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Regional Variation of the ω - Upper Bound Magnitude of GIII Distribution in and Around Turkey: Tectonic Implications for Earthquake Hazards

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Abstract—Complete data set of earthquakes in Turkey and the adjacent areas has been used in order to compute the ω values in 24 seismic regions of Turkey. The parameter is obtained through Gumbel's third asymptotic distribution of extreme values and is well known as *upper bound magnitude*. This is an interpretation that no earthquake magnitude greater than ω can occur in a region. The results also estimate the most probable magnitude for a time period of 100 years. The estimates of ω exceed the value of 7.00 in 20 of the 24 seismic regions. An effort is also made to find a relation between the magnitude and the length of a fault in the complicated tectonics of Turkey and the surrounding area. Earthquake hazard revealed as tables and maps are also considered for Turkey and the surrounding area.

Key words: ω-values, Turkey, magnitude-rupture relationship, earthquake hazard, Gumbel's distribution.

1. Introduction

Many quantitative methods have been applied over the years to estimate earthquake hazard. The most common seismic parameter analyzed is the magnitude of the earthquakes. The first and the third asymptotic distributions of extreme values of Gumbel have also proved useful in estimating earthquake hazard (EPSTEIN and LOMNITZ, 1966; MAKROPOULOS, 1978; BURTON, 1979; TSAPANOS and BURTON, 1991).

Gumbel's third (GIII) asymptotic distribution has the advantage, like Gumbel's first (GI) that it does not require analysis of the whole data set. It uses a sequence of earthquakes with the largest magnitudes in a set of predetermined equal-time intervals. These intervals (arbitrarily determined) depended on the seismicity of an area. Another advantage of Gumbel's third asymptotic distribution is the inclusion of a parameter which is an upper bound (ω) to magnitudes. Thus for calculation of the occurrence or

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expectation of extreme magnitude earthquakes using probabilistic models, this distribution allows an appropriate and natural physical interpretation (BURTON, 1979).

Studies concerning the evaluation of seismic hazard parameters in different parts of the world based on the extreme statistics, were published by many authors (YEGULALP and KUO, 1974; MAKROPOULOS, 1978; MAKROPOULOS and BURTON, 1983; TSAPANOS and BURTON, 1991) among others, who used data sets of the instrumental era (i.e., beginning of the 20th century). On the other hand problems concerning the seismic hazard parameters obtained through this technique were discussed by KNOPOFF and KAGAN (1977).

According to REITER (1990) there are three definitions of the maximum magnitude in common use in contemporary seismic hazard analysis: a) The maximum regional earthquake, which is the maximum possible earthquake that could occur in a given time interval and tectonic regime and which defines an upper bound to earthquake size determined by earthquake processes, b) the maximum credible magnitude, it is more common to be estimated in deterministic analyses and defines that earthquake which is based on a reasonable assessment of maximum earthquake potential in light of current tectonics, and c) the maximum historic earthquake, which is the maximum earthquake associated with a seismotectonic source of which there is historical or instrumental evidence.

A new approach based on the maximum likelihood method is applied by KIJKO and SELLEVOL (1989) in order to estimate the maximum regional magnitude and other related parameters (e.g., parameter β of magnitude-frequence distribution and λ which considered the mean activity rate). PISARENKO *et al.* (1996) assessed the maximum regional magnitude for California and Italy using for this purpose a Bayesian estimator. The rank-ordering statistics of extreme values is applied by SORNETTE *et al.* (1996) to the distribution of large earthquakes for extracting the tail of the distribution of sparse data sets. KRINITZSKY (2002) proposed the definition of some maximum magnitudes appropriate for use in engineering design. Seismic moment upper bound is considered by KAGAN (2002) in order to discuss various theoretical distributions that can be used to approximate the seismic moment data.

The earthquake hazard assessment requires the knowledge of the earthquake potential in a region. It is widely known that the earthquakes are generated in particular faults or in segments of them, which depends on the seismic potential of the fault. Future earthquake potential of a fault commonly is evaluated from estimates of fault rupture parameters that are, in turn, related to earthquake magnitude. Numerous empirical relationships between magnitudes and the fault lengths or related parameters (displacement, maximum surface displacement, etc.), are published (SLEMMONS, 1977; ACHARYA, 1979; BONILLA *et al.*, 1984; WELLS and COPPERSMITH, 1994; AMBRASEYS and JACKSON, 1998). Based on geological evidence PAVLIDES and CAPUTO (2004) provided relations between magnitude and: a) Surface rupture length, b) maximum vertical displacement and c) average displacement, for the entire Aegean area.

The paper confines itself to the assessment of the Gumbel's third asymptotic parameters and their distribution in the 24 seismic regions of Turkey and the adjacent areas. Moreover an effort is made to introduce a new empirical relationship between magnitudes and rupture length in the examined area.

2. *Tectonics*

Turkey forms one of the most actively deforming regions in the world and has a long history of devastating earthquakes. Tectonics of Turkey is governed by three major elements: (a) The Aegean–Cyprus arc, a convergent plate boundary where the African plate to the south is subducting beneath the Anatolian plate to the north; (b) the dextral North Anatolian Fault Zone (NAFZ); and (c) the sinistral East Anatolian Fault Zone (EAFZ). Also, the sinistral Dead Sea Fault Zone (DSFZ) has an important role (Fig. 1). The latter two (b and c) are intracontinental strike-slip faults along which the Anatolian Plate, a wedge of amalgamated fragments of crust, moves westward away from the collision zone between the Arabian and the Eurasian plates (ŞENGÖR and YILMAZ, 1981; ŞENGÖR *et al.*, 1985) at a rate of ~ 20 mm year^{-1} (BARKA, 1992; PFISTER *et al.*, 1998). This activity is the result of interactions between northward moving African and Arabian plates and the relatively stable Eurasian plate. The two strike-slip faults meet and form a continental triple junction to the east of Karlıova in northeastern Turkey. Thus, the formation of the North Anatolian and East Anatolian fault zones, and the consequent westward escape of the Anatolian plate along its boundary structures have resulted in the generation of four distinct tectonic structures in Turkey: (1) North Anatolian Province,

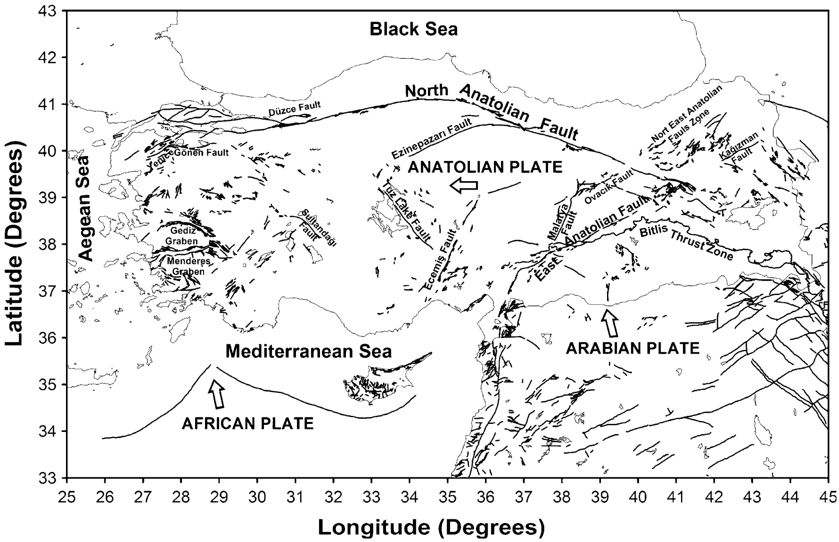

Figure 1
Tectonic structure of Turkey. The major tectonic structures are modified from ŞAROĞLU *et al.* (1992).

(2) East Anatolian Constructional Province, (3) Central Anatolian Province and (4) West Anatolian Extensional Province (ŞENGÖR *et al.*, 1985).

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 the eastern Mediterranean region (BOZKURT, 2001). 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 the southeast. This section has ruptured during two successive earthquakes on the 19th and 20th August 1966 (M = 6.8 and M = 6.2, respectively: (AMBRASEYS and ZATOPEK, 1968; AMBRASEYS, 1988). During the past 60 years, NAFZ has produced earthquakes along different sections in a system manner that is atypical of long faults. Beginning with the 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), 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 Kocaeli (M = 7.4), and 12 November 1999 Düzce earthquakes (BOZKURT, 2001).

The East Anatolian Fault Zone is a 550 km long, approximately northeast-trending, sinistral strike-slip fault zone that comprises a series of faults arranged parallel, subparallel or obliquely to the general trend (ARPAT and ŞAROĞLU, 1972; ŞENGÖR *et al.*, 1985). It was first described by ALLEN (1969). The fault zone is a transform fault forming parts of boundaries between the Anatolian and the Eurasian plates and between the Arabian and African plates. It is considered as a conjugate structure to the NAFZ. The left-lateral slip along the fault zone contributes to the westward extrusion of Anatolia. The structure of the fault zone is complicated with several pull-apart basins, conjugate fractures, folding, and considerable thrust component. Unlike the NAFZ, very little of the EAFZ has ruptured in any earthquake that has been studied in detail. The fault zone has ruptured during many destructive earthquakes, such as 22 May 1971 Bingöl (M = 6.8) and 1986 Sürgü (M = 6.0) earthquakes during the 20th Century (BOZKURT, 2001).

Convergence between the African and Anatolian plates in the Eastern Mediterranean takes place by subduction along the Aegean and Cyprus arcs (PAPAZACHOS and COMNINAKIS, 1971; MART and WOODSIDE, 1994) the African plate is descending beneath the Anatolian plate in a north-northeast direction. The Aegean arc system plays an important role in the geodynamical evolution of the Aegean region. The nature and structure of the trench is variable across the Aegean arc. The eastern part of the Aegean arc acts rather as a transform fault. Several trenches have been distinguished along the eastern parts of the Aegean arc (LE PICHON *et al.*, 1979).

Dead Sea Transform Fault Zone is a 1000-km long, approximately N–S trending, sinistral intraplate strike-slip fault zone. Its internal structure is dominated by leftstepping *en échelon* strike-slip faults separated by pull-apart basins or rhomb grabens (BOZKURT, 2001). In terms of plate tectonics, the DSFZ is considered to be a plate boundary of transform type, separating the African plate to the west and Arabian plate to the east (ŞENGÖR and YILMAZ, 1981). The Arabian plate is moving northward faster than the African plate. This differential movement between the plates is taken up by DSFZ.

Arabian and Eurasian plates collided along the Bitlis Thrust Zone (ŞENGÖR and YILMAZ, 1981). This has resulted in the uplift of mountains along the suture. The Bitlis suture is a complex continent-continent and continent-ocean collisional boundary that lies north of the fold-and-thrust belt of the Arabian platform and extends from southeastern Turkey to the Zagros Mountains in Iran (BOZKURT, 2001).

The Cyprus arc is considered the presently active plate boundary, which accommodates the convergence between the African plate to the south and the Anatolian plate to the north in the eastern Mediterranean. West of Cyprus, northeastward subduction of the eastern Mediterranean oceanic crust has been proposed on the basis of earthquake data and the assumption of the continuation of the plate boundary from the Aegean arcs (BOZKURT, 2001). Several papers have been published on the seismicity of the Cyprus area and they all documented that strong ($M = 6.0$ or larger) earthquakes occurred during the instrumental period. The research on the geometry, nature and structure of the Aegean and Cyprus arcs continues and several papers have recently been published (PINAR and KALAFAT, 1999).

3. *Data and Seismic Source Zonations*

The database which is analyzed in this study was compiled from different sources and the seismicity data from different catalogues were provided in different magnitude scales. Turkey earthquake catalogue, taken from the Boğaziçi University, Kandilli Observatory and Earthquake Research Institute (KOERI), starting from 1974 until 2005, contains 68,478 events. The earthquakes from 1900 to 1974, which come from the International Seismological Centre (ISC) and instrumental catalogue of KOERI, consist of 2,398 events. The final data catalogue consists of 70,876 earthquakes with magnitude 1.0 or greater. We carried out our analysis in a rectangular area limited by the coordinates 25°E and 45°E in longitude and by the coordinates 33°N and 43°N in latitude. Thus we used the homogeneous catalogue (BAYRAK *et al.*, 2007a) between the time interval 1900 and 2005 and shallow earthquakes (depth < 60 km) including 69,339 events for the evaluation of earthquake hazard parameters.

A complete comprehension of the historical and instrumental seismicity, tectonics, geology, paleoseismology, and other neotectonic properties of the studying region are necessary for an ideal delineation of seismic source zones. But, for the majority of the world it is not always possible to compile detailed information in all these fields. Thus, seismic source zones are frequently determined with two fundamental tools; (1) a seismicity profile, and (2) the tectonic structure of the region under consideration

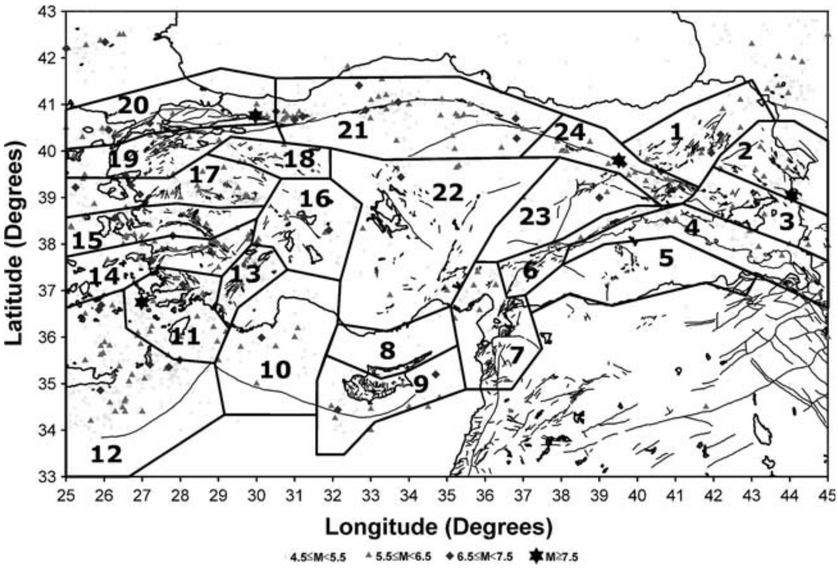

Figure 2
Different seismic source zones (Bayrak *et al.*, 2007a) and epicenter locations of earthquakes in Turkey from 1900 to 2005 with main tectonics. Magnitude size of earthquakes are shown by different symbols.

(Erdik *et al.*, 1999). It is suggested by several authors that seismic source zonation is a widely used methodology to determine the earthquake hazard and performed numerous studies. The seismic source zones used in this study are defined according to Bayrak *et al.* (2007a) as shown in Figure 2. A picture of the distribution of the earthquakes in and around Turkey is also shown in this figure.

4. *Relationship between Magnitudes and Rupture Lengths for Earthquakes in Turkey*

There is a relation between the magnitude of an earthquake and faulting length (rupture length) which is due to this earthquake. If surface faulting is seen, the rupture length can be measured directly from field observations. Otherwise, it can be determined from the distribution of aftershocks. Several authors (Acharya, 1979; Wells and Coppersmith, 1994; Ambraseys and Jackson, 1998) proposed different relationships between the magnitudes and rupture lengths for earthquakes in Turkey and the world. In Table 1 magnitudes and observed rupture lengths of certain earthquakes which occurred in Turkey are listed. Magnitude range is between 6.0 and 7.9 and rupture lengths of the earthquakes in this Table are between 4 and 340 km. Several authors suggested different rupture lengths for the 1939 Erzincan earthquake which is the largest earthquake that occurred in the instrumental time period. We find 360 km in Dewey (1976), 350 km in Ambraseys (1978), 309 km in Acharya (1979), 360 km in Wells and Coppersmith

Table 1

List of earthquakes associated with rupture length

Date (d.m.y)	Location	Magnitude	Rupture Length	References
01.24.1905	Çemişgezek	6.8	38	Nalbant *et al.* (2002)
09.02.1909	Ender	6.3	15	Ambraseys and Jackson (1998)
09.08.1912	Marmara	7.3	84	Ambraseys and Jackson (2000)
13.09.1912	Marmara	6.8	37	Ambraseys and Jackson (2000)
03.10.1914	Burdur	6.9	23	Ambraseys and Jackson (1998)
19.04.1938	Kırşehir	6.6	36	Acharya (1979)
26.12.1939	Erzincan	7.9	340	Dewey (1976)
20.12.1942	Erbaa	7.0	50	Ambraseys (1978)
26.11.1943	Ladik	7.2	265	Ambraseys (1978)
10.02.1944	Gerede	7.2	180	Dewey (1976)
25.06.1944	Saphane	6.2	18	Ambraseys and Jackson (1998)
06.10.1944	Ayvalık	6.8	37	Ambraseys and Jackson (2000)
31.05.1946	Varto-Hınıs	6.0	9	Welss and Coppersmith (1994)
17.08.1949	Elmalıdere	7.0	38	Nalbant *et al.* (2002)
13.08.1951	Kurşunlu	6.9	49	Acharya (1979)
18.03.1953	Gönen	7.2	58	Ambraseys (1978)
26.05.1957	Abant	7.1	55	Acharya (1979)
06.10.1964	Manyas	7.0	40	Ambraseys (1978)
19.08.1966	Varto	6.6	38	Acharya (1979)
22.07.1967	Mudurnu	6.9	80	Dewey (1976)
28.03.1969	Alaşehir	6.4	30	Dewey (1976)
28.03.1970	Gediz	6.9	45	Dewey (1976)
22.05.1971	Bingöl	6.7	38	Acharya (1979)
12.05.1971	Burdur	6.2	4	Acharya (1979)
06.09.1975	Lice	6.6	28	Ambraseys and Jackson (1998)
24.11.1976	Çaldıran	7.3	90	Wells and Coppersmith (1994)
30.10.1983	Horasan	6.9	50	Wells and Coppersmith (1994)
13.03.1992	Erzincan	6.8	38	Wells and Coppersmith (1994)
01.10.1995	Dinar	6.2	25	Pinar (1998)
27.06.1998	Adana	6.0	7	Ambraseys and Jackson (1998)
17.08.1999	İzmit	7.8	200	Gülen *et al.* (2002)
12.11.1999	Düzce	7.4	41	Gülen *et al.* (2002)
01.05.2003	Bingöl	6.4	20	Milkereit *et al.* (2004)
17.10.2005	Urla	6.2	10	Benatatos *et al.* (2006)

(1994) and 340 km in Ambraseys and Jackson (1998). For this earthquake, we considered the rupture length as 340 km, as this study was recently made. The rupture lengths for the other earthquakes listed in Table 1 are given in different values in the literature.

A linear relationship derived here between the magnitudes and rupture lengths for Turkey earthquakes is given in Table 1 by using the log-linear regression method;

$$M_S = 1.00(\pm 0.09) * \log \mathrm{L} + 5.21(\pm 0.15). \qquad (1)$$

The distribution of the magnitudes and rupture lengths, computed regression relationship, their uncertainty and its 95% confidence limits are shown in Figure 3. The correlation coefficient of this relationship is equal to 0.89. Acharya (1979) obtained a relationship for 11 earthquakes which occurred in Turkey

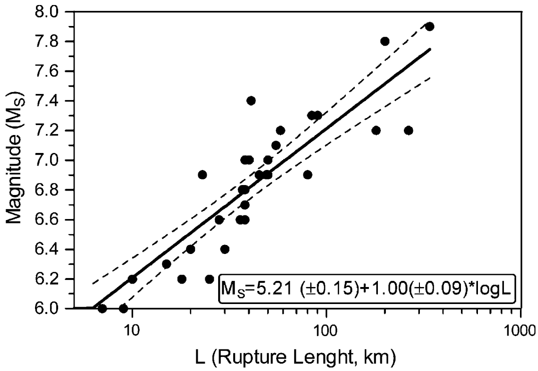

Figure 3
Relation between surface magnitude (M_S) and rupture length (L) based on Turkish earthquakes.

$$M_S = 0.92 * \log \mathrm{L} + 5.33. \tag{2}$$

WELLS and COPPERSMITH (1994) for global earthquakes;

$$M_S = 1.16 * \log \mathrm{L} + 5.08 \tag{3}$$

and AMBRASEYS and JACKSON (1998) for earthquakes in the Eastern Mediterranean including Turkey

$$M_S = 1.04 * \log \mathrm{L} + 5.27. \tag{4}$$

Equations (1)–(4) for magnitude range between 6.0 and 8.0 are drawn in Figure 4. Also, distribution of the magnitudes and rupture lengths of Turkey earthquakes listed in Table 1 are shown in this figure. Equation (1) computed in this study is very similar to Equation (2) given that ACHARYA (1979) used only Turkey earthquakes. However,

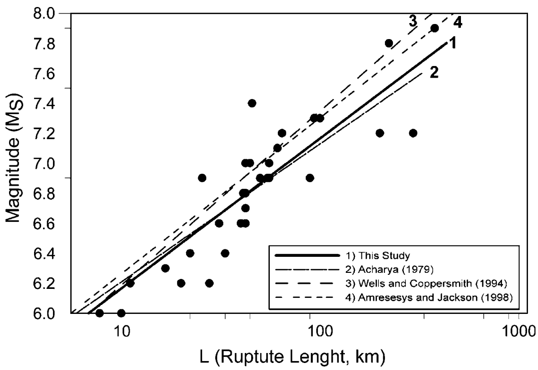

Figure 4
Relationships between surface magnitude (M_S) and surface length (L) developed in this study and given by different authors.

Eqs. (3) and (4) show differences from Eqs. (1) and (2) because Eq. (3) is computed for the data containing global earthquakes and Eq. (4) for the data containing the Eastern Mediterranean as well as Turkey earthquakes.

5. *Some Theoretical Background*

The method applied is of particular interest for earthquake hazard evaluation. Gumbel's third asymptotic distribution (GIII) has the advantage not to require analysis of the entire data set. It uses the sequence of earthquakes with the largest magnitudes in a set of predetermined equal-time intervals. These arbitrary time intervals are usually determined by the rate of seismicity in the investigated area. Another advantage of the Gumbel third asymptotic distribution is the inclusion of the parameter ω which is an upper bound to the magnitudes. Thus for the calculation of the occurrence or expectation of extreme magnitude earthquakes using probabilistic models, the GIII distribution allows an appropriate and natural physical interpretation. It is quite common, with the existing catalogues, that the need of the predetermined equal-time intervals (usually of 1, 2 or 3 years) is satisfied only for the data of the recent catalogs (YEGULALP and KUO, 1974). The disadvantage of the GIII method appears when the catalogues are extended to the historical data files and consequently the largest magnitudes must be selected from longer time intervals.

Let M_i (with $i = 1, 2, 3, \ldots, n$) be the largest earthquake magnitudes observed in successive equal-time intervals from a given area. The probability that M is an extreme value of the magnitude is given by the cumulative distribution function:

$$P(M) = \exp\left[-\left(\frac{\omega - M}{\omega - u}\right)^k\right], \tag{5}$$

where ω is the upper bound to M, k is the shape parameter and u is the characteristic value with $P(u) = 1/e$ and $P(\omega) = 1$. The three parameters allow for curvature through the shape or curvature parameter k. If the extreme equal-time interval is one year, the return period $T(M)$ years for a magnitude M is given by:

$$T(M) = \frac{1}{[1 - P(M)]}, \tag{6}$$

where $[1-P(M)]$ is the probability that an earthquake magnitude will be exceeded. It is unusual to have a full set of annual extremes for a data set of a seismic region. Generally we have extreme intervals of duration N years and the corresponding distribution of $P_N(M)$ is related to one year extremes of $P_1(M)$ by the relation:

$$\sqrt[N]{P_N(M)} = P_1(M) \tag{7}$$

derived by BURTON (1977).

Now assume that M_i are simply the extreme magnitudes during n successive years and ranked in order of increasing size so that $M_1 \leq M_2 \leq \ldots \leq M_n$. The plotting point probability value of the i-th observation is defined by:

$$P(M_i) = i/(n+1), \tag{8}$$

where i is the rank and n is the number of observations. GRINGORTEN (1963) suggests alternative plotting point values:

$$P(M_i) = (i - 0.44)/(n + 0.12) \tag{9}$$

and points out that this equation is more convenient for plotting rule use because it gives a better fit at high magnitudes and long return periods of interest and so is adopted for GIII (BURTON, 1979). Equation (9) is adopted for the present study.

For curve fitting purposes Eq. (1) is firstly transposed to:

$$M = \omega - (\omega - u)[-\ln(P(M))]^{\lambda}, \tag{10}$$

where $\lambda = 1/k$, and plotting M as ordinate and $(-\ln P(M))^{\lambda}$ as abscissa draws a straight line with ω as intercept and -(ω-u) as slope. Equation (10) is nonlinear and the curve-fitting process adopted may be read in BURTON (1979) in detail. In order to estimate the parameters (ω, u, and λ), Eq. (10) is expanded as a Taylor series in [ω, u, λ] and the partial derivations of M with respect to [ω, u, λ] which are:

$$\begin{aligned} \frac{\partial M}{\partial \omega} &= 1 - (-\ln P)^{\lambda}, \\ \frac{\partial M}{\partial u} &= (-\ln P)^{\lambda}, \\ \frac{\partial M}{\partial \lambda} &= \Big[(\omega - u)(-\ln P)^{\lambda} \ln(-\ln P)\Big]. \end{aligned} \tag{11}$$

Trial values of $[\omega, u, \lambda]_o$ are then substituted and optimum values of perturbations to $[\omega, u, \lambda]_o$ are obtained by linear least-squares following a known recipe (MARQUARDT, 1963). The method is iterative and goodness of fit is tested using x^2 at each stage. In practice the parameters [ω, u, λ] were accepted when the F-test showed that the x^2 generated by successive iterations was similar at the 95% confidence limits. A weight or uncertainty may be assigned to each individual extreme magnitude M_i (BURTON, 1977) which is of importance, particularly for the earthquakes which occurred during the earlier part of the century when uncertainties of magnitudes may have exceeded 0.4. As we referred, the goodness of fit is measured by x^2 which is:

$$x^2 = \sum \left(\frac{1}{\sigma_i^2} (y_i - y(x_i)) \right)^2, \quad i = 1, \ldots, \mathrm{n}, \tag{12}$$

where σ_i is the standard deviation associated with each datum, x^2 is minimized with respect to each parameter leading to the matrix equation:

$$\mathbf{B} = \delta p\,\mathbf{A}. \tag{13}$$

The results of elements of **A** and **B** are given by equations described in BURTON (1979) in detail. The solution of Eq. (13) is given by:

$$\delta p = \mathbf{B}\mathbf{A}^{-1} = \mathbf{B} \in, \tag{14}$$

where $\in$ the symmetrical covariance or error matrix. Then, Eq. (10) is used as the fitting function requires three parameters p_1, p_2, $p_{3,}$ which will be ω, u, λ, respectively. The covariance matrix $\in$ of Eq. (14) is then:

$$\in_{ij} = \begin{bmatrix} \sigma^2_{\omega} & \sigma^2_{u\omega} & \sigma^2_{\lambda\omega} \\ \sigma^2_{\omega\lambda} & \sigma^2_{u} & \sigma^2_{\lambda u} \\ \sigma^2_{\omega\lambda} & \sigma^2_{u\lambda} & \sigma^2_{\lambda} \end{bmatrix}. \tag{15}$$

Because Gumbel III can skew the modal, median, mean value of $M(100)$ or the values computed directly from Eq. (10), the return period value, may all be different. The parameter $M(100)$ is the most probable magnitude for a time period T-years (100) in this study, and is given by BURTON (1977):

$$RM = \omega - (\omega - u)\left(\frac{(1-\lambda)}{T}\right)^{\lambda}. \tag{16}$$

6. Results and Discussion

The aim of this study is the evaluation of the seismicity parameters of Turkey. For this purpose, we divide Turkey into 24 seismic regions shown in Figure 2 and used the data included in the instrumental period between 1900 and 2005. In Table 2 we listed the values of ω, u and λ, with their uncertainty as they are estimated through Gumbel's III technique, for whole areas referred to above. The maximum observed earthquake, M^{obs}_{max}, recorded during instrumental times, according to the catalogue used, and the difference $\omega - M^{obs}_{max}$ are also illustrated in this table. The column "extreme years" of Table 2 is deducted from the observations since we rarely have full samples with results for every year. We then applied equation (7) suggested by BURTON (1977) in order to have extremes of one year. This was followed by the assessment of the GIII estimates by using annual extremes. The Gumbel III graphs including return periods and probabilities computed for 24 regions are shown in Figure 5. Regional variability of M^{obs}_{max} and ω values for each 24 region is shown in Figures 6 and 7. We divided M^{obs}_{max} and ω values into four groups as shown by legends with different grey scale in Figures 6 and 7; 1) M^{obs}_{max}, $\omega < 6.25$, 2) $6.25 \leq M^{obs}_{max}$, $\omega < 7.00$, 3) $7.00 \leq M^{obs}_{max}$, $\omega < 7.75$ and 4) M^{obs}_{max}, $\omega \geq 7.75$.

As shown in the geographical distribution map of M^{obs}_{max}, the two largest earthquakes observed on both sides of the North Anatolian Fault are Erzincan earthquake ($M_S = 7.9$)

Table 2

Different 24 seismic regions in and around Turkey, ω, u and λ values and their standard deviations, RM (M_{100}) value and its standard deviation, extreme years (k), $M_{\max}^{\text{obs}}$, $\omega - M_{\max}^{\text{obs}}$ and $\omega - M_{100}$ values for each region

Region	Ω	$\sigma\omega$	u	σu	λ	$\sigma\lambda$	RM (M_{100})	σRM	Extreme Years (k)	$M_{\max}^{\text{obs}}$	$\omega - M_{\max}^{\text{obs}}$	$\omega - M_{100}$	Tectonics
1	7.73	1.93	4.42	0.13	0.27	0.22	6.46	0.28	3	6.8	0.93	1.27	North East Anatolian Fault Zone (NEAFZ)
2	7.85	1.73	3.38	0.22	0.29	0.18	6.42	0.28	2	7.5	0.35	1.43	Kağızman, Iğdır, Tutak and Çaldıran faults (KITÇF)
3	7.69	2.53	4.73	0.17	0.21	0.13	5.93	0.28	8	6.3	1.39	1.76	Malazgirt, Erçiş and Süphan Faults and Muş Thrust Zone (MESF)
4	6.99	1.20	4.58	0.14	0.37	0.18	6.32	0.28	3	6.6	0.39	0.67	Bitlis Thrust Zone (BTZ)
5	5.69	2.01	4.39	0.32	0.47	0.23	5.23	0.29	10	5.4	0.29	0.46	Karadağ Extension Zone (KEZ)
6	6.37	2.15	4.74	0.31	0.39	0.17	5.79	0.29	7	5.9	0.47	0.58	East Anatolian Fault Zone (EAFZ)
7	7.16	2.25	5.07	0.20	0.24	0.16	5.91	0.29	11	6.0	1.16	1.25	A part of Dead Sea Fault
8	5.20	0.79	2.05	0.35	1.19	0.43	4.98	0.34	10	5.2	0	0.22	Northern part of Cyprus
9	7.14	1.04	4.63	0.19	0.54	0.21	6.53	0.29	7	6.7	0.44	0.61	Southern part of Cyprus, including eastern part of Cyprus Arc
10	7.93	2.49	4.83	0.19	0.27	0.14	6.36	0.30	8	6.8	1.13	1.57	Western part of Cyprus Arc
11	8.32	2.36	4.47	0.08	0.18	0.08	6.64	0.29	1	7.7	0.62	1.68	Muğla and Rhodes
12	8.23	2.01	4.81	0.07	0.18	0.13	6.73	0.27	1	7.4	0.83	1.50	Aegean Arc
13	7.13	2.40	4.58	0.22	0.36	0.15	6.18	0.34	6	6.4	0.73	0.95	Burdur Fault Zone (BFZ)
14	7.37	1.44	4.59	0.09	0.26	0.11	6.37	0.27	2	6.8	0.57	1.00	Büyük and Küçük Menderes Grabens
15	7.48	1.80	5.24	0.14	0.28	0.12	6.50	0.29	5	6.6	0.88	0.98	Gediz Graben
16	7.35	0.96	4.19	0.79	0.77	0.25	6.94	0.33	7	7.0	0.35	0.41	Sultandağı, Beyşehir and Tatar Faults (SBTF)
17	7.52	1.50	4.08	0.75	0.40	0.23	6.80	0.30	2	7.2	0.32	0.72	Kütahya, Simav and Zeytindağ-Bergama Faults (KSZBF)
18	7.03	2.39	4.58	0.27	0.40	0.14	6.12	0.32	8	6.4	0.63	0.91	Eskisehir, İnönü-Dodurga and Kaymaz Faults (EİDKF)
19	7.52	1.57	3.35	0.23	0.43	0.14	6.73	0.30	2	7.2	0.32	0.79	Yenice-Gönen, Manyas, Ulubat and Etili Faults (YGMUEF)
20	7.93	2.28	4.42	0.13	0.25	0.12	6.46	0.28	3	7.8	0.13	1.47	Marmara part of North Anatolian Fault Zone (MNAFZ)
21	7.64	0.69	6.05	0.22	0.76	0.29	7.35	0.30	10	7.4	0.24	0.29	Anatolian part of North Anatolian Fault Zone (ANAFZ)
22	7.08	1.44	3.91	0.15	0.31	0.17	6.11	0.28	2	6.6	0.48	0.97	Mid Anatolian Fault System (MAFS)
23	7.44	2.45	4.06	0.60	0.40	0.18	6.32	0.29	6	6.8	0.64	1.12	Ovacık Fault and Malatya Fault (OMF)
24	7.95	1.18	4.09	0.14	0.34	0.16	6.93	0.28	2	7.9	0.05	0.98	Eastern part of North Anatolian Fault Zone (ENAFZ)

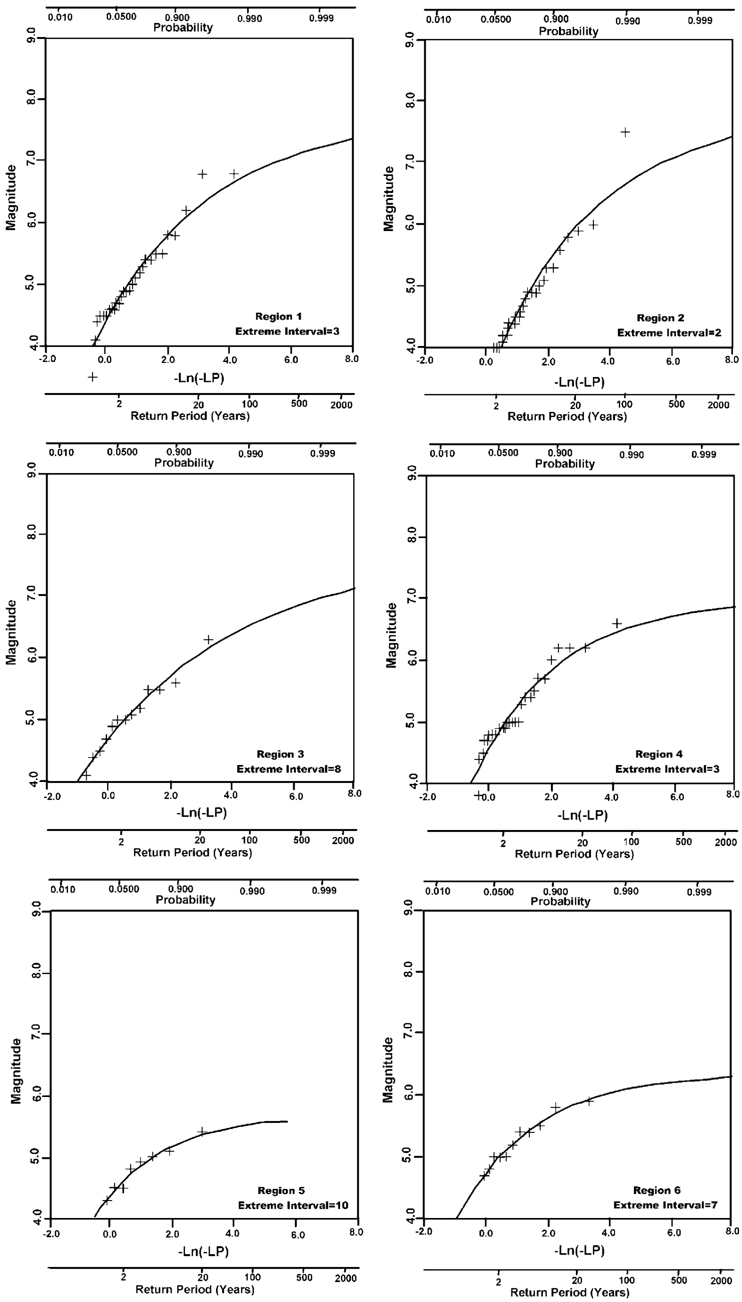

Figure 5
Gumbel III curves for 24 regions in and around Turkey.

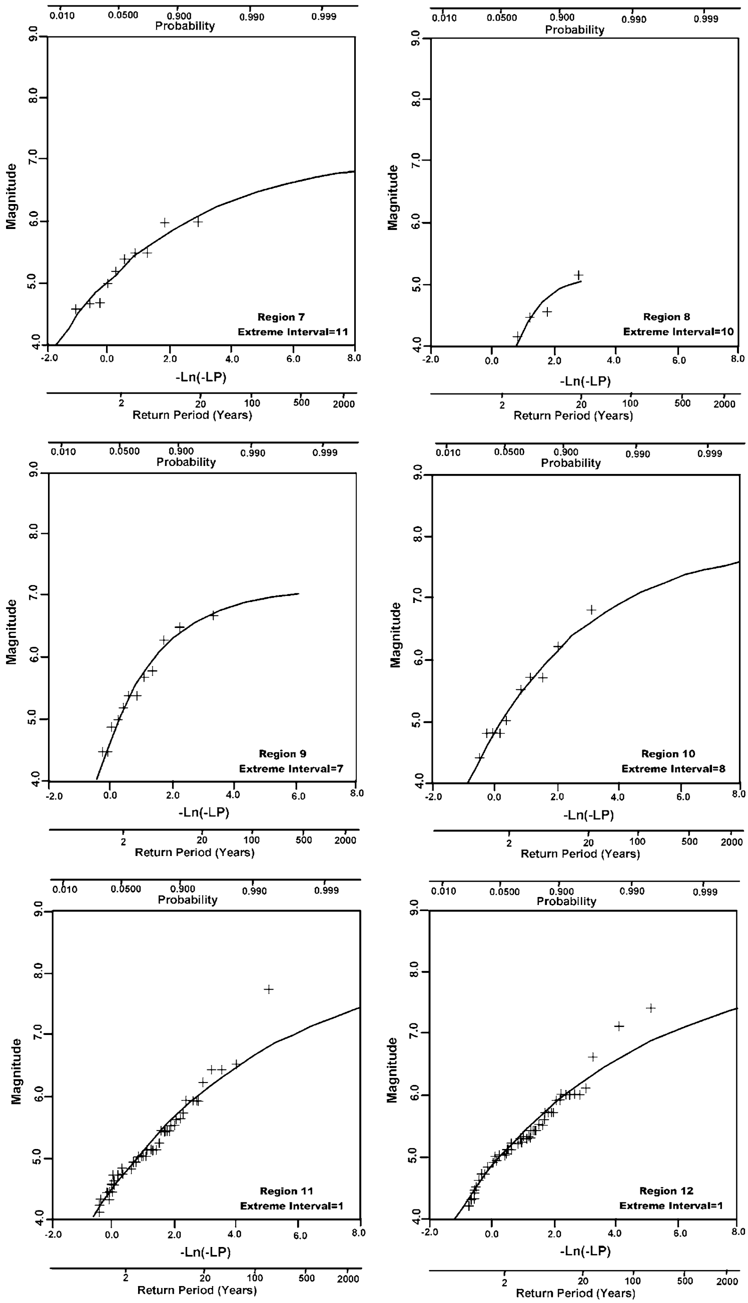

Figure 5
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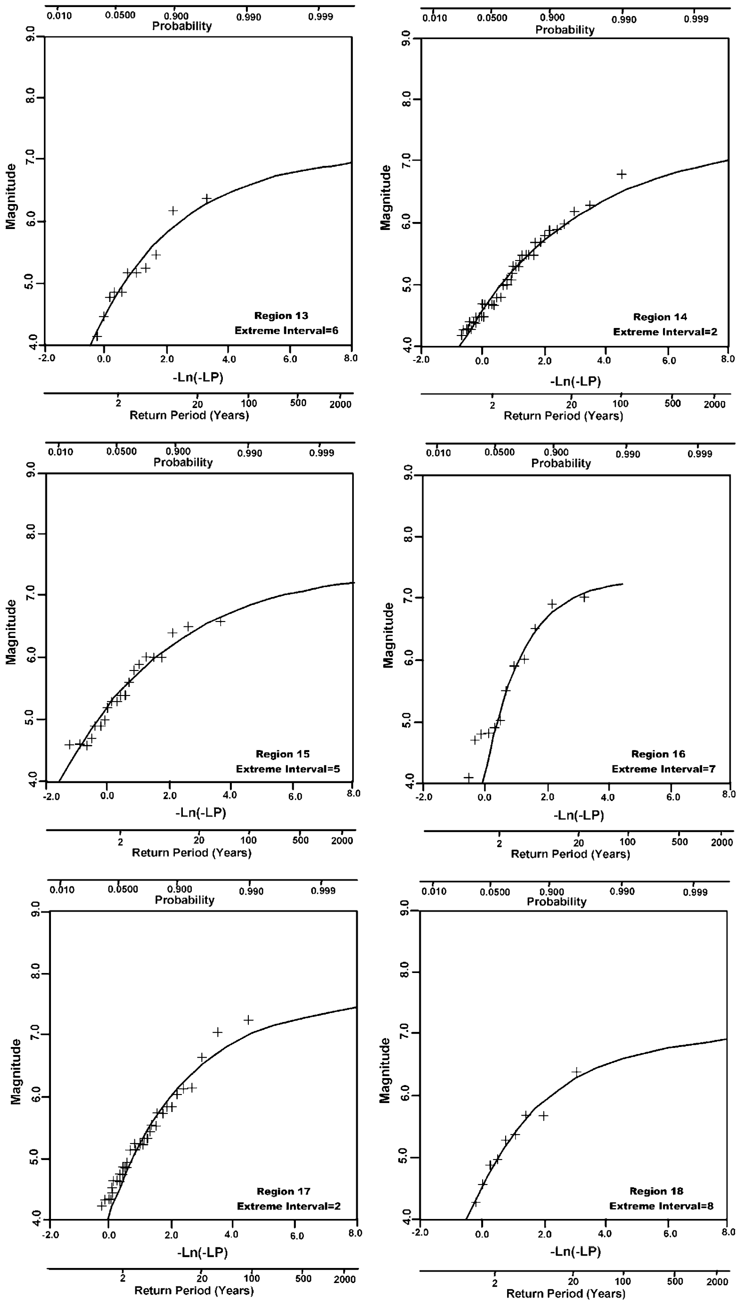

Figure 5
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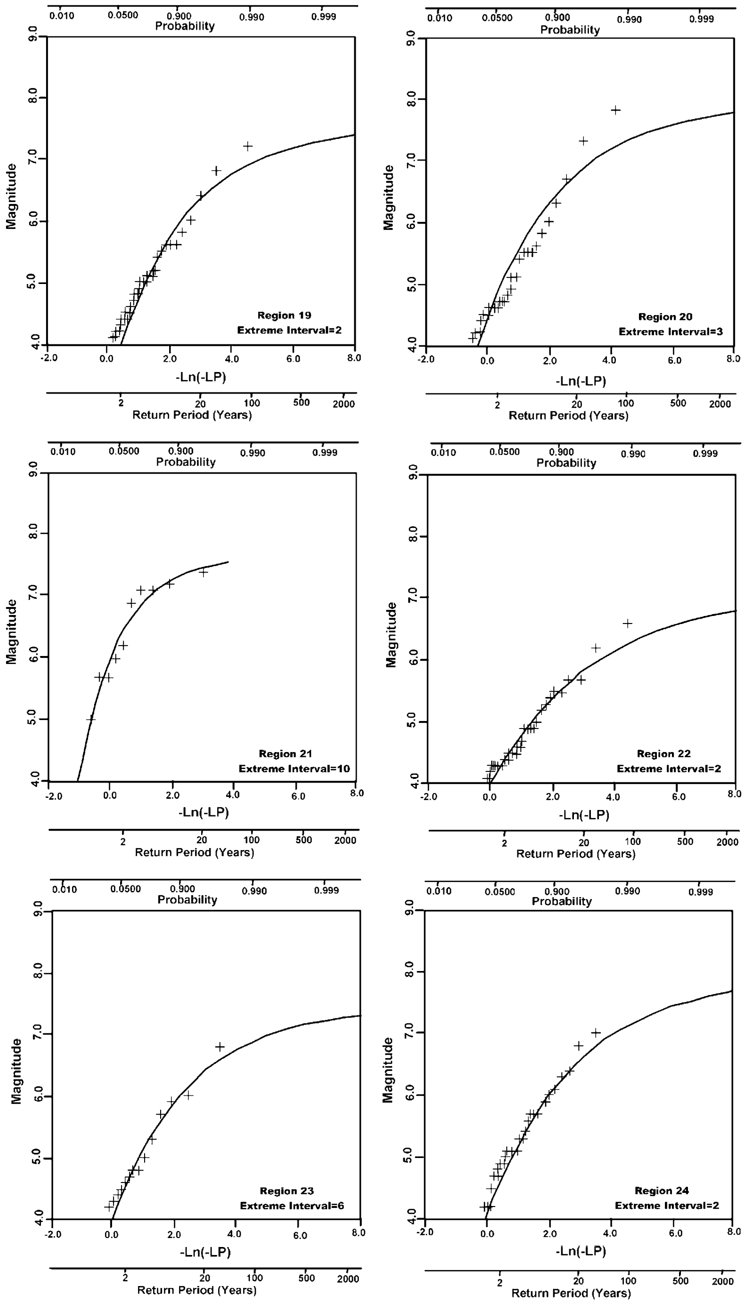

Figure 5
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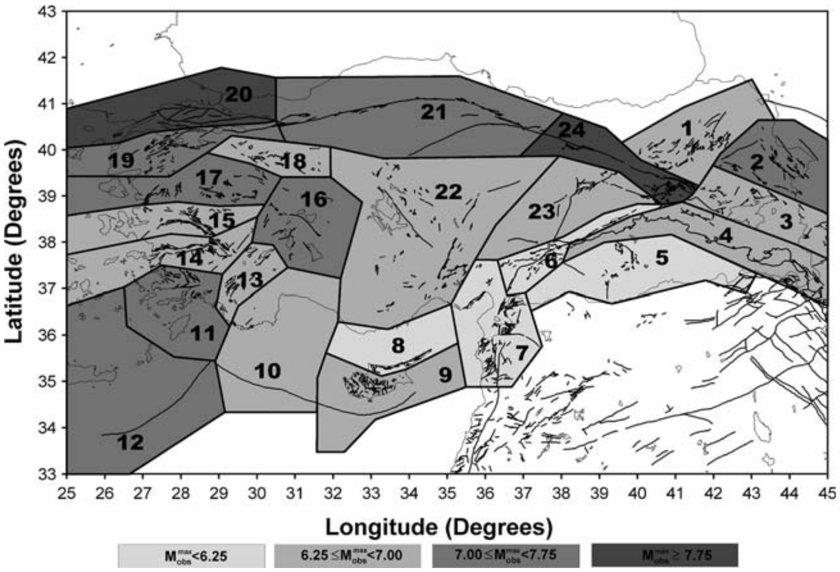

Figure 6
M_{max}^{obs} values for 24 different seismic source regions in Turkey and vicinity (after BAYRAK *et al*., 2007a).

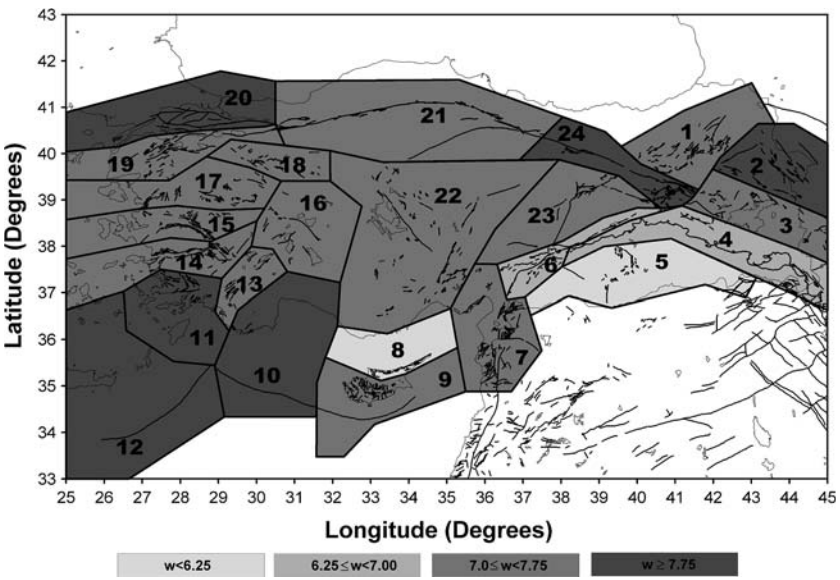

Figure 7
ω values from Gumbel III for 24 different seismic source regions in Turkey and its surrounding.

of 1939 and İzmit earthquake ($M_S = 7.8$) of 1999. The other earthquakes equal and greater than 7.0 are Rhodes earthquake ($M_S = 7.7$) of 1926; Akşehir earthquake ($M_S = 7.0$) of 1931; Çanakkale-Yenice earthquake ($M_S = 7.2$) of 1953; Aegean Sea earthquake ($M_S = 7.4$) of 1956; Çaldıran-Muradiye (Van) earthquake ($M_S = 7.5$) of 1976; Aegean Sea earthquake ($M_S = 7.2$) of 1981; and Düzce earthquake ($M_S = 7.4$) of 1999. These earthquakes occurred in NAFZ, KITÇF, SBTF, KSZBF, YGMUEF, Muğla and Rhodes and Aegean arc. The earthquakes between 6.25 and 7.00 are observed in regions 1, 3, 4, 9, 10, 13, 14, 15, 18, 22 and 23. The earthquakes whose magnitudes are smaller than 6.25 are observed in KEZ, EAFZ, Dead Sea fault region and the northern part of Cyprus. Cyprus Region earthquake, 1995 with $M_S = 5.2$ and Şanlıurfa earthquake, 1915 with $M_S = 5.4$ are the smallest earthquakes in the catalogue.

The ω value has a physical meaning and is directly related to the finite maximum stress which can be stored and then released (as earthquakes) by the rocks of an area (Tsapanos, 1997). It may be considered that ω value related to a region shows maximum earthquake size which may be occur in the future and we cannot expect a larger earthquake magnitude than ω value in this region. For the different regions in and around Turkey, ω values greater than 8.0 are computed in regions 11 and 12 related to Muğla and Rhodes and Aegean arc as listed in Table 2. These regions subjected to compression of the African plate may generate such a great earthquake. The high ω values greater than 7.75 are found in regions 2, 10, 20 and 24 as shown in Figure. 5. These regions cover Kağızman, Iğdır, Tutak and Çaldıran faults, western part of Cyprus arc, Marmara and eastern parts of NAFZ. The values of $M_{\max}^{\text{obs}}$ in these regions are larger than 7.4. According to Eq. (1) developed in this study, a rupture length of 346 km at least is necessary to cause an earthquake greater than 7.75. Considering the seismicity and tectonics of the Cyprus arc and NAFZ we can say that regions 10, 20 and 24 have the capacity to be able to generate such large earthquakes. The largest earthquake in region 2 occurred on the Çaldıran fault. Surface rupture of this earthquake is given as 48–55 km (e.g., Ambrasays and Jackson, 1998; Koçyiğit *et al.*, 2001). But, it is probable that such a big earthquake can rupture a longer fault and subsurface rupture length is larger than that of the surface. Regardless, Wells and Coppersmith (1994) suggested that the subsurface rupture length of this earthquake is equal to 90 km and also they gave the magnitude for this event as 7.3. Although the magnitude of this earthquake is given as 7.5 in our catalogue, we used the parameters suggested for this earthquake as given in Table 1 by Wells and Coppersmith (1994) in order to develop Eq. (1). We compute the ω value in this region as 7.85. According to Eq. (1), a rupture length of 436 km is necessary to cause such an earthquake equal to 7.85 but there is no tectonic structure in region 2. As shown in Figure. 5, high ω value in region 2 is due to data quality. The second level ω values between 7.00 and 7.75 are obtained in regions 1, 3, 7, 9, 13, 14, 15, 16, 17, 18, 19, 21, 22 and 23. The largest value among this group is computed as 7.73 in region 1 related to NEAFZ. This zone includes some long faults such as the Çobandere fault zone (130 km long), Tercan-Aşkale fault (150 km) and Dumlu fault zone (350 km) (Koçyiğit *et al.*, 2001). According to these tectonic structures, such a magnitude of earthquake may be strongly expected. The other largest value is found as 7.69 in region 3 related to MESFS. According to Eq. (1), for the occurrence of such a great earthquake a fault about 295 km in length should be broken. The fault lengths in this region are about 21 km for Malazgirt fault, 34 km for Erçiş fault, 47 km for Süphan fault and 88 km for Muş thrust zone (ULUSAY *et al.*, 2004). If Muş thrust zone is broken completely, the magnitude of this event will be about 7.15 according to Eq. (1). Also, as shown in Table 2 M_{max}^{obs} is 6.3, relatively small, in this region. It can result that it is not possible for such a great earthquake to occur considering tectonic structures in this region, and this is because of the data. Also, we calculated ω value as 7.64 in the middle part of the North Anatolian fault zone and this region has the potential for such a great earthquake according to the tectonics and seismicity of NAF. Other regions in the second level cover some great tectonics of Turkey such as a part of Dead Sea fault, Cyprus arc, Burdur fault zone, Gediz graben, Menderes grabens, Sultandağı fault, Yenice-Göne fault, Tuz Lake fault zone and Malatya-Ovacık fault zones. The ω values computed for these regions are between 7.03 and 7.52. Thus, for these regions we may expect the maximum magnitude of earthquakes in the size of ω values. The ω values smaller than 7.00 are obtained in regions 4, 5, 6 and 8 covering BTZ, KEZ, EAFZ, northern part of Cyprus. The ω values are 6.99, 5.69, 6.37 and 5.20, and M_{max}^{obs} are also 6.6, 5.4, 5.9 and 5.2, respectively. There is potential of generating a large earthquake according to the maximum observed earthquake sizes in these regions.

For each region $\omega - M_{max}^{obs}$ differences are shown with different grey scale in Figure 8: 1) $\omega - M_{max}^{obs} < 0.25$, 2) $0.25 \le \omega - M_{max}^{obs} < 0.75$, 3) $0.75 \le \omega - M_{max}^{obs} < 1.25$ and 4) $\omega - M_{max}^{obs} \ge 1.25$. Also, these values are listed in Table 2. The difference $\omega - M_{max}^{obs}$ is significantly lower in regions 20, 21, 24 and 8 related to NAFZ and the northern part of Cyprus compared to other regions. $\omega - M_{max}^{obs}$ values for the eastern, middle and western parts of NAFZ are 0.05, 0.24 and 0.13, respectively. The obtained results demonstrate that the middle part of NAFZ compared to the eastern and western parts of NAFZ can generate larger events than that of observed events. TSAPANOS (1997) stated that in the areas in which the difference $\omega - M_{max}^{obs}$ is low, the mechanical heterogeneity of the materials is responsible for this low difference, as they return (as earthquake) most of the stored energy. Differences of $\omega - M_{max}^{obs}$ between 0.25 and 0.75 are found in regions 2, 4, 5, 6, 9, 11, 13, 14, 16, 17, 18, 19, 22 and 23. As discussed above in detail in these regions (except region 2), it may be expected a larger earthquake than M_{max}^{obs} by the score ω. Values of $\omega - M_{max}^{obs}$ greater than 0.75 are found in regions 1, 3, 7, 10, 12 and 15. An event larger than 0.75 magnitude unit than M_{max}^{obs} may occur in other regions except region 3, which is discussed in detail above. Thus, this high difference means that the regions of this side release a large, but not the whole amount of stored energy and this can be considered as evidence of the high degree of homogeneity in this side (TSAPANOS, 1997).

Maximum expected magnitudes to be observed in the next 100 years are computed in order to test whether the earthquakes as much as ω values may occur in each 24 region. The most probable magnitude RM (M_{100}) for 100 years are listed in Table 2 and the

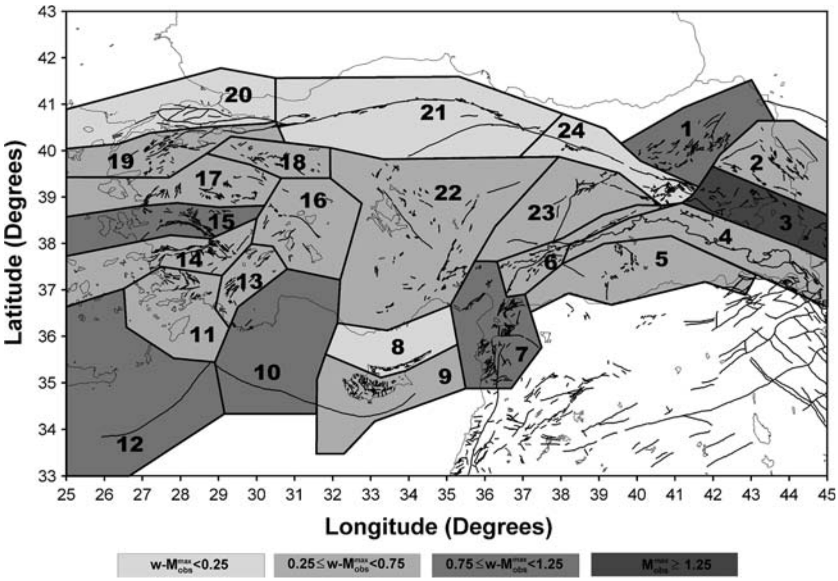

Figure 8
$\omega - M_{\max}^{\text{obs}}$ values for 24 different seismic source regions in Turkey and vicinity.

regional variability of M_{100} is shown in Figure 9. We divided M_{100} values into four groups as shown by legends with different grey scale: 1) $M_{100} < 6.0$, 2) $6.0 \leq M_{100} < 6.5$, 3) $6.5 \leq M_{100} < 7.0$ and 4) $M_{100} \geq 7.0$. As shown in Table 2, whole M_{100} values are lower than ω values. Especially, $\omega - M_{100}$ differences are greater than 1.0 in regions 1, 2, 3, 7, 10, 11, 12, 20 and 23. The return periods shown in Figure 5 greatly exceed 100 years for the occurrence of an event as much as ω values computed for these regions. In the next 100 years, the earthquakes with magnitude $M \geq 7.0$ were only estimated in region 21. This region is related to the middle part of NAFZ and has the maximum earthquake hazard level in the next 100 years. Also, in regions 9, 11, 12, 16, 17, 19, 20 and 24 related to Cyprus arc, Aegean arc, SBTF, KSZBF, YGMUEF and western and eastern parts of NAFZ the earthquakes with magnitudes between 6.5 and 7.0 may occur in the next 100 years. In the other regions, the sizes of earthquakes that are expected in the next 100 years may be smaller than 6.5 and the maximum expected magnitudes in these regions also decrease for the next 100 years, compared to the period between 1900 and 2005.

The earthquake hazard level for 24 seismic regions of Turkey from K index, defined as relative earthquake hazard scale, is calculated by Bayrak *et al.* (2007a) and they found that the middle part of NAFZ between Bolu and Erzincan (particularly region 21) is of very high level because it is unbroken for very large earthquakes ($M \geq 7.8$, like those in Erzincan in region 24 and İzmit in region 20) and the largest earthquake in this part is the 1943 Tosya-Ladik earthquake with $M = 7.2$. They also stated that regions 11 and 12 also have a very high seismicity which is closely related to the Aegean arc. Bayrak *et al.*

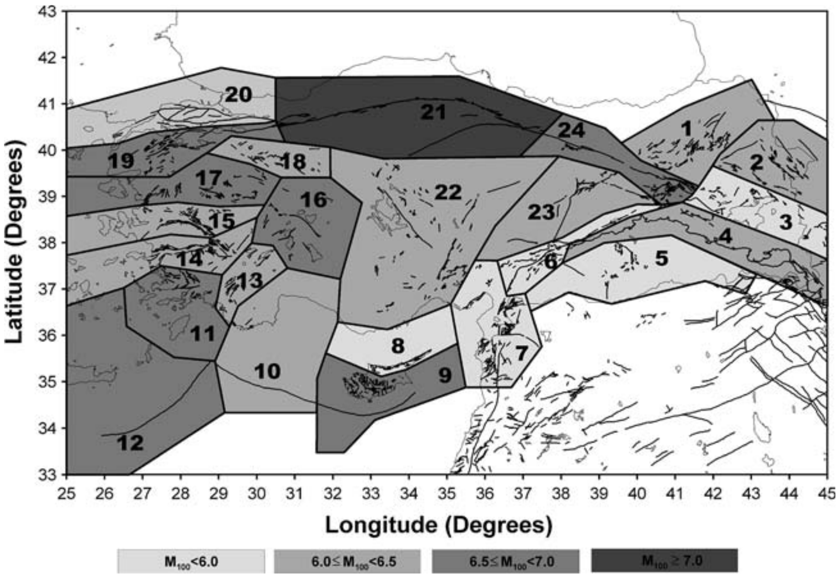

Figure 9
M_{100} values from Gumbel III for 24 different seismic source regions in Turkey and its surroundings.

(2007b) estimated the seismicity in terms of the modal values (a_m/b) for each one of the 24 seismic region and concluded that regions 20, 21 and 24 (North Anatolian fault zone) and region 12 (Aegean arc) are ranked to the first position according to their seismicity. In both studies, the maximum earthquake hazard value is observed in region 21 related to the middle part of NAFZ. Also, ÖZTÜRK *et al.* (2007) computed the maximum expected earthquake size (M_{100}) from the Gumbel I method for the 24 seismic regions of Turkey and its surroundings. They found the maximum M_{100} value in region 21 and stated that region 21 (middle part of NAFZ) is probably the next region for the occurrence of a large earthquake. The maximum expected earthquake size (M_{100}) computed, in this study from the Gumbel III method for the 24 seismic regions of Turkey and its surroundings is listed in Table 2. Values of M_{100} estimated from Gumbel III in this study are relatively lower compared to M_{100} values from Gumbel I in ÖZTÜRK *et al.* (2007). After all, we computed the maximum M_{100} value in region 21 as 7.35 and this is in accordance with the results of the studies mentioned above.

7. *Conclusions*

An attempt is made here to provide new relationships between the magnitude of earthquakes and the surface rupture for the 24 seismic regions in which Turkey and the surrounding area is divided. ACHARYA (1979) was the first who made such an attempt to find such relationships for some regions of the world among which is Turkey. He took into account only 11 events. We added more data in the present study and we considered that the relationship we found is more significant, although the values estimated are close enough to those found by ACHARYA (1979). We also computed their uncertainties for 95% confidence limits, while the correlation coefficient of the provided relationship is 0.89. We compared our relationship with others given by different authors (ACHARYA, 1979; WELLS and COPPERSMITH, 1994; AMBRASEYS and JACKSON, 1998). We can conclude that there is a great divergence between our relationship and those given by the other authors, mainly in magnitudes greater than 7.2. We also estimated the GIII parameters for each seismic region. We may conclude that GIII is considerable preferable to GI because it includes a parameter which is the *upper bound magnitude*. Plots of the earthquake magnitude-frequency distribution often show curvature especially as the larger earthquakes are approached (PAGE, 1968; UTSU, 1971; BLOOM and ERDMANN, 1980). This parameter of GIII distribution allows for any detectable curvature in addition to the *upper bound magnitude*. The method requires only the largest earthquake magnitudes occurring in each of a set of equal-time in which the whole time period is divided. In the cases in which we have no annual extremes, *N* extremes are used to reduce the number of missing extreme entries. As BURTON (1979) suggested that if missing entries are less than or equal to 25%, the parameters of the GIII distribution may be estimated without noticeable loss of accuracy. Annual extremes are used in the present work. The most probable magnitude expected during the next 100 years is also estimated for each of the seismic regions. We can conclude once more (see in BAYRAK *et al*., 2007a, b) that the middle part of the NAFZ is the most dangerous place for the next occurrence of a large earthquake which may exceed magnitude 7.0.

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