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Spatial and temporal analysis of seismicity and seismotectonic parameters in Albania region

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Abstract. A comprehensive analysis of *b*-value for the Albanian earthquakes was conducted using the instrumental earthquake catalogue of Albanian region. A total of 38,816 seismic events with magnitudes $M_L \geq 0.1$ on the Richter scale were utilized. Statistical characteristics of the seismicity were examined based on *b*-value, as defined by the Gutenberg-Richter law. Considering the magnitude completeness (*Mc*-value) as 2.7, *b*-value was estimated as 1.09 ± 0.08 and it indicates a normal stress regime in the region. The *Mc*-value varies from 1.5 to 3.4, and spatial distribution of *b*-value ranges from 0.79 to 1.16. Higher *b*-values (> 1.0) were detected in the southernmost part of Albania, whereas lower *b*-values (< 1.0) were found in the western part, particularly within the Adriatic-Ionian fault zone and the Lushnje-Elbasan-Dibër transversal fault zone, as well as in the south-eastern Leskovik-Erseka-Korça fault zone. Regions with lower *b*-values correspond to areas with larger-magnitude events, while higher *b*-values are associated with smaller earthquakes. These findings suggest that *b*-values across Albania generally round 1.0, with lower values indicating moderate stress accumulation in the western region and within two other active seismic belts. The *b*-values less than 1.0 may signal areas of increased seismic potential. The occurrence probability of earthquakes across varying magnitudes was found to be very high (99%–100%) for seismic events with M_L between 0.5 and 4.5, and lower (less than 95%) for events with $M_L \geq 5.5$; it varied from 1% to 60% for events with larger $M_L \geq 6.0$ for different *Tr* values. Recurrence periods for smaller magnitudes are relatively short (less than 1 year for magnitudes from 1.0 to 4.2), whereas for larger magnitudes (5.0 to 6.0), recurrence periods are longer, about 100 years. The Albanian region is characterized by a complex geological setting and significant seismic activity, and, thus, it can be stated that these types of analyses may be important in terms of seismotectonic evaluation and seismic hazard.

Keywords: *seismicity; b-value; probability; recurrence period; seismic hazard*

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INTRODUCTION

Numerous regional and temporal studies have analyzed the space-time characteristics of earthquake activity worldwide, yielding significant insights, particularly through the application of scaling laws (e.g., Mogi 1962; Utsu 1971; Frohlich, Davis 1993; Wiemer, Wyss 2000; Polat *et al*. 2008; Öztürk 2013, 2017; Özer 2021; Alkan *et al*. 2025). Albania, situated along the Alpine-Mediterranean seismic belt, is seismically active and has experienced numerous destructive earthquakes over the past two millennia, as detailed in historical records (Aliaj *et al*. 2010; Ormeni *et al*. 2013, 2022). The seismicity of the region is primarily driven by the collision between the Adriatic microplate and the Eurasian plate (Mazzoli, Helman 1994), resulting in a significant tectonic deformation. This continental collision particularly affects Albania's interior, especially along the longitudinal and transverse fault zones that traverse its eastern and north-eastern regions (Aliaj *et al*. 2010; Ormeni *et al*. 2013, 2022, 2023).

The tectonic landscape of Albania is marked by several major fault lines and a well-documented history of seismic activity. The main tectonic regime is dominated by microseismic activity, with frequent small- to moderate-sized earthquakes and occasional larger events. Notably, six significant earthquakes with surface wave magnitudes (*M*s) greater than 6.0 occurred in the past century: the 1905 Shkodra earthquake (*M*s = 6.6) along the Shkoder-Pej fault zone, the 1911 Ohrid Lake earthquake (*M*s = 6.7, surface wave magnitude) along the Korça-Ohrid-Peshkopi zone, the 1920 Tepelena earthquake (*M*s = 6.4) along the Vlora-Tepelena fault zone, the 1926 Durres earthquake (*M*s = 6.2) along the Adriatic fault zone, the 1967 Dibra earthquake (*M*s = 6.7) along the Lushnje-Elbasani-Dibra fault zone, and the 1979 Ulqin earthquake (*M*s = 6.9) along the Lezha-Ulqin fault zone (Aliaj *et al*. 2010; Ormeni *et al*. 2017). More recently, the 2019 Adriatic fault zone earthquake (*M*s = 6.4), with its epicentre near Durres, caused a significant impact (Marku *et al*. 2022).

This study aims to analyze the region-time-magnitude properties of seismic activity in the fault zones of Albania to assess seismic hazard potential. Specifically, we investigate size-scaling distributions, regional, temporal and magnitude distributions of seismic events. Additionally, we explore magnitude completeness (*Mc*-value), seismotectonic *b*-value and its regional variations. All statistical analyses and histograms of regional, temporal and magnitude distributions in Albania and its surrounding areas were generated using ZMAP analysis software (Wiemer 2001).

GEOLOGIC AND TECTONIC STRUCTURES IN ALBANIA

Albania, the subject of this research, shares borders with Kosovo and Montenegro to the north, is bounded by the Adriatic and Ionian Seas to the west, Greece to the south and southeast, and North Macedonia to the east (see Fig. 1). Situated inside the Alpine-Mediterranean seismic belt, it represents a convergent zone between the African and Eurasian lithospheric plates. The Albanian Mountain range, a segment of the Dinarides-Hellenides orogen, extends in the NNW–SSE orientation (refer to Fig. 1). The Albanian Mountain belt was formed during the Alpine orogenic phase, resulting from the collision between the Apulia and Eurasia plates and the closure of the Mesozoic Tethyan Ocean (Aliaj *et al.* 2010; Bejko *et al*. 2023).

The Albanian orogen and its adjacent regions are categorized into two distinct tectonic domains: an external compressional domain, forming the Adriatic collision zone (outer Albanides), and an internal extensional domain (inner Albanides) (Aliaj *et al*. 2010; Marku *et al*. 2022) (Fig. 1). The primary driver of seismic activity in Albania is the ongoing collision between the Adriatic microplate and the Albanian orogen. This tectonic activity resulted in significant historical and instrumental earthquakes, including those with magnitudes reaching M6.8 (e.g., the 1851 Vlora earthquake, the 1911 Pogradec earthquake, and the 1967 Dibra earthquake), as well as a M7.0 earthquake in Ulqin in 1979. The region continues to be a high seismic hazard zone, as demonstrated by the recent earthquake with M_L6.4 that struck Durres on 26 November 2019 (Öztürk, Ormeni 2021). The earthquake foci in Albania are predominantly condensed along active faults and low-velocity zones (Aliaj *et al*. 2010; Ormeni *et al*. 2013, 2021, 2022). The seismic activity is mostly concentrated in the upper and middle crust (Ormeni 2011) and is directly related to the tectonic deformation occurring along the western margin of the Adriatic indentation. Identifying new active faults and analyzing well-known Albanian faults is a crucial step in conducting seismotectonic studies and evaluating seismic hazards, as it allows for the definition of seismic sources that are responsible for major earthquakes.

DATA

In the Albanian seismogenic zone, a total of 38,816 tectonic earthquakes with magnitudes $M_L \geq 0.1$ were located (Fig. 2). The earthquake database used for this analysis was obtained from the Albanian Seismological Catalogue, covering the time period from 17 January 1966, to 31 December 2024 (IGEO 2025). This catalogue includes all earthquakes that occurred along the Albanian fault zones and their surrounding areas. The catalogue is complete for all magnitude levels and spans the entire period from 1966 to 2024 (Ormeni *et al*. 2022; Skrame *et al*. 2024). The epicentres of earthquakes with magnitudes between $2.0 \leq M_L \leq 6.9$, as well as strong main shocks with magnitudes $M_L \geq 5.0$ are presented in Fig. 2. Additionally, the distribution of events with varying magnitudes is represented using different symbols in the same figure. The analysis focuses on shallow earthquakes with depths smaller than 70 km, as this depth range is particularly relevant for future seismic hazard assessments and in identifying precursory quiescence anomalies associated with crustal main shocks. The focal depth analysis further reveals that the seismicity

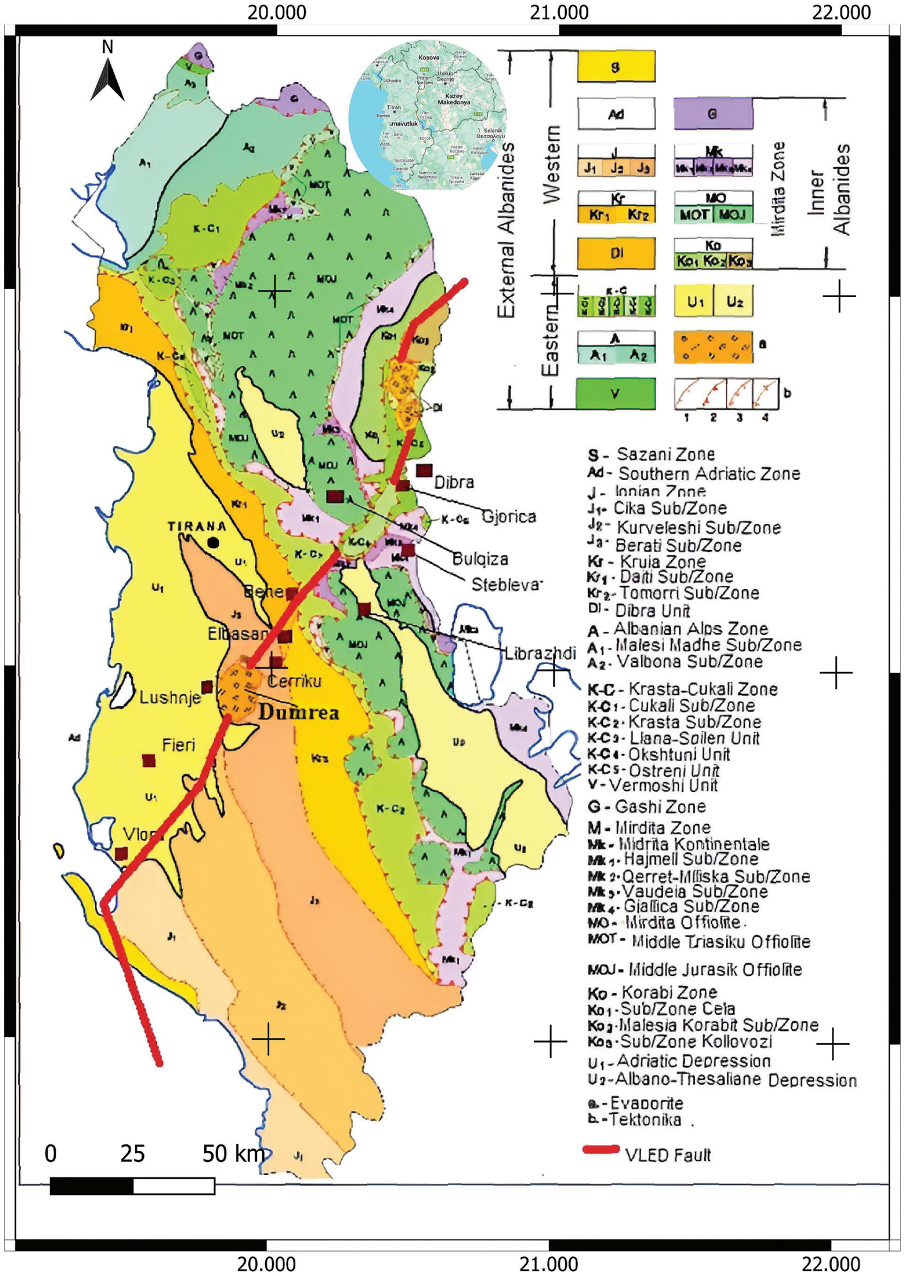

Fig. 1 Schematic tectonic map of Albania showing the main geological and structural domains (Aliaj *et al*. 2010)

in the study region primarily occurs within the shallow upper crust, consistent with the tectonic structures described earlier (Ormeni *et al*. 2022).

METHODS

Gutenberg-Richter relation, recurrence period, occurrence probability of earthquakes

The power-law distribution of earthquake occurrences, known as the Gutenberg-Richter (G-R) relation, was proposed by Gutenberg, Richter (1944) and is one of the most widely used models in earthquake statistics. The G-R relation describes the frequency-magnitude distribution of earthquake occurrences and is represented by the following equation:

$$\log_{10} N(M) = a - bM \tag{1}$$

where $N(M)$ is the cumulative number of earthquakes with magnitudes greater than or equal to M during a specified time period, and a-value and b-value are positive constants. The a-value reflects the overall seismicity of the region, with variations due to the period of time of the catalogue, the size of the analyzed area, and the number of recorded events. As such, the a-value can vary significantly depending on the seismic activity of different zones. The b-value, determined from the slope of the G-R relation, is a key

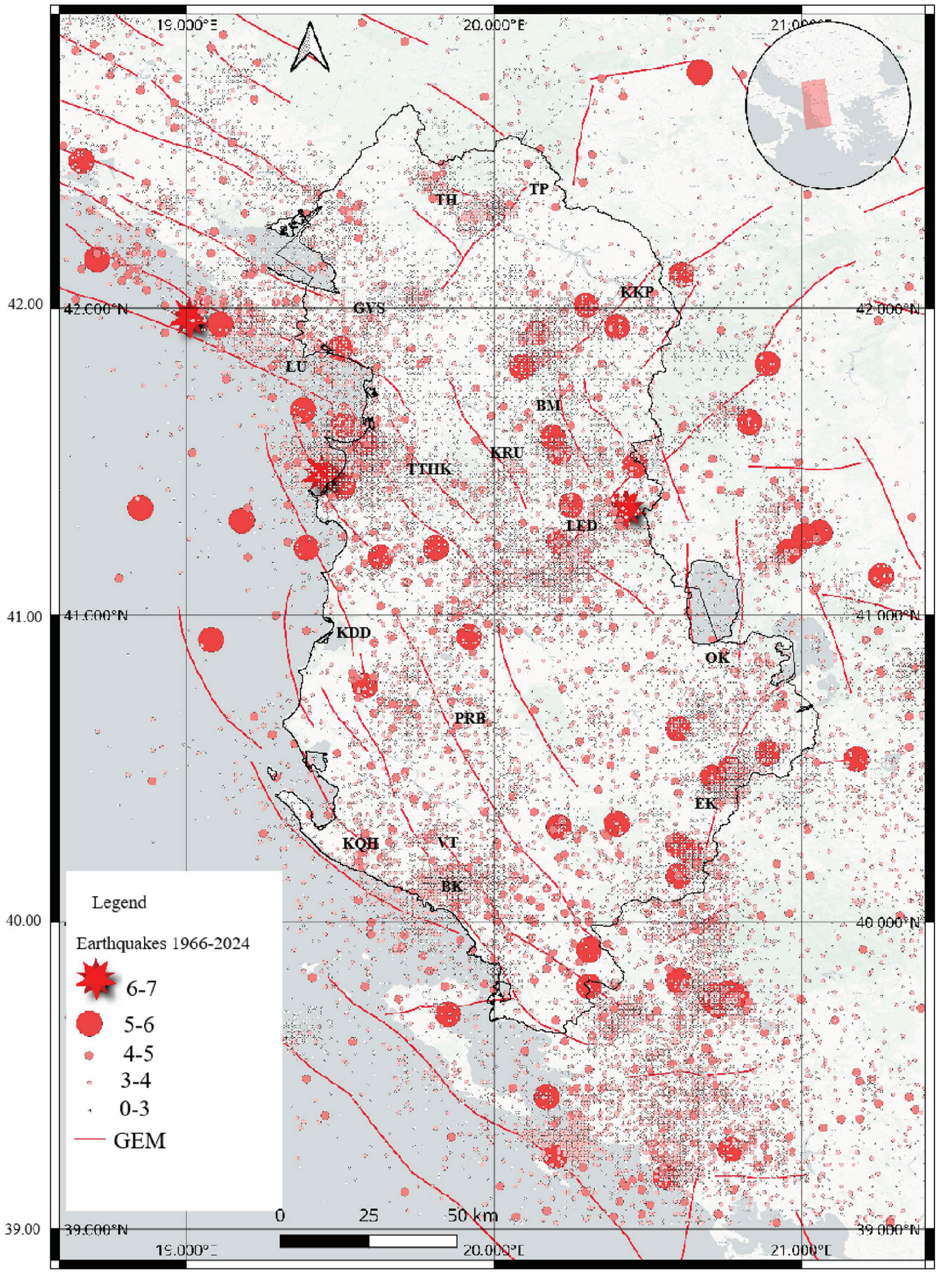

Fig. 2 Epicenter distribution in tectonic map (GEM-2024) of the earthquakes in different magnitude levels $M_L \geq 0.1$, strong main shock $M_L \geq 6.0$ star during period of time 1966–2024 and Tectonic Fault zones: LU (Lezhe-Ulqin), GVS (Gomsiqe-VauDejes-Shkoder), TH (Thethi Zone), TP (Tropoj-Peje), KKP (Kurbnesh-Kukes-Prizren), BM (Bulqiz-Macukull), KRU (Klos-Reps-Ulez), TTHK (Tirane-Thuman-Kepi Rodonit), KDD (Karavasta-Divjak-Durres), PRB (Peshtan-Rehov-Berat) KOH (Kanin-Orikum-Himare). LED (Lushnje-Elbasan-Diber), OK (Oher-Korce), EK (Ersek-Korce), BK (Borsh-Kardhiq), VT (Vlore-Tepelene)

parameter in earthquake characterization. It is associated with the relative number of smaller earthquakes compared to larger ones.

The *b*-value is influenced by various factors such as tectonic properties, anisotropic structures, stress heterogeneities, material properties, geological structure, fracture density, thermal gradients, fault length, strain conditions, seismic wave velocities, and attenuation, as well as slip distribution (Mogi 1962; Öztürk 2013; Radziminovich *et al*. 2019; Özer *et al*. 2022). A negative relationship is generally observed between *b*-value and stress distribution. The *b*-value typically varies from 0.3 to 2.0 across different zones globally (Aki 1965), with an average value of around 1.0 (Mogi 1962; Scholz 2015). Given its sensitivity to the region's rheology, the *b*-value is an essential parameter for understanding seismic behaviour. Earthquake probabilities for different magnitudes can be estimated using the following equation (Tabban, Gençoğlu 1975):

$$P(M) = 1 - e^{-N(M)*Tr} \tag{2}$$

where $P(M)$ is the probability that an earthquake of magnitude M will occur within a specified time interval Tr, and $N(M)$ is derived from the G-R relation.

The recurrence period Q for earthquakes of magnitude greater than or equal to M can be estimated by the following formula (Tabban, Gençoğlu 1975):

$$Q = 1 / N(M), \tag{3}$$

where Q represents the expected time interval between earthquakes of magnitude M.

Another important parameter for statistical analysis is magnitude completeness (Mc-value), which is the smallest magnitude that ensures the catalogue is complete. The Mc-value represents the threshold at which 90% of the earthquakes are included in the catalogue (Zuniga *et al*. 2020). Variations in the Mc-value over time can affect the estimation of other seismicity parameters, such as b-value. Therefore, the maximum number of earthquake events is considered for more accurate results in the analysis. As a result, estimating the Mc-value is a crucial first step in any seismic study. In this study, various statistical parameters, including b-value and Mc-value, were computed using the ZMAP software package developed by Wiemer (2001).

RESULTS

Figure 3a illustrates the cumulative number of earthquakes over time, based on the earthquake catalogue containing 38,816 earthquakes with magnitudes $M_L \geq 0.1$. From 1966 to 1975, seismicity remained relatively stable, with only a few events occurring between 1975 and 1979. However, a noticeable increase in earthquake activity is observed from 1979 to 1995, and this upward trend continues through 2019. A significant rise in earthquake occurrences is evident from 2019 to 2023. As indicated in the Data section, the catalogue includes earthquakes with magnitudes varying from 0.1 to 6.9, with the largest recorded earthquake being the 1979 Ulqin earthquake, which had a magnitude of $M_L = 6.9$. Consequently, a value of $M_L = 7.0$ was selected as the upper bound for the magnitude axis. Given that the Mc-value (magnitude of completeness) exhibits temporal variation, the main objective of this analysis is to use the maximum number of earthquakes to ensure reliable statistical evaluations (Fig. 3, right). The temporal variations in the Mc-value are estimated using their standard deviations over 100-sample moving windows. The analysis uses the original catalogue containing 38,816 events ($M_L \geq 0.1$). As shown in Fig. 3b, Mc-value ranged between 2.5 and 3.4 until 2019, after which it decreased to approximately 2.5 by the end of 2019. From 2019 to 2023, Mc-value fluctuated between 1.5 and 2.8. These findings indicate that Mc-value exhibited significant variation over time, ranging between 2.5 and 3.5 from 1967 to 2019. Therefore, an average Mc-value of 2.8 is considered appropriate for all statistical estimates.

Figure 4 presents the time histograms and magnitude of seismic events occurrences within and around the Albanian fault zones. As outlined in the Data section, the magnitude of earthquakes ranges between 0.1 to 6.9, with the number of earthquakes showing an exponential decay as magnitude increases. As seen in Fig. 4a, most earthquakes have magnitudes between 1.0 and 3.5, with the highest frequency occurring at $M_L = 2.5$. Earthquakes with $0.1 \leq M_L < 3.0$ total 31,062, while there are 6,912 earthquakes in the magnitude range $3.0 \leq M_L < 4.0$, 777 earthquakes in the $4.0 \leq M_L < 5.0$ range, 62 earthquakes in the $5.0 \leq M_L < 6.0$ range, and 3 earthquakes with magnitudes $M_L \geq 6.0$. As a result, earthquakes with magnitudes between 1.0 and 3.5 occur more frequently than those of larger magnitudes in Albania and its vicinity. The increasing number of small-magnitude earthquakes may reflect rising stress levels in the Eastern Fault Zones (EFZ) in recent years.

Figure 4b shows the time histogram of earthquake occurrences from 1966 to 2024. Seismic activity remained relatively stable between 1966 and 1974, with only 329 events recorded across all magnitudes dur-

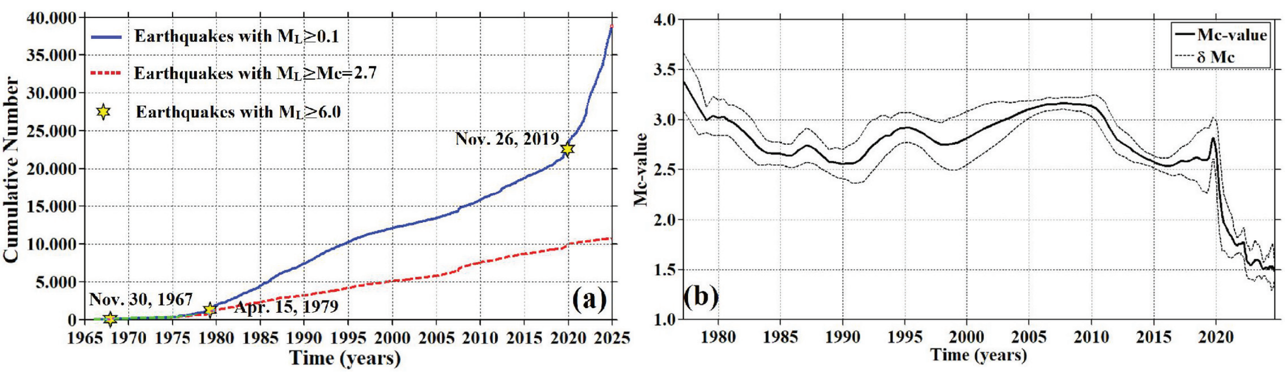

Fig. 3 (a) Time variations of the cumulative number of earthquakes between 1966 and 2024 for the catalogue with $M_L \geq 0.1$ and catalogue $Mc \geq 2.7$. (b) Temporal variation of magnitude completeness, Mc-value. The standard deviation, δMc, is also given

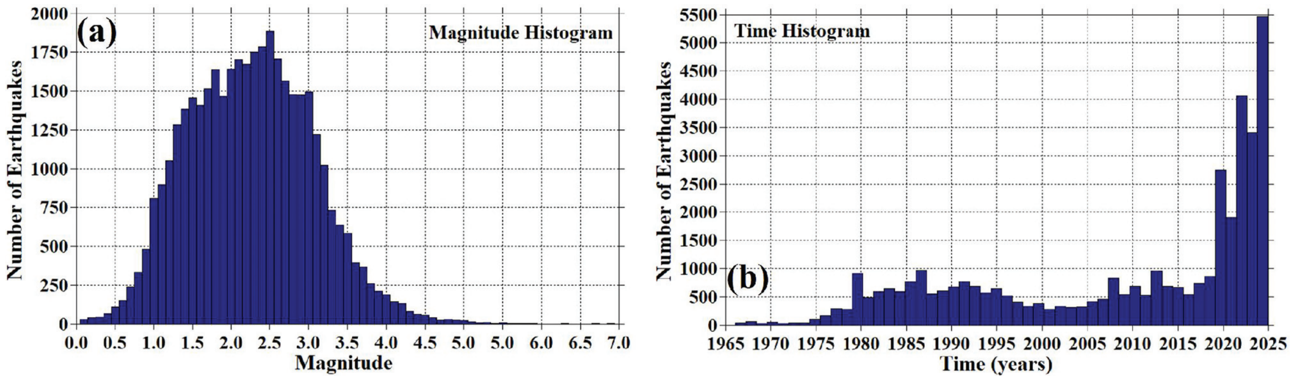

Fig. 4 (a) Magnitude histogram. (b) Time histogram of the seismicity in Albania and its surrounding from 1966 to 2024

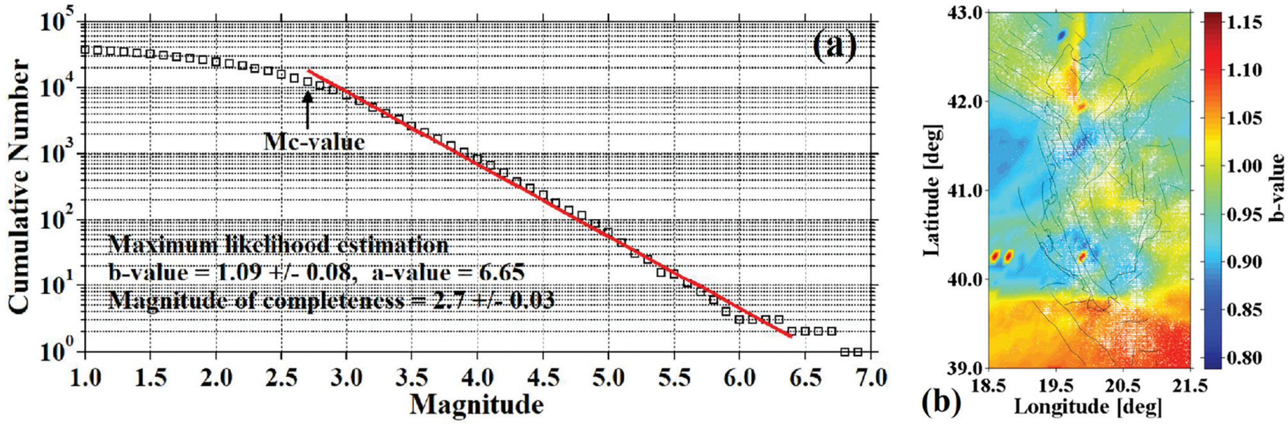

Fig. 5 (a) The distribution of frequency and magnitude along with the *b*-value from the Gutenberg-Richter (G-R) relation: the *b*-value, its standard deviation, the *a*-value, and the *Mc*-value. (b) Spatial variations in the *b*-value across the study region. The white dots represent the earthquakes included in the computation

ing this period. Between 1975 and 2018, the number of earthquakes increased significantly, with 12,537 events between 1975 and 2002, and 8,327 events from 2003 to 2018. A sharp surge in earthquake occurrences is observed after 2018, with 17,640 events recorded between 2019 and 2024. The increase in the number of recorded earthquakes between 2019 and 2024 is mainly attributed to the installation of new seismic stations and methodological improvements, which enhanced the network's sensitivity, rather than reflecting a true increase in seismic activity.

The zones with lower *b*-values reflect to larger magnitude events, while regions with higher *b*-values are associated with smaller magnitude earthquakes (Fig. 2, epicentre distribution map). Therefore, *b*-value estimation aligns closely with the observed earthquake activity. The geographical distribution of *b*-values, frequency-magnitude distributions, standard deviations, *a*-values, and *Mc*-values are shown in Fig. 5b. The *b*-value is computed using the method of maximum likelihood. As shown in Fig. 5a, the mean *Mc*-value across all catalogues is 2.8, and the surface *b*-value is determined as 1.09 ± 0.08.

As mentioned earlier, *b*-values exhibit regional variations ranging from 0.5 to 1.5, with an average value of approximately 1.0. The frequency-magnitude distribution of earthquakes follows the G-R relation, with the *b*-value is typically close to 1.0. The estimated surface *b*-value of 1.09 is relatively high compared to the global average, as shown in Fig. 5a. Regional variation in *b*-values is also depicted in Fig. 5b. This *b*-value map is derived using a moving window technique with a sample of 850 events and grid cell spacing of 0.01° × 0.01° in longitude and latitude. Regional *b*-value variations vary from 0.5 to 1.6. Regions with larger *b*-values (> 1.0) are observed in some fault zones in the north-western part of Albania and in the Kurbnesh-Kukes-Prizren transversal fault zone. Conversely, zones with smaller *b*-values (< 1.0) are found in the rest part of Albania.

At the surface, as shown in Fig. 5a, the mean *Mc*-value across all catalogues is 2.7, and *b*-value is determined to be 1.09 ± 0.08. Regional variations in the *b*-value range between 0.80 and 1.15. (Fig. 5a). Areas with larger *b*-values (> 1.0) are found in the southernmost regions south of Ksamil-Vagalat-Karroq municipalities and in the northern parts of Albania (Gomsiqe-Vau i Dejes-Boge-Shkodra zone). Conversely, regions with lower *b*-values (0.80 to 0.90) are concentrated along the Adriatic-Ionian fault zone, particularly in the Ionian zone (especially in Kanin-Qafa e Llogaras-Himar, Borsh-Kardhiq, Vlore-Tepelene-Helmes i

Ersekes fault zones), in the south-eastern part of Albania (Kakavij-Leskovik-Ersek) and in the Adriatic zone (Karavasta-Divjak-Durres fault zone, Zallher-Kruj-Thuman-Mamurras, Klos-Rrep-Ulez and Bulqiz-Macukul faults, Lezhe-Ulqin fault zone). This lower range of *b*-values is also observed in the Tropoj-Peje fault zone, and *b*-values vary from 0.92 to 0.96 in Brezhdan-Peshkopi-Rabdisht and in Ersek-Korce fault zone, while in the Lushnje-Elbasani-Diber transversal fault zone, *b*-values range from 0.95 to 0.99.

Evaluation of seismically active layers at various depths in the Albanian Earth's crust and mantle

The distribution of earthquake depths in Albania offers valuable insights into the structure of the Earth's crust and mantle. where stress accumulates. Most earthquakes with magnitudes $M_L > 0.1$ recorded by numerous seismological stations have hypocentral depths ranging from 0 to 25 km (Fig. 6a). The majority of seismic energy is released from tectonic faults at these shallow depths, which generates observable effects on the Earth's surface.

An accurate determination of the depth of an earthquake depends on the proximity of seismic stations to the event's epicentre. Depth determinations tend to have slightly higher errors compared to location determinations (Ormeni *et al*. 2022; Ormeni, Öztürk 2024). In our study, the error margin for depth is typically +/- 3 or 4 km, which is relatively small, especially when the depth is less than 25 km. On occasions when the seismic network is dense and stations are located close to the epicentre, we can achieve highly precise depth measurements.

Shallow earthquakes, in general, tend to have a greater destructive impact compared to deeper earthquakes. Seismic waves originating from deeper earthquakes lose energy as they travel toward the surface. Consequently, the tremors from a moderate to strong earthquake that occurs at a depth of more than 30 km are considerably weaker at the surface compared to those from an earthquake of the same magnitude that occurs at a depth of 10 km (Fig. 6b).

The thickness of the Moho boundary, which marks the boundary between the Earth's crust and mantle, varies across Albania. In the western part of Albania, the distance from the Moho to the surface is shallow, approximately 30 km. However, it becomes considerably thicker in the east, ranging from 40 to 55 km. Few earthquakes, however, have depths that extend below the Moho discontinuity into the uppermost mantle within this active tectonic fracture system (Fig. 6b).

The depth of earthquakes plays a crucial role in seismotectonic studies, especially when assessing seismic hazards. A key factor that influences the level of damage in an affected zone is the depth at which the main shocks and large aftershocks occur. By analyzing the depth data of earthquakes in the active faults system, it can be generalized that the earthquake depths in Albania predominantly range from the upper to the middle crust, with a bottom depth of approximately 25–30 km (Fig. 6a). The earthquake epicentres within this active fault system are largely concentrated in the upper and middle layers of the Earth's crust, with very few events occurring in the lower crust or mantle (Fig. 6a).

Assessment of *b*-value with depth in the Albanian Earth's crust and mantle

A detailed calculation of *b*-values, based on depth intervals from the surface to 50 km, is illustrated in Figs 7 and 8. To ensure data continuity, a 10-km overlapping depth interval (moving step) was applied. The analysis reveals significant variations in *b*-values, especially at a depth of 20 km, where b-values range from 0.8 to 1.4. Below 40 km, a marked decrease in *b*-values is noted between 40 km and 50 km, dropping from 0.5 to 0.75.

Low *b*-values observed in these deeper layers, particularly in the upper crust and uppermost mantle, suggest that the region is under substantial stress (Mogi 1962; Frohlich, Davis 1993). These findings may provide valuable preliminary insights into the region's seismic behaviour and help identify potential

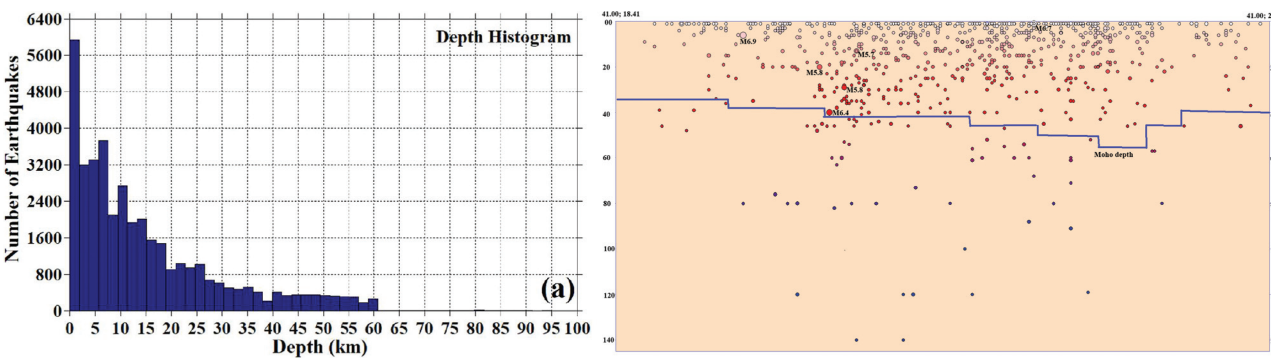

Fig. 6 (a) The number of located earthquakes categorized by depth ($M_L > 0.1$). (b) Depth distribution profile of earthquakes. $M_L > 4.0$ (big circle earthquake $M_L > 5.6$) and the Moho discontinuity (blue line)

precursory seismicity changes in and around Albania. Changes in b-value with respect to depth are shown in Figs 7 and 8, with distinct behaviours analyzed for individual zones. The geographical distribution of b-values, frequency-magnitude distributions, standard deviations, a-values, and Mc-values for the depths ranging from 10 km to 60 km are presented in Figs 7 and 8. The b-value was determined using the maximum likelihood estimation method (Aki 1965):

a) At a depth of 10 km (Fig. 7a), the average Mc-value remains 2.8 and b-value increases to 1.16 ± 0.07. The regional variation in b-values ranges from 0.8 to 1.45 (Fig. 8a). The highest b-values (1.1 to 1.4) are found in the southernmost part of Albania, particularly in the Ionian Sea, especially in Corfu Island. Larger b-values (> 1.15) are also observed in northern Albania, including the Shkoder-Puke-Fushe Arrez Burrel regions, as well as the Corovod-Gramesh-Librazhd fault zones in the south. In contrast, the rest of Albania exhibits low b-values (below 1.0), particularly in the Bulqiz-Macukull-Ulez fault zone in north-eastern Albania where b-values range from 0.89 to 0.97, as well as in the Borsh-Kardhiq, Vlore-Kanin-Himar, Vlore-Tepelene faults in Ionian seismogenic zone and Leskovik-Ersek-Korce-Oher fault zones in the southeast.

b) At a depth of 20 km (Fig. 7b), the average Mc-value is 2.7 and b-value is 1.04 ± 0.07. The regional b-value range here is between 0.80 and 1.15 (Fig. 8b). The southernmost part of Albania continues to show higher b-values (> 1.0), while the rest of the country exhibits lower b-values (< 1.0). In south-eastern Albania, particularly in the Ersek-Korc-Pojan fault zone, b-values varies from 0.95 to 0.98. In the Vlore-Fier-Lushnje-Elbasan-Diber region, b-values range from 0.81 to 0.87, with the Elbasan-Diber segment showing lower values around 0.80–0.85. In western Albania, the Divjak-Durres-Kepi Rodonit fault zone exhibits b-values varying between 0.83 and 0.88, while the Lezha-Ulqin fault zone and the Shkodra tectonic knot show values between 0.83 and 0.87. The Kurbnesh-Kukes-Prizren region also shows significant low b-values (0.85–0.93), while the Bulqiza-Macukull and Klos-Burrel fault zones have b-values ranging from 0.86 to 0.91.

c) At a depth of 30 km (Fig. 7c), the average Mc-value is 2.8 and b-value decreases to 1.0 ± 0.08. The regional variation in b-values ranges from 0.73 to 1.16 (Fig. 8c). The southern part of Albania still shows relatively high b-values (> 1.0), but the Korfuzi zone has very low b-values (0.73–0.76) with the

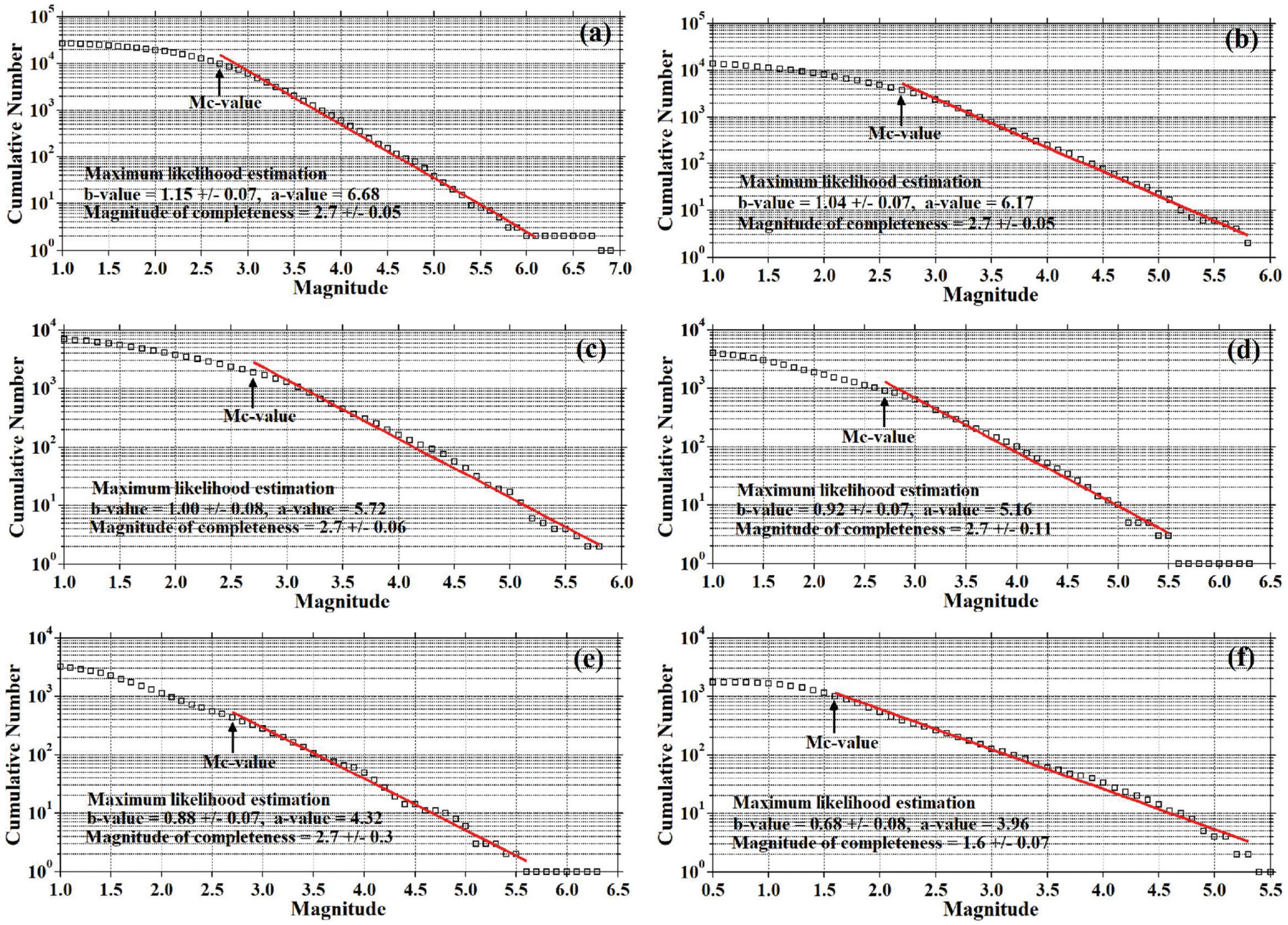

Fig. 7 Magnitude-frequency distributions and Gutenberg-Richter relations of earthquakes with depths for (a) 10 km, (b) 20 km, (c) 30 km, (d) 40 km, (e) 50 km and (f) 60 km, respectively

same low valies in Vlore-Ballesh-Berat fault zone and Korca-Oher zone. Low *b*-values (< 1.0) are found across other zones as the Borsh-Kardhiq fault zone (0.93–0.98), the Dukat-Orikum-Zverrnec fault zone (0.78–0.83), and the Frakull-Divjak-Durres and Tirane-Thuman-Kepi Rodonit fault zones (0.78–0.83). The Vlore-Lushnje-Elbasan-Diber fault zone exhibits *b*-values ranging from 0.83 to 0.87, while the Lezha-Ulqin fault zone and Shkodra tectonic knot zone show values around 0.85. The Shkoder-B. Curri-Peje and Thethi fault zones have a b-value of approximately 0.85, and the Bulqiza-Macukull-Ulez region has a *b*-value around 0.80–0.86.

d) At a depth of 40 km (Fig. 7d), the average *Mc*-value is 2.7 and b-value decreases to 1.0 ± 0.08. The regional variation in *b*-values ranges from 0.73 to 1.16 (Fig. 8d). The southern part of Albania, south of Borshi-Kardhiq, shows relatively high *b*-values (> 1.0), but the Dukat-Orikum-Vlora-Zverrnec-Adriatic Sea zone has very low *b*-values (0.68–0.72). Low *b*-values (0.68–0.72) are also found in the Peshtan-Buz-Rehov-Berat-Kucove fault zone. In the Lushnje-Elbasan-Diber fault zone, b-values range from 0.70 to 0.75. The Tirane-Thuman and Kepi-Rodonit fault zones show values between 0.68 and 0.73, while the Lezha-Ulqin fault zone and Shkodra tectonic knot zone show values around 0.72 to 0.75. The B. Curri-Peje and Rragam-Curraj i eperm fault zones exhibit *b*-values between 0.75 and 0.79, while the Leskovik-Ersek-Korce-Oher fault zone shows a *b*-value between 0.68 and 0.75. The Kurbnesh-Kukes-Prizren region and the Bulqiza-Macukull and Klosi-Burrel fault zones show low *b*-values (0.75–0.80).

e) At a depth of 50 km (Fig. 7e), the average *Mc*-value reaches 2.7 and *b*-value further decreases to 0.88 ± 0.07. The regional variation of *b*-values is between 0.51 and 1.15 (Fig. 8e). At this depth, all regions show *b*-values between 0.51 and 0.6, except for the south-eastern Leskovik-Ersek-Korca fault zone, which shows *b*-values between 0.8 and 0.9, and the Ohri zone, where high *b*-values range from 1.0 to 1.1.

f) At a depth of 60 km (Fig. 7f), the average *Mc*-value remains 2.7 and *b*-value decreases further to 0.68 ± 0.08. The regional variation of *b*-values ranges from 0.50 to 0.97 (Fig. 8f). At this depth, the south-eastern Korca-Vithkuq-Oher-Bitol fault zone shows *b*-values between 0.8 and 0.9, while Leskovik-Ersek shows values between 0.7 and 0.8. The Lushnje-Elbasan-Diber fault zone exhibits *b*-values between 0.7 and

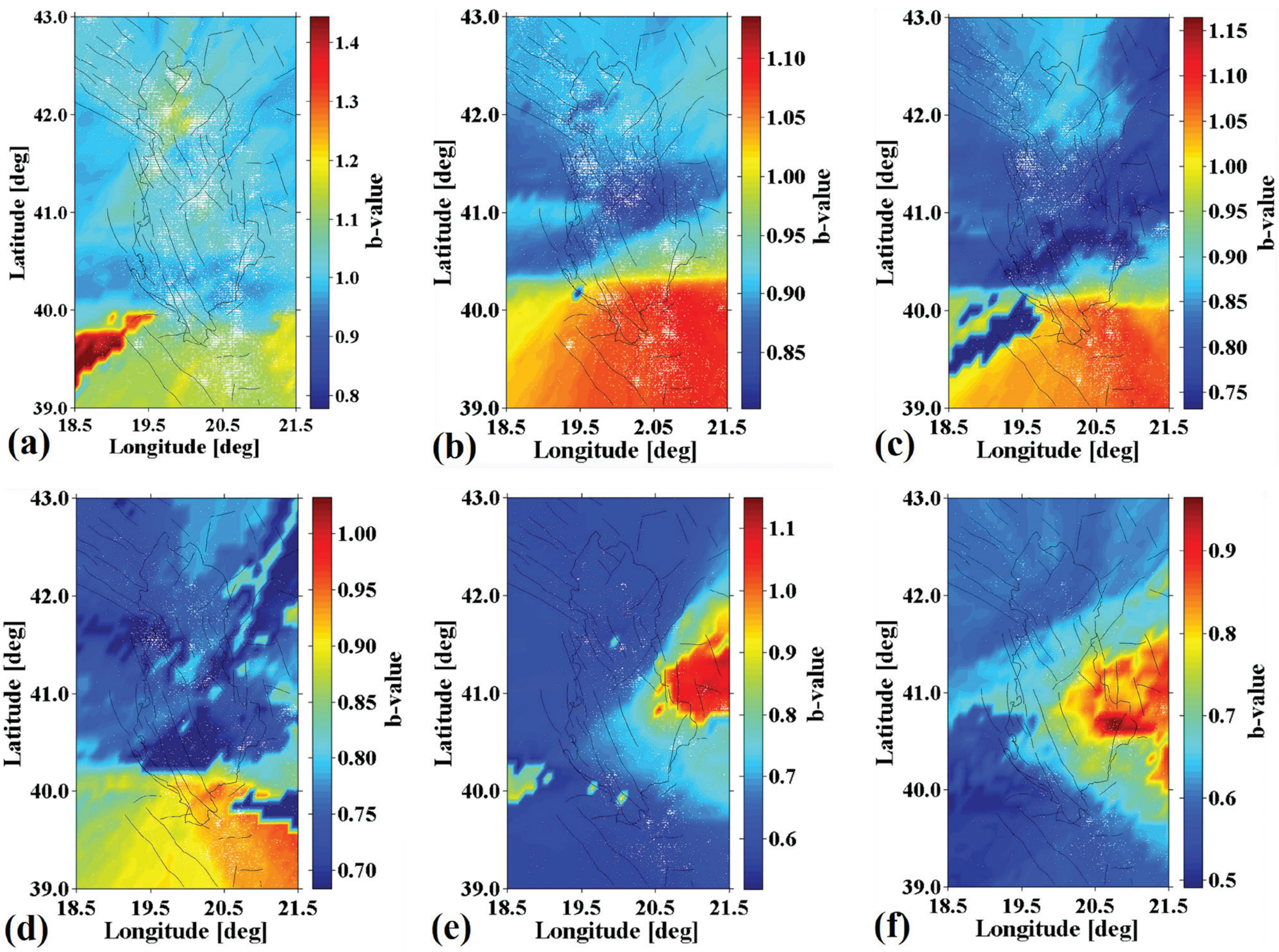

Fig. 8 Regional changes in *b*-value with depths for (a) 10 km, (b) 20 km, (c) 30 km, (d) 40 km, (e) 50 km and (f) 60 km, respectively. The white dots represent the earthquakes utilized in the calculations

0.78, and the Bulqiza-Macukull and Klos-Burrel fault zones show values between 0.6 and 0.7. The southern part of Albania, south of Borshi-Kardhiq, shows the lowest *b*-values (0.52–0.62), but the Dukat-Orikum-Vlora-Zverrnec-Adriatic Sea zone exhibits lower *b*-values (0.55–0.64). Additionally, low *b*-values are found in the Frakull-Divjak-Durres (0.58–0.65) and Tirane-Kepi Rodonit fault zones (0.55–0.64). The northern part of Albania shows *b*-values varying from 0.54 to 0.65, especially the Lezha-Ulqin fault zone and Shkodra tectonic knot zone show values around 0.54 to 0.62, as does the Shkoder-Peje region. The Kurbnesh-Kukes-Prizren and Thethi fault zones show *b*-values ranging from 0.55 to 0.64.

Estimation of earthquake probabilities and recurrence periods

One of the critical statistics for understanding earthquake behaviour involves estimating the probabilities of occurrence and recurrence periods for earthquakes of various magnitudes. For this purpose, earthquake probabilities and recurrence intervals for various magnitudes from the catalogue are shown in Fig. 9a. The probability of earthquake activity for different magnitude ranges shows relatively high values. For earthquakes with magnitudes between $0.5 \leq M_L \leq 4.5$, the probabilities range from 99.8% to 100%. For larger magnitudes ($5.0 \leq M_L$), the probabilities are slightly lower but still significant (Fig. 9a). Specifically, the probabilities of earthquakes with $M_L = 5.0$ for recurrence periods (*Tr*) of 10, 20, 50, 70, and 100 years are estimated to be about 65.74%, 88.26%, 99.52%, 99.94%, and 99.99%, respectively. The probabilities for $M_L = 6.0$ earthquakes are about 8.52%, 16.72%, 39.16%, 48.74%, and 58.87% for the same recurrence periods. Similarly, the probabilities for $M_L = 6.9$ earthquakes are 0.91%, 1.80%, 4.45%, 6.17%, and 8.69% for 10, 20, 50, 70, and 100 years, respectively. These estimates indicate that the likelihood of larger magnitude earthquakes diminishes with time, but they remain noteworthy over longer periods.

The recurrence periods for earthquakes of various magnitudes are shown in Fig. 9b. Earthquakes with magnitudes ranging from 1.0 to 4.2 exhibit relatively short recurrence intervals (less than 1.0 year). Magnitudes between 4.3 and 5.2 have recurrence periods ranging from 1 to 10 years, while for magnitudes ranging between 5.3 and 6.1, recurrence periods are estimated to range from 10 to 100 years. Earthquakes with magnitudes between 6.2 and 7.0 are expected to recur once every 100 to 1000 years.

As seen in Fig. 9b, the recurrence periods for $M_L = 6.0$ and $M_L = 6.5$ earthquakes are estimated to be about 127.99 and 454.69 years, respectively. These recurrence periods are critical for understanding a long-term seismic risk in the region and can guide seismic hazard assessments and preparedness efforts.

The recurrence periods for other magnitude levels can be observed in Fig. 9b. The findings from the probability and recurrence period analysis suggest that earthquakes with magnitudes between 4.0 and 5.5 are more likely to occur in a short term compared to those of higher or lower magnitudes. This suggests that earthquake activity within this magnitude range is more frequent and poses a relatively higher likelihood of occurrence over shorter periods.

These findings provide valuable statistical insights into the seismic behaviour of the study region. Understanding the probability of stronger earthquakes, particularly those in the 4.0 to 5.5 magnitude range, is crucial for regional seismic hazard assessments and can help inform preparedness strategies. Moreover, these results are significant for evaluating the long-term earthquake risk, as they highlight a more frequent occurrence of moderate to strong earthquakes in the near future.

DISCUSSION

The observed rise in earthquake occurrences from 2019 to 2024 suggests a more active seismic period in Albania, potentially linked to the accumulation of tectonic stress in the region. This pattern aligns with previous studies on the region's seismotectonic be-

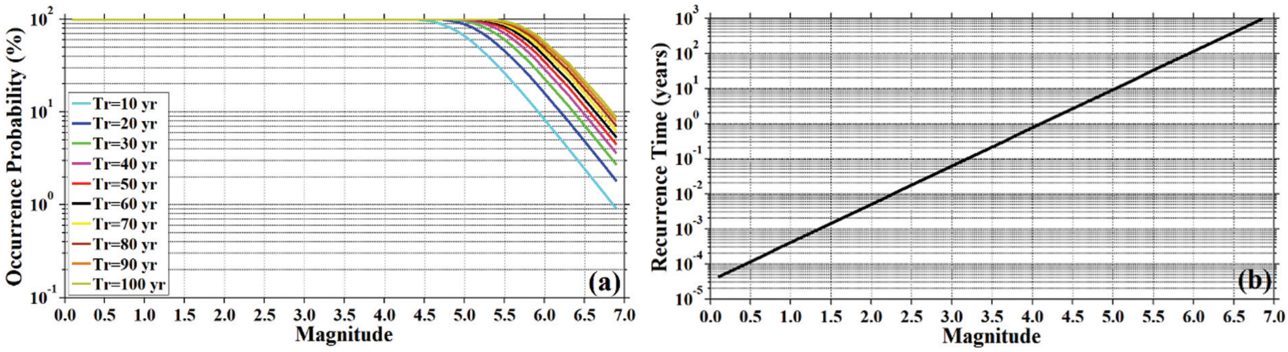

Fig. 9 (a) Probability of earthquakes that a given magnitude will be exceeded in specific times *Tr* = 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 years. (b) Recurrence periods for different magnitude sizes of the earthquake occurrences (right)

haviour (Aliaj *et al*. 2010; Ormeni *et al*. 2013; Bejko *et al*. 2023), which highlight the influence of fault dynamics and regional stress conditions on seismic activity. The increased seismicity underscores the need for enhanced earthquake hazard preparedness, particularly in areas with historically high-magnitude events. One critical aspect of seismic analysis is the fluctuation of *Mc*-values over time. The observed variations in *Mc*-values suggest potential improvements in data collection methodologies or changes in seismic monitoring capabilities. Studies by Wiemer, Wyss (2000) and Wiemer (2001) emphasize the importance of maintaining consistency in earthquake catalogues to ensure accurate seismic hazard assessments. In Albania, discrepancies in *Mc*-values could result from enhancements in the national seismic network or changes in detection thresholds (IGEO 2025). This highlights the necessity for continuous calibration of seismic data to maintain reliability. The spatial variability of *b*-values observed in this study suggests that different tectonic settings within Albania contribute to varying seismic behaviours. Fault zones exhibiting higher *b*-values are typically associated with more frequent small-magnitude earthquakes, indicative of localized tectonic activity (Mogi 1962; Scholz 2015). Conversely, lower *b*-values suggest regions where larger earthquakes are more probable due to higher stress accumulation. This trend has been documented in other seismotectonic studies of Albania (Ormeni *et al*. 2022; Skrame *et al*. 2024) and further reinforces the complex interplay between fault mechanics and seismicity.

The correlation between *b*-values and depth, as illustrated in Figs 7 and 8, reveals a decreasing trend of *b*-values with depth. This pattern aligns with previous research that associates lower *b*-values at greater depths with increased stress concentration, which may contribute to larger seismic events (Radziminovich *et al*. 2019; Öztürk 2020; Öztürk, Ormeni 2021; Öztürk, Alkan 2023, 2024). These findings provide a valuable framework for identifying potential high-risk seismic zones in Albania and improving seismic hazard assessments. The probability analysis and recurrence intervals further indicate that smaller earthquakes ($0.5 \leq M_L \leq 4.5$) have near-100% probabilities over short periods, while larger earthquakes ($M_L \geq 5.0$) remain statistically significant over longer timescales. Similar recurrence patterns have been observed in studies focusing on other tectonically active regions (Utsu 1971; Gutenberg, Richter 1944; Polat *et al*. 2002). In Albania, these recurrence statistics suggest that moderate-magnitude earthquakes (M_L 4.0–5.5) are the most recurrent and should be prioritized in short-term risk mitigation strategies. In contrast, large-magnitude events (M_L 6.0–7.0) require robust long-term seismic preparedness measures. Comparing our results with previous studies in the region, such as those by Marku *et al*. (2022) and Lule *et al*. (2024), it is evident that seismic activity in Albania is governed by complex interactions between active fault systems and regional stress redistribution. The results of this study reinforce existing knowledge while providing new insights into the evolving seismic hazard landscape of Albania. The findings are crucial for infrastructure planning, public safety initiatives, and the development of comprehensive earthquake preparedness programs in high-risk areas. Overall, the increasing seismicity, depth-dependent *b*-value trends, and recurrence period assessments highlight the dynamic nature of Albania's seismotectonic environment. Future research should focus on integrating real-time monitoring data with advanced probabilistic models to refine hazard assessments and improve earthquake forecasting capabilities.

CONCLUSIONS

The analysis of *b*-values over the past five decades provided valuable insights into the seismotectonic and geodynamic processes shaping the Earth's crust in Albania and its surrounding regions. Between 1966 and 2024, the region experienced varying levels of seismic activity, ranging from low to strong. The *b*-value, which serves as a key indicator of crustal stress conditions, exhibits spatial variations that offer significant information about the tectonic characteristics of the area. The study found that *b*-values in the region range from 0.5 to 1.6, with most of the region falling within this spectrum. *Mc*-value, representing the magnitude of completeness, varied between 1.5 and 3.4. These values suggest that seismic activity is primarily influenced by the interaction between the Adria microplate and the Albanian orogeny, especially in the western region, which is closer to the collision boundary. This region, along with fault zones in the western, south-eastern, and Lushnje-Elbasan-Diber fault zone, has lower *b*-values, indicating a higher susceptibility to moderate to strong earthquakes in the near future.

In contrast, the north-eastern and southernmost areas, which exhibit higher *b*-values, are more likely to experience smaller earthquakes. These findings highlight zones of higher seismic potential that warrant closer monitoring for possible future activity.

Given the complexity of Albania's geological structure, characterized by various fault environments and frequent seismicity, it is crucial to enhance seismic station coverage in the region. This would facilitate more comprehensive data collection and improve the interpretation of seismic activity. Additionally, field studies of the major fault systems are necessary, although challenging due to rough terrain and harsh environmental conditions.

In conclusion, *b*-value analysis plays a crucial role in understanding the seismic hazards in Albania's fault zones and contributes to the seismotectonic model of the region. It can also assist in forecasting earthquake locations and assessing future seismic risks. Furthermore, the probability and recurrence periods analysis emphasizes key aspects of seismic behaviour, particularly the frequency differences between smaller and larger earthquakes. While smaller earthquakes are more frequent and expected over short periods, larger, more destructive earthquakes remain less common but still pose significant risks over a long term. Understanding these dynamics is vital for effective seismic risk management and ensuring the region's preparedness for earthquakes of varying magnitudes.

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