Analysis of 2005-2015 Earthquake Sequence in Northern Iran Using Visibility Graph Approach

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Abstract

The seismicity of northern Iran between 2005 and 2015 is investigated by means of visibility graph (VG) method. In this study the northern Iran is divided into three tectonic seismic regions: Azerbaijan, Alborz, and Kopeh Dagh. Using declustered catalog, we studied the VG properties of the magnitude time series. The results show a relationship between the $k-M$ slope and the $b-value$ of the Gutenberg-Richter law. Topological properties (i.e. $< T_c >$, $k-M$ slope) of network and dynamic properties of magnitude time series (i.e. $b-value$) significantly decrease before large earthquakes. Combining the results of this study with two similar previous studies improves the linear correlation coefficient factor between $k-M$ and $b-value$ and empower the idea of universal relationship between $b-value$ and $k-M$ slope. The behavior of the VG's properties are similar to previous studies and could be considered as an alternative method for analyzing earthquake sequences.

Key words: Visibility Graph, Earthquake sequence, Magnitude, North Iran, b-value

1. Introduction

Lacasa et al. (2008) introduced a simple and fast computational method; known as visibility algorithm, to convert time series into graphs. Basically the visibility graph presents the connection between nodes in the network. For any time series, two characteristics are attributed to each event: occurrence time and value of the event. Two events are in connection or visible to each other, if no other event interrupts their linear

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connection. In mathematical form, event i and event j are visible to each other if the following equation fulfills:

$$\frac{y_i - y_k}{t_k - t_i} > \frac{y_i - y_j}{t_j - t_i}, \tag{1}$$

where, y is the value and t is the time of the event. k is the index of any event occurring between event i and event j. The visibility graph generated from the time series holds the following conditions, 1) each event is visible to the first event at its right and left side (if there is any) (Connectivity), 2) The algorithm is developed without defining a direction for the links (Undirected), and 3) Rescaling or translation of a time series is not changing the resulted visibility graph (Invariant under affine transformations of the series data)(Lacasa et al., 2008). This concept has applications ranging in various fields including geophysical studies.

The analysis of seismic sequence through visibility graph for various tectonic seismic regions, revealed an alternative approach to study the magnitude time series. Telesca and Lovallo (2012) studied the seismic sequence of Italy between year 2005 and 2010 through using the visibility graph method. Applying different threshold magnitudes and observing the collapsing effect of all the distribution degrees, they argued that in analyzing the magnitude time series, VG seems to depend only on the values of the magnitude and to be independent of the threshold magnitude. In another research, Telesca et al. (2013) studied the seismicity of the Mexican subduction zone through visibility graph approach. They extracted characteristics of the visibility graph for five different tectonic seismic regions. According to their study, visibility graph could distinguish the region with different seismicity characteristics, resulting from its different tectonic processes that governs the area. The relationship between Gutenberg-Richter parameters and $k - M$ slope (The slope of regression line fitting the Magnitude of each event (M) and its connectivity degree (k)) was investigated in their study. In a similar article, Telesca et al. (2014), studied the seismicity of 2002-2011 Pannonian seismicity using the visibility graph. They classified seismic catalog into shallow and deep earthquakes and extracted the visibility graph characteristics for each class. According to their study there is a close relationship between Gutenberg-Richter $b-value$ and $k-M$ slope of the visibility graph. High linear correlation coefficient value (close to 1) of $b-value$ and $k-M$ slope suggests the universal character of the relationship between these parameters (Telesca et al., 2014). Telesca et al. (2016) , defined the $< T_C >$, as the parameter window mean interval connectivity time , as an indication of the mean linkage time between earthquakes, to study the 2003-2012 earthquake sequence in the Kachchh region of western India. They found that the $< T_C >$ changes through time, indicating that the topological properties of the earthquake network are not stationary; also $< T_C >$ significantly decrees before the largest shock of the catalog. Analyzing Gutenberg-Richter values of magnitude time series of an earthquake sequence revealed more opportunities to study the magnitude time series using the features of networks.

In this study we use visibility graph analysis to investigate the earthquake sequence of northern Iran. We divided northern Iran into three tectonic seismic regions including Azerbaijan, Alborz, and Kopeh Dagh. Recently, northern Iran has been studied in detail from different seismological points of view. Nemati (2015) studied the most recent 200 years of seismicity in northern Iran. The frequency of shocks vary widely from one main shock per 6 years (0.17 event/ year) for the Azerbaijan region to 13 earthquakes per 4 years for the Kopeh-Dagh (3.25 event/year) region (Nemati, 2015) .

Northern Iran has an elaborate seismic history. Having considerable number of earthquakes and also being in different tectonic seismic region, northern Iran is a good platform to analyze the visibility graph method's capabilities for studying the magnitude time series. In this study we present the relationship between $k-M$ slope and the $b-value$ in three different tectonic seismic regions. We also investigate the variation of $< T_C >$ value through time.

2. Tectonic seismic regions and seismicity parameters

Iran is situated over Himalayan-Alpide seismic belt, which has frequently experienced strong shaking induced by earthquakes. Based on seismicity parameters, different tectonic seismic devisions have been defined for Iran. Some studies defined more detailed division (Nowroozi, 1976; Tavakoli and Ghafory-Ashtiany, 1999), and some of them defined one simplified province (Stocklin, 1968; Takin, 1972; Berberian and Arshadi, 1976). Mirzaei et al. (1998) divided Iran into five tectonic regions, including Azerbaijan-Alborz, Kopeh-Dagh, Zagros, Central-East Iran, and Makran. Considering Mirzaei et al. (1998) devision as a reference, Karimiparidari et al. (2013) divided the Azerbaijan-Alborz tectonic seismic region into two regions, which are Azerbaijan and Alborz Mountain Range (hereinafter, Alborz). Azerbaijan, Alborz and Kopeh-Dagh tectonic seismic regions encompass most of the northern Iran. Fig. 1 shows the study area and tectonic seismic regions.

Alborz tectonic seismic region has active reverse faults, which are parallel to the northwest-trending structural gain of the Alborz Mountains belt. The North Tehran Thrust (NTT) adds more complexity due to the presence of south-dipping reverse faults, which are in part blind, such as the Davudieh, Shian, and Bagh-E Feyz. The northwest continuation of the Alborz Mountains, known as the Rocks of the Talesh Mountains, have been thrust northeastward and eastward over rocks of the south Caspian depression (Berberian and Yeats, 1999).

The Tabriz region (located in Azerbaijan tectonic seismic region) is in the Araxes structural block of northwestern Iran, southwest of the continuation of the western Alborz Mountains towards the Caucasus. The North Tabriz Fault (NTF) is a complex northwest-trending structure, which contains evidence observed on aerial photographs, and vertical displacement with the north side up, of right-lateral strike-slip displacement (Berberian and Yeats, 1999). The main Kopeh-Dagh fault consists of several partly overlapping segments parallel to the overall $NW-SE$ structure with step-overs.

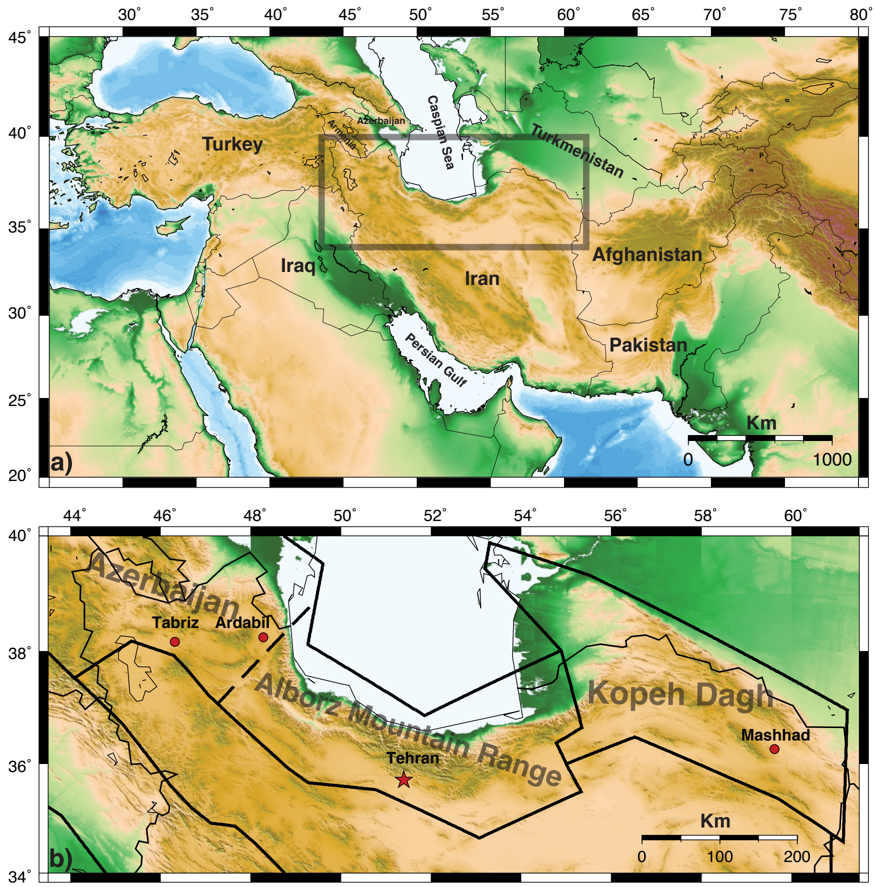

Figure 1: a) Map of Iran and surrounding countries. The study area is situated in the gray box. b) The study area containing seismotectonic provinces after Mirzaei et al. (1998) is presented, and location of big cities indicated with circles. Dashed line is the subdivision that is proposed by Karimiparidari et al. (2013)

The regions of overlap are characterized by shorter south-dipping thrust faults striking about E - W (Berberian and Yeats, 2001). Trifonov (1978) reported active displacement along the main Kopeh-Dagh fault for more than 500 km.

2.1. Magnitude Conversion

The catalog of recorded earthquakes from 2005-2015, which is downloaded from IIEES, reported the earthquakes based on different magnitude scales (IIEES, 2015). We converted the M_L, M_S, and mb magnitudes through conversion relationships which are defined in Zare et al. (2014). There are also some of data recorded in M_D (Duration magnitude). These data are reported by International Seismological Centre (ISC). Deniz and Yucemen (2010) developed a set of empirical equations to convert earthquake magnitudes from mb, M_D, M_L and M_S scales to M_W scales using orthogonal regression procedure. They used data of earthquake that occurred in Turkey from different data centers including ISC. In this study we use the conversion equation of Deniz and Yucemen (2010) to convert the M_D to M_W.

2.2. Declustering

It is generally assumed that the seismicity of each tectonic seismic source follows a Poissonian occurrence process. Therefore, in order to accomplish this, we declustered the earthquake catalog. In compiling the catalog of events, foreshocks and aftershocks were removed using a declustering methodology Gardner and Knopoff (1974). Fig. 2 shows the epicenter of declustered instrumental earthquakes.

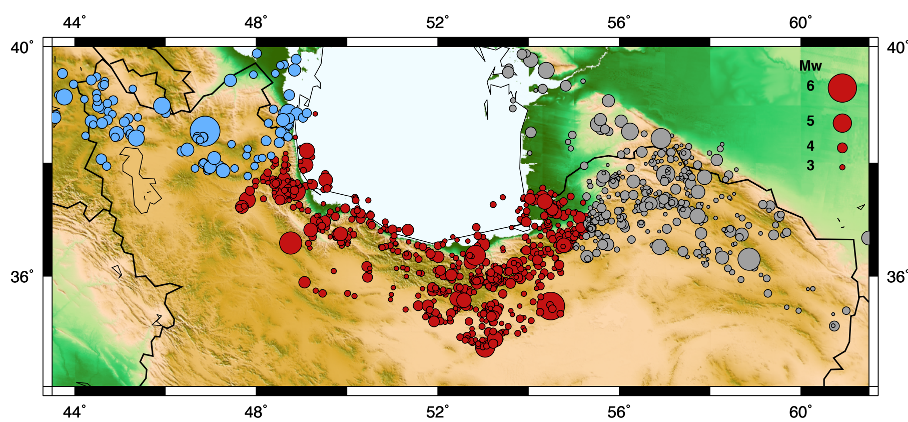

Figure 2: Declustered instrumental seismicity map (2005 - 2015) of Northern Iran.

2.3. Catalog Completeness

Completeness of catalog is an important factor in studying the earthquake sequence. In this study we used the Maximum curvature method (MAXC) (Wiemer and Wyss, 2000) to determine the completeness magnitude. According to MAXC method, a complete catalog should follow the Gutenberg-Richter power law distribution of magnitude. The steps for picking the completeness magnitude for each catalog include: 1) Calculating the $a-$ and $b-$ value based on the minimum magnitude, 2) generating synthetic events based on the achieved value somehow the cumulative number of events obey the power law distribution, and 3) Calculating the goodness of fit for predicted and observed cumulative numbers for each magnitude bin (Wiemer and Wyss, 2000). We increase the minimum magnitude and repeat the process in order to calculate the goodness of fit for each magnitude. Wiemer and Wyss (2000) assumed the goodness of fit of 90% as a threshold to select completeness of the catalog. However, not all frequency-magnitude distributions reach the 90% mark. Fig. 3 , shows the goodness of fit values for three tectonic seismic regions. For each tectonic seismic region, we pick the magnitude corresponding to the highest goodness of fit or the first magnitude with goodness of fit bigger than 90%.

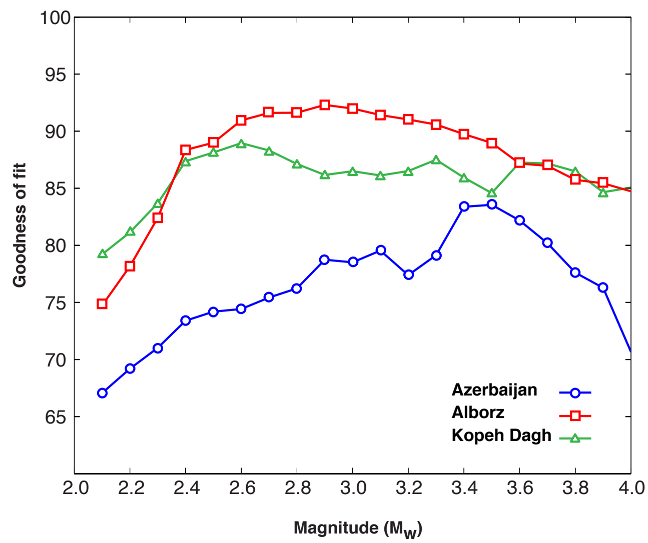

Figure 3: Goodness of fit value of MAXC method for three tectonic seismic regions for seismicity of 2005-2015 (a) Azerbaijan b)Alborz c) Kopeh Dagh)

In this study we assume the minimum magnitudes for complete recording, M_C, are 3.5, 2.6, and 2.6 for Azerbaijan, Alborz, and Kopeh Dagh, respectively. Fig. 4 shows the magnitude time series of the declustered data for the three regions. Earthquakes with magnitude bigger than completeness magnitude are represented.

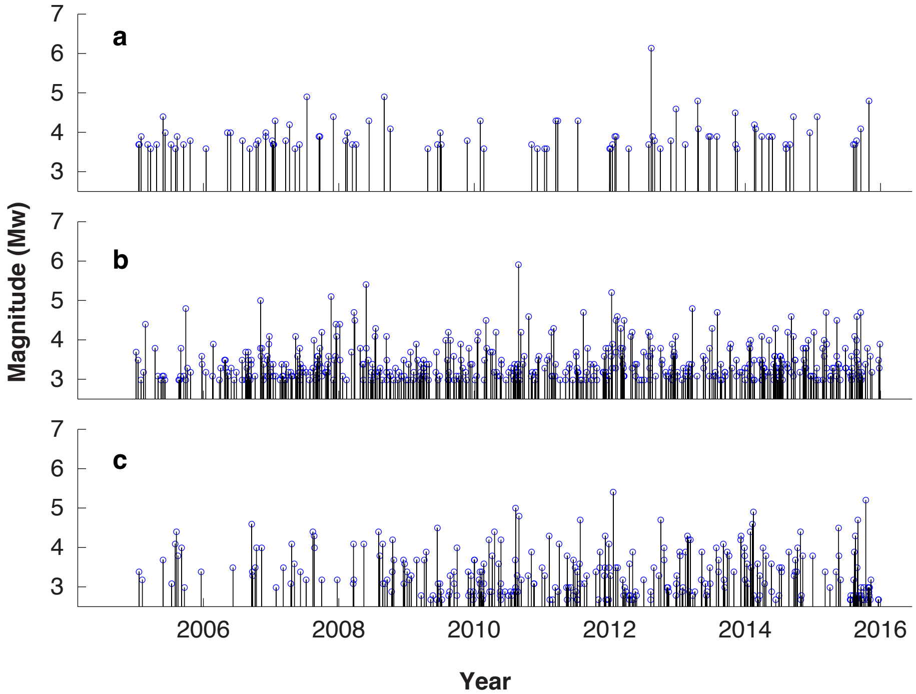

Figure 4: Variation of moment magnitude of 2005-2015 earthquake for north Iran. (a) Azerbaijan b)Alborz c) Kopeh Dagh)

3. Results

We generated the visibility graph parameters for three tectonic seismic regions in northern Iran for the period from 2005 to 2015. Number of earthquakes in each catalog after declustering and the seismicity parameters are presented in Table. 1.

Table 1: Seismic parameters and $k-M$ slope values for north Iran tectonic seismic zones.

Region	Number of Earthquake	Mc	$b-value$	$k-M$ slope
Azerbaijan	93	3.5	1.0190	9.2004
Alborz	794	2.6	0.7717	9.0461
Kopek Dagh	282	2.6	0.5799	6.5818

Fig. 5 shows the $k-M$ relationship for the study regions. In general with increasing magnitude the connectivity degree increases which results in increasing the slope of the $k-M$ relationship.

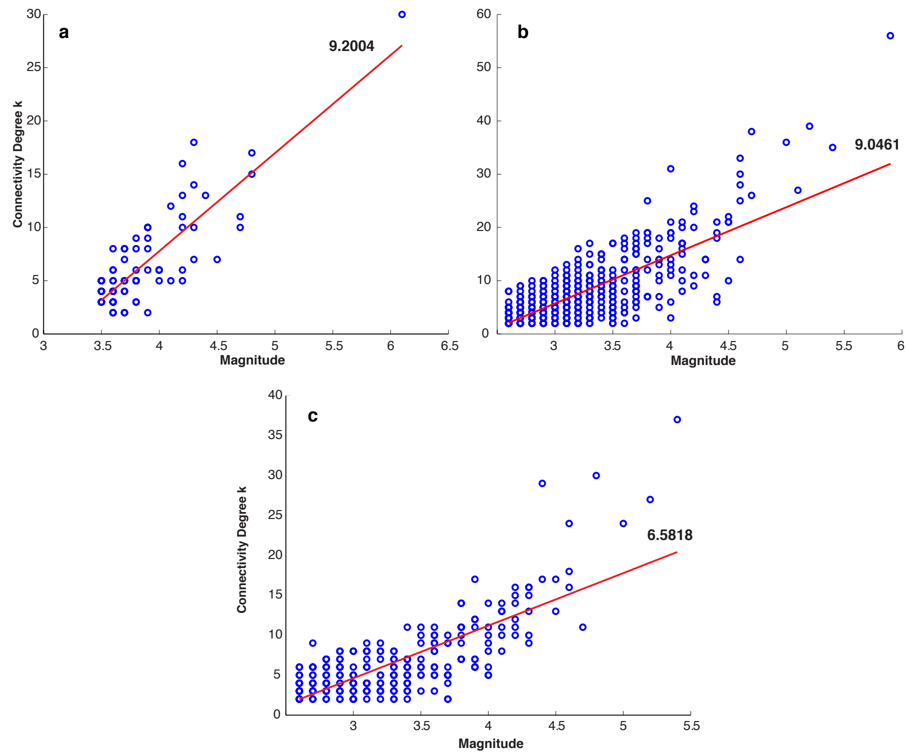

Figure 5: $k - M$ relationship for north Iran seismicity. a) Azerbaijan b) Alborz c)Kopeh Dagh

We compared the $k - M$ slope with the $b - value$ of the Gutenberg-Richter law in the whole catalog and also in the sliding windows in time. The $b - value$ is generated through the maximum likelihood estimation (Aki, 1965).

$$b = \frac{log_{10}(e)}{\overline{M} - M_{min}}, \tag{2}$$

where $\overline{M}$ is the average magnitude and M_{min} is the minimum magnitude in the sample, which in this case is the completeness magnitude for each tectonic seismic zone. Number of sequences and threshold magnitudes are considerably different for all tectonic seismic regions. Telesca et al. (2013) studied the effect of the number of earthquakes in catalog on the $k - M$ slope. Comparing the result of Guerrero region with reduced random sequence, Telesca et al. (2013) found that the number of sequence doesn't affect the $k - M$ slope. According to Telesca and Lovallo (2012), the threshold magnitude has a minor effect in the VG parameters. In order to analyze the sensitivity of the catalogs to the number of events and the threshold magnitude we randomly pick 200 sequences from the catalogs with various sequence size. The minimum size of random windows are 150 events (note that the number of events in each catalog, before removing the events with magnitude less than completeness magnitude, are 271, 1262, and 399 for Azerbaijan, Alborz, and Kopeh Dagh regions, respectively) and the maximum size is the size of the whole catalog. For each randomly picked magnitude time series we estimate the Mc and calculated the $k-M$ and $b-value$. Fig. 6 shows the relationship between $k-M$ slope and $b-value$ of the randomly selected data and statistical parameters for variables. Although changing the number of events and the threshold magnitude are slightly changes the results, they are fairly well clustered for each tectonic seismic region.

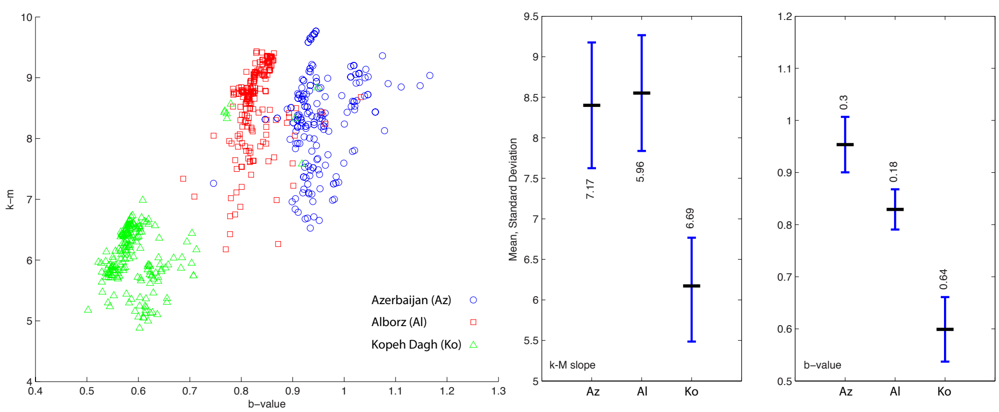

Figure 6: Relationship between $k-M$ and $b-value$ of three Iranian tectonic seismic regions for 200 random sequence. The numbers on the mean and standard deviation plots are coefficient of variations in percent($standard\ deviation/mean$).

The coefficient of variation of parameters are shown in Fig. 6. The $k-M$ slope shows higher coefficient of variation. We may argue that the $k-M$ slope is much dependent to the window size and threshold magnitude than $a-$ and $b-value$, which suggest the idea that $k-M$ slope can better represent the dynamic characteristics of the magnitude-time series.

Fig. 7 shows the relationship between the $k-M$ slope for three tectonic seismic regions in north of Iran and two other studies of Mexican zones (Telesca et al., 2013), and Pannonia zones (Telesca et al., 2014). Adding the results of the current study into the results of two previous similar studies improves the regression factor (with an increase from R=0.95 to R=0.958) and empower the idea of universal character of the relationship between the $b - value$ and the $k - M$ slope as Telesca et al. (2014) concluded.

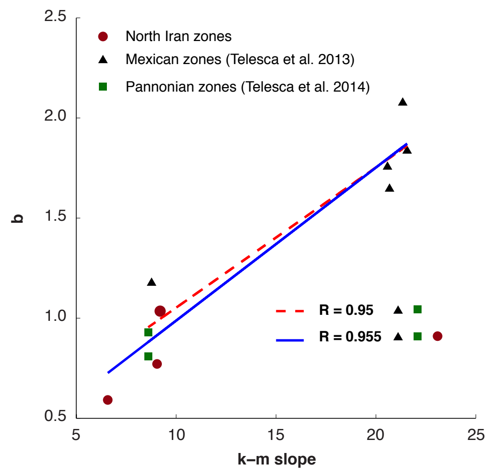

Figure 7: Relationship between $k - M$ and $b - value$ of three Iranian tectonic seismic zones (this study) and two other studies of Mexican zones (Telesca et al., 2013), and Pannonia zones (Telesca et al., 2014). The dashed red line shows the regression line for data of Mexican zones and Pannonia zones (Telesca et al., 2014), and the solid blue line shows the regression line for data of all regions (Mexican, Pannonian and north Iran)

Fig.8 shows the variation of the $k - M$ slope and $b - value$ with time. Having lower number of event, we used 20 events as a window length with shift of one event between two successive windows. The calculated parameters of each window was associated with the time of occurrence of the last event in sliding window. There is a very good similarity between the $k - M$ slope and $b - value$ in all tectonic seismic regions. In general, In all regions the $b - value$ and $k - M$ slope considerably drop before big earthquakes. Dropping the $b - value$ before large earthquakes have been studied in many different region (e.g. Wyss et al., 2000; Wyss and Stefansson, 2006; Schorlemmer et al., 2005; Chan et al., 2012)

Telesca et al. (2016) observed the decreasing in $< Tc >$ before large earthquake of

Western India earthquake sequence. Fig. 8 shows the time variation of $< Tc >$ in the study area and decrease in $< Tc >$ befor large earthquakes is clearly visible. Telesca et al. (2016) demonstrated that the decrement of $< Tc >$ before large earthquake are independent of window size and the threshold magnitude. Fig. 8 shows the decrement of value of $< T_C >$, $k - M$, and $b - value$ before big earthquakes.

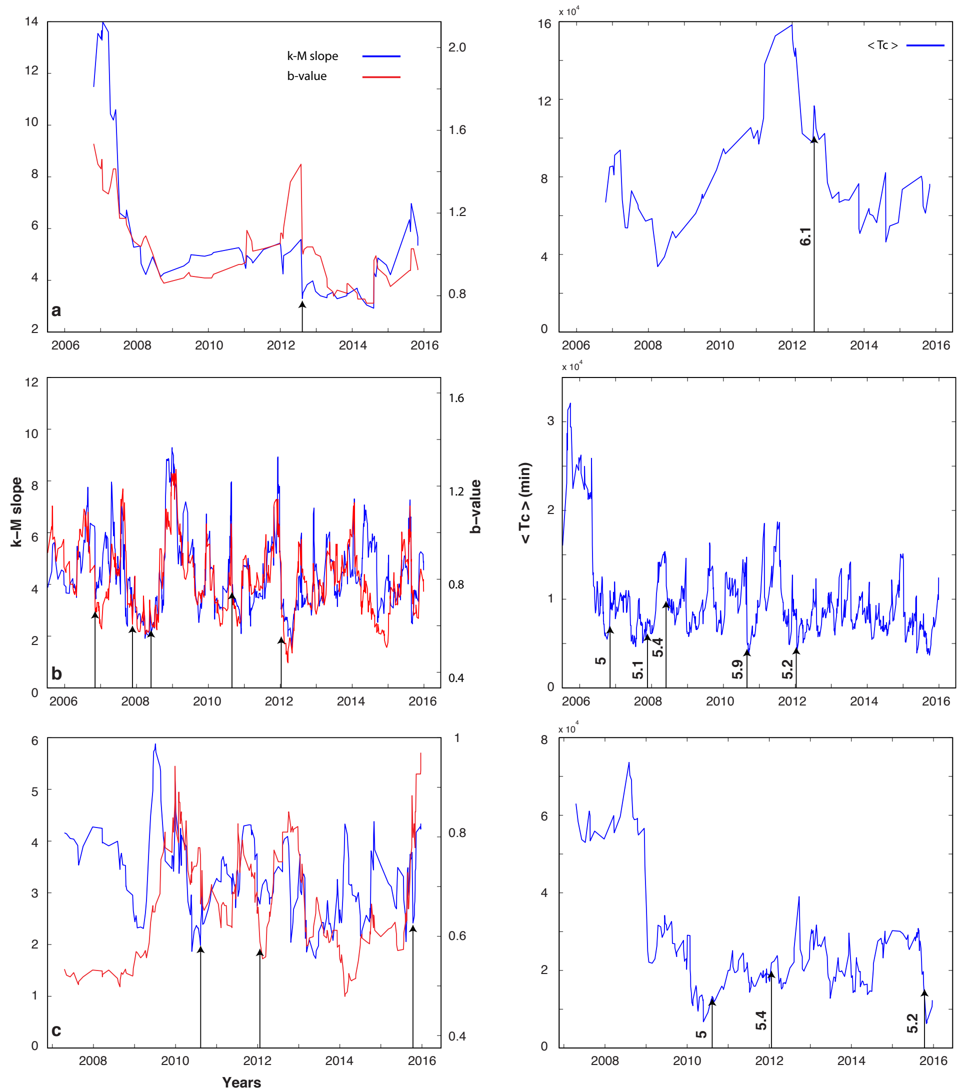

Figure 8: Variation of $k - M$ slope and $b - value$ (Left), and $< T_C >$ (Right) with time. Black arrows show the occurrence of the major earthquakes. Numbers on arrows indicate the moment magnitude of the earthquake.

4. Conclusion

We studied the earthquake sequence of three tectonic seismic regions of north Iran. Results manifest the strong relationship between $k - M$ slope and Gutenberg-Richter parameters. The variation of $k - M$ slope and $b - value$ with time in sliding windows have similar behavior and drops down before big earthquakes. Significant reduction of $< T_C >$ value before big earthquake is observed. Higher coefficient of variation of $k-M$ slope in comparison with $b-value$, suggests the $k-M$ slope as better parameter for studying the magnitude time series due to higher sensitivity to window size and threshold magnitude than $b - value$. In general, $k - M$ and $b - value$ relationship preserves the behavior with variation of the window size and threshold magnitude, and could be an alternative approach for clustering the earthquake sequences based on different tectonic seismic zones.

5. Acknowledgements

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