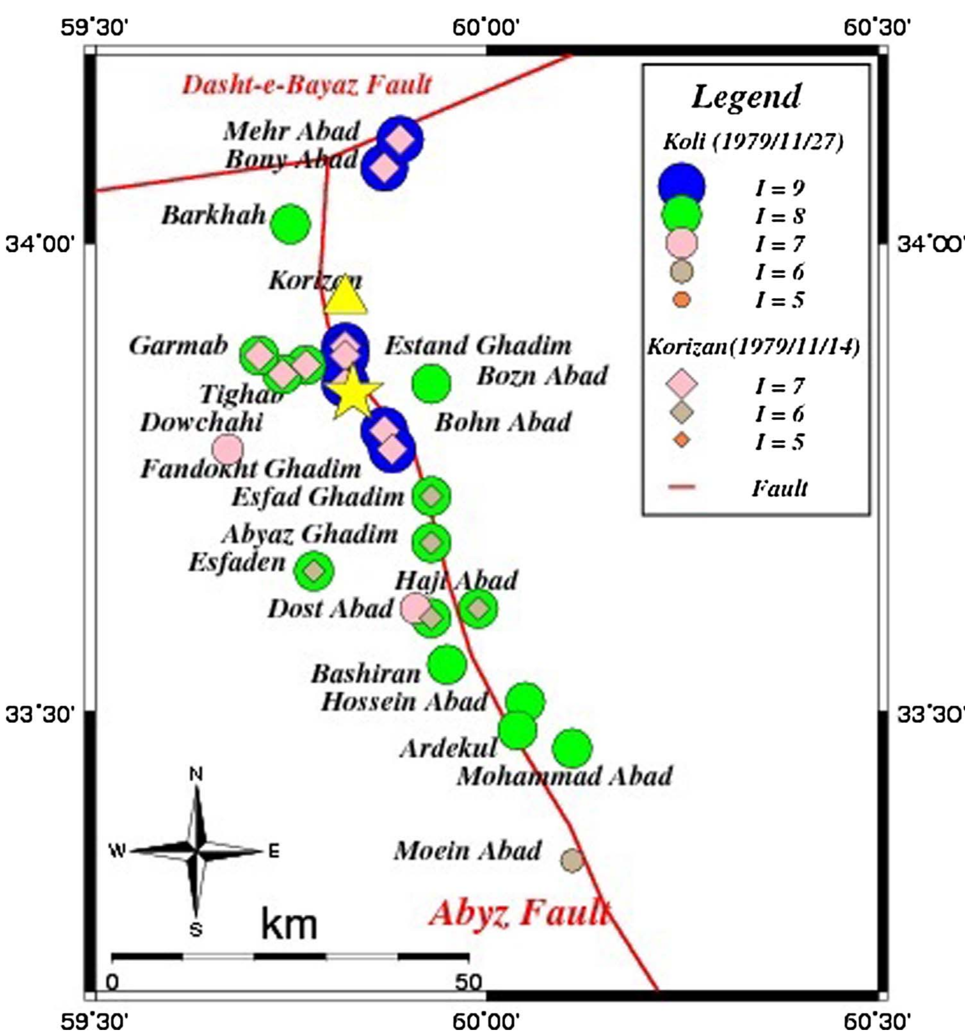

Fig. 6. MDPs Location of the Korizan-Khaf (1979.11.14) and the Koli-BonyAbad (1979.11.27) earthquakes; the size of MDPs depends on revaluated intensity values in EMS-ESI scale. Macroseismic epicenters of Korizan-Khaf and Koli-BonyAbad earthquakes, computed by Boxer method based on MDPs are indicated by the yellow square and circle, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5
Instrumental and macroseismic information of two Korizan-Khaf (1979.11.14) and Koli-BonyAbad (1979.11.27) earthquakes (Y: Year; M: Month; D: Day; Lat: Latitude; Lon: Longitude; M: Magnitude; I_{max}: maximum intensity; N_{MDPs} number of MDPs).

Region	Y	M	D	H	Instrumental Information			Macroseismic information				
					Lat	Lon	M	Lat	Lon	M	I_{max}	N_{MDPs}
Korizan-Khaf	1979	11	14	10	33.92	59.74	6.50 ± 0.10	33.94 ± 5.3 km	59.82 ± 7.3 km	6.06 ± 0.19	8	22
Koli-BonyAbad	1979	11	27	09	33.96	59.70	7.10 ± 0.10	33.84 ± 8.3 km	59.83 ± 2.2 km	6.76 ± 0.12	10	34

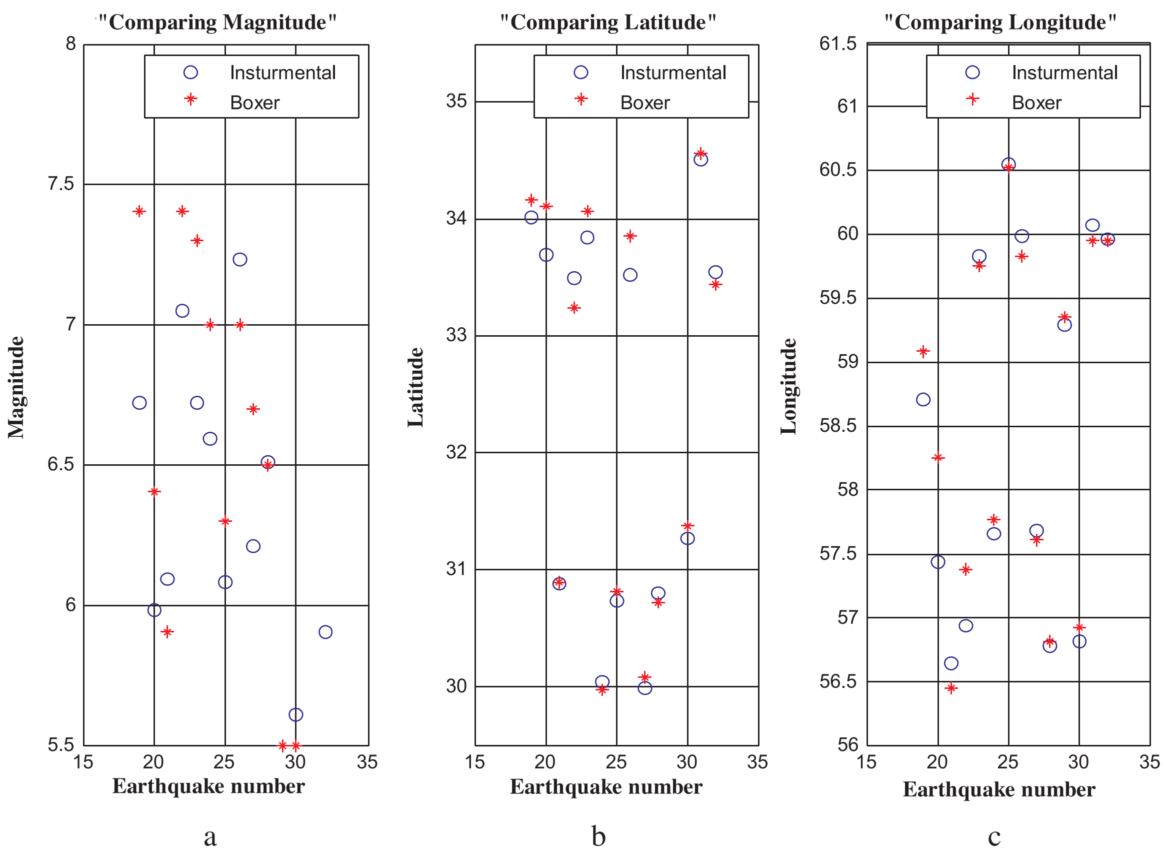

Fig. 7. Comparison between (a) magnitudes, (b) latitudes and (c) longitudes computed by Boxer and corresponding instrumental estimates.

Where $h = 3.7 \pm 1.2$ km is a common average of depth assumed for all earthquakes, $D = \sqrt{R^2 + h^2}$, the hypocentral distance (where R is the epicentral distance), and I_E, the average expected intensity at the epicenter.

The frequency distribution of intensity values showed that intensities 6 and 8 (with more than 200 MDPs) were the intensity levels with maximum number of reports in Iran region (Fig. 4). In our instrumental earthquake dataset, these intensity values were reported for 21 and 19 numbers of earthquakes, respectively. The residuals of the instrumental and macroseismic magnitudes for each intensity class were also shown in Fig. 5. The average of residuals and standard deviation were 0.10 and 0.15, respectively. Magnitude residuals for magnitudes higher than 6.0 tends to be slightly positive, whereas those of smaller earthquakes tends to be negative.

5. Estimating earthquake parameters

If there are complete MDP descriptions of each earthquake, it is possible to distinguish between the main shock, foreshock, and aftershock. For instance, the intensity information of Korizan-Khaf (1979.11.14) and Koli-BonyAbad (1979.11.27) earthquakes were published as two separate earthquakes (e.g. Haghipour and Amadi, 1980; Mohajer-Ashjai et al., 1980; Ambraseys and Melville, 1982; Adeli, 1981); and different MDPs and intensity values were reported for them (Fig. 6). The results of estimating the macroseismic parameters using their MDPs showed that Korizan-Khaf earthquake (1979.11.14) was located very close to the Koli-BonyAbad earthquake (1979.11.27) with lower intensity values (Table 5); then, it has to be considered as foreshock of it. As in declustering stage of preparing catalogs for seismic hazard assessment (such as Shahvar et al., 2013; Zare et al., 2014), this earthquake has to be removed from the main events in final catalog. Then, according to the instrumental and macroseismic information, Koli-BonyAbad (1979.11.27) was the main shock.

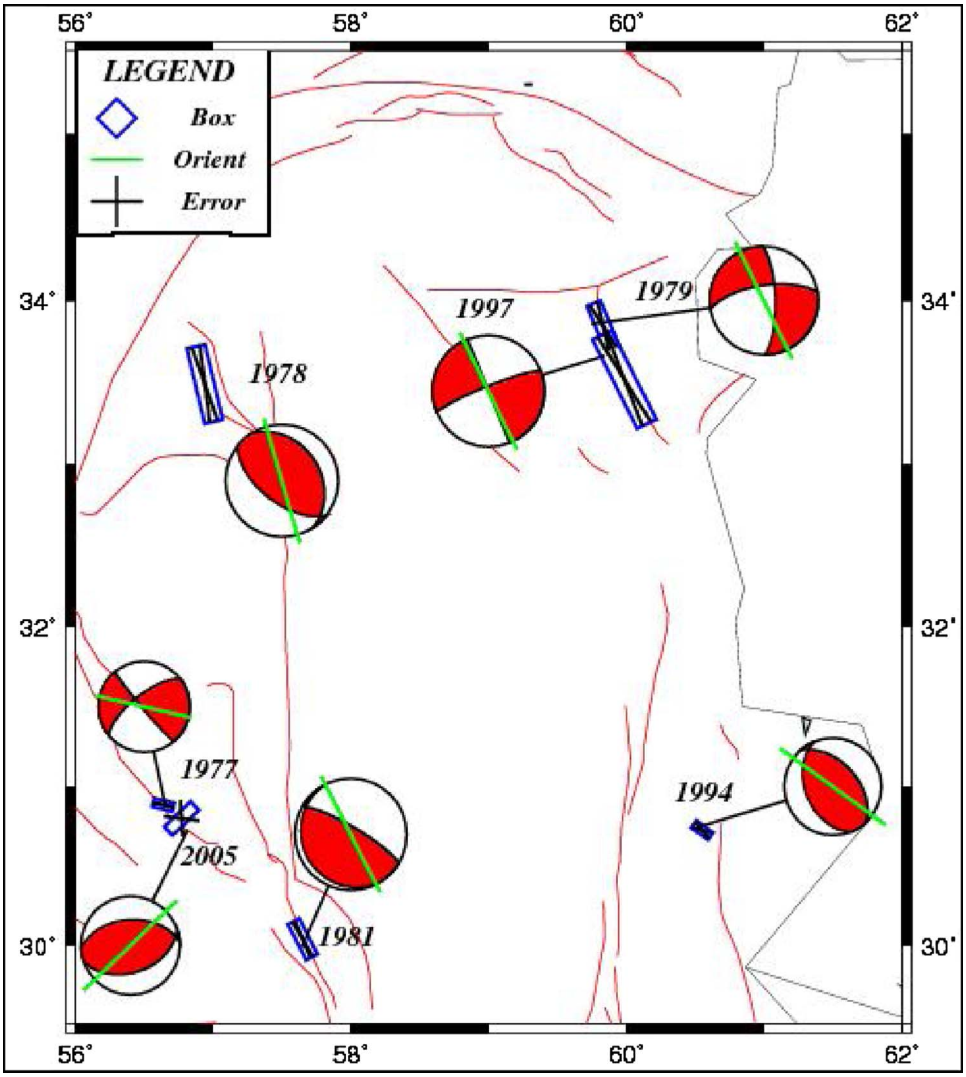

Fig. 8. Comparison focal mechanism from GCMT catalog with orientation estimated by Boxer for instrumental earthquakes in Eastern Iran.

Table 6

Comparison of source orientations of instrumental earthquakes in eastern Iran reported by the GCMT catalog with the results of Boxer method [Y: Year; M: Month; D: Day; Boxer Results (Lat: Latitude; Lon: Longitude; Az: Azimuth; M: Magnitude); GCMT Solutions (M: Magnitude; St: Strike of each plane; Diff: Differences between strike of each plane and Boxer azimuth estimate); Min Diff: minimum differences between strikes].

Region	Y	M	D	Boxer Results				GCMT Solutions					
				Lon	Lat	Az	M	M	First Plane		Second Plane		Min abs Diff
									St	Diff	St	Diff	
Gisk	1977	12	19	56.64	30.89	103 ± 004	6.1	5.90	140	37	231	−52	37
Tabas	1978	09	16	56.94	33.51	164 ± 008	7.1	7.30	128	−36	328	−16	16
Koli Bony Abad	1979	11	27	59.83	33.84	154 ± 010	6.7	7.00	358	24	261	−73	24
Sirch	1981	07	28	57.65	30.04	153 ± 004	6.6	7.20	150	−3	300	−33	3
Sefidabeh	1994	02	24	60.55	30.73	126 ± 017	6.1	6.30	158	32	318	12	12
Ardekul Ghaen	1997	05	10	59.99	33.52	154 ± 005	7.2	7.23	338	4	248	−86	4
Zarand	2005	02	22	56.77	30.80	46 ± 050	6.5	6.40	71	25	266	40	25

Table 7
Parameters computed in this study for the earthquakes with reported MDPs in eastern Iran; (Y: Year; M: Month; D: Day; Lat: Latitude; Lon: Longitude; M: Magnitude; Az: Azimuth; L: Length; W: Width; *: Bootstrap estimation of uncertainty).

Region	Y	M	D	Lat	Lon	M	AZ (Degree)	L (km)	W (km)
Qahestan	1066	5	0	33.16°	59.71°	7.0	–	51.71	17.49
Gonabad	1238	0	0	34.36°	58.69°	6.2	–	16.06	9.27
Khaf	1336	10	21	34.46°	60.00°	6.5	–	23.71	11.46
Momen Abad	1493	1	10	32.92°	59.81°	6.5	139.7	23.71	11.46
Doghabad	1619	0	0	35.08°	58.85°	6.8	–	35.02	14.16
Gonabad	1678	0	0	34.36°	58.69°	7.0	–	51.71	17.49
Kerman	1864	1	17	30.45°	57.00°	5.9	–	10.87	7.51
Kuhbanan	1875	5	1	31.25° ± 8.83 km	56.38° ± 2.34 km	6.5 ± 0.26	164.9 ± 9.7	23.71 ± 5.64	11.46 ± 1.74
Kerman	1897	5	27	30.54°	57.10°	6.8	–	35.02	14.16
Torshiz	1903	9	25	35.22° ± 0.85 km	58.30° ± 8.92 km	6.2 ± 1.33	–	16.06 ± 3.72	9.27 ± 38.7
Ravar	1911	4	18	31.19° ± 4.01 km	57.00° ± 7.16 km	6.1 ± 0.33	110.4 ± 13.2	13.55 ± 10.21	8.46 ± 2.71
Kaj-Drakht	1923	5	25	35.30° ± 7.69 km	59.16° ± 3.48 km	6.8 ± 0.20	–	35.02 ± 6.40	14.16 ± 1.65
Laleh Zar	1923	9	22	29.72° ± 12.31 km	56.46° ± 15.9 km	6.6 ± 0.24	129.2 ± 10.6	27.30 ± 12.09	12.37 ± 2.55
Mohammadabad	1941	2	16	33.45° ± 6.40 km	58.86° ± 2.88 km	6.9 ± 0.14	166.4 ± 10.5	42.26 ± 8.66	15.68 ± 1.67
Dolat-Abad	1947	9	23	33.94° ± 8.52 km	57.54° ± 37.26 km	7.5 ± 0.55	85.2 ± 18.10	97.95 ± 33.36	24.73 ± 6.25
Musaviyeh	1962	4	1	33.24° ± 15.51 km	58.89° ± 4.68 km	5.8 ± 0.27	177.8 ± 13.4	9.12 ± 3.53	6.82 ± 1.37
Dash-e-Bayaz	1968	8	31	34.01° ± 2.60 km	58.71° ± 5.92 km	6.7 ± 0.12	77.9 ± 21.9	33.45 ± 5.05	13.81 ± 1.17
Gisk	1977	12	19	30.89° ± 1.86 km	56.64° ± 4.18 km	6.1 ± 0.12	103.4 ± 16.6	14.29 ± 2.28	8.71 ± 0.76
Tabas	1978	9	16	33.49° ± 4.72 km	56.94° ± 0.97 km	7.1 ± 0.08	166.8 ± 8.3	52.43 ± 5.57	17.62 ± 1.04
Koli-BonyAbad	1979	11	27	33.84° ± 7.40 km	59.83° ± 1.89 km	6.7 ± 0.18	157.4 ± 17.3	33.66 ± 6.44	13.86 ± 1.58
Sirch	1981	7	28	30.04° ± 9.56 km	57.65° ± 4.47 km	6.6 ± 0.33	153.2 ± 4.5	28.09 ± 16.75	12.56 ± 3.41
Sefidabeh	1994	2	24	30.73° ± 5.99 km	60.55° ± 3.59 km	6.1 ± 0.16	125.6 ± 19.3	14.12 ± 2.98	8.65 ± 1.00
Ardekul-Ghaen	1997	5	10	33.52° ± 4.43 km	59.99° ± 1.85 km	7.2 ± 0.16	153.5 ± 7.3	67.39 ± 11.06	20.19 ± 2.03
Fandoga	1998	3	14	29.99° ± 10.34 km	57.69° ± 9.22 km	6.2 ± 0.28	–	16.83 ± 6.74	9.51 ± 1.96
Zarand	2005	2	22	30.80° ± 3.92 km	56.77° ± 4.14 km	6.5 ± 0.20	46.5 ± 65	25.21 ± 5.90	11.85 ± 1.61
Someh	2010	7	30	35.30° ± 0.79 km	59.29° ± 2.20 km	5.3 ± 0.13	95 ± 21.3	4.97 ± 0.83	4.91 ± 0.45
Ravar	2012	2	27	31.27°	56.81°	5.6	–	7.36	6.08
Khaf	2012	7	1	34.51° ± 2.58 km	60.08° ± 1.93 km	5.3 ± 0.23	35.3 ± 17.7	4.63 ± 2.18	4.73 ± 0.97
Zahan	2012	9	2	33.55° ± 8.12 km	59.96° ± 10.01 km	5.9 ± 0.29	46.2 ± 18.4	10.93 ± 2.80	7.53 ± 1.25

5.1. Results on instrumental earthquakes

Magnitudes, latitudes and longitudes of instrumental earthquakes in Eastern Iran were calculated by considering their MDPs. The comparison between Boxer and instrumental magnitudes indicated that they were consistent to each other (Fig. 7). Magnitude and location uncertainties are in the range of 0.2–0.5 unit and 0.8–9.6 km, respectively.

GCMT focal mechanisms give two fault planes among which the main plane should be determined based on geological or other kind of information on the region where the earthquake occurred. Conversely, Boxer estimates only the main fault plane for each earthquake. Gasperini et al. (2010) tested the consistency between the box orientations and the strikes of focal mechanisms available for Italy; for magnitudes 5.7 or more, 80% of orientations were within 10 ° from one of the nodal planes (90% within 20°). This good statistic could reasonably provide a robust evaluation of the seismogenic fault orientation for all sufficiently large earthquakes.

The orientations of Iranian instrumental earthquakes estimated by Boxer in this study were compared with GCMT (Fig. 8; Table 6). The difference between Boxer azimuth and that of the closest GCMT plane is lower than 25 ° for all except one earthquake (Gisk, 1977).

5.2. Results on pre-instrumental and historical earthquakes

The estimated results of instrumental earthquakes using Boxer and macroseismic dataset were consistent with values reported by the catalog in selected area (Section 5.1). Therefore, Boxer could also be suitable to estimate the parameters of historical earthquakes using their MDPs. Final results of latitude, longitude, magnitude, source dimension, and orientation of all earthquakes are listed in Table 7. A list of these earthquakes with their MDPs information is also reported in Appendix C in Supplementary materials.

5.2.1. Earthquakes with magnitude larger than 7

Earthquakes with the largest magnitudes (larger than 7) are located in the North of the selected area (Fig. 2). From them, three earthquakes, Qahestan, Gonabad and Dolat-Abad, occurred in 1066, 1678 and 1947, respectively, have MDPs report. Qahestan and Gonabad have only one MDP concerning the main city affected by the earthquake; then, Boxer could estimate their epicenters and magnitudes but could not estimate the uncertainties and orientations (Fig. 9). Conversely, 13 MDPs were reported for Dolat-Abad earthquake (Fig. 10). The location and magnitude differences between Boxer estimate and that reported by Ambraseys and Melville (1982) were in ∼40 km and ∼0.7 unit, respectively. We do not know exactly how such authors computed the epicenter and the magnitude but we believe that our estimates are more objective because are based on a standardized procedure (Boxer).

5.2.2. Earthquakes with magnitude lower than 6

Fig. 11 shows locations and uncertainties of the only two earthquakes with magnitude lower than 6. For Kerman earthquake (1864), only 2 MDPs were reported. Ambraseys and Melville (1982) reported that a destructive earthquake took place in 1864 and many people and animals were killed in Chatrud. The shock caused considerable damage in Kerman where the ivan of the Jami Muzaffar collapsed and the walls of the Qubbeh-e-Sabz were damaged. Because of a few numbers of MDPs, estimating its orientation was impossible; but its macroseismic magnitude and location was estimated by Boxer and they were

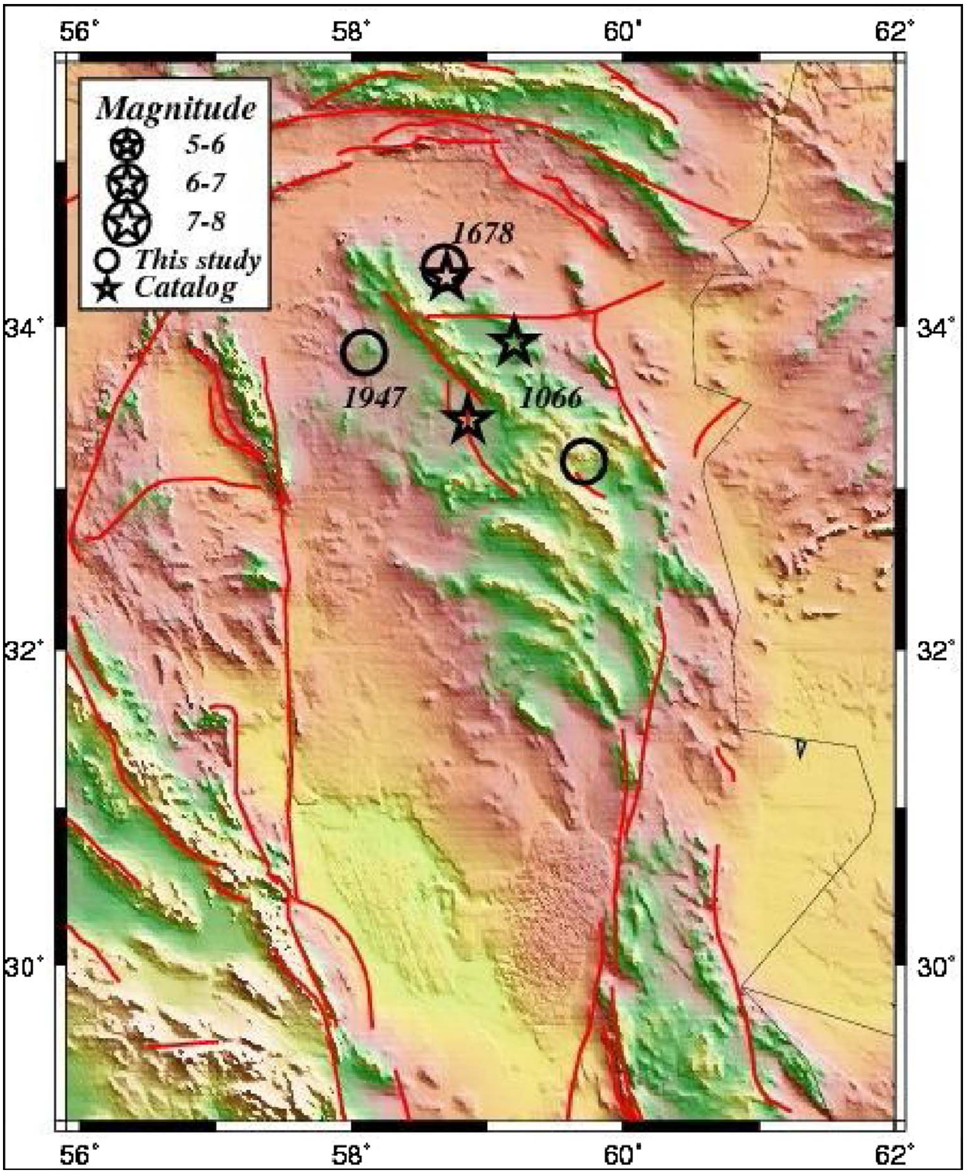

Fig. 9. Locations of Qahestan (1066), Gonabad (1678), and Dolat-Abad (1947) earthquakes as reported by catalog (stars) and computed from their MDPs in this study (circles).

consistent with the macroseismic magnitude reported by Ambraseys and Melville (1982) for this earthquake.

For Musaviyeh earthquake (1962), with 13 reported MDPs, the estimated magnitudes (this study) are almost the same as reported by Ambraseys and Melville (1982) (Fig. 13). The computed orientation of this event is consistent with the Mohammad-Abad Fault located close to this earthquake. According to Ambraseys and Melville (1982), this damaging earthquake ruined a number of villages in the North of Birjand on the 1st of April. The lower part of Musaviyeh was totally destroyed. Chahak, Chilunak, Tajkuh and Nuj were also ruined with the loss of a few lives and a large number of animals. Water springs changes and liquefaction phenomena were also reported at Muhammad-Abad and Shah Qiyath. The earthquake was strongly felt at Birjand, Khur, Khusf and as far as Ferdows.

5.2.3. Earthquakes with magnitude between 6 and 7

Most earthquakes with macroseismic information belong to the macroseismic magnitude range from 6 to 7. From them, estimated locations of Gonabad (1238), Momen Abad (1493), Dogh Abad (1916), Kaj Derakht (1923), Mohammad Abad (1941) (Fig. 12), Kuhbanan (1875), and Kerman (1897) (Fig. 13) earthquakes are consistent with those reported by earthquake catalog (e.g. Zare et al., 2014). However, the number of their MDPs is not enough to estimate the earthquake orientations for all of them.

Location of estimated epicenter of Khaf earthquake (1336) was at a distance of ~40 km from epicenter reported by Ambraseys and Melville (1982). For Laleh Zar earthquake (1923) the differences between the estimated epicenter (by Boxer) and its macroseismic and instrumental reported epicenter (by Ambraseys and Melville, 1982) were at distances

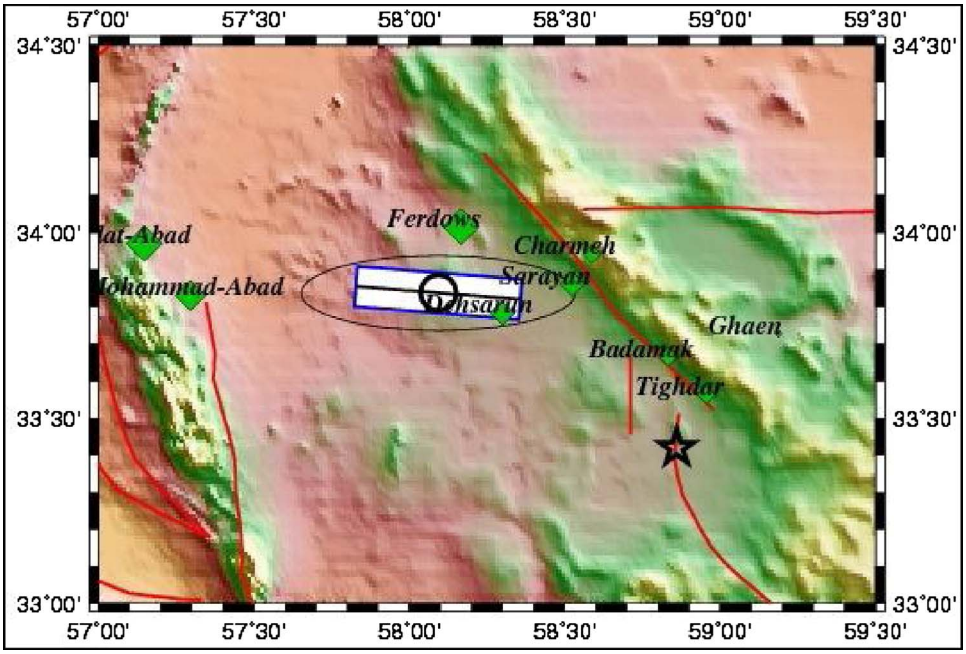

Fig. 10. Dolat-Abad earthquake (1947); the map show the macroseismic (circle) and instrumental (star) epicenters, MDP locations (diamonds), epicenter error (ellipse), and the source projection of the seismogenic fault (large box).

of ~30 and ~75 km, respectively. The maximum differences between the estimated and the instrumental reported locations were related to Torshiz (1903) and Ravar (1911) earthquakes with differences of ~140 km (Fig. 13). According to their descriptions published by Ambraseys and Melville (1982) and presented in the following, the differences between the estimated (this study) and macroseismic (Ambraseys and Melville, 1982) epicenter are in about 10 and 6 km, respectively.

Torshiz (1903.09.25) was a severe earthquake which caused extensive damage in the region of Torshiz (Kashmar) to the west of Torbat-e-Heydariyeh in Khorasan. The earthquake killed 350 people and destroyed the carpet factories of the district, particularly at Kondor and Kashmar. In Torshiz, which is the largest settlement in the region, the damage was very severe, particularly in the Southern parts of the town where almost all houses were destroyed and 80–100 people lost their lives. The shock was felt in Shahrud and Torod, and it was perceptible in Dost Abad, but not in Mashhad. Aftershocks were felt for over two months causing further damage in the area.

Ravar (1911.04.18) was a destructive earthquake that killed about 700 people. The small villages of Abdirjan, Maki and Deh Lakarkuh in the sparsely populated area, East of Ravar, were totally destroyed with many casualties. Almost all houses in Ravar and its settlements were ruined. Ravar remained in ruins for a long time and its public buildings were only being rebuilt thirty years later. Many rockfalls were triggered from the Northeast face of Lakar Kuh, and it is very possible that the shock was associated with faulting West of Abdirjan. Minor damage extended to a number of villages; the shock was strongly felt in Kerman, Deh Zuiyeh, and Kuhbanan. It was also felt in Birjand, Nasrat Abad, and Duzdab.

The low number of instruments installed in the area and their low accuracy (at least before year 1964) could be the reasons to low reliability of instrumental parameters that suggests considering their macroseismic parameter as more reliable. Ambraseys and Melville (1982) estimated the macroseismic location of some earthquakes using their macroseismic descriptions. The comparison between the earthquake locations estimated by Ambraseys and Melville (1982) and Boxer estimation of this study for the same earthquakes showed that they were more consistent to each other than with the instrumental records (Fig. 14).

In some cases, there are differences of several tens of km between the macroseismic epicenter estimated in this study and that reported in earthquake catalogs (e.g. Zare et al., 2014). We believe that, at least for the earthquakes occurred before 1964, macroseismic parameters are preferred to instrumental ones in preparing catalogs.

6. Conclusions

Considering a large set of available descriptions from different published documents (books, articles, reports, web reports), a dataset of some Iranian earthquakes with Macroseismic Data Points (MDPs) was prepared. As most earthquakes with macroseismic descriptions and large magnitude concentrate in Eastern Iran, we focused on this region (56.0–62.0°E, 29.5–35.5°N).

Intensity values estimated by other authors in four different intensity scales (MMI, MSK, EMS and AMS) were collected. For MDPs with descriptions, we directly revaluated the intensity values from descriptions using EMS and ESI scales. For MDPs without any descriptions, the intensity values reported by other authors were converted to the EMS-ESI scale using table of correspondence computed in another work (Amini et al., 2017) (Table 2).

To estimate the earthquake parameters, we adopted Boxer “Method 0” defined by Gasperini et al. (1999, 2010), which computes the barycenter of distributions of sites with the highest intensities and is scarcely sensitive to irregularly distributed intensities. The

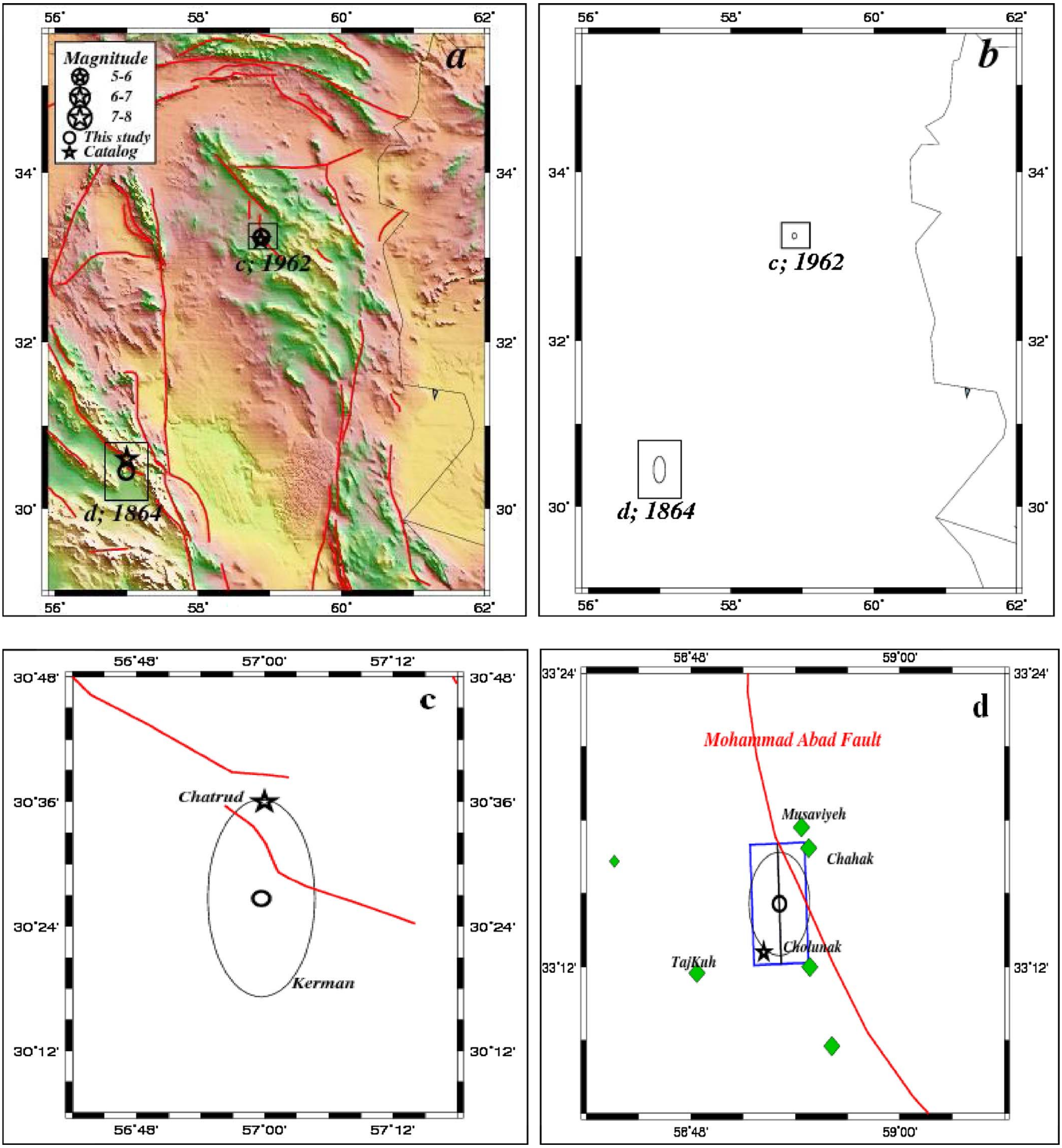

Fig. 11. (a) Locations of Kerman (1864), and Musaviyeh (1962) earthquakes as reported by catalog (According to Ambraseys and Melville, 1982) (stars) and as determined in this study by Boxer (circles); (b) location uncertainties calculated by Boxer; (c) Kerman 1864 earthquake, and (d) Musaviyeh 1962 earthquake with more details (for more explanation see Fig. 10).

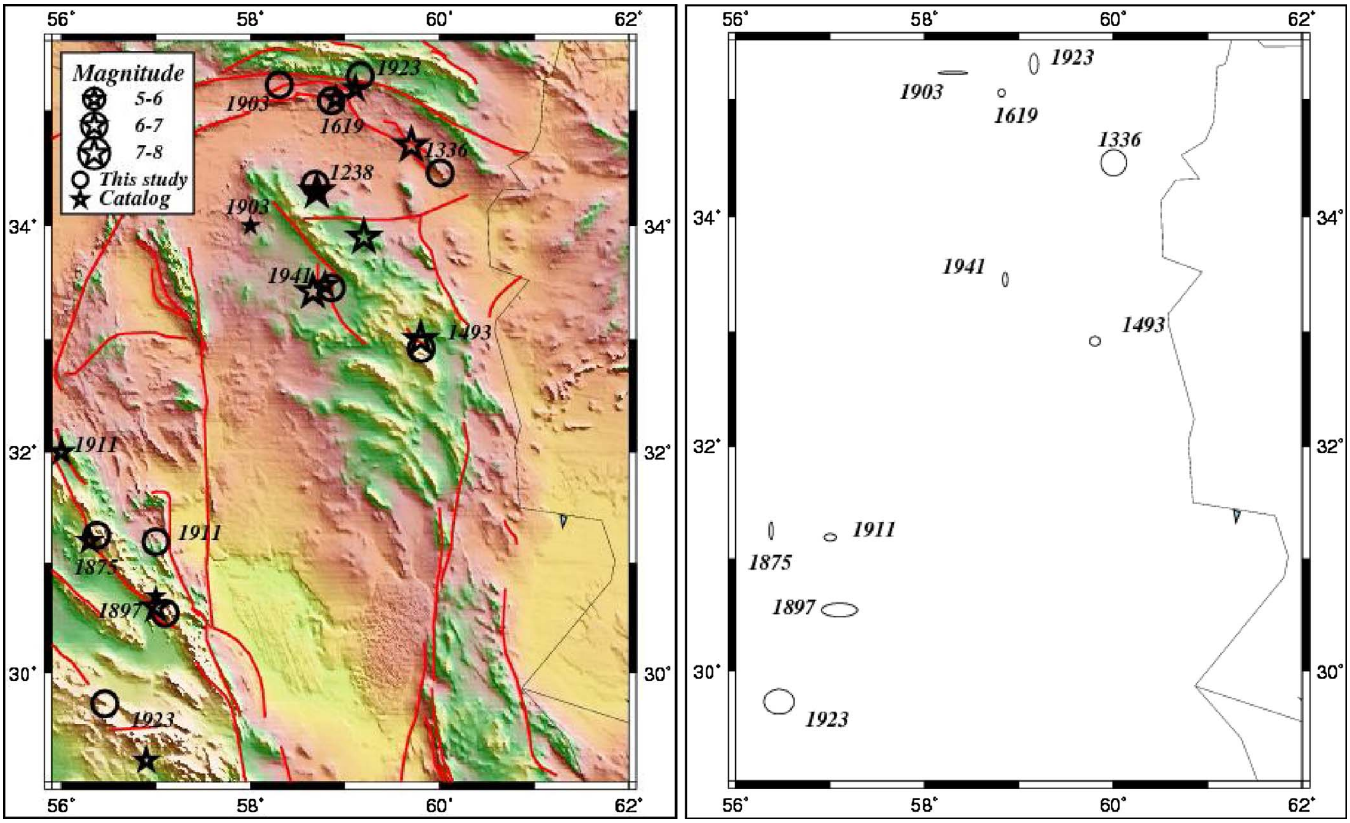

Fig. 12. Left: Macroseismic (estimated in this study) and catalog locations of earthquakes with macroseismic magnitude between 6 and 7. Right: Location uncertainties estimated for these earthquakes.

uncertainties of the parameters were estimated by bootstrap simulations. The first step of Boxer method: the calibration of magnitude regression coefficients was performed using MDPs of 22 instrumental earthquakes. Attenuation relationship was also determined according to Pasolini et al. (2008) (Eq. (1)) and the dataset of Iranian instrumental earthquakes from 1964 to 2012.

Parameters of instrumental earthquakes estimated by Boxer were found to be consistent with instrumental reports from the GCMT catalog (Table 6 and Fig. 8). Then, the parameters of both historical and instrumental earthquakes with macroseismic information in Eastern Iran were estimated using our macroseismic dataset and Boxer method (Table 7 and Figs. 9–13). According to the results of this study, using MDPs and Boxer method, the earthquake macroseismic parameters could be estimated with the average of uncertainties lower than ~0.2 and 0.3 for magnitude and lower than ~10 km and 25 km for location of earthquakes in period of after and before 1970, respectively.

The comparison between these results and other macroseismic estimates published by Ambraseys and Melville (1982) shows that they were consistent to each other. The comparison with instrumental data show maximum location differences of ~140 km for Torshiz (1903) and Ravar (1911) earthquakes, and ~75 km for Laleh Zar (1923) earthquake (Figs. 12 and 13).

These differences are possibly related the low accuracy of instrumental networks in the first decades of the 1900′s. This new dataset including the uncertainties of parameters extends our knowledge on the seismicity of the study area especially for pre-instrumental era and provides insights for the characterization of seismotectonic and the improvement of hazard assessments in the study area. Then, at least for earthquakes occurred before 1964, macroseismic parameters have to be preferred to instrumental ones.

7. Data and resources

International Institute of Earthquake Engineering and Seismology (IIEES); http://www.iiees.ac.ir/fa/eqreports/, Building and Housing Research Centre (BHRC); http://bhrc.ac.ir/, Geological Survey of Iran (GSI); http://www.gsi.ir/General/Lang_fa.html, and National Geoscience Database of Iran (NGDIR); http://www.ngdir.com/Downloads/PDownloadList.asp, Statistical Centre of Iran; http://amar.org.ir/

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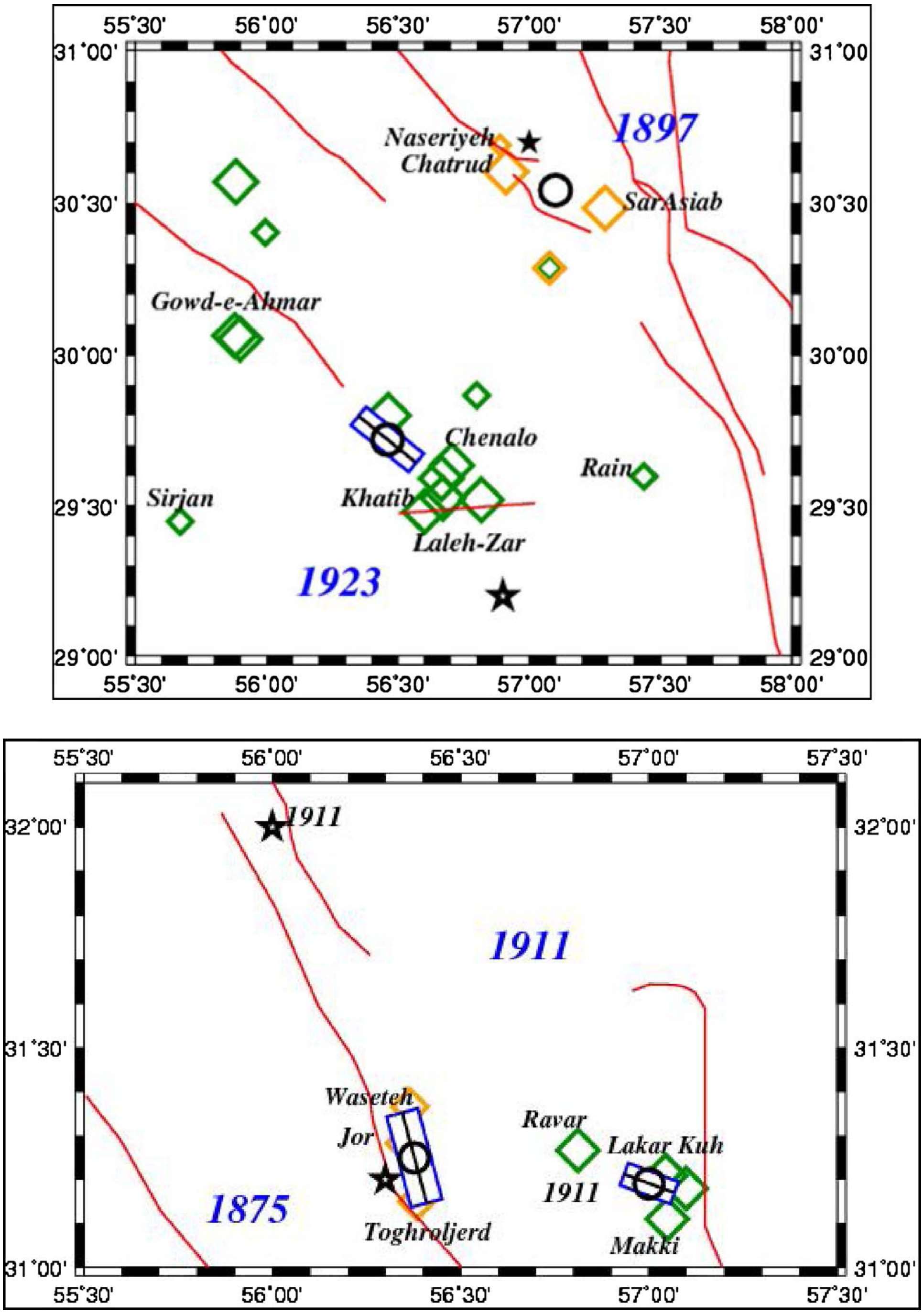

Fig. 13. Catalog reported (stars) and Boxer estimated (circles) parameters of earthquakes with macroseismic magnitude between 6 and 7 in south of selected area; Top) Kerman (1897) and Laleh Zar (1923) earthquakes; and Down) Ravar (1911) and Kuhbanan (1875) (for more explanation see Fig. 12).

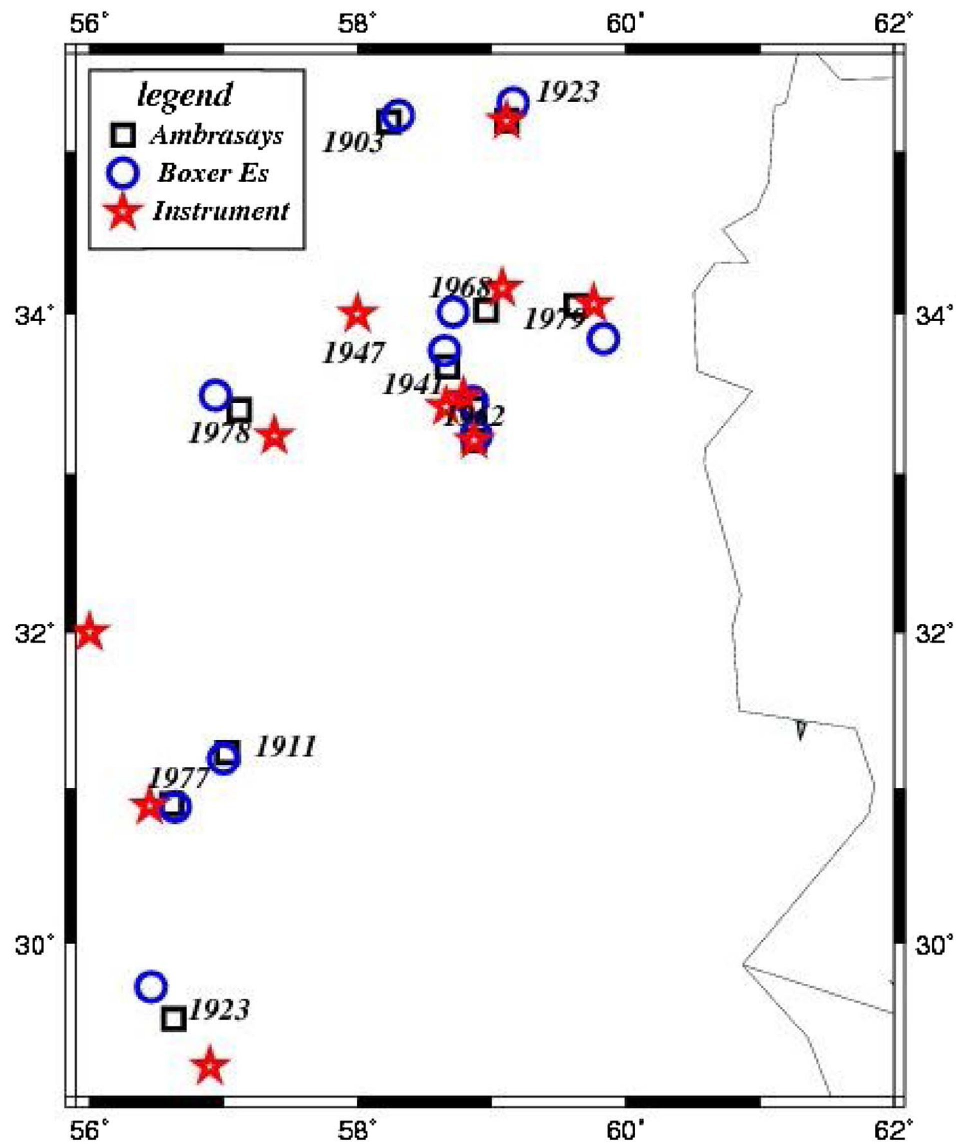

Fig. 14. Comparing the macroseismic locations of earthquakes estimated in this study by Boxer method (circle), those reported by Ambraseys and Melville using macroseismic information (squares), and their instrumental ones (stars).

Appendices A, B, C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jog.2017.07.005.

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