Iranian Earthquakes, a uniform Catalogue with Moment Magnitudes

Sepideh Karimiparidari

Seismology Research Centre, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, email sepideh-karimi@iiees.ac.ir

Mehdi Zaré

Seismology Research Centre, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran, email mzare@iiees.ac.ir (corresponding author)

Hossein Memarian

Exploration Engineering Department, Faculty of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran, email memarian@ut.ac.ir

Andrzej Kijko

Aon Benfield Natural Hazard Centre, University of Pretoria, Pretoria, South Africa,
email andrzej.kijko@up.ac.za

Abstract

A uniform earthquake catalogue is an essential tool in any seismic hazard analysis. In this study a seismic catalogue of Iran and adjacent areas was compiled, using international and national databanks. The following priorities were applied in selecting magnitude and earthquake location: a) local catalogues were given higher priority for establishing the *location* of an earthquake; and b) global catalogues were preferred for determining earthquake *magnitudes*. Earthquakes that have occurred within an area 23–42°N and 42–65°E, with magnitude range M_W 3.5–7.9, from the 3rd millennium BC until April 2010 were included. In an effort to avoid the 'boundary effect', since the newly compiled catalogue will be mainly used for seismic hazard assessment, the study area includes the areas adjacent to Iran. The standardization of the catalogue in terms of magnitude was achieved by the conversion of all types of magnitude into moment magnitude, M_W.

In the newly compiled catalogue all aftershock and foreshocks were disregarded, based on the procedure described by Gardner and Knopoff (1974). The magnitude of completeness for the three main tectonic seismic zones of Iran, i.e. the Zagros Mountain Range, the Alborz Mountain Range, and Central Iran, was established for the entire time span of the catalogue. The most recent period, 2000 to 2010, was studied in more detail. The seismicity parameters were calculated for each of the three main seismogenic zones.

Key words: earthquake catalogue, magnitude of completeness, seismic parameters, Zagros, Alborz, Central Iran

Introduction

A homogeneous earthquake catalogue is an essential tool in any seismic hazard study. The aim of this study was to develop a seismic event catalogue for Iran, which would be as accurate and homogeneous as possible. The catalogue lists all known earthquakes of magnitude 3.5 and above. All available national and international databanks were used to compile the new catalogue. A comprehensive historical catalogue for Iran earthquakes was compiled by Ambraseys and Melville in 1982, and by Berberian in 1994. Unfortunately, these catalogues used a variety of earthquake magnitude scales, which makes it difficult to use them in any reliable seismic hazard assessment. However, the newly compiled catalogue uses homogenized magnitudes, expressed in terms of one standard scale, i.e. moment magnitude, M_W. In addition, all foreshock and aftershocks were disregarded, as well as events with magnitudes smaller than M_W 3.5. The final catalogue comprises the time span from the 3rd millennium BC to 2010, and includes more than 10 000 earthquake events.

An additional goal of this study was to assess the level of magnitude completeness in each of the major tectonic zones of Iran. Analysis indicated that the catalogue could be divided into two distinct periods of completeness, the first running from the 3rd millennium BC to 1960, while the second runs from 1960 till the present.

Tectonic Framework of the Region

The Iranian plateau is a part of the Alpine–Himalayan orogenic belt, which has a high level of seismic activity and a unique pattern of deformation. The Iranian plateau accommodates the 35 mm/yr convergence rate between the Eurasian and Arabian plates by strike-slip and reverse faults, with relatively low slip rates in a zone 1 000 km across (Berberian and Yeats, 1999). Based on the global positioning system (GPS), Vernant *et al*. (2004) indicated the rate of deformation from less than 2 mm/yr in Central Iran to 19.5 ± 2 mm/yr in the Makran subduction zone.

Based on the tectonic setting (Nabavi, 1976), active fault map (Hessami *et al*., 2003), seismicity, and total airborne magnetic intensity map (Geological Survey of Iran, 1998), the country can be divided into three zones, each with distinct properties (Fig. 1). The first zone is the Alborz Mountain Range, which wraps around the South Caspian Sea. The Alborz Range contains three different fault trends. In the western part the faults trend northwest to southeast, the faults located in the middle part trend east–west, and in the eastern part the faults trend southwest–northeast. Focal mechanism solutions derived from earthquakes that occurred in Alborz show that in the western and eastern parts there is a compressional or left-lateral strike-slip fault system, but in the middle zone there is a typical compressional system. The Khazar reverse fault, with a southward dip direction, is the longest active fault in Alborz and is located at the northern edge of the Alborz Mountains (Hessami and Jamali, 2006). This is a zone of high seismicity, and strong earthquakes have been recorded in the area. The strongest earthquake on record is the Damghan earthquake of M_S 7.9, which occurred on 856/12/22 and caused 200 000 fatalities (Ambraseys and Melville, 1982).

The second seismotectonic area is the Zagros continental collision zone, which is one of the youngest and most active tectonic regions on Earth. The Zagros fold belt is the result of the continued convergence between the Arabian and Eurasian plates that has been in progress since the Miocene episode of continental collision (Stocklin, 1968; Falcon, 1974; Colman-Sadd, 1978 in Hessami *et al.*, 2006). The Zagros fold-thrust belt is bounded on the northeast by both the Main Zagros reverse fault and the Main Recent fault. The Main Zagros reverse fault is a suture zone between the Arabian and Eurasian plates (Dewey *et al.*, 1973; Sengor, 1984; Dercourt *et al.*, 1986 in Ghabeishavi *et al.*, 2009). Most focal mechanism solutions of earthquakes in the Zagros region indicate the presence of active reverse faults (Berberian, 1995; Jackson and McKenzie, 1984; Nowroozi, 1972; and Talebian and Jackson, 2004 in Hessami *et al.*, 2006). Recent studies on focal mechanisms and the depth of earthquakes in the Zagros area suggest a depth of about 8–14 km for moderate and large earthquakes (Hessami and Jamali, 2006)

The third tectonic zone of Iran is Eastern and Central Iran, located between Alborz and Zagros, and which contains some notable active faults. The fault systems in this region are different from those in other parts of Iran because of the orientation and geometric characteristics of the faults; for instance, they are linear, long and narrow (Hessami and Jamali, 2006). The longest fault in this area, and the longest in Iran, is the Doruneh fault of about 600 km.

The large scale of this study necessitated that the tectonic setting be simplified, therefore Kope Dagh in the northeast, Makran in the southeast, and Azerbaijan in the northwest of Iran were assumed as part of Central Iran and the seismicity of these areas was therefore not assessed separately (Fig. 1).

Sources and Data

In order to compile a new seismic catalogue for Iran the authors investigated all the accessible national and international seismological databases. There are two main sources of information on historic Iran earthquakes, one compiled by Ambraseys and Melville (1982) and the other by Berberian (1994). Moinfar *et al*. 1994 collected a set of historical and instrumental earthquake data which was checked to confirm the magnitude of some events. Some of the obstacles encountered during research were that the catalogues cover a different time period and that earthquake magnitudes were expressed in different scales.

The instrumental data were compiled from several national and international catalogues provided by the following organizations:

National Agencies

1- IIEES, International Institute of Earthquake Engineering and Seismology: This institute has 25 broadband seismographs and its online database contains recorded earthquakes since 2000 (IIEES website, 2010).

2- IRSC, The Iranian Seismological Centre, University of Tehran: This centre, which operates 74 seismographs is the largest seismic network in Iran, was established in 1957 (IGTU website, 2010) and provides data online from 2006 up to the present.

3- BHRC, Building and Housing Research Centre (Iran Strong Motion Network): At present this centre operates 1 065 digital strong motion and 29 analogue accelerographs, and contains the records of about 6 120 accelerograms (BHRC website, 2010).

Global Agencies

1- ISC, International Seismological Centre UK: This centre collects and recalculates earthquake locations from national and local agencies. The online catalogue of this centre contains instrumentally recorded events back to about 1900 (ISC website, 2010).

2- NEIC, National Earthquake Information Center: The PDE (Preliminary Determinations of Epicenter) catalog from this agency website contains recorded earthquakes from 1973 to the present (USGS website, 2010).

3- EHB, Bob Engdahl: Using a proper reference Earth model, improving usage of the data, and limiting the events of interest to those that are well constrained render this catalogue more reliable for the location of events. Data from this catalogue are available for the period 1960 to 2006 (ISC website, 2010).

4- HRVD, Harvard CMT catalog, Harvard Centroid Moment Tensor Catalog: Online data from 1976 up to the present (Harvard CMT catalog website 2010).

5- MOS, Institution of the Russian Academy of Sciences, Geophysical Centre of RAS: This centre provides information collected by one teleseismic and nine regional seismic networks (GCRAS website, 2010).

Table 1 shows the catalogues used for this study. The authors had to set some priority for both the magnitude and the location of an event in order to choose specific data from the collected information. The first assumption was that earthquake magnitudes available from *global* catalogues are more accurate than those provided by the *local* catalogue for the same earthquake. In addition, an obvious criterion for catalogue selection was the magnitude uncertainty; earthquake magnitudes were selected from catalogues that provide the most reliable magnitudes with the lowest uncertainty.

The location of seismic events was selected according to the following procedure: a) the location provided by a *local* catalogue was assumed more accurate than that from a *global* catalogue, and b) a catalogue with lower location uncertainty had higher priority. Table 2 shows the applied strategy used in the determination of earthquake magnitude and location.

To avoid duplication of the data, the following strategy was applied: 1) first, the replica of the same event was removed for each analyzed catalogue; then 2) any two reports in two different catalogues which are within 16 seconds difference in origin time and 0.5 degree difference in location were considered as the same event.

Where only intensity reports were available for some historical earthquakes, the magnitudes of these were calculated according to a formula by Ambraseys and Melville (1982):

$$M_S = 0.77 \times I_0 - 0.07. \quad (1)$$

There is neither reported magnitude nor information about the intensity of several events; however, taking into account the importance of such historical events, especially for seismic hazard analysis, the authors did not remove them from the catalogue (Fig. 2). On the other hand, several other historical events were disregarded because there was no clear evidence that these events were in fact earthquakes.

Estimating the Moment Magnitude

One of the main goals of this study was to develop a uniform magnitude-type catalogue and moment magnitude, M_W, was chosen as the standard. The moment magnitude has a strong physical foundation and most of the ground-motion prediction equations use M_W magnitude as an input parameter. The authors therefore developed several relationships between moment magnitude and other magnitude types in order to convert them into M_W. Linear relationships were developed for m_b, M_S, M_L and M_N versus M_W magnitude, when respective magnitudes of overlapping events were used as input data.

A total of 486 earthquake events were used to establish a relationship between M_W and the corresponding m_b magnitude (Fig. 3a). The relationship is valid in the range $3.5 \leq m_b \leq 6.7$ and is of the form

$$M_W = 1.0\ (\pm\ 0.05) \times m_b + 0.19\ (\pm\ 0.23) \qquad (2)$$

The square root of the variance of the residuals of equation (2), also known as the root mean squared error (RMSE), is 0.27 and $R^2 = 0.79$.

In order to develop a reliable relationship between magnitude M_S and M_W, the authors applied regression analysis for two magnitude ranges: (a) events with magnitude $M_S < 6.1$, and (b) earthquakes with magnitude $6.1 \leq M_S$.

The established relationship between magnitude M_W and M_S within range $3.0 \leq M_S < 6.1$ is:

$$M_W = 0.59\ (\pm\ 0.03) \times M_S + 2.46\ (\pm\ 0.12) \qquad (3)$$

A total of 405 magnitudes was used in establishing the above relationship (Fig. 3b); the RMSE = 0.18 and $R^2 = 0.80$.

For magnitude range $6.1 \leq M_S \leq 7.4$ the relationship is of the form:

$$M_W = 0.92\ (\pm\ 0.14) \times M_S + 0.51\ (\pm\ 0.9) \qquad (4)$$

The relationship is based on 32 pairs of M_S and M_W magnitudes, the RMSE = 0.15, and $R^2 = 0.86$ (Fig. 3c).

A further relationship (Fig. 3d) was established between magnitude M_W and M_N, by considering 67 events within the magnitude range $3.5 \leq M_N \leq 6.3$:

$$M_W = 0.67\ (\pm 0.09) \times M_N + 1.73\ (\pm 0.43) \qquad (5)$$

The RMSE of the established relationship is 0.20 and $R^2 = 0.79$.

Since reports on earthquakes with magnitudes 5.5 and stronger often include information on other types of magnitudes, such as M_W, M_S or m_b, there was no real need to develop a relationship between M_N or M_L versus M_W. Furthermore, for magnitude range $3.4 \leq M_L \leq 6.3$ the relationship between M_W and M_L was established:

$$M_W = 0.54\ (\pm 0.07) \times M_L + 2.34\ (\pm 0.34). \qquad (6)$$

A total of 225 events was used in the derivation of (6). The RMSE = 0.31 and $R^2 = 0.49$ (Fig. 3e).

Unfortunately, the relationship (6) is not accurate enough and cannot be used as a conversion relation between M_W and M_L. Therefore, the authors developed a relationship between M_N and M_L.

$$M_N = 0.90\ (\pm 0.03) \times M_L + 0.51\ (\pm 0.13) \qquad (7)$$

which is valid within the magnitude range $2.7 \leq M_L \leq 6.1$. A total of 856 observations was used in this derivation. The relationship is reliable; the RMSE = 0.23 and $R^2 = 0.78$ (Fig 4a).

Therefore, in order to convert M_L to M_W when only the M_L magnitude is known, a two-step procedure is applied: first M_L is converted into M_N and then M_N is converted into M_W with the help of equation (5).

Since there is a saturation of the m_b scale for $6.0 < m_b$ the authors have developed a relationship (Fig. 4b) between M_S and m_b:

$$M_S = 1.17\ (\pm 0.03) \times m_b - 1.23\ (\pm 0.13) \qquad (8)$$

For this derivation 2 946 pairs of observations were used in magnitude range $3.1 \leq m_b \leq 7.6$ (Fig. 4b); the RMSE = 0.43, and $R^2 = 0.69$. Again, in order to convert $6.0 < m_b$ into M_W, a two-step conversion was applied: first m_b was converted into M_S, and then with the help of equations (3) or (4) M_S was converted into M_W.

After converting all magnitudes into M_W, all earthquakes with M_W <3.5 were removed from the newly compiled catalogue. In order to create a uniform catalogue in terms of M_W magnitude, the following procedure was applied:

1- If M_W is available: use M_W

2- If M_W is not available and $6.1 \leq M_S \leq 7.4$: use equation (4)

3- If M_W is not available and $3.5 \leq m_b \leq 6.0$: use equation (2)

4- If M_W and m_b are not available and $3.0 \leq M_S < 6.1$: use equation (3)

5- If M_W and M_S are not available and $6.0 < m_b$: first use equation (8), then use provision 2 or 4

6- If M_W , M_S and m_b are not available and $3.5 \leq M_N \leq 6.3$: use equation (5)

7- If M_L is the only available magnitude: first use equation (7), then use provision 6

Figure 5 shows the seismicity of Iran and vicinity over the time span from the 3rd millennium BC to 2010. Studying this map shows that although most of the largest events took place in the Alborz area and Central Iran, the seismicity of the Zagros area is higher than that of the other two areas.

Elimination of For- and Aftershocks

The well-known procedure by Gardner and Knopoff (1974) was applied for the exclusion of for- and aftershocks. The procedure was applied to the three main tectonic zones, i.e. the Alborz Mountain Range, Central Iran and the Zagros Mountain Range. The total number of events in the Alborz Mountain Range zone is 509, including 210 dependent events. The catalogue for Central Iran lists 1 977 earthquakes, with the number of dependent events in this area being 775. The Zagros Mountain Range has a high level of seismic activity and the total number of events listed in this part of the catalogue is 4 536, including 2 178 foreshocks and aftershocks. Finally, the total number of independent earthquakes that are listed in the catalogue for Alborz, Central Iran and Zagros is 299, 1 202 and 2 358 respectively.

Determination of Level of Completeness

In order to establish the level of completeness of the newly compiled catalogue, the authors plotted a number of graphs. The first set of graphs (Fig. 6) shows a cumulative number of events plotted for different magnitude thresholds. The analysis of the plots indicates that the completeness of all three zones starts approximately from magnitude 4.0, although the frequencies of events with magnitude 4.0 are different. The next set of diagrams illustrates yearly number of events as a function of time and magnitude (Fig. 7). The authors found a clear change at the year 1960, where the annual number of events with magnitude less than 5.0 appears with a gradually increasing trend. The trend that took place after 1960 is mainly attributable to the setting up of the World-Wide Standard Seismograph Network (WWSSN) in the early 1960s. The International Seismological Centre (ISC) was formed in 1964 to continue the work of the International Seismological Summer (ISS), which initiated the establishment of the first worldwide database of seismological observations (ISC website, 2010).

The IIEES broadband network was started in 1994 and has reported the online data since 2000. Therefore, for the period 2000 to 2010 more precise analyses for the new catalogue were done. Figure 8 illustrates magnitude versus cumulative number of earthquakes for the period 2000–2010 for the three tectonic zones of Iran. Here the authors could not detect any changes in magnitude completeness compared with Figure 6, which shows the entire compiled catalogue for the area. Cumulative numbers of events above different magnitude thresholds for the three tectonic zones are shown in Figure 9.

Therefore, the authors concluded that starting from 1960 the newly compiled catalogue is complete for all three tectonic zones, starting from magnitude M_W 4.0. Adding data (seismic events with magnitudes less than 4.0), recorded by recently established local seismic networks, would not improve the completeness of the catalogue.

Seismicity Parameters

The area-characteristic seismicity parameters, the maximum magnitude, M_{max}, the b-value of Gutenberg-Richter and the mean seismic activity rate λ were calculated for each of the three seismogenic zones. The M_{max}, b and λ parameters were calculated by Matlab code, which takes into account the latest extension of the procedure developed by Kijko and Sellevoll (1989; 1992). The applied procedure takes into account incompleteness of the seismic event catalogue, the uncertainty of earthquake magnitudes and the approximate nature of distributions describing the seismicity of the area (Kijko, 2010). The estimated M_{max}, b-value and lambda for the three seismotectonic zones are as follows:

Alborz Mountain Range: $b = 1.00 \pm 0.03$; λ (M_W=4.0) = 4.02 ± 0.39; M_{max} = 8.2 ± 0.5 ($M_{max\ obs}$. = 7.8)

Central Iran: $b = 0.97 \pm 0.02$, λ (M_W=4.0) = 7.00 ± 0.36; M_{max} = 7.7 ± 0.2 ($M_{max\ obs}$. = 7.6)

Zagros Mountain Range: $b = 0.92 \pm 0.02$, λ (M_W=4.0) = 14.57 ± 0.67; M_{max} = 7.4 ± 0.2 ($M_{max\ obs}$. = 7.3)

The assessment of M_{max} for the Alborz Mountain Range is not without controversy. There are at least three questions regarding estimated $M_{max.}$ The first is that this magnitude was calculated based on the maximum observed magnitude, which is the historic event that occurred on 856/12/22 in the Damghan area; however, with a high level of magnitude uncertainty. Ambraseys and Melville (1982) report the magnitude M_S 7.9 for this event, which was accepted for this study; however, Berberian (1983, 1994) believes the magnitude of this historical event is much lower at M_S 7.4. The second point relates to the recurrence time. Magnitude 8.2 has 26 200 years of return period, which doe not fall within the Holocene era and would, therefore, not be important for hazard studies. The last point is about the tectonics. Geologists believe that there is no possibility that the faults in the Alborz region are capable of producing an earthquake of $M \geq 8$ (Berberian and Yeats, 1990). Therefore, the authors of this study conclude that magnitude 8.2 is not realistic. The assumption that the Damgan earthquake had a magnitude of M_S 7.4 (Berberian, 1983, 1994) leads to M_{max} 7.9 ± 0.6.

Discussion and Conclusions

The newly compiled seismic events catalogue developed for Iran and vicinity contains more than 10 000 earthquakes, dating from the 3rd millennium BC to April 2010. The catalogue covers the area with the following coordinates 23–42°N and 42–65°E. All available international and national sources of information were used in this compilation.

In order to standardize the newly compiled catalogue in terms of magnitude, several relationships between different types of magnitude were developed. The relationships make it possible to convert magnitude m_b into M_W, m_b into M_S, M_S into M_W, M_N into M_W and M_N into M_L. The conversion relationships are in good agreement with the results of a similar investigation done by Scordilis (2006). Comparing the results of the present study with those of Scordilis (2006), the M_S–M_W relationships for both magnitude ranges are similar (Fig 10a), while for the m_b–M_W relationships the curves are significantly different (Fig 10b). Hence, based on this study, for magnitude $m_b < 5.0$ the conversions result in underestimation of M_W.

To achieve a unified catalogue, a procedure was defined in seven steps to convert all magnitude types into M_W. The steps are based on the availability of reported magnitudes for each event. For historical data, when information on earthquake magnitude was not available, the magnitude was calculated from the relation between *MM* intensity and M_S, as derived by Ambraseys and Melville (1982). Despite the fact that some estimated magnitudes are in doubt, they could not be disregarded as that would lead to the underestimation of the seismic hazard. Some historical events were disregarded because of lack of sufficient evidence that these events were in fact earthquakes. As the procedures and priorities of utilization of data from national and international databases are established, updating this catalogue should be a straightforward task.

In addition, the seismic parameters, M_{max}, the *b*-value and λ were calculated for each of the three seismic zones. The M_{max} for Alborz, Central Iran and Zagros is 7.9 ± 0.6, 7.7 ± 0.2 and 7.4 ± 0.2 respectively. The *b*-value for different seismic zones is ranged between 0.92 and 1.00. The lambda for M_W 4.0 is 4.02 ± 0.39, 7.00 ± 0.36 and 14.57 ± 0.67 for Alborz, Central Iran and Zagros respectively. The mean seismic activity rate shows the high level of seismicity in Zagros.

The catalogue is complete for all three tectonic zones after 1960 at magnitude M_W 4.0 and above. Inclusion of recent data (events with magnitudes less than 4.0) recorded by the national seismic networks does not affect the completeness of the catalogue. This newly developed catalogue should be useful for large-scale seismic hazard studies.

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TABLES:

Table 1. Catalogues used for different time periods

Before 1900	1900	1960	1973	2000	2006	After 2006
Amb	ISC	ISC	ISC	ISC		ISC
Ber	Amb	Amb	EHB	EHB		BHRC
	Ber	EHB	BHRC	BHRC		USGS
		MOS	USGS	USGS		HRVD
			HRVD	HRVD		IIEES
			MOS	IIEES		IRSC
				MOS		MOS

Table 2. Priority to choose magnitude and location from international and national databanks

Priority	
Magnitude	**Location**
ISC	EHB
NEIC	IIEES
HRVD	IRSC
MOS	BHRC
IIEES	ISC
IRSC	NEIC
BHRC	HRVD
---	MOS

Figures

Figure 1. Simplified tectonic map of Iran. This map is developed based on the tectonic setting (Nabavi, 1976), active fault map (Hessami *et al.*, 2003), seismicity and the airborne magnetic intensity map (Geological Survey of Iran, 1998). In this map the country is divided into three seismotectonic zones, i.e. the Alborz Mountain Range, Central Iran and the Zagros Mountain Range

Figure 2. Historical events, without magnitude and intensity. The years in which events happened are shown.

Figure 3. Regression relation between a) M_W data vs. m_b data for $3.5 \leq m_b \leq 6.7$ b) M_W data vs. M_S data for $3.0 \leq M_S < 6.1$c) M_W data vs. M_S data for $6.1 \leq M_S \leq 7.4$ d) M_W data vs. M_N data for $3.5 \leq M_N \leq 6.3$ e) M_W data vs. M_L data for $3.4 \leq M_L \leq 6.3$ for Iran earthquakes from 3rd Mill. to 2010 (the dashed lines denote the 95% confidence bounds)

Figure 4. Regression relation between a) M_N data vs. M_L data for $2.7 \leq M_L \leq 6.1$ b) M_S data vs. m_b data for $3.1 \leq m_b \leq 7.6$ for Iran earthquakes from 3rd Mill. to 2010 (the dashed lines denote the 95% confidence bounds)

Figure 5. Map showing catalogued earthquakes for the period 3rd Mill. to 2010. Symbol size and colour is proportional to earthquake magnitude

Figure 6. Frequency of the earthquakes in the three main tectonic zones (period of time 3rd Mill. to 2010)

Figure 7. Cumulative number of earthquakes above different magnitude values in the three main tectonic zones (period of time 3rd Mill. to 2010)

Figure 8. Frequency of earthquakes in the three main tectonic zones (period of time 2000–2010)

Figure 9. Cumulative number of earthquakes above different magnitude values in the three main tectonic zones (period of time 2000–2010)

Figure 10. Comparison of the result of this study a) M_W vs. M_S and b) M_W vs. m_b with that obtained by Scordilis (2006)

Figures:

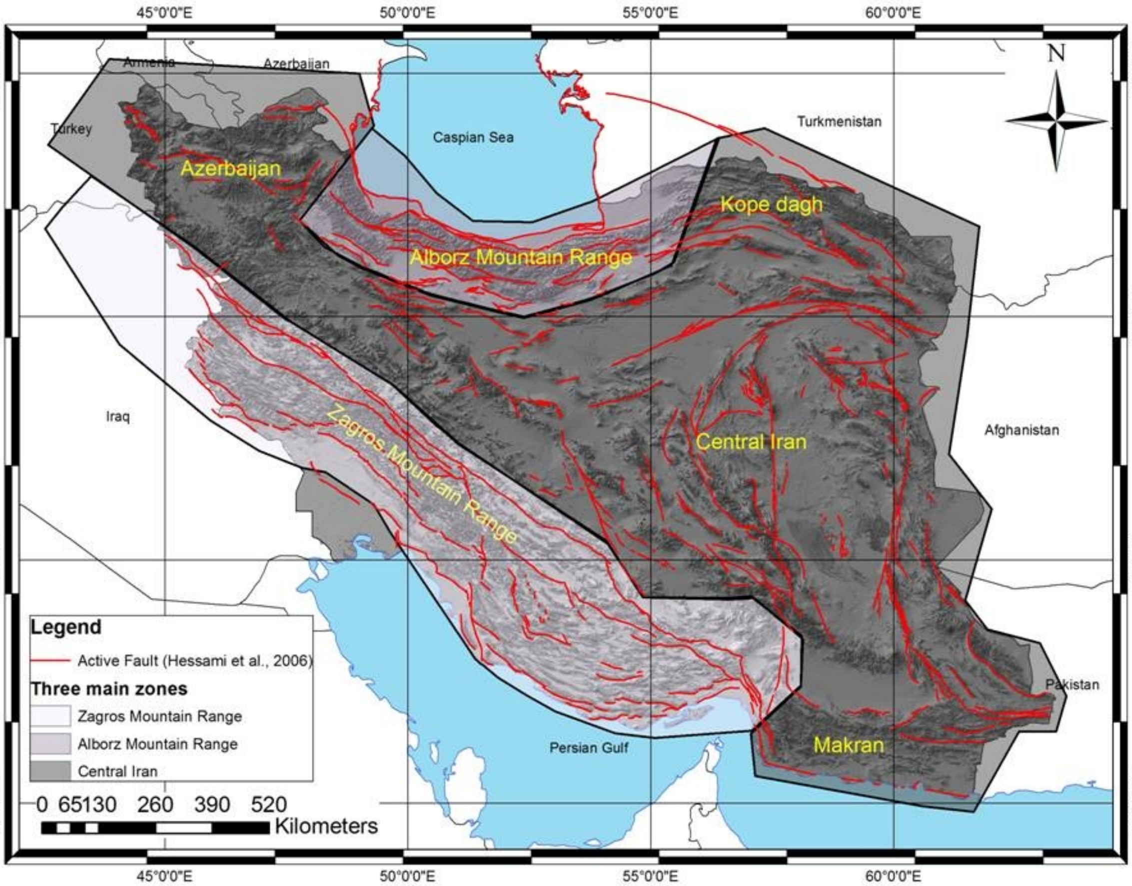


Figure 1.

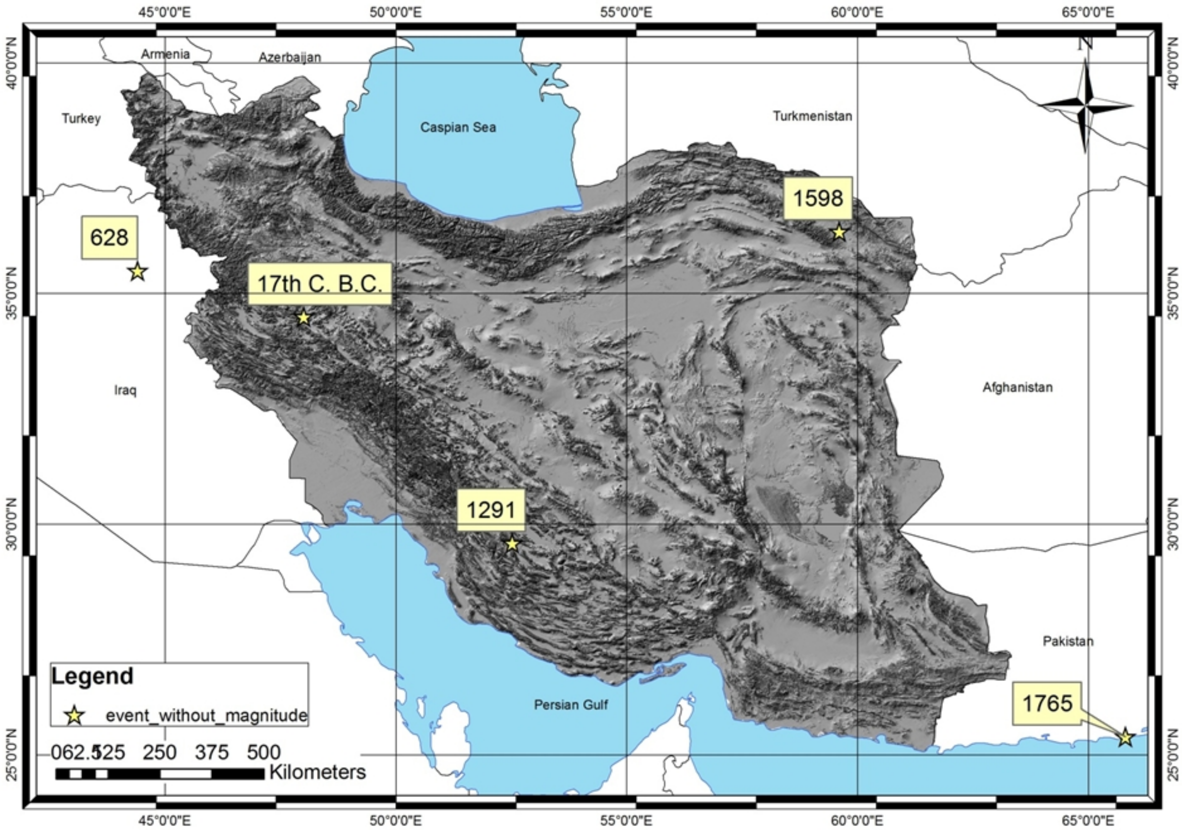

45°0'0"E
50°0'0"E
55°0'0"E
60°0'0"E
65°0'0"E
40°0'0"N
35°0'0"N
30°0'0"N
25°0'0"N
N
Armenia
Azerbaijan
Turkey
Caspian Sea
Turkmenistan
1598
628
17th C. B.C.
Iraq
Afghanistan
1291
Pakistan
Persian Gulf
1765
Legend
event_without_magnitude
062.5125 250 375 500
Kilometers

Figure 2.

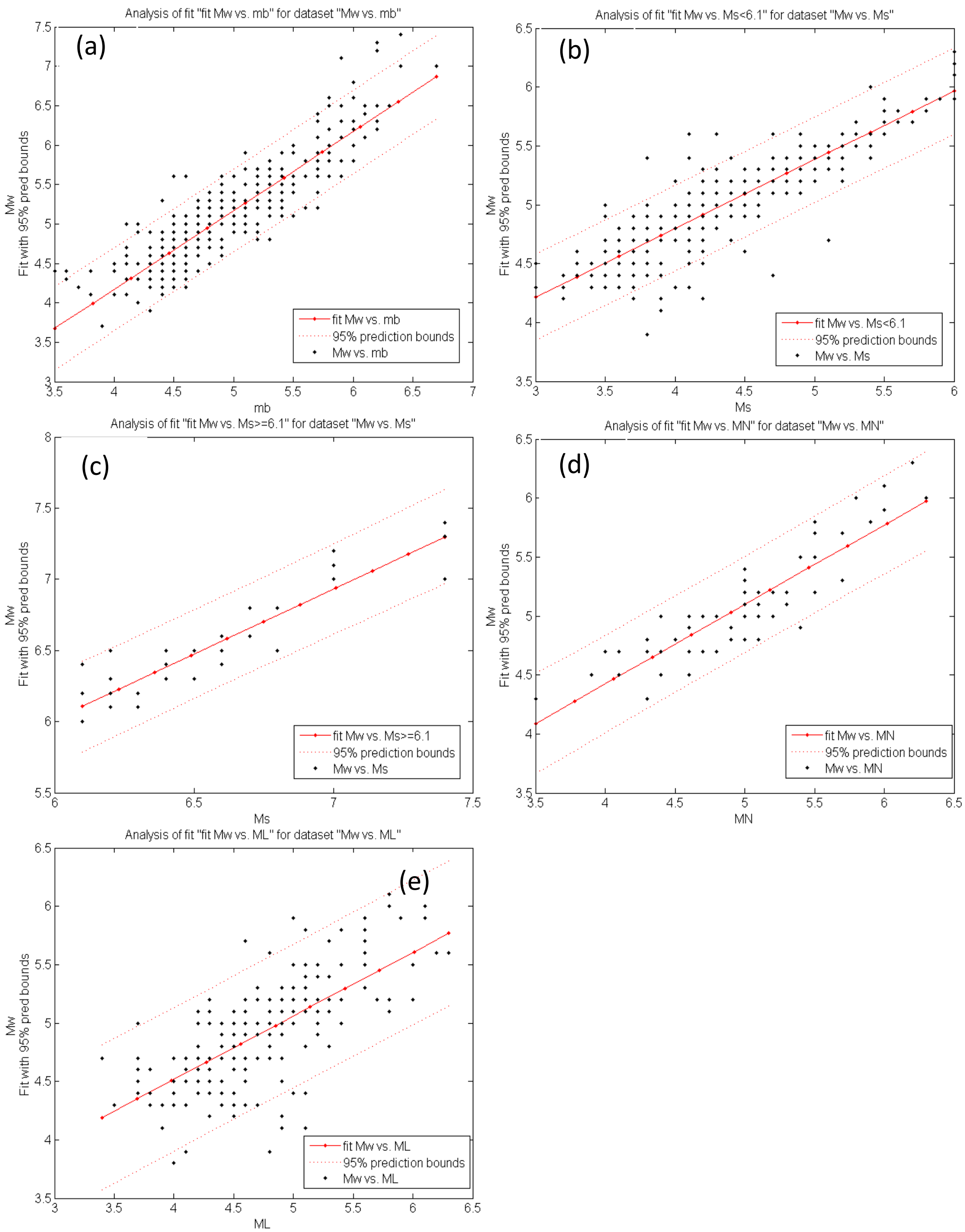

Analysis of fit "fit Mw vs. mb" for dataset "Mw vs. mb"
(a)
Mw
Fit with 95% pred bounds
mb
fit Mw vs. mb
95% prediction bounds
Mw vs. mb
Analysis of fit "fit Mw vs. Ms<6.1" for dataset "Mw vs. Ms"
(b)
Ms
fit Mw vs. Ms<6.1
95% prediction bounds
Mw vs. Ms
Analysis of fit "fit Mw vs. Ms>=6.1" for dataset "Mw vs. Ms"
(c)
fit Mw vs. Ms>=6.1
Analysis of fit "fit Mw vs. MN" for dataset "Mw vs. MN"
(d)
MN
fit Mw vs. MN
Mw vs. MN
Analysis of fit "fit Mw vs. ML" for dataset "Mw vs. ML"
(e)
ML
fit Mw vs. ML
Mw vs. ML

Figure 3.

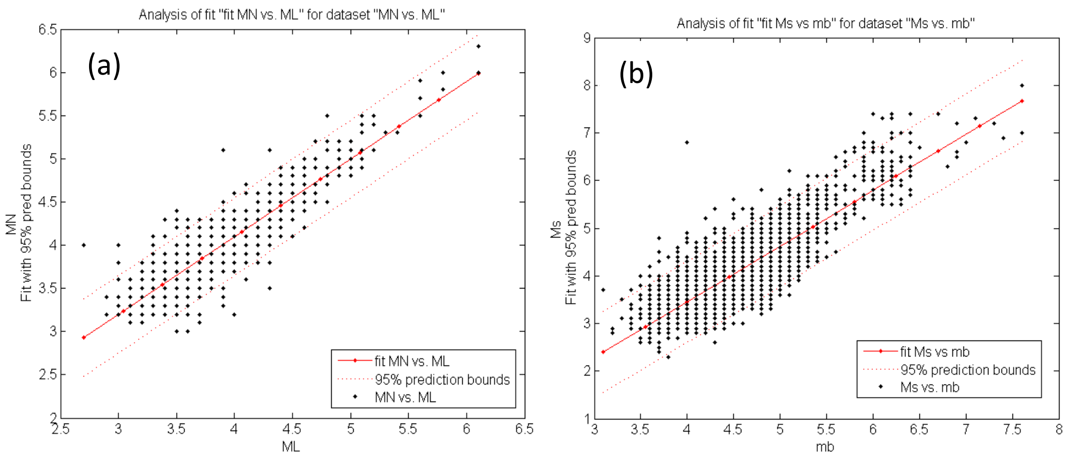


Figure 4.

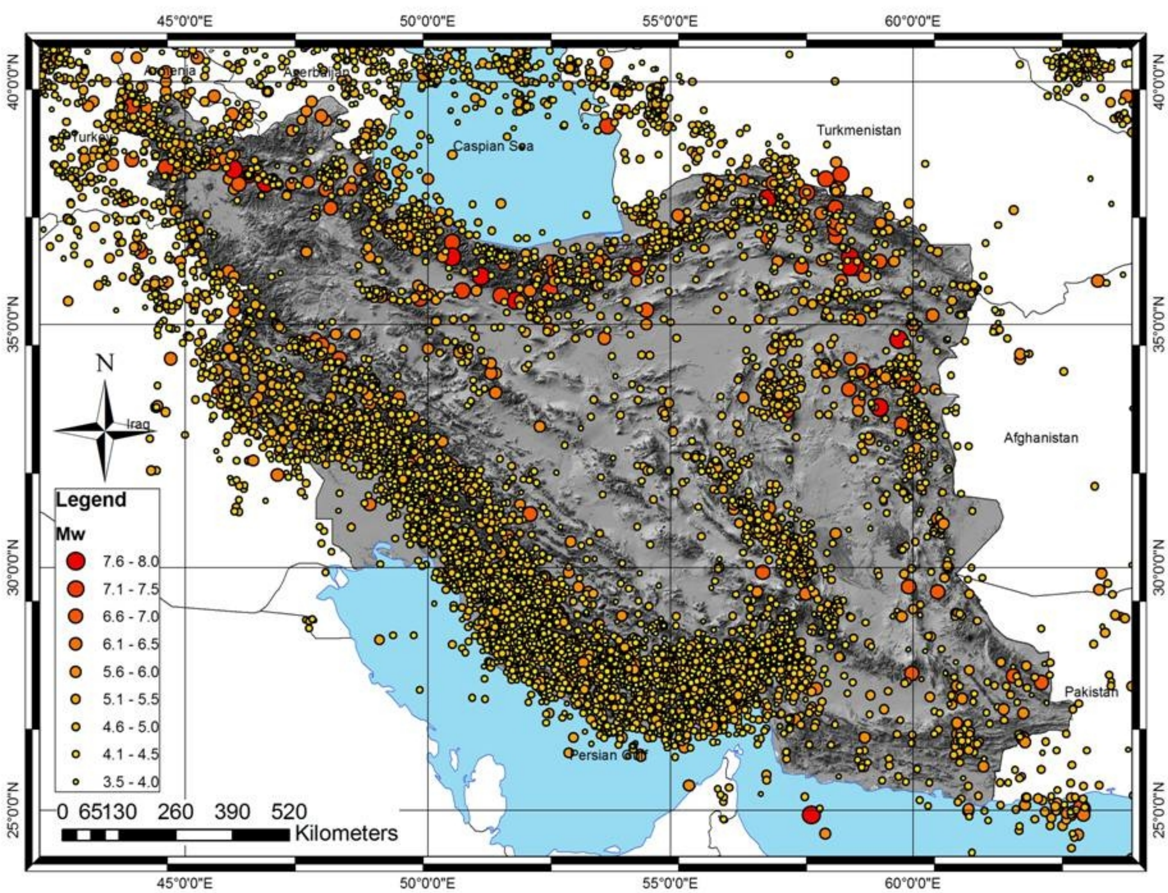


Figure 5.

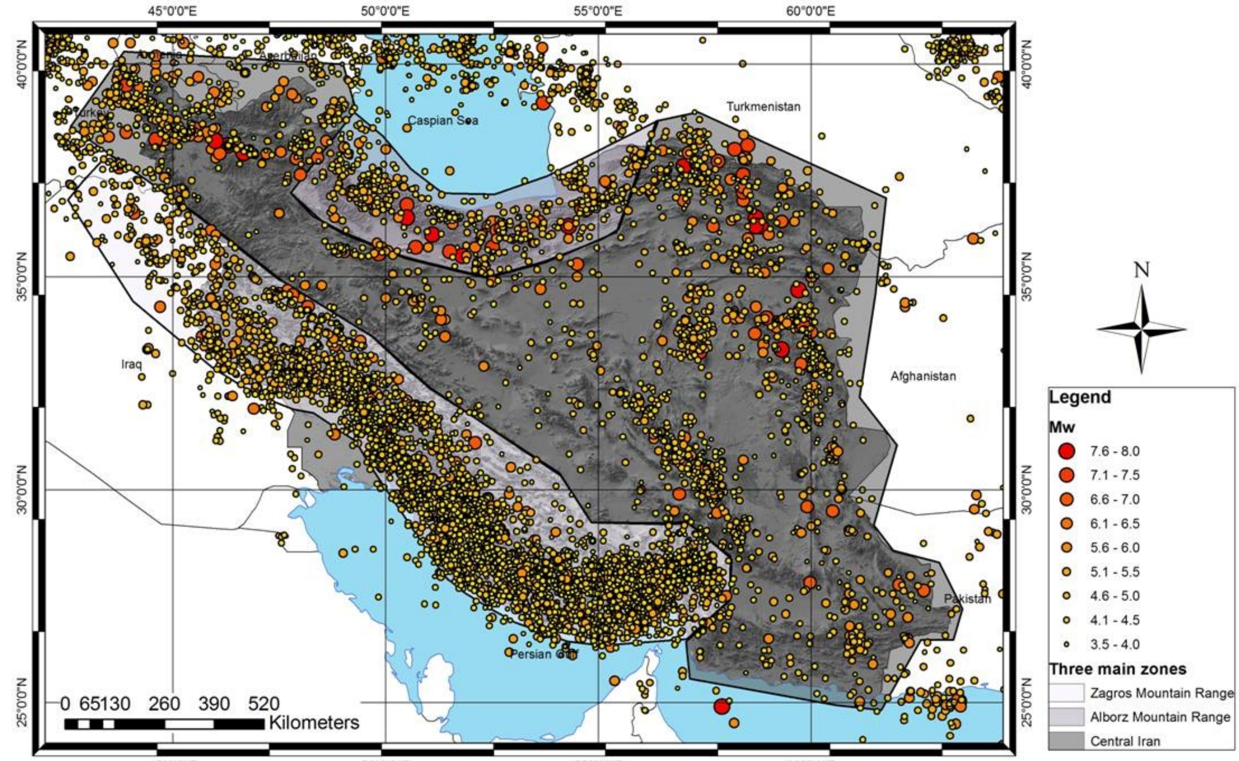
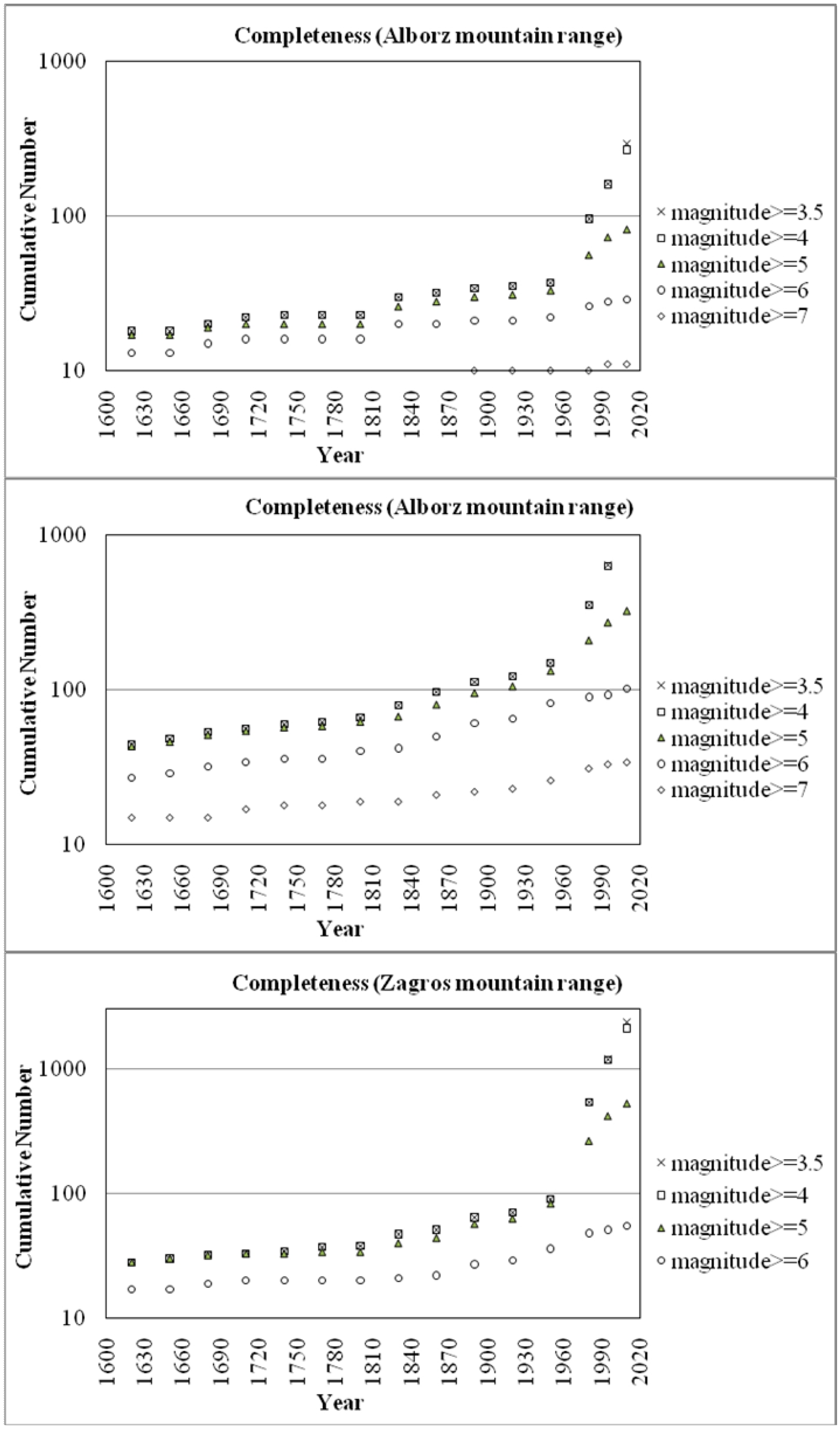

45°0'0"E
50°0'0"E
55°0'0"E
60°0'0"E
40°0'0"N
35°0'0"N
30°0'0"N
25°0'0"N
Caspian Sea
Turkmenistan
Iraq
Afghanistan
Pakistan
Persian Gulf
N
0 65130 260 390 520
Kilometers
Legend
Mw
7.6 - 8.0
7.1 - 7.5
6.6 - 7.0
6.1 - 6.5
5.6 - 6.0
5.1 - 5.5
4.6 - 5.0
4.1 - 4.5
3.5 - 4.0
Three main zones
Zagros Mountain Range
Alborz Mountain Range
Central Iran

Figure 6.


Completeness (Alborz mountain range)
Cumulative Number
Year
1000
100
10
1600
1630
1660
1690
1720
1750
1780
1810
1840
1870
1900
1930
1960
1990
2020
× magnitude>=3.5
□ magnitude>=4
▲ magnitude>=5
○ magnitude>=6
◇ magnitude>=7
Completeness (Alborz mountain range)
Cumulative Number
Year
× magnitude>=3.5
□ magnitude>=4
▲ magnitude>=5
○ magnitude>=6
◇ magnitude>=7
Completeness (Zagros mountain range)
Cumulative Number
Year
× magnitude>=3.5
□ magnitude>=4
▲ magnitude>=5
○ magnitude>=6

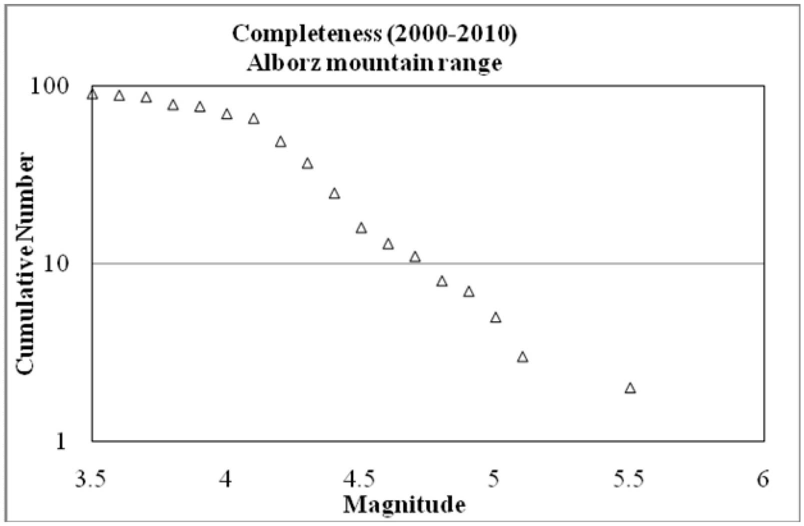


Figure 7.

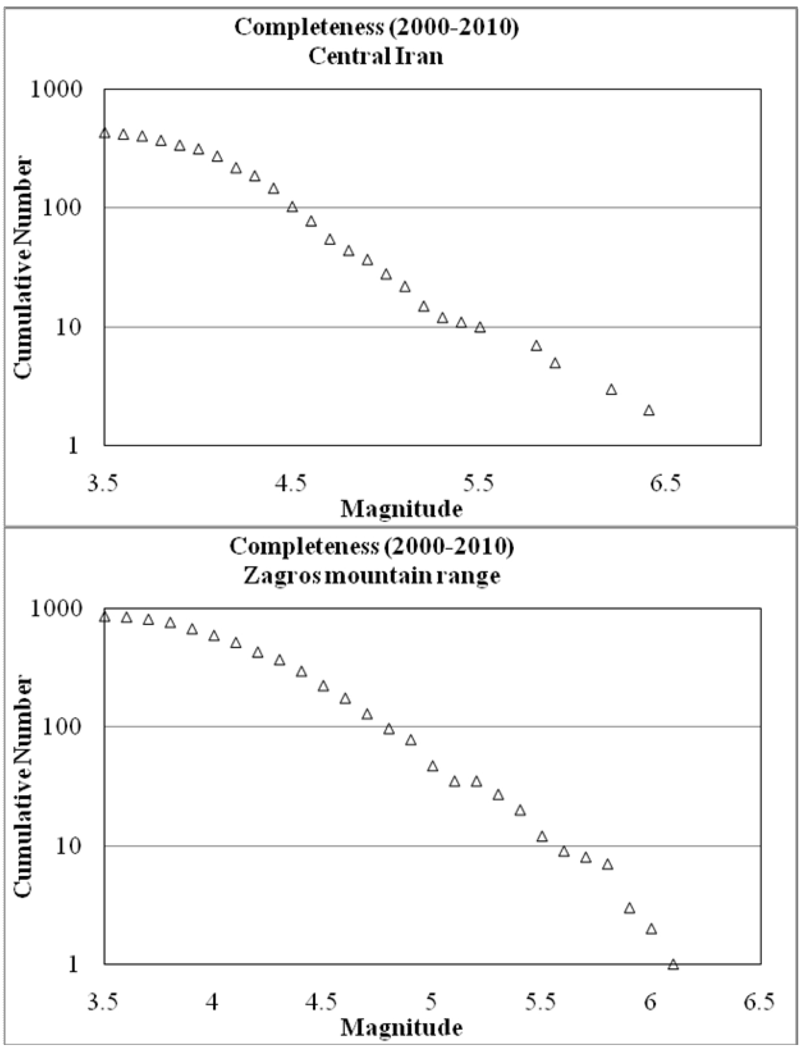
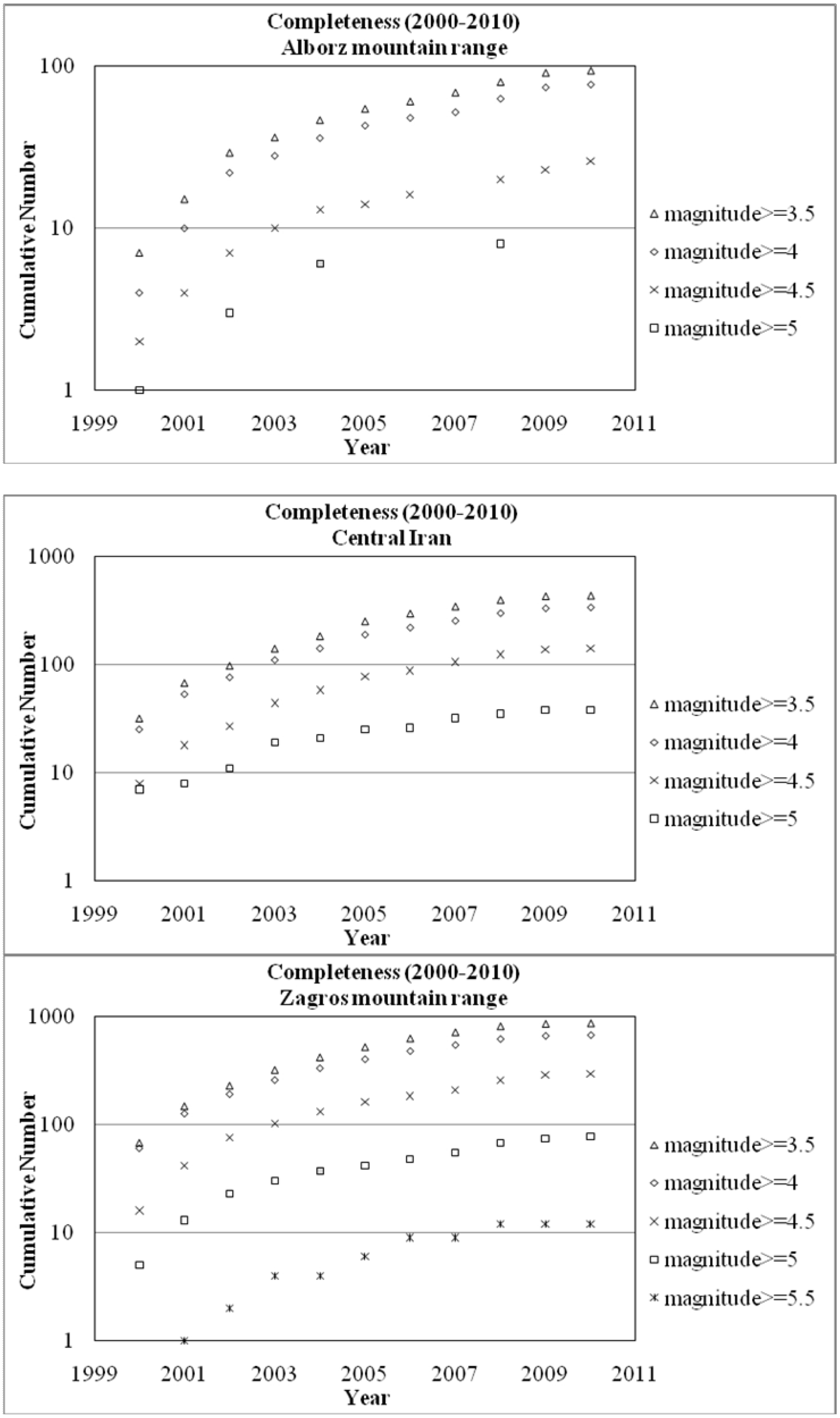
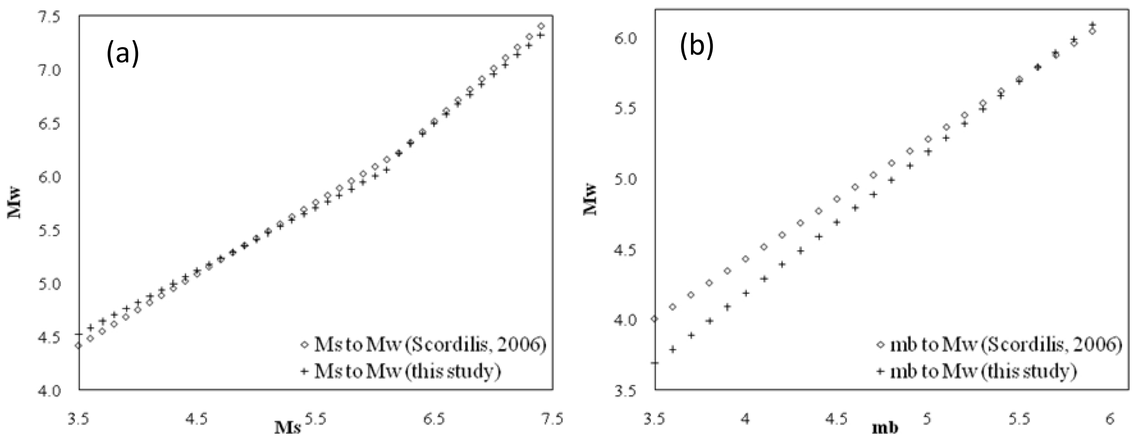


Figure 8.



Completeness (2000-2010)
Alborz mountain range
Cumulative Number
Year
magnitude>=3.5
magnitude>=4
magnitude>=4.5
magnitude>=5
Completeness (2000-2010)
Central Iran
Cumulative Number
Year
magnitude>=3.5
magnitude>=4
magnitude>=4.5
magnitude>=5
Completeness (2000-2010)
Zagros mountain range
Cumulative Number
Year
magnitude>=3.5
magnitude>=4
magnitude>=4.5
magnitude>=5
magnitude>=5.5

Figure 9.



(a)
Mw
Ms
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
4.5
5.5
6.5
7.5
◇ Ms to Mw (Scordilis, 2006)
+ Ms to Mw (this study)
(b)
Mw
mb
6.0
5.5
5.0
4.5
4.0
3.5
3.5
4
4.5
5
5.5
6
◇ mb to Mw (Scordilis, 2006)
+ mb to Mw (this study)

Figure 10.