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The Reliance of the Earthquake B-Value on Depth and Focal Mechanism

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Abstract

The earthquake size distribution (b-value) is a significant factor to recognize the seismic activity, seismotectonic, and seismic hazard assessment. In the current work, the connection of the b-constant value with the focal depth and mechanism was studied. The effect of the study scale (global, regional and local) on the dependence of b-value on the focal mechanisms was investigated. The database is quoted from the Global Centroid Moment Tensor catalog. The selected earthquakes are the shallow normal, reverse and strike-slip events. The completeness magnitude (M_c) is 5.3. The maximum likelihood method is utilized to compute the b-value. The obtained results show that the b-value is decreasing with depth to range 10-20 km, then increases to the depth of 40km. The turning point of b-value (increasing of b-value) locates at the depth of the transition brittle-ductile zone. Globally and regionally, low, moderate, and high b-values are associated with reverse, strike-slip, and normal focal mechanisms, respectively, while locally, the relation between b-values and focal mechanisms shows different association trends, such as low, moderate, and high b-values are associated with normal, strike-slip, and reverse focal mechanisms and so on.

Keywords: b-value; Focal depth; Focal mechanisms; Maximum likelihood

1. Introduction

The earthquake-magnitude distribution follows the Gutenberg-Richter power law (Gutenberg and Richter, 1944). This distribution is described by $\log_{10}N = a - bM$, where N is the total number of earthquakes with magnitude $\geq M$, and a , b are constants. The a -constant indicates the total number of earthquakes, and the b -constant (b-value) describes the frequency of earthquake size distribution. The dependence of b-value on depth has attracted the attention of many seismologists. Gutenberg and Richter (1944) investigated the depth variation of the b-value. They found that the b-value of shallow events is less than b-value of intermediate and deep events. After the pioneering work of Gutenberg and Richter, many authors showed that the b-constant value reduces with depth (Evernden, 1970; Wyss, 1973; Mori and Abercrombie, 1997; Gerstenberger et al. 2001; Zhu et al. 2005; Popandopoulos and Lukk, 2014, Spada et al. 2013; Al-Heety 2011; Rigo et al., 2018). Wyss et al. (2008) found that b-constant value rises with the increasing of the earthquake's depth. Other authors discussed the reliance of b-value on depth from a statistical point of view. Variation of b-value is often statistically insignificant and that the lowering of b-constant value with depth should be explained with care (Amorese et al. 2010). The b-value variation can be interpreted as the artifact arising due to the absence of statistical significance (Del Pezzo et al., 2003). The dependence of b-constant value on depth value was investigated locally and/or

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regionally, in California/USA (Mori and Abercrombie, 1997; Grestenberger et al. 2001; Wyss et al. 2008; Amorese et al. 2010), in Beijing area/ China (Zhu et al. 2005), in Garm, Tajikistan (Lukk and Popandopoulos, 2012; Popandopoulos and Lukk, 2014), in Koyna-Warna region / India (Singh and Chadha, 2010), in regions of Iceland and Japan (Wyss et al. 2008), in Pyrenees/France (Rigo et al. 2018), in Abu Dabbab area, Red Sea (Abu El-Nader et al. 2016) and in Taiwan (Hui et al. 2020). Globally, the reliance of b- constant value on focal depth in the continental seismicity regions was achieved by Al-Heety (2011). The reliance of b-constant value on the fault plane solutions was discussed locally and/or regionally, in California and Japan by Schorlemmer et al. (2005), in Japan by Ishibe et al. (2008), in Italy by Gulia and Wiemer (2010), and in India by Bora et al. (2018). Based on the global scale, Al-Heety and Al Esho (2019) studied the relationship of b-constant value with faulting type. Regardless of the study scale, the previous studies showed a low b- constant value in reverse faulting regions, a moderate in strike-slip faulting regions, and a high b-value in normal faulting regions. There are two reasons motivate us to conduct this study: (1) the lack of studies related to the relationship of b- constant value with focal mechanism on a global scale and (2) ambiguity of the observed relationship between b-value and depth. The aims of this study are to investigate (1) the dependence of b-value on the focal depth and the focal mechanism, and (2) does the focal mechanism effect on the connection of b-constant value with the depth of earthquakes.

2. Data and Methodology

The earthquakes catalog of this study was quoted from the Global Centroid Moment Tensor (GCMT) Catalog, from 1976 to 2018. Earthquakes with magnitude $M \geq 5.1$ and depth of 0-70 km were selected in this study, (Fig. 1). The earthquake catalog completeness magnitude (M_c) is estimated using the maximum curvature method introduced by Wiemer and Wyss (2000) methodology. The correct estimation of the values of a and b constants requires the calculation of the earthquake catalog's completeness (Woessner and Wiemer, 2005).

Fig.1. Spatial distribution of the shallow earthquakes ($M \geq 5.1$) for the period 1976-2018

To investigate the dependence of b-value on the focal mechanism, we sorted the selected earthquakes based on the rake of slip of fault plane into three types of focal mechanism: normal, reverse, and strike-slip faulting mechanism. The spatial and earthquake magnitude distribution for each class are shown in Figs. 2 and 3, respectively. The b-value and its uncertainty are calculated using the following maximum likelihood method (Aki, 1965):

$$b = \frac{0.4343}{(M_{\text{mean}} - M_c)} \quad (1)$$

M_{mean} is the mean of magnitudes and M_c is the completeness magnitude. Uncertainty about the value of b- constant has been calculated by the following equation:

$$\delta b = b / \sqrt{N} \quad (2)$$

Where N is the number of earthquakes.

Fig. 2. Spatial distribution of (a) the normal, (b) strike-slip and (c) reverse faulting earthquakes for the period 1976 – 2018

Fig. 3. The number of earthquakes as function of magnitude for (a) normal, (b) strike-slip and (c) reverse faults. The completeness magnitude M_c is 5.3 for reverse, strike-slip and normal faulting events, are presented in Fig. 4.

Fig. 4. The completeness magnitudes of the (a) normal, (b) strike-slip and (c) reverse faulting earthquakes

3. Results and Discussion

3.1. The Relation Between the B-Value and The Depth

Results of variation of b-value in magnitude-frequency relation of all events, normal faulting events, reverse faulting events and strike-slip events as function of depth are listed in Table 1. The remarkable trend in the reliance of b-value on depth is the decreasing in b-constant value at depth about

10km and increasing after that depth for all shallow, normal faulting, and strike-slip events, while the b-value of reverse faulting events decreases at depth of about 20 km and then increases beyond that. Beneath the depth of about 10km, the b-value increases with depth and reaches the highest value at depth of about 35 km and 45 km for strike-slip and normal faulting events, respectively, and then the b-values fluctuates up and down. For the reverse faulting events, the b-value increases below the depth of about 20km with the increasing of the focal depth to the maximum value at a depth of about 35km and after this depth the b-value fluctuates down and up. All used shallow events show maximum b-value at depth of about of 12km and decreases at depth of about 18km and then increases with increasing depth and the highest value is at depth of about 35km. Beneath the depth of 35km, the b-value oscillates up and down, for example, the b-value increases at depth of about 40km and decreases at depth of 45km, and so on. The obtained result shows decreasing in b-constant value up to 10km followed by an increase. This result is in good agreement with the b-value reported in California (Mori and Abercrombie 1997), in Beijin area, China (Zhu et al. 2005), in Koyna-Warna, India (Singh and Chadha, 2010), and in Pyrenees (Rigo et al. 2018). In the current study, we find that the b-constant value in the lower crust is more than in the upper crust.

Table 1. b-constant value as function of depth

Depth (Km)	b-constant value							
	Normal faulting earthquakes		Reverse faulting earthquakes		Strike-slip faulting earthquakes		All earthquakes	
0-5	1.50	± 0.143	1.40	± 0.149	1.11	± 0.214	1.40	± 0.093
5-10	1.03	± 0.049	1.14	± 0.055	0.99	± 0.095	1.09	± 0.034
10-15	1.06	± 0.047	1.11	± 0.046	0.94	± 0.087	1.04	± 0.017
15-20	1.28	± 0.061	1.03	± 0.040	1.11	± 0.103	1.11	± 0.031
20-25	1.36	± 0.064	1.03	± 0.036	1.17	± 0.101	1.14	± 0.030
25-30	1.55	± 0.079	1.17	± 0.040	1.36	± 0.108	1.28	± 0.034
30-35	1.74	± 0.087	1.28	± 0.042	1.50	± 0.145	1.36	± 0.015
35-40	1.97	± 0.083	1.55	± 0.040	1.61	± 0.119	1.61	± 0.034
40-45	1.67	± 0.098	1.32	± 0.046	1.61	± 0.149	1.40	± 0.040
45-50	1.55	± 0.105	1.36	± 0.049	1.81	± 0.176	1.45	± 0.044
50-55	1.36	± 0.106	1.55	± 0.063	1.50	± 0.149	1.50	± 0.050
55-60	1.55	± 0.120	1.40	± 0.063	1.74	± 0.192	1.45	± 0.053
60-65	1.55	± 0.118	1.61	± 0.080	1.32	± 0.156	1.55	± 0.060
65-70	1.24	± 0.097	1.45	± 0.079	1.32	± 0.153	1.36	± 0.056

A high b-values were observed in the lower crust of Shilling Plateau, India (Khan and Chakraborty, 2007), and in Garm Region of Tajikistan (Popandopoulos and Lukk, 2014). The point at which the b-constant value changes is called the inflection point. In our current study, we find that the depth of the inflection point of b-value ranges from 10 to 20 km. The inflection point of b-value in Italy, Greece, Turkey, and Japan is at depth of 15km, in Swiss foreland at depth of 25 km (Spada et al. 2013), and at depth of 15-16 km in Garm Region of Tajikistan (Popandopoulos and Lukk, 2014). We agree with the interpretation proposed by a number of authors which states that the inflection point depth of b-value is interpreted as depth of brittle-ductile transition BDT (Spada et al. 2013; Popandopoulos and Lukk, 2014; Dolioni et al. 2011, 2015; Petricca et al. 2015, Rigo et al. 2018). We can also interpret the inflection point depth of b-constant value in terms of the depth of the Conrad discontinuity, particularly in the continental crust regions. Conrad discontinuity is not related to the change in the chemical composition from granitic to basaltic rocks, but to change in the physical state of the rock from brittle

to ductile (Zhamaletdinov, 2014). We can make the conclusion that the BDT is associated with the Conrad discontinuity.

3.2. Reliance of B-value on Focal Mechanisms

Results of the reliance of b-value on the focal mechanisms are listed in Table 2. The remarkable trend of b-value and its relation with the focal mechanism of earthquakes is in the following descending order: b-normal focal mechanism > b-strike-slip focal mechanism > b-reverse focal mechanism. The high b-value of the normal faulting events may be interpreted in terms of that the maximum volume comprised by these earthquakes is smaller than the strike-slip and reverse events, being the activated fault mostly about three times the focal depth (Doglioni et al. 2015). The differential stress is inversely proportional to the b-constant value in the continental crust. The high b-constant values associate with the low differential stress whereas the low b-constant values correlate with the high differential stress. The potential reliance of b-constant value on focal mechanism was investigated in different regions. In California and Japan, the reverse faulting earthquakes have the lowest b-constant values, the strike-slip earthquakes the moderate values and normal faulting earthquakes the highest values (Schorlemmer et al. 2005). They inferred that the b-value acts as a stress meter that depends inversely on differential stress. The relation between b-constant value and faulting style was investigated in Italy (Gulia and Wiemer, 2010). They found that the lowest b-values are obtained for reverse faulting, highest for normal, followed by the strike-slip. In Indo-Burma ranges of northeast India, the b-constant has high value in normal faulting regions, the moderate value in strike-slip faulting regions, and low value in reverse faulting regions (Bora et al. 2018). In a young orogenic belt in Taiwan, the b-value of normal faulting events is higher than of the strike-slip faulting events, which in turn is higher than the reverse faulting events (Wu et al., 2018). The reverse and normal faulting areas of the subduction zone in Mexico, have low and high b-values, respectively (Rodríguez-Pérez and Zuñiga 2018). On a global scale, Al-Heety and Al Esho (2019) and Al-Heety (2020) found that reverse, strike-slip and normal faulting earthquakes happen in regions of low, moderate, and high b-value, respectively. The results of the current study are consistent with the results of the previous studies mentioned above.

3.3. Effect of Study Scale on The Relation Between B-Value and Focal Mechanisms

To investigate the effect of using different study scales on the relationship between b-value the focal mechanism types, the b-values for the three focal mechanism types were calculated globally, regionally and locally, Table 2. Globally and regionally, the remarkable trend of the b-value in its relation to the focal mechanisms is: b normal mechanism > b strike-slip mechanism > b reverse mechanism. The b-values calculated based on the local scale show different patterns. For example, in Fiji, Solomon and South Sandwich Islands Regions, the order of b-value is b reverse mechanism > b strike-slip mechanism > b normal mechanism. In Kuril and Vanuatu Islands, the b normal mechanism > b reverse mechanism > b strike-slip mechanism. The obtained b-values of the events occurred in Tonga Islands show that b strike-slip mechanism is more than b reverse mechanism which in turn is greater than b normal mechanism. The different patterns mentioned above can be explained in the context of the effect of the ratio of the larger magnitude earthquakes to the smaller magnitude and the prevailing tectonic environment, extensional (normal mechanism), compressional (reverse mechanism), and shearing (strike-slip mechanism). There is an inverse relationship between the b-value and the ratio of the number of larger magnitudes to number of the smaller magnitude earthquakes. The higher b-value is the lower ratio of the larger magnitude to smaller magnitude earthquakes and vice versa. We postulate that the scale of study affects the connection trends between the b-constant value and the focal mechanisms as mentioned above. For example, the study based on the global and regional scales showed a connection trend as follows: b normal mechanism > b strike-slip mechanism > b reverse mechanism,

while the connection trend resulting from a local study is shown as follows: b reverse mechanism > b strike-slip mechanism > b normal mechanism.

Table 2. b-value and focal mechanisms based on different scales

Scale	b-value		
	Normal focal mechanism	Strike-slip focal mechanism	Reverse focal mechanism
Global	1.61 ± 0.015	1.50 ± 0.027	1.36 ± 0.011
Regional (Northern hemisphere)	1.61 ± 0.022	1.50 ± 0.040	1.32 ± 0.015
Regional (Southern hemisphere)	1.61 ± 0.021	1.50 ± 0.036	1.40 ± 0.016
Regional (Eastern hemisphere)	1.55 ± 0.019	1.40 ± 0.031	1.32 ± 0.013
Regional (western hemisphere)	1.67 ± 0.026	1.74 ± 0.052	1.45 ± 0.020
Local (Fiji Islands Regions)	1.50 ± 0.135	1.97 ± 0.232	2.17 ± 0.283
Local (Kuril Islands)	1.24 ± 0.153	0.92 ± 0.107	1.17 ± 0.050
Local South Sandwich Islands Regions	1.67 ± 0.175	1.74 ± 0.243	1.81 ± 0.123
Local Solomon Islands	1.14 ± 0.096	1.14 ± 0.120	1.21 ± 0.049
Local Tonga Islands	1.45 ± 0.095	1.50 ± 0.168	1.50 ± 0.066
Local Vanuatu Islands	1.50 ± 0.116	1.21 ± 0.176	1.36 ± 0.063

4. Conclusions

We have investigated variations of b constant value of the earthquake's frequency-magnitude relation with the focal depth and the focal mechanisms. From the obtained results, we draw the following conclusions:

- Globally, the inflection point depth of b-constant value ranges from 10 to 20 km. This depth is interpreted as depth of the brittle-ductile transition.
- The brittle – ductile transition may be associated with the depth Conrad discontinuity that related with change in the physical properties of the upper granitic layer and lower basaltic layer
- Based on global and regional scales, high b-value is associated with normal focal mechanism, intermediate b-value with strike-slip focal mechanism, and low b-value with the reverse focal mechanism. The b-values calculated based on the local scale show different patterns of the connection between the b-value and the focal mechanisms.
- The study scale (globally, regionally and locally) may affect the relation trend between b-value and the focal mechanisms.

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