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Research Article

THE SPATIAL ANALYSIS OF b-VALUES OF THE AREA BETWEEN BODRUM AND FETHIYE DISTRICTS, THE SOUTH-WESTERN ANATOLIA, TURKEY

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Keywords
Guttenberg-Richter Relationship,
b-value,
Seismic Hazard,
The Maximum Likelihood Method.

Abstract
The estimation of the variation of the b-value, which is frequency distribution of a magnitude given in an earthquake data set of any region, is important parameter for interpretation of tectonic mechanism and seismic hazard assessment of that region. There is an inverse correlation between stress and b-value. The magnitude-frequency relationship is described by the well-known the Gutenberg-Richter relationship. The purpose of this paper is to investigate the recent seismicity of the region between the Bodrum and Fethiye, the south-western Anatolia in Turkey. A total of 27357 earthquake data is taken into account in this study in the period between 2004 to 2020 with magnitude (Ml) larger than 2. The majority of focal depths of earthquakes are concentrated between 0 and 33 km. The b-value in the Gutenberg-Richter relationship was estimated by the maximum likelihood method in this study. The estimated b-values range between 0.5 and 2 in the study region. While the lower b-values (0.5-1) are located at the SE of the study area (mainly the Beydağları unit), higher values (1-2) are trending on the west-east direction along the fault zones. The highest b-values in the study area are possibly related with the brittle lower-mid crust, thermal regime, normal faults and young basins bounded by these faults.

BODRUM VE FETHİYE İLÇELERİ ARASINDAKİ BÖLGENİN b-DEĞERLERİNİN UZAYSAL ANALİZİ, GÜNEYBATI ANADOLU, TÜRKİYE

Anahtar Kelimeler
Gutenberg-Richter İlişkisi,
b-değeri,
Sismik Tehlike,
Maksimum Likelihood Yöntemi.

Öz
Herhangi bir bölgenin deprem veri setinde verilen bir büyüklüğün frekans dağılımı olan b-değerinin değişiminin tahmini, o bölgenin tektonik mekanizmasının yorumlanması ve sismik tehlike değerlendirmesi için önemli bir parametredir. Gerilme ile b-değeri arasında ters korelasyon bulunmaktadır. Magnitüd-frekans ilişkisi, iyi bilinen Gutenberg-Richter ilişkisi ile tanımlanır. Bu makalenin amacı, Bodrum ve Fethiye ilçeleri arasındaki bölgenin (GB Anadolu, Türkiye) yakın zamandaki sismisitesini araştırmaktır. Bu çalışmada 2004-2020 yılları arasında magnitüdü (Ml) 2'den büyük toplam 27357 deprem verisi kullanılmıştır Depremlerin büyük çoğunluğunun odak derinlikleri 0 ile 33 km arasında yoğunlaşmaktadır. Bu çalışmada, Gutenberg-Richter ilişkisindeki b-değeri, maksimum likelihood yöntemiyle hesaplanmıştır. Hesaplanan b-değerleri çalışma bölgesinde 0.5 ile 2 arasında değişmektedir. Daha düşük b değerleri (0.5-1) çalışma alanının GD'sunda (esas olarak Beydağları birimi) yer alırken, batı-doğu yönelimli yüksek değerler (1-2) fay zonları boyunca yer almaktadır. Çalışma alanındaki en yüksek b değerleri muhtemelen kırılgan alt-orta kabuk, termal rejim, normal faylar ve bu faylarla sınırlanan genç havzalarla ilgilidir.

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1. Introduction

The Western Anatolia is characterized by a very complex geology, high seismic activities, and several tectonic zones due to the deformation of the northern margin of the Anatolide-Tauride Block during the Alpine orogeny. The study area is located at the south western Anatolia, where it is one of the most seismically active region (Figure 1a). Numerous earthquakes have occurred during the historical and instrumental periods in this region. Some moderate and large earthquakes have been investigated by several researchers for determining the fault mechanism and the source parameters of the mainshock (e.g., Ambraseys and White, 1997; Hall et al., 2014; Yolsal-Çevikbilen et al., 2014; Karasözen et al., 2016; Konca et al., 2019; Ganas et al., 2020).

In the study area, the latest strong even occurred on July 20, 2017 (the Gulf of Gökova), with a magnitude of Mw=6.6 (USGS). Konca et al. (2019) proposed that the Gokova earthquake ruptured a north-dipping fault and occurred on a 20-25 km long, E-W striking, 40° north-dipping, pure normal fault with the largest slip exceeding 2 m between 4 km and 10 km depths. Ganas et al. (2020) determined also the dip-direction of the fault plane as north-dipping with an angle of 37°±3°. Yolsal-Çevikbilen et al. (2014) investigated the Gulf of Gökova earthquakes occurred at 1986-2005 (Mw≥5.0) and concluded that the EW- trending high-angle normal faulting mechanisms reveal extensional tectonics in the Gulf of Gokova. In the study region, the other important structural element is the Fethiye-Burdur Fault Zone (Figure 1a) that is composed of several NE-SW striking active faults (Hall et al., 2014). A devastating earthquake in Fethiye occurred on April 25, 1957 (Mw=7.1), which was connected with the rupture of a left lateral strike-slip fault (Tan et al., 2008). Över et al. (2016) investigated to the regional stress regime in SW Anatolia in detail by using fault kinematic analysis and inversion of focal mechanisms of shallow earthquakes occurring between 2001 and 2015 along the Fethiye-Burdur Fault zone and its surroundings. They determined that a normal faulting stress regime is a NE-SW trending $\sigma 3$ axis for the Fethiye-Demre zone.

In the study area and its surroundings, studies mostly focused on the determination of earthquake focal mechanism. But, the regional and temporal variations of seismicity studies are few and covered whole western Anatolia. For example, Bayrak and Bayrak (2012) and Öztürk (2015) studied the correlations between seismotectonic b-value and Dc-value in the western Anatolia. Recently, Bayrak et al. (2017) determined the temporal and spatial variations of Gutenberg-Richter parameter (b) and fractal dimensions (Dc) using the earthquakes with magnitude 2.0≤ Ms ≤7.7 between 1900 and 2010 for whole western Anatolia. Çoban and Sayıl (2019) investigated the Bodrum-Kos earthquake (21 July 2017, Mw=6.5) and calculated the Weibull, gamma, log-normal, and Rayleigh distribution models parameters by using the inner-event time of earthquake recurrences. They proposed that the conditional probability results contribute to seismic hazard assessment in the western Anatolia. Mesimeri et al. (2018) investigated the earthquake swarm near the Aegean coast of NW Turkey and suggested that the earthquake swarm is most probably connected with minor faults accommodating moderate earthquakes (M ~5).

In quantitative seismicity analysis, the *b*-parameter related with the Gutenberg-Richter frequency-magnitude relation is important to identify seismicity properties of any region (Gutenberg and Richter, 1944). The scope of this study is to determine b and Mc values and form the b-map of the study area using the earthquake data set between the periods of 2004-2020 with magnitude-Ml ≥ 2.0 for future earthquake potential occurrences.

2. Simplified tectonic and geologic setting

The Anatolian Plate has been rotating counter clockwise and moving westwards by lateral extrusion along the North Anatolia and East Anatolia Fault Zones (NAFZ, EAFZ, respectively) at a rate of 30-40 mm/year since about 5 Ma, as a result of the collision of Africa- Arabia and Eurasia plates along the Bitlis-Zagros Suture Zone (McKenzie, 1972; Şengör and Yılmaz, 1981; Le Pichon et al., 1995; McClusky et al., 2000) (Figure 1a). The west-southwestward escape of the Anatolian plate along the NAFZ and EAFZ has been postulated as one of the cause of the N-S extension of western Anatolia (e.g., Şengör and Yılmaz, 1981). This extensional phase produced the several low/high-angle faults controlling the western Anatolia graben systems (e.g., Alaşehir, Büyük Menderes, Küçük Menderes).

There are two main faults in the study area (Figure 1b). The Datça-Kale main breakaway fault is associated with the exhumation as an asymmetric core complex of the Menderes Massif (Seyitoğlu et al., 2004). The Fethiye-Burdur fault zone is developed within a NE-SW trending left-lateral shear zone (Akyüz and Altunel, 2001; Karabacak, 2011; Elitez and Yaltırak, 2016; Elitez et al., 2016, 2017). In this fault zone, a recent large earthquake was occurred on 25 April 1957 (Magnitude=7.1, Fethiye earthquake) (Ambraseys, 1989).

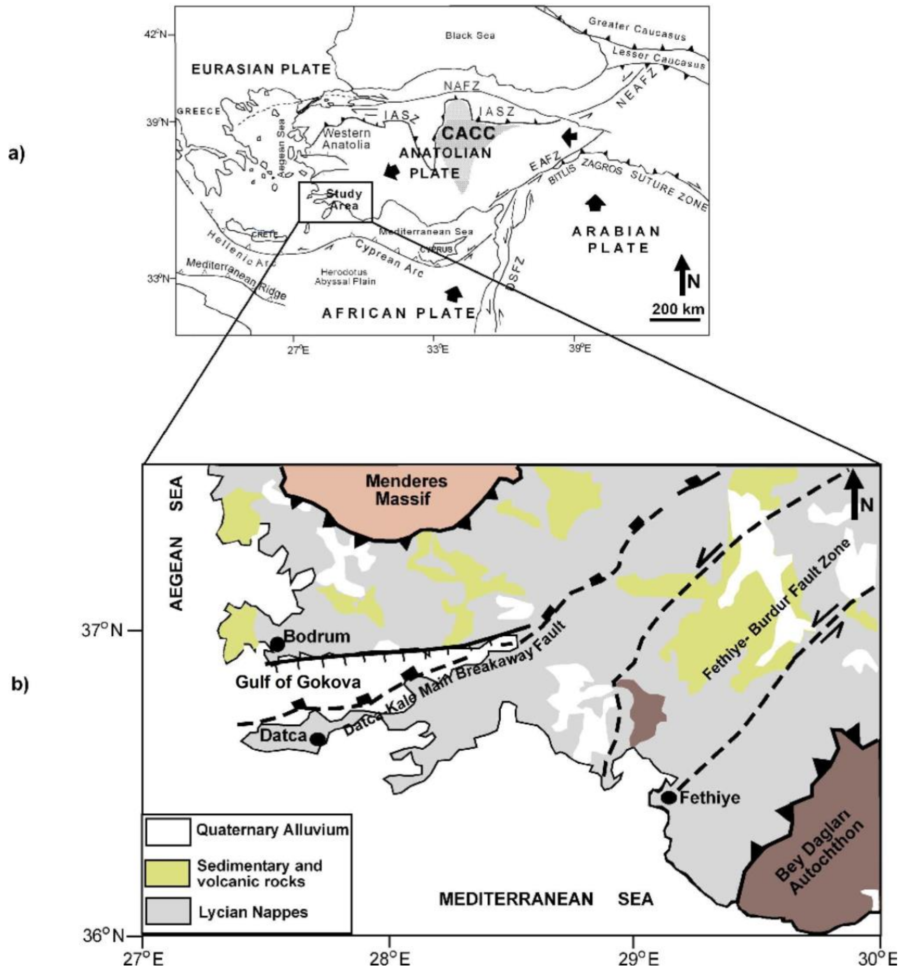

Figure 1. a) The major tectonic elements of Turkey (modified from Bozkurt and Mittwede, 2005). The large arrows show relative motions of the Anatolian Block and convergent motions of the African Plate and Arabian Platform. NAFZ: Nort Anatolian Fault Zone, DSFZ: Dead Sea Fault Zone, NEAFZ: North-East Anatolian Fault Zone, EAFZ: East Anatolian Fault Zone, IASZ: Izmir-Ankara-Erzincan Suture Zone. **b)** Simplified geological map of the study area (modified from Çemen et al. 2014)

The study area is mostly covered with the Lycian Nappes, lied between the Menderes Massif and the Bey Dağları Autochthon (Figure 1b). The Lycian Nappes consists of thrust sheets (nappes piles) of Paleozoic-Cenozoic rocks, ophiolitic and tectonic melanges and serpantinized peridodites (Collins and Robertson, 1997; Özer et al., 2017). The Lycian allochthon is thrust over autochthonous, unmetamorphosed, platform sediments of the Bey Dağları unit (Collins and Robertson, 1998). The southern part of the Menderes Massif is located in the north-west of the study area and bordered on the south by the Lycian Nappes (Figure 1b). It is covered with the augen gneisses of the core series (Hetzel et al., 1998).

3. Data and Method

In this study, an updated catalog of 27357 earthquakes with a magnitude Ml≥ 2.0 between 2004 and 2020 is used. The data are obtained from the Bogazici University Kandilli Observatory and Research Institute Regional Tsunami-Earthquake Monitoring Center of Turkey (KOERI-RETMC). The study area is within 36°N to 37.5° N and 27°E to 30°E (Figure 2a). The magnitude scale (Md) calculated from duration was converted to local magnitude to ensure magnitude homogeneity. We used the following empirical relations for the conversion (Kalafat et al., 2011) Md=1.0377+0.7863Ms and Ml=1.0553+0.7782Ms.

The magnitude (Ml) of total 23161 events ranges between 2 and 3. There are 3911 events within magnitude (Ml) range between 3-4. The magnitude of 259 events is between 4 and 5. The magnitude of 24 events range between 5 and 6. The W-E vertical cross section of the hypocenter distribution of earthquakes indicates that they are mostly concentrated around 33 km (Figure 2b). The study area is characterized by low magnitude and shallow depth in general. There are 26620 events up to 33 km. Only 737 events have a depth of more than 33 km. It can be suggested that the depth of the seismogenic zone in the study region is about 33 km depth. In earthquake sequences, the main shocks are independent events. Foreshock and aftershocks are dependent events resulting from stress changes caused by the main shock. Dependent earthquakes should be declustered from earthquake catalogs. The process of distinguishing dependent and independent events from each other is called 'declustering' (e.g., Gardner and Knopoff, 1974). The decluster method (Gardner and Knopoff, 1974) is a window method that grouped earthquakes according to the space-time distances among them. For every cluster, the event with the maximum magnitude was indicated as the mainshock and events within the space-time window of the mainshock were removed. 15939 earthquakes remained after the elimination of deep earthquakes and declustering.

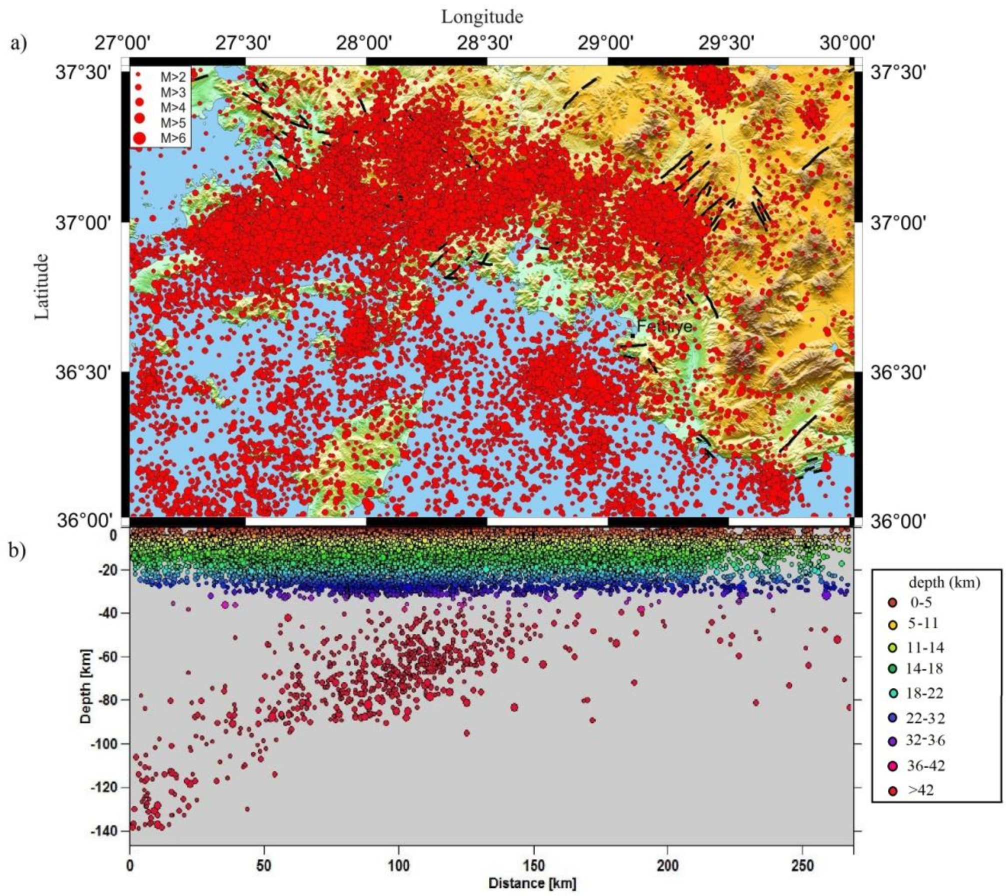

Figure 2. a) Map of epicenters of earthquakes with Ml≥2.0 between 2004 and 2020 occurred in the study region. **b)** the hypocentral depths of earthquakes

Figure 3 shows the time histogram for the study region between 2004 and 2020. The number of earthquakes does not change much over years, except for those occurred between 2012 and 2014, and between 2017 and 2018. 3000 events were recorded between 2017 and 2018 (Figure 3).

The b-value is an important parameter that can be related to the crustal stress conditions and has been used effectively since 1940s to investigate seismicity of a region (e.g., Gutenberg and Richter, 1944; Scholz, 1968; Wiemer and Benoit, 1996; Enescu and Ito, 2002; Sayıl and Osmanşahin ,2008; Roy et al., 2011; Mesimeri et al., 2018; Özer et al., 2018; Çoban and Sayıl, 2019; Chorozoglou and Papadimitriou, 2019; Çoban and Sayıl, 2020; Taroni and Akinci, 2021). The b-value is related with the crustal heterogeneity, earthquake occurrence and volcanic activity of a region.

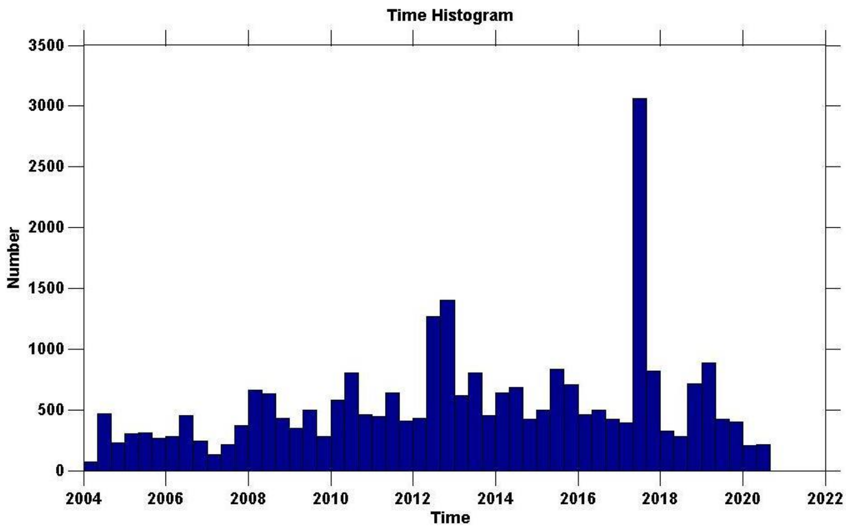

Figure 3. The time histogram for the study region between 2004 and 2020

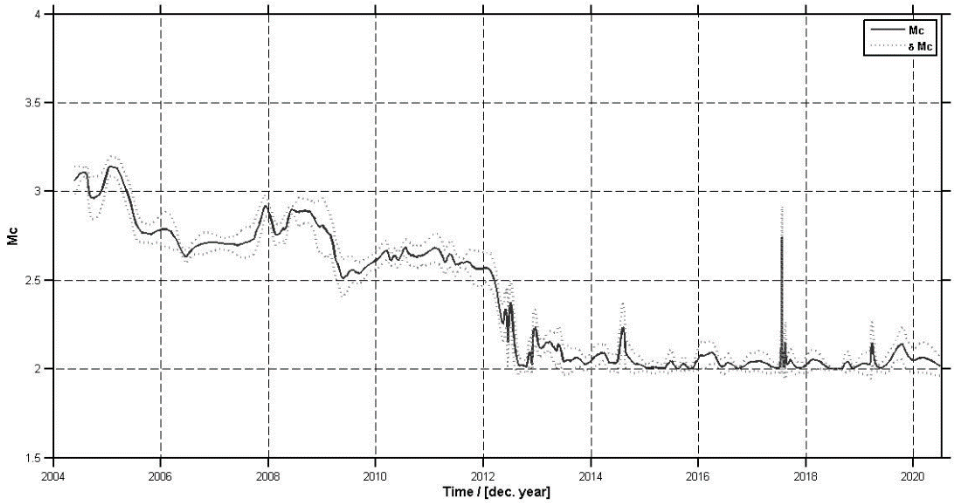

Figure 4. The variation of the Mc, from 2004 to 2020 in the study region. Standart deviation (δMc) of the completeness is plotted with dash line. Mc is illustrated with overlapping samples and each sample contains 250 events

We used the ZMAP software package (Wiemer, 2001) for determining the b-value and its spatial variations from maximum likelihood method (Aki, 1965; Utsu, 1999). According to Aki (1965) and Utsu (1999), b-value depends on the magnitude completeness (Mc). Therefore, firstly, we calculated the magnitude of completeness (Mc). Figure 4 shows the distribution of Mc values with time. Mc value was determined by maximum curvature method in the ZMAP software. The magnitude corresponding to the point of the maximum curvature deviating from Gutenberg-Richter law is considered as Mc, as the magnitude connecting to the linear cumulative part of a log linear frequency magnitude distribution (Wiemer and Wyss 2000; Zhou et al. 2018). The b-value can be estimated by using the maximum likelihood equation (Aki, 1965; Utsu, 1999), b= $\log_{10}e/(Mm-(Mc(-\Delta m/2))$. Mm is the mean of the magnitudes that are larger than Mc; Δm is the width of the magnitude bin, commonly chosen to be 0.1. In this case, b=Log10(e)/[Mm-(Mc-0.05)]. Figure 5 shows the maximum likelihood solution of the frequency-magnitude distribution for the study area. The line represents the Gutenberg-Richter equation fit. Mc and Mm values were selected as 2.1 and 4.1, respectively. The vertical axis shows the cumulative earthquake occurrence number (logaritmic) versus magnitude (Figure 5). To form the b-map of the study region, the region is divided into 0.3° x 0.3° grids. The b-map of the study region is given in Figure 6.

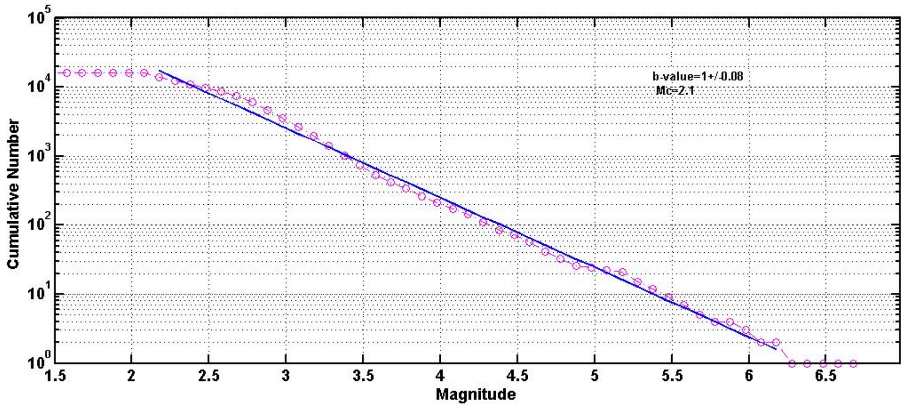

Figure 5. Gutenberg-Richter relationships, *b* and Mc-values of the study region for all earthquakes from 2004 to 2020. The solid line is the best fit with respect to the least-squares method

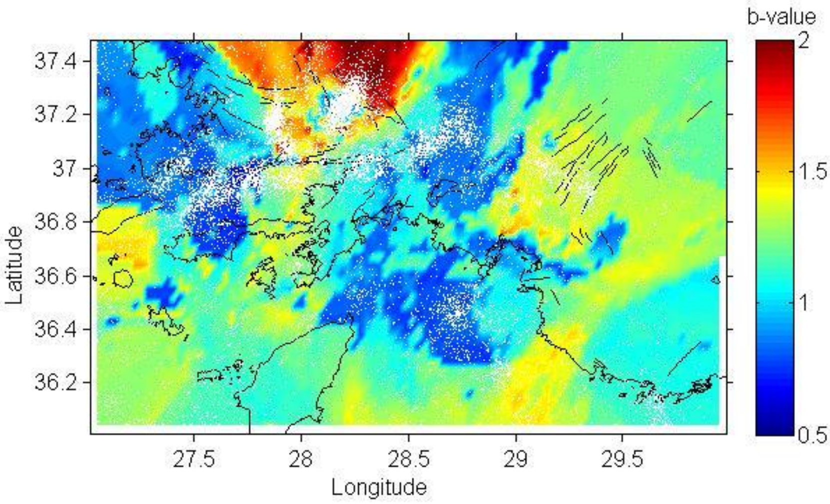

Figure 6. Regional distribution of b-value for the study region. White dots are earthquakes.

4. Result and Discussion

The variation of b-values of the region between Bodrum and Fethiye (SW Anatolia) was determined by using the maximum likelihood method based on the earthquake catalog from 2004 to 2020. The earthquakes in the study region are mostly shallow and of low magnitude. The b values can reflect the stress level of the study region. The variation of b values displays the heterogeneity of earth. The recent seismicity of the study region (Figure 2a) seems mainly concentrating on the EW-trending along the Gulf of Gökova, related to the normal faults that can be resulted from N-S extension of the region and along the NE-SW trending Datça-Kale main breakaway fault (Figure 1b). Seyitoğlu et al. (2004) suggested that the fill of the Kale and Gökova basins, the Lycian ophiolites and the cover rocks of the Menderes massif are composed of the upper plate rocks of the large main breakaway. The low seismicity is mainly observed the Beydağları autochthon unit and the east of the study area (Figure 1b, Figure 2a). The west of the study area is a more active region than the east and south east (Figure 2a). The hypocentral depths of the earthquakes range between about 5 km and 140 km (Figure 2b). The distributions of deep-events (Figure 2b) are observed along the subducting slabs where the Aegean plate can easily override the subducting edge of the African plate (e.g., McKenzie, 1972). Although focal depths reach up to 140 km (Figure 2b), most of the earthquake focal depths range between 5-33 km. It can be suggested that the depth of the seismogenic zone in the study region is about 33 km.

Ateş et al. (2012) estimated the crustal thickness of western Anatolia of 26-34 km from gravity data. Kind et al. (2015) suggested that the crustal thickness increases from the Aegean to Eastern Anatolia from 2-5 to 40 km. Saunders et al. (1998) calculated a crustal thickness of 30 km for western Anatolia. Akyol et al. (2006) determined the depth of the Moho and the velocity of upper mantle is 29 km and 7.8 km s^{-1}, respectively. Endrun et al. (2008) determined an average moho depth of 28 km and low S velocities (<4 km s^{-1}) by analysis of Rayleigh wave fundamental mode dispersion measurements for the Aegean region. The 33 km depth chosen in this study is consistent with previous studies in the region.

In the study region, the earthquakes occurred on between 2004 and 2020 take place mainly at middle and lower crust (Figure 2b). According to the time histogram (Figure 3), it can be seen that the number of microearthquakes has increased especially in recent years. It is observed that the change of Mc is almost constant after the year of 2012 (Figure 4). Mc was calculated as 2.1 for the study region (Figure 5). For Mc values between 1.2 and 2.2, the estimated b value is about constant (Wiemer and Wyss, 2002).

We estimated that the b-values varies between 0.5 and 2 (Figure 6). It is found that the values increase from west to east except the Beydağları autochthon unit where exhibits the moderate values (about 0.8-1.25). Bayrak and Bayrak (2012) estimated the b-value as 0.80-0.89 using earthquake data from 1974 to 2010 in the SE of the study area. Our results are consistent with their result in the Beydağlari autochthon unit. The north of the Beydağlari unit is bounded by the major thrust fault (Figure 1b). Our b-value results are in a good agreement with the P-wave travel time tomography results of Biryol et al. (2011) who estimated the slow velocity perturbations ($\delta Vp \approx -1.4$ per cent) in there. Tezel et al. (2013) investigated the moho depth and shear wave velocity of Turkey by using the teleseismic receiver function method. They determined that the depth of moho is between 28 and 38 km in the southwestern Anatolia and the uppermost mantle S-wave velocity is between 4.1 and 4.4 km s^{-1}. They suggested that the low velocity zone is located at between 15 km and 30 km in SW Turkey, where it may be related with molten or hot upper mantle material. Al-Lazki et al. (2004) estimated the very low Pn velocity (about 7.5 km s^{-1}) in SW Turkey. Our results indicate that the Beydağları unit exhibits low-b values, low earthquake activity, low seismic velocity, moderate Curie point depth (16-19 km, Dolmaz et al., 2005). Lower values (<1) are observed in the region between two fault zones (the center of the study area, Figure 6). Sayıl (2014) found a crustal P and S wave velocity of 6.3 km s^{-1} and 3.63 km s^{-1} ,respectively at 10 km for western Turkey using surface wave discrimination. The low velocities may be associated with a hot crust in the western Turkey. Endrun et al. (2008) found low S wave velocities in the northern Aegean moho by using surface wave dispersion. They also calculated that the northern Aegean moho is located at a shallow depth of around 28-30 km.

The Gulf of Gökova exhibits the moderate/high b-values (1-1.3) that can be related with the high seismic activity. Sayıl and Osmanşahin (2008) investigated the seismicity of western Anatolia and determined the high b values around the Gulf of Gökova –Muğla by using Gutenberg-Richter method. The high b-values (>1.5) are shown on the land of the study area (Figure 6) where may be related with the different stress level and faulting type. The high b-values (Figure 6) are observed at the north of the study area where it correlates with the south of Menderes Massif and along onland Fethiye-Burdur Fault Zone. Mogi (1962) suggested that the high b-values may be sign of the lower stress and more heterogeneous state of the crust. It can be concluded from Figure 6 that while the normal faults may exhibit high b-values, the thrust fault may exhibit low b-values. The b-value can be correlated with the heat flow in the study region. Dolmaz et al. (2005) estimated the high heat flow values (80 to100 mW m^{-2}) in SW Anatolia from spectral analysis of magnetic anomalies. In this study, the comparison of the NW-SE trending high b-values and heat flow shows that while the b-values increase the heat flow values increase. Wiemer and Wyss (2002) suggested that geothermal areas may induce high-b-values. We suggest that the estimated high b-values can be associated with both a high temperature and active fault zones in the study area and active tectonic zone is located at moderate and lower crust weakened by crustal thickening, N-S extensional regime and geothermal mechanism.

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Conflict of Interest

No conflict of interest was declared by the authors.

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