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Seismic hazard parameter estimation for north-western Turkey based on combination of disparate catalogues

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Abstract - The most widely accepted procedure for maximum magnitude estimation is the extreme value theory. The method is however subjected to great uncertainties associated with earthquake data incompleteness. The combination of large historical events with complete instrumental data is a tool to overcome this limitation. This procedure is applied here for the maximum likelihood estimation of earthquake magnitude and activity rates in the main seismogenic sources in north-western Turkey. Highest probabilities are found to correlate with the western section of the North Anatolian Fault in Marmara Sea, and the North Aegean Sea.

1. Introduction

The most common shortcoming in the probabilistic methods of seismic hazard analysis is the difficulty of including historical data in the earthquake catalog. Thus, the data set the statistical estimations of seismicity parameters are based on is usually inadequate to obtain highly reliable results. The commonly used methods for analyzing incomplete data sets are extreme distributions. Large uncertainties however arise in extreme value estimates of seismicity parameters in comparison with those obtained from the full catalog. Knopoff and Kagan (1977) and Kagan and Knopoff (1981) concluded that extreme value procedures are unsatisfactory for the determination of hazard parameters, being unreliable for return periods greater than about one half the span of the earthquake catalog. The same authors indicate the importance of including historical (non-instrumental), but also other geophysical data to extend the complete (instrumental) earthquake catalogs. Campbell (1977), Anderson (1979) and Molnar (1979) used slip rate information to obtain recurrence relationships. Slip rate measurements from geological data was incorporated by Papoulia et al. (2001) in the estimation of maximum expected

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magnitude for seismic hazard purposes. Papastamatiou (1980), Doser and Smith (1982), Anderson and Luco (1983) and Wesnousky et al. (1984) involved long-term slip rate data in seismic hazard estimation. Dong et al. (1984) applied the maximum entropy principle to incorporate geological, historical and instrumental information of varying quality into a single minimally biased recurrence relationship.

In 1989, Kijko and Sellevoll developed a method to obtain maximum likelihood estimates of seismic hazard parameters (maximum magnitude, activity rate, b-value), together with their uncertainties, by combining historical and instrumental data of varying quality. This overcomes the problems related to inhomogeneity and incompleteness of earthquake catalogs. This method is applied in the following to obtain the seismicity parameters associated with the main seismogenic sources in north-western Turkey.

More specifically, the purpose of this study is to test the applicability of the algorithm proposed by Kijko and Sellevoll (1989) to the region near the western end of the North Anatolian Fault (NAF) that has come into renewed interest following the Mw 7.4 earthquake that centered near Izmit in 1999, and the publication of the paper by Parsons et al. (2000) following it. In the latter the authors point out the historic precedents of earthquake occurrence along the NAF since 1939, and argue that the sequence of large events seems to indicate that a major earthquake always sets up the next one further west. They give probabilities for large earthquakes in the Sea of Marmara over the coming years and decades. These estimates, which differ from simple Poisson probabilities, are calculated by considering the current state of each active fault in the Sea of Marmara in terms of its renewal period for large earthquakes, and also the effect of interaction from earthquakes on adjacent faults increasing the stresses on these faults. Their estimates suggest that there is 62% probability of an earthquake in the Sea of Marmara causing strong shaking (defined in their paper as MM intensity of about VIII or higher) in the next 30 years. The standard deviation on this estimate is 15%, so the 84-percentile estimate is 77% probability of such an event, which is very high indeed.

The question addressed in this article is, given one particular seismotectonic model for the area, and the corresponding earthquake catalog gathered from different sources, is there support for the forecasts based on these arguments, and does the pattern of events in the 20th century match the hazard parameters?

2. Tectonic setting of the study area

Turkey is located in the most tectonically active Eastern Mediterranean basin, and is bisected by two of the world’s major strike-slip fault zones: the North Anatolian Fault Zone (NAFZ) and the East Anatolian Fault Zone (EAFZ). The North Anatolian Fault Zone was first recognized as a powerful seismogenic source in the 1940s (Çemen et al., 2000). It has an average slip rate of 24 mm/year (Stein et al., 1997), and controls the northern margin of the westward escape of the Anatolian Plate (Sengör et al., 1985) or its lateral extrusion due to the collision between the Arabian and Eurasian Plates in southeastern Turkey (Çemen et al., 1993). The maximum likelihood calculations discussed in this paper concern the western transition zones of NAFZ that have come under close scrutiny since the occurrence of two major events with magnitudes greater than 7 in 1999.

The Turkish peninsula has been divided into 17 tectonic units that define the source of the seismic hazard in Turkey (Gülkan et al., 1993). The brief description below has been excerpted from this study that has formed the background of the current seismic zone map in Turkey. While tectonic features are subject to different interpretations leading to competing definitions of seismotectonic provinces, we note that the geologic entities described below have resulted in estimates of ground shaking that are in very good agreement with earlier versions. They have been checked on local scale by independent studies, and evidenced good acceptance. These sources, each given either a numeral or a numeral-alphabetic designation are displayed in Fig. 1. For purposes of this paper, only a subset located in the western part of the country constituting the eastern half of the seismogenic area examined in this study will be considered. In our description of the characteristics of these sources we will emphasize only briefly the geologic and seismic parameters that justify the interpretation that these regions may be considered as consistent tectonic entities.

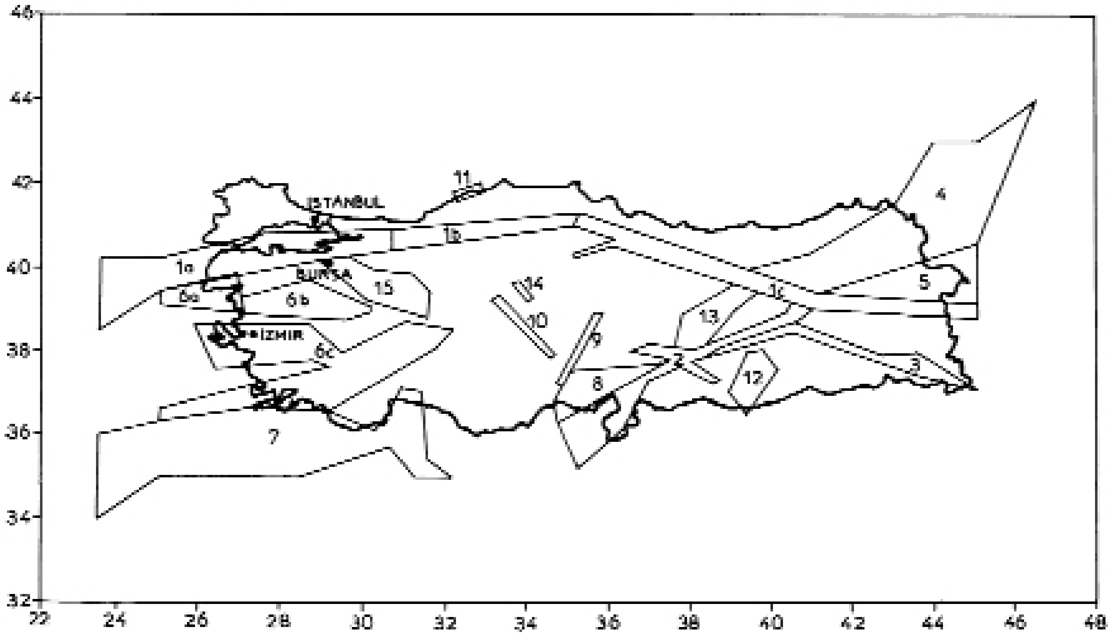


Fig. 1 - Seismic source zones in Turkey.

2.1. Zone 1: North Anatolian Fault Zone

NAFZ is a right-lateral intra-continental transform fault that separates the Eurasian plate from the Anatolian platelet. It runs a WNW course from the triple junction at Karlıova in the east until Havza in the province of Samsun, approximately the common boundary between subzones 1b and 1c. It then becomes a 50 km long E-W extension between Havza and Kargi (province of Çorum) before turning into a WSW orientation between Kargi and Akyazi (province of Sakarya). This 950 km long lineament concave toward the south has been approximated as zone 1 in Fig. 1. In Akyazi, NAFZ splits into two branches. The WSW arm runs along the southern shore of the Sea of Marmara through Geyve as far as Bandırma before turning into a SW direction reaching the Aegean Sea. The northern branch traverses Lake Sapanca to the south of Adapazarı, then courses an EW path along the southern shore of the Bay of Izmit. It continues in a single line underneath the northern half of the Sea of Marmara, and then connects into Mürefte near the northern part of the Gelibolu peninsula. After extending along the southern edge of Ganos mountain it runs into the sea in Saros Gulf. A major transformation occurs in both of these two branches within the Sea of Marmara when they begin to interact with the western Anatolian-Aegean horst graben system with significant vertical displacement components.

Both the Geyve and the Adapazarı branches are a complex system of parallel or semi-parallel sub-segments displaying variable widths of between several hundred meters to 10 km. For purposes of this study we will consider three principal sub-regions from the west toward the east. 1a is the Sea of Marmara-northern Aegean subset, 1b is used to define the Akyazi-Kargi segment, and 1c the next extension as far as Karlıova.

1a: SEA OF MARMARA - NORTHERN AEGEAN REGION. - We consider the three major fault belts in Sakarya, Geyve and Bursa which have both lateral and skew displacements. In general, the southern extensions display greater vertical throws than do the northern faults, even within the same lineament. This proves the interaction between the two different regimes in the north and the Aegean system.

Most faults within this subset are active. This is supported by field work as well as large-magnitude historic earthquakes associated with the Sakarya fault such as the1878 Izmit-Sapanca (M = 6.3), 1894 Izmit-Istanbul (M = 7) and 1912 Sarköy-Mürefte (M = 7.3) events. The Bursa segment ruptured twice in 1855 (M = 6.8, 7.3) and near Manyas (M = 7) in 1964. The Geyve-Akyazi segment ruptured last in 1967 (M = 5.6). In a trench study carried out 20 km to the east of Iznik, evidence of faulting approximately 500 years before the present was uncovered. The total displacement here measures 40 m. The 500-year seismic gap between Bandırma-Pamukova has led to an anticipation of a large earthquake there.

1b: AKYAZI - KARGI SEGMENT. - This segment is approximately 350 km long, and includes the Akyazi-Gerede, Akyazi-Bolu, Bolu-Eskipazar, Çerkes-Ilgaz and Kursunlu-Kargi faults. The transform fault zones that have come to be associated with notoriously damaging earthquakes are Düzce, Bolu, Yeniçaga, Çerkes, Kursunlu, Tosya and Ilgaz. The Akyazi-Kargi earthquake source zone is a mylonitic zone of between several hundred m to 25 km. The geomorphologic evidence for active right-lateral faulting is evident within the entire zone (e.g., Koçyigit, 1987). Recent seismic activity in the sub-zone are the 1943 Kastamonu-Ladik-Ilgaz (M = 7.2), 1944 Gerede-Bolu (M = 7.2), 1951 Kursunlu (M = 6.9), 1957 Abant (M = 7.1) and 1967 Mudurnu Valley (M = 6.8) events. Right-lateral slips ranging from 0.7 m to 3 m have been reported after these earthquakes (Koçyigit, 1990). To the east of Yeniçaga, andesitic volcanic formations exhibit total rightward movements of 35 km before they resurface on the northern block.

1c: KARGI-KARLIOVA SEGMENT. - This structure is some 625 km long, and consists of many segments of variable length with pull-apart basins at either the ends or in between fault segments. The principal lineaments are associated with the settlements at Kargi-Havza, Ladik-Destek, Tasova-Niksar, Resadiye-Susehri, Erzincan, and Karasu-Karlıova. These formations display also many splay faults: Almus, Amasya-Merzifon and Laçin. All of these lineaments display geomorphic structures characteristic of active right-lateral faults. Where the principal lineament changes directions or makes right or left step-overs, it displays wide angle reverse fault appearance. The ophiolitic melange on the northern edge of the Erzincan basin has been displaced 50 km to the right (Koçyigit, 1990). Since 1939 a general westward migration of major earthquake epicenters have been associated also with this segment: Erzincan 1939 (M = 7.9), Niksar-Erbaa 1942 (M = 7), Ladik-Ilgaz 1943 (M = 7.2), and Erzincan 1992 (M = 6.8). During these events the entire length of the segment was ruptured, with displacements ranging from 1 m to 7.5 m. These destructive earthquakes serve as reminders that similar magnitude shaking is to be expected in the future as well.

2.2. Zone 6: West Anatolian Horst-Graben System

Going from the north southward this system is described through depressions in the Gulf of Edremit, Bakırçay-Simav, Gediz-Küçük Menderes and the Büyük Menderes-Gulf of Kerme grabens and the EW trending elevations located in between them. Subtle differences in their activity rates and tectonic environments have led to subcategorizations designated 6a-d in Fig. 1.

6a: GULF OF EDREMIT. - Subzone 6a centers around the Gulf of Edremit and inclined normal faults that circumscribe it. This area falls within the transition range of the transform faults to the north and the pull-apart regimes to the south and west. For this reason the vertical or horizontal displacement of faulting may be observed as the dominant component. For example, several parallel step-like faults are observed along the northern edge of the gulf. The southern blocks of these have dropped, and the northern edges have risen. Late Miocene-Pliocene carbonates and fractured surficial terraces have also been affected by this process. This set of faults and several other discontinuous faults in the south have defined the Gulf of Edremit subsidence zone that widens towards the west.

6b: BAKIRÇAY – SIMAV GRABEN. - Zone 6b is described by the Bakırçay graben and the Simav graben that sits on its northeastern edge. Cities such as Çandarlı, Bergama, Dikili and Soma within the Bakırçay graben have witnessed destructive historic earthquakes. The width of the graben is 10 km wide and 80 km long. Its edges are lined with reverse faults that have affected early Quaternary river terraces that have in some cases remained hanging on the lineaments.

6c: GEDIZ - KÜÇÜK MENDERES GRABEN. - Zone 6c is characterized by the Gediz graben to the north and the Küçük Menderes graben in the south separated by a horst structure. This structure is wider in the west than in the east, varying from 10 to 20 km, with a 140 km long extension. The age of the sub-faults decreases toward the center of the graben. The total vertical displacement of these faults, from the Pliocene until the present, is 1.5 km. The Salihli-Alasehir 1969 earthquake (M = 5.5) has caused damage in many settlements. The southern edge is described by the Küçük Menderes graben containing the cities of Ödemis, Bayındır, Torbalı, Tire and Selçuk. The width here ranges between 5-10 km, and continues for 100 km. Activity in this area has been manifested by the Torbalı 1928 event (M = 6.5).

6d: BÜYÜK MENDERES GRABEN. - Subzone 6d represents the Büyük Menderes graben with the largest length of the EW trending lineaments described so far. From the Aegean Sea to Sarayköy it extends for about 225 km with a width of between 10-25 km. Important cities within this region are Germencik, Aydın, Nazilli and Denizli. Each of these cities as well as ancient Aphrodisias near Nazilli have experienced damaging earthquakes in the past.

3. Seismic hazard parameters estimation

The methodology proposed by Kijko and Sellevoll (1989) is applied in the following for the estimation of the hazard seismicity parameters (b-value, rate of occurrence and maximum magnitude) expected from the main seismogenic zones in Turkey. Two different earthquake data sets are used in the analysis:

- large historical earthquakes for the period 473 BC to 1899 AC (Papazachos and Comninakis, 1982; Papazachos and Papazachou, 1989);
- instrumental data of varying completeness for the period 1900 to 1992.

The latter are divided into five subsets, and assigned to a threshold magnitude above which the catalog is assumed to be complete (Papazachos and Papazachou, 1989): 1900-1922 with $M > 5.5$, 1923-1942 with $M > 5.2$, 1943-1962 with $M > 4.8$, 1963-1982 with $M > 4.5$, and 1983-1992 with $M > 4.0$. Unless otherwise stated these are surface wave magnitudes.

More specifically, the instrumental catalog utilized for the area of study is the product of an internal compilation by the Earthquake Research Division of the General Directorate of Disaster Affairs. This as-yet unpublished catalog with more than 6200 entries covers the period 1900-1992, and has many sources that have been cross-checked for consistency and accuracy. The principal source is the compilation for 1881-1980 by Ayhan et al. (1984). In selecting data for the catalog used in our calculations we have discarded data in Ayhan et al. (1984) prior to 1902 because maximum intensity at the epicenter had been used for that period, with an empirical conversion to magnitudes. The two-year gap between 1900-1902 was complemented by entries from the USSR Academy of Sciences (1977), Karnik (1971), Shebalin et al. (1974) and Soysal et al. (1981).

For the period up to 1970 only the surface wave magnitude Ms was used in Ayhan et al. (1984). For entries after that date multiple magnitude expressions containing m_b, ML, and (after 1986) Mw are also listed when these are available.We have not changed this basic character of the source for events up to 1970, but note that beyond this threshold the same measurement needs to be used for consistency. The twelve-year period from 1981 was collected from ISS, PDE, national and international sources including Comninakis and Papazachos (1986) and Gencoglu et al. (1990). Input parameters are summarized in Table 1.

Table 1 - Number of earthquakes over a threshold magnitude in the seismic source zones of north-western Turkey.

Source	**Historical Events 23 BC - 1899**	**Complete Part of the Catalogue**				
		1900 – 1922 (5.5)*	1923 – 1942 (5.2)	1943 – 1962 (4.8)	1963 – 1982 (4.5)	1983 – 1992 (4.0)
1a (7.3)**	31	8	6	25	101	118
1b (7.1)		1	2	19	6	
1c (7.9)		5	4	2	16	7
6a (7.0)	8	1	3	15	28	34
6b (6.6)		1	6	4	83	23
6c (7.1)	33	10	19	53	117	108

*Threshold magnitude
**Maximum observed magnitude

Theoretical aspects of the method are analytically described in previous studies (Kijko and Sellevoll, 1989; Garcia-Fernandez et al., 1989; Papadopoulos and Kijko, 1991; Slejko and Kijko, 1991), and only a short description of its main aspects is given below.

Incompleteness of the earthquake catalog from which hazard parameters are derived can be addressed in several ways. For example, Stepp (1973) has formulated an algorithm that enables the calculation of “unbiased” values for a and b in the relation

$$\log N(M) = a - bm \tag{1}$$

for patchy catalog completeness. In this procedure, earthquakes are grouped into magnitude interval bins, and each bin is modelled as a point source in time. The variance of the estimate of a sample mean is inversely proportional to the number of observations in the sample. Thus, the variance can be made as small as desired by making the number of observations sufficient, in the large enough sample, provided that reporting is complete in time, and the process is stationary, i.e. the mean variance and other moments of each observation remain unchanged. For purposes of obtaining a sufficient estimate of the variance of the sample mean, it is assumed that the earthquake occurrence sequence can be modelled as a Poisson process. If k_1, k_2, ..., k_n are the number of earthquakes per unit time interval the biased estimate of the mean rate per unit time interval and variance of this sample, respectively, are

$$\lambda = 1/n \sum_{t=1}^{n} k_t \tag{2}$$

$$\sigma^2_{\lambda} = \lambda / n \tag{3}$$

where n is the number of unit subintervals. If the unit time interval is one year then the standard deviation of the estimate of the mean becomes

$$\sigma_\lambda = \sqrt{\lambda} / \sqrt{T} \tag{4}$$

where T is the sample length. Thus σ_λ is expected to behave as $1 / \sqrt{T}$ in a given sample in which the mean rate of occurrence in a magnitude interval is constant. If the mean rate of occurrence is constant (as implied by the Poisson process) the stability is expected to occur only in the subinterval that is long enough to give good enough estimate of the mean but short enough so that it does not include intervals in which records are incomplete. Then, this subinterval becomes the arbiter for deriving the regression constants in Eq. (1). We note that the question of determining the maximum magnitude is not addressed.

Kijko and Sellevoll (1989) approach the issue of sparsity of earlier parts (where, typically, stronger earthquakes find mention) of most earthquake catalogs by utilizing extreme probability distributions to construct a likelihood function $L_0\ (\Theta \mid X_0)$ for the seismicity parameters $\Theta = (\beta, \lambda)$ and m_{max} where Θ defines the (doubly truncated) Gutenberg-Richter parameters:

$$L_0\ (\Theta \mid X_0) = \prod_{i=1}^{n} g\ (X_{0i}, t_i \mid \Theta) \tag{5}$$

where

$$1\mathrm{n}\ g\ (x, t \mid \Theta) = \frac{\exp(-\beta m_{max}) - \exp(-\beta m)}{\exp(-\beta m_0) - \exp(-\beta m_{max})} + 1\mathrm{n}\ \frac{\lambda\,\beta_t}{\exp(-\beta m_0) - \exp(-\beta m_{max})} - \beta x \tag{6}$$

In Eq. (6), m_0 is the threshold magnitude for the earlier part of the catalog. The comple-

Table 2 - Seismicity parameters and non-exceedance probability of M=6.0 and M=6.6 with corresponding return period for the seismic sources of northwestern Turkey.

Source	b ± σb	λ ± σλ	$M_{max} \pm \sigma M_{max}$	Non-exceedance Probability M = 6.0 1 year / 50 years*	Non-exceedance Probability M = 6.6 1 year / 50 years*
1a	0.88 ± 0.03	10.20 ± 0.81	7.8 ± 0.40	0.85 / 0.00 (6.4)	0.95 / 0.12 (23.8)
1b	0.62 ± 0.15	0.71 ± 0.16	7.2 ± 0.17	0.93 / 0.03 (15)	0.97 / 0.35 (55)
1c	0.71 ± 0.12	1.29 ± 0.29	7.3 ± 0.23	0.96 / 0.13 (24.8)	0.98 / 0.56 (86)
6a	0.79 ± 0.08	2.76 ± 0.42	7.3 ± 0.14	0.94 / 0.05 (16.7)	0.98 / 0.45 (64.1)
6b	0.92 ± 0.08	4.62 ± 0.57	6.8 ± 0.52	0.95 / 0.08 (20.3)	0.99 / 0.75 (175)
6c	0.83 ± 0.03	10.40 ± 0.81	7.4 ± 0.42	0.82 / 0.00 (5.2)	0.95 / 0.08 (20.1)
*Return Period (in years)					

te (i.e., instrumental) and earlier parts of the catalog are then combined, and expected values for the seismicity parameters are derived. In this paper, we apply this procedure primarily to seismogenic sources in north-western Turkey, and provide judgement on how well the parameters agree with results determined independently from the Stepp (1973) procedure.

The obtained estimates of the b-value, mean rate of occurrence and maximum magnitude for each seismogenetic zone of Turkey together with their standard deviation are given in Table 2. Additionally, the non-exceedance probability over 1 and 50 years for a M 6.0 and M 6.6 earthquake with their corresponding return periods are estimated. Fig. 2 presents the return period versus magnitude distribution, and the non-exceedance probability over different times for different magnitudes for each seismogenetic zone.

4. Discussion and conclusions

It is of interest to compare the relative consistency of the procedure outlined in this article against studies concerned with the seismic hazard in Turkey. The utilization of the seismicity parameters for engineering purposes ultimately governs either some design parameter group that determines the design capacity of engineered structures, or is transformed into loss estimates for insurance purposes. The study by Gülkan et al. (1993) was oriented toward the first goal, and more recently similar studies have been conducted for the second type of goal (Bommer, 2001). The catalogs utilized in these other studies differ in a substantial way from the combined catalog from which the data in Table 2 were derived. Moreover, differences exist in the boundaries of the sources, so the causes for the differences cannot be assigned to only differences of the methods used. We list the results in Table 3. The subscripts “raw” and “corr” refer to the value of corresponding variable before and after the application of the Stepp (1973) procedure, respectively. The b-parameter of the frequency magnitude distribution in Table 2 varies between 0.62 and 0.92 in the seismic zones considered. The mean annual rate for magnitude $M > 4$ varies from 0.7 events/yr (source 1c) to 10.2-10.4 events/yr (sources 1a, 6c), while the largest value of maximum expected magnitude is 7.8 ± 0.4 (source 1a), justified in terms of the seismological

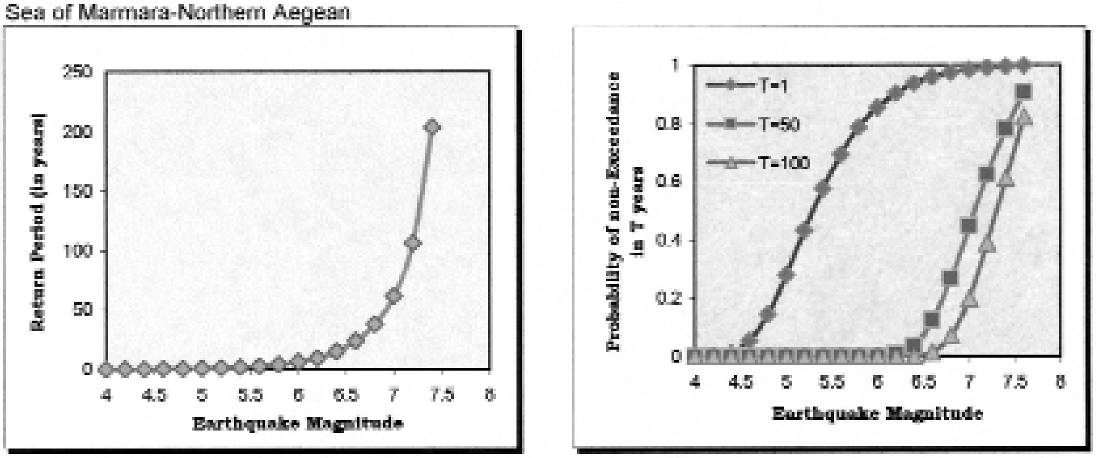
Table 3 - Comparison of seismicity parameters from previous studies.

Source	**Gulkan et al. (1993)**					**Bommer (2001)**		
	$M_{max}^{(1)}$	**b_{raw}**	**b_{corr}**	**λ_{raw}**	**λ_{corr}**	**M_{max}**	**$b^{(2)}$**	**λ**
1a	7.4	0.61	0.80	2.22	3.90	7.5	0.8	3.7
1b	7.2	0.47	0.70	0.79	1.16	7.5	0.8	3.7
1c	7.9	0.58	0.72	1.23	1.87	7.5	0.8	4.2
6a	7.0	0.44	0.70	0.47	0.66	7.0	0.8	3.9
6b	7.2	0.98	1.14	1.54	2.75	7.0	0.8	3.9
6c	7.4	0.77	0.83	2.52	4.25	7.2	0.9	4.1

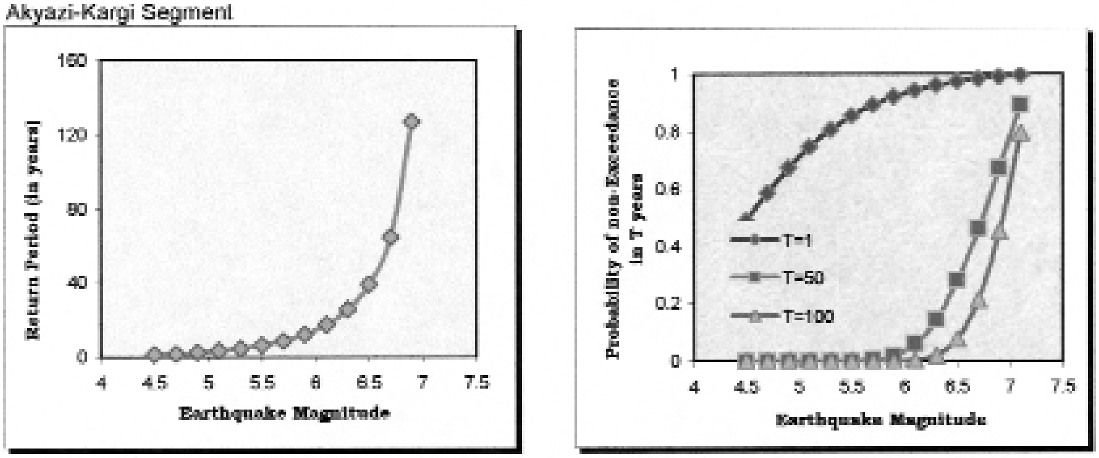
(1) Historic maximum

(2) Maximum capable event based on fault length, slip rate, and segment properties

Seismic Zone 1a:
Sea of Marmara-Northern Aegean



Seismic Zone 1b:
Akyazi-Kargi Segment



Seismic Zone 1c:
Kargi-Karliova Segment

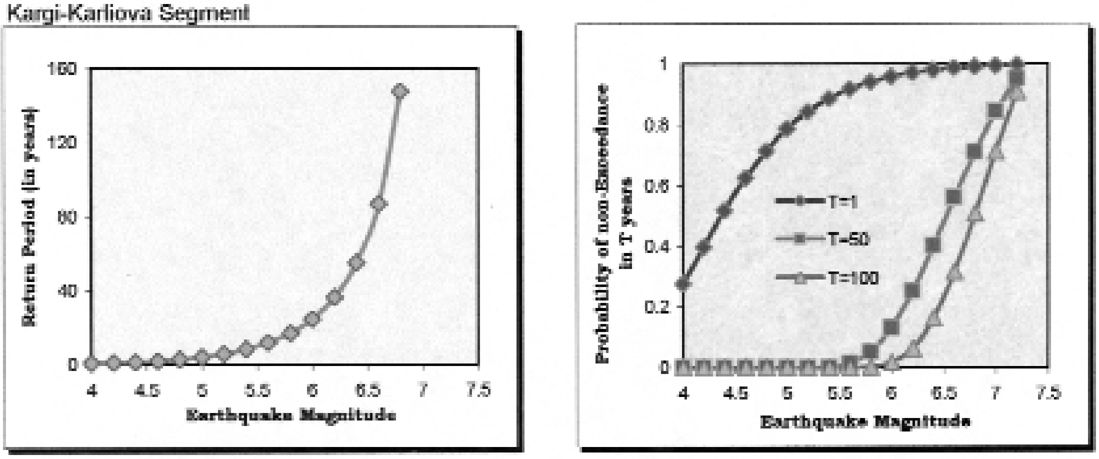
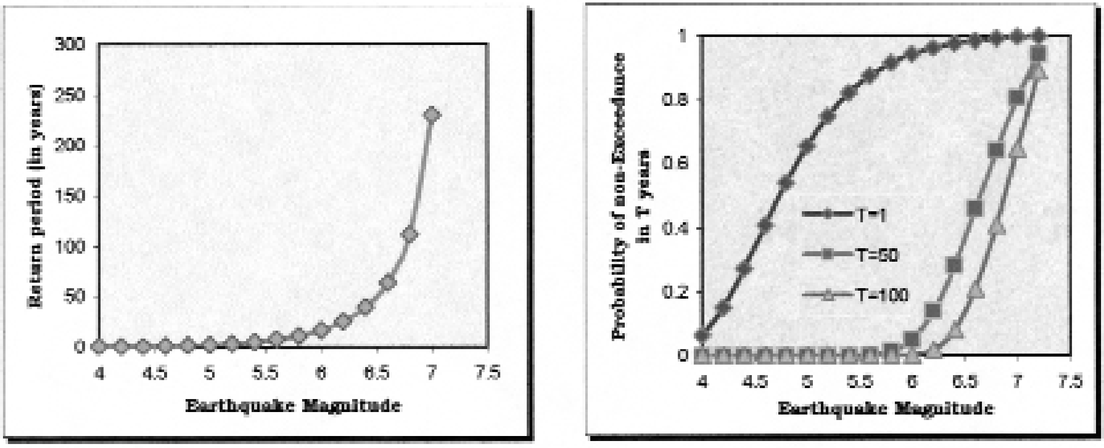
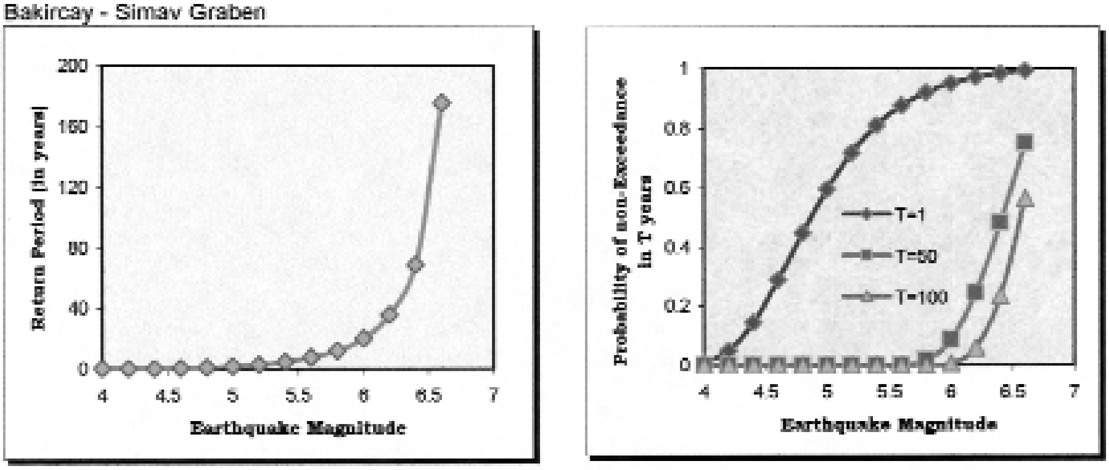


Fig. 2 - Earthquake magnitude distribution and non-exceedance probability for each seismic source of north-western Turkey.

Seismic Zone 6a:
Gulf of Edremit



Seismic Zone 6b:
Bakircay - Simav Graben



Seismic Zone 6c:
Gediz - Kucuk Menderez Graben

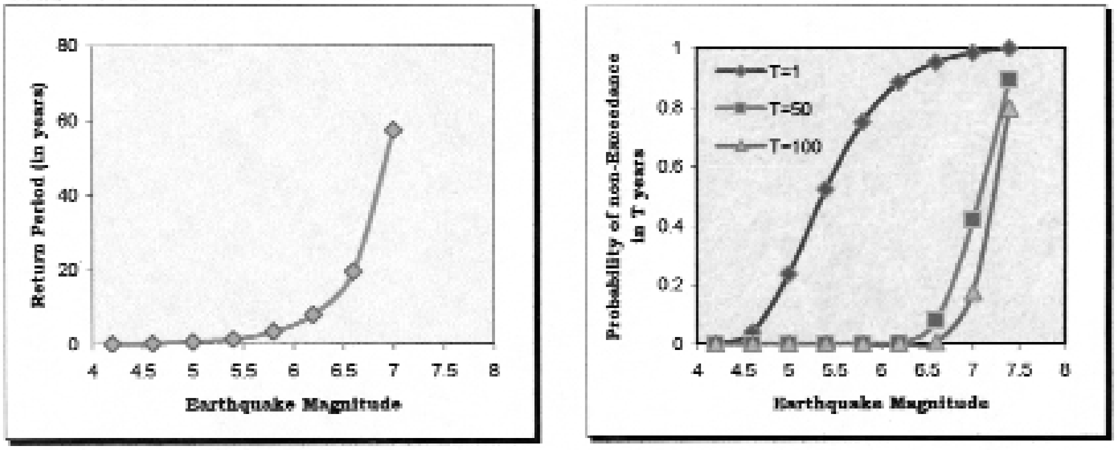


Fig. 2 - continued.

data, and the catastrophic event of August 17, 1999. Additionally, the hazard values obtained by Papoulia and Stavrakakis (1995) applying the same methodology but using the seismogenic source model proposed by Papazachos (1988) are in good accordance with these of the present study, regarding the maximum expected seismic magnitude.

While the results of parameter estimation of the present study listed in Table 2 do not match the entries in Table 3, there is some confirmation of the general patterns. For example, the non-exceedance probability for M 6.6 in 50 years is the lowest for regions 1a and 6c confirming that the westward migration of seismic activity along the NAFZ hypothesized by Parsons et al. (2000) is supported by interpretation of the catalog data. Long term fluctuations in seismicity rates and spatial migrations that violate the Poisson process assumption are not considered in this treatment. Source 6c contains the basin and range type of geologic structure that characterizes the Denizli-Aydin corridor. Denizli (ancient Hieropolis, abandoned as a human settlement during the Roman era because of relentless earthquake damage there) has been experiencing frequent swarms of microactivity for the last 25 years, but no event of catastrophic magnitude (such as is visible in, e.g., Aphrodisias) has occurred during the last two centuries (Ambraseys and Finkel, 1995).

In broad outline, Table 2 matches expected severity of earthquake activity derived by Gülkan et al. (1993) and Bommer (2001). While the geometry of the data sources is not the same, and the way in which these were treated are radically different, the overall agreement with the statistically derived conclusions in this article is judged to be satisfactory. This also confirms the general pattern of seismic activity in the 20th century of the western end of the NAFZ in terms of rates and magnitudes, and provides a tentative concurrence with Parsons et al. (2000).

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