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Earthquake Hazard of the Aegean Extension Region (West Turkey)

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Abstract: West Turkey, one of the most seismically active regions of Turkey, has been analysed to reveal seismic hazard by using fractal behaviour, seismic quiescence *z*- and Gutenberg-Richter *b*-parameters. Starting from raw earthquake catalogue, we performed completeness analysis on recorded events, and a final catalogue, could be accepted as homogeneous, was obtained. According to the results obtained from the Frequency-Magnitude Distribution (FMD), seismic activity rates (*b*- and *z*-values) and fractal correlation dimension, we detected three anomalous zones throughout the Aegean Extension Region (AER). These are: (1) Çandarlı Bay and Bergama-Zeytindağ Fault Zone, (2) İzmir fault and Orhanlı Fault Zone, and (3) Buldan and surrounding areas. The relatively infrequent occurrence of the great earthquakes in the AER and present hazard parameters obtained by this study suggest that magnitude of a destructive earthquake may reach up to Ms= 6.5. Hence, it is also possible to say that large earthquakes are generally not expected in those related zones because of seismic moment release from small-moderate sized earthquakes.

Key Words: West Turkey, earthquake catalogue, fractal analysis, seismic hazard

Ege Genişleme Bölgesinin (Batı Türkiye) Deprem Tehlikesi

Özet: Fraktal davranışı, sismik hareketsizlik *z*- ve Gutenberg-Richter *b*-parametreleri kullanılarak, sismik bakımdan Türkiye'nin en aktif bölgelerinden biri olan Batı Türkiye depremleri analiz edilmiştir. Ham deprem kataloğundan hareketle, kaydedilen olaylar üzerinde tamlık analizi gerçekleştirilmiş ve homojen olarak kabul edilebilen bir final katalog elde edilmiştir. Fraktal ilişki boyutu, sismik aktivite oranları (*b*- ve *z*-değerleri) ve Frekans-Büyüklük Dağılımı (FBD)'ndan elde edilen sonuçlara göre, Ege Genişleme Bölgesi (EAR) boyunca üç anomali alanı tespit edilmiştir. Bunlar sırasıyla: (1) Çandarlı Körfezi ve Bergama-Zeytindağ Fay Zonu, (2) İzmir Fayı ve Orhanlı Fay Zonu, ve (3) Buldan ve çevresi. EAR'de büyük depremlerin göreceli olarak daha seyrek meydana gelmesi ve bu çalışmadan elde edilen güncel tehlike parametreleri nedeniyle, hasar yapıcı olası bir depremin büyüklüğü Ms= 6.5'a kadar çıkabilir. Buradan hareketle küçük-orta ölçekli depremlerden açığa çıkan sismik moment (veya enerji) nedeniyle, sözkonusu alanlarda büyük depremlerin genellikle beklenmemesi gerektiğini söylemek doğru bir yaklaşım olabilir.

Anahtar Sözcükler: Batı Anadolu, deprem kataloğu, fraktal analizi, sismik tehlike

Introduction

The Aegean Extension Region (AER) is one of the most seismically active and rapidly prolongating areas of the Eastern Mediterranean region (e.g., Bozkurt 2001). Two principal tectonic features play an important role in the neotectonic context of the AER. The first one is the Aegean Subduction Zone (ASZ) at the south where the African Plate is subducting beneath the Anatolian Plate (see the inset map of Figure 1a). The Aegean arc consists of the outer sedimentary arc and of the inner volcanic arc, while its outer borders are bounded by the Aegean trench with a maximum water depth of 5 km (Papazachos & Kiratzi 1996). The other important tectonic element is the dextral North Anatolian Fault Zone (NAFZ) in the north. The plate motion of Western Anatolia relative to Europe can be defined by an anticlockwise rotation with an average velocity of 24 mm/yr (McClusky *et al.* 2000).

Figure 1a shows the location map with grabens-active faults and study area (26–29° E, 36.5–39.5° N) which include the seismic stations operated by Kandilli Observatory (KOERI). Focal mechanisms of most reliable 36 shallow events ($h \leq 35$km) with $4.8 \leq Mw \leq 6.1$ occurred in the study area during the period 1979–2005, and are presented in Figure 1b. Epicentres of historical earthquakes and focal mechanisms of large 20th century earthquakes which concentrate mainly near Metropolitan İzmir, are also added. E–W-trending grabens (e.g., Simav, Gediz, Küçük Menderes Graben-KMG and Büyük Menderes Graben-BMG) and their basin-bounding active normal faults are the most prominent neotectonic

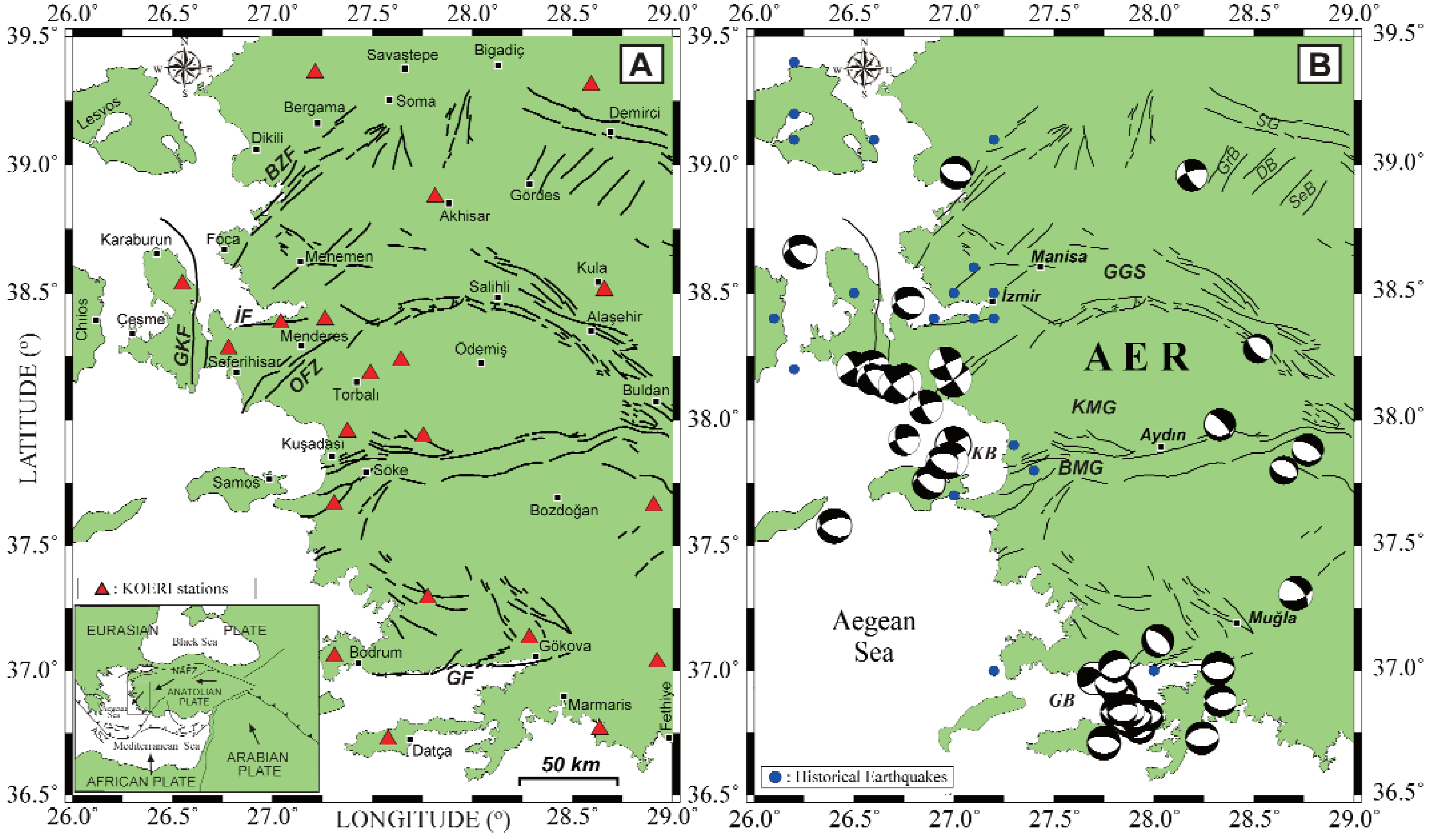

Figure 1. (A) Main tectonic elements, and (B) Seismotectonic properties of the Aegean extension region (AER). Figures are plotted in GMT software (Wessel & Smith 1995). Tectonic features were compiled from Aktuğ & Kılıçoğlu (2006), Bozkurt (2001), Emre *et al.* (2005); Eyidoğan (1988); Ocakoğlu *et al.* (2004, 2005) and Şaroğlu *et al.* (1992). Historical earthquakes are taken from USGS-NEIC. Focal mechanisms were compiled from HARVARD-CMT, USGS-NEIC and CSEM databases. BMG– Büyük Menderes Graben, BZF– Bergama-Zeytindağ Fault, ÇB– Çandarlı Bay, DB– Demirci Basin, GB– Gökova Bay, GrB– Gördes Basin, GF– Gökova Fault, GGS– Gediz-Graben System, GKF– Gülbahçe-Karaburun Fault, İF– İzmir Fault, KB– Kuşadası Bay, KMG– Küçük Menderes Graben, SB– Sığacık Bay, SeB– Selendi Basin, SG– Simav Graben, OFZ– Orhanlı Fault Zone, Inset Map– ASZ: Aegean Subduction Zone, NAFZ– North Anatolian Fault Zone.

features of the studied region (e.g., Şengör *et al.* 1985; Şengör 1987; Seyitoğlu & Scott 1992; Seyitoğlu *et al.* 1992; Koçyiğit *et al.* 1999; Yılmaz *et al.* 2000; Lips *et al.* 2001; Sözbilir 2001, 2002; Bozkurt & Sözbilir 2004; Kaya *et al.* 2004; Erkül *et al.* 2005; Emre & Sözbilir 2007). Other less prominent structural elements are the NNE–SSW-trending basins and their intervening horsts such as Gördes, Demirci and Selendi basins (e.g., Bozkurt 2003; Ersoy and Helvacı 2007). 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 (Yılmaz *et al.* 2000; Uzel & 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 E–W direction (Bozkurt & Sözbilir 2006). The Karaburun-Gülbahçe Fault (KGF) occurs in the Karaburun Peninsula, and is supposed to be predominantly strike-slip fault. Gökova Fault (GF) can be traced on a line trending E–W direction along the northern coast of the Gökova Bay (GB) at the south of the study area (e.g., Şaroğlu *et al.* 1992; Eyidoğan 1988; Ocakoğlu *et al.* 2004, 2005; Emre *et al.* 2005; Aktuğ & Kılıçoğlu 2006).

The potential seismic risk is very high due to the close vicinity of the developed and well-developed and populated cities such as Manisa, Aydın, Muğla, Buldan, Kuşadası, Bodrum, etc. The seismicity of the region is poorly known except for the numerous earthquakes which occurred during the historical and instrumental periods (Taymaz *et al.* 1991; Akyol *et al.* 2006; Zhu *et al.* 2006; Tan *et al.* 2008; Firuzan 2008) (Table 1).

Fractal properties of seismicity in the different regions of Turkey have been analyzed by using different catalogues and methods (Turcotte 1990). Size-scaling and seismic properties of the earthquakes which occurred in the Marmara Sea region have been analyzed (Polat *et al.* 2002a, b), and the results obtained from Hurst (1951) algorithm revealed maximum earthquake magnitude in the region at Mw= 7.4. Further to the east of the country, the seismicity has been analyzed by using instrumental catalogues of the Eastern Anatolian earthquakes, and reported clear seismic quiescence (gap) evidences along several segments of the East Anatolian Fault (EAF) Zone.

Several studies have been carried out to reveal the seismicity and kinematic relation of the AER in Turkey. But, to date, no study has implicitly addressed the mapping of size-scaling distributions (e.g., *b*- and *a*-values; seismic quiescence *z*-value; recurrence periods Tr; fractal dimension Dc; fractal slope changes) along the regional scale, and the correlation of results with the structural elements which carry high risk for the region. In the present study, we investigate earthquake hazard potential of the AER by characterising size-scaling and self-similar fractal behaviour.

With regard to the accuracy of the seismic catalogue used in the present study, we can say that for earthquakes since 1970's, errors in the epicentres are within 0–15 km and the errors in the magnitudes within 0.2, while the corresponding errors for the earthquakes prior to the 70's are 0–30 km in epicentres and 0.5 in the magnitudes (Kalafat *et al.* 2007). In this paper, we focus on the relationship between seismic b-value and the damage evaluations (seismic quiescence, return period) of the anomalous areas of the AER. The area investigated is a part of the Western Anatolia, with associated spatio-temporal variations of *b-value* on a regional scale. Thus, evaluating the power of *b-value* is used as a tool to monitor small-scale changes in the state of deformation of the studied area.

Method

To characterize seismic behaviour, a number of statistical parameters are used; namely size-scaling parameters (such as slope of recurrence curve *b*- and *a*-values), seismic quiescence *z*-value, temporal and spatial distribution of earthquakes with characteristic of fractal correlation dimension, D_C.

Spatial patterns of earthquake distribution and temporal patterns of occurrence are demonstrated to be fractal using the two-point correlation dimension D_C (Kagan & Knopoff 1980). The relationship at larger scale is implicitly assumed in much of the recent literature on the non-linear dynamics of earthquakes. However, either before major earthquakes or in laboratory tests, systematic change in *b*-value has been reported. This variation could be attributed to rock heterogeneity, heterogeneous stress distribution, micro-fracturing in rocks or fractal correlation dimension. The correlation dimension D_C measures the spacing or clustering properties of a set of points, and has also been applied both to earthquake epicentres and to the hypocentre

Table 1. Destructive earthquakes (Io≥ VII, Ms≥ 5.6) in the west Anatolia, during the historical and instrumental periods between 17 A.D. to 2003 (compiled from Ergin *et al.* 1967; Eyidoğan *et al.* 1991; Finkel & Ambraseys 1995; Erdem & Lahn 2001; Kalafat *et al.* 2007). a: Ms values are derived from the Magnitud-Intensity relation given by Kalafat *et al.* (2007).

Period	Day	Month	Year	Place	Mag. (Ms)
HISTORICAL	-	-	17	İzmir-Ege	7.4[a]
	-	-	688	İzmir	6.8[a]
	-	-	1644	İzmir	5.6[a]
	-	-	1664	İzmir	5.6[a]
	22	02	1653	İzmir-Ege	7.4[a]
	-	11	1668	İzmir	6.8[a]
	10-12	07	1688	İzmir-Ege	7.4[a]
	24	03	1739	İzmir	6.2[a]
	-	07	1776	İzmir	6.2[a]
	-	-	1850	İzmir-Ege	6.2[a]
	29	06	1880	İzmir, Manisa	6.8[a]
	15	10	1883	Chios, Çeşme-İzmir	6.8[a]
	01	11	1883	İzmir	6.2[a]
	-	05	1888	Chios, Çeşme-İzmir	6.2[a]
	-	10	1888	Ödemiş-İzmir, Aydın	6.2[a]
	13-25	10	1889	Chios, Karaburun-İzmir	5.6[a]
	19	08	1895	Aydın	6.2[a]
	-	-	1895	Menemen-İzmir	6.8[a]
	26	06	1896	Marmaris-Muğla	5.6[a]
	-	05	1897	Marmaris-Muğla	5.6[a]
	20	09	1899	Menderes-İzmir	6.8[a]
INSTRUMENTAL	11	08	1904	Samos, Kuşadası-Aydın	6.2
	18	08	1904	Seferihisar-İzmir	6.0
	19	01	1909	Foça-Manisa	6.0
	18	11	1919	Soma-Manisa	7.0
	31	03	1928	Torbalı-İzmir	6.5
	23	04	1933	Gökova-Muğla	6.5
	22	09	1939	Bergama-İzmir	6.6
	23	05	1941	Muğla	5.9
	13	12	1941	Muğla	6.2[a]
	28	10	1942	Soma-Manisa	6.0
	25	06	1944	Manisa	6.0
	21	12	1945	Denizli	6.8[a]
	23	07	1949	Chios-Karaburun	6.6
	16	07	1955	Söke, Aydın	6.8
	25	04	1959	Fethiye-Muğla	5.9
	02	03	1965	Salihli-Manisa	5.8
	13	06	1965	Buldan-Denizli	5.6
	23	05	1961	Marmaris-Muğla	6.3
	23	03	1969	Demirci-Manisa	5.9
	25	03	1969	Demirci-Manisa	6.5
	28	03	1969	Alaşehir-Manisa	6.5
	06	04	1969	Karaburun-İzmir	5.9
	01	02	1974	İzmir	5.8
	14	06	1979	Karaburun-İzmir	5.7
	06	11	1992	Seferihisar-İzmir	6.0
	10	04	2003	Seferihisar-İzmir	6.1

distributions of acoustic emissions in laboratory experiments (Mogi 1962; Grassberger & Procaccia 1983; Hirata *et al.* 1987; Scholz 1990; Main 1992, 1996).

Gutenberg & Richter (1956) *b*- and *a*-values represent generalized '*fractal dimension*' of earthquake magnitude distributions and this interpretation assumes a dislocation model for the seismic source and also requires a scale invariant recurrence interval (Turcotte 1986). Two hypotheses suggest that the slope (*b*-) and intercept (*a*-) derived from the Gutenberg-Richter relation provide useful information about earthquake behavior and fault zone orientation. Estimates of *a*- and *b*-values

$$\log N = a - bM \qquad (1)$$

imply a fractal relation between frequency of occurrence and the radiated energy, seismic moment and fault length. Regional scale estimates of *b*-value generally range between 0.5 and 1.5 (Öncel & Wyss 2000; Wyss *et al.* 2000; Öncel *et al.* 2001; Öncel & Wilson 2002). However, on average, the regional scale estimates of *b*-value are approximately equal to 1 (Frohlich & Davis 1993; Jackson & Kagan 1999). The *b*-value represents different tectonic sources in the area. The *a*-value is directly computed as the intercept in the Gutenberg-Richter relationship.

It has been suggested that the *a*-value (or activity rate) maps are the most likely locations of asperities (higher *a*-value), based on analysis of short term seismicity Jackson & Kagan (1999). Differences in terms of higher activity rates (*a*-value) indicate that research on earthquake forecasting requires analysis of changes in *b*-value. Epicentral location of the İzmit earthquake (Mw=7.4; Delouis *et al.* 2002; Polat *et al.* 2002a) corresponds to a region associated with higher *a*-value and average *b*-value.

Local recurrence times (Tr), which can be related directly to the local probability, could be derived from information contained in the heterogeneous distribution of both parameters *a*- and *b*- values. Öncel & Wyss (2000) interpreted the changes in Tr as high *a*- and low *b*-values before and during the İzmit earthquake.

The Recurrence Time, Tr

Tr can be estimated from the fractal parameters of the frequency-magnitude distribution for different target magnitudes, this is an important parameter that has been proven to be useful in earthquake engineering design applications. The local recurrence time is defined as:

$$\mathrm{Tr}\,(A) = \frac{\Delta T}{10^{a-bM}} \qquad (2)$$

where ΔT is the observation period and M is the target magnitude. Using this target magnitude, it is possible to estimate the probabilistic recurrence time associated with the occurrence of local asperities (Öncel & Wilson 2002).

The Fractal Dimension, D_C

Complex structures found in nature are often heterogeneous, and earthquake magnitudes are examples of complex natural phenomena that have scale invariant structure (Mandelbrot 1982). The evolution of ideas concerning the fractal characterization of natural phenomena has been expanded to incorporate fractal dimension as below:

$$D = \frac{1}{N}\sum_{j=1}^{N}\left(\frac{N_j(R \le r)}{N-1}\right) \qquad (3)$$

The angular distance *r* in degrees between two events is calculated using the formula for the angular distance *r* in degrees between two events.

$$r = \cos^{-1}[\cos\theta_1.\cos\theta_2 + \sin\theta_1.\sin\theta_2.\cos(\phi_1 - \phi_2)] \qquad (4)$$

where (θ_1, ϕ_1) and (θ_2, ϕ_2) are the colatitudes (θ) and longitudes (ϕ) of the two events respectively. Fractal dimension is defined by fitting a straight line to a plot of log *C* (*r*) against log *r* (converted to a distance using 1°= 111 km) as *r* tends to zero over a data range for the first 1.5 orders of magnitude for which the data were considered reliable.

Data

We carried out the seismicity catalogue from the Kandilli Observatory and Earthquake Research Institute (KOERI)-İstanbul (see http://www.koeri.boun.edu.tr), and used the data from 1900 to 2002 for the West Anatolian Region covering an area between 26–29° E longitudes and 36.5–39.5° N latitudes. We first observed that the catalogue is very different in time span, magnitude and depth distributions of recorded events. In order to obtain reliable results for realistic earthquake hazard, a complete earthquake catalogue must be used. For this purpose we performed completeness analysis on the location parameters such as magnitude and depth unifications, cleaning, and declustering procedures.

We examined raw earthquake catalogue and detected a total number of 14289 events. In order to decrease the number of uncertainties and consequently improve the reliability of the data associated with the seismicity in the study area, a detailed magnitude unification analysis has been applied to the catalogue. Earthquake size in the present study was characterized by Ms. However, the magnitudes reported in the catalogues are in various scales. Based on the databases, magnitudes are given in Mb, Md, ML, Ms and Mw scales. In other words, Ms magnitude is not available for all events. In this aspect, we derived Ms values from Mb, Md, ML and Mw empiric relations developed by Kalafat *et al.* (2007).

A very strong time dependency, in 1976, was observed in the raw catalogue, and could probably be related with the coverage of a seismic stations or upgrading the computation software. Therefore, earthquakes before 1976 were removed from the catalogue. After this initial treatment, total number of events was obtained as 13527 for the time period 1976–2002.

Most of the seismicity catalogues are contaminated by quarry blasts. Typically, these explosions exhibit an unusually high b-value for b >1.5. Therefore we carefully mapped (Figure 2a) the ratio of day- to night-time events in order to detect quarries that were not identified by the network operators. An unusually high number of daytime events in a volume are a likely sign of explosion activity. Our mapping found almost no quarry contamination in the study area except one or two small-scale zones in the west and northern half of the study area; where we performed an analysis on the daytime events between the hours 08–17 (local time). The number of events as a function of their occurrence hour shows a strong clustering at the 'working' hours of the quarries. One can notice the significant difference between the stacked numbers of cumulative earthquakes occurring in daytime and at night (Figure 2b). Most of the quarries have almost identical locations, depths, occurrence times, and Ms ≤ 3.0 (Figure 2c) magnitudes. Hence, we removed contaminated data by using standard parameters defined by Habermann (1987). But, eliminating these data from the catalogue did not significantly alter our results. Figure 3a defines spreaded cumulative number of magnitudes. Most of the earthquakes were below 3.0. We mapped Mc using a sample size of n= 500 and a node spacing of 5 km (0.05°) with 95% goodness fit of the observed distribution (Figure 3b). Completeness magnitude is performed as described by Wiemer & Wyss (2000) on the final catalogue and a straight line was fitted by least-square technique for the events. It was immediately apparent that the completeness of the threshold magnitude varied through the region from minimum magnitudes of Mc= 3.0. Since the catalogue consisted of a considerable amount of data below Mc, we only restrained earthquakes below M ≤ 3.0, removed quarries and obtained 5373 data over 13527.

According to the Frequency-Magnitude Distribution (FMD), Gutenberg-Richter relation was found logN= 6.53–0.9 M. Hence size scaling *b*- and *a*-values were estimated as 0.90 and 6.53, respectively (Figure 3c). The tectonic earthquakes are characterized by the *b*-value from 0.5 to 1.5 and are more frequently around 1.0 (Mogi 1967), which is almost the same as observed in the present study.

The hypocentral distribution of the earthquakes in the region outlines significant clustering at the upper crust of the earth's surface. After examining recorded earthquakes as a function of depth, we found that hypocentres are significantly below 35 km (Figure 4a). We also observed two maxima (5 and 10 km) which are clearly an artifact of the catalogue and fixed depth of the location program. Since our hypothesis applies to crustal earthquakes only, we restricted this study to the top of 35 km by removing deeper events, and obtained a number of 5196 (out of 5373).

A time histogram between 1976–2002 indicates an increase in the number of recorded events after the year of 1989 (Figure 4b). The further improvement of the catalogue since then could probably be associated with man-made effects, tectonic stress changes in the region or changing of used software during the computation of magnitude (Habermann 1987; Öncel & Wilson 2002; Kalafat *et al.* 2007). One of the most common changes in earthquake catalogues is the magnitude shift. In order to evaluate the variation of magnitude with time, we found that the suggested magnitude shift was –0.2 before 1989. Hence we corrected it by adding shifting to the magnitude values before this time.

To separate dependent events from independent seismicity, earthquake catalogue can be declustered. The decluster method used in ZMAP 6.0 (Wiemer 2001) is

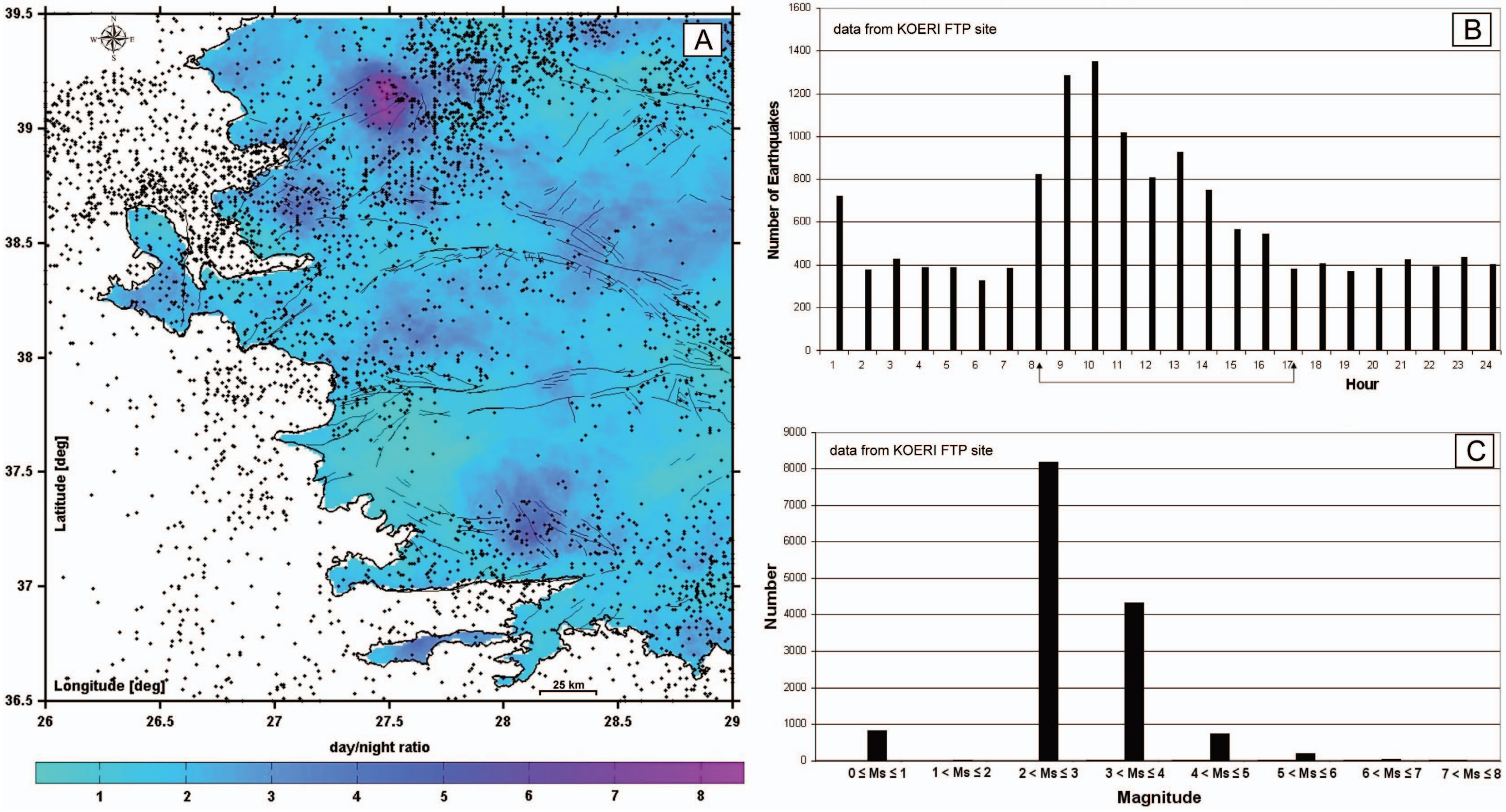

Figure 2. (A) Quarry blast mapping, (B) occurrence time of recorded events, and (C) number of event histogram according to the magnitude interval, during the period from 1900 to 2000 for raw data.

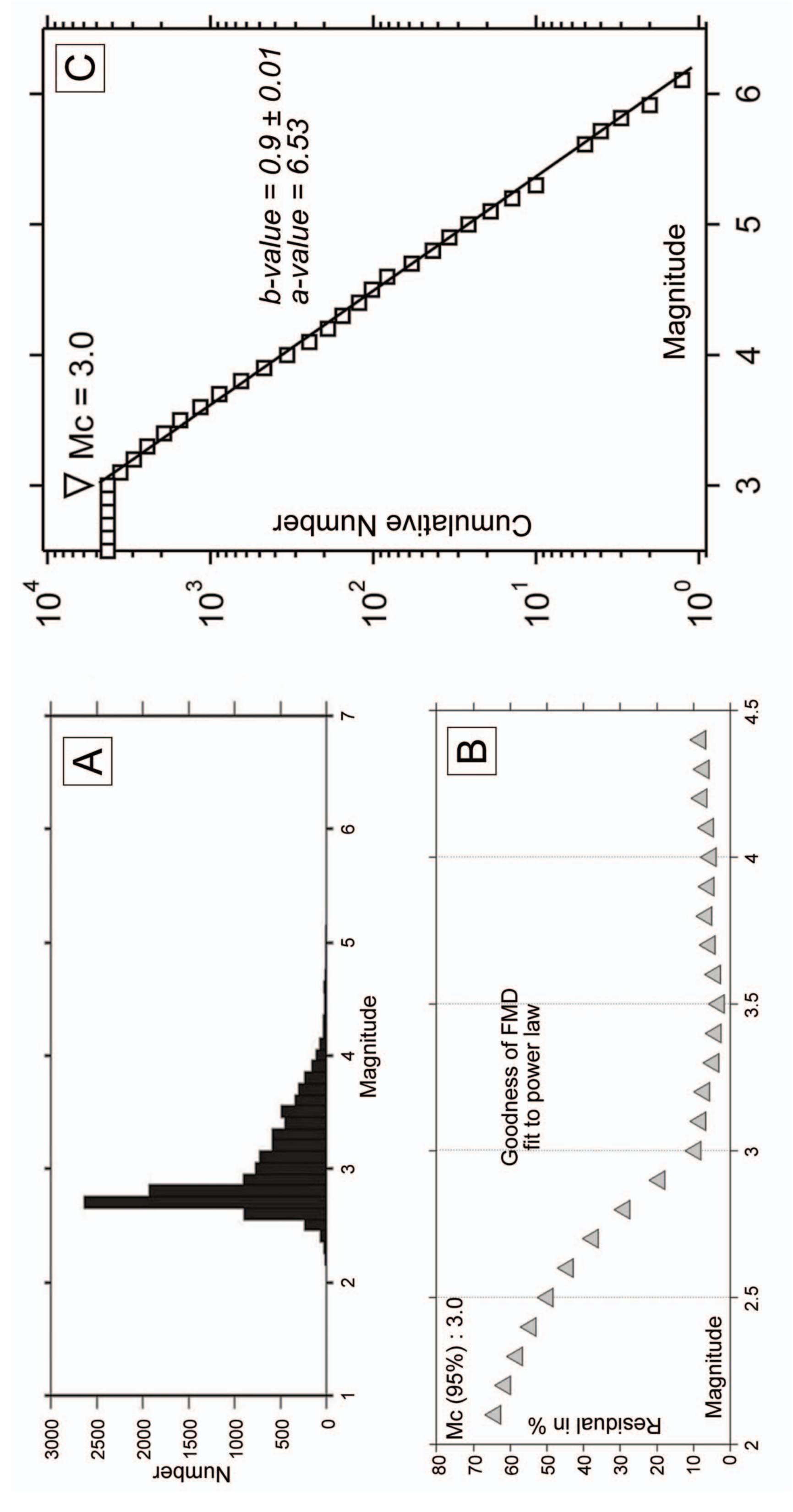

Figure 3. (A) Magnitude histogram of the earthquakes, (B) completeness magnitude (Mc) as a function of time (96%, Mc= 3.0), and (C) Gutenberg-Richter relations and frequency magnitude distribution of events, for the final catalogue used in this study.

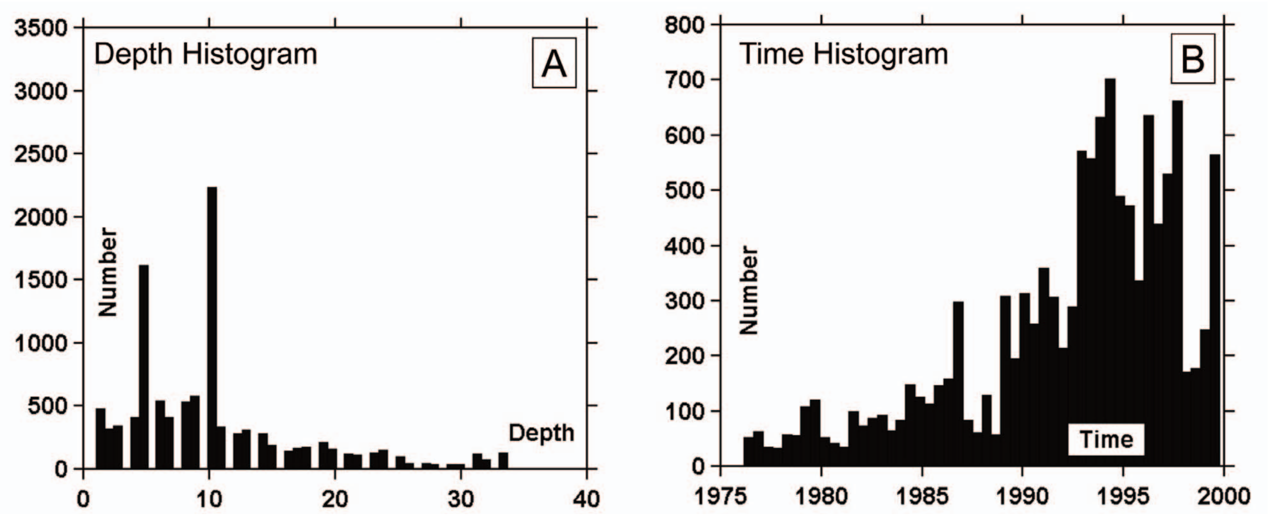

Figure 4. Various histograms from number of recorded events versus **(A)** depth histogram, **(B)** time histogram in Western Anatolia (1976–2000, M≥ 3.0).

based on the algorithm developed by Reasenberg (1985). We only changed epicentre and depth error values. Other standard parameters are defined as given in the software. Hence, the catalogue has been declustered as a final stage and cleaned-up for dependent events. The declustering found 333 clusters of earthquakes, a total of 934 events (out of 5196). The final catalogue, describes the seismicity in the study area which contained a total of 4262 events. Magnitudes (Ms) in the final catalogue vary between 3.0 and 6.0. After completing these processes, a more reliable, homogeneous and robust seismicity data has been obtained.

Figure 5 shows spatial distributions of earthquake epicentres according to the (A) raw- and, (B) final-catalogues, respectively. It is immediately apparent that the seismicity is not distributed homogeneously and displays spatio-temporal variations. These can been attributed to the fault complexities, tensional and compression stresses, and thermal gradients especially over the northeastern-most corner (İlkışık 1995) within the frame of the AER. Spatio-temporal variations concentrate at the north of Akhisar-Gördes, near Demirci, southwest of ÇB, near Karaburun, western part of BMG, near Buldan in the east, GB and surrounding areas in the South. It is also clearly evident a precise N–S alignment in the Sığacık Bay (SB) where a series of earthquakes with moderate-size intensity from I= V to VII took place along the southern half of the KGF on October, 2005 (Benetatos *et al.* 2006; Aktar *et al.* 2007).

We plan to investigate the seismicity using local computations of Gutenberg-Richter value (*b*-), seismic activity rate (*a*-), fractal correlation dimension (*Dc*) throughout AER over comparable time intervals. The Gutenberg-Richter *b*-value is the slope of the FMD and provides a relative measure of the likelihood of large and small magnitude seismicity in the region. The seismic activity rate, *a*-, represents the intercept derived from the FMD plot and describes the background levels of seismicity within the area. The correlation between seismicity and the fractal properties of epicentre distribution characterize complex properties and patterns of earthquake seismicity. Fractal analysis undertakes direct comparison of seismicity and maximum magnitude variation. The correlation of seismicity (*b*- and *a*-values), seismic quissence *z*-value, fractal dimension Dc, and interrelationships between these parameters is the central issue addressed in the present study.

Our research evaluates interrelationships between complex non-linear seismotectonic processes. Quantification and analysis of these interrelationships will help identify and differentiate between normal and abnormal conditions and thus provide information of value to seismic hazard assessment, not only in the study

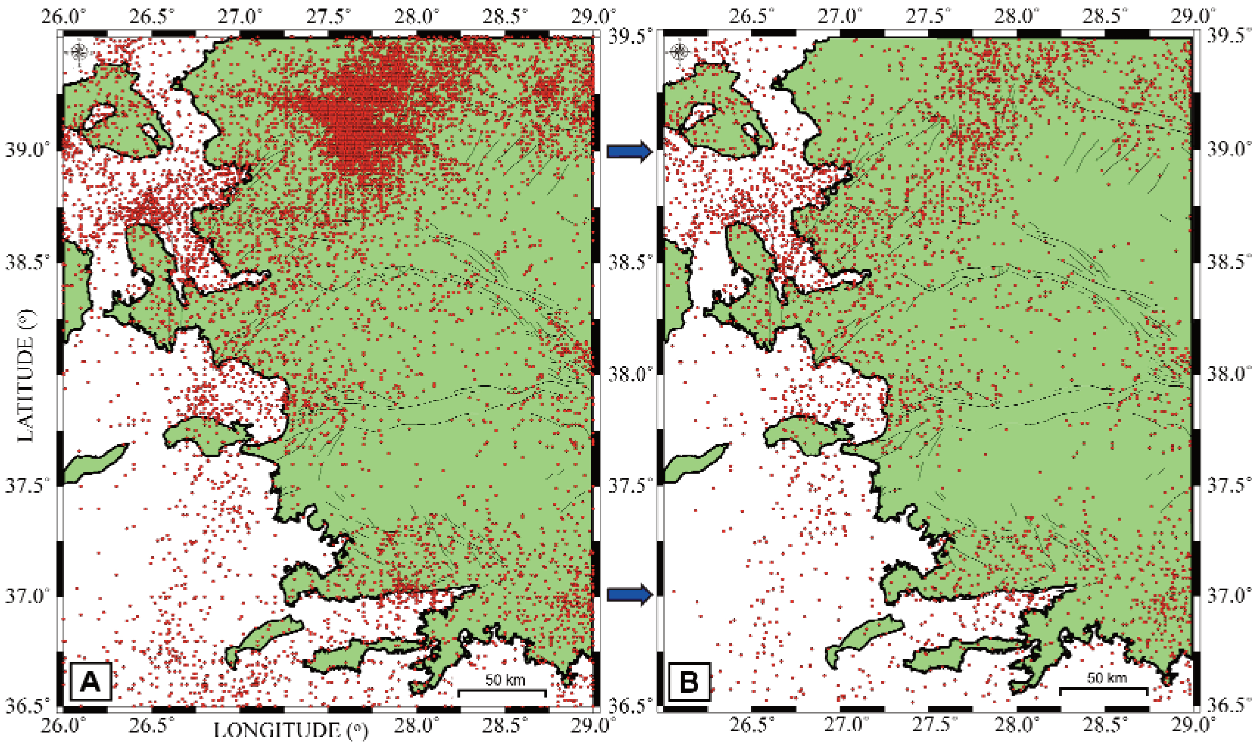

Figure 5. Seismicity of the Western Anatolia according to the (A) raw (1900–2002, 14289 events), and (B) final earthquake catalogues (1976–2002, 4262 events).

area, but also throughout the earth's active tectonic regions of Turkey.

Results

Earthquakes were selected by sampling the closest 100 earthquakes to each node according to spatial map size-scale (such as *b*- and *a*-) values and seismic quiescence *z*-value; the study area was then gridded at 5 km node spacing. This was done separately by using a forward modelling technique, as described in Wiemer & Wyss (2000) and Wiemer (2001). Calculation of *b*-value was done using the maximum likelihood method based on Aki (1965).

The *b*-value map was shown in Figure 6a. We detected that b-values ranges between 0.7 and 1.2 and show a clear strong heterogeneity where low *b*-values are mostly dominant in the region except for a few local areas. We identify several areas of anomalously low *b*-values, these are: (1) Çandarlı Bay and Bergama-Zeytindağ Fault Zone at the northwest of Manisa, (2) İzmir Fault and Orhanlı Fault Zone near İzmir; (3) northern part of Kuşadası city at the west, (4) area near Buldan in the east and (5) the last one is observed around Gökova Bay towards to the south of the study area (see Figure 1 for abbreviations and city locations). Distribution of b-value errors in the study area are shown in Fgure 6b. Error interval changes between 0.02 and 0.16, and it does not effect the computed *b*-values all over the study area, except for the İzmir and Gökova Bay area on small-scale deviations. The low *b*-values were correlated with high stress environments in the laboratory tests and field experiments (Wyss & Matsumura 2002). It may be associated with Bouguer gravity anomaly and usually linked with low *b*-values (Wilson & Kato 1992, 1995; Khan 2005). The gravity anomaly was studied in detail by Sarı & Şalk (2006), and the high Bouguer anomalies coincide for low *b*-value area in the present study. We interpreted these areas in asperities as expressions of stress levels and high stress accumulation which probably cause lower *b*-values.

A trend of increasing *b-values* from moderate to high was generally detected along two local zones. The first one is observed around Akhisar and Gördes in the north

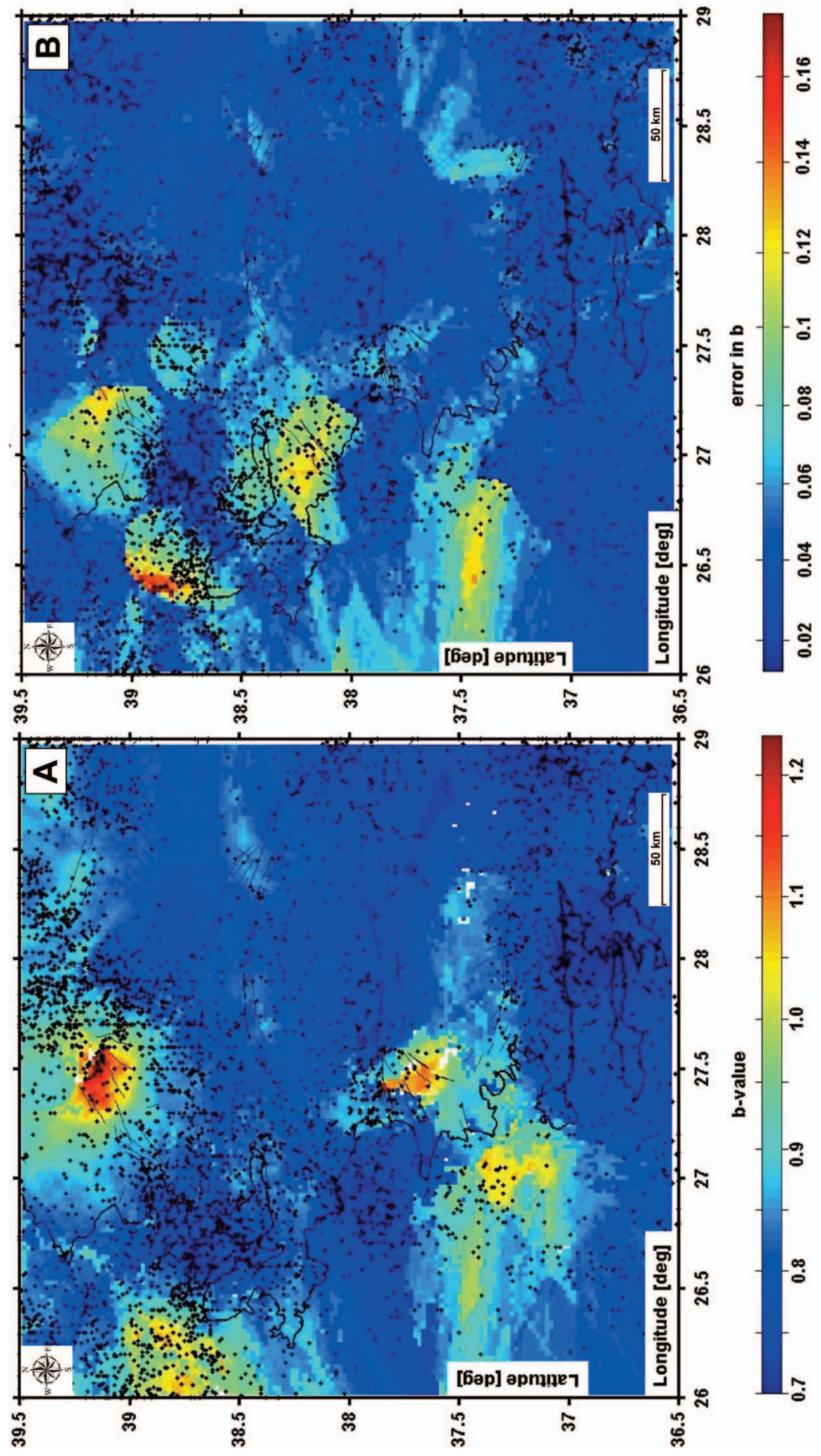

Figure 6. Mappings for (A) Gutenberg-Richter *b*-value distribution, (B) standard deviation of *b-value*, for the study area.

and it is attributed to high heat flow reported already by various researches (İlkışık 1995). The second area with high b-value was detected at sea, west of Kuşadası and Bodrum and it is explained by high heterogeneity in this area. There is much literature on *b*-values, and its interval was given as $0.5 \leq b \leq 1.5$ by Turcotte (1990). The estimation of *b*-value is performed in detail by various studies and the results obtained in the present study are in good agreement with them (Papazachos & Kiratzi 1996; Bayrak *et al.* 2002)

Seismic quiescence *z*-value was calculated by using the LTA function (Habermann 1987). For this computation, 250 neighbouring earthquakes have been considered. Positive *z*-values are associated with a decrease in the seismic rate (Figure 7). Clear quiescence anomalies were identified at several seismogenic sources. Obviously, two anomalous quiescence zones have been detected along the Çandarlı Bay and Bergama-Zeytindağ Fault Zone, on İzmir Fault and Orhanlı Fault Zone in the east of Sığacık Bay, between Savaştepe and Bigadiç, near Demirci, around Buldan city, and the eastern part of Marmaris city. Increasing *z*-values demonstrates a decrease in the seismicity rate. The abnormal high *z*-values are partly due to the presence of low-magnitude earthquakes (low *b*-values). On the other hand, the slightly lower *z*-values are observed in a large circular area centred around Ödemiş, Bozdoğan and Muğla.

As a consequence of the Gutenberg-Richer *b*- and seismic quiescence *z*-values are in agreement over the three suspicious areas; namely Çandarlı Bay and Bergama-Zeytindağ Fault Zone, İzmir Fault and Orhanlı Fault Zone in the east of Sığacaık Bay, and near Buldan in the east of the study area. The mappings of *b*- and *z*-values show irregular pattern along these zones. The comparison reveals remarkable seismic hazard based on the size-scaling parameters. Thus, the site of lower *b*-values and higher *z*-values has been considered to be the most likely place for a major earthquake. This could be explained with most promising environment where decrease in b-value is detected with an increase in mean stress (Westerhaus *et al.* 2002). Similar conclusions are also confirmed by Smith (1986) and Öncel & Wyss (2000) for the İzmit earthquake with epicentre located at the anticipated site. Thus, it is reasonable to assume that a destructive earthquake could occur in one of these zones.

We also inferred the nature of temporal-spatial fractal properties of the earthquake epicentres (Kagan 2007). They are characterized by fractal, in particular by the correlation dimension; Dc fractal dimension can be calculated to avoid the possible unbroken sites, and it has been suggested as potential 'seismic gaps' to be broken in the future (Toksöz *et al.* 1979). Dc is related to hypocentral distance and to the physical models based on fluctuations in the elastic interactions between individual earthquake events. In order to evaluate the seismicity with time, we show the temporal distributions of the earthquakes during the time period from 1976 to 2002 (Figure 8). The seismicity associated with the clustering features is observable and they correspond to a major event in the region. Temporal clustering behaviour of the seismic sequence associated with the major earthquakes is not very strong, except for some events which occurred in 1979, 1989 and 1998.

In order to characterize the whole area by fractal dimension, we used 100-event window moving through the earthquake catalogue. The variation with respect to time of the fractal dimension was shown in Figure 9a. The comparison of correlation dimension with *b*-values is also seen in Figure 9b. Fractal characteristic showed a strong decline in 1989–1990. The decrease in Dc can be explained by improvement of dense recording instrument coverage as already reported by Kalafat *et al.* (2007). We obtained the correlation dimensions for the distributions of earthquake epicentres in order to investigate the possible spatial variability. Correlation dimension was estimated by fitting a straight (solid) line to the curve of mean correlation integral against the event distance, R (Figure 10a). Dc was obtained with 95% confidence limits as 1.73 by ±0.02 by linear regression. This log-log correlation function exhibits a clear linear range and scale invariance in the cumulative statistics between 3.6 and 70 km (indicated by arrows). Local slope curve for numerous series of earthquakes was shown in Figure 10b. Changes in the slope of cumulative curves, namely the *b*-values, can clearly be seen and illustrate the heterogeneity of the seismic activity. Local slope curve exhibits variation over the range $0.7^\circ < \log R < 2.2^\circ$ (or $5 < r < 160$ km) and shows a systematic curvature. Outside the boundary values, it reveals strong perturbations (values before 5 km) or sharp falling (distances after 160 km). Dc and standard error in Figure 10a were also determined within these distances. It is reasonable to assume that the higher Dc and lower *b*-values are the dominant structural feature in the study area and may arise due to clusters as shown in Figure 5. It is also an indication of changes in stress since the region of present paper reveals a change of GPS-

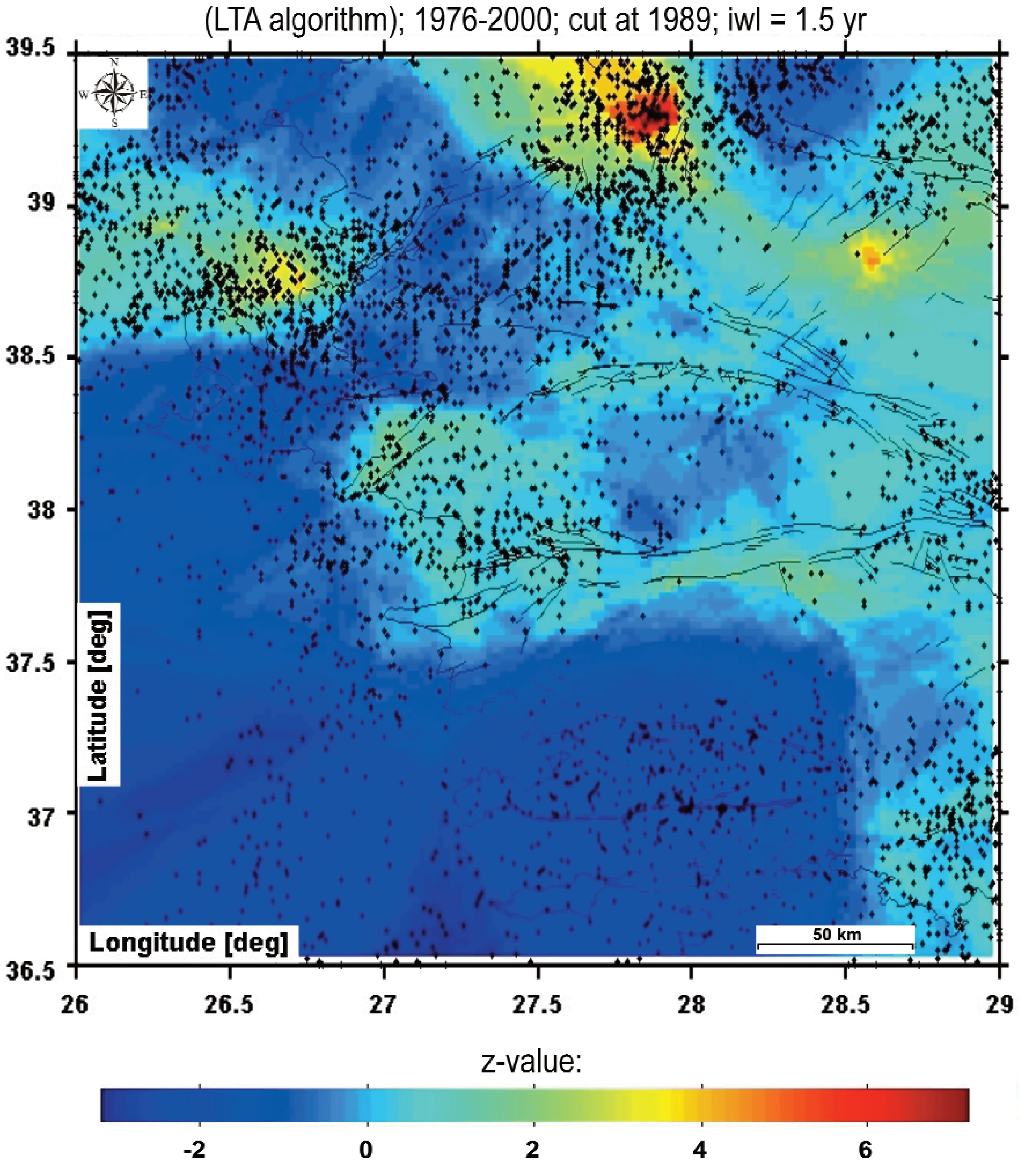

Figure 7. Seismic quiescence *z*-value mapping after LTA analysis (n= 250 earthquakes at each node).

derived dilatational stress (Aktuğ & Kılıçoğlu 2006). Hence, the study area has been deformed by a different rate of normal stresses and by several tectonic elements.

Nevertheless, we also consider it more likely that even smaller target events may take place inside or outside according to the mapped anomalies of local recurrence

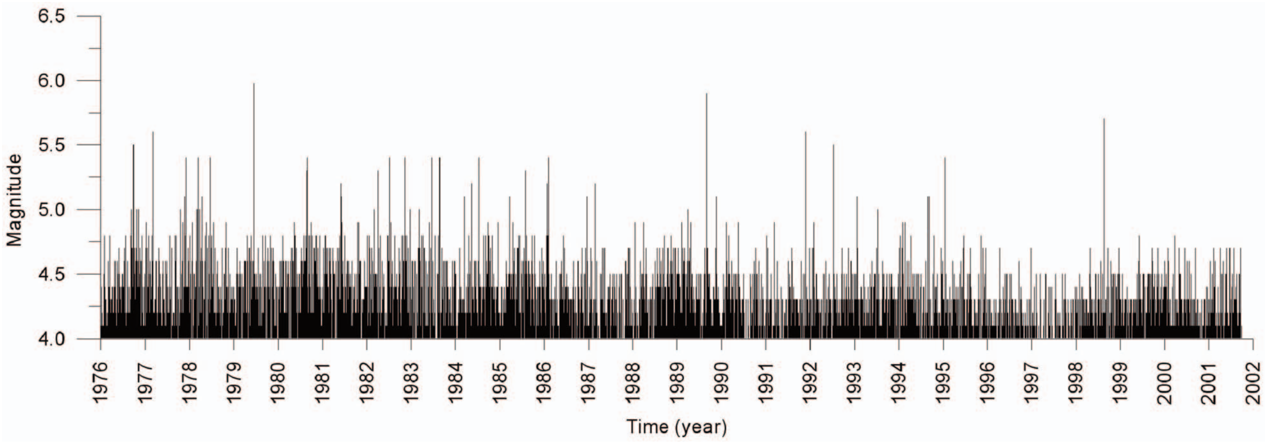

Figure 8. Temporal distributions of the earthquakes occurred in Aegean region between 1976 and 2002 (M≥ 4.0 earthquakes only).

times (Tr) obtained for large magnitudes (Ogata & Abe 1988). The seismicity rates showed that no significant large events occurred in these zones. Hence, the probability of occurrence of a large earthquake in these volumes is low, because the Tr is large. Variations of the mean Tr with magnitude Ms≥ 6.0 and Ms≥ 6.5 are plotted in Figure 11a and 11b, respectively. These maps have been produced by using maximum curvature algorithm defined as a standard parameter of ZMAP tool. We detected four anomalous zones in both figures. Return periods are observed below 30 years around the Gökova Bay area, in the south. Further to the east, Tr reaches up to 60 years near Buldan city for Ms≥ 6.0. Distribution of Tr is clearly present around Sığacık Bay and to the north of the area of Karaburun-Çandarlı Bay. But obtained values are longer than two other southern areas. The discrepancies between the return times are about 100 years in the south, and in Çandarlı Bay area, for Ms≥ 6.5. Differences in mean return periods for larger earthquakes of Ms≥ 6.5 increases around Manisa city (200 years), in the northeast and southeast corners of the study area (more than 250 years). But these changes may not be realistic due to lack of macro-seismic data over these zones. Some of the long return anomalies in Tr are found in locations of high *b*- and average *z*-values (e.g., Akhisar-Gördes and Kuşadası-Bodrum areas). This should be the case to explain the complexity in the region. Intermediate layers (second and third) possibly account for higher heterogeneity or may be indicative of low strength rocks constituting in the upper part of the earth crust. The unusual mean *z*- with high *b*-values may characterize complex rupture planes and geologically young faults (Wyss & Matsumura 2002). Thus, in the related area either *b*- or *z-values* can be responsible for long Tr anomalies. But for the case of Gökova Bay (at the south), Buldan city (at the east), İzmir Fault and Orhanlı Fault Zone (south of İzmir city), and Çandarlı Bay and Bergama-Zeytindağ Fault Zone areas, we found that *b*-values mostly dominate and harmonize with return periods.

Discussion and Conclusion

For the study area, we identified four volumes of seismic quiescence in real time that could be interpreted as precursors to possible target events. These areas, showing low *b*-values, could be interpreted as meaning sizable target events, and are likely to be generated in these volumes. The seismicity rates in these volumes, which had shown quiescence, returned to normal and no target events occurred. Thus, it seems that transients in the production of earthquakes occurred in these three volumes, but the probability that large shocks could occur in these volumes is low, because the recurrence time is large. This latter conclusion is supported by Wyss & Matsumura (2002) who obtained similar results for the Kanto-Tokai area in Japan. Jenny *et al.* (2004) combined geodetic (GPS) data with the seismic catalogue of the Eastern Mediterranean, and also reported long recurrence times between 100–700 years for magnitudes 7.2 ≤ Ms ≤ 7.5. Assessment of earthquake hazard in the Aegean

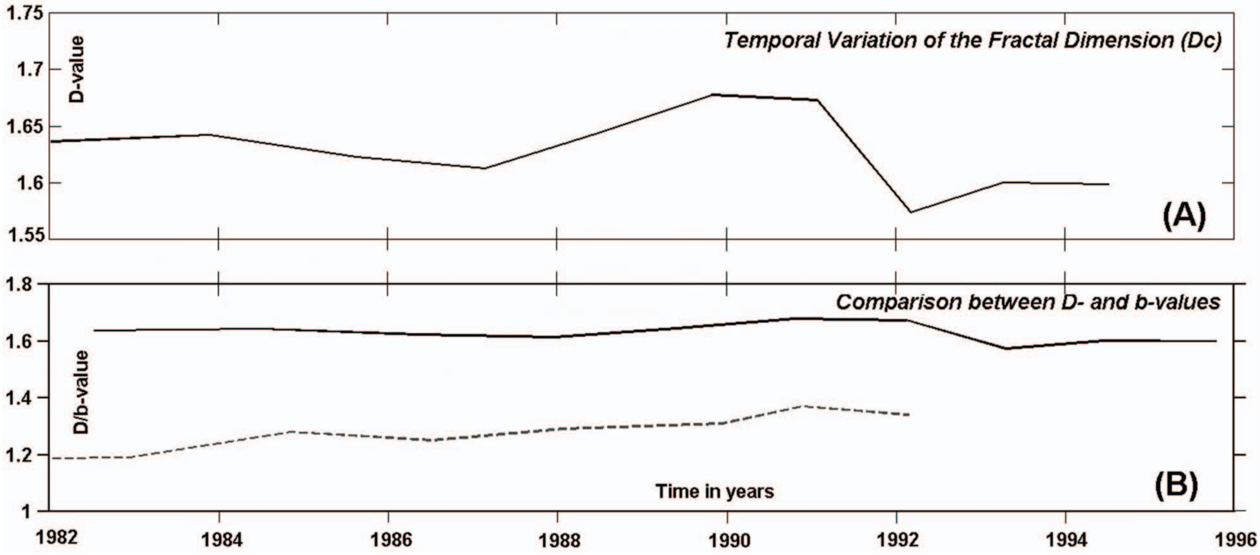

Figure 9. **(A)** Temporal variation of time with the fractal dimension, **(B)** comparison of *Dc* with *b*-values (dashed line). Solid line indicates Dc changing with time in both figures.

Region of Turkey has also been reported on the regional scale for site selection and design of engineering structures by using probabilistic seismic hazard analysis (PSHA). The peak ground acceleration (PGA) maps have been contoured with a 10% probability of exceedence and produced for a 475 years return period over the region for magnitudes M ≥ 7.0. But, the PSHA studies are mostly intended to serve as a reference for more advanced approaches and to stimulate discussion and suggestions on the database, assumptions and the inputs, and to pave the way for the probabilistic assessment of seismic hazard in the site selection and the design of engineering structures (Bommer *et al.* 2002; Erdik *et al.* 1999; Weatherill & Burton 2006).

The quiet volume near Savaştepe and Bigadiç could not be analyzed here, because of being partially outside the study area and contamination by explosions. However, since we used the local dataset itself to optimize the result, we may not rigorously conclude that results of Jenny *et al.* (2004) show highly significant correlation for the epicentre of future target event with anomalously long recurrence times. Whether this test will have to come with future events or not, we have defined the most likely candidate areas for future earthquakes with Ms ≤ 6.5

The anomalously short Tr are in part due to the presence of intermediate magnitude earthquakes (low *b*-values) and in part due to strong seismicity rate (high *a*-value). Low *b*-values have been associated with high stress environments in the laboratory (Scholz 1968) and in the field (Wyss & Matsumura 2002). Therefore, we interpret the anomalies of short local recurrence times (Figure 11) as asperities, where high stresses accumulate.

Mapping of the Gutenberg-Richter *b*- and seismic quiescence *z*-values and investigation of fractal dimensions show irregular spatial patterns. The higher order fractal dimension is increasingly sensitive to heterogeneity in the distribution of magnitudes. This suggests that seismicity is more clustered at larger scales (or in smaller areas) in the Aegean extension region. Significant spatial variation has been documented as fractal dimension of the active fault complex (Öncel *et al.* 2001). We did not observe a negative correlation with the drop in *b*-values and this suggests increased probability of larger magnitude seismicity. Our results reveal parallel or slightly increasing in D/b values (Figure 9b) which are associated with denser and more complex regions of the active fault network. We suggest that this occurrence could be linked with the greater density of faults and accommodated rupture on interconnected faults. This positive correlation arising from parallel variation in Dc/b suggests that the increased fault density allows stress to be released through lower magnitude scales on smaller fault strands. Hence, it probably reduces occurrence of

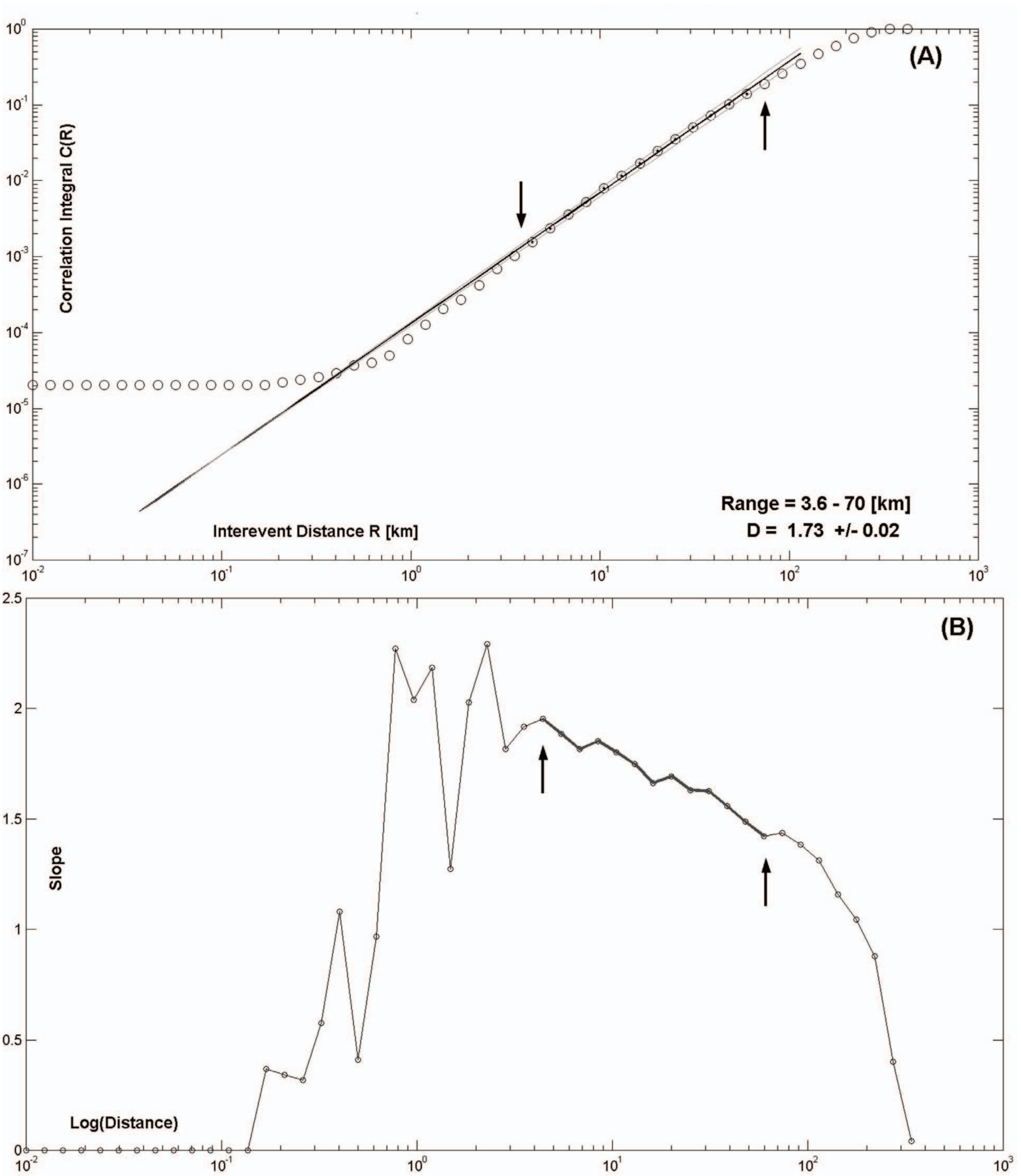

Figure 10. (A) Mean correlation integral, and (B) slope curve calculated for several sequence generated with the same mean rates for the earthquakes occurred in the Aegean extension region.

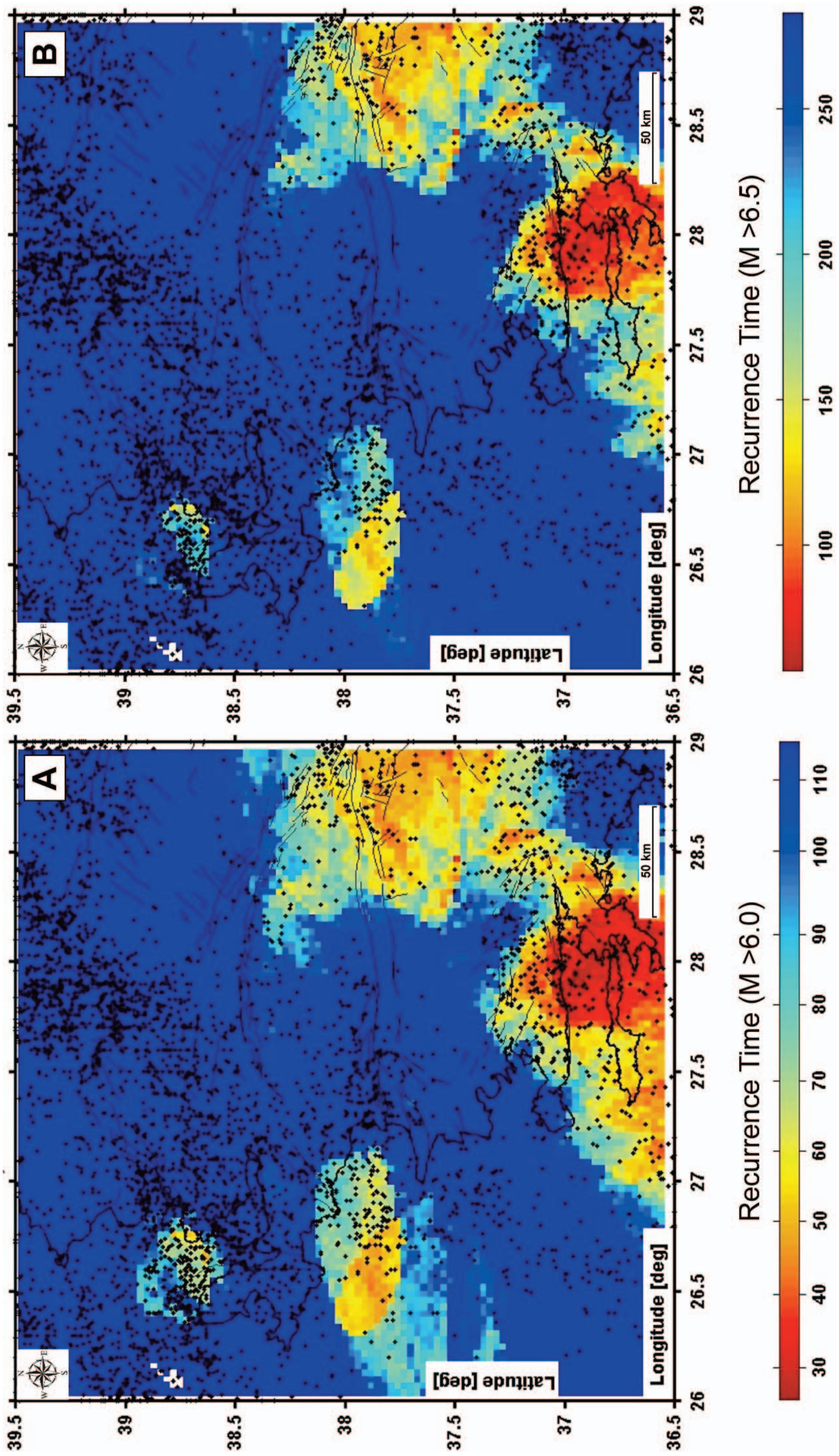

Figure 11. Recurrence time distribution of the WAER for magnitudes (A) Ms≥6.0, and (B) Ms≥ 6.5 by using maximum likelihood algorithm.

large magnitude earthquakes in the Aegean region. Abik *et al.* (2005) investigated the seismic moment release using rescaled range of Hurst algorithm, and reported that a possible magnitude of a major earthquake could reach up to Mw= 6.5. Thus, one way of discussing our result is to say that large earthquakes are generally not expected in volumes with a preponderance of small-moderate size earthquakes.

The distribution of the seismicity clusters and active faults have a significant effect on our results. The active faults of the Aegean extension region are considered to be active or potentially active if there has been some movement along the fault during the Quaternary. The geological nature of the systems present in the Aegean extension region (e.g., Gediz Graben, Küçük Menderes Graben and Büyük Menderes Graben, Selendi Basin, Demirci Basin, Gördes Basin and structural elements of Buldan-Denizli-İzmir areas) is a matter of ongoing debate (e.g., Koçyiğit *et al.* 1999; Gessner *et al.* 2001; Lips *et al.* 2001; Seyitoğlu *et al.* 2002; Sözbilir 2001, 2002; Bozkurt & Sözbilir 2004; Purvis & Robertson 2004). These complex tectonic features still play an important role in the geodynamical and seismic hazard evolution of the Aegean extension region. Hence, a rupture may have had a tendency to occur largely on one of these faults within one period of time, or the stress can be released along smaller fault strands at other times.

The relationships between the Gutenberg-Richter *b*-value, seismic quiescence *z*-value and fractal properties along the complex faultings provide significant information about the dynamics of the earths crust. In the Aegean extension region, correlation of obtained results identifies differences in a way that stress is released within complex fault systems. The positive correlation between *b*-value and *Dc*, the increased complexity and fragmentation of the fault system present an abundance of small fault strands along which stress can be released through more frequent but lower magnitude scales. In areas of increased complexity in the active fault system (higher *Dc*) associated with lower *b*-value, stress release occurs on fault planes of smaller surface area (Öncel & Wilson 2002). The recent positive trend covers a relatively short-time interval but reveals behaviour which is significantly different from the preceding 30 year time period. Between 1976–2002, the tendency was for seismicity to be less clustered (high *Dc*) and to consist of more frequent but smaller magnitude earthquake activity. The variations of *b*-value and *Dc* through time are unusual and their seismotectonic significance in relation to the earthquakes could not be clear as one has seen recently near Metropolitan İzmir on October 17–21, 2005.

We propose that future target events with M ≤ 6.5 should preferentially be expected in the anomalous areas that we mapped and explained in the present study. Since we do not have enough earthquakes to map asperities with radii of less than 10 km, we must expect that target events of magnitude 6.0 class, for which an asperity could have dimensions of R= 5 km (Wiemer & Wyss 1997), could occur inside of asperities. Nevertheless, we consider it more likely that even these smaller target events occur inside, rather than outside the mapped anomalies of Tr.

Aegean extension region is classified as areas where large earthquakes within the top 35 km of the earth crust are not likely. However three areas (Çandarlı Bay and Bergama-Zeytindağ Fault Zone, İzmir Fault and Orhanlı Fault Zone, and near Buldan city) are identified as a likely source of target events (M ≤ 6.5). These zones further support the hypothesis that a large earthquake may be possible in the study area. During the post-2002 period, some moderate size-earthquakes already occurred along the areas mentioned above. These are; ML= 5.2 on March 2004 near Çandarlı Bay, ML= 5.6 on April 2003 and Md=5.9 on October 2005 near Orhanlı Fault Zone and Sığacık Bay areas at the South of Metropolitan İzmir, and the last one was Md= 5.6 earthquake on July 2003 near Buldan city, respectively. Since our analysis merely identifies volumes with increased probability for target events, we propose that one or more of these locations may contribute significantly to the moment release of future earthquakes in the area.

We conclude that recent attempts to evaluate hypotheses by algorithms (Cisternas *et al.* 2004) have led to many advances in earthquake prediction research, such as sharpening definitions of predictions and hypotheses, but that it can also lead to erroneous rejection of a hypothesis that can be demonstrated to be supported by case histories. Since great earthquakes occur relatively infrequently in the study area, it may be very difficult to statistically test the effectiveness of models concerning the results. Added to this, we consider that our conclusions and speculations are reasonable, they should not be taken as hard evidence of what to expect in the future certainly. Therefore, we advocate that both testing by algorithm as well as evaluation by common sense based on the earthquake catalogues should be exercised to advance our knowledge of the physics of earthquake failure processes.

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