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Assessing of Earthquake Activity in the East Anatolian Part of Turkey: A General Overview to the Main Seismotectonic Parameters

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Abstract

In this study, a region-time analysis of seismicity in the East Anatolian part of Turkey is carried out by considering the recent changes in seismotectonic *b*-value, fractal dimension *Dc*-value, seismic quiescence Z-value, annual probability and recurrence time of earthquakes. Magnitude completeness is computed as 2.8 and *b*-value is estimated as 1.12±0.07. This *b*-value of East Anatolian earthquakes is well represented by the Gutenberg-Richter law. *Dc*-value is calculated as 1.87±0.03 and this high *Dc*-value indicates that seismicity in the East Anatolian region is more clustered at larger scales or in smaller areas. Recurrence times of earthquake occurrences show that East Anatolian region has a noticeable seismic hazard for the possibility of strong earthquake occurrences. Some clear anomaly areas of low *b*-value and high *Z*-value are observed at the beginning of 2018. It is clear that there is an important earthquake potential in the East Anatolian part of Turkey in the intermediate-term.

Key words: East Anatolia, *b*-value, *Dc*-value, *Z*-value, recurrence time

1. Introduction

An important tool for the seismicity based studies is to make a space-time assessment of earthquake activity and many seismotectonic parameters have been used in order to achieve a quantitative regional and temporal seismicity assessment by different authors for different parts of the world [1, 2, 3, 4, 5, 6, 7, 8, 9]. In this study, the most frequently used seismic parameters are considered in order to analyze the general statistical characteristics of earthquake activity in the East Anatolian part of Turkey. These parameters can be given as (*i*) regional, temporal and magnitude distribution of earthquake activity, (*ii*) completeness magnitude, *Mc*-value, which defines the minimum magnitude of complete reporting, (i*ii*) *b*-value, which describes the power-law distribution of earthquakes, (*iv*) *Dc*-value, which implies the number of objects greater than a specified size has a power law dependence on the size, (*v*) standard normal deviate *Z*-value, which is one of the most frequently used variable in the assessment of precursory seismic quiescence before an earthquake occurrence and (*vi*) annual probabilities and recurrence times for different magnitude levels.

The magnitude-frequency distribution is one of the most frequently used as the power-law distribution of earthquakes and is known as the *b*-value of Gutenberg-Richter [10] relationship. Analyzing the variations of *b*-value may give some useful statistics between the frequency of earthquakes, seismic moment or energy. The *b*-value reflects the relative numbers of both large and small earthquakes and, is related to the properties of the seismotectonic structures and stress

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distributions in time and space. When *b*-value shows a decrease for a given region, one can make an assessment that there is a possibility of an earthquake occurrence. Fractal properties characterize the evolution of earthquake system to a self-organized critical state. It is well known that tectonically and seismically active regions exhibit a fractal correlation or scale invariant between earthquakes both spatially and temporarily [11]. Some structural, geological, or mechanical changes in heterogeneity can be described by using fractal dimension (*Dc*-value) and can also define the heterogeneity of seismicity in an active fault system. Thus, an assessment of the relationship between fractal properties of complex seismotectonic variables may determine the earthquake hazard and risk analyses in a specific region. In addition to these variables, the evaluation of the seismicity rate changes by considering the precursory seismic quiescence may supply important results. A definition of seismic quiescence phenomenon was made in the following way [12]: "*The seismic quiescence means that a significant decrease in the average seismic activity rate as compared to declustered background activity rate in the same crustal volume may be observed before the occurrences of some main shocks. This decrease in seismic activity may occur within part, or all of the source volume of the subsequent main shock. Also, this decreasing trend may continue to the main shock time, or may be separated from it by a relatively short period of increasing trend in seismic activity*". Thus, the mapping of precursory seismic quiescence can supply evidence to earthquake forecasting and a statistical assessment for detecting the next quiescence period in real time for a given region can be achieved.

There are few studies generally considering the regional and temporal variations of seismotectonic *b*-value, seismic quiescence *Z*-value, and some other statistical parameters for the analysis of earthquake behaviors, and their possible usage as precursors for the East Anatolian region part of Turkey. For this reason, seismic and tectonic assessments of temporal changes in *b*, *Dc* and *Z*-values, annual probability and recurrence time of the earthquakes are analyzed in this study with recent earthquake data and it is presented some important results for the future earthquake potential in the East Anatolian region. *ZMAP* analysis software [13] was used for statistical analyses and for all histograms of regional, temporal and magnitude distribution in this part of Turkey.

2. Main Tectonic Environments in the East Anatolian Region and Earthquake Database

The East Anatolian part is well-known to be one of the most seismically and tectonically active regions in Turkey. Since many strong and destructive earthquakes have occurred in the past and recent years, these types of detailed studies for the assessment of earthquake potential have become more and more important. Major earthquake activity of the East Anatolia during the 20th century can be given with a series of destructive earthquakes in December 26, 1939 in Erzincan (*M8*.0), August 17, 1949 in Elmalıdere-Bingöl (*M7*.1), March 13, 1992 in Erzincan (*M6*.8), January 27, 2003 in Tunceli (*M6*.1), May 1, 2003 in Bingöl (*M6*.4), August 11, 2004 in Elazığ (*M5*.7), January 25, 2005 in Hakkari (*M5*.9), March 12, and 14, 2005 in Bingöl (*M5*.7 and *M5*.9), March 8, 2010 in Elazığ (*M6*.0), September 22, 2011 in Erzincan (*M5.5*) and October 23, 2011 in Lake Van (*M7.2*).

Active fault structures in this part of Turkey are tectonically very complex. The fundamental tectonic zones in the East Anatolian part can be given as the East Anatolian Fault Zone (EAFZ), the Bitlis Thrust Zone (BTZ), the Karlıova Triple Junction (KTJ) and the Dead Sea Fault Zone (DSFZ). The EAFZ is a transform fault and, the parts of the boundaries between the Anatolian and the Eurasian plates and, between the Arabian and African plates give its shape [14]. The length of this zone is about 550 km and it is a sinistral strike-slip fault zone. The EAFZ is considered to be a conjugate structure to the North Anatolian Fault Zone (NAFZ). The DSFZ is a sinistral intraplate strike-slip fault zone, approximately north-south direction. This zone separates the Arabian Plate to the east and the African Plate to the west. It has approximately 1000 km long and is considered as a plate boundary of transform type [15]. The African plate moves northward slower than the Arabian Plate and the DSFZ takes up this different movement between these plates. Thus, the DSFZ and EAFZ meet in a triple junction among the Anatolian, African and Arabian plates. The BZTZ has a complex boundary including continent-continent and continent-ocean collisions. A collision takes place between the Eurasian and Arabian plates along the BZTZ and this conflict comes to end an uplift of mountains along the suture zone. BZTZ reaches to the north of fold-and-thrust belt of the Arabian platform and it extends from southeastern Turkey to the Zagros Mountains in Iran [15]. There is a dominant north-south compressional tectonic system in the area to the east of the KTJ. This zone is described with two combined sinistral strike-slip faults and dextral character which is parallel to the NAFZ and EAFZ [16]. Simplified tectonic environments of the East Anatolian region are modified from different authors such as Bozkurt [16], Şaroğlu et al. [17] and Ulusay et al. [18], and given in Figure 1a.

The earthquake catalogue is taken from Boğaziçi University, Kandilli Observatory and Earthquake Research Institute (KOERI) and, is between April 21, 1970 and December 31, 2017. This catalogue has a time interval of 47.70 years and is homogeneous for duration magnitude, M_d. It consists of 44,359 shallow earthquakes with magnitudes between M_d=1.0 and M_d=6.6. Shallow earthquakes less than 70 km were selected for the analyses because seismic hazard is related to the crustal events. Epicenter distributions of the earthquakes were shown in Figure 1b.

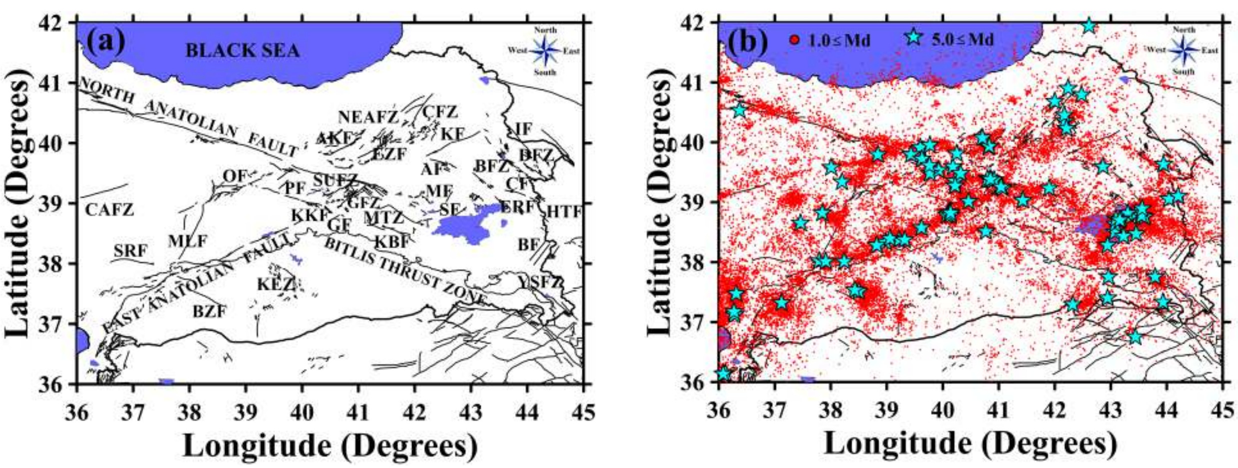

Figure 1. a) Main tectonic environments in the East Anatolian part of Turkey. Names of the faults: NEAFZ: North East Anatolian Fault Zone, ÇFZ: Çobandede Fault Zone, AKF: Aşkale fault, EZF: Erzurum fault, KF: Kağızman fault, AF: Ağrı fault, IF: Iğdır fault, DFZ: Doğubeyazıt Fault Zone, BFZ: Balıklıgölü Fault Zone, ÇF: Çaldıran fault, ERF: Erciş fault, HTF: Hasan-Timur fault, BF: Başkale fault, YSFZ: Yüksekova-Şemdinli Fault Zone, SF: Süphan fault, MF: Malazgirt fault, SUFZ: Sancak-Uzunpınar Fault Zone, GFZ: Göynük Fault Zone, PF: Pülümür fault, KKF: Karakoçan Fault Zone, GF: Genç Fault, MTZ: Muş Thrust Zone, KBF: Kavakbaşı fault, KEZ: Karacadağ Extension Zone, BZF: Bozova fault, SRF: Sürgü fault, CAFZ: Central Anatolian Fault Zone, MLF: Malatya fault, OF: Ovacık fault. **b)** Epicenters of 44,359 shallow earthquakes (depth ≤ 70 km) with M_d≥1.0 and strong events with M_d≥5.0 between 1970 and 2018.

3. Method

In this study, the most frequently used seismotectonic parameters, such as the *b*-value, *Dc*-value, *Z*-value, annual probability and recurrence times of the earthquakes are considered in terms of space-time analysis of seismicity in the East Anatolian part of Turkey.

3.1. Gutenberg-Richter Relation (b-value) and Magnitude Completeness (Mc-value)

The frequency-magnitude relation of earthquakes was described by Gutenberg-Richter [10]. This power-law distribution of earthquakes is given as:

$$\log_{10} N(M) = a - bM \quad (1)$$

where *N(M)* is the expected number of earthquakes with magnitudes greater than or equal to *M*, *b*-value is the slope of the frequency-magnitude distribution, and *a*-value is proportional to the earthquake activity rate. *a*-value varies from region to region. These changes depend on the observation period, length of the study region and also size of the events. As stated in Utsu [19], *b*-value changes roughly between 0.3 and 2.0, depending on the different regions. However, the changes in *b*-value can be caused by several factors such as the number of small and large events, geological complexity and degree of heterogeneity of cracked medium, strain and stress condition in the region, and the regional scale of average *b*-value for tectonic earthquakes is approximately equal to 1.0 [20].

Magnitude completeness, *M*c, is one of the most important parameter in seismicity studies, especially in investigation of frequency-magnitude relation. The maximum number of events is necessary for the high quality and reliable results. The power-law distribution of Gutenberg-Richter against magnitude is used in order to estimate *Mc*-value and the variation in *Mc*-value is calculated with a moving time window approach [21]. If *Mc* changes systematically as a function of time and space, temporal variations of *Mc* can cause potential wrong value of seismicity parameters, especially in *b*-value.

3.2. Fractal Dimension (Dc-value)

Earthquake distributions are considered fractal. Fractal dimension is a real number and is often used to evaluate the clustering properties and size scaling attributes of seismotectonic parameters. Regional and temporal patterns of earthquake occurrence are demonstrated to be fractal using the two-point correlation dimension, *Dc*-value. Fractal dimension analysis is a powerful tool for quantifying the self-similarity of a geometrical object.

Fractal dimension *Dc* and the correlation sum *C(r)* was defined as in the following equations [22]:

$$Dc = \lim_{r \to 0} \left[\log C(r) / \log r \right] \quad (2)$$

$$C(r) = 2N_{R<r} / N(N-1) \quad (3)$$

where $C(r)$ is the correlation function, r is the distance between two epicenters and N is the number of earthquakes pairs separated by a distance $R<r$. If the epicenter distribution has a fractal structure, following relation is obtained:

$$C(r) \sim r^{Dc} \tag{4}$$

where Dc is a fractal dimension, more strictly, the correlation dimension. The distance r (in degrees) between two earthquakes is calculated from:

$$r = \cos^{-1}\left(\cos\theta_i \cos\theta_j + \sin\theta_i \sin\theta_j \cos\left(\phi_i - \phi_j\right)\right) \tag{5}$$

where (θ_i, ϕ_i) and (θ_j, ϕ_j) are the latitudes and longitudes of the i^{th} and j^{th} events, respectively [1]. By plotting $C(r)$ against r on a double logarithmic coordinate, Dc is practically obtained from the slop of the graph.

Fractal dimension characterizes the nature of spatial and temporal properties of the earthquakes and is calculated to evaluate the possible unbroken sites which have been mentioned as seismic gaps that may be broken in the next [5]. That means that the fluctuations in fractal properties principally depend on the complexity or quantitative measure of the degree of heterogeneity of seismic activity in the fault systems. Larger Dc-value associated with smaller b-value is the dominant structural feature in the areas of increased complexity in the active fault system and it may be resulted from clusters. So, this property may be an indication of stress changes on fault planes of smaller surface area [1, 11].

3.3. Standard Normal Deviate (Z-value)

The phenomenon of precursory seismic quiescence was originally proposed by Wyss and Habermann [12]. Wiemer and Wyss [2] introduced a methodology that can be performed in *ZMAP* software and the recognizing of the seismic quiescence for different parts of the world has been reported in many papers. A continuous image of rate changes in the earthquake activity and plotting the areas showing seismic quiescence in space and time can be provided by *ZMAP* by plotting in geographical coordinates. This software package is a tool for investigation of seismic quiescence and artificial seismic rate changes. The standard normal deviate Z-test is one of the most common technique generally used for detecting of precursory seismic quiescence. In this study, Z-test is applied to detect the anomaly regions of precursory quiescence and Log Term Average (LTA) function is generated for the statistical assessment of confidence level in standard deviation units:

$$Z = (R_{all} - R_{wl}) / \sqrt{(S_{all}^2 / N_{all}) + (S_{wl}^2 / N_{wl})} \tag{6}$$

Where R_{all} is the mean rate in the overall background period, R_{wl} is the average earthquake activity rate in the foreground window, S_{all} and S_{wl} are the standard deviations in these periods, and N_{all} and N_{wl} are the number of samples with a measured earthquake activity rate. Z-value is estimated as a function of time and named LTA.

4. Results and Discussions

In the scope of this study, space-time assessments of the earthquake distributions in the East Anatolian part of Turkey are achieved by considering the main sesimotectonic parameters such as seismotectonic *b*-value, fractal dimension *Dc*-value, seismic quiescence *Z*-value, annual probabilities and recurrence times of the earthquakes. Since some occurrences such as foreshocks, aftershocks or swarms generally masks temporal changes of the earthquake numbers, removing the dependent earthquakes from catalog is an important stage in these types of statistics. In order to achieve a quality assessment of earthquake rate changes and to remove the dependent events from the catalog, Reasenberg's [23] algorithm can be preferred. This algorithm "declusters" or decomposes an earthquake catalogue into main and secondary events [24]. It removes all the dependent events from each cluster, and define them as a unique earthquake.

In this study, earthquake catalogue was declustered with the Reasenberg's [23] algorithm to provide a quantitative evaluation of the precursory seismic quiescence. There are totally 44,359 shallow events with magnitudes larger than or equal to 1.0. By using declustering technique, 11,565 earthquakes are removed from the catalog and 32,794 earthquakes remained. *Mc*-value for study region is taken as 2.8, and the number of events exceeding this magnitude level is 18,257. After declustering and the excluding M_d<2.8 events, approximately 67.23% of the catalog is removed in total and the number of events for *Z*-test is reduced to 14,537. The cumulative number of earthquakes *versus* time for the original catalog, for the declustered catalog and for the declustered catalogs with $M_d \geq 2.8$ is shown in Figure 2. Any significant seismic activity is not observed from 1970 to 1995 and there is a little variation between 1995 and 2000. Conversely, there is a significant earthquake activity after 2000. However, it can be said that the database is separately homogeneous between 1970 and 1995, between 1995 and 2002, and between 2002 and 2018. As shown in Figure 2, the slope of cumulative number curve of the declustered data is smoother than that of the original catalog. It is a remarkable fact that these two processes removed the dependent events from the original data set and, after these two process, a more reliable, homogeneous and robust database was obtained for the imaging of seismic quiescence.

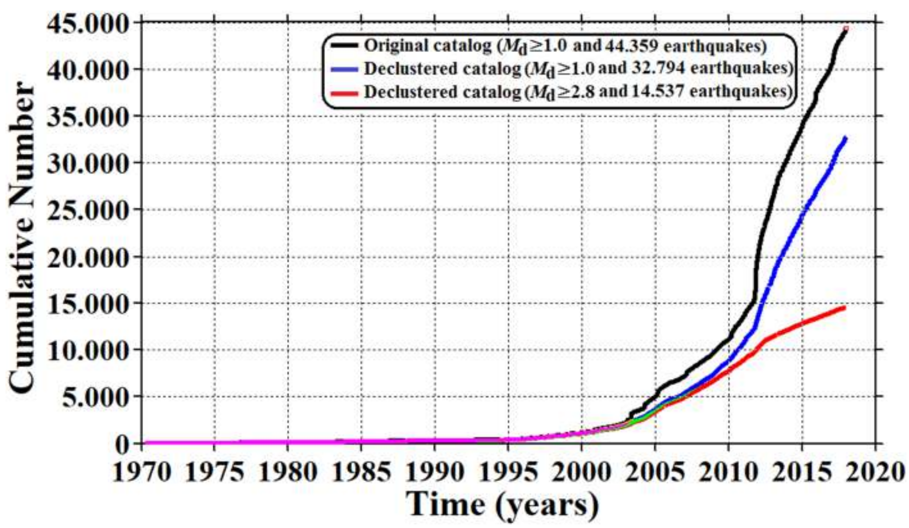

Figure 2. Cumulative number of earthquakes *versus* time for the original with $M_d \geq 1.0$ (black line), for the declustered (blue line) catalogs with $M_d \geq 1.0$, and for the declustered catalog with $M_d \geq 2.8$ (red line).

b-value in Gutenberg-Richter [10] relationship is estimated by the maximum likelihood method, because it gives a more robust estimation than the least square method. This power law defines the statistical characteristics of seismic zones in energy domain using the frequency-magnitude of earthquakes. Figure 3a shows the plot of cumulative number of the earthquakes against the magnitude for study region. *Mc* value is calculated as 2.8 and using this value the *b*-value is calculated as 1.12±0.07. *b*-value for tectonic earthquakes changes between 0.3 and 2.0 depending on region [19] and is more frequently equal to 1.0 on average [20]. Both the *Mc* and *b*-value estimations in this study are similar to the results of the analyses by Öztürk and Bayrak [25] and Öztürk [26]. Thus, the magnitude-frequency distribution of the earthquakes in the East Anatolia is well represented by the Gutenberg-Richter power law distribution with the *b*-value close to 1.0. Fractal dimension *Dc*-value is estimated by fitting a straight line to the curve of mean correlation integral *versus* the earthquake distance, *R* (km). *Dc*-value is calculated as 1.87±0.03 with 95% confidence limit by linear regression (Figure 3b). This log-log correlation function exhibits a clear linear range and scale invariance in the cumulative statistics between 5.03 and 59.44 km. The areas of increased complexity in active fault systems show higher *Dc*-value and seismicity is more clustered at larger scales (or in smaller areas) in these areas [5, 11]. The higher *Dc*-value is also quite sensitive to the heterogeneity in magnitude distribution [25]. As an important result, it can be assumed that this large *Dc*-value is the dominant structural properties in the East Anatolia and it may result from the earthquake clusters.

Annual probabilities and recurrence times for different magnitudes were given in Figure 4. As seen in Figure 4a, annual probabilities for different magnitude sizes show relatively higher (30 and above) values between 3.5 and 4.0 magnitude sizes, intermediate values (between 1 and 10) from 4.5 to 5.5 magnitude sizes, and quite smaller values (<1.0) between 5.5 and 7.0 magnitude sizes. Recurrence times for different magnitude ranges were also shown in Figure 4b. Relatively smaller (<1.0) years were observed for magnitude levels between 3.5 and 5.7. For magnitude size between 5.7 and 6.0, the values between 1.0 and 2.0 years are estimated whereas the values between 2.0 and 9.0 years are estimated for magnitude sizes between 6.0 and 7.0. The occurrences of earthquakes between 4.0 and 5.5 magnitude level are more likely than those of the others, and an earthquake occurrence for a magnitude size 6.5 can be expected in every decade. These results can also be seen from the earthquake catalog, and the recurrence times analyses support the existing earthquake potential [26] in the East Anatolia. Thus, these types of analyses on the probabilities and recurrence times of earthquake occurrences for different magnitude sizes present that the East Anatolia has a significant potential for the possibility of strong earthquake occurrence in the near future.

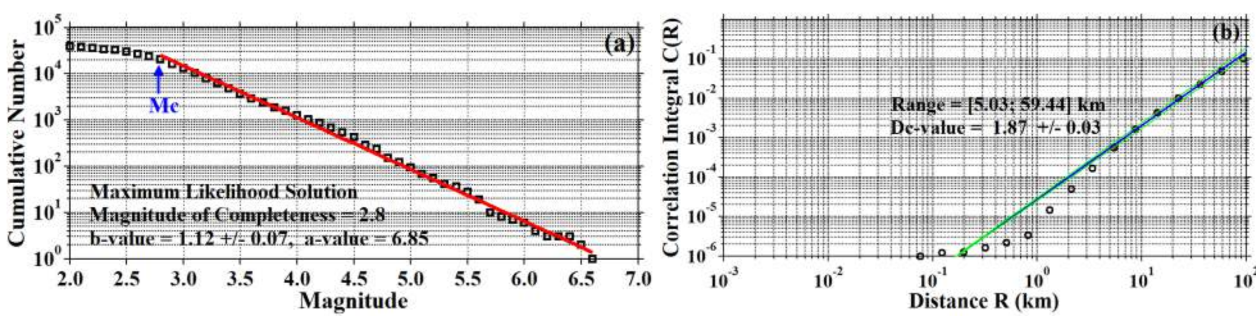

Figure 3. a) Gutenberg-Richter relation and *b*-value with its standard deviation. **b)** Fractal dimension *Dc*-value. The slope of the blue lines gives the *Dc*-values. Standard deviations of the *Dc*-values are also given in green lines.

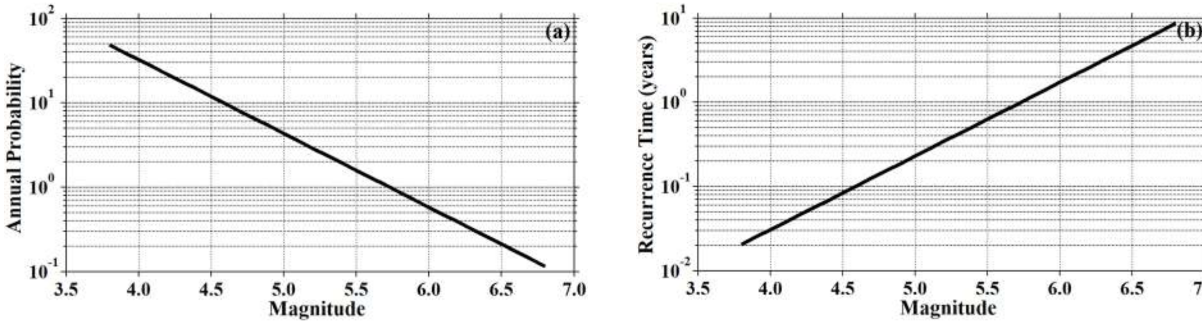

Figure 4. a) Annual probability, **b)** Recurrence time of the earthquakes for different magnitude levels.

Regional distribution of *b* -value is mapped at every node of the 0.1º grid (Figure 5a). Original earthquake catalogue with $M_d \geq 1.0$ is included in the estimation of *b*-value with samples of 1250 events/windows. Regional variations of *b*-value are between 0.4 and 1.8. The largest *b*-values (>1.2) are observed on the NAFZ, on NEAFZ including AKF and EZF, among the MLF, OF and PF, between KKF and GFZ, among SF, MTZ and KBF, in the south of KEZ. However, the lowest *b*-values (<0.9) are estimated in the east, southeast and northeast parts of the study region including ÇFZ, KF, IF, DFZ, BFZ, ÇF, HTF, BF, YSFZ, BZF, in the eastern part of KEZ, among CAFZ, SRF and MLF, on the junction of EAFZ and DSFZ (the southwestern part of the region). Regional changes of *Z*-value are mapped by using declustered catalog $M_d \geq 2.8$ and shown in Figure 5b. The area under analysis is divided into rectangular cells spacing 0.1º. The nearest earthquakes, *N*, at each node are taken as 50 events. T_W=5.5 years is used as the window length because the quiescence areas are better visible for a window of 5.5 years. At the beginning of 2018, there are several regions exhibiting seismic quiescence: on the NAFZ, CAFZ, MLF, OF, PF, between MTZ and MF, around AKF, north part of the Lake Van, between BZF and KEZ, on the southwestern tip of EAFZ (junction of EAFZ and DSFZ). There are clear decreases in *b*-value and increases in Z-value in the several same areas: between CAFZ and MLF, between MF and MTZ, the southwestern part of the EAFZ, and the junction of the EAFZ and DSFZ. These regions can be considered to be the most likely areas for future strong earthquakes, and this can be explained with most promising environment in which *b*-value show a decrease with an increase in mean stress [5, 25, 26]. Also, these results are quite similar with those of Öztürk and Bayrak [25], and Öztürk [26].

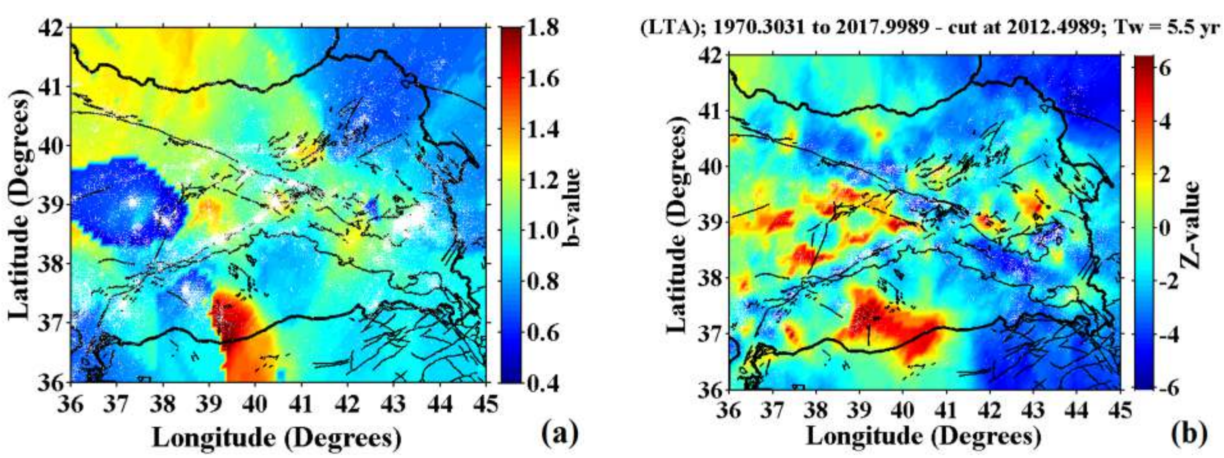

Figure 5. Regional maps of **a)** *b*-value, **b)** *Z*-value at the beginning of 2018. White dots in both figures represent the earthquakes used in the calculation.

Conclusions

The Eastern Anatolian part of Turkey is one of the most seismically and tectonically active regions due to the frequent occurrence of strong earthquakes. The main purpose of this study is to make a statistical assessment of earthquake activity in the Eastern Anatolia part of Turkey at the beginning of 2018. For this purpose, a region-time assessment based on the recent changes in *b*-value, *Dc*-value, *Z*-value, annual probability and recurrence time of earthquakes is carried out. The catalog of the KOERI including 44,359 earthquakes with magnitude equal to and larger than 1.0 from 1970 until 2018 is used. The catalogue has a time interval of 47.70 years and is homogeneous for duration magnitude, M_d. This analysis is limited in the rectangular area covered by the co-ordinates 36ºN and 42ºN in latitude and by the co-ordinates 36ºE and 45ºE in longitude. In order to separate the dependent events, Reasenberg's algorithm is used and the earthquake catalogue is declustered for the standard deviate *Z*-test. After declustering process and the excluding $M_d<2.8$ events, approximately 67.23% of the catalog is removed in total and the number of events for *Z*-test is reduced to 14,537. *Mc*-value is calculated as 2.8 and *b*-value is estimated as 1.12±0.07. This *b*-value is well represented by the Gutenberg-Richter relation for the East Anatolian earthquakes. *Dc*-value is calculated as 1.87±0.03 and this high *Dc*-value indicates that seismicity in the East Anatolian region is more clustered at larger scales or in smaller areas. Analyses of probability and recurrence time of the earthquakes suggest that the East Anatolian part of Turkey has an earthquake potential for the probability of strong earthquake occurrence in the intermediate-term. Significant low *b*-values and large *Z*-values regions are observed at the beginning of 2018. Thus, a combination of these seismotectonic variables may supply significant clues for the seismic potential in the East Anatolia and so, special interest needs to be given to these anomaly areas.

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