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A Poisson method application to the assessment of the earthquake hazard in the North Anatolian Fault Zone, Turkey

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ABSTRACT

North Anatolian Fault (NAF) is one from the most important strike-slip fault zones in the world and located among regions in the highest seismic activity. The NAFZ observed very large earthquakes from the past to present. The aim of this study; the important parameters of Gutenberg-Richter relationship (*a* and *b* values) estimated and this parameters taking into account, earthquakes were examined in the between years 1900-2015 for 10 different seismic source regions in the NAFZ. After that estimated occurrence probabilities and return periods of occurring earthquakes in fault zone in the next years, and is being assessed with Poisson method the earthquake hazard of the NAFZ. The 10 different seismic source regions are determined the relationships between the cumulative number-magnitude which estimated *a* and *b* parameters with the equation of $LogN=a-bM$ in the Gutenberg-Richter. A homogenous earthquake catalog for M_S magnitude which is equal or larger than 4.0 is used for the time period between 1900 and 2015. The database of catalog used in the study has been created from International Seismological Center (ISC) and Boğazici University Kandilli observation and earthquake research institute (KOERI). The earthquake data were obtained until from 1900 to 1974 from KOERI and ISC until from 1974 to 2015 from KOERI. The probabilities of the earthquake occurring are estimated for the next 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 years in the 10 different seismic source regions. The highest earthquake occur probabilities in 10 different seismic source regions in the next years estimated that the region Tokat-Erzincan (Region 9) 99% with an earthquake occur probability for magnitude 6.5 which the return period 24.7 year, 92% with an earthquake occur probability for magnitude 7 which the return period 39.1 year, 80% with an earthquake occur probability for magnitude 7.5 which the return period 62.1 year, 64% with an earthquake occur probability for magnitude 8 which the return period 98.5 year. For the Marmara Region (Region 2) in the next 100 year estimated that 89% with an earthquake occur probability for magnitude 6 which the return period 44.9 year, 45% with an earthquake occur probability for magnitude 6.5 which the return period 87 year, 45% with an earthquake occur probability for magnitude 7 which the return period 168.6 year.

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1. Introduction

The earthquake hazard of regions represented a possible potential or level of expected hazard and caused by geological structure features, tectonic movements, geophysical fields etc. At the same time, the satisfactory evaluation of earthquake hazard was one of the major problems of engineer seismology. The appraisal of earthquake hazard of the territory is realized using essentiality and probabilistic methods. The indifferent information

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of some parameters and random character of seismic events were caused the probabilistic analysis of earthquake hazard evaluation included some models of seismic sources, the earthquake return periods, the seismic signal attenuation, and distance addiction, and much uncertainty. Although in the obligation analysis of earthquake hazard evaluation the uncertainty was not believed, just the extreme seismic effect is estimated in the real territory, using near earthquake source with constant magnitudes. (Zaalishvili, 2012).

The probabilistic evaluation described first by Cornell which used in most earthquake hazard analysis, and usually receivable for four important information (Reiter 1991).

- Description of earthquake source regions
- Description of recurrence characteristic for each region
- Evaluation of earthquake effect
- Description of hazard at the territory.

The amount, sizes, and location of future earthquakes were determined a true approach by probabilistic estimates. (Bazzuro and Cornell, 1999).

In the past years, stochastic models of earthquake occurrence have been recommended (Kagan, 1996). The firstly reasons for the stochastic model formulation, the small number of parameters evaluated, the different of regions could be applied and the about ease with which hazard although a few sources might be combined. The hazard evaluation most important for earthquake forecasts knowledgeable determinations in of earthquakes hazard and exigency responsibility (Kagan, 2010). The occurring randomly in time, space and magnitude have long been determined by earthquake events. According to an assumption, earthquakes estimated a stochastic process free sequence of events space and extrication all of the energy at a point, space and in time. The happening of a next event was not attached to at the time, size or location of the last or no of the proceeding events. The detached supposition pleased the Poisson process. In accordance with the Poisson process, if a large earthquake consisted on at a point in time, the likelihood of another large event occurred in the near future is not changed (Anagnos and Kiremidjian, 1988). The Poisson model was well definitional earthquake occurrence which used for determined of the earthquake hazard analysis extensively in the time (Cornell, 1968).

The different researchers have applied the Poisson models in the world. The Poisson distribution used for determined the statistical distributions of earthquake numbers by Kagan (2010). The negative binomial distribution (NBD) has got a higher variance than the Poisson law, which could be shown (Kagan, 1973a; 1973b). The generalized Poisson distributions could be used to about earthquake numbers (Cornell, 1968). The some arbitrary compounding distributions from the empirical observations on the earthquake sequences which determined earlier for earthquake occurrences for the compound Poisson process models (Moharir, 1992) and compound Poisson models determined as alternatives to the Poisson process model (Singh 1983). The earthquake sequences which used estimating seismic risk relate to Poisson model (Molchan et al., 1970). Lenord et al. (2001) and more extensively and appropriated method based on the Poisson distribution which assumed different unknown variances for the frequencies, equal to the means.

The NAFZ has been the highest earthquake activity among regions in the world. Most large earthquakes have occurred on this fault system in Turkey. A lot of studies have been made to evaluate of earthquake hazards in the NAFZ. Semi-Markov method is applied for earthquakes larger than 5.5 magnitude occurred between 1900 to 1986 years (Altınok, 1988). Öncel et al. (1996) and Mäntyniemi and Kijko (1991) studied earthquake risk using maximum likelihood method. The earthquake hazard parameters are estimated with Kijko and Sellevoll method (Bayrak et al., 2011). Türker and Bayrak (2015b) determined the earthquake hazard using the Bayesian method in the NAFZ. Also, Bayrak and Türker investigated the earthquake hazard using different statistics methods in different areas of Turkey (Bayrak and Türker, 2015a; 2016a; 2016b).

The aim of this study; the important parameters of Gutenberg-Richter relationship (a and b values) estimated and these parameters taking into account, earthquakes were examined in the instrumental period for 10 different seismic source regions in the NAFZ. After that, estimated occurrence probabilities and return periods of occurring earthquakes in fault zone in the future years (10, 20, 30, 40, 50, 60, 70, 80, 90 and 100), and is appraised with Poisson method the earthquake hazard of the NAFZ.

2. Data and Seismic Source Regions

In this study; is used the instrumental earthquake catalog by Bayrak et al. (2009). A homogenous earthquake catalog for M_S magnitude which is equal or larger than 4.0 is used for the time period between 1900 and 2015. The catalogs contain the origin time, different magnitudes scales (M_B-body wave magnitude, M_S-surface wave magnitude, M_L-local magnitude, M_D-duration magnitude, and M_W-moment magnitude), epicenter and depth information of earthquakes. The database of catalog used in the study has been created from International Seismological Center (ISC) and Boğaziçi University Kandilli observation and earthquake research institute (KOERI). The earthquake data were obtained until from 1900 to 1974 from KOERI and ISC until from 1974 to 2015 from KOERI.

We prepared a homogenous data catalog for that period fulfill the basic requirement of homogeneity of M_S magnitude using relationship which is equal or larger than 4.0, and used only instrumental part of the earthquake catalogue. We applied decluster on the earthquake catalog. Earthquake catalogs were frequently declustered which using a pioneer to modeling the residual events as a substantiation of a spatially inhomogeneous in temporally homogeneous Poisson process (Luen and Stark, 2012).

We updated different nine seismic sources defined by Bayrak et al. (2011). We divided Region 3 given by Bayrak et al. (2011) into two different source regions considering Düzce Faults is a different source. Finally, 10 different seismic source regions shown in Fig. 1 are defined to study earthquake hazard parameters of NAFZ.

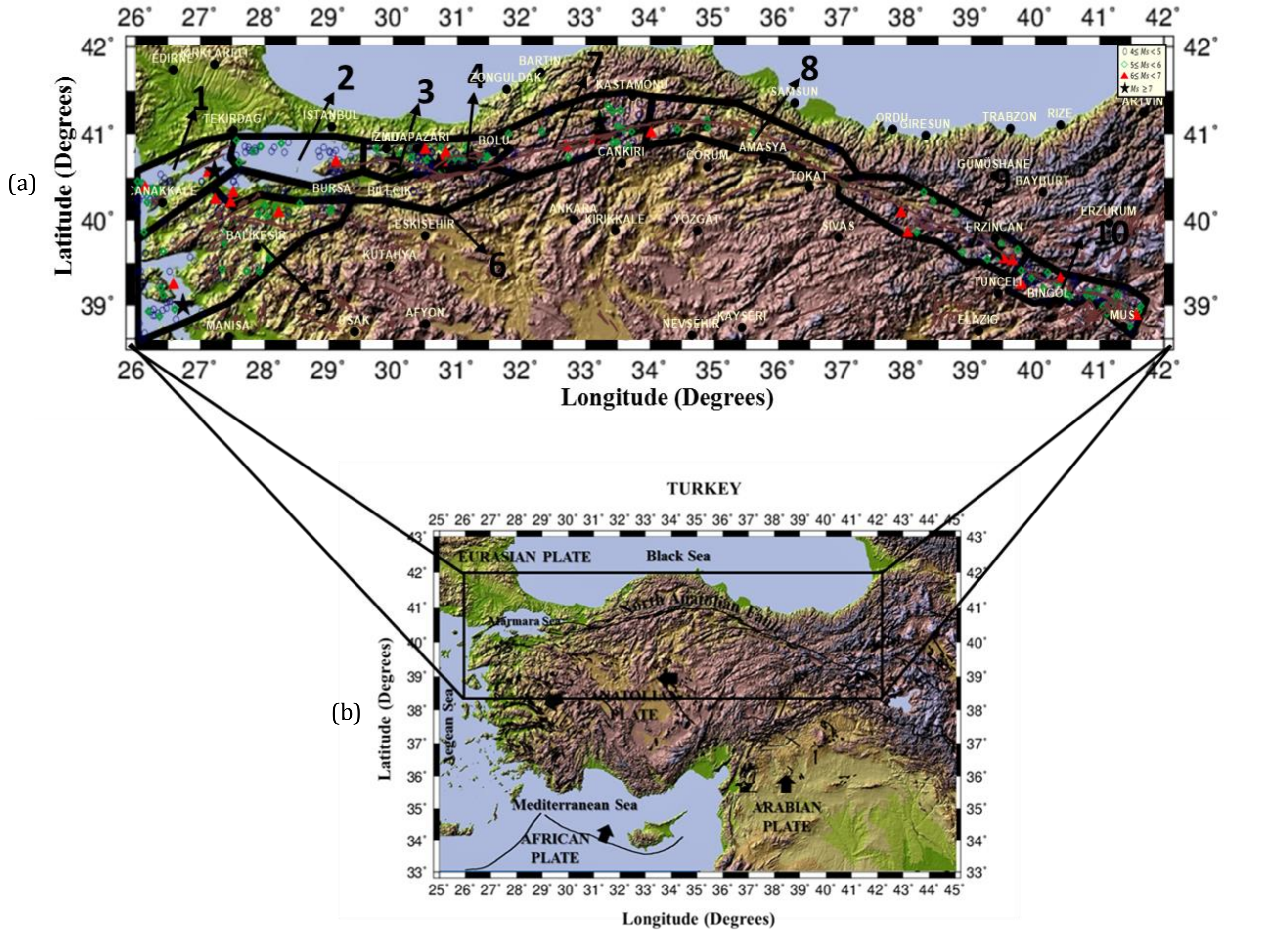

Fig. 1. a) The 10 different seismic source regions are shown on the North Anatolian Fault Zone (NAFZ); b) The epicenter of $M_S \geq 4.0$ are shown with different symbols. The NAFZ is demonstrated on Turkey map.

We divided into 10 different seismic source regions based on epicenter distribution, tectonics, seismicity and focal mechanism solutions as shown in Table 1.

3. Tectonic in the North Anatolian Fault Zone

The tectonic and seismicity of Turkey which were formed with plate movements in between African, Arabian, Eurasian and Anatolian (McKenzie, 1972; Alptekin, 1978; Dewey 1986; Şengör, 1979; Şengör et al., 1985). Many the large earthquakes occurred on the North Anatolian fault zone along which Turkey is moving westward. The North Anatolian Fault Zone (NAFZ) from tectonism the East Anatolian convergent zone and the Hellenic Arc occurred that the motion of Asia Minor is compensated by the completion of oceanic crust (McKenzie, 1972). The NAFZ has been a dextral strike-slip fault zone (Ketin, 1948) extending about 1200 km (Bozkurt, 2001) across northern Turkey and marking the boundary between the Anatolian and Eurasian plates (Ketin, 1969; Şengör et al., 1985; Barka, 1996; Şaroğlu, 1988). Developing hard localization in a usually westerly widening right-lateral kerogen in northern Turkey commonly along an interface arranging subduction-expansion material to its south and older and rigid continental basements to its north was occurred in the NAFZ.

Table 1. Seismic source regions.

Region	Region Name
1	Saroz Gulf
2	Marmara Sea
3	İzmit-Sakarya
4	Sakarya-Düzce
5	The Southern Branch of NAF
6	The Southern of Marmara
7	Düzce-Tosya
8	Tosya-Erbaa
9	Tokat-Erzincan
10	The East of Erzincan

Morphologically different and seismically active extends from the Gulf of Saros in the northern Aegean Sea from Karlıova, paralleling approximately the southern Black Sea support and keeping a rather ordinary distance of some 100 km to the coast, connecting the Aegean taphrogen (Şengör et al., 2005) with the East Anatolian high plateau (Koçyiğit et al., 2001; Şengör et al., 2003). The fault occurred roundly 13 to 11 Ma ago in the east and propagated westward. It achieved the Sea of Marmara no earlier than 200 ka ago, though shear concerned deformation in a wide zone there had anyway introduced in the late Miocene (Şengör et al., 2005). The NAFZ starts around Karlıova triple junction in the east, and it runs NW to Vezirköprü that it makes a left bend and constant westward. Around Kargı, it makes another left bend and then runs in an SW direction (Bozkurt, 2001). The NAFZ is 85±5 km (Bozkurt, 2001; Şengör et al., 2003). Along of the NAFZ, the right-lateral slip has a rate of 24±1 mm/yr (McClusky et al., 2000; Flerit et al., 2004; Reilinger et al., 2006).

The western part of the NAFZ is an in the Marmara Sea region and the NAFZ divided into a complex fault structure, however, the eastern part of the NAFZ is a narrow strike-slip zone. The transition of the strike-slip regime in the east into a stress regime with N-S extension formed from this branching. The next, if the predominant E-W purposed graben structures in Western Anatolia could accountable, the Aegean region could have been typical. The northern branch of NAFZ is the most active fault zone in the Sea of Marmara according to the southern branch of NAFZ. The North branch exists as a zone comprised of boundary faults, normal faults and reverse faults in the Sea of Marmara. The NAFZ is young (~5 Ma) and has about 85 km of cumulative displacement (Hubert-Ferrari et al., 2009).

The NAFZ has been devastating earthquakes along with both historical and instrumental periods so the most active fault zone in Turkey. Historical investigations of major earthquakes along the NAFZ have revealed that in the twentieth century, ruptures migrated westward after the 1939 Erzincan earthquake in eastern Turkey (Barka and Kadinsky-Cade, 1988; Barka, 1996). This fault observed a lot of earthquakes of $M_S \geqslant 7.0$. In the instrumental period, the earthquakes in the NAFZ migrated from east to west and this process have begun with 1939 Erzincan earthquake (M_S=7.8).

4. Method

The Poisson method used one of the most common models to estimate the earthquake occurrences. According to the Poisson model was not affected since passing the time by the formation of a previous earthquake, distribution of waiting time by the formation of the next earthquake (Özdemir et al., 2000). The Poisson model is especially important for large earthquakes.

The sequence of events forms a Poisson process where the occurrence of a subsequent event did not depend on time, size or location of the last any of the preceding events. $N(t)$ as the number of events in the interval (0,t) the counting sequence ($N(t)$, t>=0) is Poisson provided.

$$P\{N(t+s)-N(t)=k\}=\frac{e^{-\lambda s}(\lambda s)^k}{k!} \quad k=0,1,2,\ldots;\ \lambda>0\,. \tag{1}$$

This relationship has been used as a model of the earthquake process in the Poisson process (Lomnitz, 1966).

The interval times for the Poisson process $\{T_1, T_2, T_3, \ldots\ldots, T_n\}$ should be exponentially distributed with probability density function $f_T(t)$ or $f_M(m)$and cumulative distribution $F_T(t)$ or $F_M(m)$ given.

$$f_T(t)=\lambda e^{-\lambda t} \qquad t\geq 0, \lambda>0, \tag{2}$$

$$F_T(t)=1-e^{-\lambda t} \qquad t\geq 0, \lambda>0\,, \tag{3}$$

where λ is the rate of occurrence of events. The Gutenberg-Richter relationship describing the number of earthquake events, $N(m)$, of a given magnitude, m or greater in time t was given.

$$Log\ N(m) = a - bm\,, \tag{4}$$

where a and b are earthquake hazard parameters. Thus for a given magnitude of exceedance the frequency of occurrence.

$$\lambda(t)=e^{\alpha-\beta m} \qquad m_o \leq m \leq m_{max}\,, \tag{5}$$

where m_o and m_{max} are the lower and upper bound magnitudes respectively. The lower magnitude arises from practical considerations. The upper magnitude is determined by the maximum earthquake capacity of a fault.

The earthquake hazard parameters for investigated area with the Poisson method were calculated using different equations.

$$a' = a - log\,(b * ln10)\,, \tag{6}$$

$$a_1 = a - log\,T\,, \tag{7}$$

$$a_1' = a' - log\,T\,. \tag{8}$$

T in this equation shows period for the next years and calculated for 100 years. The normal frequency value was used for annual average the number occurring of earthquakes which were shown by the following equation.

$$N(M) = 10^{a_1'-b*M}\,. \tag{9}$$

$N(M)$ value indicated determining of the earthquake risk and has been calculated according to the seismic parameters.

$$R(M) = 1-e^{-N(M)*T}\,. \tag{10}$$

T value in this model was different from other models and used to calculate of the earthquake occurring risk.

The return periods according to the Poisson model was calculated for the next years using the following equation.

$$Q(M)=\frac{1}{N(M)}\,. \tag{11}$$

The risk rate of the Poisson process is equal to the constant implying that the probability of occurrence of an earthquake in a future small increment of time, Δt, remains constant regardless of the size of the last event or the elapsed time since its occurrence.

5. Chi-Square Test for Poisson method

The chi-square test has used the fact that, conditional on the total number of events and the add distribution of the numbers of events in the probabilities.

The test statistic is;

$$\chi^2 = \sum_{k=1}^{K} \frac{(N_k - \hat{\lambda})^2}{\hat{\lambda}} \qquad k = \{1, \dots\dots, K\}. \tag{12}$$

If the hypothesis for applied Poisson method was true, the distribution of X^2 was determined from the Chi-square with K-1 degrees of freedom. The chi-square test involved choosing the number of intervals K. The chi-square test investigated only at the change of the observed number of events across intervals.

6. Results and Discussions

The NAFZ is one of the most seismically active regions of the Turkey and has been affected large earthquakes in the past years. The Poisson method is applied in order to check the potentiality of the different seismic source regions in the NAFZ for the future earthquake hazard. For this purpose, a homogeneous and complete seismicity database of the instrumental period during is used in 10 different seismic source regions in the examined region. For this aim; a and b parameters of Gutenberg-Richter relationship, the annual occurring number of earthquakes, return periods and earthquake risk in the next years.

The 10 different seismic source regions are estimated a and b parameters with equation (Eqs. (4) and (5)) of $LogN$=a-bM in the Gutenberg-Richter which are determined the relationships between the cumulative number-magnitude in shown Fig. 2. The earthquake hazard parameters are estimated for the 10 different seismic source regions of the NAFZ and shown in Table 2.

The b value is lower than the local mean value of 1.0, which indicates that the data consists of the larger earthquake and high differential crustal stress in the region (Wiemer and Katsumata, 1999; Wiemer and Wyss, 2002).

Table 2. The earthquake hazard parameters are estimated for 10 different seismic source regions on the NAFZ.

Region	Region name	a	$b \pm \sigma_b$	a/b	a'	a_1	a_1'	N	M_{max}^{obs}
1	Saroz Gulf	4.75	0.630±0.08	7.53	3.66	1.75	1.66	65	7.3
2	Marmara Sea	5.00	0.688±0.09	7.26	3.79	1.92	1.78	53	7.3
3	İzmit-Sakarya	4.92	0.685±0.09	7.18	3.79	1.92	1.79	59	7.8
4	Sakarya-Düzce	4.68	0.611±0.07	7.65	3.60	1.68	1.60	87	7.2
5	The Southern Branch of NAF	5.64	0.859±0.1	6.56	4.39	2.64	2.39	44	7.0
6	The Southern of Marmara	5.56	0.731±0.06	7.60	4.39	2.56	2.39	117	7.2
7	Düzce-Tosya	4.53	0.548±0.05	8.26	3.51	1.53	1.51	54	7.3
8	Tosya-Erbaa	4.42	0.617±0.1	7.16	3.34	1.42	1.34	20	7.1
9	Tokat-Erzincan	4.18	0.501±0.05	8.34	3.21	1.18	1.21	44	7.9
10	The east of Erzincan	5.12	0.651±0.04	7.86	4.01	2.12	2.01	94	6.8

The b values which is one of the most important earthquake hazard parameters are estimated using Eq. (4) with Poisson method for 10 different seismogenic source regions of the NAFZ. The map of estimated b values is plotted (Fig. 6). The estimated b values for the 10 different regions of the NAFZ vary between 0.501 and 0.859. The highest b value is observed in region 5 covering the Southern Branch of NAFZ, while the lowest b value is observed in region 9 covering the Tokat-Erzincan. The a/b values are estimated with Poisson method for 10 different seismogenic source regions. The map of estimated a/b values is plotted (Fig. 7). The highest a/b value is observed in region 9 covering the Tokat-Erzincan. The lowest a/b value is observed in region 5 covering the Southern Branch of NAFZ.

We plotted the maps of the occurrences probability of the earthquakes and return periods in the 6.5, 7.0, 7.5 and 8.0 magnitudes in next 100 years, respectively that shown in Figs. 8 and 9. The calculated changes between regions observed from a region to another region, clearly.

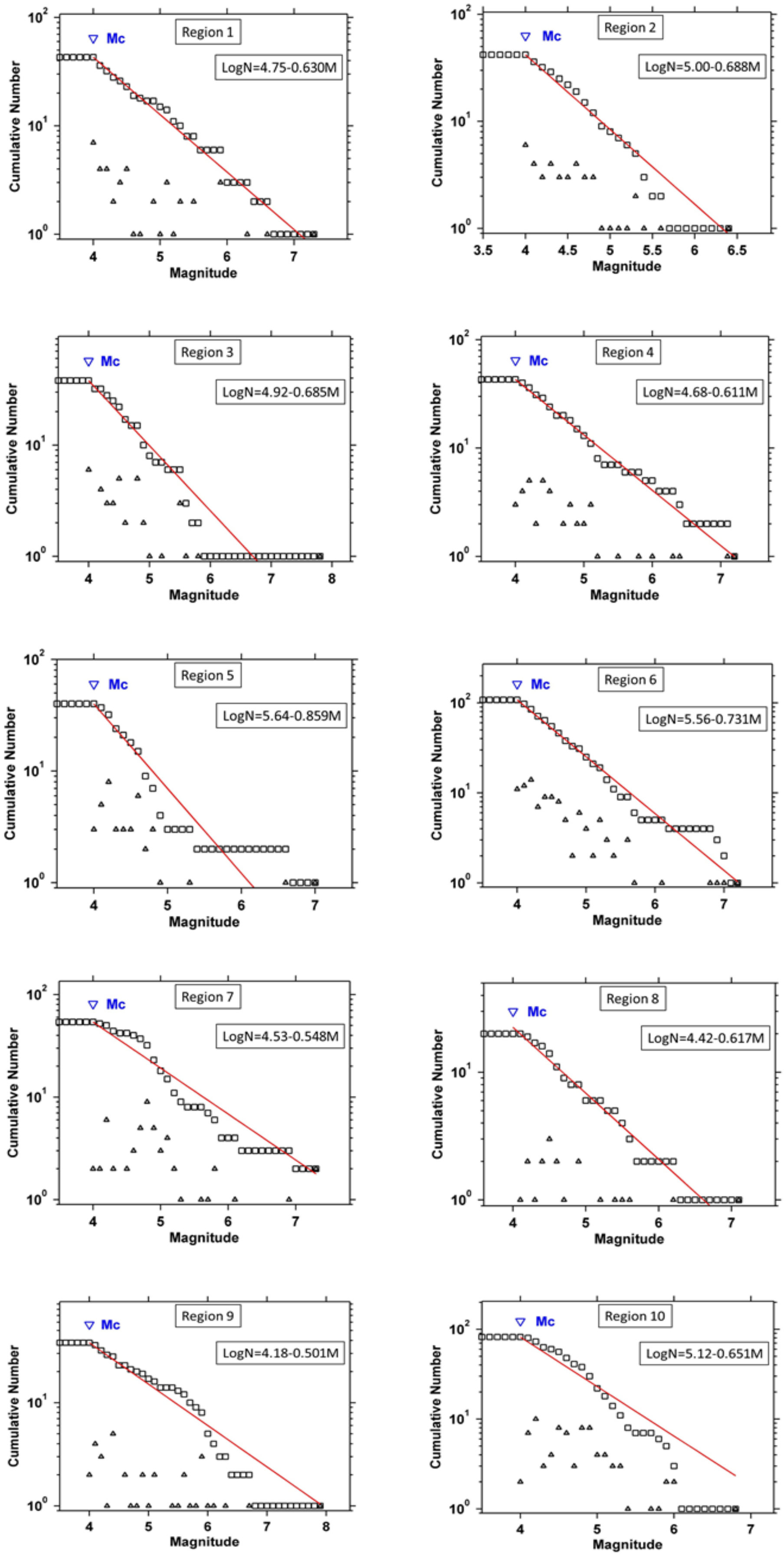

Fig. 2. The Magnitude-Frequency (Gutenberg-Richter) relationships are shown for occurring earthquakes on the NAFZ. The overall catalog plotted is observed both the cumulative (squares) and noncumulative form (triangles) in frequency magnitude distribution.

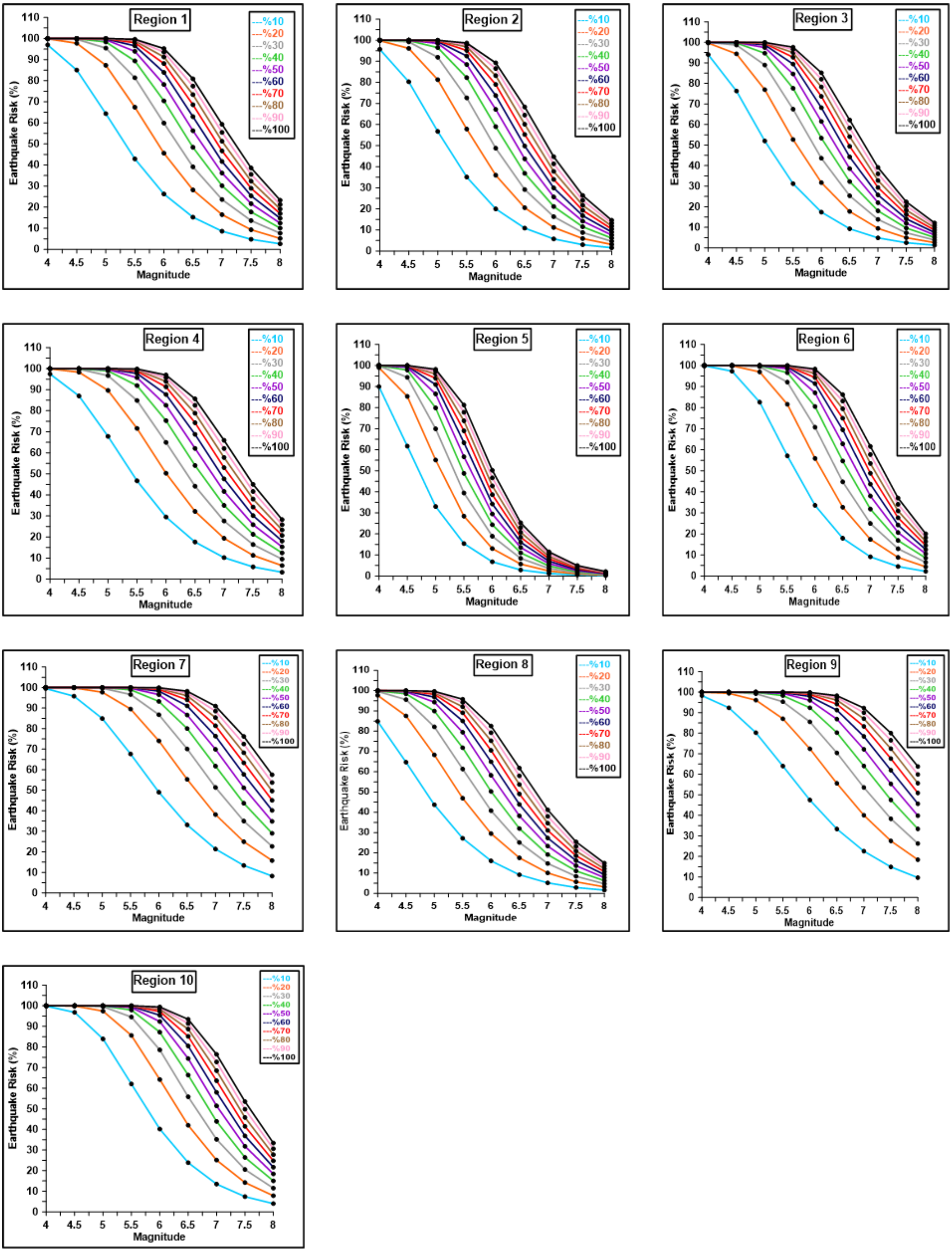

Fig. 3. The earthquake risk (%) values are estimated for the 10 different seismic source regions.

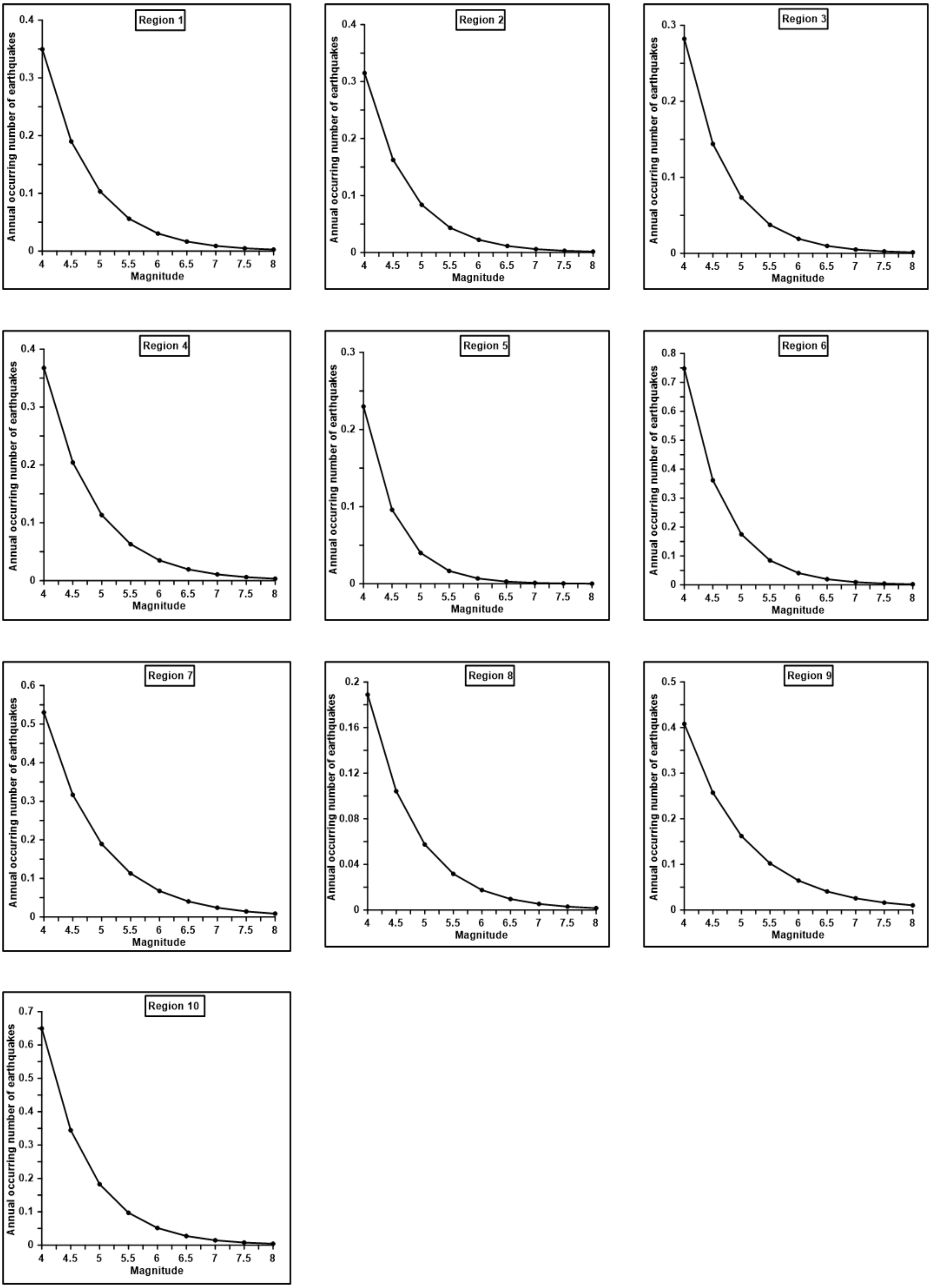

Fig. 4. The annual occurring number of earthquakes are estimated for the 10 different seismic source regions.

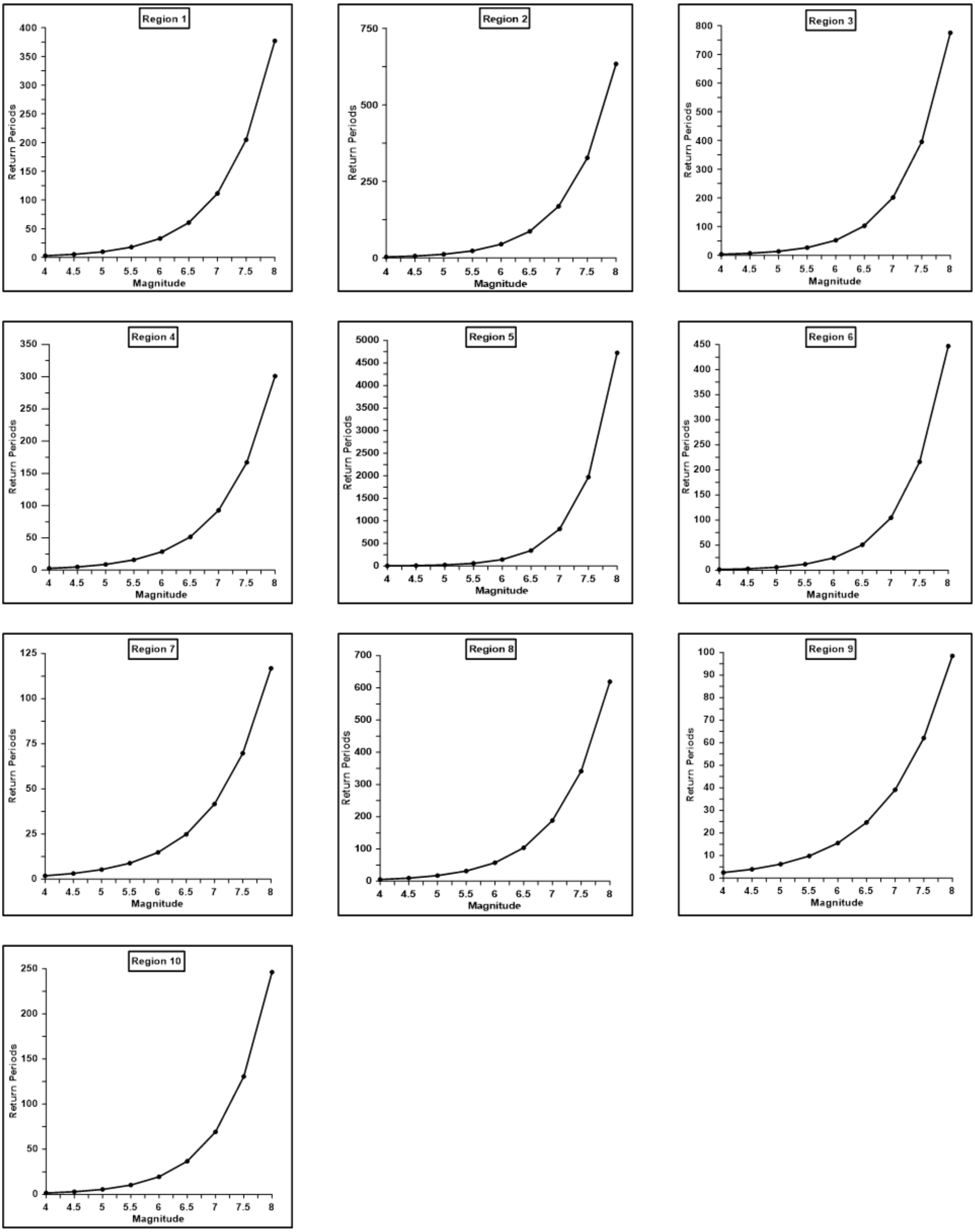

Fig. 5. The return periods are estimated for the 10 different seismic source regions.

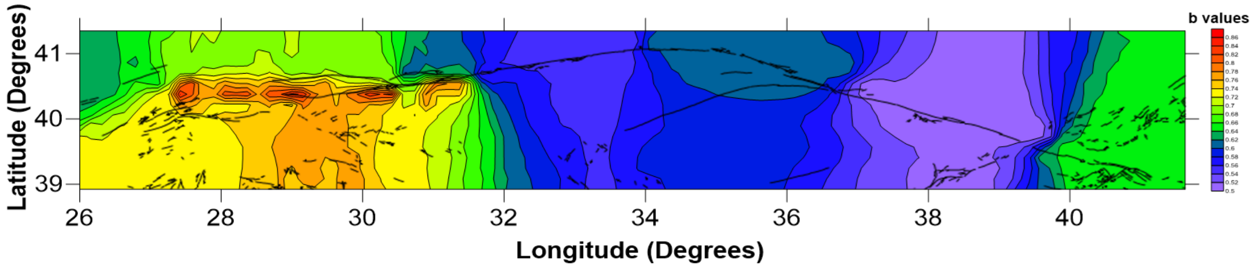

Fig. 6. The map of estimated b values are plotted for 10 different seismic source regions of the NAFZ.

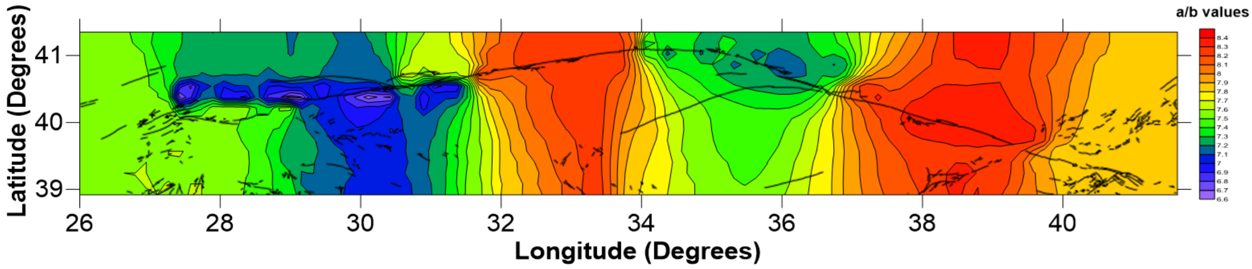

Fig. 7. The map of estimated a/b values are plotted for 10 different seismic source regions of the NAFZ.

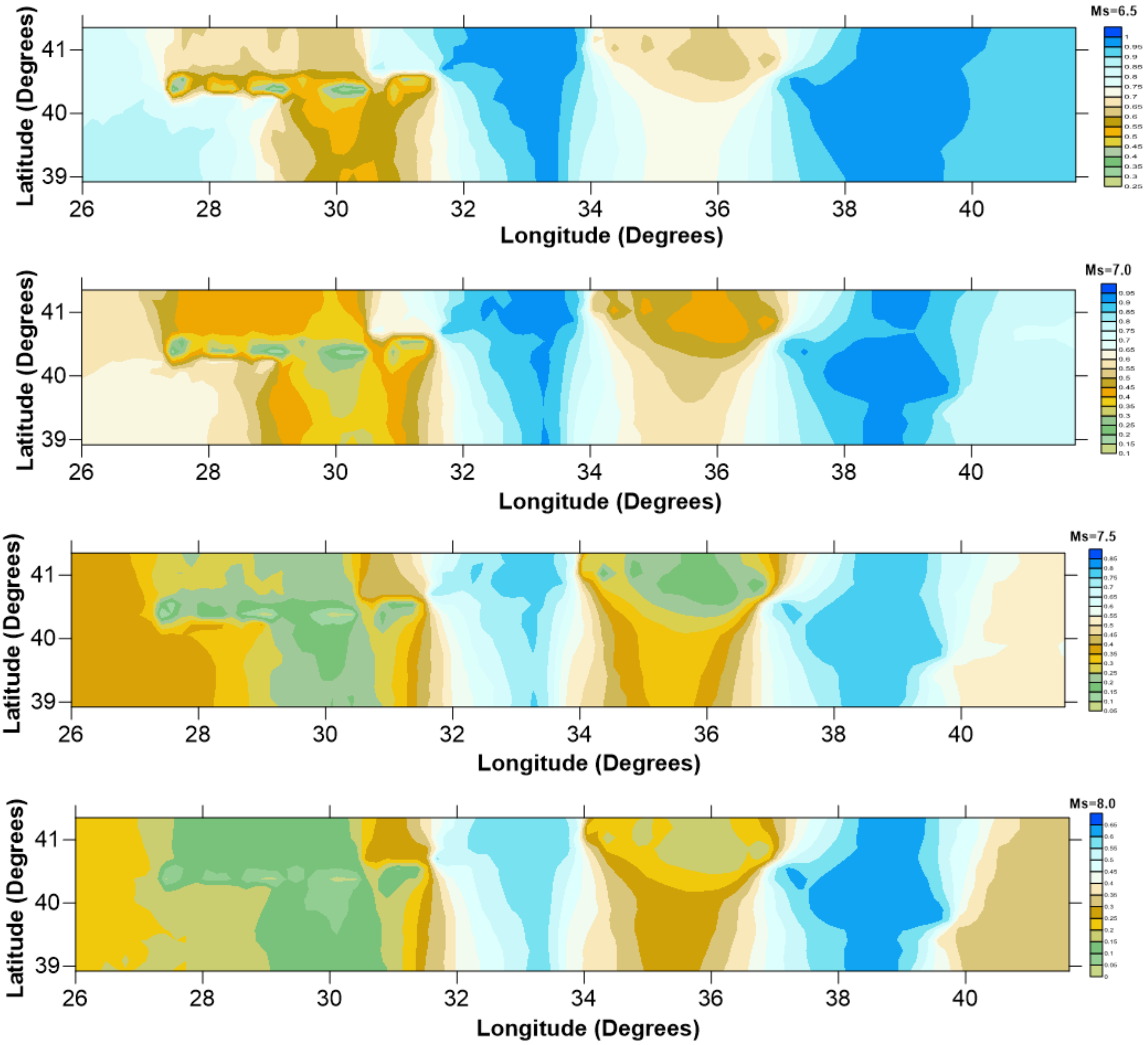

Fig. 8. The maps of the occurrences probability of the earthquakes in the 6.5, 7.0, 7.5 and 8.0 magnitudes are plotted in next 100 years, respectively.

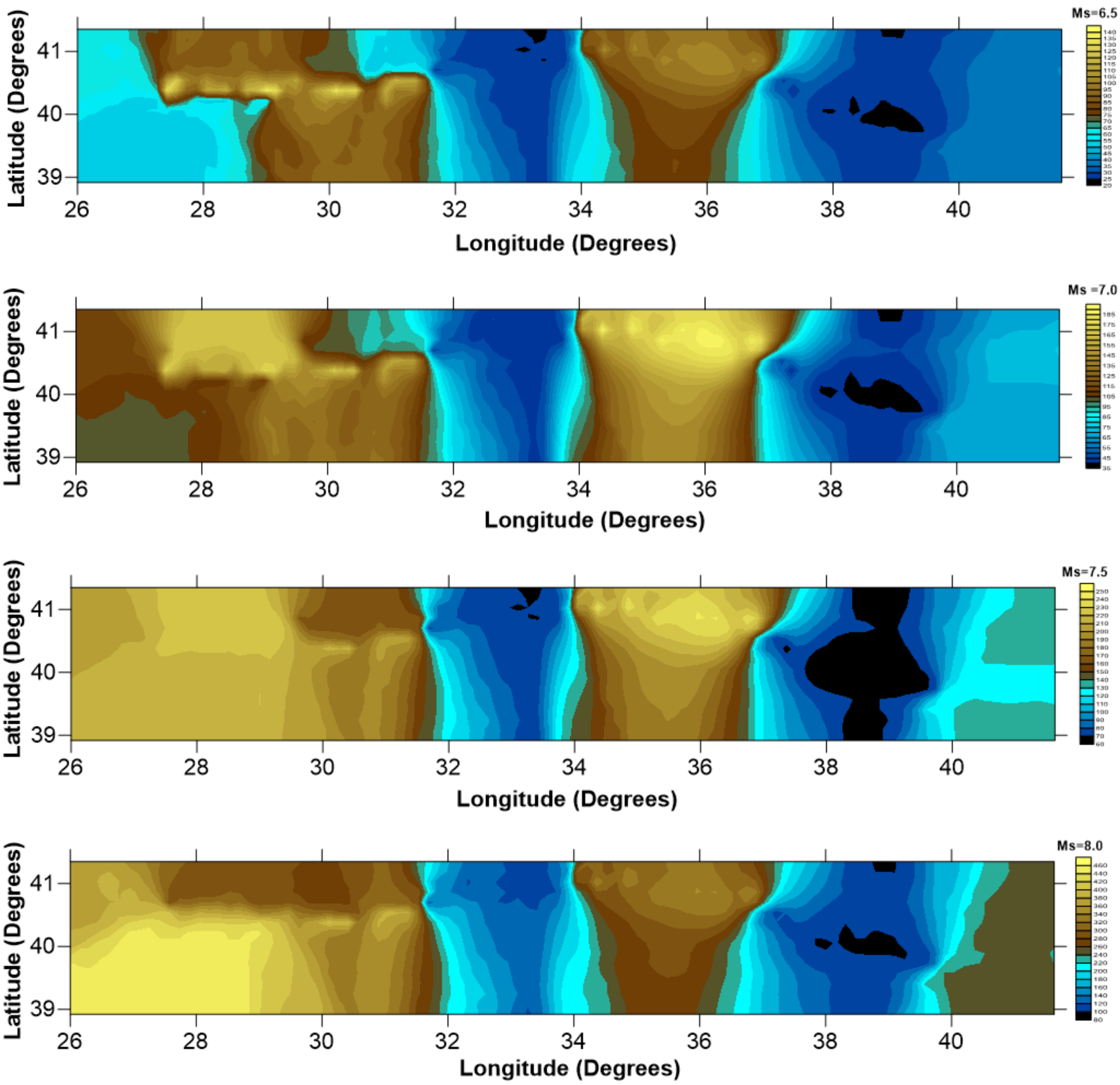

Fig. 9. The maps of the return periods in the 6.5, 7.0, 7.5 and 8.0 magnitudes are plotted for in next 100 years, respectively.

The probabilities of the earthquake occurring are estimated for the future 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 years in the 10 different seismic source regions and are shown in Fig. 3. The highest earthquake occurring probabilities in 10 different seismic source regions in the next years estimated that the region 9. We estimated annual occurring number of earthquakes ($N(M)$) using Eq. (10) for 10 different seismic regions which are shown in Fig. 4. The region 9 is observed 0.0644 annual occurring number of magnitude of 6 magnitude, 0.0406 annual occurring number of magnitude of 6.5 magnitude, 0.0256 annual occurring number of magnitude of 7 magnitude, 0.0161 annual occurring number of magnitude of 7.5 magnitude, 0.0102 annual occurring number of magnitude of 8 magnitude. If region 2 observed 0.0223 annual occurring number of magnitude of 6 magnitude, 0.0115 annual occurring number of magnitude of 6.5 magnitude, 0.0059 annual occurring number of magnitude of 7 magnitude.

Earthquake recurrence times (return periods, $Q(M)$) estimated using the parameters of Gutenberg-Richter relationship and are shown in Fig. 5. The region Tokat-Erzincan (Region 9) is estimated for the future 100 years using Eqs. (9) and (11), respectively. The region 9 is estimated 99% with an earthquake occur probability for magnitude 6.5 which the return period 24.7 year, 92% with an earthquake occur probability for magnitude 7 which the return period 39.1 year, 80% with an earthquake occur probability for magnitude 7.5 which the return period 62.1 year, 64% with an earthquake occur probability for magnitude 8 which the return period 98.5 year. For the Marmara Region (Region 2) in the next 100 year is estimated that 89% with an earthquake occur probability for magnitude 6 which the return period 44.9 year, 45% with an earthquake occur probability for magnitude 6.5 which the return period 87 year, 45% with an earthquake occur probability for magnitude 7 which the return period 168.6 year.

In the past, Bayrak and Türker (2015b) estimated an earthquake occurrence probability (in the next 100 years) in region Tokat-Erzincan using the Bayesian method for the NAFZ. In this study, we are estimated the same of results. Both the Bayesian method and the Poisson method are estimated an earthquake occurrence probability with most probably in the region Tokat-Erzincan for the next 100 years in the NAFZ.

7. Conclusions

In this study, The NAFZ was estimated earthquake hazard parameters (*a* and *b* values and their different values of Gutenberg-Richter relationship) in the future years for instrumental catalog during complete seismic catalogue with $M_S \geq 4.0$. For this aim, the annual occurring number of earthquakes, return periods and earthquake risk were estimated in the next 100 years. *a* and *b* values for this time period were estimated to be equal to 0.501 and 0.859, respectively. *b* values were observed the data form of larger earthquakes and high diversity crustal stress. We were applied the chi-square test for estimated values with Poisson method. Therefore, we were tested to the accuracy of the Poisson method. According to the chi-square test was applied for Poisson method and significance level estimated as α=0.05 in this study. Also, whole estimates were determined with Matlab program. Maps were plotted using GMT program. The annual occurring number of earthquakes were estimated for magnitudes 6.5, 7, 7.5 and 8 at region 9 while 6, 6.5 and 7 at region 2 in the NAFZ. This values were estimated respectively in region 9, 0.0644 for magnitude 6, 0.0406 for magnitude 6.5, 0.0256 for magnitude 7, 0.0161 for magnitude 7.5, 0.0102 for magnitude 8. In region 2, 0.0223 for magnitude 6, 0.0115 for magnitude 6.5, 0.0059 for magnitude 7, 0.0031 for magnitude 7.5. Also, the return periods were estimated for magnitude 6.5, 7, 7.5, and 8 at region 9, while 6, 6.5 and 7 at region 2. This values were estimated in region 9, respectively which 24.7 years for magnitude 6.5, 39.1 years for magnitude 7, 62.1 years for magnitude 7.5, 98.5 years for magnitude 8. Their earthquake risk values were estimated respectively, 99%, 92%, 80% and 64%. If region 2, 44.9 years for magnitude 6, 87 years for magnitude 6.5, 168.6 years for magnitude 7. Their earthquake risk values estimated respectively, 89%, 45% and 45%.

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