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TEMPORAL AND DEPTH VARIATION OF SEISMIC PARAMETERS PRIOR TO MAJOR EARTHQUAKES IN PALU REGION, INDONESIA

VARIASI TEMPORAL DAN KEDALAMAN PARAMETER SEISMIK SEBELUM GEMPA BUMI BESAR DI WILAYAH PALU, INDONESIA

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Abstract. The Palu region in Central Sulawesi is high tectonic activity area due to a subduction zone and major fault system, which resulted in high seismic intensity. The b value, as the seismic characteristic, is a valuable parameter for evaluating stress conditions and earthquake precursors. This study aimed to investigate the temporal and depth variations of the b-value in the Palu region. We observed earthquake distribution over 75 years from 1950 to 2025, which was obtained from the United States Geological Survey catalog. We applied the declustering analysis to isolate the mainshock events by using the space-time window method. We also conducted the magnitude completeness estimation and b-value calculation with ZMAP. This result showed that the average b-value was around 0.88, which was indicated as an intermediate level of seismic activity, influenced by subduction and the Palu-Koro Fault. Decreasing b-value was observed prior to the 1996 and 2018 earthquakes, followed by an increase in the parameter. This pattern exhibited stress accumulation and release, which was represented by the magnitude distribution. This lowering characteristic of b-value could be a long term precursor to major earthquakes. Furthermore, the depth variation of b-value revealed high values in the upper crust (0–10 km), a decrease around 20–30 km, and a secondary increase near 40 km, which corresponds to the Moho, as

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indicated by shear wave velocity profiles. These results provide insight into the crustal structure and seismic behavior in a tectonically complex and tsunami-prone region.

Abstrak. *Wilayah Palu di Sulawesi Tengah merupakan wilayah dengan aktivitas tektonik tinggi akibat adanya zona subduksi dan sistem patahan mayor, yang mengakibatkan intensitas seismik tinggi. Nilai b, sebagai karakteristik seismik, merupakan parameter berharga untuk mengevaluasi kondisi tegangan dan prekursor gempa bumi. Penelitian ini bertujuan untuk menyelidiki variasi temporal dan kedalaman nilai b di wilayah Palu. Kami mengamati distribusi gempa bumi selama 75 tahun dari tahun 1950 hingga 2025, yang diperoleh dari katalog United States Geological Survey. Kami menerapkan analisis declustering untuk mengisolasi kejadian gempa utama dengan menggunakan metode jendela ruang-waktu. Kami juga melakukan estimasi kelengkapan magnitudo dan perhitungan nilai b dengan ZMAP. Hasil ini menunjukkan bahwa nilai b rata-rata berada di kisaran 0,88, yang diindikasikan sebagai tingkat aktivitas seismik menengah, dipengaruhi oleh subduksi dan Sesar Palu-Koro. Penurunan nilai b diamati sebelum gempa bumi tahun 1996 dan 2018, diikuti oleh peningkatan parameter. Pola ini menunjukkan akumulasi dan pelepasan tegangan, yang direpresentasikan oleh distribusi magnitudo. Karakteristik penurunan nilai-b ini dapat menjadi pertanda jangka panjang terjadinya gempa bumi besar. Lebih lanjut, variasi kedalaman nilai-b menunjukkan nilai yang tinggi di kerak atas (0–10 km), penurunan sekitar 20–30 km, dan peningkatan sekunder mendekati 40 km, yang sesuai dengan Moho, sebagaimana ditunjukkan oleh profil kecepatan gelombang geser. Hasil ini memberikan wawasan tentang struktur kerak dan perilaku seismik di wilayah yang kompleks secara tektonik dan rawan tsunami.*

1. INTRODUCTION

Indonesia is located in a complex tectonic setting region, which is characterized by high level of seismicity and volcanic activity (Hall & Spakman, 2015). The tectonic framework in the eastern part of Indonesia is more complex than that of western Indonesia due to the convergence of multiple tectonic plates (Nugraha & Hall, 2018). In Northern Sulawesi, the Indo-Australian Plate and Pacific-Philippine Plate convergence that subduct beneath the Eurasian plate (Socquet et al., 2006). This movement contributes to the development of major fault systems, including the Palu-Koro Fault, which has been identified as a strike-slip fault zone with an estimated slip rate of 42 mm per year (Bellier et al., 2001). The fault system influences the distinctive narrow coastal feature and complex bathymetry around Palu city, which compound the risks associated with shoaling and amplification of tsunamis (Cilia et al., 2021; Sutapa & Galib, 2016).

Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) reported that an earthquake with a magnitude 7.5 hit the Palu region on September 28, 2018. The earthquake triggered widespread liquefaction and a tsunami in Palu Bay, leading to over 4,300 fatalities and extensive damage to infrastructure and residential areas (Liu & Shi, 2021). The tsunami runups more than 5 m were contributed by submarine landslides as the secondary effect of the earthquake (Carvajal et al., 2019).

One important parameter in seismic studies is the b-value analysis, which describes the relationship between the magnitude and total number of earthquakes in a given area. Several studies observed temporal variation in b-value where a decrease in b-value often precedes a large earthquake and interpreted it as an indicator of increasing stress accumulation in the crust (Rigo et al., 2018; Zakhra et al., 2023; R et al., 2024) . The temporal and spatial b-value also were investigated in the Palu region from 2008 to 2018 (Simangunsong et al., 2019). In this study, we utilized a longer earthquake catalog over 75 years, which analyzed the temporal and depth variation of b-value. This research observed the temporal variation of b-value before major earthquakes and tsunamis around the Palu area. The relation between b-value variation in depth and stress distribution within the crust was also examined in this approach to understand the earthquake hazard behavior in the area.

2. LITERATURE REVIEW

In the past century, the tsunamigenic earthquakes were recorded in 1967, 1996, and 2018 around Palu (**Figure 1**). The 1967 and 1996 events were primarily associated with vertical displacements resulting from thrust or normal faulting mechanisms, leading to tsunamis with wave heights reaching up to 10 meters (Prasetya et al., 2001). The 1967 earthquake generated a tsunami with wave heights between 8 to 10 meters, inundating coastal areas up to 300 meters inland. On January 1, 1996, a magnitude 7.9 earthquake hit the central part of Sulawesi Island with the epicenter was located in the Makassar Strait, north of Minahasa. The event triggered a tsunami with run-up heights around from 2 to 4 meters, affecting over 100 kilometers of coastline (Pelinovsky et al., 1997).

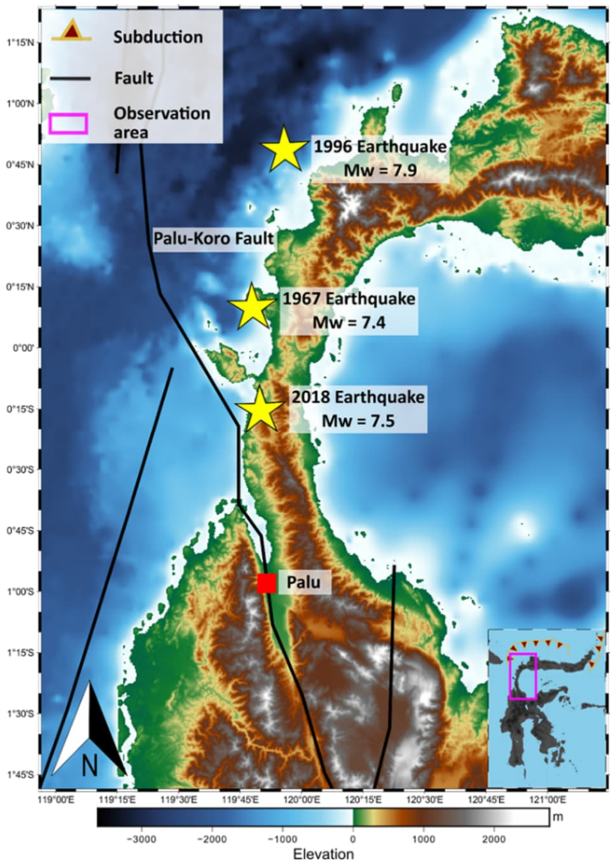

Figure 1. Map of the tectonic setting around Palu area, Indonesia. The major historical tsunamigenic earthquakes were denoted as yellow-star symbols, with earthquake parameters obtained from the United States Geological Survey (USGS) catalog (USGS, 2025).

The 2018 Palu tsunami was preceded by the on land earthquake with a strike-slip mechanism, which was associated with Palu-Koro Fault, typically not linked to large tsunamis (Cilia et al., 2021; Omira et al., 2019; Sepúlveda et al., 2020). However, Carvajal et al. (2019), explained that the tsunami was associated with submarine landslides around Palu Bay as the effect after the earthquake.

The seismic characteristic is represented by constant coefficients a and b-values of the FMD. The increasing or decreasing of b values indicates local seismic stress level (Wyss & Molnar, 1972; Scholz, 1968). A high b-value around 1.0 is identified in tectonically active region and a balanced proportion of small and large seismic events. While a low b-value suggests increased stress accumulation, potentially leading to major seismic events (Schorlemmer et al., 2005). The seismic properties along the subduction zone in the southern part of Java Island were analyzed by (Muntafi & Nojima, 2021). They explained that the seismic activity is related to a-value, while b-value is related to high and low magnitude proportions. Their results indicated that regions with low seismic activity tend to coincide with low b-values, which may be associated with higher stress accumulation.

3. RESEARCH METHODS

The earthquake data in the period of 1950 to 2025 from the United States Geological Survey (USGS) catalog (USGS, 2025) was investigated in this work. This period recorded 884 earthquakes and three major events with a moment magnitude (Mw) of more than 7 around the Palu area. The various magnitude types such as moment magnitude (Mw), body-wave magnitude (Mb), and surface-wave magnitude (Ms), were covered in this dataset. The summary of the statistical overview of the seismic events and the type of magnitudes is provided in **Table 1**. The empirical relationships published by the National Earthquake Study Center (PuSGeN, 2017) were applied to convert different magnitude scales into a unified moment magnitude (Mw), where Equation 1 and 2 standardized from Mb and Ms into Mw as follows:

$$Mw = 1.0107\, m_b + 0.0801, for\ 3.7 \leq m_b \leq 8.2 \quad (1)$$

$$Mw = 0.6016\, m_s + 2.476, for\ 2.8 \leq m_s \leq 6.1 \quad (2)$$

Table 1. Magnitude Distribution

Type of Magnitude	Earthquake Frequency	*Minimum*	Maximum
Mw	117	4.4	7.9
Mb	776	3.5	5.9
Ms	4	4.7	6

The magnitude conversion for this period resulted in a distribution of earthquake magnitudes from 3.6 Mw to 7.9.Mw (**Figure 2**). The majority of events were concentrated at shallow depths, primarily between 10 and 40 km, including several mainshocks exceeding Mw 7.0. The increasing seismic activity was accompanied by a sharp rise in cumulative moment release, as depicted in **Figure 2d**, where a substantial build-up of seismic energy was observed prior to the mainshock events. Furthermore, the earthquake catalog was declustered using the space-time window method proposed by (Gardner & Knopoff, 1974). The declustering procedure was conducted to eliminate earthquake clusters, allowing the mainshock events to be analyzed independently of their foreshocks and aftershocks.

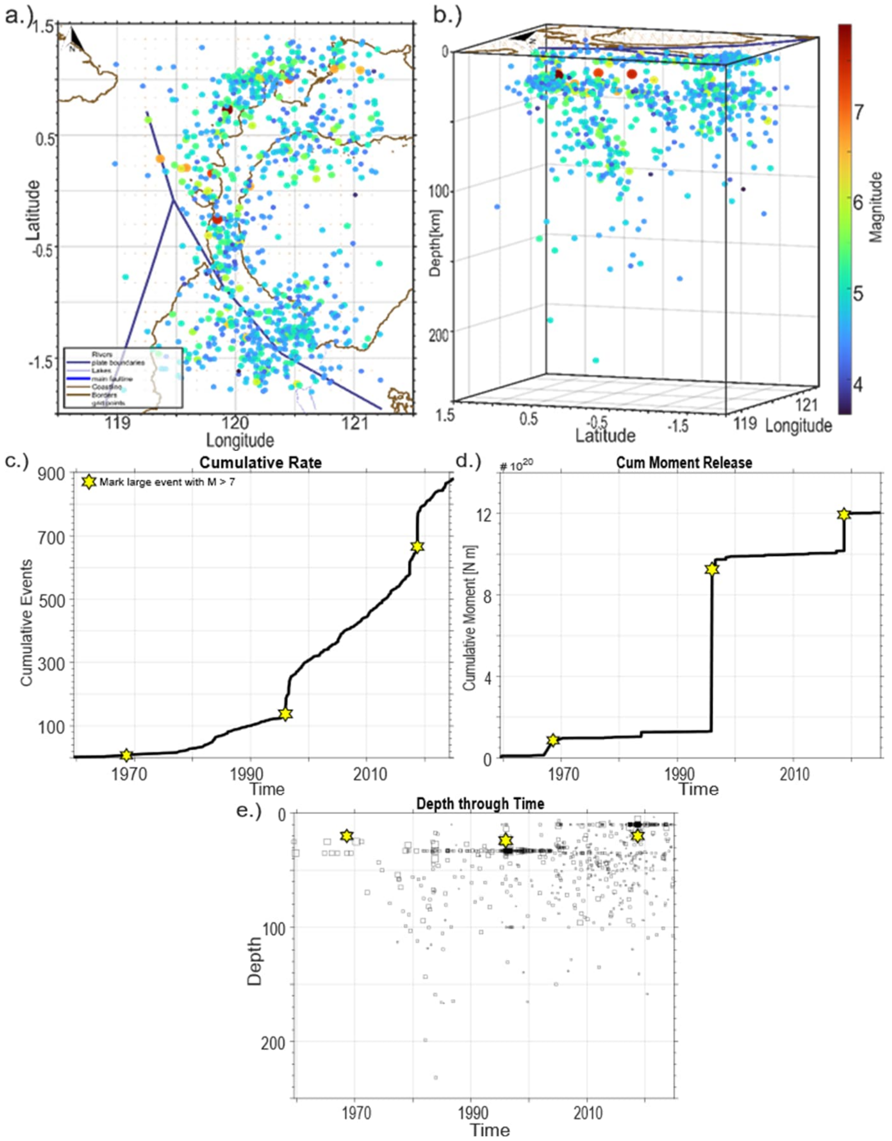

Figure 2. Seismicity characteristics of the Palu region from 1950 to 2025. (a) Map view of earthquake epicenters, colour-coded by magnitude, (b) 3D distribution of earthquake hypocenters, (c) Cumulative number of earthquakes over time, (d) Cumulative seismic moment.

The magnitude of completeness (Mc) was evaluated using the maximum curvature method, which represents the lowest magnitude above which all earthquakes in the catalog are reliably recorded (Hanafi et al., 2024). The result was validated using the goodness-of-fit test at the 90% confidence level. We observed that the magnitude completeness of the Palu region was around 4.5 Mw and removed the events below the Mc for valid b-value analysis. The b-value was represented by the frequency-magnitude distribution (FMD) of earthquakes as explained by Equation 3.

$$\log(N) = a - bM \quad (3)$$

The magnitude (M) can be related to the cumulative number (N) of earthquakes with a magnitude ≥ M. The temporal b-value analysis was conducted using a moving window technique. Each window contained 40 events with a 5% overlap to ensure continuity across the time series. The b-value was calculated using the maximum likelihood method, and 200 bootstrap resamples were applied to quantify uncertainty. The depth variation of the b-value was analyzed by dividing the earthquake catalog into depth intervals and applying the maximum likelihood method for each interval. The calculation of the study was executed by the ZMAP software package (Wiemer, 2001).

4. RESULT AND DISCUSSION

The declustered events remain 63% of the drowned earthquake catalog that was about 330 events which independent and represent the mainshock in each event. The Gardner and Knopoff (1974) declustering method was employed in this study due to its simplicity and computational efficiency. This method tends to remove more events than necessary, potentially excluding some independent earthquakes. Its robustness and ease of use make it preferable over more parameter-sensitive methods such as Reasenberg (1985), which was shown to inadequately filter out aftershocks in several tectonic settings (Perry & Bendick, 2024).

The declustered earthquake distribution resulted in 332 events and was dominated by shallow earthquakes from 0-40 km, covering magnitudes from 5.65 to 7.9 Mw (**Figure 3**). We excluded deep seismicity to minimize the influence of subduction-related events and only focused on the shallow and Palu-Koro fault earthquake distribution.

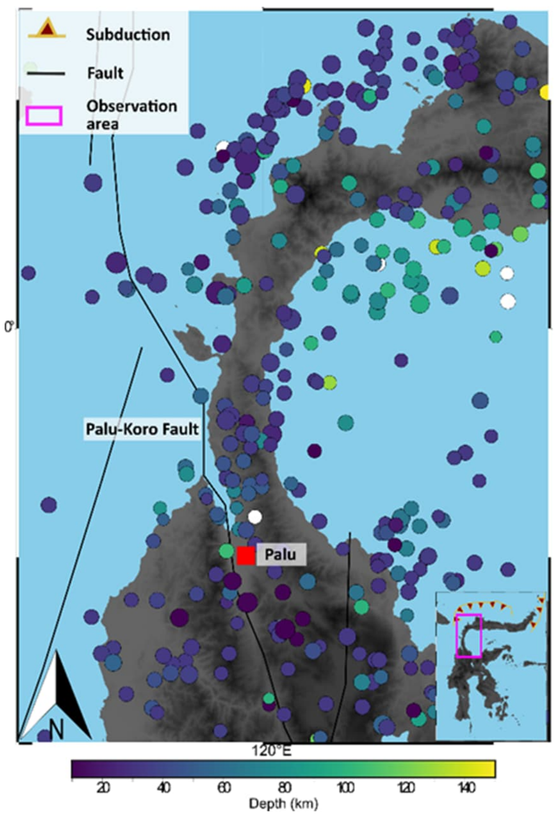

Figure 3. Spatial distribution of declustered earthquake events in the Palu region. The epicenters are colour-coded by depth, with shallow events in purple and deeper events shown in yellow and smaller events in purple.

5. RESULTS AND DISCUSSION

The diagram in **Figure 4** explains the calculated a and b-values as a function of cumulative frequency magnitude distribution (FMD). We found the magnitude of completeness (Mc) around 4.5, which was on the higher end. This is attributed to the limited detection capability of the regional seismic network, especially in capturing smaller-magnitude events in a tectonically active and complex area. The a and b-value were 6.805 and 0.88 with standard deviation of about 0.03, respectively. The average b-value represented the intermediate level, which reflected a balanced proportion of small and large seismic events around the Palu area. Several studies have shown that the b-value is strongly influenced by the focal mechanism of an earthquake, with thrust faults exhibiting lower b-values, normal faults displaying higher values, and strike-slip faults exhibiting intermediate values (Gulia & Wiemer, 2010; Scholz, 2015). Considering that the observed b value suggested that seismicity around the Palu region is dominated by the Palu-Koro strike-slip fault. A higher a-value reflects greater seismic productivity with more earthquakes at all magnitude, while lower values indicate relatively quiescent regions (Schorlemmer et al., 2005; Muntafi & Nojima, 2021). The calculated a-value of 6.805 indicated moderate to high seismic productivity when considering the entire catalog, which is typical for active strike-slip fault systems (Wiemer & Wyss, 2002).

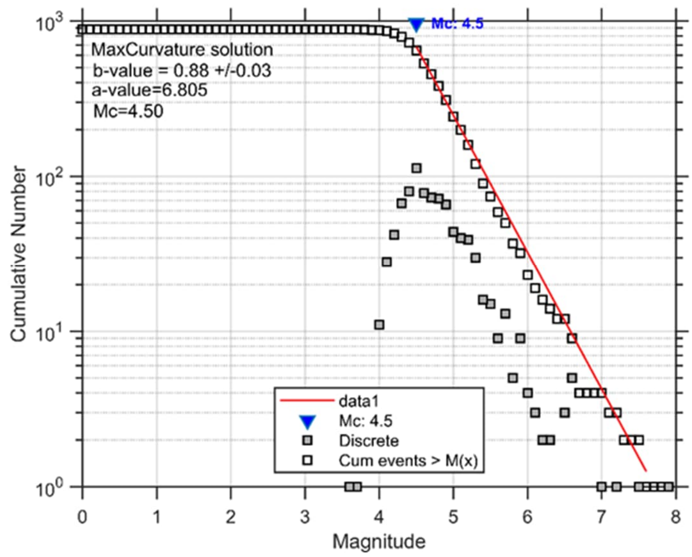

Figure 4. The cumulative frequency magnitude distribution (FMD) for 75 years. The red line represents the linear regression fit of earthquake frequency versus magnitude as described by the Gutenberg–Richter relationship (Gutenberg & Richter, 1944).

The temporal variation of b-value exhibited a declining pattern just before the 1996 earthquake with 7.9 Mw and the 2018 earthquake with 7.5 Mw, as highlighted in **Figure 5**. This pattern was consistent with previous studies that the b-value had an inverse relationship with crustal stress. A higher b-value was identified in a lower stress environment within the crust, while a low b-value suggests increased stress accumulation (Gulia & Wiemer, 2010; Scholz, 2015). The stress characteristic is explained by the magnitude distribution, where the area dominated by small magnitudes is associated with the low lithospheric stress and the higher magnitude describes higher tectonic loading that may lead to major seismic events (Hussain et al., 2020; Schorlemmer et al., 2005).

We inferred that the temporal declines in b-value before the earthquakes in 1996 and 2018 around the Palu area corresponded with stress accumulation, followed by energy discharge as mainshocks. The post-event increase in b-value observed after each mainshock reflects a stress release phase, where the crust undergoes temporary relaxation following a large energy discharge (Schorlemmer et al., 2005; Wiemer & Wyss, 2000).

The temporal variation of b-value is important as a precursor to a major earthquake, especially for an offshore event that might trigger a tsunami. In some cases, strong shaking from an earthquake can also produce a submarine landslide, which may lead to tsunami waves that hit Palu in 2018. Furthermore, the steep coastal slopes and enclosed nature of these bays around Palu area can cause an amplification of tsunami waves, with higher inundation and increasing local damage (Amlani et al., 2022).

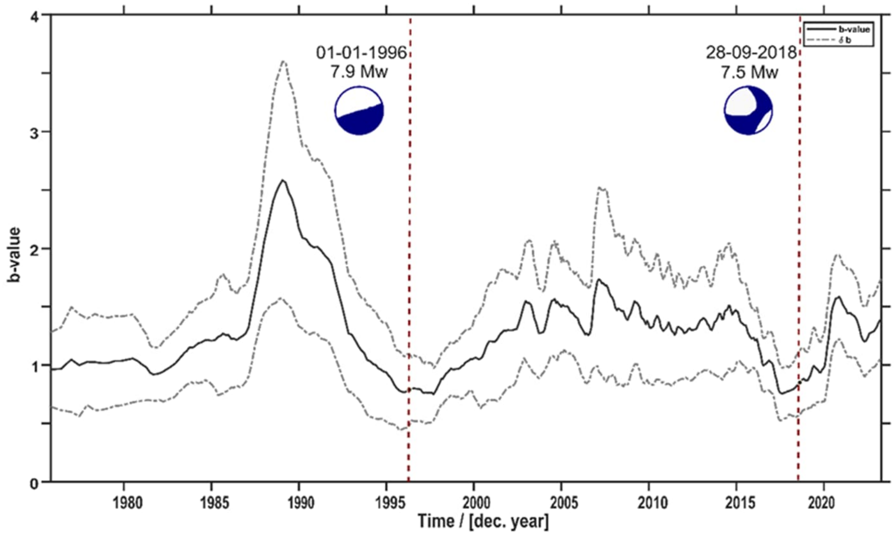

Figure 5. Temporal variation of the b-value in the Palu region from 1970 to 2025. The black line represents the estimated b-value, while the surrounding grey bands indicate ±1 standard deviation (σ). Two major earthquakes are marked by red dashed lines: the 1996 Mw 7.9 event and the 2018 Mw 7.5 Palu earthquake, each accompanied by their respective focal mechanism symbols.

This work also investigated the depth variation of b-value around the Palu area and compared with the shear-wave velocity structure that was analyzed by (Heryandoko et al., 2024). We observed the high b values at shallow depth around 10 km, followed by a decrease to the depths around 20 km (**Figure 6**). The high b-values in the upper crust are associated with lithological heterogeneity and fractures, which might produce frequent small magnitude events (Lewerissa et al., 2021). Furthermore, the lower b-values at intermediate depths indicate more homogeneous conditions due to increased lithostatic pressure (El-Isa & Eaton, 2014; Gerstenberger et al., 2020; Lewerissa et al., 2021).

Additionally, the secondary increase in b-value was observed around 40 km depth, which coincided with the increasing shear wave velocity (Vs) and gradient beneath Central Sulawesi (**Figure 6**). The increasing shear velocity was analyzed by ambient noise tomography and interpreted as Moho (Heryandoko et al., 2024). The increasing b-values indicate a change in deformation associated with the transition between crustal rocks and mantle with brittle to ductile behavior. The pattern of b-value variation in depth around the Palu area offered a better understanding of the crustal deformation.

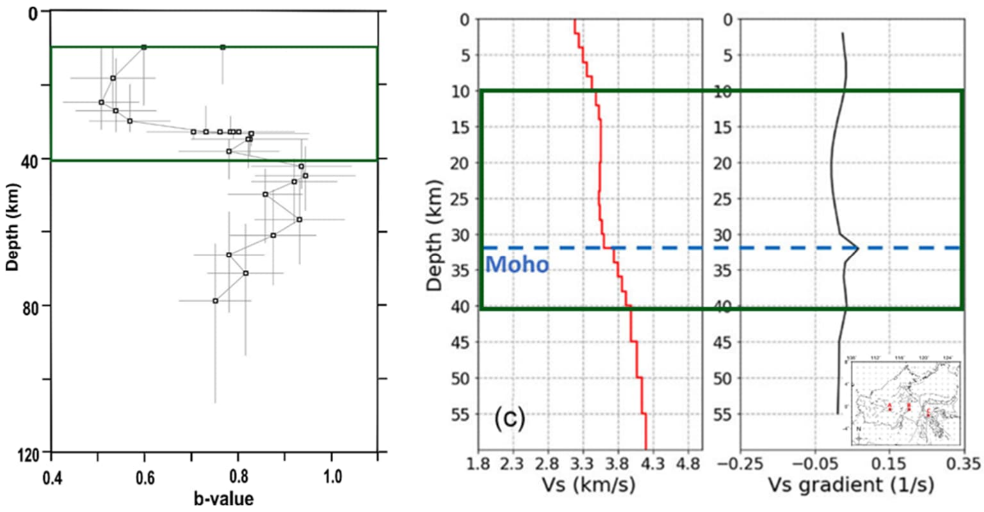

Figure 6. The diagram shows the depth variation of b-values (left panel) and shear wave velocity (Vs) structure (right panel) by Heryandoko et al. (2024) around Sulawesi, which is denoted by a C symbol. The significant behavior in b-value and velocity structure is delineated by green boxes.

6. CONCLUSION

According to the b-value analysis for 75 years, we infer that b-value variations were associated with the tectonic behaviour. The variations in b-value were influenced by the magnitude distributions that related to the crustal loading. The average b-value was about 0.88, which indicated an intermediate stress level around the Palu area that probably associated with the Palu-Koro strike-slip Fault. Furthermore, the temporal declining pattern in b-value prior to the 1996 (Mw 7.9) and 2018 (Mw 7.5) earthquakes corresponded with stress accumulation, followed by energy discharge as mainshocks. The post-event increase in b-value observed after each mainshock reflects a stress release phase.

This study revealed that the higher b value at shallow depth around 10 km is related to lithological heterogeneity. Then, a gradual decrease to depths around 20 km indicates more homogeneous conditions due to increased lithostatic pressure. We compared the shear wave velocity (Vs) beneath Central Sulawesi with the b-value variation in depth. The secondary increase in b-values was observed around 40 km depth, which coincided with the increasing Vs and Vs gradient beneath Central Sulawesi, interpreted as Moho with the transition between crustal rocks and mantle. The temporal and depth variation in b-value provides a better insight into earthquake precursors related to crustal behavior before large earthquakes.

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