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TEMPORAL AND THREE DIMENSIONAL SPATIAL ANALYSIS OF EARTHQUAKE ACTIVITY BETWEEN 1970 AND 2010 ALONG THE NORTH ANATOLIAN FAULT ZONE, TURKEY

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ABSTRACT

Characteristics of seismic activity from 1970 to 2010 along the North Anatolian Fault Zone (NAFZ) are analyzed to make a statistical assessment by using the Gutenberg-Richter *b*-value, seismic quiescence *Z*-value, fractal dimension *Dc*-value, and spatial, temporal and magnitude distributions. Magnitude completeness, *Mc*, changes between 2.7 and 2.9 in all parts of the NAFZ. Frequency-magnitude distribution of the earthquakes is well represented by the Gutenberg-Richter law with a *b*-value typically close to 1. A strong decrease in temporal distribution of *b*-value is observed before the great main shocks. *Dc*-values are relatively large and the seismic activity is more clustered at larger scales for all parts of the NAFZ. From the standard normal deviate *Z*-value test, eight significant anomalous zones are centered at 41.08ºN-28.58ºE (around Silivri), 41.47ºN-29.51ºE (in the Black Sea), 40.69ºN-29.78ºE (including Izmit), 40.26ºN-26.46ºE (around Gelibolu, Canakkale), 40.59ºN-31.03ºE (including Duzce fault), 40.86ºN-35.30ºE (around Amasya), 39.48ºN-39.74ºE (around Erzincan), and 39.06ºN-40.50ºE (around Bingol).

Keywords*: Seismicity, North Anatolian Fault Zone, b-value, Dc-value, Z-value.*

1. INTRODUCTION

The variation of the seismic patterns in space and time in the North Anatolian Fault Zone (NAFZ), Turkey, is analyzed statistically and physically by many authors and some significant results are obtained [e.g., 1,2,3,4,5]. The NAFZ is one of the most seismically active regions of Turkey. The NAFZ is a major tectonic feature with a well-defined fault trace and an established history of seismicity. Because of topography and water resources, the fault zone is a relatively densely populated, agricultural area dotted by many villages and small towns. Most intermediate and large magnitude earthquakes occurring along the North Anatolian Fault (NAF) have produced surface breaks. Activity of the NAF during the 20^{th} century began with the destructive Erzincan earthquake in 1939 in northeast Turkey and it migrated westwards by a series of earthquakes in 1942, 1943, 1944, 1951, 1957 and 1967 [6,7].

At the turn of the previous century, two destructive earthquakes occurred on the western continuation of the NAFZ in northwestern Turkey. The 17 August 1999, M_W 7.4, Izmit earthquake ruptured the NAFZ along a 125-km segment, which extended from Golyaka, Duzce, in the east through the Izmit Bay into the Sea of Marmara in the west. The 12 November 1999, M_W 7.2, Duzce earthquake ruptured a segment about 50 km long, further to the east [8]. These two earthquakes are the latest in a sequence of large events that have ruptured an approximately 1000-km-long section of the NAFZ. This sequence began with the 1939 Erzincan earthquake in the northeastern part of Turkey, followed by a generally westward migration of earthquakes [6,7].

This work aims to identify the seismicity behaviors in the North Anatolian Fault Zone in order to better understand the earthquake properties in this significant area. For this purpose, this study is addressed the mapping of size-scaling distributions such as spatial, temporal and magnitude distribution of seismic activity, completeness magnitude *Mc* and *b*-values with time, seismic quiescence *Z*-value, fractal dimension *Dc* and the correlation of results with the structural elements which carry high risk for the region.

2. DATA AND ACTIVE TECTONICS OF THE NORTH ANATOLIAN FAULT ZONE

A part of the database used in this study is taken from Öztürk [9]. Öztürk [9] developed some relationships between different magnitude scales (m_b-body wave magnitude, M_S-surface wave magnitude, M_L-local magnitude, M_D-duration magnitude) in order to prepare a homogenous earthquake catalogue from different data sets. For this purpose, he used the catalogue data from the website of the International Seismological Centre (ISC) for the time period from 1970 to 1973 and Bogazici University, Kandilli Observatory and Research Institute (KOERI) for the time interval 1974 and 2005. He prepared a homogenous instrumental data catalogue for M_D magnitude using these relationships. This homogeneous catalogue for duration magnitude includes 73530 earthquakes whose magnitudes are equal to or larger than 1.4, which occurred in Turkey between 1970 and 2006. Öztürk [9] used the empirical relations in order to get a homogenous catalogue from 1970 to 2006 and so this relatively smaller magnitude level M_D>1.4 is obtained. For the time period between 2006 and 2010, KOERI catalogue is also used. The bounds of the region analyzed in this study are provided from Öztürk [9]. Since Öztürk [9] made a detailed zonation, a part of these seismic source zones is considered in this study. The North Anatolian Fault Zone is selected as an area of investigation in this study. According to Öztürk [9], region 20 (region 1 in this study) covers the Marmara part of the North Anatolian Fault Zone (MNAFZ), region 21 (region 2 in this study) is the Anatolian part of the North Anatolian Fault Zone (ANAFZ) and region 24 (region 3 in this study) is the Eastern part of the North Anatolian Fault Zone (ENAFZ). The major tectonic structures of the region adopted from Şaroğlu et al. [10] and the zones from Öztürk [9] are shown in Figure 1.
There are total 2804 events in these three regions between 2006 and 2010. The time interval considered for the present work is 1970 to 2010. The magnitudes in the used catalogue are M_D-duration magnitude. Thus, the final data catalogue for region 1 (9884 events), region 2 (4669 events) and region 3 (2645 events) consists of 17198 earthquakes in total (depth<70 km) with magnitudes greater than or equal to 1.4. Epicenter distributions of whole earthquakes ($M_D \geq 1.4$) and the principal main shocks ($M_D \geq 5.5$) in the study region are shown in Figure 2.
The North Anatolian Fault Zone is one of the best-known strike-slip faults in the world because of its remarkable seismic activity, extremely well developed surface expression and importance for the tectonics of eastern Mediterranean region [11]. The NAFZ is a very active structure, and according to geodesy it accommodates 24-30 mm/yr of dextral motion [12]. The NAFZ is an approximately 1500 km-long, broadly arc-shaped, dextral strike-slip fault system that extends from eastern Turkey in the east to the north Aegean in the west. It is predominantly a single zone of a few hundred meters to 40 km wide. Along much of its length, this fault zone consists of a few shorter sub-parallel fault strands that sometimes display an anatomizing pattern [11]. To the east, the NAFZ forms a typical triple-junction and joins with the sinistral East Anatolian Fault Zone at Karlıova. The NAFZ does not terminate at the Karlıova triple junction but, continues towards south east. During the past 60 years, NAFZ has produced earthquakes along different sections in a system manner that is atypical of long faults. Beginning with 1939 Erzincan earthquake (M=7.9 to 8.0), which produced about 350 km of ground rupture, the NAFZ ruptured by nine moderate to large earthquakes (M>6.7), and formed more than 1000 km surface rupture along the fault. Most of the earthquakes occurred sequentially in a westward progression. These include 26 December 1939 Erzincan (M=7.9 to 8.0), 20 December 1942 Erbaa-Niksar (M=7.1), 26 November 1943 Tosya (M=7.6), 1 February 1944 Bolu-Gerede (M=7.3), 13 August 1951 Çankırı (M=6.9) 26 May 1957 Abant (M=7.0), 22 July 1967 Mudurnu valley (M=7.1), 13 March 1992 Erzincan (M=6.8), 17 August 1999 Izmit (M=7.4), and 12 November 1999 Duzce (M=7.2) earthquakes [11].

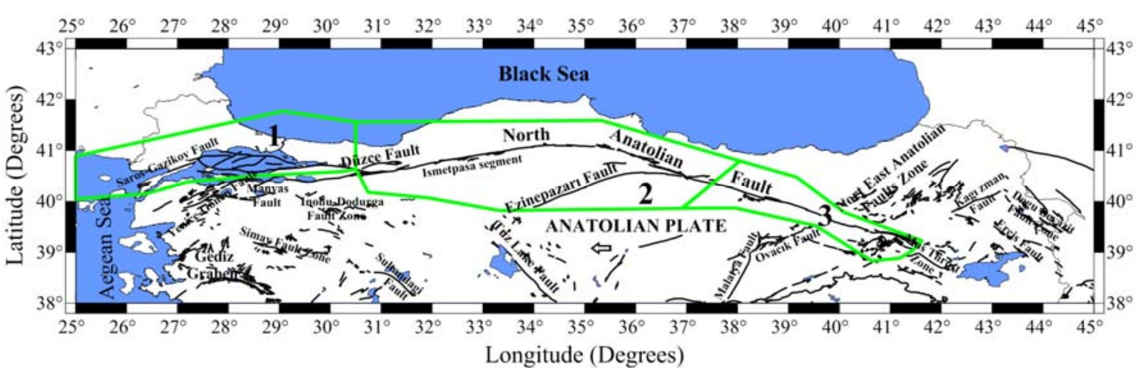

Figure 1. Tectonic structures and seismic source zones in the North Anatolian Fault Zone. Faults were modified from Şaroğlu et al. [10] and the seismic regions from Öztürk [9]. (1: Marmara part of the North Anatolian Fault Zone, 2: Anatolian part of the North Anatolian Fault Zone, 3: Eastern part of the North Anatolian Fault Zone).

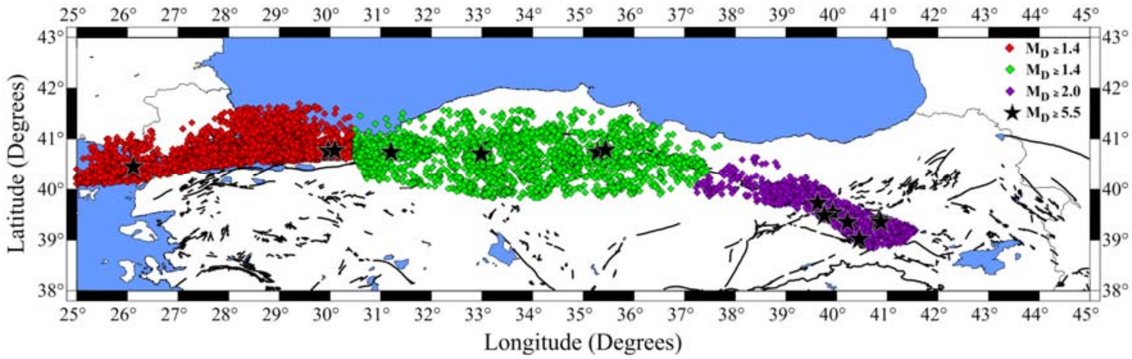

Figure 2. Seismicity in the North Anatolian Fault Zone including all earthquakes with M_D≥1.4 and depth<70 km between February 1970 and December 2009. Stars represent the principal main shocks with M_D≥5.5.

3. DEFINITION OF THE THEORETICAL BACKGROUND

A number of seismicity parameters are used in order to characterize the seismic behavior along the North Anatolian Fault Zone. These parameters are size-scaling parameters (such as slope of recurrence curve *b*-value), temporal and spatial distribution of earthquakes with characteristic of fractal correlation dimension, *Dc*, and seismic quiescence *Z*-value as well as the histograms of temporal, spatial and magnitude distribution.

3.1. Magnitude-frequency relation (*b*-value) and completeness magnitude (*Mc* value)

Size distribution of earthquakes in most cases is well described by the Gutenberg and Richter [13] relationship:

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

where *N(M)* is the cumulative number of earthquakes with magnitudes equal to or larger than *M*, *b* describes the slope of the size distribution of events, and *a* is proportional to the seismicity rate. *b*-value is one of the most widely used statistical parameters to describe the size scaling properties of seismicity. Utsu [14] summarized that *b*-values change roughly in the range 0.5 to 1.5, depending on the different region. However, on average, the regional scale estimates of *b*-value are approximately equal to 1 [15]. The maximum likelihood method provides the least biased estimate of *b*-value [16]:

$$b = 2.303/(M_{mean} - M_{\min} + 0.05) \tag{2}$$

where M_{mean} is the mean magnitude of events and M_{min} is the minimum magnitude of completeness in the earthquake catalogue. Accurate estimates of local changes of M_{min} can be made if relatively large numbers (100 or so) of local observations are available for analysis [17]. The value 0.05 in Eq. (2) is a correction constant that compensates for round off errors. The 95% confidence limits on the estimates of *b*-value are $\pm 1.96b/\sqrt{n}$, where *n* is the number of earthquakes used to make the estimate. This yields confidence limits on *b*-value of ±0.1-0.2 for a typical sample consisting of *n*=100 earthquakes.

The magnitude above which all events have been recorded is important for all seismicity-based studies because it is frequently necessary to use the maximum number of events available for high-quality results. The estimate of the magnitude of completeness (*Mc*) is based on the assumption of Gutenberg Richter's power-law distribution against magnitude [17]. Completeness in magnitude reporting varies systematically as a function of space and time, and particularly the temporal changes can potentially produce erroneous estimates of seismicity parameters, especially in *b*-value. Since a part of this study deals with the seismicity rate change, the magnitude of completeness of the catalog used to detect the quiescence is an important parameter.

3.2. Fractal Dimension, *Dc*

Fractal distributions imply that the number of objects larger than a specified size has a power law dependence on the size. Spatial patterns of earthquake distribution and temporal patterns of occurrence are demonstrated to be fractal using the two-point correlation dimension *Dc*. The correlation integral method was developed by Grassberger and Procaccia [18] and correlation dimension *Dc* is obtained from following equations:

$$Dc = \lim_{r \to 0} \left[\log C(r) / \log r \right], \tag{3}$$

$$C(r) = 2N_{R<r} / N(N-1), \tag{4}$$

where $C(r)$ is the correlation function, r is the distance between two epicenters or hypocenters and N is the number of events pairs separated by a distance $R<r$. Fractal dimension is defined by fitting a straight line to a plot of log $C(r)$ against log r. The nature of temporal-spatial fractal properties of the earthquake epicenters is characterized by fractal, in particular by the correlation dimension [19]. For the hypocenter distribution (3-D space), the uniform distribution equals the Eq. 4 and it decreases with an increase in the clustering of events [20]. It is reasonable to assume that the higher *Dc* and lower *b*-values are the dominant structural feature in the study area and may arise due to clusters.

3.3. Seismic quiescence *Z*-value and declustering of the catalogues

For the quantitative analysis of seismicity rate changes, it is necessary to eliminate the dependent events from the catalog. To separate the dependent events from the independent ones the earthquake catalog is declustered using the Reasenberg [21] algorithm. The cluster analysis algorithm of Reasenberg [21] "declusters" or decomposes a regional earthquake catalogue into main and secondary events. It removes all the dependent events from each cluster, and substitutes them with a unique event, equivalent in energy to that of the whole cluster. *ZMAP* software in Wiemer [22] is used for the declustering method. It is only changed epicenter and depth error values. Other standard parameters are defined as given in the software.

There are 9884 events in region 1 with magnitudes greater than or equal to 1.4. *Mc* value is 2.7 for region 1 and the number of earthquakes exceeding this magnitude threshold is 6514. The declustering procedure took away 258 (about 4%) events and 37% of the events in total were removed from whole catalogue of region 1. Thus, the number of events for *Z*-value analysis was reduced to 6256 for the Marmara part of the North Anatolian Fault Zone. There are 4669 events in region 2 with magnitudes greater than or equal to 1.4. *Mc* value for this region is 2.9 and the number of earthquakes exceeding this magnitude threshold is 3224. The declustering algorithm took away 267 (about 8%) events and 37% of the events were totally removed from whole catalogue of region 2. As a result, the number of events for *Z*-value analysis was reduced to 2957 for the Anatolian part of the North Anatolian Fault Zone. In region 3, there are 2645 earthquakes with magnitudes greater than or equal to 2.0. The *Mc* value for region 3 is 2.9 and the number of earthquakes exceeding this magnitude threshold is 1980. The declustering process took away 417 (about 21%) events and thus 41% of the events were totally removed from whole catalogue of region 3. Consequently, the number of events for *Z*-value analysis was reduced to 1563 for the Eastern part of the North Anatolian Fault Zone and after completing the declustering processes, a more reliable, homogeneous and robust seismicity data has been obtained.

The standard normal deviate *Z*-test is one of the statistical methods frequently used for analyzing seismic quiescence. A continuous image of space and time rate changes in seismicity is produced by *ZMAP*, creating a grid of geographical co-ordinates, and associating to each grid node a selected number of nearest events. It is applied the *ZMAP* method for imaging the areas exhibiting a seismic quiescence. In order to rank the significance of quiescence, it is used the standard deviate *Z*-test [23,24], generating the LTA (Log Term Average) function for the statistical evaluation of the confidence level in units of standard deviations:

$$Z = (R_1 - R_2) / (S_1^2 / N_1 + S_2^2 / N_2)^{1/2} \tag{5}$$

where R_2 is the mean seismicity rate in the foreground window, R_1 is the average number of events in the whole background period, S and N are the standard deviations and the number of samples, within and outside the window. The *Z*-value computed as a function of time, letting the foreground window slide along the time duration of catalogue, is called LTA.

4. SEISMICITY PROPERTIES OF THE NORTH ANATOLIAN FAULT ZONE

Many statistical analysis techniques of *ZMAP* software package have been used for the 3 data set of seismicity catalogues of the NAFZ. The *b*-value in Gutenberg-Richter relationship is calculated by the maximum likelihood method, because it yields a more robust estimate than the least-square regression method [25]. Figure 3 shows the Gutenberg-Richter relations for all parts of the NAFZ. The *b*-values are calculated as 1.13±0.01 with *Mc*=2.7 for region 1 (Figure 3a), 1.02±0.02 with *Mc*=2.9 for region 2 (Figure 3b), and 1.01±0.02 with *Mc*=2.9 for region 3 (Figure 3c). It is clearly seen that magnitude-frequency distributions of the earthquakes are well represented by the Gutenberg-Richter law with the *b*-value typically close to 1.

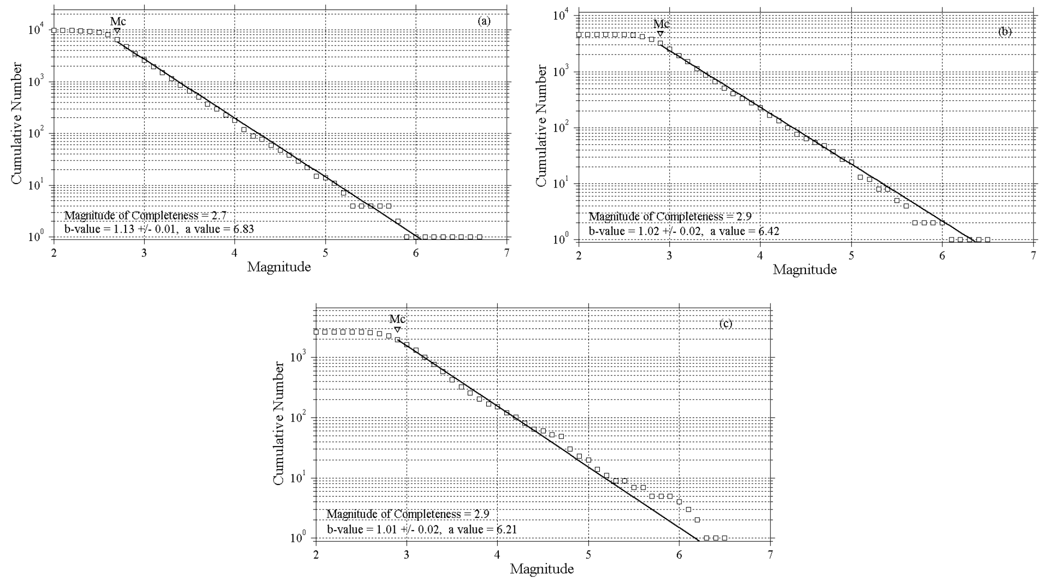

Figure 3. The *b*-value of the frequency-magnitude relationships for (a) region 1, (b) region 2 and (c) region 3. The *b*-value and its standard deviation, as well as the *a*-value in the Gutenberg-Richter relation are given.

Correlation dimension *Dc* is estimated by fitting a straight (solid) line to the curve of mean correlation integral against the event distance, R (km). *Dc*-values for all parts of the study area are obtained with 95% confidence limits by linear regression (Figure 4). The earthquake distribution of 9884 earthquakes in the MNAFZ is shown in Figure 4a. *Dc* is calculated as 2.20±0.03 and this log-log correlation function exhibits a clear linear range and scale invariance in the cumulative statistics between 0.50 and 32.15 km (indicated in Figure 4a). The earthquake distribution of 4669 events in the ANAFZ is shown in Figure 4b. *Dc* is computed as 2.40±0.03 and this log-log correlation function exhibits a clear linear range and scale invariance in the cumulative statistics between 0.63 and 24.26 km (indicated in Figure 4b). The earthquake distribution of 2645 earthquakes in the ENAFZ is shown in Figure 4c. *Dc* is calculated as 2.37±0.04 and this log-log correlation function exhibits a clear linear range and scale invariance in the cumulative statistics between 1.19 and 11.32 km (indicated in Figure 4c). *Dc* and standard error in Figure 4 are also determined within these distances.

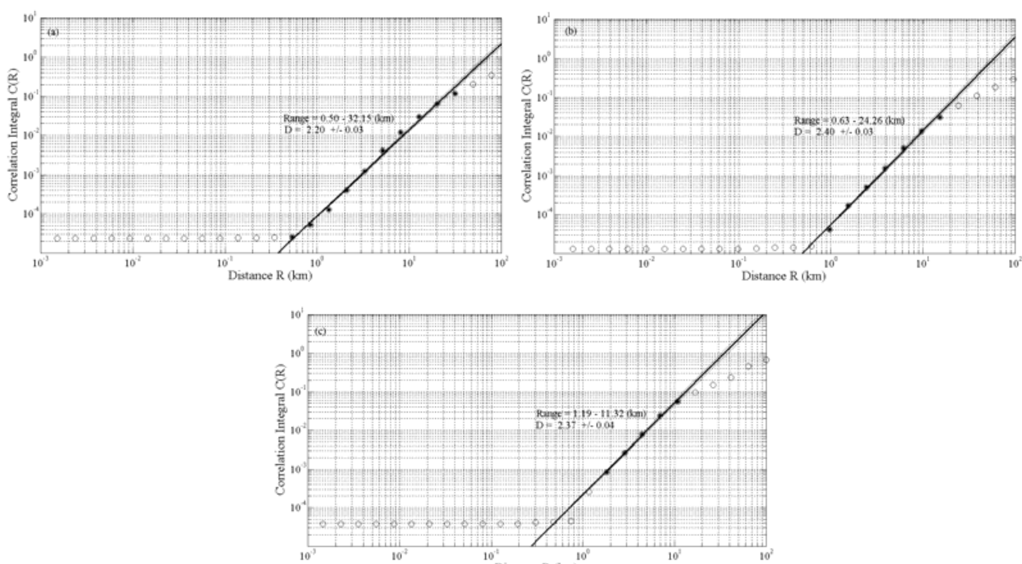

Figure 4. Fractal dimension for (a) region 1, (b) region 2 and (c) region 3. The slope of the black line corresponds to the *Dc* value and the gray lines illustrate the standard errors.

The variation of the *b*-value as a function of time in different parts of the NAFZ is also analyzed (Figure 5). Temporal changes of *b*-value are calculated for sample size of 1000 earthquakes for region 1, 250 earthquakes for regions 2 and 3. A systematic increase in *b*-value can be observed until 1996 with $b>1.5$ in region 1. *b*-value shows a great decrease with $b\approx0.9$ before the occurrence of 1999 Izmit earthquake and a clear increase after the main shock (Figure 5a). Such kind of behaviors is also observed for some great earthquakes in regions 2 and 3. In region 2, there is a clear tendency of decrease with $b\approx0.7$ before the 1999 Duzce earthquake and an increase with $b>1.0$ after the main shock (Figure 5b). In region 3, the same properties of *b*-values showing a decrease are observed before the three great earthquakes. *b*-values shows a decrease before the occurrence of 2003 Tunceli, 2003 Bingol and 2005 Bingol earthquake sequences and a clear increase after the main shocks (Figure 5c). The *b*-value for a region does not reflect only the relative proportion of the number of large and small earthquakes in the region, but is also related to the stress condition over the region [14]. Therefore, it is interpreted that the anomalies of decreases in *b*-value before the main shocks may be due to an increase in effective stress and can be used as an indicator of the future earthquake by observing the changes in *b*-value with time in all parts of the NAFZ. Also, the step increase in *b*-value is related to the reduced stress in these times after the main shocks.

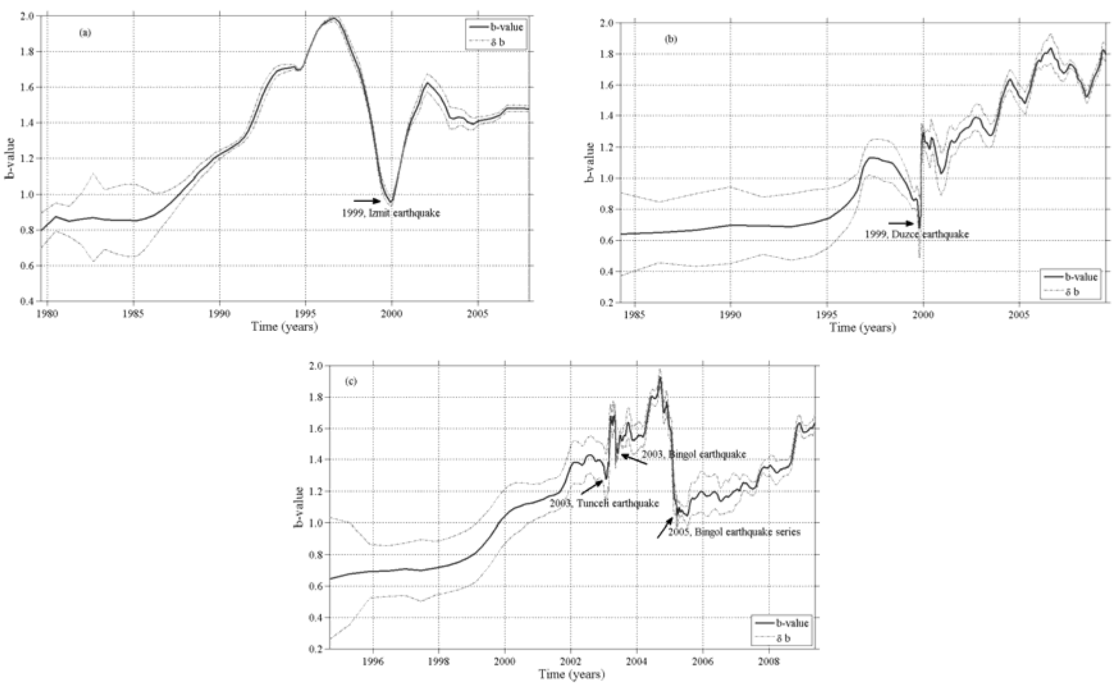

Figure 5. The *b*-value as a function of time for (a) region 1, (b) region 2 and (c) region 3. Standard deviation (δb) (dashed lines) is also given. Arrows show the great decrease in *b*-values before the large earthquakes.

Regional distribution of the standard deviate *Z*-value for all parts of the NAFZ is presented for the beginning of 2010 (Figure 6). To establish the regional distribution of the seismic quiescence, it is applied the Reasenberg [21] algorithm to decluster data. The areas under analysis were divided into rectangular cells spacing 0.02º in longitude and latitude. The nearest earthquakes, *N*, at each node are taken as 50 events for all regions and the seismicity rate changes are searched by a moving time window T_W=5.5 years. For each grid point we binned the earthquake population into many binning spans of 28 days for all regions in order to have a continuous and dense coverage in time. Eight significant quiescence anomalies were identified in the study regions. In region 1 covering the MNAFZ, the first significant anomaly is found centered at 41.08ºN-28.58ºE (region A, around Silivri) and the second one is found centered at 41.47ºN-29.51ºE (region B, in the Black Sea). The third significant quiescence is observed centered at 40.69ºN-29.78ºE (region C, including Izmit) and the fourth significant anomaly is found centered at 40.26ºN-26.46ºE (region D, around Gelibolu, Canakkale). In region 2 including the ANAFZ, the first significant anomaly is found centered at 40.59ºN-31.03ºE (region E, including Duzce fault) and the second quiescence area is found centered at 40.86ºN-35.30ºE (region F, around Amasya). In region 3 covering the ENAFZ, the first significant anomaly is found centered at 39.48ºN-39.74ºE (region G, around Erzincan) and the second anomaly is found centered at 39.06ºN-40.50ºE (region H, around Bingol).

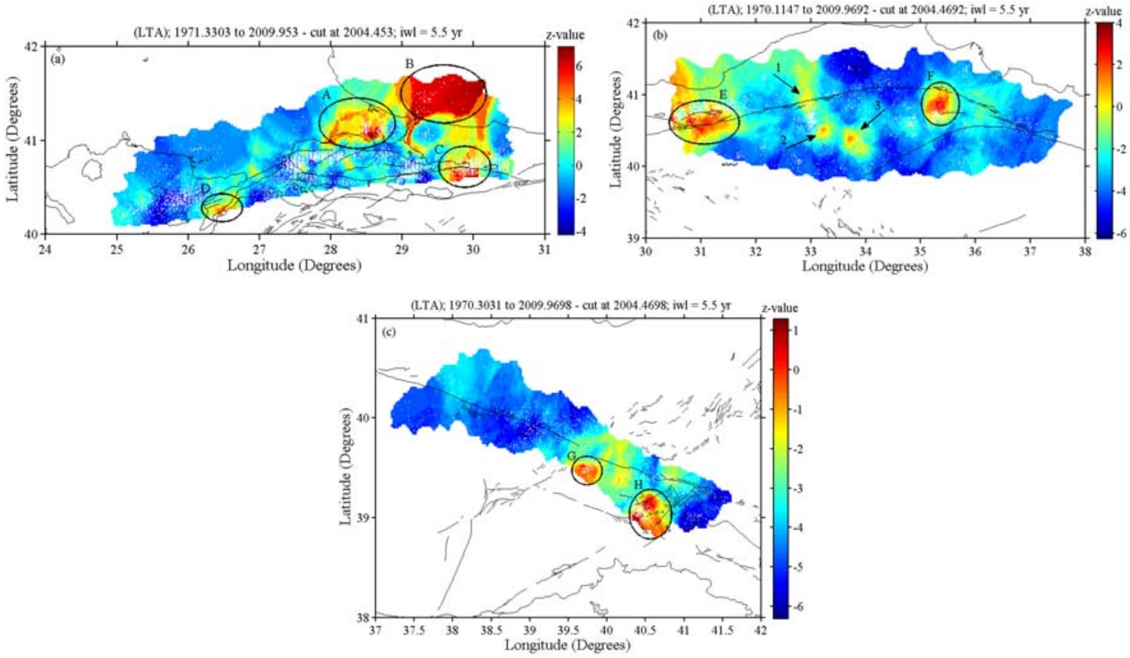

Figure 6. Z-value distributions in the beginning of 2010 with T_W =5.5 years for (a) region 1, (b) region 2 and (c) region 3. White dots show the declustered earthquakes with $M_D \geq 2.7$ for region 1, $M_D \geq 2.9$ for regions 2 and 3.

5. CONCLUSIONS

Spatial and temporal properties of the seismic activity from 1970 to 2010 in the North Anatolian Fault Zone are investigated in order to characterize the seismic behaviors. For this purpose a number of statistical parameters are used; namely size-scaling parameters (such as slope of recurrence curve b-value), seismic quiescence Z-value, temporal and spatial distribution of earthquakes with characteristic of fractal correlation dimension, Dc, as well as the histograms of temporal, spatial and magnitude distribution. For this purpose, statistical analysis techniques based on the seismic tool *ZMAP* are applied. The instrumental earthquake catalog of the Bogazici University, Kandilli Observatory and Earthquake Research Institute between 1970 and 2010, for 17198 crustal earthquakes of magnitude equal and greater than 1.4, with depths less than 70 km is used. The catalogue is homogeneous and complete for duration magnitude.

Magnitude completeness analyses present a value between 2.7 and 2.9 for all parts of the NAFZ. The b-values for all regions are close to 1 and typical for earthquake catalogs. Temporal distributions of b-values show a strong tendency of decreases before the great main shocks and this behavior can be used as an indicator of the next earthquake. Correlation dimension values are greater than 2.20 for all parts of the NAFZ. This suggests that seismic activity is more clustered at larger scales (or in smaller areas) in the North Anatolian Fault Zone.

There are eight regions exhibiting significant seismic quiescence on the North Anatolian Fault Zone in the beginning of 2010. On the Marmara part of the North Anatolian Fault Zone, four anomalies are found centered at 41.08ºN-28.58ºE (around Silivri), 41.47ºN-29.51ºE (in the Black Sea), 40.69ºN-29.78ºE (including Izmit) and 40.26ºN-26.46ºE (around Gelibolu, Canakkale). The other two quiescence areas are found centered at 40.59ºN-31.03ºE (including Duzce fault) and 40.86ºN-35.30ºE (around Amasya) on the Anatolian part of the North Anatolian Fault Zone. The rest of the quiescence anomalies are found centered at 39.48ºN-39.74ºE (around Erzincan) and 39.06ºN-40.50ºE (around Bingol) on the Eastern part of the North Anatolian Fault Zone.

The North Anatolian Fault Zone was struck with devastating earthquakes in recent years. Therefore, prediction of the future large earthquake on the NAFZ would be useful. Such a prediction must be relied on the observation of phenomena related to precursory quiescence. Previous studies for the North Anatolian Fault zone show that the return periods of $M_D \geq 5.5$ have been exceeded in the Anatolian part of the North Anatolian Fault Zone. However, the return periods of $M_D \geq 5.5$ for the Marmara and the Eastern part and the return period of $M_D \geq 6.0$ for the Anatolian part of the North Anatolian Fault Zone will be exceeded between 2010 and 2012. For this reason, special attention should be given to these regions where the seismic quiescence is observed.

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