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Correlations between seismic *b*-value and heat flow density in Vlora-Lushnja-Elbasani-Dibra Fault Zone in Elbasani area, central Albania

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Abstract. In this study, the correlations between the heat flow density and seismotectonic *b*-value in the Elbasani area of Albania were investigated to understand the how low-velocity layers underneath the Elbasani area in central Albania struggling the large-scale Vlora-Lushnja-Elbasani-Dibra Fault Zone affect the heat flow data. For this purpose, the heat flow and regional distribution of *b*-value were imaged for different locations and depths. To achieve the analysis, the Albanian Seismological Catalogue for the period between 1 July 1968 and 26 December 2022, including 1830 earthquakes with a local magnitude of $0.5 \leq M_l \leq 5.2$ that occurred at the depths below 70 kilometres, was considered. The *b*-value was calculated as 1.03 ± 0.06 by considering the magnitude of the completeness value as *Mc*-value = 2.6. This result shows that the *b*-value of earthquake distribution in the Vlora-Lushnja-Elbasani-Dibra (VLED) fault zone is well represented by the Gutenberg and Richter (G-R) scaling law with the *b*-value close to 1.0. The regional variations of the *b*-value show that *b*-values smaller than 0.9 were observed in the western and south-western parts of the Llinxha-Kozan thermal water belt. The depth distribution of the *b*-value indicates that there exists a sharp decrease in the *b*-values from 1.15 to 0.7 in the depths varying from 5 to 20 km. The highest heat flow values were observed on the Dumrea diapiric dome and in the central part of the Elbasani area. Thus, our analysis indicates significant and robust correlations between the geothermal and earthquake distribution. The discontinuity of Moho interface is deep in the regions where high *b*-values were observed. Low *b*-values are found at the depths ranging from 20–25 km and 35–40 km in the Dumrea evaporite massif area. We have evidence that high *b*-values and large heat flow values are related to the low seismic velocity layers underneath the Elbasani area. The low-velocity zone (LVZ) in Albania occurs in the Earth's crust and in the upper mantle. It is characterized by an unusually low seismic shear wave velocity compared to the surrounding depth intervals. It is well known that the low-velocity layers in the Elbasani area are determined in the upper crust, at shallow depths of 2–4 km, and in the middle crust at a 10–14 km depth. Hence, it is suggested that the Moho interface in the eastern part of the Elbasani area is relatively deep (45 km) compared to the western part of Albania (35 km), and the magnitude of earthquakes is smaller where the high heat flow values were observed.

Keywords: *VLED fault zone; geothermal; earthquakes; Moho; low-velocity zone; tectonics; b-value*

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INTRODUCTION

Albania is located in an area where earthquakes occur due to the collision of two tectonic plates. One of the plates is the Adriatic microplate, and the other is the Eurasian plate. The Albanides is divided into two main domains. The external domain is located in the western part of Albania, and the internal domain is distributed in the eastern part. The external collision domain in compression is characterized by reverse faulting, and the internal extensional domain is characterized by the normal faulting (Fig. 1). The strongest earthquakes in Albania occur generally in well-defined seismic belts (Ormeni 2010). One of the

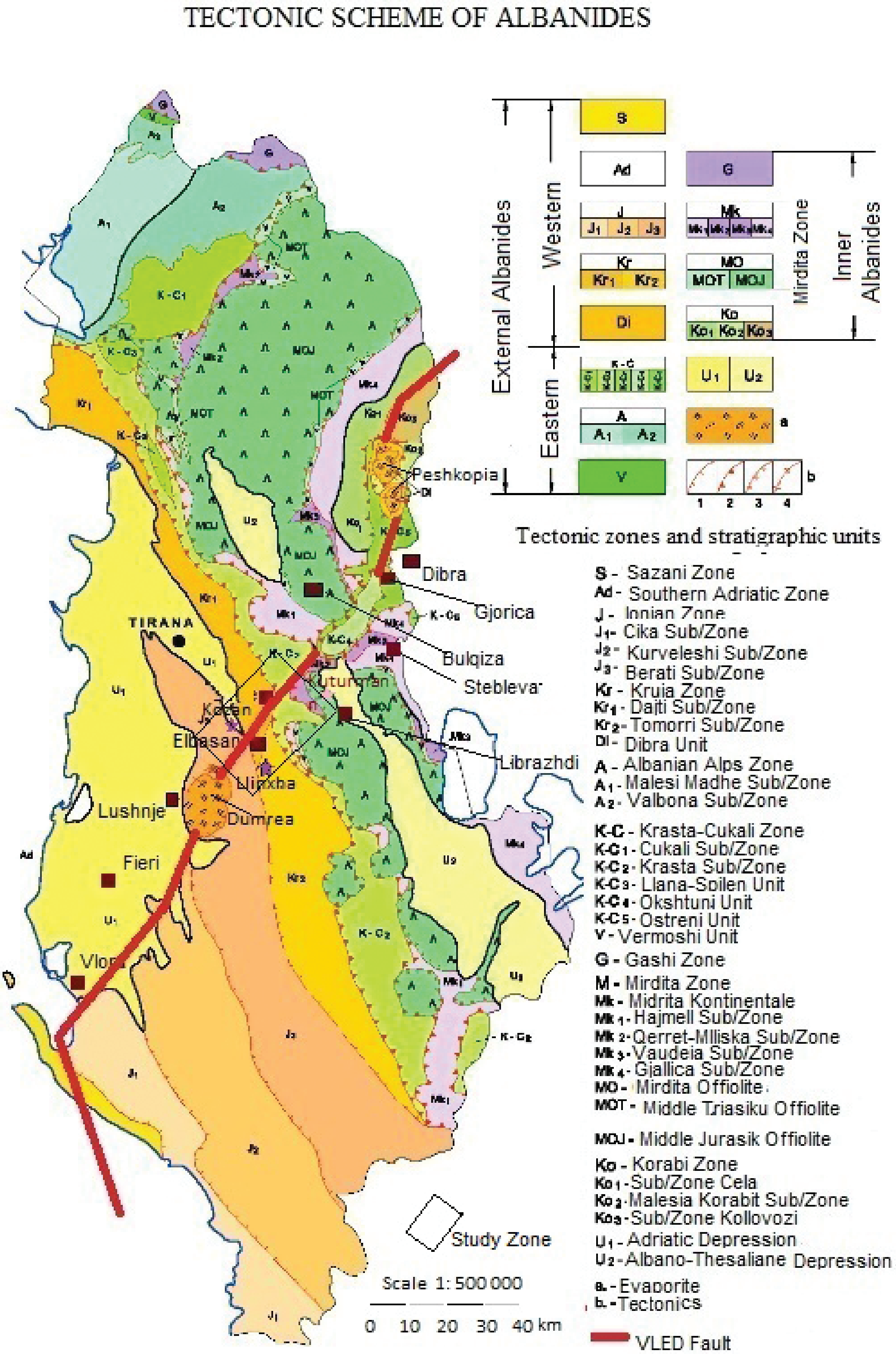

Fig. 1 Combined geological-tectonic map of Albania. VLED fault zone is shown

best-defined seismic belts is confined to the Vlora-Lushnje-Elbasani-Dibra (VLED) transversal fault zone (Aliaj *et al*. 2010). The Elbasani area is located in the central part of the VLED transversal fault zone in Albania, which is historically subjected to moderate to strong earthquakes. The current seismicity of the five last decades since 1968 in the Elbasani area is characterized by micro-earthquakes, small earthquakes, and one moderate earthquake with surface magnitude $Ms \approx 5.2$ (www.geo.edu.al).

The *b*-value is one of the best-known seismotectonic parameters related to the tectonic structure, geothermal features and material heterogeneity for the seismically active region. This parameter tells us about the structure and features of the Earth's crust in an area in which earthquakes occurred. It is related to the type of rocks, how they are arranged, and their ductility under stress (Aki 1965; Wyss 1973; Fytikas 1980; Katsumata 2006; Utsu 1971; Bayrak, Öztürk 2004; Polat *et al*. 2002; Öztürk, Bayrak 2012; Öztürk 2011; Ormeni *et al.* 2017; Nanjo 2020; Ormeni *et al*. 2022). However, the correlation between heat flow data and seismic *b*-value has not been studied intensively for different parts of the world. There are few studies for spatial and temporal evaluation of the *b*-value for different parts of Albania (Aliaj *et al*. 2010; Ormeni 2015; Ormeni *et al*. 2017; Özturk, Ormeni 2021). However, the correlation between the heat flow density and seismotectonic *b*-value was not studied for different zones of Albania. According to the tectonic implications, previous studies have been done only on mapping and temporal assessment of the *b*-value. In this work, as an important tectonostructural tool, we tried to reveal the correlation between the seismotectonic *b*-value and the heat flow density in the Elbasani zone. The *b*-value is evaluated from the Gutenberg-Richter law (Gutenberg, Richter 1944), which is a well-known equation in the statistical seismology. The Gutenberg-Richter (G-R) formula describes the number of earthquakes expected of each size, or magnitude, in a given area. In this relation, the *b*-value depends on some variables such as the geological complexity, thermal gradient, crack density, material properties, seismic wave velocity changes, fault length, seismic attenuation, strain circumstances, and slip distribution (Mogi 1962; Schorlemmer *et al*. 2005; Scholz 2015).

Heat flow studies and 3D-seismic tomography can identify the Earth's crust and heterogeneity of the upper-most mantle. The changes in *b*-value from its average value of about 1.0 for different parts of Albania may result from many reasons such as heterogeneity or an increase in microcrack density (Aliaj *et al*. 2010; Ormeni *et al*. 2017; Öztürk, Ormeni 2021). If the Earth materials have different properties or lots of cracks, a large *b*-value may be observed. On the other hand, if there is more shear stress or less pressure, a small *b*-value may be obtained. The *b*-value may also be related to heat flow data. Consequently, this research considers the comparison of lateral distribution of the *b*-value to heat flow maps and may help us understand how low velocity layers underneath the Elbasani zone affect heat flow data.

GEOLOGIC AND TECTONIC STRUCTURES OF ELBASANI AREA

Regional tectonics and active extensional regime in the study area

The Elbasani Sedimentary Basin, a small, only 30×30 km, sedimentary basin, is cut by the deep-sited Vlora-Lushnja-Elbasani-Dibra transversal fault, which is an important tectonic feature in Albania (Sulstarova *et al*. 2000; Frashëri, Čermak 2004; Ormeni *et al*. 2013, 2017). The VLED fault zone (Fig. 1), striking north-east (NE-SW), dislocates the structure of the Albanides (Sulstarova *et al*. 2000; Aliaj *et al*. 2010). It is expressed by the Vlora and Lushnja flexures, the Dumrea evaporite massif, the Elbasani Quaternary depression, the Labinoti transversal structure, and marked by a significant Quaternary infill. The manifestation of this transverse fault is evident through the Dumrea evaporite massif and the Krasta tectonic subzone, which assumes an east-west orientation in this particular segment. From the geological and tectonic point of view, the region is a part of the Krasta tectonic sub-zone, which includes an area of Alpine folding. The Krasta sub-tectonic zone has been deformed by folds, normal faults, and strike-slip faults from movement of the main Alpine orogenic phases (Ormeni *et al*. 2013). This fault is also characterized by the occurrence of the tectonic front of the ultrabasic massif of Shpati along with the formations of the Krasta subzone. Such tectonic indicators serve as a direct evidence of the transverse fault in the region. The VLED fault zone shows NE trending nearly 100 km in Albanian region. It is composed of fragmentary normal faults cutting across the Krasta zone and dividing the Mirdita ophiolites zone into two main segments (Aliaj *et al*. 2010; Ormeni *et al*. 2013).

The manifestation of recent activity is evidenced through seismic events (Ormeni *et al*. 2017; Ormeni, Daberdini 2021), the emergence of novel tectonic plates, and quaternary formations (Naço *et al*. 2005), with a particular emphasis on those resulting from fluvial processes. The VLED transversal fault zone is responsible for the altered flow of the Shkumbini River in the designated sector, and has consequently facilitated the deposition of sizable beds of gravel. The formations of the Elbasani aquifer basin and its perpendicular positioning in relation to the Krasta, Kruja, Ionian and Mirdita tectonic zones is a consequence of the VLED transversal fault zone. The evaporate massif of Dumrea situated along the VLED transversal fault zone is bounded to the eastern periphery by the carbonate anticline of Maraku. The anticlinal structure undergoes a perpetual compressional regime, while its lateral extension experiences an extensional regime that is conducive to the creation of units with graben characteristics (Bridge 2003). The Aquifer Basin of Elbasani area (refer to Fig. 2) was formed under comparable tectonic conditions (Naço *et al*. 2005).

The creation of the Shkumbini River valley in this area can be explained by the tectonic and geomorphological processes that happened because of the way the Earth's plates moved. Formerly, the valley experienced subsidence and had a lot of erosion on the bed-rock because of the impact of normal faults. Throughout the Quaternary period, the valley has been characterized by the presence of a sizable graben, serving as a conduit for the flow of the Shkumbini River. During specific epochs of the Quaternary era, it is possible that the subsidence zone referred to as graben was possibly inundated by a body of water, within which fluvial processes resulted in the accumulation of gravel sediments.

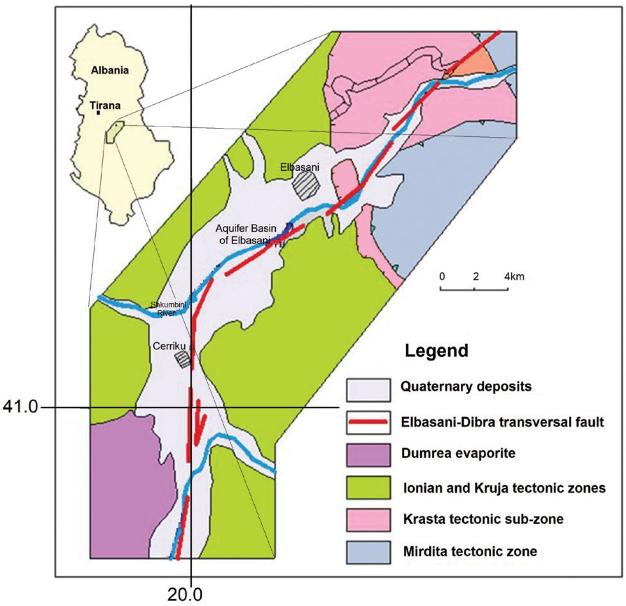

Fig. 2 Outcropping geological-tectonic map of the Elbasani Aquifer Basin and the Vlora-Lushnja-Elbasani-Dibra fault

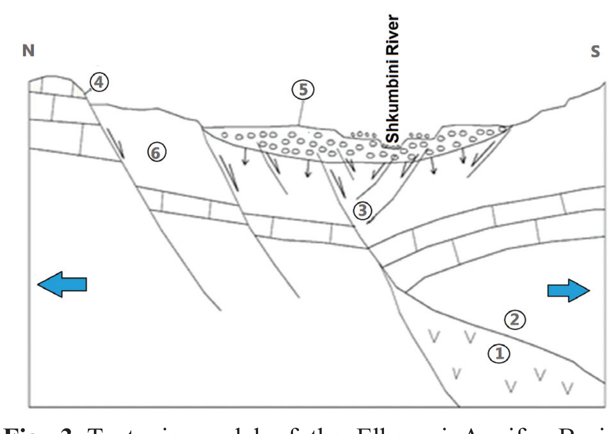

Fig. 3 Tectonic model of the Elbasani Aquifer Basin: 1. Vlora-Lushnja-Elbasani-Dibra fault and evaporite dome. 2. Extensional tectonic regime. 3. Faults. 4. Surface faults. 5. The aquifer. 6. Flysch

Under the given circumstances, the gravel stratum of the aquifer underwent its genesis, which may have resulted in a thickness that exceed 200 m. The presence of the extensional regime is discernible as evidenced by the presence of recent faults and the expansive riverbed of the Shkumbini River. A schematic representation of a tectonic model for the Elbasani Aquifer Basin is presented in Fig. 3 as follows: 1. Elbasani-Dibra fracture and evaporite uplift. 2. Extensional tectonic regime. 3. Faulting system. 4. Surface faults. 5. The aquifer basin. 6. Flysch (Aliaj *et al*. 2010). The evaporite massifs of Dumrea and Peshkopia are prominent surface manifestations of the Elbasani-Dibra transversal fault (Fig. 1). These regions demonstrate the phenomenon of diapiric uplift originating from subsurface zones through pre-existing transverse faults, resulting in complex tectonic regimes. The evaporite formations are observed to possess a continuous expansion, whereby their frontal regions are known to induce compressional tectonic regimes, while extensional regimes are developed in the inner Albanides (Bridge 2003).

DATA AND METHODS

This work focusing on conducting statistical analyses of seismic activities in country-scale data, about 40 × 40 km, was restricted only to shallow earthquakes exhibiting the depths less than 70 kilometres. The reason for choosing a maximum depth of 70 km is based on the data that earthquakes in Albania generally have their hypocenter up to this depth. The present analysis draws upon earthquake records sourced from Albanian Seismological Catalogues (www.geo.edu.al) from 1 July 1968 up to 26 December 2022. The seismic activity documentation, time period from 1968 to 2023, includes 1830 earthquakes that occurred at the depths below 70 kilometres, exhibiting magnitudes equal to or exceeding 0.5 on the Richter scale M_l (www.geo.edu.al). The magnitudes of all events observed ranges from 0.5 and 5.2. The epicentre distributions of all events are shown in Fig. 4. According to the focal mechanism solutions obtained in this zone, earthquakes are predominantly generated within the upper and middle crust as a direct consequence of tectonic conditions (Sulstarova *et al*. 2000; Ormeni 2011a; Ormeni *et al*. 2013; Ormeni, Daberdini 2021). Moreover, certain seismicity analyses, including investigations of pre-earthquake silence in seismological activity, yield noteworthy outcomes in uncovering potential earthquake hazards within a particular geographic area (Marku *et al*. 2022). In the way, to analyze the behaviours of the seismic activity of this fault zone, some statistical parameters are estimated: histograms of magnitude and time distribution of seismic events, spatial and temporal distributions of the seismic *b*-value of G-R law.

The present study is focused on the low-velocity layers identified via Albanian 3D-tomography. Ormeni (2011b) shows that in the Elbasani area low-velocity layers are determined in the upper crust, at shallow depths of 2–4 km, and in the middle crust at a 10–14 km depth. The study discovers correlations between these low-velocity layers and geothermal energy reserves that contribute to the development of our knowledge of geodynamic phenomena in the region under consideration. The temperatures have been measured and the heat flow density at two different profiles has also been calculated by Frashëri and Čermak (2004). They generated a new heat flow map of density for Albania through the determination of geothermal gradients, utilizing a constant thermal conductivity value in exploration wells and springs. They updated the first heat flow map of the Elbasani area by using temperatures measured in 8 thermal wells mostly drilled in the Elbasani Basin. According to Frashëri (2000), the average value is 30 mWm^{-2} in the western and central Albania, and the average value is 40 mWm^{-2} in the north-eastern and south-eastern Albania. In the Dumrea evaporate massif, the heat flow density is 37 mWm^{-2}. The hydrogeochemical study using the STIFF diagrams as a study methodology approves the direction of changes in the chemical composition of the thermal water from well-washed zones to less washed zones (Çomo *et al*. 2023). According to Çomo *et al.* (2023), the sources of Llixha, Elbasan, with the same composition, as well as the same geological conditions, prove that they have the same provenance.

The *b*-value of Gutenberg-Richter (magnitude-frequency) law and magnitude of completeness (*Mc*-value)

The current investigation aims to analyze the relations between the tectonic phenomenon of regional heat flow and seismotectonic *b*-value distribution in the Elbasani area in the central part of Albania. This selection criterion is based on the proposition that the

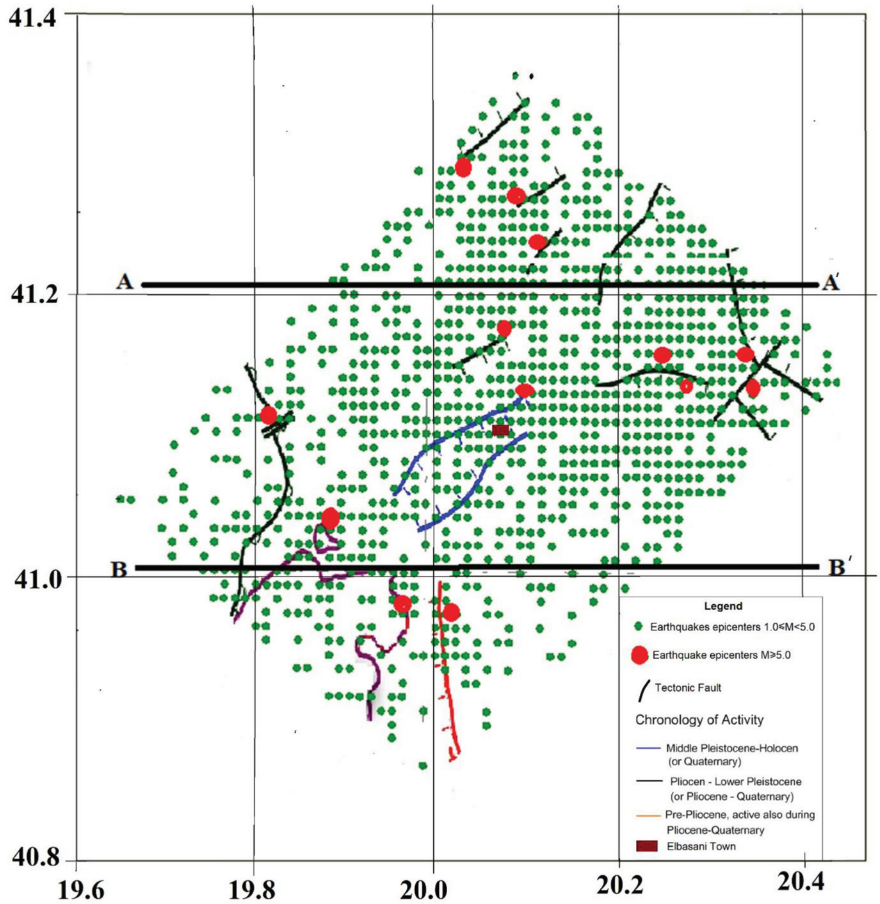

Fig. 4 The tectonic map illustrating small faults of the Elbasani area, showing the epicentres of $M_l \geq 0.5$ earthquakes registered between 1967 and 2023 (A–A' profile cut Kozani thermal water anomaly, B–B' profile cut Llinxha thermal water anomaly)

seismogenic layer in the eastern region of Albania is relatively shallow, with a thickness estimated to be around 25–30 km (Ormeni 2010; Ormeni *et al*. 2022). This means that seismic events recorded in the eastern region of Albania have a sharp cut-off at the depth of 25–30 km. The magnitude distribution of earthquakes is effectively characterized by Gutenberg and Richter (1944) relation:

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

$N(M)$ refers to the cumulative number of seismic events exhibiting magnitudes that are higher than or equal to M. The b-value describes the gradient of the size distribution of seismic events, while a-value denotes a measure of volume productivity or seismicity rate. The empirically derived parameters of a-value and b-value, as obtained from seismic catalogues, require a thorough comprehension of their underlying physical significance. The estimation of b-value conveys a fractal association between the frequency of occurrence and factors such as radiated energy, seismic moment, or fault length. This statistical parameter holds significant value in characterizing the size scaling properties of seismic activity and is extensively utilized in this context. According to Utsu (1971), the variations in b-values occur approximately within the range of 0.3 to 2.0, depending on the geographic location (Hirata 1987). The average b- value for the global-scale estimation is approximately equivalent to 1.0, as reported by a scholarly source (Frochlich, Davis 1993). The maximum-likelihood method is a way to estimate the b-value without any bias, as found in previous research (Aki 1965).

$$b = 2.303(M_{mean} - M_{min} + 0.05) \quad (2)$$

The parameter M_{mean} signifies the average magnitude of recorded seismic events, while M_{min} denotes the threshold magnitude that must be reached for inclusion in the earthquake catalogue, as per defined criteria. According to Aki (1965), the precise evaluation of local variations in M_{min} can be achieved with a significant volume of local observations for analysis, numbering around 100 or more. The numerical value denoted by 0.05 in the equation (2) is significant and holds practical significance within the context of the study. The correction constant denoted as 0.05 serves as a compensatory measure for the purpose of rectifying the effects of rounding discrepancies.

The estimation of b-value is accompanied by a 95% confidence interval, which can be computed as $\pm 1.96b/\sqrt{n}$, where n represents the total number of seismic events. The resultant outcome provides confidence intervals ranging from ± 0.1–0.2, typically observed in datasets comprising $n = 100$ earthquakes. The determination of the completeness magnitude, which represents the threshold beyond which all seismic events have been effectively detected and documented, is a crucial factor in seismicity-related investigations. This is due to the fact that utilizing the maximum possible number of earthquakes within such studies is crucial in attaining the outcomes of optimal quality. We estimate the completeness magnitude (Mc) by assuming that earthquakes follow the Gutenberg-Richter distribution (Gutenberg, Richter 1944).

The completeness magnitude exhibits variability which is contingent upon spatial and temporal considerations. Consequently, the possibility arises for temporal fluctuations to lead to inaccurate evaluations of parameters of seismicity, specifically the b-value. The possibility of portable stations being installed after the main shock and amid the initial peak of activity poses a challenge in accurately determining the spatial location of minor shocks as they tend to occur within the aftershock sequence of more significant occurrences. The temporal changes of the Mc-value, which is related to both seismic activity and station sensitivity, may significantly influence the findings. As a result, the magnitude of the completeness threshold (Mc-value) is anticipated to register higher values in the initial section of the earthquake catalogue (Wiemer *et al*. 1998; Wiemer, Wyss 2000). As this study concerns the spatial variability of b-values rather than energy or moment release, a crucial aspect of the analysis involves the completeness magnitude of the events utilized in evaluating the distribution of b-value.

RESULTS AND DISCUSSION

The Elbasani area has been subject to spatial analysis in order to deduce the relationships between heat flow and seismotectonic b-value patterns. The b-value, as expressed in the Gutenberg-Richter model, denotes the gradient of the frequency distribution of earthquake magnitudes and serves as an indicator of the comparative probability of occurrence of seismic events of large and small magnitudes within the region. Figure 5 portrays the cumulative quantity of earthquakes located within the study area during the time frame of 1968 to 2022.

There is no significant temporal variation in the frequency of earthquakes between 1968 and 1975, attributed to the sparsity of station coverage. The seismic activity exhibited a minor increase from 1975 to 1980, following which a moderate change was observed from 1980 to 1993. Subsequently, from 1994 to 2002, there was a minor change in seismic activity. However, from 2002 to 2009, there is a notable change in seismic activity, while concurrently a noteworthy alteration in seismic activity was documented between the years 2009 and 2020, with a significant change in activity occurring after the year 2020. The histogram for the Elbasani area (Fig. 6) between 1967 and 1976 indicates a very little number of earthquakes due to sparse station coverage. Between 1976 and 1989, it indicates an increase of the located earthquakes in the years 1979, 1982, 1983, 1985 and 1985. Also, between 2003 and 2023, it indicates a significant increase in the years 2003, 2010, 2011, 2013, 2015 and a major increasing trend between 2020 and 2023, with the total number of earthquakes between these years being 352. However, the maximum increase in the number of earthquakes to about 178 is observed in the year 2023 due to automatic location.

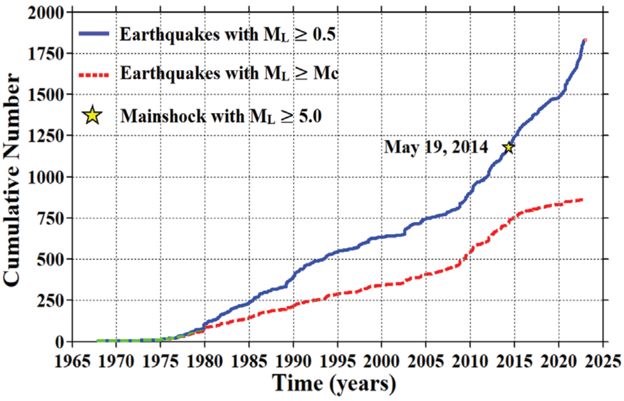

Fig. 5 The cumulative number of seismic tremors versus time in the Elbasani study area

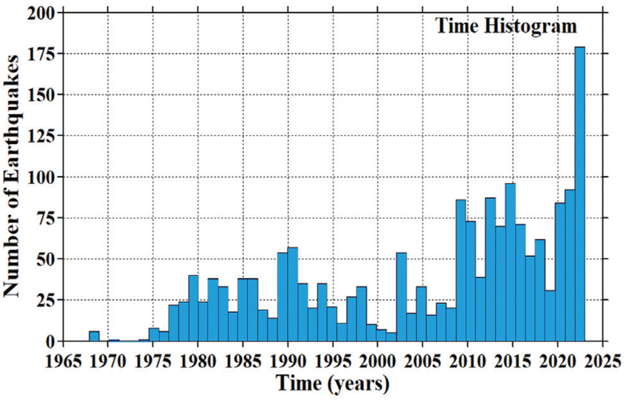

Fig. 6 Time histogram of earthquakes for the time period 1967–2023 for the Elbasani area

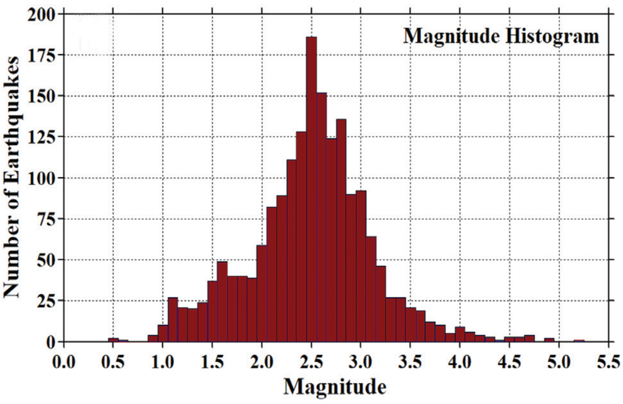

Fig. 7 Magnitude histogram of earthquakes for the time period 1967–2023 for the Elbasani area

The histogram of the magnitude distribution of earthquakes in the Elbasani area is presented in Fig. 7. The majority of seismic events exhibit the magnitudes ranging between 1.5 and 3.5, with the maximum observed at $M_l = 2.5$. The total number of events having magnitudes in the range of $0.5 < M_l < 3.0$ on the Richter scale is recorded as 1471. It has been observed that there exist 323 recorded earthquakes occurred within the magnitude range of $3.0 \leq M_l < 4.0$, with 35 earthquakes with magnitudes $4.0 \leq M_l < 5.0$. Furthermore, there has been an earthquake with magnitude $M_l > 5.0$. Consequently, seismic events possessing a magnitude range of 1.5–3.5 occur with a greater frequency as compared to other magnitudes within the Elbasani area and its surrounding region. Figure 8 exhibits the temporal change of *Mc*-value by employing a moving window strategy to compute the seismic *b*-value derived from the frequency-magnitude correlation. The *Mc*-value is determined through the assessment of 100 occurrences per window using all 1831 recorded earthquakes with a magnitude $M_l > 1.0$. As indicated in Fig. 8, the average *Mc*-value for all catalogues is taken as 2.6. The *Mc*-value is between 2.4 and 2.9 until 2018. The *Mc*-value has rather large values over 2.8 during 1975–1980 and during 2008–2010, while it decreases to about 2.4–1.6 between 2018 and 2022. The temporal variation of the magnitude completeness *Mc*-value typically displays unstable values across varying time intervals.

The estimation of the *b*-value is performed using the maximum likelihood method as prescribed by the G-R law. According to scholarly literature, this approach produces an estimate that is more resilient than the least squares regression approach (Aki 1965). The graph depicted in Fig. 9 presents the accumulated frequency of earthquakes in relation to their corresponding magnitude. The average *Mc*-value for all catalogues is taken as 2.6 ± 0.12 and the *b*-value is determined as 1.03 ± 0.06. The earthquakes have a *b*-value that ranges from 0. 9 to 1.3, with an average of about 1.0. It means that the way earthquakes are distributed in terms of how often they happen and how

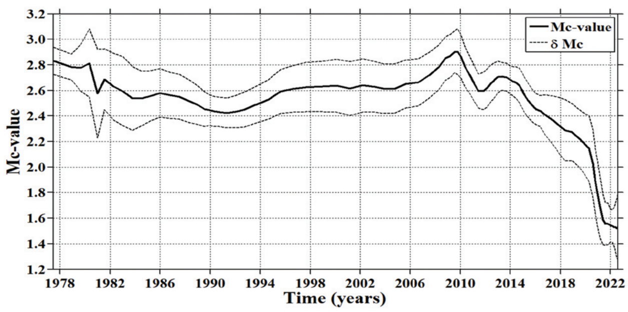

Fig. 8 Temporal variation of magnitude completeness, Mc-value. The standard deviation and δMc

strong they are can be explained by a mathematical relationship called the G-R relation. This relationship usually has a value close to 1. 0. The *b*-value estimated of 1.03 in Fig. 9 can be accepted as relatively greater from the average value of 1.0. The computation of the *b*-value involves employing a moving window methodology in conjunction with the maximum curvature method (MAXC), as described in Woessner and Wiemer (2005) aforementioned work. The *b*-value map is obtained with a sample of 850 events and prepared by grid cell spacing of 0.01° × 0.01° in longitude and latitude. The spatial changes of the *b*-value vary between 0.9 and 1.3 with an average of ~ 1.0. The highest *b*-values (> 1.1) are located in the eastern parts of the Llinxha-Kozan thermal water belt in the Labinoti-Mirak transversal fault zone, and in the Librazhdi-Dardh-Qukes fault zone. Also, the varying *b*-value between 1.05 and 1.15 is observed in the northeast part of the Llinxha-Kozan thermal water belt (between Librazhdi town and Gezavash, Kostenja, Bene villages). However, the lower *b*-values (0.9) are found in the west and southwest of the Llinxha-Kozan thermal water belt (Fig. 10).

The average *b*-value equal to1.0 is observed in a narrow area, mainly in the Llinxha-Kozan narrow thermal water belt. Figure 11 shows the varying of *b*-value versus depth, and these analyses were made to understand the different behaviours of the particular areas. In Table 1, detailed *b*-value changes according to the depth of up to 70 km are computed for every 5-km-depth interval. To ensure the continuity of the data, an overlapping depth of 5 km (moving step) is used. Figure 11 shows that there is sharp decrease in the *b*-values (from 1.15 to 0.7) in the depth ranging from 5 to 20 km.

An appreciable increase from 0.7 to 10 has been observed within the depth range of 40 to 45 kilometres. The observation of a significant high *b*-value at deeper depths, which corresponds to the lower crust, suggests that the study area is underpinned by a robust lithospheric structure, as per previous research studies (Khan, Chakraborty 2007). The potential influence of low-velocity layers and associated reduction in normal stress on high *b*-values warrants consideration. Furthermore, the present study presents graphical representations of regional variations in *b*-values versus depths (Fig. 9). The comprehensive method of *b*-value depth slices is discussed by Lamessa *et al*. (2019). As shown in Fig. 12, *b*-values usually show a clear pat-

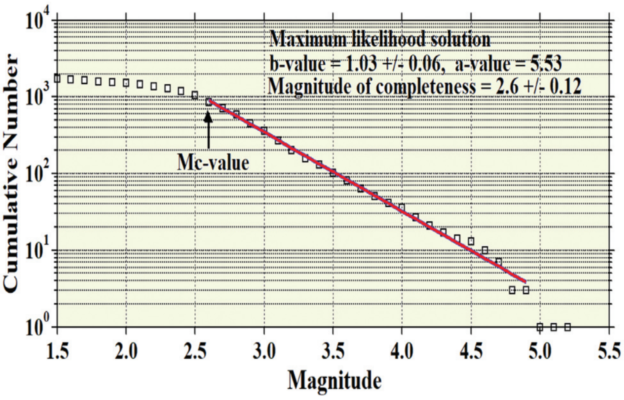

Fig. 9 Gutenberg–Richter Law and frequency – magnitude distributions of earthquakes for the period 1968–2023 from the Elbasani area, *a*-value and *Mc*-value are also given

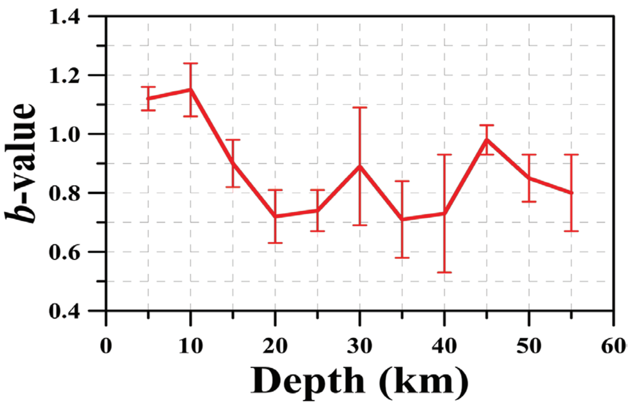

Fig. 11 The average *b*-value variations according to different depths for the Elbasani area

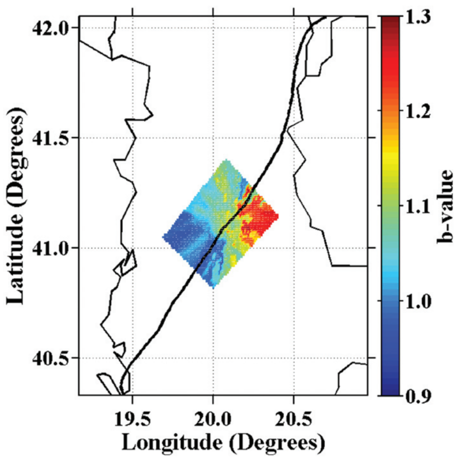

Fig. 10 Regional distribution of *b*-value from the Elbasani study area

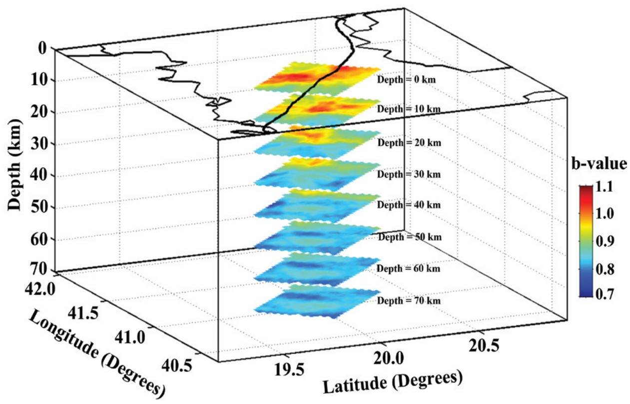

Fig. 12 Depth slices of *b*-values for the Elbasani area at depths of: 10 km, 20 km, 30 km, 40 km, 50 km, 60 km, and 70 km

Table 1 Some parameters for different depth slices of earthquakes in the Elbasani area. *NOAE*: Number of all earthquakes, *NEUCB*: Number of earthquakes used for the calculation of *b*-value, *MIOAE*: Magnitude interval of all earthquakes, *MIEUCB*: Magnitude interval of earthquakes for the calculation of *b*-value, *PEUCB*: Percentage of earthquakes used for the calculation of *b*-value.

Depth (D) interval (km)	NOAE	NEUCB	MIOAE	MIEUCB	Mc-value	b-value	a-value	PEUCB (%)
$0.0 \le D < 10.0$	1182	593	0.5–4.9	2.6–4.8	2.6 ± 0.15	1.12 ± 0.04	5.78	50.14
$5.0 \le D < 15.0$	737	346	0.9–4.5	2.6–4.5	2.6 ± 0.17	1.15 ± 0.09	5.50	46.95
$10.0 \le D < 20.0$	420	224	0.9–5.2	2.4–5.0	2.4 ± 0.09	0.90 ± 0.08	4.60	53.33
$15.0 \le D < 25.0$	281	159	0.5–5.2	2.2–4.9	2.2 ± 0.17	0.72 ± 0.09	3.76	56.58
$20.0 \le D < 30.0$	164	96	0.5–4.7	2.4–4.7	2.4 ± 0.17	0.74 ± 0.07	3.69	58.54
$25.0 \le D < 35.0$	87	50	1.1–4.7	2.5–4.5	2.5 ± 0.21	0.89 ± 0.20	3.99	57.47
$30.0 \le D < 40.0$	43	21	1.1–4.7	2.7–4.5	2.7 ± 0.41	0.71 ± 0.13	3.29	48.84
$35.0 \le D < 45.0$	23	12	1.5–4.7	2.7–4.4	2.7 ± 0.64	0.73 ± 0.20	3.23	52.17
$40.0 \le D < 50.0$	17	12	1.1–3.5	2.4–3.2	2.4 ± 0.36	0.98 ± 0.05	4.23	70.59
$45.0 \le D < 55.0$	19	14	1.1–3.5	2.2–3.3	2.2 ± 0.32	0.85 ± 0.08	4.66	73.68
$50.0 \le D < 60.0$	13	10	1.1–3.1	2.1–3.1	2.1 ± 0.37	0.80 ± 0.13	3.60	76.92
$55.0 \le D < 65.0$	3	–	2.2–2.9	–	–	–	–	–
$60.0 \le D < 70.0$	1	–	–	–	–	–	–	–
$65.0 \le D < 75.0$	1	–	–	–	–	–	–	–

tern of changing up and down in the same areas for the depths of 0–5 km, 5–15 km, and 15–25 km. High *b*-values (greater than 1.0) can be seen in the Tregan-Kozan thermal water belt and in the northeast of it (Fig. 1). The high *b*-value aberration could plausibly arise from the release of geothermal energy resulting from the reduction of pressure at shallow depths. The potential influence of ground water dynamics on the observed high *b*-values (Sanchez *et al*. 2004) and the consequent normal stress reduction is observed.

The average *b*-values of about 1.0 are observed in the northern part of the Elbasani area, which is shown in Fig. 12. Similarities of this nature are similarly observed at the depths of 25–35 km and 35–45 km. The assertion that the *b*-value shows an upward trend in volcanic areas and a downward trend in non-volcanic areas has gained widespread acceptance (Wiemer, Katsumata 1999). Figure 12 shows a general decrease in the depths between 40–70 km. In these levels of depth, the *b*-values decrease and change from 0.9 to 0.7.

The heat flow data are obtained from Atlas of Geothermal Resources in Albania (Frashëri, Čermak 2024). In the Elbasani area, the heat flow density changes from 20 to 50 mWm^{-2}. While the small heat flow values of 20 mWm^{-2} are observed in the north-western part of the Elbasani area along the north-eastern part, the heat flow values increase to 50 mWm^{-2} within 30 km from the west to east direction.

The Paper zone in the southeast of Elbasani and Kuturman zones in the northeast of the Elbasani area exhibits the highest recorded heat flow values (55 mWm^{-2}) and is characterized by prominent Quaternary activity (Fig. 13). This sharp increment can be caused by a deeper Moho discontinuity (Maden, Öztürk 2015). There is a very low velocity of Pn seismic wave in the Llinxha-Kozan thermal water belt, of about 17% of Vp, and a low seismic Pn velocity in its surrounding region. In the southwest of Elbasani, the highest heat flow values are located on the Dumrea diaperic dome (55 mWm^{-2}). Other high heat flow values are observed in the central part of the Elbasani region (40–44 mWm^{-2}) according to the geothermal model of Frashëri, Čermak 2004. Hence, it

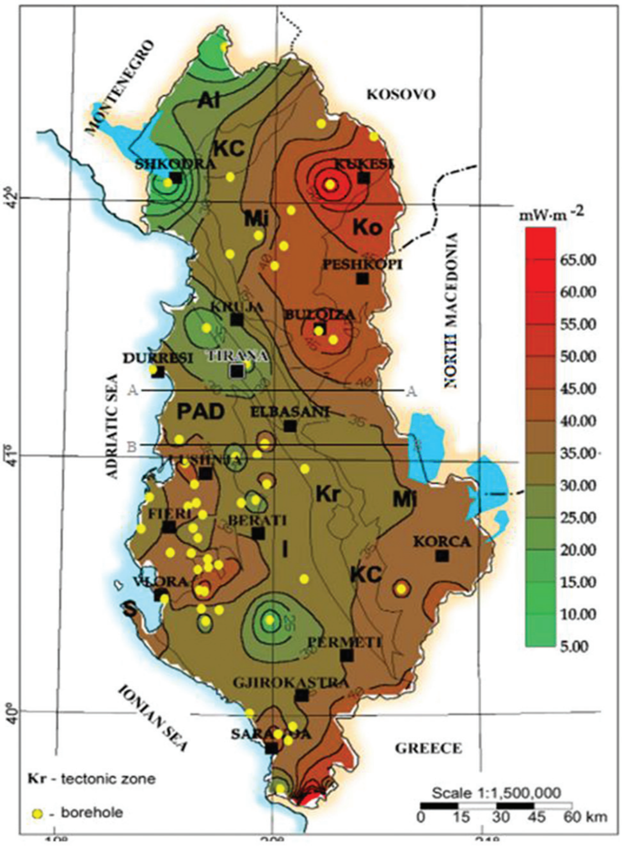

Fig. 13 Map of heat flow density of Albania (Frashëri, Čermak 2004)

is postulated that the elevated thermal flux anomalies correspond to tectonic areas that exert significant influences on the geodynamic development of the Elbasani area.

Comparing the map of surface heat flow data (Fig. 13) to the *b*-value map (Fig. 10) gives some important results or consequences. The high *b*-values observed in the north-eastern and south-western parts of the Elbasani area are likely to be related to low-velocity zones of the Earth's crust as stated by Ormeni (2011b) and Ormeni (2015). The eastern Elbasani area is supported by a thick crust (Ormeni 2010). The observed high *b*-value indicatives reduced stress concentrations, wherein the energy dissipation has occurred intermittently through the occurrence of earthquakes. The phenomenon of *b*-value decreases preceding macroscopic failure, ascribed to the reduction of external stress, was observed (Mogi 1962; Utsu 1971). A reduction in nominal stress results in the manifestation of earthquakes of smaller magnitudes and is associated with an increase of *b*-values (Sanchez *et al*. 2004). According to Scholz (1968), there exists an inverse relationship between the *b*-value and the stress that is imparted onto a rock sample. According to the findings in references (Fytikas, Kolios 1978), there exists a positive correlation between a distribution of high *b*-value and high heat flow data. However, there are also areas where there is not a lot of seismic activity, but there is more heat being released (Sanchez *et al*. 2004). The usual amount of heat that comes from the surface in central Elbasani zone is about 30 to 40 milliwatts per square meter. In some areas of that region, it can be even higher, around 50 to 55 mWm^{-2} in the Tregan-Kozan thermal water belt. The largest heat flow values in this zone are related to the low-velocity layers.

The great *b*-values and great heat flow values observed in the Llinxha-Kozan thermal water belt and in the east of it might be related to the low-velocity layers under the Earth's crust associated with the eastward deeper Moho discontinuity of mountain crust. On the other hand, the Eurasia plate had moved from north to south over the Adria-microplate along the eastern Adriatic Sea coast.

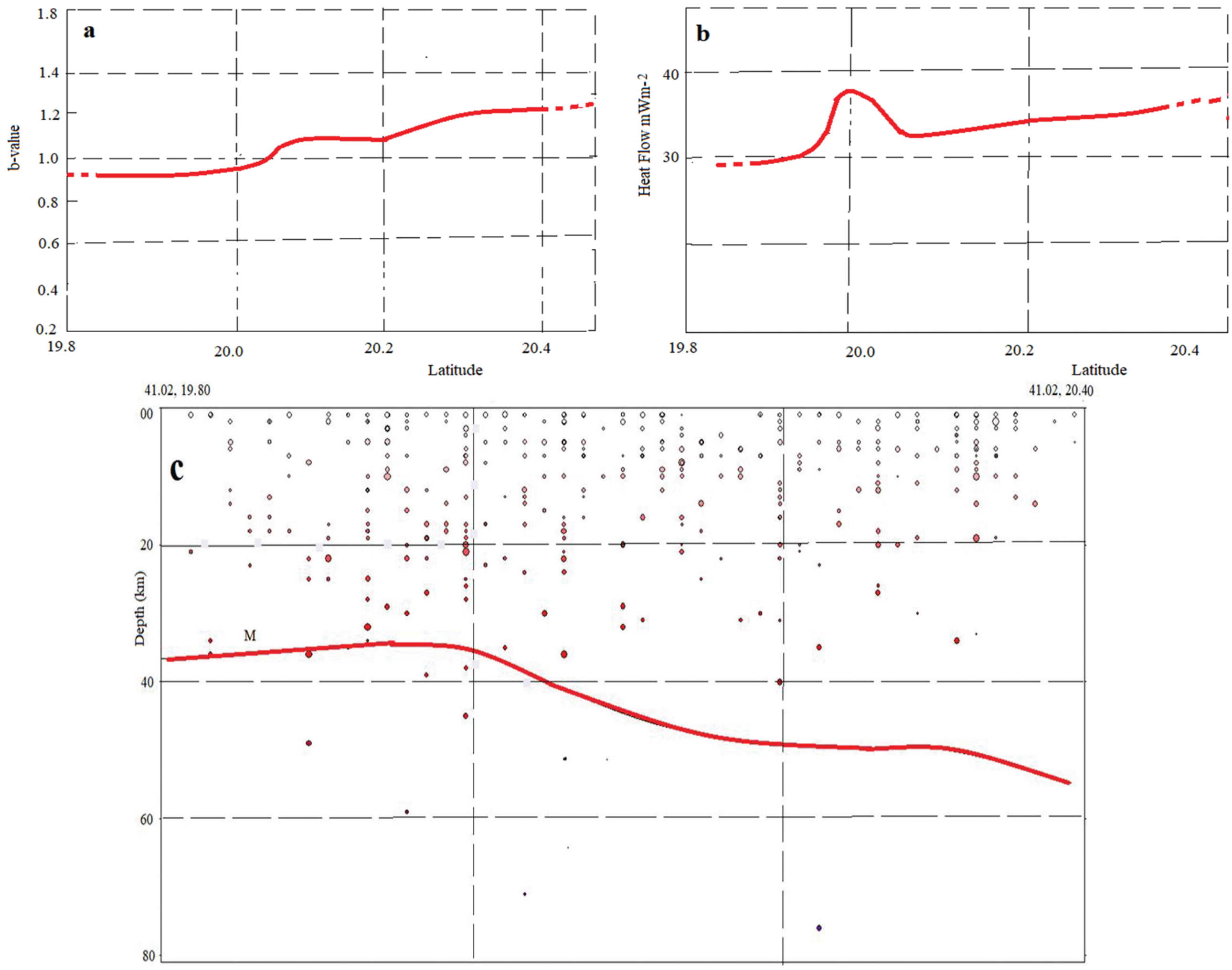

Fig. 14 a) *b*-value, b) surface heat flow density, and c) distribution of earthquake with depth along the 40.02° longitude. "*M*" refers to the Moho discontinuity. The profile location is shown in Fig 4

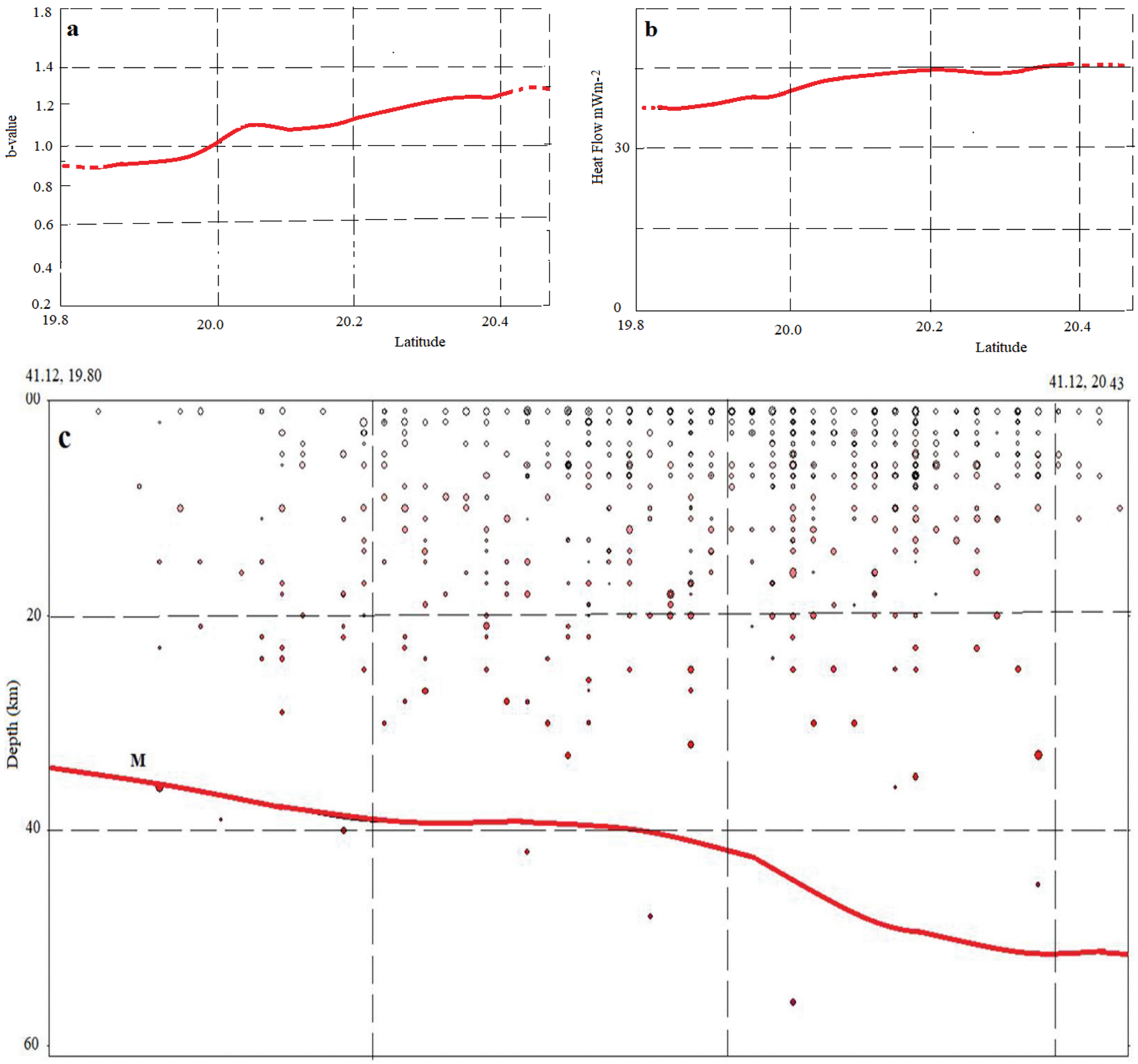

Fig. 15 a) *b*-value, b) surface heat flow density, and c) distribution of earthquake with depth along the 40.18° longitude. "*M*" refers to the Moho discontinuity. The profile location is shown in Fig. 4

Two profiles have been selected; their positions are displayed in Fig. 4 at the latitudes 41.01 and 41.21 in the east-west direction. Figures 12, 13, 14a, b, c and 15a, b, c show the *b*-values, surface heat flow data, earthquake locations with depths and with Moho, and topography of the selected profiles. These profiles demonstrate the amount of heat that is coming out from the surface.

The present investigation reveals that within the Elbasani area, the surface heat flow values exhibit a variation, whereby a low range is evident in the western territories and a high range is observed towards the eastern localities as reflected in our profiles. The thickness of the Moho to surface distance is considerable with earthquakes exhibiting small magnitudes beneath the geothermic chain, where elevated values of surface heat flow are detected. The shared characteristics of profound Mohorovičić discontinuity basins in conjunction with surface heat flow are demonstrated in Figs 14c and 15c. The present study portrays the thermal characteristics of several geothermal regions found in the Kuturman zone, Dumrea evaporite massif, and north-western Elbassani area. The thermal regimes of these regions, identified as points 11, 12, 13 and 14, have been summarized as follows: (1) high, but variable, heat flow over the Kuturman zone and Dumrea diaper dome; (2) smaller than average heat flow over the north-western part of the Elbasani area; and (3) mean heat flow in thermal water sources.

The way the Llinxha-Kozan mountain range was formed is still being debated because there is a lack of organized information about the rocks, forces, and chemicals involved. It is widely believed that the

Llinxha-Kozan mountain range was formed by the evaporite massif of Dumrea and the Labinoti transverse fault segment (Aliaj *et al*. 2010). The regional tomographic analysis of travel time and the identification of broad-scale low-velocity regions, as inferred from determinations of seismic Pn and Sn phases beneath the Elbasani zone, have been interpreted as areas possessing a mantle lid that is both thermally increased and unstable or lacking in mantle lithosphere. Figures 4 and 10 show the tectonic elements defined in the Elbasani area (Ormeni *et al*. 2023) and the normal and strike-slip faults that occurred at the Elbasani geothermal zone (Ormeni *et al*. 2013). The stress in the western part has increased, and the *b*-value has decreased, as shown in Fig. 10, 12, 14, and 15. These movements can make the fractures weaker. The Belshi earthquake happened near the Dumrea diaper dome in 2014. This earthquake had a magnitude of 5.2 and occurred at a Thrust fault. Thus, this area can cause future earthquakes (Fig. 10).

CONCLUSIONS

In the context of tectonic analysis, the seismotectonic *b*-value and heat flow data within the Elbasani area of Albania were subjected to investigation. The present study employed an earthquake catalogue encompassing a total of 1830 seismic events with depths below 70 km and magnitudes varying between 0.5 and 5.2. The heat flow data sourced from the Albanian Geothermal Atlas were utilized in the investigation. The Elbasani area is characterized by various tectonic elements that comprise clearly well-defined faults and well-known history of seismic events. This particular aspect warrants an assessment of the valuable insights that may be derived from examining the correlation between heat flow data and *b*-values, which may hold significant tectonic implications for the geographical area under consideration. The magnitude of completeness and *b*-value were found to be 2.6 and 1.03 ± 006, respectively. This *b*-value is well represented by the Gutenberg-Richter law, commonly observed close to 1.0. The *b*-value exhibits a range between 0.7 and 1.3. There is an absence of significant variation in the *b*-value between the 20 to 25 km and 40 to 45 km depths. Significant variations in the *b*-value ranging from 0.7 to 1.0 are observed between the subsurface depths of 40 and 55 kilometres. Certain characteristics, including low-velocity layers, *b*-values, and heat flow, have the capacity to induce such kind of fluctuations. Based on the spatial analysis of the three aforementioned parameters, a significant correlation exists between them. The small *b*-values are found to be associated with the presence of a relatively thick crustal structure in these regions. In contrast, the increase of *b*-value in the aforementioned regions are construed as characterizing low-velocity zones within the orogenic belt. The present study postulates that the presence of crustal low-velocity zones within orogenic belts may be consistent with increased *b*-value and heat flow values. Based on the analysis of the chosen profiles, several conclusions can be drawn. Firstly, it appears that the Moho boundary is situated at a considerable depth and that seismic activity is generally less pronounced beneath areas characterized by lower crustal velocities and higher surface heat flow values. Secondly, it is plausible that zones characterized by a destabilized mantle lid or a lithosphere that lacks an underlying mantle exist beneath the Elbasani area. Thirdly, the eastward expansion of the inner Albanides has likely contributed to an increase in stress along the Dumrea diaperic dome, while the northward movement of the Adria-microplate has likely contributed to stress along the VLED transversal fault zone leading to a decrease in *b*-values. It is conceivable that these movements could result in the accumulation of stress energy in fault systems, thereby precipitating moderate to strong earthquakes in the Lushnje-Elbasani area.

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