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Spatial and Depth-Dependent Patterns of Seismicity in the Baghlan Region, Afghanistan

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Spatial and Depth-Dependent Patterns of Seismicity in the Baghlan Region, Afghanistan

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Abstract

This study examines spatial, depth-dependent, and temporal variations in the Gutenberg–Richter b-value in the Baghlan region of northern Afghanistan, focusing on the Andarab and Khanjan fault systems and the 25 March 2002 Nahrin earthquake (Mw 6.1). An earthquake catalogue for 1959–2024 was compiled from the International Seismological Centre (ISC) and United States Geological Survey (USGS) databases. After magnitude homogenization, declustering with the Reasenberg algorithm, and magnitude-completeness assessment using the maximum curvature (MAXC) method, 1,232 earthquakes with Mw ≥ 4.3 were selected from 1,301 events. The b-value was estimated using the maximum-likelihood method, and its spatial distribution was examined using a moving-window approach. The results show spatial variability, with b-values ranging from 0.80 ± 0.03 to 1.40 ± 0.16. Lower values (0.60–0.80) occur at depths of approximately 10–45 km, suggesting higher differential stress and variations in crustal mechanical properties. Most earthquakes occur at depths of 0–40 km, with the highest frequency at 15–20 km. Low b-values are concentrated between 36°–36.5°N and 69°–70°E, particularly near the Andarab and Khanjan faults. A b-value of about 0.80 is also identified near the 2002 Nahrin earthquake epicentre. These findings highlight the influence of regional tectonic structures and complex crustal heterogeneity on earthquake-size distribution in Baghlan.

Keywords

Gutenberg–Richter relationship; b-value; spatial seismicity; depth-dependent variation; Khanjan Fault; Nahrin earthquake.

1 Introduction

Afghanistan, as part of the active Himalayan–Hindu Kush–Pamir mountain belt, is among the most seismically active regions of Asia, and its tectonic activity results from the convergence of the Indian and Eurasian plates (Akhundzadah, 2025; Ambraseys & Bilham, 2003; Boyd et al., 2007; DeMets et al., 1990; Mansouri et al., 2024; Wheeler et al., 2005). The convergence rate between these plates is estimated at approximately 35–40 mm yr^{-1} and has produced a complex network of strike-slip, compressional, and reverse faults throughout the region (Wheeler et al., 2005). In northeastern Afghanistan, particularly within Baghlan Province, active faults such as the Andarab, Khanjan, Baghlan–Pul-e-Khumri, and North Kabul faults generate considerable seismicity (Ayaz & Rashad, 2020, 2020; Boyd et al., 2007; Faryad et al., 2013; Prevot et al., 1980; Wheeler et al., 2005). The occurrence of historical earthquakes of moderate to large magnitude in this area, including Mw ≥ 6 events in recent decades, makes the quantitative analysis of seismic patterns and the identification of stress-prone zones increasingly necessary (Borisov & Vitanov, 2025; Chen & Zhu, 2020; Hisyam et al., 2024) .

In seismotectonic studies, the b-parameter of the Gutenberg–Richter relationship is a key indicator of the statistical and physical characteristics of earthquakes (Borisov & Vitanov, 2025; Chen & Zhu, 2020; Faenza & Pierdominici, 2007) .It describes the relative proportion of small to large earthquakes and is directly related to stress conditions, temperature, mechanical heterogeneity, and the fracturability of the crust crust (Aki, 1965; Bellalem et al., 2008; Sornette & Sornette, 1999). A low b-value generally indicates stress concentration and a higher likelihood of large earthquakes, whereas a high b-value is associated with highly heterogeneous zones and smaller-scale fracturing (Aki, 1965; Chang et al., 2025; Kijko et al., 2016).

In recent decades, advanced methods have been developed for the spatial and temporal analysis of b-value variations (Chang et al., 2025; Chen & Zhu, 2020; Godano, 2015; Rydelek, 2003; Wiemer, 2000; Wiemer & Wyss, 2000). These studies have shown that spatial and depth variations in b can reflect changes in the stress field and can even help identify seismogenic zones approaching failure before major earthquakes (Kijko et al., 2016; Singh, 2016). Despite these advances, most research has focused on regions such as Japan, the Alps, and the Zagros, whereas data for Afghanistan, and Baghlan in particular, remain very limited and fragmentary.

The relationship between the b-value and other parameters, including crustal stress, crustal heterogeneity, seismic moment, Bouguer gravity, and focal mechanism solutions, has been investigated for Afghanistan (Aki, 1965; Chatelain et al., 1980; H. Mohammadi & Bayrak, 2016; Sahraei et al., 2023; Scholz, 1968; Singh & Singh, 2015;

Wang et al., 2025; Yadav et al., 2013).. This is especially relevant in northeastern Afghanistan (the Hindu Kush and Pamir region), where the collision of the Indian and Eurasian plates produces deep and complex seismicity (Akhundzadah, 2025; Hawadi, 2027; Mohadjer et al., 2010; Singh & Singh, 2015). In a recent study, Singh and Singh demonstrated correlations between the b-value and depth variations, crustal stress, and hydration-related phenomena (such as high pore-fluid pressure in the lower lithosphere) in the Pamir–Hindu Kush region, and attributed high b-values (>1.2) at a depth of 150 km beneath the Hindu Kush to zones of low seismic velocity (Singh, 2016; Singh & Singh, 2015; Yadav et al., 2013).

Barkat examined the correlation between b-value and earthquake depth across northeastern Afghanistan and the Pakistan border, showing that b-values for deep earthquakes (0.90–1.07) are lower than those for shallow earthquakes (1.06–1.32) (Rehman et al., 2017). Umer, Bilal, and Maqsoom calculated a b-value of approximately 1.02 for the aftershocks of the 2015 Afghanistan earthquake 02 (Khalil et al., 2021; Mohadjer et al., 2010; Rehman et al., 2017; Yi-Lei et al., 2016). Ambraseys and Bilham investigated the relationship between b-value and seismic moment in the historical context of Hindu Kush earthquakes, while Rehman and colleagues linked it to focal mechanisms and Bouguer gravity anomalies in northeastern Afghanistan, emphasizing low b-values at great depths as an indicator of high stress (Ambraseys & Bilham, 2003; Desio & Poretti, 1991; Jadoon & Khurshid, 1996; Jung et al., 2013; Rehman et al., 2017).

Despite these studies, only a few works, such as K. Mohammadi et al. (2021) and Singh & Singh (2015), have examined the overall stress regime and seismic zonation, and a comprehensive, quantitative, spatially resolved analysis of the Gutenberg–Richter parameters has not yet been reported(K. Mohammadi et al., 2021; Singh & Singh, 2015). This lack of data has led to high uncertainty in seismic hazard assessment for northern Afghanistan (Ambraseys & Bilham, 2003; Yadav et al., 2013). A recent study by Hawadi (2026) investigated the temporal, spatial, and depth-dependent seismicity of Takhar Province, reporting an overall b-value of 1.18 ± 0.02 and pronounced spatial variations ranging from approximately 0.8 to 2.2. These findings demonstrate considerable seismic heterogeneity in Takhar and highlight the importance of spatially resolved b-value analysis for understanding regional seismic characteristics (Hawadi, 2027). Furthermore, existing research on the b-value in northeastern Afghanistan (particularly the Hindu Kush and Baghlan) generally does not cover extensive areas and focuses on depth differences (shallow versus deep earthquakes) (Singh & Singh, 2015)., while large-scale heterogeneities such as variations in crustal stress, fault types, and tectonic structures have often been overlooked.

Nevertheless, there is clear evidence that b depends on these heterogeneities, with lower values associated with higher stress and larger earthquakes at intermediate to great depths in the Hindu Kush (Singh & Singh, 2015; Yadav et al., 2013).

2 *Research Objective*

The primary aim of this study is a comprehensive analysis and spatial mapping of the Gutenberg–Richter parameters, particularly the b-value, in the Baghlan region of Afghanistan. This research examines variations in b and their correlation with focal depth along the Andarab and Khanjan faults, in adjacent areas, and for the Nahrin–Baghlan earthquake (25 March 2002, Mw 6.1) (Yeats & Madden, 2003), and proposes an in-plane model to explain the main earthquakes.

Similar studies in other active regions indicate that b depends on focal depth and on temporal variations (Rehman et al., 2017). Based on laboratory experiments, b-values range from 0.5 to 1.5 (Schorlemmer et al., 2005). For earthquakes such as Tohoku (2011), Sumatra (2004) (Nanjo & Yoshida, 2021; Nuannin et al., 2005), and Hindu Kush (2015, Mw 7.5), a decrease in b at intermediate depths has been interpreted as an earthquake precursor (Molnar & Bendick, 2019).

This study uses a homogenized seismic catalogue (1959–2024) and established statistical methods (maximum-likelihood estimation, maximum curvature method, Shi–Bolt uncertainty estimation, and moving-window mapping) (Aki, 1965; Shi & Bolt, 1982; Wiemer & Wyss, 2000).The paper is organized as follows: tectonic setting, data, estimation of b with sufficient sample sizes, and discussion of the results. The findings will contribute to seismic hazard modeling and the assessment of high-risk areas in Baghlan, Afghanistan.

The Baghlan region in northern Afghanistan, as shown in Figure 1, is characterized by high seismic activity and forms part of the active Hindu Kush–Pamir Mountain belt, one of the most tectonically active areas of Central Asia (Ambraseys & Bilham, 2003; Chatelain et al., 1980; Mohadjer et al., 2016). The subduction of the Indian plate beneath the Eurasian plate produces the complex seismicity of this region (Ayaz & Rashad, 2020; Mansouri et al., 2024). The map of the study area is shown in Figure 1. The study area lies between 35°–37° N and 68°–71° E and mainly comprises parts of (a) the Hindu Kush region, (b) the northern valleys of Afghanistan (such as Andarab and

Khanjan), and (c) the Turan Platform to the north. Baghlan is bounded to the north by the Amu Darya plains and to the south by the central highlands of Afghanistan, with a marked elevation contrast between the mountainous east and the western plains (from 400 to over 3,500 m above sea level). The Andarab and Khanjan valleys host the two main seismogenic faults, the Andarab Fault and the Khanjan Fault (Chatelain et al., 1980; Shnizai, 2020b, 2020a).The Andarab Fault reportedly extends approximately 150 km in an east–west direction and is an active, Quaternary-age, right-lateral strike-slip fault that accommodates part of the lateral extrusion and shortening in the northern Hindu Kush; it extends from southern Baghlan to the eastern border with Badakhshan. The 2002 Nahrin earthquake (Mw 6.1) has likewise been attributed to the activity of thrust and reverse faults associated with the Andarab system and the Hindu Kush (Mansouri et al., 2024; Mohadjer et al., 2016; Shnizai, 2020b).

There is evidence of active seismicity in the Andarab region, extending toward the central Hindu Kush faults (Chatelain et al., 1980; Javadi et al., 2015; Shnizai, 2020b). Higher activity is also observed along the Khanjan Fault, where it joins northern fault systems such as the Alborz–Marmul and Harirud (Barnhart, 2017; Mohadjer et al., 2016; Shnizai, 2020b; Wheeler et al., 2005). The 25 March 2002 earthquake provides evidence of this activity, and its aftershocks occurred near the junction of the Andarab Fault with the Hindu Kush ranges (Chatelain et al., 1980; Faryad et al., 2013; Mansouri et al., 2024). These events have mainly been described as shallow-focus, with right-lateral strike-slip faulting and a compressional component (Barnhart, 2017; Dogru, 2018; Javadi et al., 2015; Shnizai, 2020b, 2020a) The Andarab Fault, east of the Pamir arc and north of the Hindu Kush, can therefore be regarded as being in an ongoing compressional and transpressional phase, in which compressive stress from the Indian plate convergence is released through right-lateral strike-slip motion and a compressional component along transverse faults faults (Barnhart, 2017; Janin et al., 2023; Javadi et al., 2015; Sharon et al., 2020; Shnizai, 2020b). Geologically, the formations in the area consist mainly of igneous and sedimentary rocks of Paleozoic to Neogene age, which have undergone folding and multiple episodes of fracturing due to compressional stresses from the Indian plate collision (Ayaz & Rashad, 2020; Janin et al., 2023; Mansouri et al., 2024).

Based on USGS and ISC data, the highest density of events occurs in central Baghlan and along the Baghlan–Pul-e-Khumri fault boundary. The seismic history of Baghlan includes moderate to large events (Mw 5–6.4), concentrated particularly along the active faults to the south and southeast. This structural and geological diversity has produced a complex stress regime and seismic behavior at the local scale (Chatelain et al., 1980; Janin et al., 2023; Shnizai,

2020a). The seismogenic zone extends to a depth of approximately 50 ± 10 km for shallow crustal faults, but toward the center of the Hindu Kush the focal depth increases markedly (to more than 200 km) (Chatelain et al., 1980).. Figure 1 shows the current seismicity relative to the Andarab and Khanjan faults and neighboring areas, together with prominent tectonic features. The yellow stars indicate the epicenter of the 25 March 2002 earthquake (Mw 6.1).

3 Materials and methods

The relationship between b and focal depth was also examined, and the next section provides a more in-depth analysis (Sarjan, 2025). The earthquake catalogue used in this study was compiled from the International Seismological Centre (ISC) and the United States Geological Survey (USGS) databases, covering the period from 1959 to 2024. The study area is geographically defined by longitudes of 68°–71° E and latitudes of 35°–37° N, encompassing Baghlan Province and its surrounding seismically active regions in northern Afghanistan (Hawadi, 2027; Herrmann & Marzocchi, 2021; Kagan, 1991; Maiti & Kim, 2025; Zhou et al., 2018).The initial catalogue consisted of 1,301 earthquake events with reported magnitudes ranging from 4.0 to 6.4. The methodology adopted in this study follows the general analytical framework applied in previous regional seismicity investigations, with modifications to account for the tectonic and seismological characteristics of the Baghlan region (Hawadi, 2027). To improve the consistency and reliability of the earthquake catalogue, different magnitude scales reported by the ISC and USGS databases, including body-wave magnitude (mb), local magnitude (ML), and surface-wave magnitude (Ms), were converted to moment magnitude (Mw) using empirical relationships. The conversion equations and their corresponding magnitude ranges are presented in Table 1. This homogenization was performed to minimize inconsistencies arising from the use of different magnitude scales and to establish a uniform magnitude dataset for subsequent analyses(Hawadi, 2027; Maiti & Kim, 2025; Scordilis, 2006; Zhou et al., 2018).

After magnitude homogenization, dependent earthquake events were identified and removed using the declustering algorithm proposed by Reasenberg (1985). This procedure separates background seismicity from earthquake clusters associated with mainshock–aftershock sequences, thereby reducing the influence of dependent events on the frequency–magnitude distribution and the estimation of the Gutenberg–Richter parameters (Bhattacharya & Chakrabarti, 2011; Reasenberg, 1985).

The magnitude of completeness (Mc), defined as the minimum magnitude above which earthquake events are considered to be completely recorded, was evaluated using the maximum curvature (MAXC) method (Gong et al., 2024; Woessner & Wiemer, 2005). To improve the reliability of the estimated completeness magnitude, a correction of 0.2 magnitude units was added to the maximum-curvature value, following Woessner and Wiemer (2005) (Woessner & Wiemer, 2005):

$$M_c = M_{c(\mathrm{MAXC})} + 0.2 \quad (1)$$

The completeness analysis was performed using ZMAP7, considering a minimum of 250 earthquake events within the analysis windows. The spatial and temporal variations in catalogue completeness were also examined to evaluate changes in earthquake detection capability over the study period (Wiemer, 2000; Wiemer & Wyss, 2000).. The results indicate an improvement in earthquake recording, particularly after 1995, reflecting changes in seismic monitoring and data availability. The estimated completeness magnitude is illustrated in Figure 2, while the temporal distribution of cumulative earthquake events from 1959 to 2024 is presented in Figure 4a. Earthquakes with Mw ≥ 5.9 are highlighted using star symbols (Alamilla et al., 2015; Gong et al., 2024; Rydelek, 2003; Woessner & Wiemer, 2005).

Following declustering, magnitude homogenization, and completeness analysis, a final catalogue of 1,232 earthquakes with Mw ≥ 4.3 was selected for subsequent analyses. The spatial distribution of these selected events is shown in Figure 3. This homogenized and declustered catalogue provides the basis for investigating the spatial, depth-dependent, and temporal characteristics of seismicity in the Baghlan region.

The frequency–magnitude distribution was evaluated using the Gutenberg–Richter (G–R) relationship (Gutenberg and Richter, 1944):

$$\log_{10} N\,(M) = a - bM \quad (2)$$

where (N(M)) represents the cumulative number of earthquakes with magnitudes equal to or greater than (M), (a) is a parameter describing the overall level of regional seismicity, and (b) is the slope of the frequency–magnitude distribution (De Santis et al., 2011; Gong et al., 2024; Hawadi, 2027; Kamer, 2014b; Sornette & Sornette, 1999).. The b-value represents the relative proportion of small to large earthquakes and is commonly used to characterize

variations in seismicity and the physical conditions of the seismogenic crust (Amorese et al., 2010; Sharon et al., 2020; Woessner & Wiemer, 2005).The b-value was estimated using the maximum-likelihood method (MLE) introduced by Aki (1965), which is widely applied in statistical seismology. Considering the magnitude-bin correction, the b-value was calculated as (Aki, 1965; Shi & Bolt, 1982):

$$b = \frac{\log_{10} e}{\overline{M} - (M_c - \Delta M/2)} \tag{3}$$

where $\overline{M}$ is the mean magnitude of earthquakes with magnitudes equal to or greater than Mc, Mc is the magnitude of completeness, and ΔM represents the magnitude-bin width. The correction term $\Delta M/2$ accounts for the effect of magnitude discretization on the b-value estimate (Aki, 1965; Scholz, 1968).

The uncertainty associated with the estimated b-values was calculated using the approach proposed by Shi and Bolt (1982) (Aki, 1965; Shi & Bolt, 1982):

$$\delta b = 2.30 b^2 \sqrt{\frac{\sum_{i=1}^{n} \left(M_i - \overline{M}\right)^2}{n(n-1)}} \tag{4}$$

where (M_i) represents the magnitude of the (i)-th earthquake, $\overline{M}$ is the mean magnitude of the selected events, and (n) is the total number of earthquakes included in the calculation. This approach provides an estimate of the statistical uncertainty associated with the b-value.

The spatial distribution of the b-value was investigated to identify variations in earthquake-size distribution across the study area. For this purpose, a regular spatial grid with a cell size of 0.16° × 0.16° was established, and a moving-window approach was applied to estimate local b-values. The calculations were performed using ZMAP7, while ArcGIS 10.8 was used for spatial visualization and mapping (Borgohain et al., 2018; Hawadi, 2027; Kamer, 2014a, 2014b; Li et al., 2025; Mousavi, 2017; Ningrum et al., 2024; Schorlemmer et al., 2005; Tsukakoshi, 2010). The resulting b-value estimates were interpolated using the Kriging method to produce continuous spatial representations of seismicity patterns. These maps were used to examine spatial variations in the b-value and their possible relationships with the principal tectonic structures, particularly the Andarab and Khanjan faults. The spatial distributions of the estimated b-values are presented in Figures 10 and 11(Sarjan, 2025).

The depth-dependent variation of the b-value was also examined to investigate changes in earthquake-size distribution within the seismogenic crust. Earthquake events were analyzed according to their focal depths, extending to approximately 90 km. The b-values were estimated for the selected depth intervals using the maximum-likelihood method, while maintaining the magnitude-completeness criterion. This analysis was conducted to identify possible variations in seismicity characteristics with depth and to evaluate the relationship between earthquake occurrence and the regional seismotectonic structure. The corresponding results are presented in Figure 8 (Wiemer, 2001).

In addition to the spatial and depth-dependent analyses, temporal variations in the b-value were investigated to examine changes in seismicity patterns during the study period, with particular attention to the destructive Nahrin earthquake of 25 March 2002. The temporal b-value estimates were calculated using the maximum-likelihood method and the Gutenberg–Richter frequency–magnitude relationship (De Santis et al., 2011; Gong et al., 2024; Hawadi, 2027; Kamer, 2014b; Sornette & Sornette, 1999). This analysis was designed to evaluate variations in the relative occurrence of small and large earthquakes before and after the Nahrin event. Temporal changes in the b-value were interpreted cautiously, taking into account the possible influence of catalogue completeness, earthquake clustering, and the number of events included in each analysis window. Although variations in the b-value may provide useful information about changes in seismicity, they should not be considered a deterministic method for predicting individual earthquakes. The temporal variations in the estimated b-values are illustrated in Figure 5 (Ernandi, 2020).

Finally, the spatial, depth-dependent, and temporal results were considered together to investigate the seismic characteristics of the Baghlan region and their possible association with the Andarab and Khanjan fault systems. Particular emphasis was placed on identifying areas characterized by relatively low or high b-values and examining their relationship with the distribution of moderate-to-large earthquakes, including the 2002 Nahrin earthquake. This integrated approach provides a basis for interpreting regional seismicity patterns and improving the understanding of the seismotectonic characteristics of Baghlan Province (S. -K. Kufner et al., 2023; S.-K. Kufner et al., 2021; Rehman et al., 2015, 2017).

4 Results and Discussion

Previous studies have demonstrated that the frequency–magnitude distribution parameter (b-value) is influenced by various factors, including focal depth, crustal stress accumulation, tectonic regime, and faulting mechanism (Bellalem et al., 2008; Borgohain et al., 2018; Chatelain et al., 1980; Gong et al., 2024; Hawadi, 2027; Kamer, 2014a; S.-K. Kufner et al., 2021; Rehman et al., 2015, 2017; Sarjan, 2025; Singh, 2016; Singh & Singh, 2015; Yadav et al., 2013). The study area is located within the tectonically active Hindu Kush–Pamir region, where the ongoing convergence of the Indian and Eurasian plates contributes to considerable crustal deformation and tectonic stress accumulation. Figure 7 illustrates the variation in b-value with respect to the focal depths of earthquakes in the study area, particularly around the Andarab and Khanjan faults. The ZMAP7 software was used to investigate the depth-dependent variation of the b-value (Wiemer, 2001). In this analysis, the magnitude of completeness (Mc) was kept constant to allow comparisons among different depth intervals (Woessner & Wiemer, 2005; Yi-Lei et al., 2016).. For this purpose, the study area was divided into nine depth layers, each with a thickness of 10 km, extending from the surface to an approximate depth of 90 km. The b-value was then calculated separately for each layer and plotted against the corresponding average focal depth (Figure 8).

The results indicate that relatively low b-values are mainly observed in the upper crust, particularly at depths of approximately 10–45 km. In some parts of this depth range, b-values between 0.60 and 0.80 were obtained. These values indicate a relatively higher proportion of moderate-to-large earthquakes compared with smaller events. Such low values may be associated with increased differential stress, stress concentration, and variations in the structural properties of the crust. Similar observations have been reported by Rehman et al. (2017) and Singh and Singh (2015) in the Hindu Kush–Pamir region, where b-values below 1.0 at depths of approximately 20–40 km were attributed to crustal heterogeneity and elevated stress conditions(Rehman et al., 2017; Singh & Singh, 2015). Furthermore, relatively low b-values were also observed at depths of approximately 40–50 km in the central and southern parts of Baghlan. These variations may be related to changes in the regional stress regime, including possible increases in shear stress within a transpressional tectonic environment, as well as differences in the mechanical properties of the underlying lithospheric materials.

The shallow focal depth of the destructive Nahrin earthquake of 25 March 2002 (Mw 6.1), which was reported at approximately 8–10 km, provides an important context for interpreting upper-crustal seismicity in the region (Yeats & Madden, 2003).The occurrence of this earthquake demonstrates that significant seismic ruptures can take place

within the shallow crust of the Hindu Kush–Pamir tectonic system. Therefore, the relatively low b-values identified in parts of the upper crust may be consistent with elevated stress conditions and the potential for larger earthquake ruptures. However, spatial and depth-dependent b-value patterns alone cannot establish a direct causal relationship with the Nahrin earthquake or determine the timing and location of future earthquakes. Studies by Rehman et al. (2015, 2017) and Kufner et al. (2021, 2023) have shown that shallow and intermediate-depth earthquakes in the Hindu Kush region occur at depths of up to approximately 70 km, whereas deeper earthquakes have also been observed at depths exceeding 200 km. These findings highlight the complexity of the depth distribution of seismicity associated with the regional tectonic system (S. -K. Kufner et al., 2023; S.-K. Kufner et al., 2021; Rehman et al., 2015, 2017).

The depth-frequency distribution of earthquakes, presented in Figure 9, illustrates the concentration of seismic activity within the upper crust. The number of recorded earthquakes is considerably higher at depths of 0–40 km, with the maximum frequency observed at approximately 15–20 km. In contrast, the number of seismic events decreases substantially at depths greater than 70 km. This distribution indicates that most earthquakes included in the catalogue used in this study occurred within the shallow and intermediate-depth portions of the study area. The Nahrin–Baghlan earthquake of 25 March 2002 (Mw 6.1), with a reported focal depth of approximately 8–10 km, is also consistent with the occurrence of significant shallow seismic events in the region (Yeats & Madden, 2003). Similar results have been reported by Rehman et al. (2017) and Kufner et al. (2021), who showed that many shallow and intermediate-depth earthquakes in the Hindu Kush region occur within the upper 50 km of the crust(S. -K. Kufner et al., 2023; S.-K. Kufner et al., 2021; Rehman et al., 2015, 2017).

The earthquake magnitude distribution shown in Figure 9 further indicates that events with magnitudes of approximately Mw 4–5 constitute the dominant proportion of the recorded seismicity, whereas the number of earthquakes with $Mw \geq 5$ is comparatively limited. This pattern is consistent with the general frequency–magnitude relationship, according to which smaller earthquakes occur more frequently than larger ones. Nevertheless, the relatively small number of moderate-to-large earthquakes does not diminish their importance for regional seismic hazard assessment, particularly in tectonically active areas surrounding major fault systems.

The spatial distribution of the b-value in the study area is presented in Figure 10. The calculated values range from 0.80 ± 0.03 to 1.40 ± 0.16, indicating considerable spatial variability in the relative proportions of small and large

earthquakes. Previous studies have also reported similar values in the Hindu Kush–Pamir region. For example, Rehman et al. (2015) and Singh and Singh (2015) reported that the b-value across the Hindu Kush–Pamir region varies approximately between 0.9 and 1.5. Similarly, studies by Chatelain et al. (1980) and Roecker (1975, 2017) reported b-values ranging from approximately 0.8 to 1.4 in the Hindu Kush region(Chatelain et al., 1980; S. -K. Kufner et al., 2023; Rehman et al., 2015; Singh & Singh, 2015) (S. Roecker et al., 2017; S. W. Roecker, 1981, p. 1975). Therefore, the range obtained in the present study is broadly consistent with previous regional observations and confirms the spatial variability of seismicity characteristics in northeastern Afghanistan (Chatelain et al., 1980; Roecker et al., 2017; Roecker, 1975).

One notable feature of the spatial distribution of the b-value is the occurrence of relatively low values within the area bounded by latitudes of 36°–36.5° N and longitudes of 69°–70° E, particularly near the Andarab and Khanjan fault systems. These areas may represent zones of relatively elevated stress concentration or variations in the mechanical properties of the crust. Such spatial variations may be associated with the complex tectonic forces generated by the convergence of the Indian and Eurasian plates, together with local fault geometry and regional deformation patterns (Rehman et al., 2017; Shnizai, 2020a; Singh & Singh, 2015). These findings are also consistent with the general framework proposed by Ruff and Kanamori (1980), who investigated the relationship between seismicity, the degree of tectonic coupling, and the physical characteristics of convergent plate boundaries (Ruff & Kanamori, 1980).

A relatively low b-value of approximately 0.80 was identified around the epicentral area of the Nahrin earthquake of 25 March 2002 (Mw 6.1), located at approximate coordinates of 36.27° N and 69.92° E (Figures 10 and 7). The presence of low b-values in this area may indicate conditions associated with increased stress and a relatively higher proportion of larger earthquakes. This observation is particularly important because the Nahrin earthquake occurred in a region characterized by considerable tectonic activity, complex faulting, and ongoing continental convergence. Although b-values close to 1 are commonly reported in many seismically active regions, previous studies have demonstrated substantial spatial variations, including values reaching approximately 1.4, across the Hindu Kush region (S. Roecker et al., 2017). Therefore, the range of 0.80–1.40 obtained in the present study is consistent with the variations reported in previous regional investigations.

Overall, the results of the spatial, depth-dependent, and frequency–magnitude analyses conducted in this study are broadly consistent with previous investigations of northeastern Afghanistan and the Hindu Kush–Pamir region (S.-K. Kufner et al., 2021; Rehman et al., 2017; Singh & Singh, 2015). In particular, the relatively low b-values observed in certain areas near the Andarab and Khanjan faults may indicate zones characterized by elevated stress conditions and a potentially greater likelihood of seismic rupture. However, variations in the b-value should be interpreted as statistical indicators of seismicity characteristics rather than direct measurements of crustal stress or deterministic tools for predicting future earthquakes. Considering the active tectonic setting of the region and the occurrence of destructive earthquakes, such as the 2002 Nahrin event, the findings of this study provide valuable information for understanding regional seismicity in Baghlan Province.

5 Conclusions

This study investigated the spatial and depth-dependent variations of the Gutenberg–Richter b-value in the Baghlan region of northern Afghanistan, focusing on the Andarab and Khanjan fault systems and the 2002 Nahrin earthquake. Based on a homogenized earthquake catalogue (1959–2024), comprising 1,232 events with $Mw \geq 4.3$, the b-value was estimated using the maximum-likelihood method (MLE).

The results reveal considerable spatial and depth-dependent variations in b-values. Relatively low values (0.60–0.80) occur mainly at depths of 10–45 km, while spatial estimates range from 0.80 ± 0.03 to 1.40 ± 0.16. The lowest spatial values are concentrated between 36°–36.5° N and 69°–70° E, particularly near the Andarab and Khanjan fault systems. Earthquake activity is predominantly concentrated within the upper 40 km, with the highest frequency at approximately 15–20 km depth.

A notable finding is the relatively low b-value (~0.80) near the epicentre of the 25 March 2002 Nahrin earthquake (Mw 6.1; 36.27° N, 69.92° E), which occurred at a focal depth of approximately 8–10 km. This pattern may indicate locally elevated differential stress and variations in crustal mechanical properties. However, the observed association does not establish a causal relationship or provide a deterministic basis for earthquake prediction.

Overall, the findings highlight the heterogeneous seismic characteristics of the Baghlan region and the influence of regional tectonic processes and major fault systems. Spatial and depth-dependent b-value analysis provides valuable insights into earthquake-size distributions and the possible stress conditions of the upper crust. Future studies

integrating seismic tomography, focal mechanisms, GPS measurements, and more comprehensive seismic catalogues could further clarify the tectonic processes governing seismic activity in northern Afghanistan.

Table 1. *Empirical relationships for converting different magnitudes to Mw used in this study* (Scordilis, 2006)**.**

Type of magnitude	Empirical relationship	Range
Ms	$M_w = 0.67(\pm0.005)M_s + 2.07(\pm0.03)$	$3.0 \leq MS \leq 6.1$
Ms	$M_w = 0.99(\pm0.020)M_s + 0.08(\pm0.13)$	$6.2 \leq MS \leq 8.2$
Mb	$M_w = 0.85(\pm0.040)m_b + 1.03(\pm0.23)$	$3.5 \leq mb \leq 6.2$
Ml	$M_w = 0.934(\pm0.135)M_L + 0.356(\pm0.714)$	$3.4 \leq ML \leq 7.6$

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Saeed Zarei: Writing – review & editing, Project administration.

Data availability: The earthquake data used in this study are publicly available from the International Seismological Centre (ISC; https://www.isc.ac.uk) and the United States Geological Survey (USGS) ComCat catalogue (https://earthquake.usgs.gov/earthquakes/search/), covering the period 1959–2024 for the Baghlan region. The homogenized and declustered catalogue and the derived b-value results are available from the corresponding author (hidayatullahhawadi371@gmail.com) upon reasonable request.

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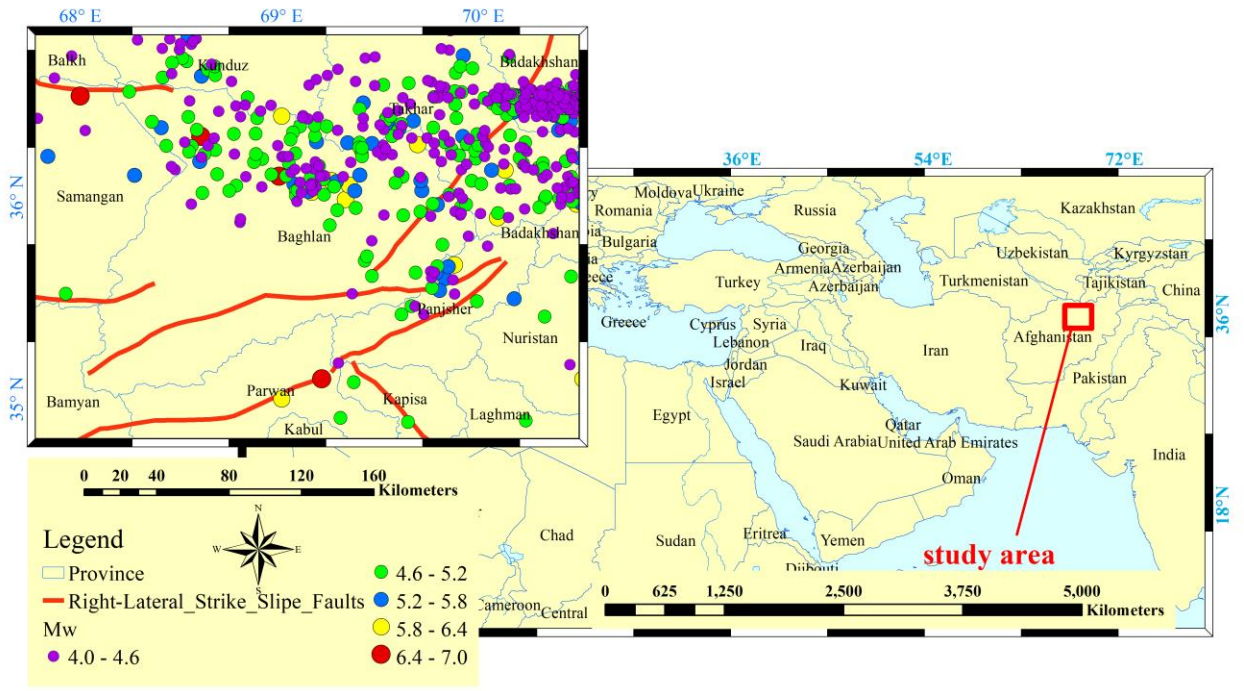


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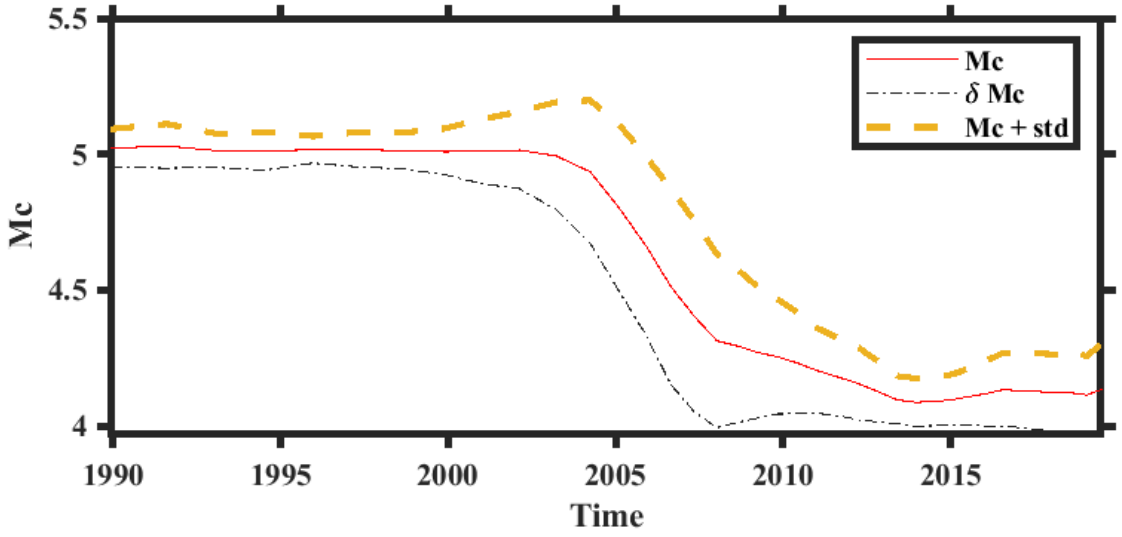


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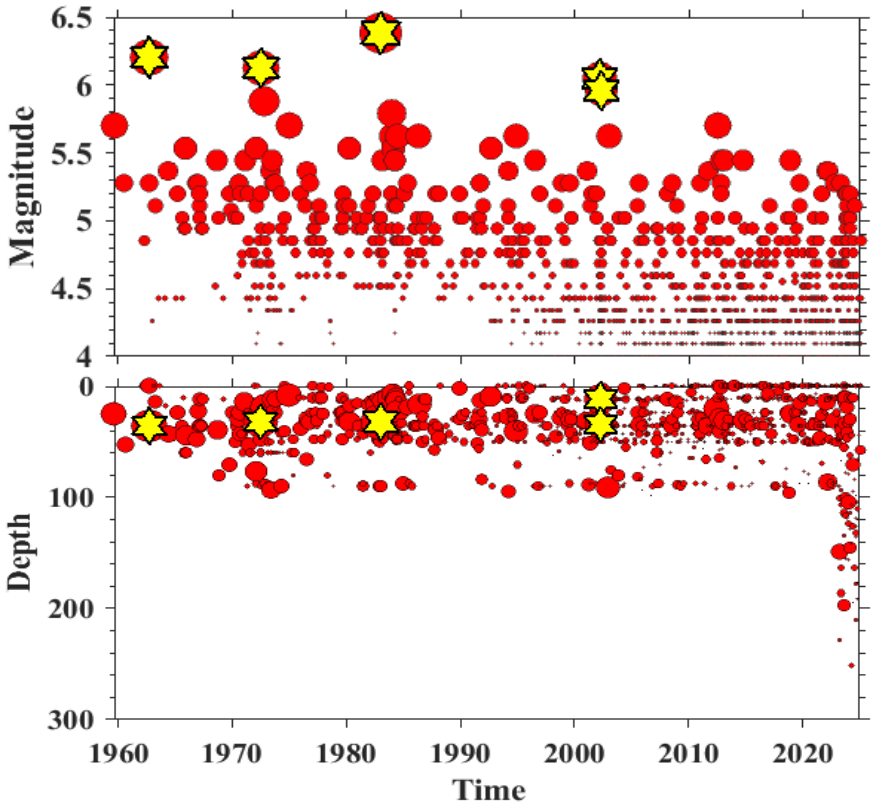


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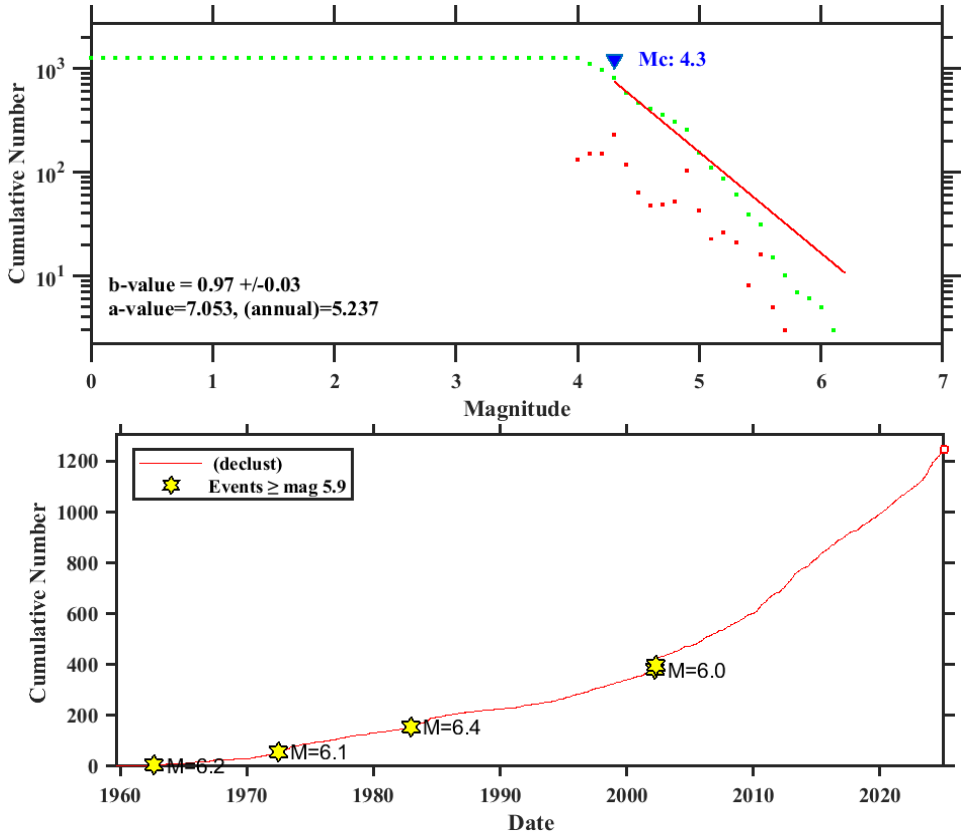


Fig. 4 (a) Cumulative number of declustered earthquakes in the Baghlan region (1959–2024), with major events (Mw ≥ 5.9) indicated by yellow stars. (b) Cumulative frequency–magnitude distribution, showing the Gutenberg–Richter relationship, magnitude of completeness (Mc = 4.3), and estimated b-value (0.97 ± 0.03) for the study area.

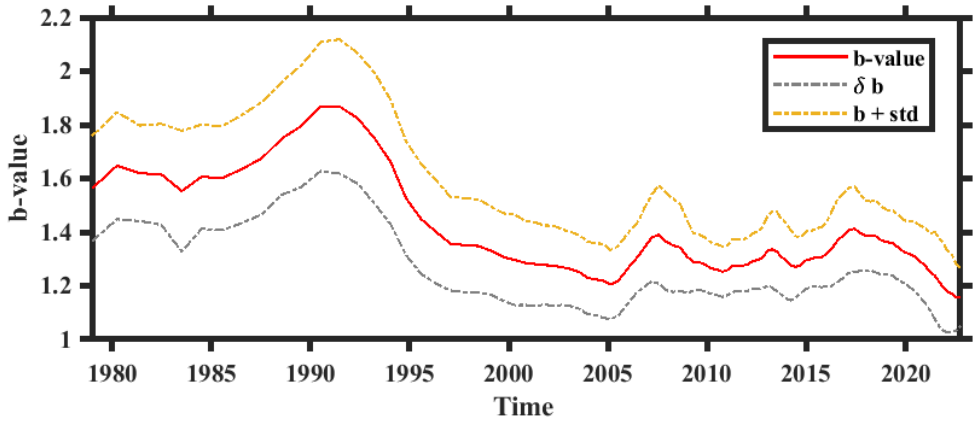


Fig. 5 Temporal variations in the Gutenberg–Richter b-value in the Baghlan region (1959–2024). The gray dashed lines indicate the standard deviation.

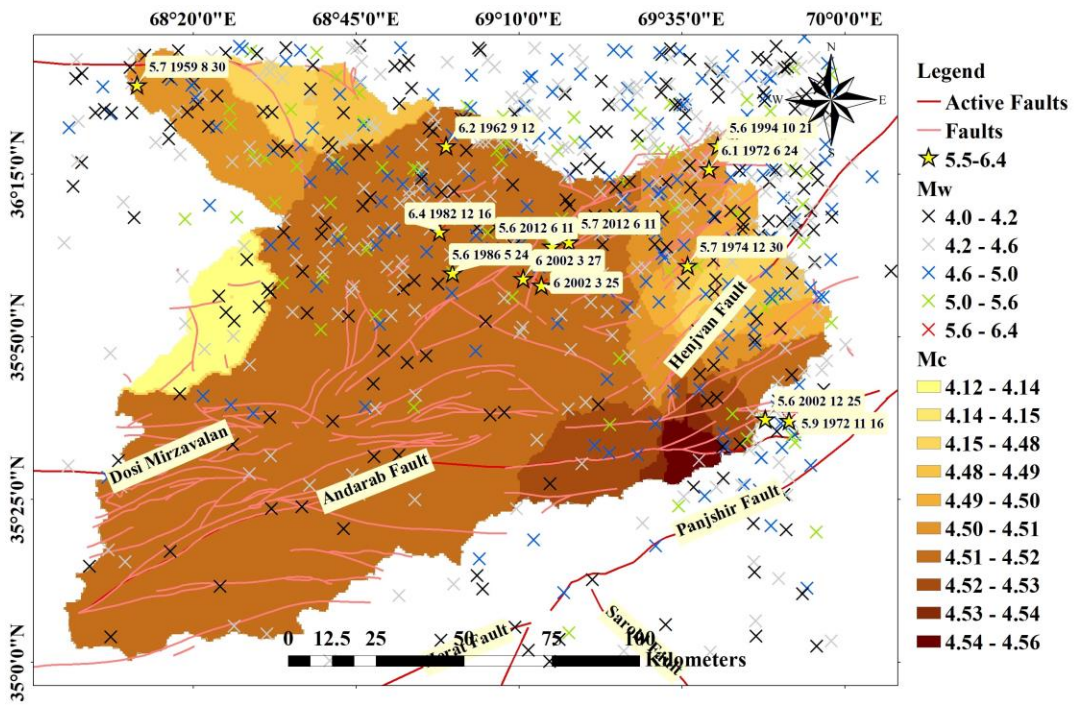


Fig. 6 Spatial distribution of the magnitude of completeness (Mc) in the Baghlan region.

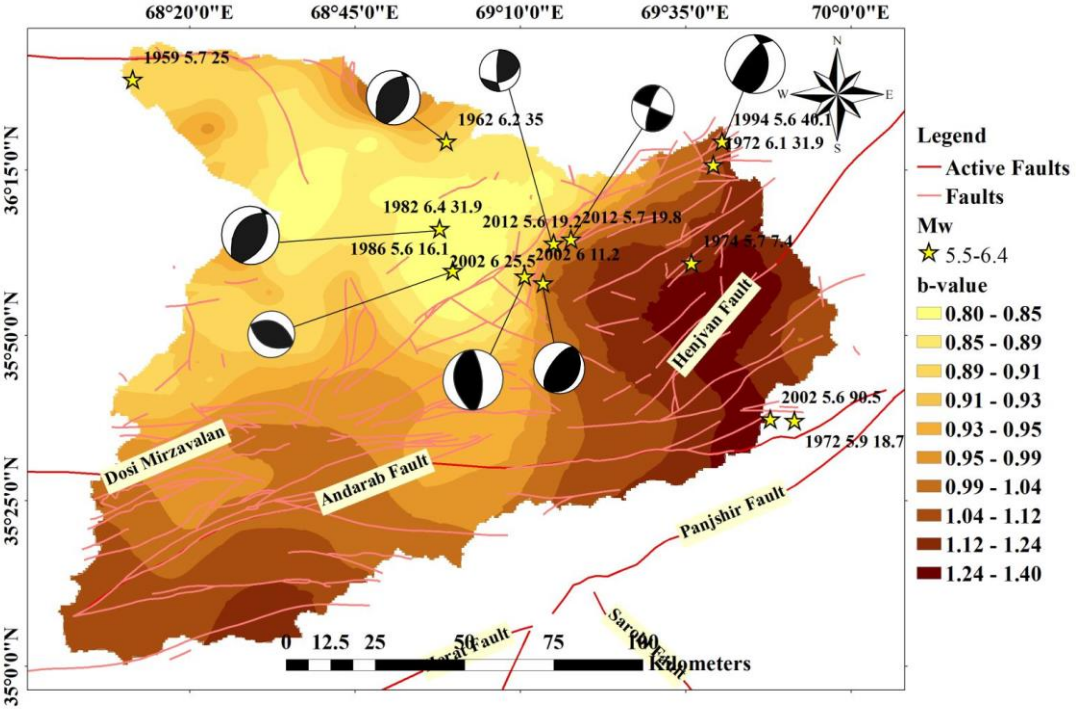


Fig. 7 Spatial distribution of earthquake focal mechanisms and Gutenberg–Richter b-values in the study area (Baghlan, 1959–2024).

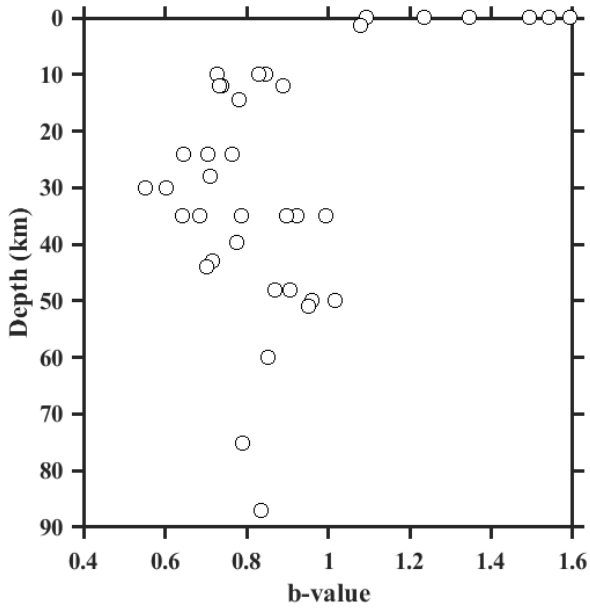


Fig. 8 Depth-dependent variations in the Gutenberg–Richter b-value in the study area.

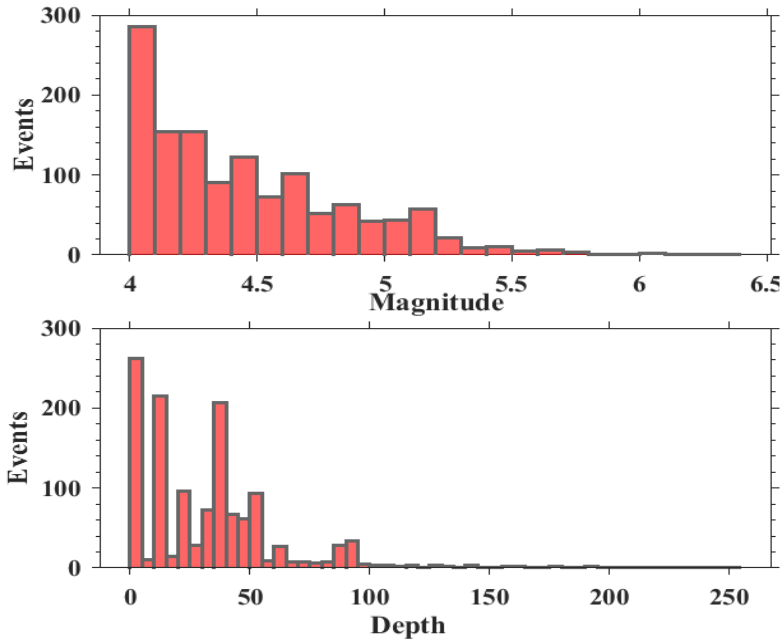


Fig. 9 Histogram of focal depths for 1,301 selected earthquake events (Mw ≥ 4.0), showing a concentration of seismic activity at a depth of 45 km.

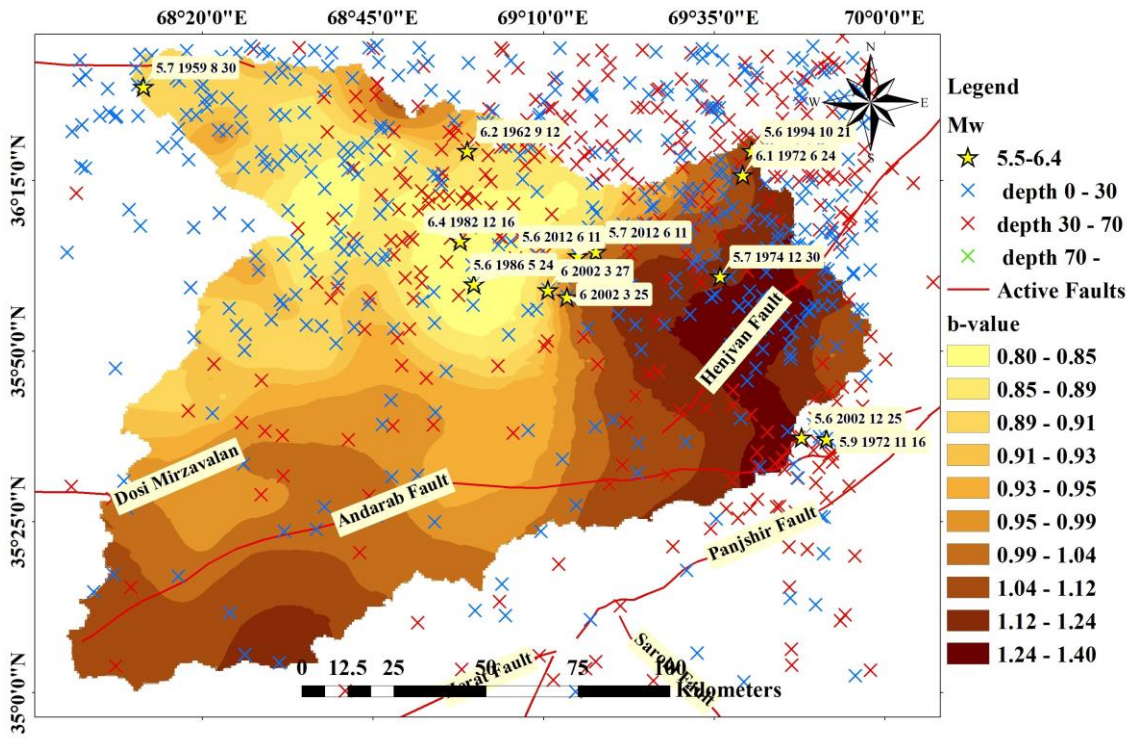


Fig. 10. Spatial distribution of Gutenberg–Richter b-values in the study area.

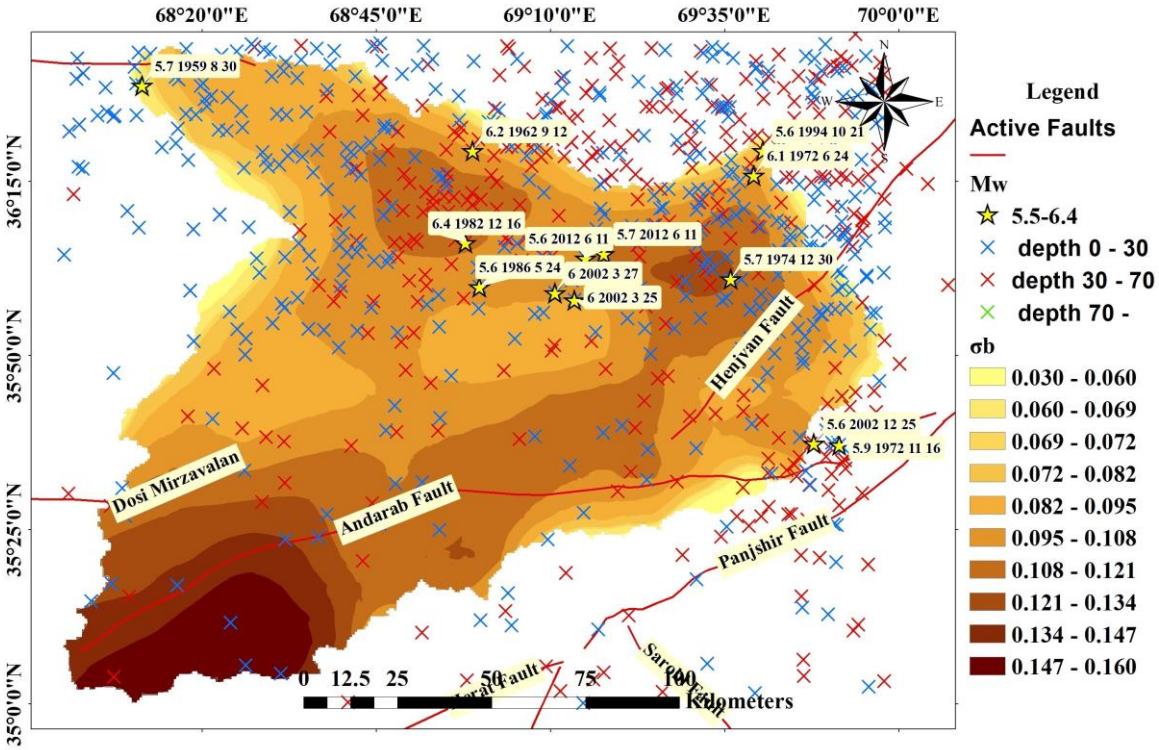


Fig. 11 Spatial distribution of the standard deviation (δb) of b-value estimates and the study area.

Cover Letter

To: The Editor-in-Chief
Arabian Journal of Geosciences

Subject: Submission of Manuscript for Publication Consideration

Dear Editor-in-Chief,

We are pleased to submit our manuscript entitled **Spatial and Depth-Dependent Patterns of Seismicity in the Baghlan Region, Afghanistan** for consideration for publication in the *Arabian Journal of Geosciences*. This study investigates the spatial, depth-dependent, and temporal variations of the Gutenberg–Richter b-value in the Baghlan region of northern Afghanistan, with particular attention to the Andarab and Khanjan fault systems and the 25 March 2002 Nahrin earthquake (Mw 6.1). Using a homogenized earthquake catalogue covering the period 1959–2024, we applied statistical methods to examine earthquake-size distribution and its relationship with regional seismotectonic structures.

The main contribution of this study is the detailed analysis and mapping of b-value variations across the Baghlan region, providing insights into the spatial distribution of seismicity and the possible influence of active faults and crustal heterogeneity on earthquake occurrence. The findings identify areas characterized by relatively low b-values and reveal variations in earthquake activity with focal depth. We believe that this research is relevant to the scope of the *Arabian Journal of Geosciences*, particularly its interests in seismology, tectonics, earthquake processes, and regional geoscientific investigations. The study also contributes to the limited understanding of the seismotectonic characteristics of northern Afghanistan.

We confirm that this manuscript is original, has not been published previously, and is not currently under consideration for publication by another journal. All authors have reviewed and approved the manuscript and agree to its submission to the *Arabian Journal of Geosciences*. We declare that any potential conflicts of interest will be disclosed in the manuscript. Thank you for considering our work for publication. We look forward to your response.

Sincerely,

Hedayatullah Hawadi
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Persian Gulf University, Bushehr, Iran
Email: hedayat.hawadi@mehr.pgu.ac.ir
ORCID: 0009-0009-3802-2145

On behalf of all authors
Saeed Zarei

Figure Captions

Fig. 1 (a) Geographical location and seismotectonic setting of the study area in Baghlan Province, northern Afghanistan. (b) Regional geographical map showing the location of the study area in Baghlan Province, Afghanistan, highlighted by the red rectangle.

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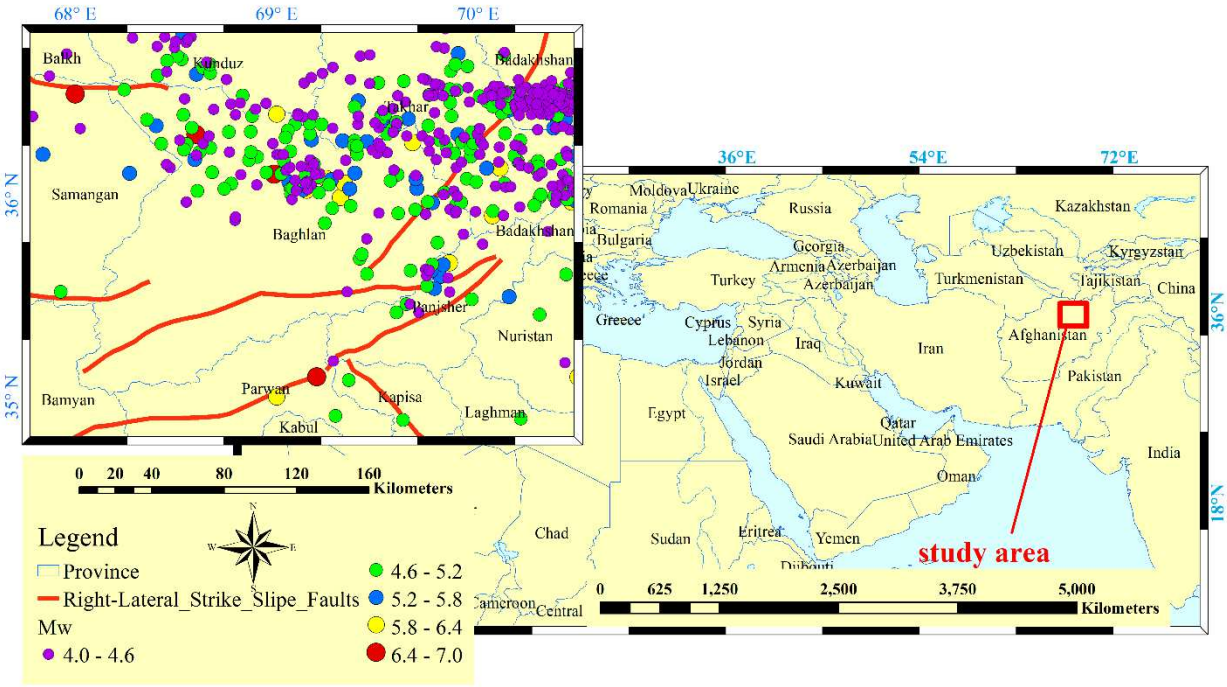

68° E
69° E
70° E
36° N
35° N
Balkh
Kunduz
Badakhshan
Samangan
Baghlan
Panjsher
Nuristan
Bamyan
Parwan
Kapisa
Laghman
Kabul
0 20 40 80 120 160
Kilometers
Legend
Province
Right-Lateral_Strike_Slip_Faults
Mw
4.0 - 4.6
4.6 - 5.2
5.2 - 5.8
5.8 - 6.4
6.4 - 7.0
36°E
54°E
72°E
36°N
18°N
Moldova
Ukraine
Romania
Russia
Kazakhstan
Bulgaria
Georgia
Armenia
Azerbaijan
Uzbekistan
Kyrgyzstan
Turkey
Turkmenistan
Tajikistan
China
Greece
Cyprus
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Lebanon
Iraq
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Jordan
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Kuwait
Pakistan
Egypt
Qatar
Saudi Arabia
United Arab Emirates
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study area
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Kilometers

Figure 1

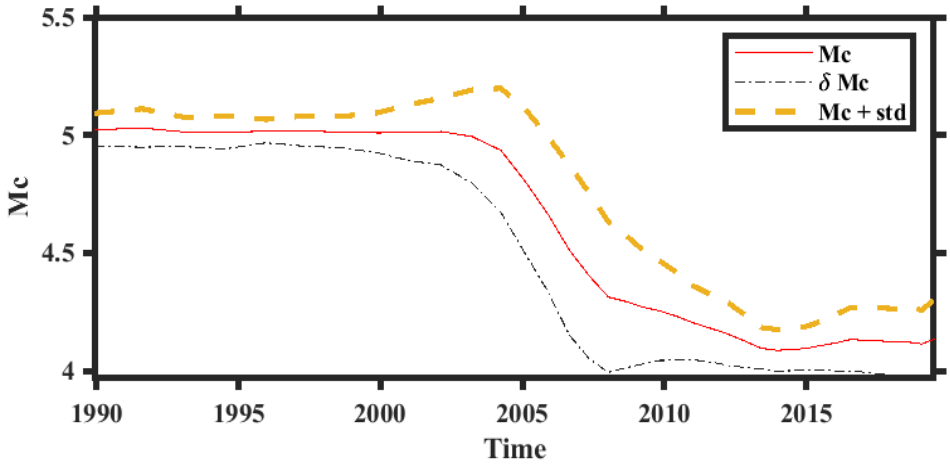

5.5
5
4.5
4
Mc
1990
1995
2000
2005
2010
2015
Time
Mc
δ Mc
Mc + std

Figure 2

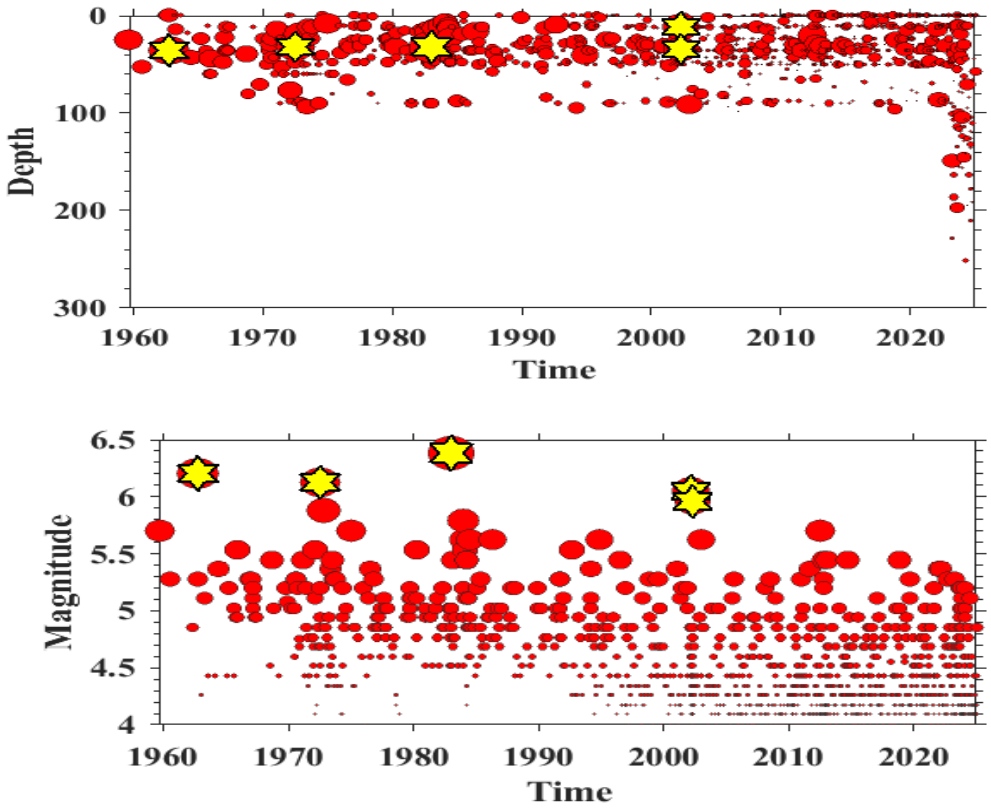
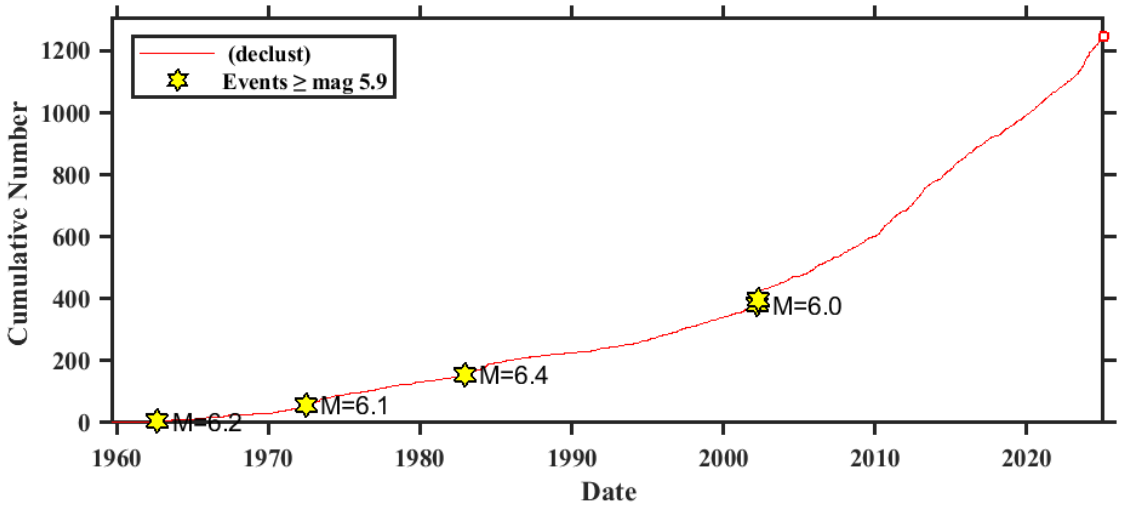


Figure 3



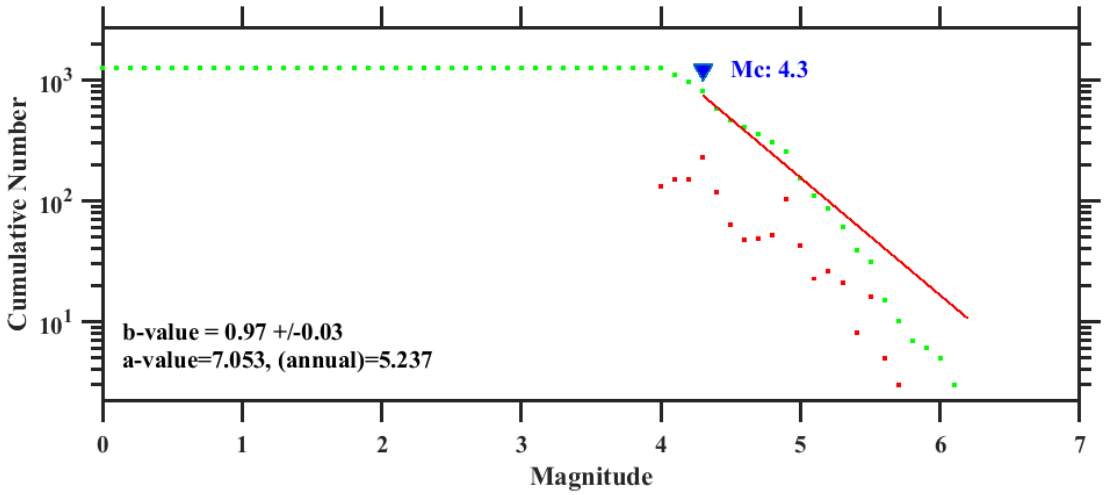


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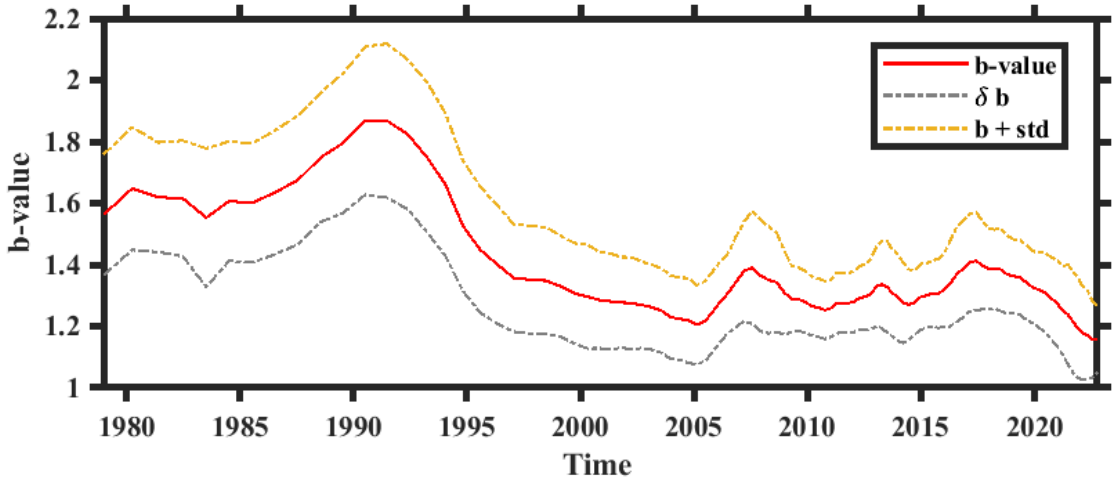


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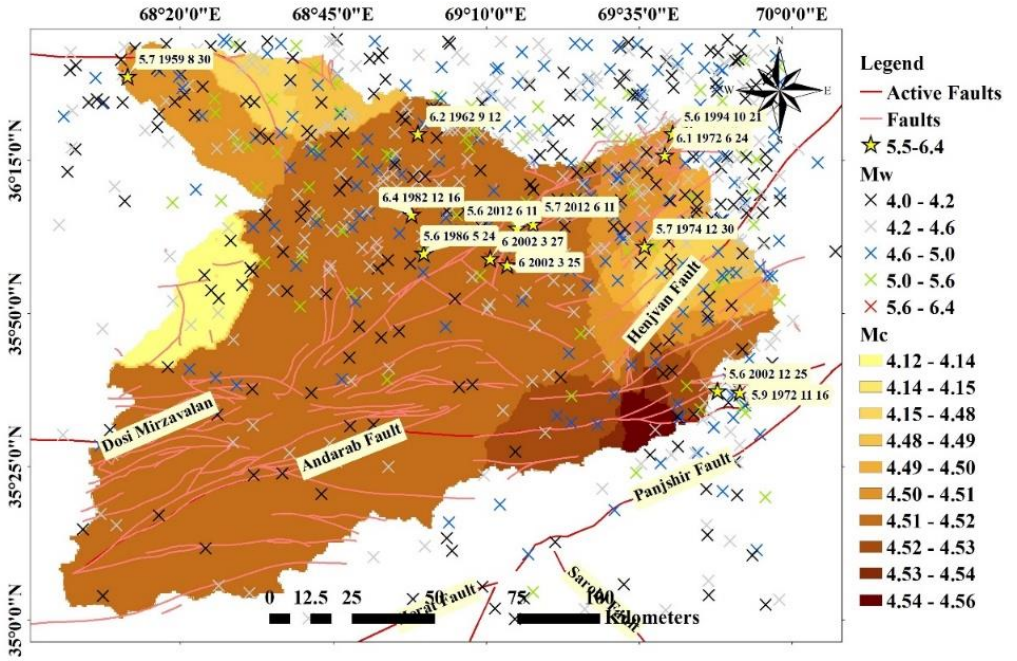


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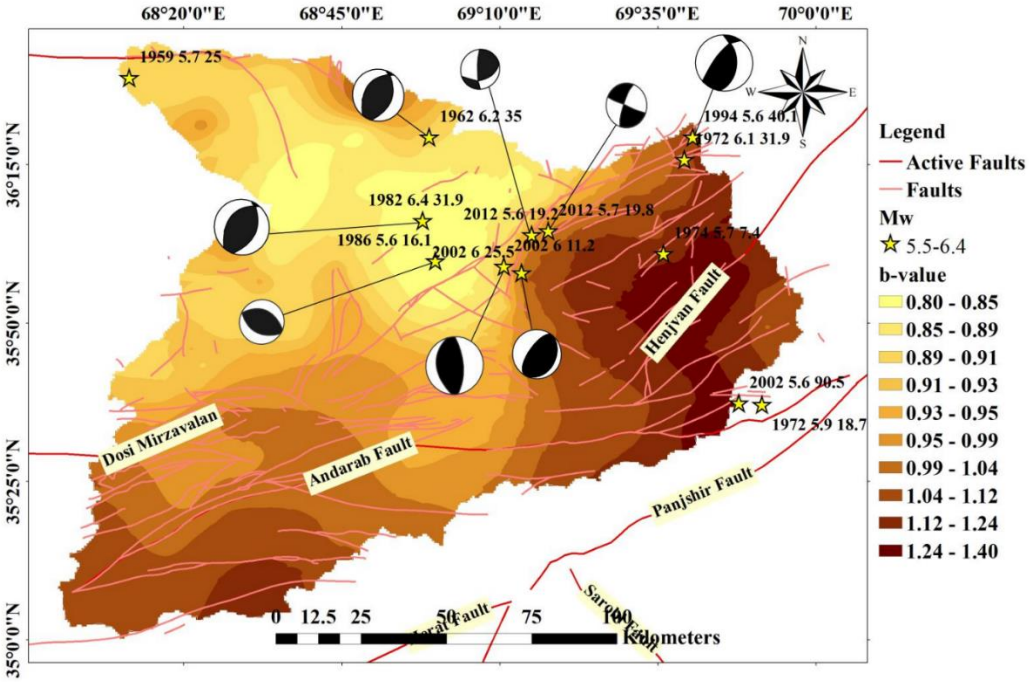


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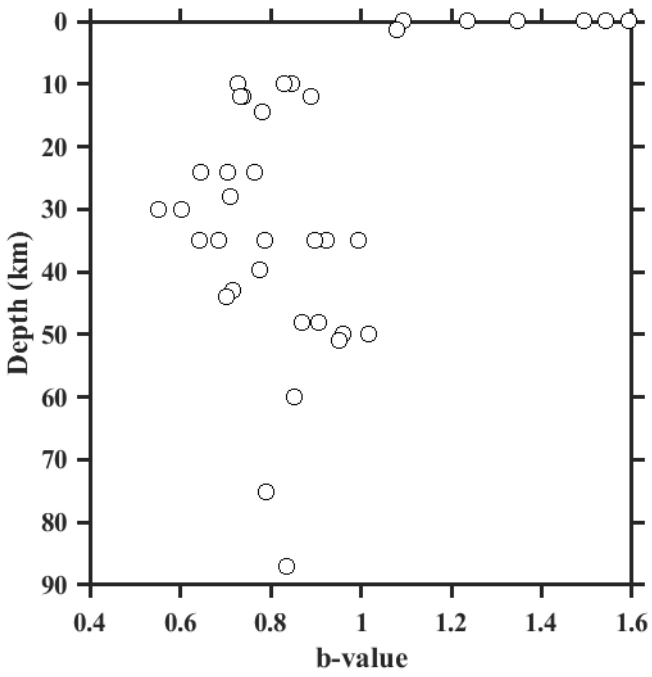

Depth (km)
0
10
20
30
40
50
60
70
80
90
0.4
0.6
0.8
1
1.2
1.4
1.6
b-value

Figure 8

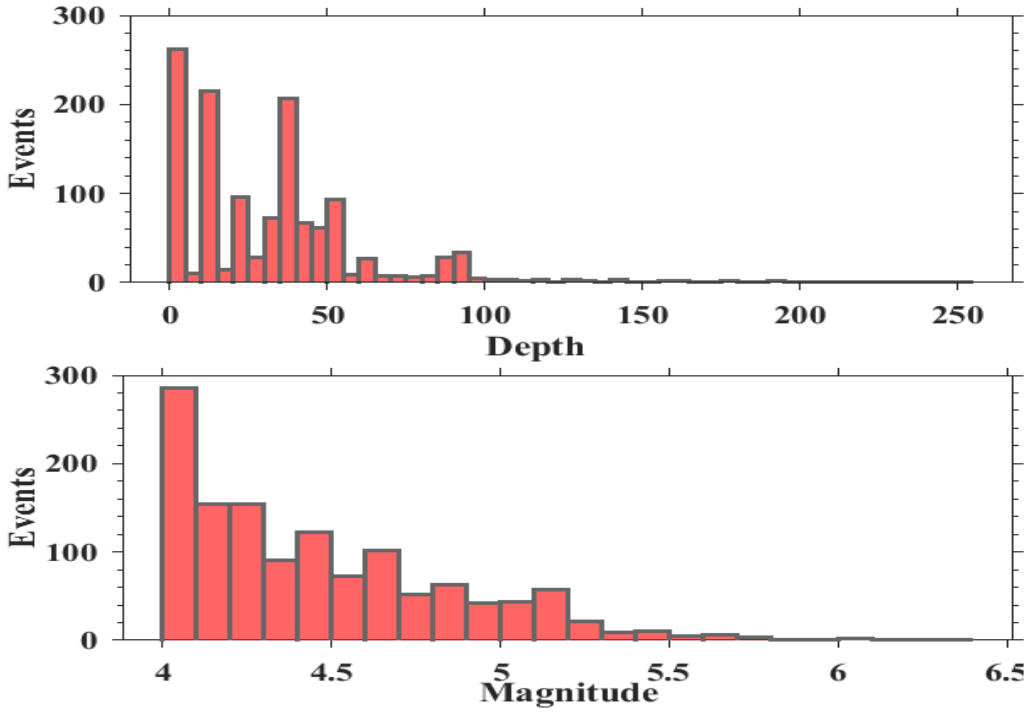

Events
300
200
100
0
0
50
100
150
200
250
Depth
Events
300
200
100
0
4
4.5
5
5.5
6
6.5
Magnitude

Figure 9

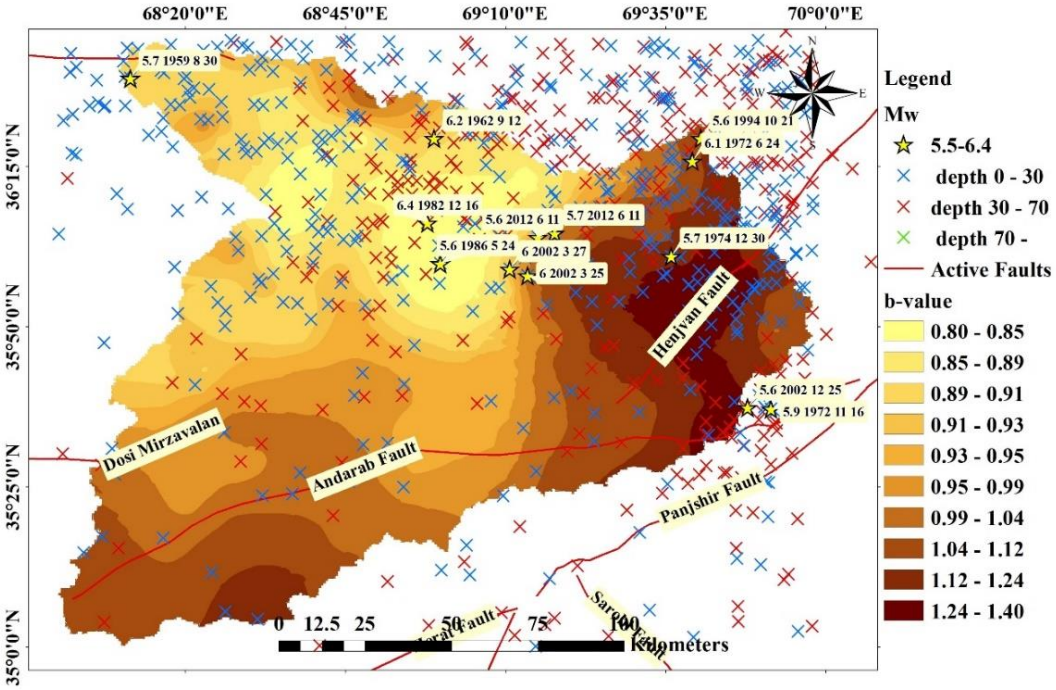


Figure 10

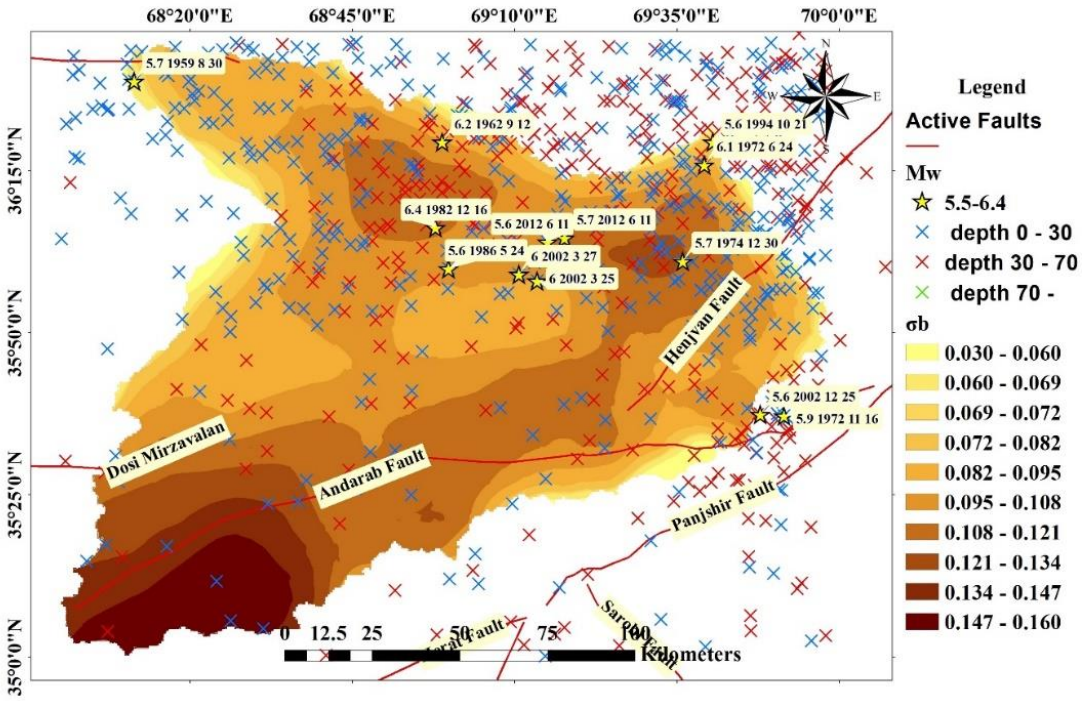

68°20'0"E
68°45'0"E
69°10'0"E
69°35'0"E
70°0'0"E
36°15'0"N
35°50'0"N
35°25'0"N
35°0'0"N
5.7 1959 8 30
6.2 1962 9 12
5.6 1994 10 21
6.1 1972 6 24
6.4 1982 12 16
5.6 2012 6 11
5.7 2012 6 11
5.7 1974 12 30
5.6 1986 5 24
6 2002 3 27
6 2002 3 25
5.6 2002 12 25
5.9 1972 11 16
Henjvan Fault
Dosi Mirzavalan
Andarab Fault
Panjshir Fault
0 12.5 25 50 75 100 Kilometers
Legend
Active Faults
Mw
5.5-6.4
depth 0 - 30
depth 30 - 70
depth 70 -
σb
0.030 - 0.060
0.060 - 0.069
0.069 - 0.072
0.072 - 0.082
0.082 - 0.095
0.095 - 0.108
0.108 - 0.121
0.121 - 0.134
0.134 - 0.147
0.147 - 0.160

Figure 11

Table

Table 1. Empirical relationships for converting different magnitudes to Mw used in this study (Scordilis, 2006).

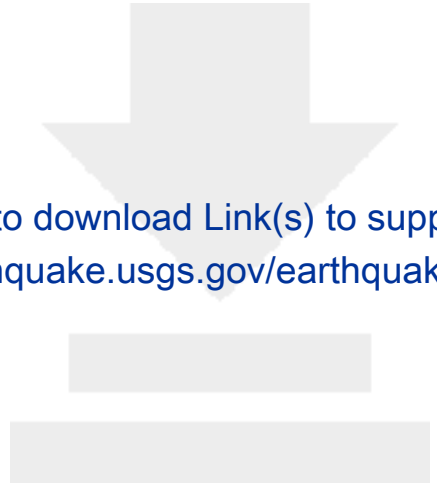
Type of magnitude	Empirical relationship	Range
Ms	$M_w = 0.67(\pm 0.005)M_s + 2.07(\pm 0.03)$	$3.0 \leq MS \leq 6.1$
Ms	$M_w = 0.99(\pm 0.020)M_s + 0.08(\pm 0.13)$	$6.2 \leq MS \leq 8.2$
Mb	$M_w = 0.85(\pm 0.040)m_b + 1.03(\pm 0.23)$	$3.5 \leq mb \leq 6.2$
Ml	$M_w = 0.934(\pm 0.135)M_L + 0.356(\pm 0.714)$	$3.4 \leq ML \leq 7.6$

Link(s) to supporting data



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Link(s) to supporting data



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http://earthquake.usgs.gov/earthquakes/search/