The correlation of b-value in the earthquake frequency-magnitude distribution, heat flow and gravity data in the Sivas Basin, central eastern Turkey

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ABSTRACT

In this study, the seismicity in the Sivas Basin, central eastern Turkey from 1903 to 2018 is investigated by the Gutenberg and Richter relationship (1944) and the maximum likelihood method (Aki, 1965) to explore the b-value. The b-value is regarded as one of the important parameters representing the nature of the occurrence of earthquakes. Particularly, the b-value characterizes the state of stress in the crust. The Sivas Basin exhibits the low b-value (0.52 and 0.9), moderate/high heat flow values (70-80 mWm$^{-2}$), large negative anomalies owing to sedimentary basin and low seismicity and the epicenter distributions of earthquakes are located at the upper crust and along the Deliler-Tecer and Yukarı Kızılırmak Fault Zones in the study region.

1. Introduction

The Gutenberg-Richter parameters ($a$, $b$) are used to examine seismic activity in an area. Particularly, $b$-value is an important parameter that describes the characteristics of an ensemble of earthquakes. The calculation of $b$-value has been successfully used by several authors since 1940's (e.g., Gutenberg and Richter, 1944; Aki, 1965; Scholz, 1968; Fiedler, 1974; Smith, 1981; Bender, 1983; Imoto, 1991; Burroughs and Tebbens, 2002; Bhattacharya and Kayal, 2003, Bridges and Gao, 2006; Katsumata, 2006; Bhattacharya et al., 2010; Mousavi, 2017; Chiba and Shimizu, 2018). The $b$-value can be related to the material heterogeneity, thermal gradient, volcanic activity, stress regime, tectonic events in the Earth's crust (Utsu, 1965; Scholz, 1968; Warren and Latham, 1970; Katsumata, 2006).

In the Sivas Basin, earthquake catalogs indicate that earthquakes generally have low magnitudes (3.5≤$M_b/M_s$≤5.0) between 1903 and 2018. Although the basin is tectonically active, investigation of the seismic activity using $b$-value estimation is limited. Seismicity studies are generally concentrated on a regional basis. For example, Kalyoncuoglu et al. (2013) studied the $b$-value of the Aegean region. Bayrak et al. (2017) investigated the spatial variations of Gutenberg-Richter parameters in western Turkey. Ozturk (2018) studied the seismic hazard potential of the eastern Anatolia region. In this paper, the Gutenberg-Richter $b$-value for the Sivas Basin was estimated using the least-square fit method and the maximum likelihood method and the results were correlated with the gravity anomalies and heat flow values.

2. Regional Tectonics and Geology

The Sivas basin is located in the collision zone between the Pontides and Anatolides (Figure 1a). The boundaries of the basin are overthrusts to the north and left-lateral oblique faults with reverse components in the south (Figure 1b). According to Gursoy et al. (1992), the post-collisional tectonic development of the basin has been dominated by N-S to NW-SE compressional forces, commenced in mid-Eocene (post Lutetian) times and continued up to the present day. The basin was divided into subbasins by predominantly left lateral strike-slip oblique faults. There are two main east-west trending fault zones in the Sivas basin: 1) The Yukarı-Kızılırmak Fault Zone, and 2) The
Deliler-Tecer Fault Zone (Figure 1b). The Yukarı Kızılrmak Fault Zone has reverse motion with the upthrust hanging wall dipping to the south (Yılmaz and Yılmaz, 2006). The Deliler- Tecer Fault Zone is also reverse but dips to the north. The amount of upthrust increases towards the eastern part of the basin (Yılmaz and Yılmaz, 2006).

Figure 1b shows the simplified geological map of the study area (modified from Yılmaz and Yılmaz, 2006; Yalçın-Erik et al., 2015).

Figure 1b shows the simplified geological map of the study area (modified from Yılmaz and Yılmaz, 2006; Yalçın-Erik et al., 2015). The basement of the Sivas Basin is composed of ophiolitic units originated from the northern branch of Neo-Tethys obducted onto the Tauride Platform and its metamorphic equivalents, and represents mainly a suture zone developed between the Pontide Arc and Tauride Platform (Yılmaz and Yılmaz, 2006). The young sedimentary units of the basin overlie the basement. Small outcrops of plutonic rocks are mainly located around Divriği and Yıldızeli (Figure 1b). In addition, volcanic rocks have small outcrops to the south and SW of the Sivas Basin.

3. Data and Method

This study was carried out in the area bounded by the latitudes 39°-40° N and longitudes 36°-39° E. Data were selected between 1903 and 2018, with the magnitudes of body-wave magnitude (Mb), and surface-wave magnitude (Ms), ≥ 3.5 from the International Seismological Centre (ISC) and the United States Geological Surveys (USGS) catalogues. Moment-magnitude (Mw) relations have played an important role in the earthquake mechanism studies since seismic source parameter determinations started in the early 1970's (Hanks and Boore, 1984). Recently, moment magnitude frequently has been used to estimate the seismic b-value of an investigated region (e.g., Gulal et al., 2016; Raub et al., 2017; Pudi et al., 2018). Using equations below developed by Scordilis (2006), all earthquake magnitudes converted to a uniform catalogue of Mw ≥ 4.0:

\[
M_w=0.67 \cdot M_s + 2.07, \quad 3.0 \leq M_s \leq 6.1 
\]

\[
M_w=0.99 \cdot M_s + 0.08, \quad 6.2 \leq M_s \leq 8.2 
\]

\[
M_w=0.85 \cdot M_b + 1.03, \quad 3.5 \leq M_b \leq 6.2 
\]

The b-value was estimated using two methods in this study:

3.1. The least-square fit method:

Earthquake frequency-magnitude distributions were developed by Gutenberg and Richter (1944) as

\[
\log N(M) = a - bM, 
\]

where N(M) is the number of earthquakes with magnitude larger than M per year; a and b are the constant parameters. a-value is the measure of the regional level of seismicity and depends on the extent of the area, a number of earthquakes occurred in the region, the largest seismic magnitude and time interval (Gutenberg and Richter, 1944). The b-value is the slope of the frequency-magnitude distribution and related to the distribution of stress and strain (Usu, 1965; Scholz, 1968). Scholz (1968) suggested an inverse relationship between the stress level in a given region and the local b-values. High b-value indicates a large number of small earthquakes and large heterogeneity (Tsapanos, 1990). Gutenberg and Richter (1944) found that b-values range from 0.45 to 1.5. Miyamura (1962) suggested that b-values change from 0.4 to 1.8 depending on the geological age of the tectonic area.

Using Equations 1, 2, and 3, a uniform catalogue Mw ≥ 4.0 is constructed. Figure 2 shows the cumulative frequency-magnitude distribution of earthquakes. Linear straight line is fitted on the data using the least-square method. The completeness magnitude (Mc) of the data set is another important parameter for seismicity analysis (e.g. Woessner and Wiemer, 2005; Wiemer et al., 2009; Mignan et al., 2013). Mc is determined by plotting the cumulative number of events as a function of magnitude (Figure 2).
value was estimated in the study area because there are the possible relationships between the b-value and a crustal heterogeneity, volcanic activity, earthquake occurrence, geothermal potential. The a- and b-values for the Sivas Basin from Gutenberg and Richter (1944) relationship using the least-square fit method were estimated as 5.77 and 0.90, respectively (Figure 2). The estimated high-b value for the Sivas Basin may indicate the insufficiency of the data or low seismic activity. In addition, b-value was estimated by using the maximum likelihood method as 0.52 (completeness, Mc=4.4). According to the result of the maximum likelihood method, there may be high rheological strength in the crust. However, frequent seismic activity in the Sivas Basin was not observed until the date. The estimated low-b value from the maximum likelihood method may be resulted from overthrusts or left-lateral oblique faults with reverse components on the boundaries of the Sivas Basin. In addition, low-b value may be associated with thick crust in the study region.

Figure 3a shows the Bouguer gravity anomalies in the study area. They are good correlation with the main faults (Figure 1b). The anomalies in the Sivas Basin are integrated with the effects of fractures, faults and intrusive bodies of basement, where there are changes in the density of the rock masses (Buyukserac, 2007; Bektas, 2013). Therefore, faults can be identified on gravity anomaly map. The major trend of the contours related to the fault zones is along southwest-northeast direction, parallel to the trend of the basin. There are two prominent closure of gravity lows: 1) between Ulas and Sarkisla (about -92 mGal), and 2) around Divriği (about -121 mGal) (Figure 3a). The low gravity values in these areas can be correlated with the thick-crustal structures and also thick sedimentary basin fill in the study region (Onal et al., 2008). The gravity values increase towards the north particularly between Sivas and Imranlı (about -56 mGal) (Figure 3b). Onal et al. (2008) produced the three-dimensional gravity model of the Sivas Basin. They found that deepest parts (12-13km) of the basin were located beneath Hafik, to the south of Zara and at the S-SE of Imranlı (Figure 3c). The crustal thickness of the study area was determined as about 40 km by Zor (2008). When Figure 3c is examined, it is seen that the focal depths of earthquakes are mainly located in the upper crust (< 20 km), around 10 km, where they were determined as the upper crustal discontinuities associated with the volcano-sedimentary successions by Angus et al. (2006).

The epicentres of earthquakes are densely located to the north of Divriği in relation with the Dililler-Tecir Fault Zone (Figure 4). The distribution of the epicenters of events shows that the Deliller-Tecir and Yakti Kızılirmak Fault Zones are still active in the study area. The heat flow values of the Sivas Basin are about 80 mWm⁻² obtained from İliski (1995) (Figure 4, red lines). The typical heat flow values are 70-80 mWm⁻² in back-arc regions and more than 80-100 mWm⁻² in the volcanic regions (Hyndman and Lewis, 1999). Generally, the Sivas Basin exhibits the low b-value (0.52 and 0.9), moderate/high heat flow values, large negative anomalies owing to sedimentary basin and low seismicity.

3. Discussion and Conclusions

The b-value can be estimated from the maximum likelihood method (Aki, 1965; Bender, 1983; Utsu 1999; Kalyoncuoglu et al., 2013; Nava et al., 2017) given as:

\[
b = \log e \left( \frac{\sum_{i=1}^{N} M_i}{N} \right) - Mc
\]

(4)

Where e and N is the base of natural logarithm (e=2.1718) and number of earthquakes, respectively. Mc= The completeness magnitude.

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Figure 4. The correlation map of heat flows (red lines obtained from Ilkisik, 1995) and the epicenter distributions of earthquakes. Contour interval 10 mWm$^{-2}$.

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