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An Evaluation of Earthquake Hazard Potential for Different Regions in Western Anatolia Using the Historical and Instrumental Earthquake Data

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Abstract—We applied the maximum likelihood method produced by KIJKO and SELLEVOLL (Bull Seismol Soc Am 79:645–654, 1989; Bull Seismol Soc Am 82:120–134, 1992) to study the spatial distributions of seismicity and earthquake hazard parameters for the different regions in western Anatolia (WA). Since the historical earthquake data are very important for examining regional earthquake hazard parameters, a procedure that allows the use of either historical or instrumental data, or even a combination of the two has been applied in this study. By using this method, we estimated the earthquake hazard parameters, which include the maximum regional magnitude $\hat{M}_{\max}$, the activity rate of seismic events and the well-known $\hat{b}$ value, which is the slope of the frequency-magnitude Gutenberg-Richter relationship. The whole examined area is divided into 15 different seismic regions based on their tectonic and seismotectonic regimes. The probabilities, return periods of earthquakes with a magnitude $M \geq m$ and the relative earthquake hazard level (defined as the index K) are also evaluated for each seismic region. Each of the computed earthquake hazard parameters is mapped on the different seismic regions to represent regional variation of these parameters. Furthermore, the investigated regions are classified into different seismic hazard level groups considering the K index. According to these maps and the classification of seismic hazard, the most seismically active regions in WA are 1, 8, 10 and 12 related to the Aliağa Fault and the Büyük Menderes Graben, Aegean Arc and Aegean Islands.

Key words: Western Anatolia, earthquake hazard, mean return period, probability, the most probable maximum magnitude.

1. Introduction

The evaluation of earthquake hazard parameters such as mean activity rate $\hat{\lambda}$, $\hat{b}$ value of the G-R relationship and maximum regional magnitude $\hat{M}_{\max}$ is the first step in the preparation of a probabilistic seismic hazard map in any seismically active region. The earthquake hazard is estimated as the probability of occurrence of an earthquake with a magnitude larger than or equal to a particular value within a specified region and a given time period. The mean probability of occurrences of a seismic event with a certain magnitude within a given time interval is necessary to understand the seismic hazard. The maximum regional magnitude $\left(\hat{M}_{\max}\right)$ and the activity rate or the mean return periods of earthquakes with magnitudes greater than or equal to a given threshold value are the most common quantities considered as measures of seismicity.

The Aegean extension region is one of the most seismically active and rapidly prolongating areas of the Eastern Mediterranean region (BOZKURT, 2001). Large and destructive earthquakes have occurred in both historical and instrumental periods in this region. Several seismic hazard studies (e.g., PAPAZACHOS, 1999; PAPAIOANNOU and PAPAZACHOS, 2000; JENNY *et al.*, 2004; POLAT *et al.*, 2008; SAYıL and OSMANŞAHIN, 2008; BAYRAK *et al.*, 2005, 2009) have been performed in order to estimate the earthquake hazard in and around western Anatolia.

We applied a procedure developed by KIJKO and SELLEVOLL (1989, 1992) in order to examine earthquake hazard for the different regions of western Anatolia (WA). The proposed approach is very flexible and provides several attractive properties. It accommodates "gaps" in both historical and complete parts of the catalog. It makes it possible to estimate the maximum regional magnitude $\hat{M}_{\max}$ from the largest historically known earthquake, which occurred before the catalog's beginning. It allows for the combination of earthquakes of the historical epoch and those extracted from short periods of instrumental data. The complete part of the catalog can be divided into time intervals of different

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levels of completeness. An illustration of the quality of the data, which can be used to obtain the seismic parameters through this approach, can be seen in Kijko and Sellevoll (1992).

Bayrak *et al.* (2009) used 24 different source regions considering the different previous zonation studies for modeling of seismic hazard in Turkey, and 9 seismic source zones in these 24 regions are related to WA. They computed the earthquake hazard parameters for only instrumental earthquakes in the 24 different regions of Turkey. In this study, we updated the regions used by Bayrak *et al.* (2009) and divided WA into 15 new seismic zones to make a detailed analysis of seismic hazard in the considered region. Furthermore, the earthquake catalog used in this study was updated for the historical period earthquakes. Since a large proportion of the earthquakes with $M \geq 6.5$ occurred in the historical period in WA, it is necessary to use the historical earthquakes to compute sensitive earthquake hazard parameters for the different regions of WA.

In this study, a method for estimating $\hat{M}_{\max}$ and other related parameters such as the magnitude-frequency relationship $\hat{b}$ (or $\hat{\beta}$) and the mean seismic activity rate $\hat{\lambda}$ introduced by Kijko and Sellevoll (1989) is applied for the different regions of WA. We applied maximum likelihood estimation on the basis of a procedure that uses data from both incomplete and complete files. The computations of the method are based on the assumption that earthquakes have a Poisson occurrence over time with a mean activity rate $\hat{\lambda}$ and a doubly truncated frequency magnitude Gutenberg-Richter relation. The standard deviations of these parameters are also estimated. The mean return periods (RP) of earthquakes with a certain magnitude $M \geq m$ and probability for an earthquake occurrence (Pr) are determined.

2. *Tectonics*

Main tectonic structures playing important roles in the geodynamic evolution of the Aegean region are the Aegean Arc and Western Anatolian Extension Zone. Figure 1 shows the tectonic structures and focal mechanisms of 190 events ($h \leq 70$ km) with $4.7 \leq m_b \leq 7.1$ occurring in the study area (26–33°E, 33–40.5°N) during the 1953–2010 period. The convergence between the Arabian and Eurasian plates in Eastern Anatolia pushes the Anatolian Plate westwards along the North Anatolian Fault Zone and the East Anatolian Fault Zone, and the Anatolian Plate rotates anticlockwise with an average velocity of 24 mm/year (McClusky *et al.*, 2000). This motion is transferred into the Aegean in the southwestern direction (McKenzie, 1972, 1978), which results in the northern Aegean being dominated by dextral strike-slip faulting of northeastern strike. The African Plate subducts beneath the Anatolian Plate in a N-NE direction in the Eastern Mediterranean (McKenzie, 1978). The Aegean Arc consists of the outer sedimentary arc and the inner volcanic arc, while its outer borders are bounded by the Aegean trench with a maximum water depth of 5 km (Papazachos and Kiratzi, 1996). The Western Anatolian zone is one of the most seismically active and rapidly extending areas in the world (e.g., Bozkurt, 2001). It is currently experiencing an approximately N-S continental extension at a rate of 30–40 mm/year (Oral *et al.*, 1995; Le Pichon *et al.*, 1995).

Approximately E-W trending grabens (e.g., Edremit, Bakırçay, Kütahya, Simav, Gediz, Küçük Menderes, Büyük Menderes and Gökova grabens) and their basin-bounding active normal faults are the most prominent neotectonic features of western Anatolia (e.g., Şengör *et al.*, 1985; Şengör, 1987; Seyitoğlu and Scott, 1992; Seyitoğlu *et al.*, 1992; Koçyiğit *et al.*, 1999; Yilmaz *et al.*, 2000; Lips *et al.*, 2001; Sözbilir, 2001, 2002; Bozkurt and Sözbilir, 2004; Kaya *et al.*, 2004; Erkul *et al.*, 2005; Emre and Sözbilir, 2007). Other less prominent structural elements of western Turkey are the N-NE-trending basins and their intervening horsts (e.g., Gördes, Demirci, Selendi, and Uşak-Güre basins; (e.g., Ersoy and Helvaci, 2007).

The eastern part of the studied region includes the NW-SE trending Dinar, Beyşehir and Akşehir-Afyon grabens and NE-SW trending Burdur, Acıgöl, Sandıklı, Çivril and Dombayova grabens and their bounding faults (e.g., Bozkurt, 2001). The existence of two sets of normal faults indicates that the region is extending biaxially, with both NE-SW and NW-SE components of extension (Westaway, 1994). Barka *et al.* (1997) suggested that the NE-SW trending

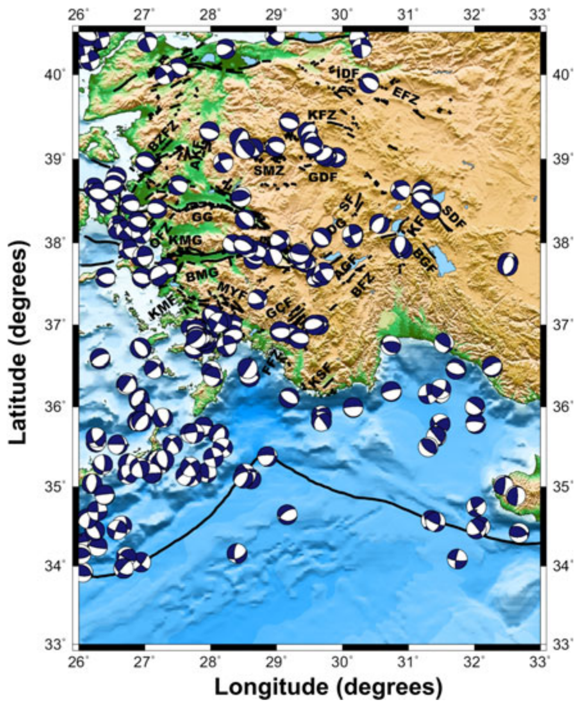

Figure 1
Main tectonics of western Anatolia and focal mechanisms of 190 events ($h \leq 70$ km) with $4.7 \leq m_b \leq 7.1$ occurring in the study area (26–33°E, 33–40.5°N) during the 1953–2010 period. Abbreviations: *AGF* Acıgöl Fault, *AKF* Akhisar Fayı, *BFZ* Burdur Fault Zone, *BGF* Beyşehir Gölü Fault, *BMG* Büyük Menderes Graben, *BZFZ* Bergama-Zeytindağı Fault Zone, *DG* Dinar Graben, *EFZ* Eskişehir Fault Zone, *FFZ* Fethiye Fault Zone, *GÇF* Gölhisar-Çameli Fault, *GDF* Gediz-Dumlupınar Fault, *GG* Gediz Graben, *İDF* İnönü-Dodurga Fault, *KF* Kumdanlı Fayı, *KFZ* Kütahya Fault Zone, *KMF* Karova-Milas Fault, *KMG* Küçük Menderes Graben, *KSF* Kaş Fayı, *MYF* Muğla-Yatağan Fault, *OFZ* Orhanlı Fay Zone, *SDF* Sultandağı Fault, *SF* Sandıklı Fault, *SFZ* Simav Fault Zone

left-lateral Fethiye-Burdur Fault Zone (FBFZ), which is interpreted as the northeastern continuation of the Pliny-Strabo Fault Zone on the land, and the Eskişehir Fault form the major boundary between the Western Anatolian extensional province and the Isparta Angle area. GPS measurements indicate slip rates of 1.5 cm/year along the FBFZ (Reilinger *et al.*, 1997; Barka and Reilinger, 1997). The recent GPS studies, the distribution of historical and instrumental earthquakes, and morphological features indicate that the FBFZ is active. However, others claimed that the FBFZ is not a transform fault boundary and the dominant motion is dip-slip (normal) normal, not sinistral (Koçyiğit, 2000). The WNW-ESE trending Eskişehir Fault Zone is a dextral structure with considerable amount of normal components. It extends from Bursa to Afyon.

The N-S-striking active normal faults and some NNE-SSW-trending strike-slip faults such as the Orhanlı Fault Zone (OFZ) and the Bergama-Zeytindağ Fault (BZF) zone are also present in the region (Yilmaz *et al.*, 2000; Uzel and Sözbilir, 2008). The most continuously traceable fault is the OFZ. Other potentially active faults are the Manisa Fault near Manisa city and İzmir Fault (İF) trending in an E-W direction (Bozkurt and Sözbilir 2006). The Karaburun-Gulbahce Fault (KGF) occurs in the Karaburun Peninsula and is supposed to be predominantly strike-slip fault. Gokova Fault (GF) can be traced on a line trending in an E-W direction along the northern coast of Gökova Bay (GB) in the south of the Western Anatolian zone (e.g., Şaroğlu *et al.*, 1992; Eyidoğan, 1988; Ocakoğlu *et al.*, 2004, 2005; Aktuğ and Kiliçoğlu, 2006).

3. *Data, Source Zonation and Completeness Analysis*

The database used in this work was compiled from different sources and catalogs such as TURKNET, the International Seismological Centre (ISC), Incorporated Research Institutions for Seismology (IRIS) and The Scientific and Technological Research Council of Turkey (TUBITAK), and is provided in different magnitude scales. The catalogs include 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), the origin time, epicenter and depth information of earthquakes. Turkey's earthquake catalog, starting in 1974 and continuing to 2010, was taken from the Boğaziçi University, Kandilli Observatory and Earthquake Research Institute (KOERI). The earthquakes from 1900 to 1974 were obtained from the International Seismological Centre (ISC) and instrumental catalog of KOERI. The historical earthquake catalog used in this study was taken from the database of the Global Seismic Hazard Assessment Program (GSHAP) being compiled by Erdik *et al.* (1999).

An earthquake data set used in seismicity or seismic hazard studies must certainly be homogenous, in other words, it is necessary to use the same magnitude scale. However, the earthquake data obtained from different catalogs have been reported in different magnitude scales. Therefore, all earthquakes must be defined in the same magnitude scale. Bayrak *et al*. (2009) developed some relationships among different magnitude scales (m_b body wave magnitude, M_S surface wave magnitude, M_L local magnitude, M_D duration magnitude and M_W moment magnitude) in order to prepare a homogenous earthquake catalog from different data sets. We prepared a homogenous earthquake data catalog for M_S magnitude using these relationships. The time interval considered for the present work changed between BC 1303 and AD 2010.

A complete understanding of the historical and instrumental seismicity, tectonics, geology, paleoseismology and other neotectonic properties of the considered region is necessary for an ideal delineation of seismic source zones. Several authors used different seismic source zones to study the seismic hazard of Turkey (e.g., Alptekin, 1978; Erdik *et al*., 1999; Kayabalı, 2002; Bayrak *et al*., 2005, 2009). Bayrak *et al*. (2009) used 24 different source regions considering the different previous zonation studies for modeling of seismic hazard in Turkey, and 9 seismic source zones in these 24 regions are related to WA. Sayıl and Osmanşahin (2008) used 13 elliptic regions in WA to compute seismicity parameters. Their regions are not realistic and are unsuitable for earthquake hazard studies because the geometries of faults and graben systems in WA are suitable to the use of polygonal seismic zones. Furthermore, in the case of using elliptical seismic zones, earthquakes that occurred outside the considered fault system are joined to a studied seismic zone. In this study, we updated the regions defined by Bayrak *et al*. (2009) and divided WA into 15 seismic zones to make a detailed analysis of seismic hazard in the considered region with an updated and more reliable earthquake catalog. These regions are shown in Fig. 2 and listed in Table 3. The epicentral distributions of the historical and instrumental earthquakes are shown in Fig. 2 on different seismic source zones in WA. Bayrak *et al*. (2009) used only instrumental earthquakes to estimate earthquake hazard parameters for 24 different regions in and around Turkey. The earthquakes with $M \geq 6.5$ are listed in Table 2 for 15

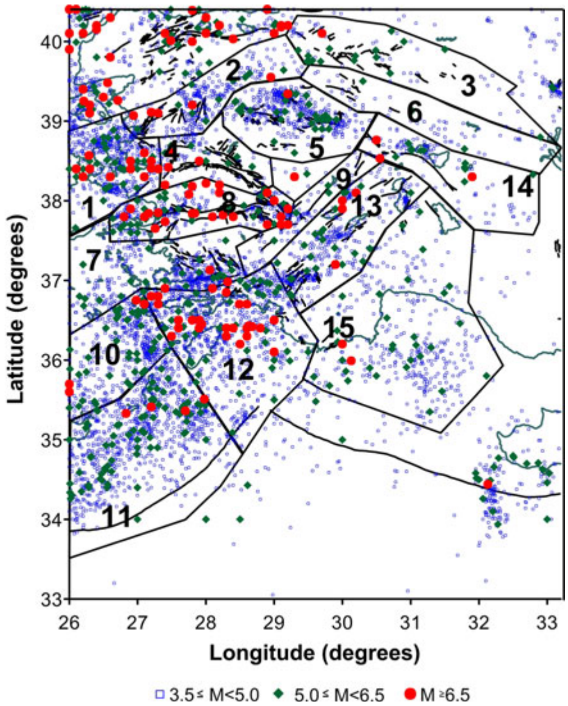

Figure 2
Earthquake epicenter distribution and 15 different seismic regions in western Anatolia

different regions in WA. It is seen in Table 1 that a large part of major earthquakes occurred in the historical period. So, it is necessary to use the historical earthquakes to compute sensitive earthquake hazard parameters for the different regions of WA.

It is frequently necessary to use a great number of events available for high-quality results in seismicity studies. The fact that magnitude completeness changes with time in most catalogs and usually decreases is well known. So, the minimum magnitude of completeness is an important parameter for seismicity studies. The catalog used in this study encompasses the time period between BC 1303 and AD 2010, and these are the historical and instrumental parts of the catalog. For the historical and instrumental periods, results of completeness analysis made in this study are shown in Table 2. The method used to assess the completeness of the data of this catalog has been described in the literature (e.g., Tsapanos, 1990; Tsapanos and Papazachos, 1998). The completeness was assessed assuming the cumulative frequency distribution of the magnitudes and of the cumulative

Table 1

The earthquakes with $M \geq 6.5$ for 15 different seismic regions in western Anatolia

Year	Month	Day	Latitude	Longitude	Magnitude	Region
1644			38.41	27.20	6.50	1
1664			38.41	27.20	6.50	
1667	4	6	38.41	27.20	6.50	
1668			38.41	27.20	7.00	
1688	7	12	38.40	26.90	7.50	
1739	4	4	38.50	26.90	6.80	
1828	6	15	38.41	27.20	6.50	
1871	10	8	38.40	26.10	6.50	
1880	3		38.40	26.10	7.00	
1880	7	29	38.50	27.20	6.70	
1881	4	3	38.30	26.20	6.50	
1883	10	15	38.30	26.60	6.80	
1888	5		38.40	26.10	6.70	
1895			38.60	27.10	7.00	
1949	7	23	38.57	26.29	6.60	
1625	5	18	39.20	27.80	7.00	2
1886	10	6	39.55	28.95	6.50	
1939	9	22	39.07	26.94	6.60	
1794	8	5	40.10	29.70	7.00	3
1845	6	23	38.60	27.50	6.70	4
1850			38.42	27.45	6.70	
1862	11	3	38.50	27.90	6.90	
1896	4	16	39.34	29.20	6.50	5
1869	12	1	36.98	28.32	6.80	7
1941	12	13	37.13	28.06	6.50	
1646			37.80	28.40	6.60	8
1651	6	8	37.80	29.10	6.70	
1653	2	23	38.20	28.20	7.50	
1702	2	25	37.70	29.10	7.00	
1873	1	31	37.80	27.10	6.50	
1874	6	28	37.80	26.80	6.50	
1880			38.08	27.75	6.50	
1887	8		38.10	28.20	6.50	
1888	10		38.22	28.00	6.50	
1893	3	12	37.90	26.90	6.60	
1895	8	19	37.84	27.80	6.70	
1899	9	20	37.82	28.25	7.00	
1928	3	31	38.18	27.80	6.50	
1955	7	16	37.65	27.26	6.80	
1717	11	19	37.70	29.20	6.60	9
1493	8	18	36.70	27.10	6.80	10
1926	6	26	36.75	26.98	7.70	
1922	8	11	35.36	27.70	6.50	11
1922	8	13	35.51	27.98	6.90	
1935	3	18	35.33	26.83	6.50	
1948	2	9	35.41	27.20	7.10	
1303	8	8	36.10	29.00	8.00	12
1481	10	3	36.40	28.60	7.20	
1609	4		36.40	28.40	7.20	
1741	1	31	36.20	28.50	7.30	
1756	2	13	36.30	27.50	7.70	
1851	2	28	36.50	29.00	7.10	
1852	10	19	36.40	28.60	6.50	
1863	4	22	36.40	27.60	7.80	
1869	4	18	36.50	27.60	6.90	
1870	2	22	36.40	28.80	7.00	
1871	6	7	36.85	28.30	6.50	
1874	11	16	36.50	27.90	7.00	
1896	6	26	36.90	28.10	6.50	
1897	5		36.70	28.60	6.50	
1943	10	16	36.45	27.94	6.60	
1957	4	24	36.43	28.63	6.80	
1957	4	25	36.42	28.68	7.10	
1961	5	23	36.70	28.49	6.60	
1875	5	3	38.10	30.20	7.00	13
1914	10	3	38.00	30.00	6.90	
1795			38.76	30.50	6.70	14
1931	4	9	38.30	31.90	7.00	
1926	3	18	35.99	30.13	6.80	15

frequency distribution of the number of earthquakes with magnitudes larger than a certain value.

4. Method for the Estimation of the Earthquake Hazard Parameters

Estimation of earthquake hazard parameters (maximum regional magnitude, $\hat{M}_{\max}$, earthquake activity rate $\hat{\lambda}$, and $\hat{b}$ (or $\hat{\beta}$) parameter in the Gutenberg-Richter equation) is extended to the case of mixed data containing large historical and recent instrumental events. The method accepts variable quality of complete data in different parts of a catalog with different threshold magnitude values. The available earthquake catalogs usually contain two types of information: historical observations including major seismic events that occurred over a period of a few hundred years and instrumental data for relatively short periods of time. The most suitable methods for analyzing the historical part of the catalog are the extreme distributions, extended to allow varying time intervals from which maximum magnitudes are selected. Assuming that this part of a catalog contains only the largest seismic events, and having the possibility of dividing the catalog into time intervals of different lengths, it can be in practice to analyze all the historical data. This method of incorporating the incomplete part of the catalog into the analysis is very far from optimum, as a great deal

Table 2

The results of completeness analysis for 15 different seismic regions in western Anatolia

Region no.	Period	Cutoff magnitude
1	2005	$M_S \geq 2.2$
	1994	$M_S \geq 2.6$
	1976	$M_S \geq 3.3$
	1942	$M_S \geq 4.1$
	1904	$M_S \geq 5.0$
	1644	$M_S \geq 6.0$
2	1990	$M_S \geq 2.1$
	1974	$M_S \geq 3.0$
	1942	$M_S \geq 4.0$
	1903	$M_S \geq 5.3$
	1625	$M_S \geq 6.0$
3	2005	$M_S \geq 2.1$
	1983	$M_S \geq 3.0$
	1940	$M_S \geq 4.0$
	1918	$M_S \geq 5.0$
	1794	$M_S \geq 7.0$
4	1990	$M_S \geq 2.2$
	1983	$M_S \geq 2.9$
	1965	$M_S \geq 4.0$
	1926	$M_S \geq 5.4$
	1595	$M_S \geq 6.4$
5	1992	$M_S \geq 2.0$
	1976	$M_S \geq 3.0$
	1957	$M_S \geq 4.1$
	1942	$M_S \geq 5.0$
	1896	$M_S \geq 6.5$
6	1993	$M_S \geq 2.0$
	1984	$M_S \geq 3.0$
	1970	$M_S \geq 4.0$
	1919	$M_S \geq 4.8$
7	2004	$M_S \geq 2.2$
	1989	$M_S \geq 3.1$
	1956	$M_S \geq 4.0$
	1926	$M_S \geq 5.2$
	1769	$M_S \geq 6.8$
8	1997	$M_S \geq 2.3$
	1977	$M_S \geq 3.0$
	1928	$M_S \geq 4.0$
	1904	$M_S \geq 5.0$
	1646	$M_S \geq 6.0$
9	1995	$M_S \geq 2.2$
	1983	$M_S \geq 3.0$
	1965	$M_S \geq 4.0$
	1920	$M_S \geq 5.1$
	1717	$M_S \geq 6.6$
10	1990	$M_S \geq 2.8$
	1974	$M_S \geq 4.0$
	1918	$M_S \geq 5.0$
11	1990	$M_S \geq 3.0$
	1975	$M_S \geq 4.0$
	1950	$M_S \geq 4.5$
	1910	$M_S \geq 5.1$
12	1994	$M_S \geq 2.3$
	1977	$M_S \geq 3.5$
	1959	$M_S \geq 4.2$
	1925	$M_S \geq 5.0$
	1303	$M_S \geq 6.2$
13	1995	$M_S \geq 2.3$
	1979	$M_S \geq 3.1$
	1950	$M_S \geq 4.0$
	1925	$M_S \geq 5.0$
	1875	$M_S \geq 7.4$
14	2000	$M_S \geq 2.1$
	1980	$M_S \geq 3.5$
	1956	$M_S \geq 4.3$
	1921	$M_S \geq 5.5$
	1795	$M_S \geq 6.6$
15	1993	$M_S \geq 2.6$
	1980	$M_S \geq 3.3$
	1951	$M_S \geq 4.3$
	1911	$M_S \geq 5.0$
	1717	$M_S \geq 6.6$

of information contained in small shocks is wasted (Kijko and Sellevoll, 1989).

The maximum regional magnitude earthquake, $\hat{M}_{\max}$, is defined as the upper limit of the magnitude for the given seismic tectonic source or region (Reiter, 1990). The procedure for evaluating the maximum regional magnitude $\hat{M}_{\max}$ is based on the equation that compares the largest *observed* magnitude $\hat{M}_{\max}^{\text{obs}}$ and the maximum *expected* magnitude $E\left(\hat{M}_{\max}/T\right)$ during the span, T, of the catalog (Kijko, 1988, 2004). If this condition is applied to the Gutenberg-Richter frequency-magnitude distribution, the following estimator of maximum regional magnitude $\hat{M}_{\max}$ is obtained (Kijko, 1988):

$$\hat{M}_{\max} = M_{\max}^{\text{obs}} + \frac{E_1(TZ_2) - E_1(TZ_1)}{\hat{\beta}\exp(-TZ_2)} + M_{\min}\exp\left(-\hat{\lambda}T\right) \quad (1)$$

The above estimator of $\hat{M}_{\max}$ for the doubly truncated Gutenberg-Richter relation was first obtained by Kijko (1983). The quantities in Eq. 1 are computed as: $Z_1 = \hat{\lambda}A_2/(A_1 - A_2)$, $Z_2 = \hat{\lambda}A_2/(A_1 - A_2)$, $A_1 = \exp(-\hat{\beta}M_{\min})$, and $A_2 = \exp(-\hat{\beta}M_{\max}^{\text{obs}})$, and $E(.)$ denotes an exponential integral function (Abramowitz and Stegum, 1970):

$$E_1(z) = \int_z^{\infty} \exp(-\zeta)/\zeta \mathrm{d}\zeta \quad (2)$$

It is not difficult to show that the approximate variance of the maximum regional magnitude $\hat{M}_{\max}$, estimated according to Eq. 1, is equal to that derived by KIJKO (2004):

$$\mathrm{Var}\left(\hat{M}_{\max}\right) = \hat{\sigma}_M^2 + \left[\frac{E_1(TZ_2) - E_1(TZ_1)}{\hat{\beta}\exp(-TZ_2)} + M_{\min}\exp\left(-\hat{\lambda}T\right)\right]^2 \quad (3)$$

where it is assumed that the observed (apparent) magnitude is distorted by an observational error, which is distributed normally with a known standard deviation $\hat{\sigma}_M$ (KIJKO and DESSOKEY, 1987).

The parameters $\hat{\beta}$ and $\hat{\lambda}$ for a given area are estimated by the maximum likelihood procedure described by KIJKO and SELLEVOLL (1989, 1992). This method allows for all available seismicity information to be used, as it makes use of an earthquake catalog containing both incomplete historical observations and more congruous and complete instrumental data. Periods with gaps in the catalog can also be taken into account. Equation 1 is applicable even in cases where the considered magnitude interval, $M_{\max} - M_{\min}$, is short and the number of events small.

5. Results and Discussion

In order to evaluate the earthquake hazard potential using the historical and instrumental data, WA is divided into 15 different source regions. The earthquake catalog includes the time period between BC 1303 and 2010. The earthquake hazard has been assessed in terms of the maximum regional magnitude $\hat{M}_{\max}$, the mean seismic activity rate $\hat{\lambda}$, the mean return period, RP and probability for an earthquake occurrence, Pr, as well as the $\hat{b}$ parameter of the magnitude-frequency relationship. These parameters obtained through the method of KIJKO and SELLEVOLL (1989, 1992) are listed in Table 3.

Regional variability of the maximum expected magnitudes for 15 different regions in WA is shown in Fig. 3. The estimated $\hat{M}_{\max}$ values are between 5.38 and 8.03. These values were distributed into four groups, smaller than 6.50, 6.50–6.99, 7.00–7.50 and greater than 7.5. These four groups of $\hat{M}_{\max}$ values are shown with different color scales in Fig. 3. The values greater than 7.50 are found in regions 1, 8, 10 and 12. The largest $\hat{M}_{\max}$ value is calculated in the eastern part of the Aegean Arc (region 12 with $\hat{M}_{\max} = 8.03$), where the largest earthquake occurred in the historical period in 1303, with a maximum observed magnitude $M_{\max}^{\mathrm{obs}} = 8.0$. The other largest values of $\hat{M}_{\max}$ are calculated in the Aegean Islands (region 10 with $\hat{M}_{\max} = 7.95$), where the largest event occurred in 1926 with $\hat{M}_{\max}^{\mathrm{obs}} = 7.7$; in Büyük

Table 3

Earhquake hazard parameters computed from Kijko-Sellevoll method for 15 different seismic regions in western Anatolia

Region no.	Tectonics	$M_{\max}^{\mathrm{obs}}$	$\hat{b}$	$\sigma\hat{b}$	$\hat{\lambda}$	$\sigma\hat{\lambda}$	$\hat{M}_{\max}$	$\sigma\hat{M}_{\max}$
1	Aliağa Fault	7.50	0.83	0.01	130.02	13.51	7.54	0.25
2	Akhisar Fault	7.00	1.15	0.01	249.55	32.68	7.11	0.24
3	Eskişehir, İnönü Dodurga Fault zones	7.00	0.87	0.03	46.95	7.04	7.16	0.34
4	Gediz Graben	6.90	0.97	0.03	50.90	8.01	7.02	0.28
5	Simav, Gediz-Dumlupınar Faults	6.50	0.87	0.02	301.63	42.35	6.60	0.22
6	Kütahya Fault Zone	5.30	1.11	0.03	72.44	12.23	5.38	0.13
7	Karova-Milas, Muğla-Yatağan Faults	6.80	0.93	0.01	262.47	33.85	6.83	0.20
8	Büyük Menderes Graben	7.50	0.96	0.02	112.65	14.28	7.62	0.26
9	Dozkırı-Çardak, Sandıklı Faults	6.60	0.87	0.03	37.74	5.63	6.70	0.22
10	Aegean Islands	7.70	0.75	0.03	28.91	4.75	7.95	0.39
11	Aegean Arc	7.10	0.78	0.03	41.64	5.98	7.20	0.27
12	Aegean Arc, Marmaris, Köyceğiz, Fethiye Faults	8.00	0.71	0.01	81.13	8.93	8.03	0.30
13	Gölhisar-Çameli, Acıgöl, Tatarlı Kumdanlı Faults, Dinar Graben	7.00	0.80	0.02	85.06	11.23	7.10	0.22
14	Sultandağı Fault	7.00	0.83	0.02	61.04	8.50	7.11	0.23
15	Beyşehirgölü, Kaş Faults	6.80	0.83	0.02	39.01	5.45	6.93	0.24

Menderes Graben (region 8 with $\hat{M}_{\max} = 7.62$), where the largest earthquake occurred in 1653 with a maximum observed magnitude of $M_{\max}^{\text{obs}} = 7.50$; on Aliağa Fault (region 1 with $\hat{M}_{\max} = 7.54$), where the largest earthquakes occurred in 1688 with $M_{\max}^{\text{obs}} = 7.50$. The second large level of $\hat{M}_{\max}$ values between 7.00 and 7.50 are calculated in the regions 2, 3, 4, 11, 13 and 14. The $M_{\max}^{\text{obs}}$ of earthquakes that occurred in these regions varies between 6.90 and 7.00, as listed in Table 3. These $\hat{M}_{\max}$ values are related to AKF, İDF, EFZ, GG, GCF, DG, KFZ, AGF and SDF (see

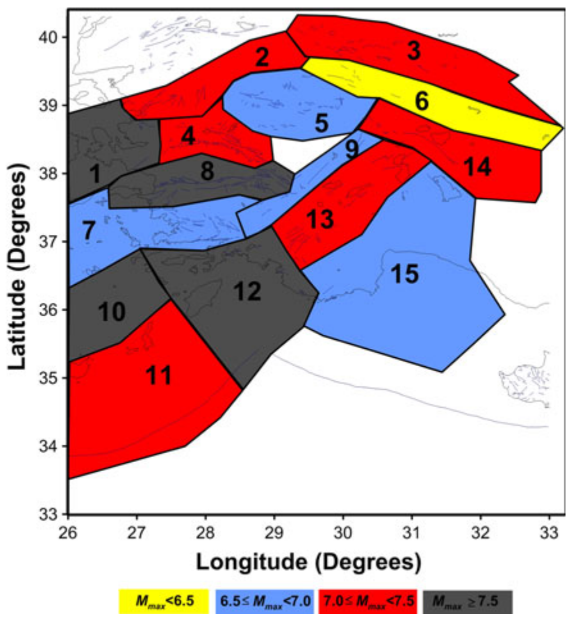

Figure 3
$M_{\max}$ values computed from Kijko-Sellevoll method for 15 different seismic regions in western Anatolia

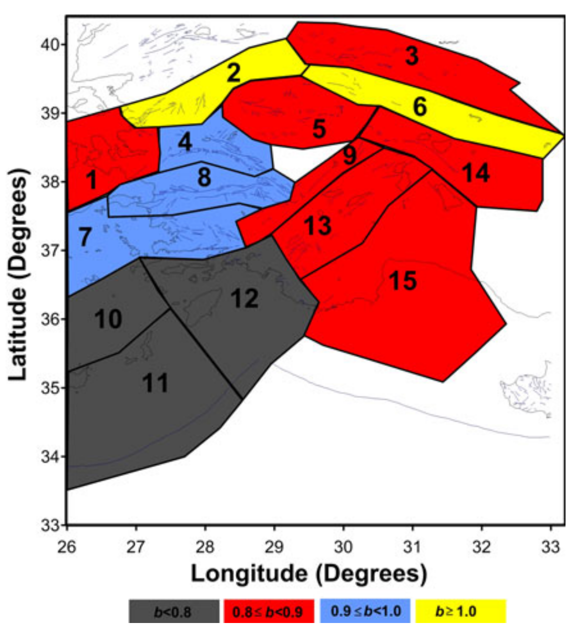

Figure 4
b Values computed from the Kijko-Sellevoll method for 15 different seismic regions in Western Anatolia

Table 4

Earthquake return periods for magnitudes between 5.0 and 7.5 for 15 different seismic regions in western Anatolia

Region no.	Magnitude					
	5.0	5.5	6.0	6.5	7.0	7.5
1	0.8	1.7	3.6	8.1	22.6	425.0
2	2.2	5.4	13.9	41.6	355.0	
3	3.2	7.0	15.9	42.1	250.0	
4	4.1	9.5	23.3	71.2		
5	0.6	1.5	4.1	35.8		
6	15.6					
7	0.7	1.6	4.0	15.0		
8	1.5	3.3	7.4	17.3	47.9	360.0
9	3.6	8.5	22.5	116.0		
10	1.1	2.2	4.4	9.1	20.4	60.9
11	0.7	1.2	3.2	8.4	42.5	
12	0.6	1.2	2.4	4.7	9.9	26.7
13	1.0	2.1	4.6	12.6	106.0	
14	2.0	4.4	9.8	26.5	208.0	
15	1.6	3.6	8.7	28.0		

Table 5

Earthquake probabilities versus magnitudes between 6.0 and 7.5 for 50 and 100 years for 15 different seismic regions in western Anatolia

Region no.	6.0		6.5		7.0		7.5	
	50	100	50	100	50	100	50	100
1	0.99	1.00	0.98	0.99	0.87	0.98	0.11	0.21
2	0.96	0.99	0.69	0.89	0.13	0.24		
3	0.94	0.99	0.74	0.93	0.18	0.33		
4	0.91	0.99	0.50	0.74	0.02	0.04		
5	0.99	1.00	0.74	0.92				
6								
7	0.99	1.00	0.95	0.99				
8	0.99	1.00	0.93	0.99	0.64	0.86	0.13	0.24
9	0.87	0.98	0.35	0.57				
10	0.99	1.00	0.98	0.99	0.90	0.99	0.55	0.79
11	0.99	1.00	0.98	0.99	0.67	0.89		
12	1.00	1.00	1.00	1.00	0.98	0.99	0.83	0.97
13	0.99	1.00	0.97	0.99	0.37	0.60		
14	0.99	1.00	0.83	0.97	0.21	0.38		
15	0.99	1.00	0.82	0.96				

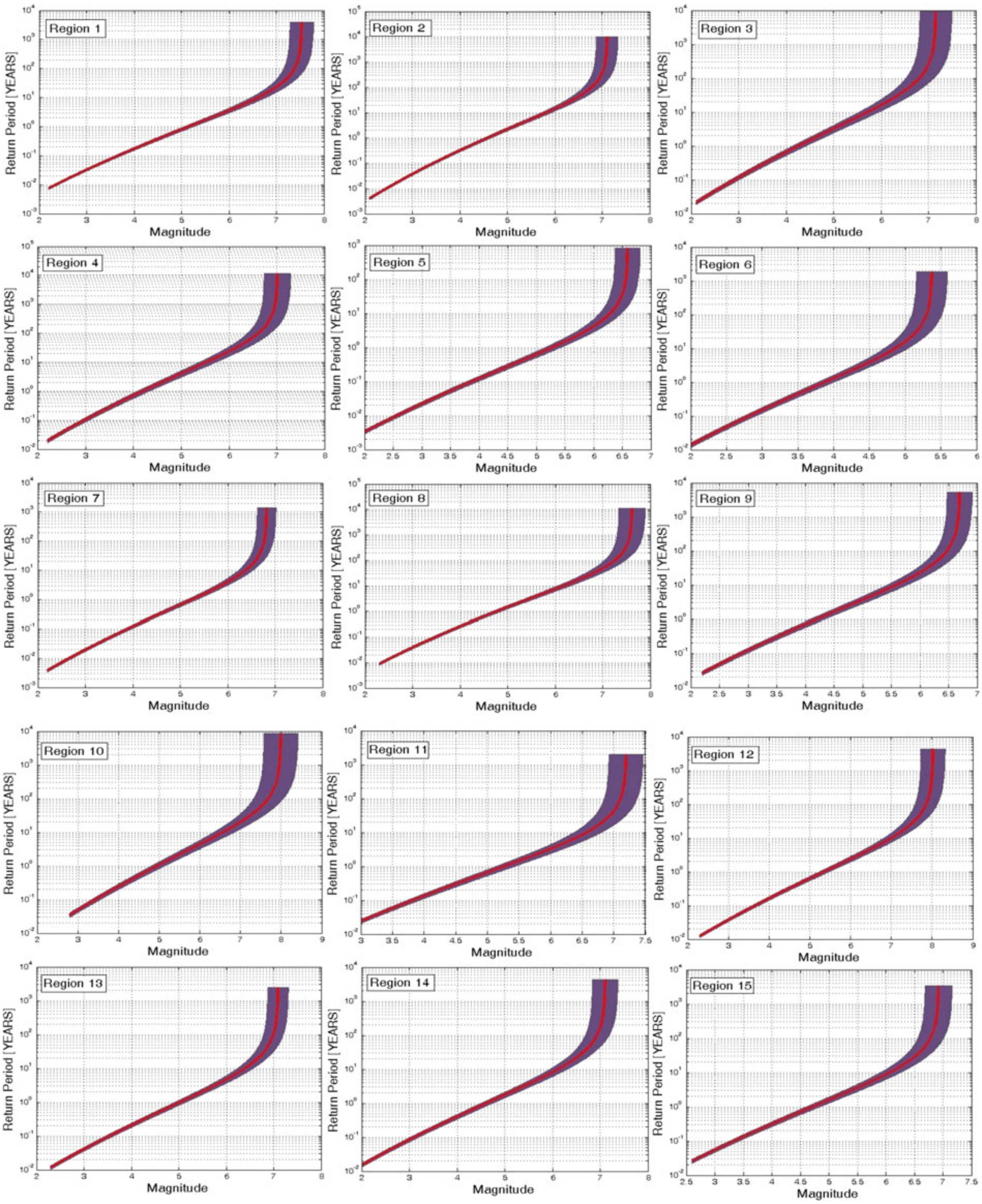

Figure 5
Return period versus magnitudes for 15 different seismic regions in western Anatolia

Fig. 1 for abbreviation). The third level of $\hat{M}_{\max}$ values between 6.50 and 6.99 are computed in the regions 5, 7, 9 and 15 related to SFZ, GDF, SF, DÇF, KMF, MYF, BGF and KSF. The $M_{\max}^{\text{obs}}$ of earthquakes that occurred in these regions varies between 6.90 and 7.00, as listed in Table 3. $\hat{M}_{\max}$ value lower than 6.50 is calculated in region 6 related to the KFZ where the $M_{\max}^{\text{obs}}$ value is 5.30.

The $\hat{b}$ values for 15 different regions change between 0.71 and 1.15. Computed $\hat{b}$ values were distributed into four groups, lower than 0.80, 0.80–0.89, 0.90–0.99 and larger than 1.00. Figure 4 shows these three groups plotted with different color scales. The $\hat{b}$ values smaller than 0.80 are computed in regions 10, 11 and 12. These regions related to the Aegean Arc and Aegean Islands, where large earthquakes occurred in historical and instrumental periods, are seen in Table 1. The $\hat{b}$ values between 0.80 and 0.89 are computed in regions 1, 3, 5, 9, 13, 14 and 15. These regions contain İDF, EFZ, SFZ, GDF, SDF, GÇF, KF, SF, BGF and KF, which are related to normal and strike slip faults, as seen in Fig. 1. The computed $\hat{b}$ values for graben systems such as GG and BMG are around 1.00. Since the seismicity in WA related to graben systems is high and displays swarm-type activity with remarkable clustering of low-magnitude earthquakes in time and space (Üçer *et al.*, 1985; Eyidoğan, 1988), the computed $\hat{b}$ values will be higher than those of the Aegean Arc. Papaioannou and Papazachos (2000) studied $\hat{b}$ values in detail for the Aegean and surroundings and found that the values changed between 0.83 and 0.89 for the different regions of WA covering the same regions used in this study for both historical and instrumental periods. Papazachos (1999) mapped $\hat{b}$ values for Greece and the surrounding area and observed that the values vary between 0.8 and 1.0 for western Anatolia. Jenny *et al.* (2004), for the period 550 B.C. to 1995 A.D., computed a $\hat{b}$ value equal to 1.00, and Bayrak *et al.* (2009) computed $\hat{b}$ values varying by 0.82–1.15 for the instrumental time period for different regions in WA. The $\hat{b}$ values computed in this study are consistent with those of previous studies published in the literature. However, Sayıl and Osmanşahin (2008) calculated a change of $\hat{b}$ values of between 0.42 and 0.66 for 13 different regions in WA. These values are too low, and are not consistent with the tectonics of WA and the results of previous studies published in the literature.

The mean return periods (RP) of earthquakes for which a certain magnitude will not be exceeded in any year are listed in Table 4. Furthermore, the earthquake hazard curves expressed in terms of the mean return period of earthquakes that are expected for the maximum observed magnitudes are shown in Fig. 5. The lower RP values are found in region 10 and 12, which are covered by the subduction zone of the south Aegean area. The seismicity of these regions is examined in detail in recent studies by Manakou and Tsapanos (2000), Tsapanos (2001), Tsapanos and Christova (2003). The large earthquakes occurred in these regions in both historical and instrumental periods. Two large earthquakes are the 8 August 1303 ($M_S = 8.0$) and 26 June 1926 ($M_S = 7.7$) earthquakes. Also, the largest earthquake in region 12 in the historical period is the one on 22 April 1863 ($M_S = 7.8$), while the largest earthquake in the instrumental period is the 25 April 1957 ($M_S = 7.1$) earthquake.

The probabilities (Pr) are computed for a certain magnitude that will not be exceeded in 50 and 100 and 1,000 years, and are listed in Table 5 for 50 and 100 years. Furthermore, the earthquake hazard curves expressed by the probability expected for earthquakes with the maximum observed magnitudes are plotted and shown in Fig. 6. Regional distribution of the probabilities in the next 50 years, P_{50}, with a magnitude $\geq$6.5 in each 15 seismic region, is shown in Fig. 7. Probability values are divided into four groups on a color scale, and regions with different probabilities are indicated in this way. The probability of occurrence for the earthquakes with $M_S \geq 6.5$ is greater than 90 percent in regions 1, 7, 8, 10, 11, 12 and 13, which are related to the Aliağa Fault, KMF, MYF, BMG, SF, Aegean Arc and Aegean Islands. Especially region 12 (Aegean Arc) has the greatest probability value. P_{50} value with a magnitude $\geq$6.5 is computed as 100% in region 12. The second-level probability values of earthquake occurrences with $M_S \geq 6.5$ changing between 75 and 90% are found in regions 14 and 15. These regions are related to SDF, BGF and KSF. The third level probability changing between 60 and 75% is computed in regions 2, 3 and

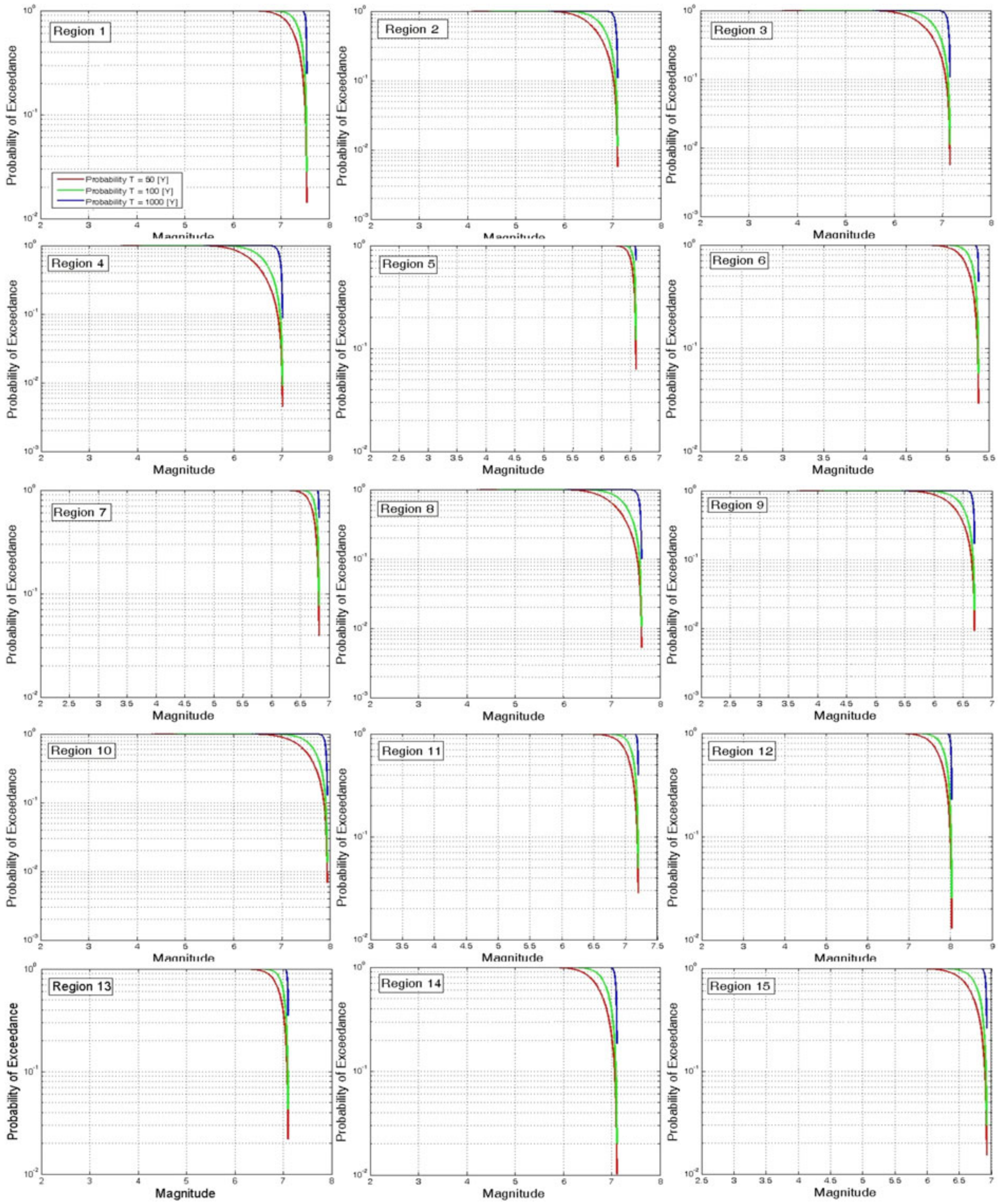

Figure 6
Earthquake probabilities versus magnitudes for 50, 100 and 1,000 years for 15 different seismic regions in western Anatolia

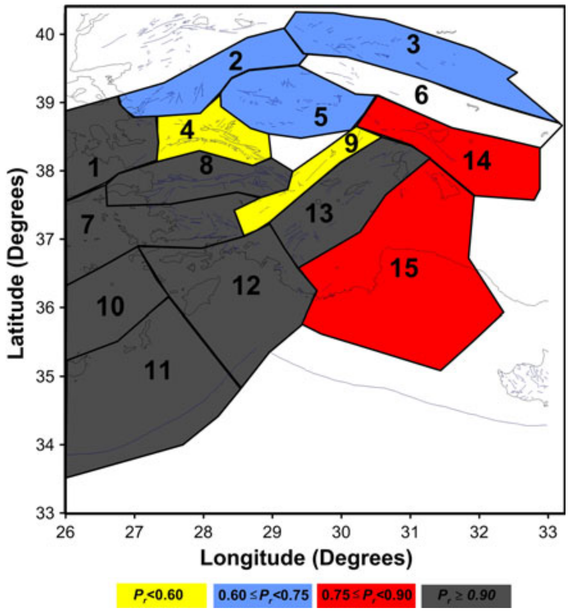

Figure 7
Pr (the probabilities in the next 50 years with magnitude $M_S \geq 6.5$) values for 15 different seismic regions in Western Anatolia. The region with *white color* means that there is not a probability of earthquake occurrence for magnitude $M_S \geq 6.5$ in the next 50 years

Table 6

Rank of 15 different regions in WA in terms of earthquake hazard level (K index)

S. no.	Region	Tectonics	K index	Hazard level
1	1	Aliağa Fault	6	Very high
2	8	Büyük Menderes Graben	6	
3	10	Aegean Islands	6	
4	12	Marmaris, Köyceğiz Fayı-Fethiye Faults	6	
5	2	Akhisar Fault	5	High
6	3	Eskişehir, İnönü Dodurga Fault zones	5	
7	4	Gediz Graben	5	
8	7	Karova-Milas, Muğla-Yatağan Faults	5	
9	11	Aegean Arc	5	
10	9	Dozkırı-Çardak, Sandıklı Faults	4	Intermediate
11	13	Gölhisar-Çameli, Acıgöl, Tatarlı Kumdanlı Faults, Dinar Graben	4	
12	14	Sultandağı Fault	4	
13	15	Beyşehirgölü, Kaş Faults	4	
14	5	Simav, Gediz-Dumlupınar Faults	3	Low
15	6	Kütahya Fault Zone	–	

5 covering AF, EFZ, İDF, SFZ and GDF. The smallest level probability values of earthquake occurrence with $M_S \geq 6.5$ are less than 60% and calculated in regions 4 and 9. In region 6 with white color, we cannot expect an earthquake for magnitude $M_S \geq 6.5$ in the next 50 years.

Almost all the examined regions are characterized by medium to high levels of seismicity beyond those individual regions. All of them have frequently experienced large earthquakes ($M \geq 6.0$) that caused damage and/or fatalities. As shown in Table 4, the return periods (RP) of earthquakes with $M \geq 6.0$ are important, because this magnitude is considered to be dangerous, and the values of RP are reliable for further processing. In order to classify the examined regions in groups based on their hazard level, we applied the technique of Tsapanos (2001). Along with this technique, the $\hat{M}_{\max}$ and $RP_{6.0}$ for each region are also taken into account. We considered that the seismic hazard is a function of the form $\Theta\left(\hat{M}_{\max}, RP_{6.0}\right)$, increasing with $\hat{M}_{\max}$ and decreasing with $RP_{6.0}$. In this way, the following groups were reconstructed: $6.00 \leq \hat{M}_{\max} \leq 6.80$, $6.81 \leq \hat{M}_{\max} \leq 7.49$ and $\hat{M}_{\max} \geq 7.50$, and we defined $\Theta\left(\hat{M}_{\max}\right)$ to be equal to 2, 4 and 6, respectively. Similarly, $\Theta(RP_{6.5})$ is defined as equal to 6, 4 and 2 for the corresponding $RP_{6.0} \leq 50$, $51 \leq RP_{6.0} \leq 100$ and $RP_{6.0} \geq 101$. The arithmetic mean $K = \frac{1}{2}\left[\Theta\left(\hat{M}_{\max} + \Theta(RP_{6.0})\right)\right]$ signifies the adopted relative earthquake hazard level of a specific region. The index K takes values of 2, 3, 4, 5 and 6. Based on the above five groups, the relative earthquake hazards are defined as: very low, low, intermediate, high and very high, respectively (Table 6). Admittedly, a number of exceptions exist: in region 6, neither $\hat{M}_{\max}$ nor $M_{\max}^{obs}$ exceeds a magnitude of 6.5. Table 6 can be used as an indicator of the seismic hazard level for 15 different regions of WA. According to index K, regions 1, 8, 10 and 12 have first level seismic hazard. In other words, seismic hazard is very high in these regions covering the Aliağa Fault, Büyük Menders Graben, Aegean Islands and Aegean Arc.

6. Conclusions

A combination of historical and instrumental earthquake catalogs was used to evaluate seismic hazard for 15 different source regions of WA. The seismic hazard is described in the form of hazard curves (probabilities versus magnitude), return periods that are expected for a given magnitude in each zone and spatial distribution of hazard parameters in the examined area. For this purpose, the maximum regional $\hat{M}_{\max}$, the mean seismic activity rate $\hat{\lambda}$, the mean return period RP and probability for an earthquake occurrence Pr, as well as the $\hat{b}$ parameters of the magnitude-frequency relationship are computed.

The b values exhibit two different clusters. While high $\hat{b}$ values are found in the regions related to the western Anatolian extensional zone and high degree of heterogenic faulting, low b values are obtained in regions 10, 11 and 12, which are related to the Aegean Arc and Aegean Islands located in the south Aegean. The large earthquakes occurred in both historical and instrumental periods. We may conclude that the stress level is very high in these regions. It was found that the $\hat{b}$ values are around 1.0 in the regions covering graben systems.

The results led us to a general conclusion that regions related to the Aegean Arc, Aegean Islands, Aliağa Fault and Büyük Menderes Graben are probably the next regions for the occurrence of a large earthquake. In these regions, the computed $\hat{M}_{\max}$ values are larger than 7.5, and the probabilities in the next 50 years with a magnitude $\geq$6.5 are greater than 90%. Furthermore, the mean return period for such a magnitude is lower than 20 years.

Numerate methods of earthquake hazard are essential and provide a clear statistical guide in order to show earthquake hazard levels of the regions examined in this study. We rank these regions in terms of their earthquake hazard values (K index) and compare them in Table 6. An attempt is made to form a simple quantitative classification of the studied regions in terms of their earthquake hazard level. According to this table, the most seismically active regions are 1, 8, 10 and 12 related to the Aliağa Fault and Büyük Menderes Graben, Aegean Arc and Aegean Islands.

The maps (Figs. 3, 4 and 7) provide a brief atlas that depicts variations of earthquake hazard throughout Western Anatolia.

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