SEISMICITY ANALYSIS ON SULAWESI REGION BASED ON VALUES OF *a* AND *b* FOR THE PERIOD 1976–2024

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ABSTRACT

Seismicity analysis is an essential approach to understanding earthquake occurrence patterns, seismic activity levels, and the potential for large-magnitude earthquakes. This study aims to analyze seismicity parameters in the Sulawesi region using earthquake data from 1976 to 2024 obtained from the United States Geological Survey (USGS). The parameters examined include *a*-value and *b*-value derived from the frequency-magnitude distribution (FMD) curve using the ZMAP package on Python. The results show that seismic activity in Sulawesi is dominated by earthquakes of magnitude 4–5 with depths of less than 100 km. The magnitude of completeness (M_c) is determined as 4.5. Spatial maps indicate that high *a*-values (> 4.0) are concentrated primarily in Central and North Sulawesi, reflecting intense seismic productivity in these regions. Conversely, low *b*-values (< 0.8) are prominently clustered in West and Central Sulawesi and in parts of Gorontalo. These findings highlight that while North Sulawesi exhibits high event frequency, West and Central Sulawesi are characterized by high tectonic stress accumulation and major asperities. This spatial correlation underscores the elevated seismic hazard in these areas. This study provides a valuable contribution by complementing seismicity parameter information in Sulawesi, particularly in previously uncovered areas, and serves as a basis for earthquake hazard mitigation efforts.

Keywords: *a*-value; *b*-value; seismicity; Sulawesi; ZMAP.

Introduction

Seismicity analysis is a crucial approach in earthquake studies to understand the characteristics of seismic activity in a region. Information on seismicity levels not only provides a general overview of the distribution and intensity of earthquake events but also plays a role in disaster mitigation efforts, spatial planning, and the development of future earthquake risk reduction strategies.

In Indonesia, seismicity studies have been extensively conducted by researchers. One particularly comprehensive study was conducted by Rohadi[1] using earthquake data from 1964–2008. The results showed that the *a*-value in Indonesia generally ranges from 4 to 12, while the *b*-value ranges from 0.6 to 1.8. These values reflect variations in the level of earthquake activity and tectonic complexity across Indonesia.

Subsequently, seismicity research in Indonesia has evolved into more specific studies at a regional scale. Several studies have been conducted on the main islands, such as Sumatra and its surrounding areas,[2–6] Java,[7–9] Bali,[10] West Nusa Tenggara (NTB),[11–13] East Nusa Tenggara (NTT),[14,15] Maluku,[16,17] and Papua.[18] These studies provide a more detailed picture of regional seismicity patterns and the tectonic factors that influence them.

However, Sulawesi Island, as a region with complex tectonic conditions and high seismic activity, has not received much comprehensive attention. To date, seismicity analysis in this region has only been conducted on a limited basis, for example, in southeastern Sulawesi[19]. However, historical seismic records show that Sulawesi is frequently hit by large earthquakes, including

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the 2018 Palu-Donggala[20,21] and the 2021 Majene[22] earthquakes, both of which caused significant impacts in terms of casualties and infrastructure damage.

Given this background, this research focuses on a broader analysis of seismicity in the Sulawesi Region. This study is expected to contribute to understanding the characteristics of seismicity in the region and support efforts to reduce the risk of future earthquake disasters.

Methods

This study uses a seismicity analysis approach, focusing on the parameters of *a*- and *b*-values derived from earthquake data. These two parameters are the main components of the Gutenberg–Richter equation, which describes the relationship between earthquake magnitude and frequency. The analysis procedures used in this study are as follows:

Initial data processing

This data includes information on the epicenter location, hypocenter depth, magnitude, and time of the event. All data were then processed and analyzed to obtain the distribution of seismicity across the Sulawesi region. The distribution of this seismicity data is shown in Figure 1.

Magnitude homogenization

The magnitude types in the USGS catalog are not uniform, especially in the period before 2000, which is still mostly used M_b (body wave magnitude) and M_s (surface wave magnitude), while in the more recent period, most use M_w (moment magnitude). To avoid bias in the analysis, all earthquake data were converted to the M_w scale. The conversion was carried out using the following empirical equation[7]:

$$M_w = 1.0332M_b - 0.0834 \quad (1)$$

$$M_w = 0.6354M_s + 2.3115 \quad (2)$$

Estimation of seismicity parameters

Seismicity analysis refers to the Gutenberg–Richter equation[1–3]:

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

with the following information:

$N(M)$: cumulative number of earthquakes,
M : earthquake magnitude in M_w,
a : *a*-value, indicating the level of seismic activity or frequency of earthquake occurrences in a region, and
b : *b*-value, indicating the relative ratio between the number of small and large earthquakes in the region.

A higher *a*-value indicates a greater level of seismic activity, while the *b*-value reflects tectonic conditions and the degree of rock heterogeneity; in general, $b \approx 1$ indicates balanced tectonic conditions. The *a*-value and *b*-value parameters were estimated using the maximum likelihood estimation (MLE) method. The *b*-value estimation using MLE[7,9] is written in Equation (4), while the *a*-value is calculated by substituting the Gutenberg–Richter equation after obtaining the *b*-value. These parameters were calculated computationally using ZMAP[23] in a Python environment.

$$b = \frac{\log e}{\bar{M} - M_{min}} \quad (4)$$

Description:

$\bar{M}$: average earthquake magnitude in M_w, and
M_{min} : minimum earthquake magnitude in M_w.

Mapping and analysis

The spatial distribution was visualized in Python using the ZMAP[23] algorithm. The seismic data were first categorized into shallow (depth ≤ 70 km) and deep (> 70 km) events. Magnitude histograms were constructed to determine the completeness magnitude (M_c), followed by the generation of Frequency-Magnitude Distribution (FMD) curves to calculate the values of *a* and *b*. Finally, a spatial analysis was performed to interpret the results.

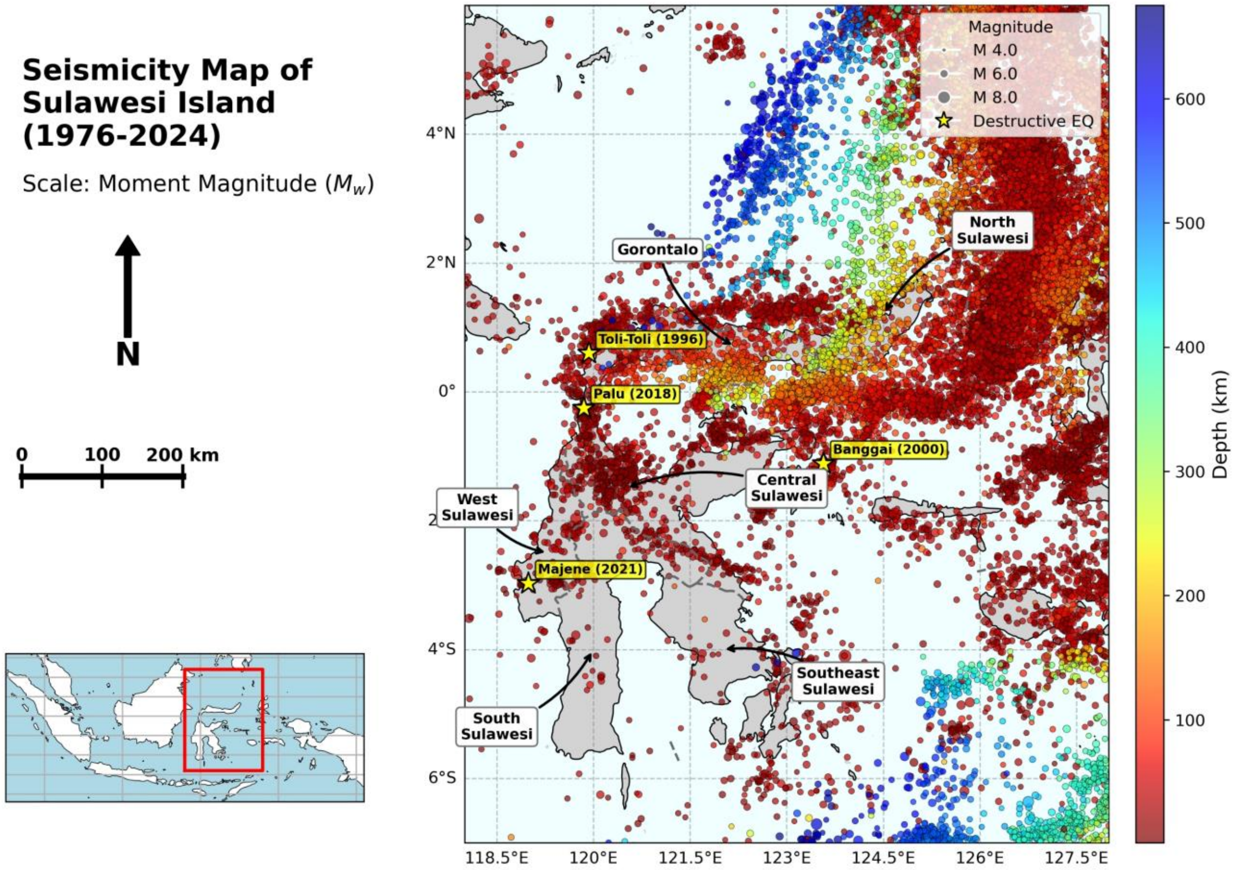

Figure 1. Map of the distribution of seismicity data in the Sulawesi region.

Results and Discussion

Based on earthquake data for the period 1976–2024, the number of earthquakes in the Sulawesi region shows a dominance of medium magnitudes, particularly with a M_w range of 4–5 (Figure 2). This magnitude distribution is consistent with seismicity patterns in tectonically active regions, where medium-sized earthquakes occur more frequently than large ones. In terms of depth, most earthquake events occurred at depths of less than 100 km, indicating that seismic activity in Sulawesi is dominated by shallow crustal earthquakes (Figure 3). Earthquakes at this depth generally have a greater potential for damage than deep earthquakes, because the energy released is still close to the surface. This finding is consistent with Sulawesi's complex geology, resulting from the interaction among the Eurasian, Indo-Australian, and Pacific Plates, which leads to intense deformation of the Earth's crust.

Based on the analysis of the Frequency-Magnitude Distribution (FMD) curve in Figure 4, the magnitude of completeness (M_c) was determined to be 4.5 using the maximum curvature method. Notably, both shallow and deep earthquakes yielded the same magnitude value (M_c). This M_c value indicates that earthquakes with magnitudes less than 4.5 have not been fully recorded in the catalog, so the analysis was carried out only on earthquakes with magnitudes greater than or equal to 4.5. From the Frequency-Magnitude Distribution (FMD) curve, the total a-values for depths below and above 70 km are 8.27 and 8.48, respectively. The difference between these values is 0.21. Based on the Gutenberg-Richter law, the number of seismic events in the deep region is approximately 1.6 times that in the shallow region. The relatively high a-value indicates a fairly high level of seismic activity in the Sulawesi region. This figure indicates that, in the long term, there is a tendency toward a relatively high frequency of earthquakes, especially those with low to medium magnitudes.

Meanwhile, from the FMD curve, *b*-values of 0.96 and 1.05 were obtained for shallow and deep earthquakes, respectively. A *b*-value approaching 1 indicates that the distribution of earthquake magnitudes is quite balanced between small and large earthquakes. However, because the value is slightly lower than 1 (shallow depth), this can also be interpreted as an indication that the probability of a large-magnitude earthquake is relatively higher than in areas with a larger *b*-value. In other words, the tectonics in this region have the potential to produce large earthquakes, as evidenced by the 2018 Palu-Donggala earthquake.

The *a*-value distribution map (Figure 5 and 6 on the left side) shows that the Sulawesi region has values ranging from 2 to 6. Areas with higher *a*-values (greater than 4.0) are primarily found in Central and North Sulawesi. Physically, the high *a*-value in this region reflects a high level of seismic activity, in both earthquake frequency and magnitude. This condition is closely related to the complexity of the active fault systems spanning the region, including the Palu-Koro Fault[20,21] and other fault systems associated with microplate collisions around Sulawesi. Thus, *a*-value information can be used to assess the level of seismic vulnerability in a particular region.

Moreover, the *b*-value distribution map (Figure 5 and 6 on the right side) shows that the *b*-value in Sulawesi ranges from 0.7 to 1.3. Areas with high *b*-values (greater than 1.0) are primarily found in part of North Sulawesi. A relatively high *b*-value generally indicates heterogeneous crustal stress conditions or complex tectonic activity, so earthquake energy release tends to be dominated by small- to medium-magnitude events. Conversely, areas with low *b*-values (< 1.0) indicate relatively uniform stress conditions and have a greater potential to produce large-magnitude earthquakes. This finding suggests that although high earthquake activity occurs in Gorontalo and West Sulawesi, as well as parts of Central, South, and Southeast Sulawesi, these areas also exhibit quite variable *b*-values, so the potential for large earthquakes remains significant.

Spatial analysis of seismicity parameters in those regions shows a significant contrast between shallow and deep earthquake activity. At shallow depths (≤ 70 km), a concentration of low *b*-values (less than 0.8) is found covering those areas. This condition indicates the accumulation of high tectonic stress in the Earth's crust. However, when examining deep earthquakes (depths > 70 km), these low anomalies disappear and are replaced by more stable values in the range of 0.8 to nearly 1.0, reflecting a more gradual energy release in the subduction zone or upper mantle.

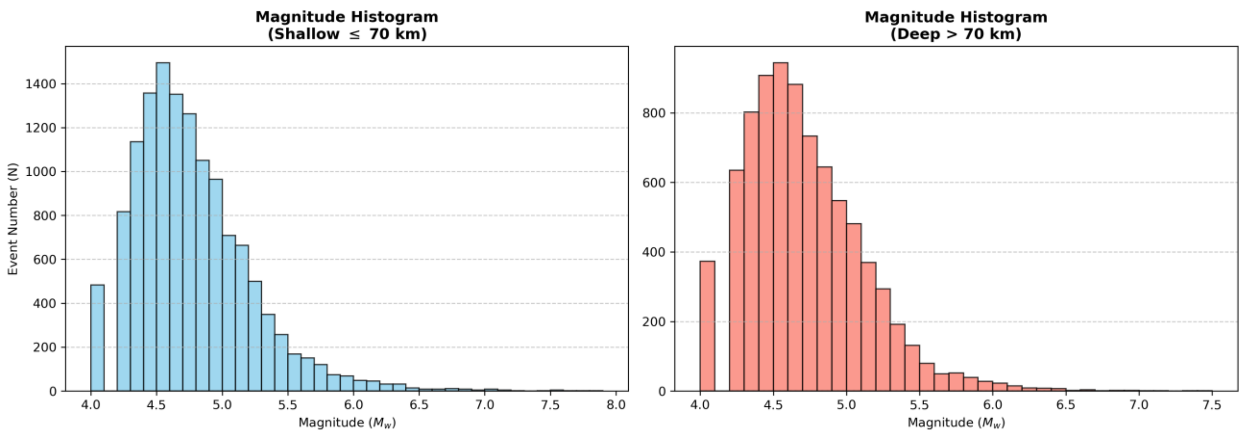

Figure 2. Magnitude histogram of the number of earthquake events: shallow (left) and deep (right).

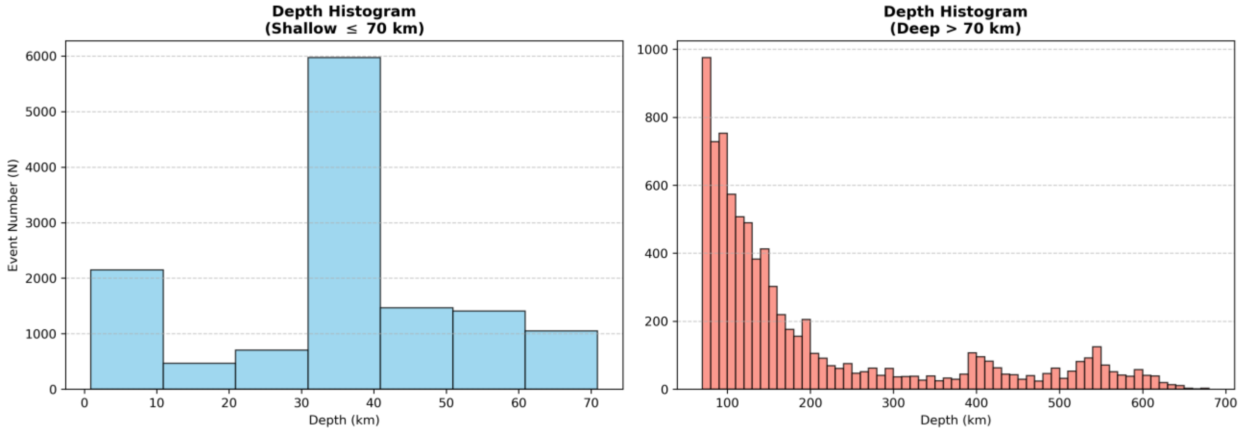

Figure 3. Magnitude histogram of the number of earthquake events: shallow (left) and deep (right).

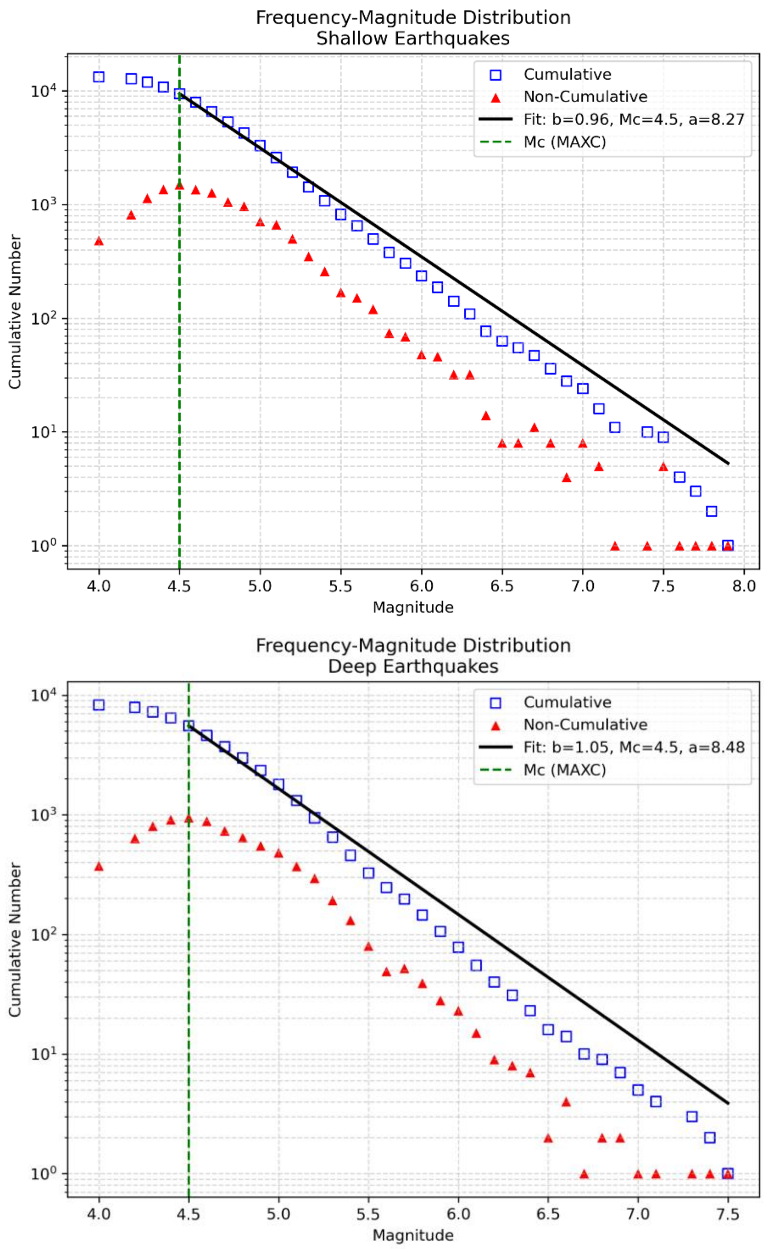

Figure 4. Frequency–Magnitude Distribution (FMD) of the Sulawesi region, shallow and deep.

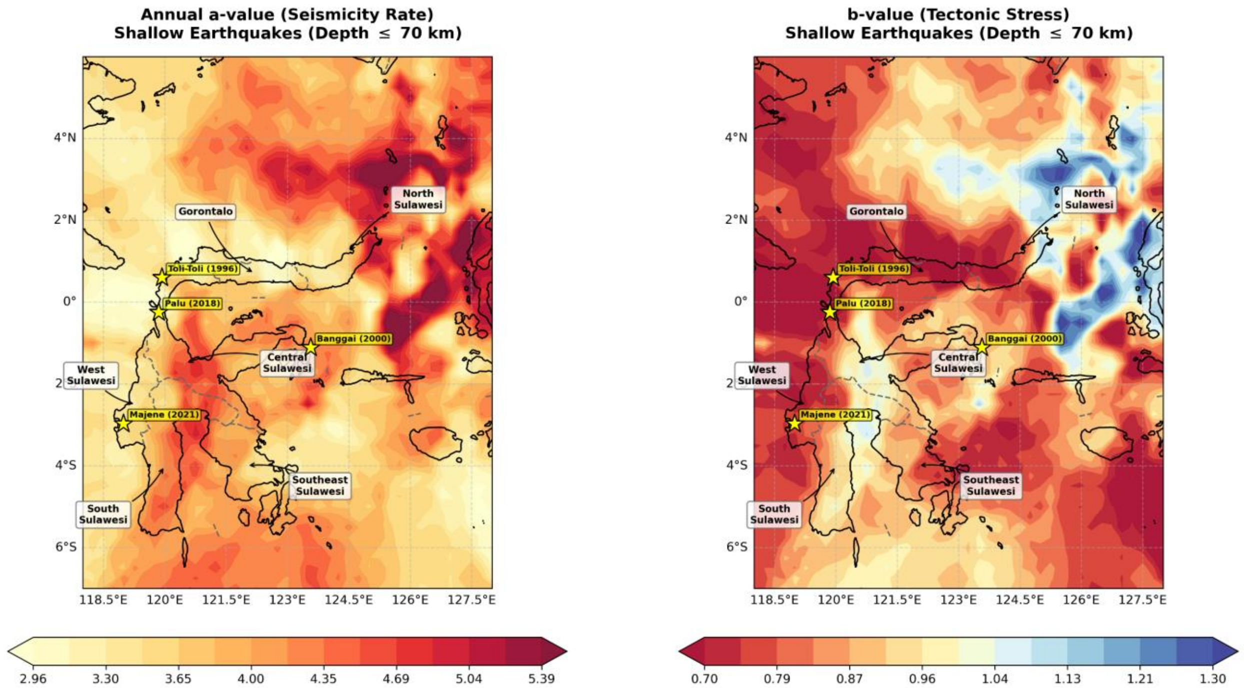

Figure 5. Map of a-value (left) and b-value (right) in the Sulawesi region for shallow earthquakes.

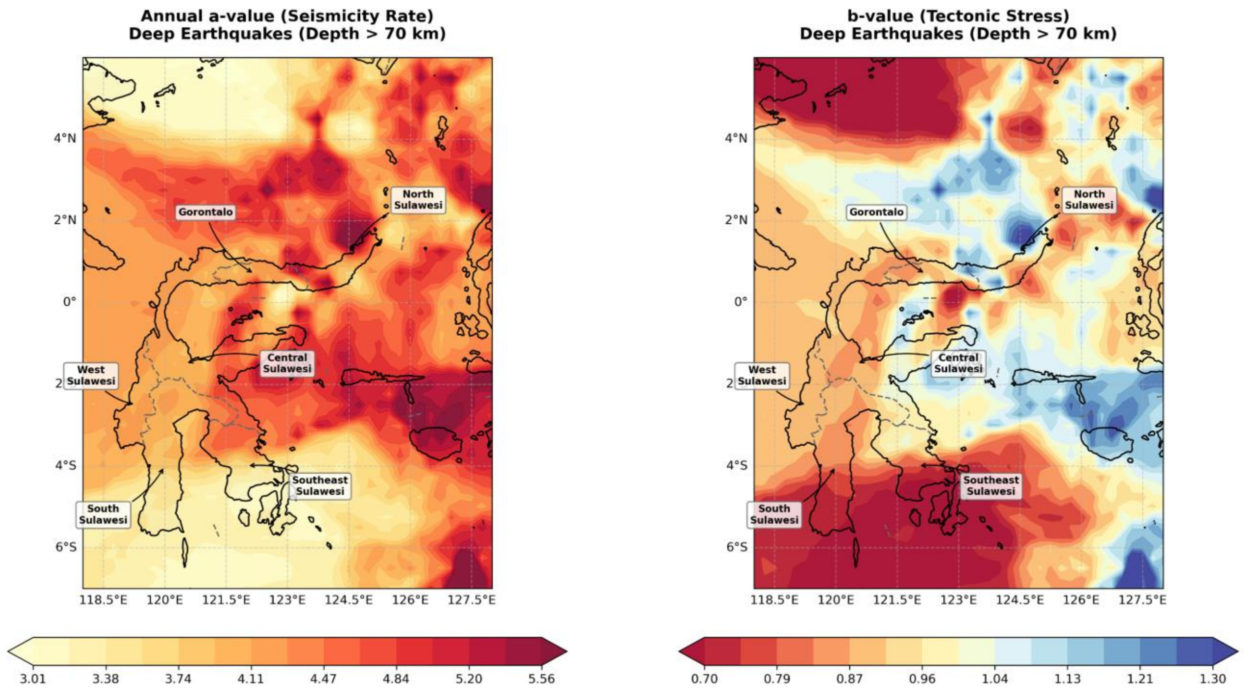

Figure 6. Map of a-value (left) and b-value (right) in the Sulawesi region for deep earthquakes.

In the shallow zone, the dominance of asperities and major active fault systems—such as the Palu-Koro, Matano, and Lawanopo faults—is closely correlated with low b-values (lower than 0.8) concentrated in West and Central Sulawesi. This condition reflects the existence of a tightly locked fault plane (locked zone), where tectonic stress continues to accumulate massively without significant release through small earthquakes. The concrete manifestation of this stress accumulation is evidenced by a series of destructive seismic events, such as the 2018 Palu earthquake (M_w 7.5), which devastated Central Sulawesi[20,21] due to the catastrophic release of energy along the Palu-Koro fault segment. A similar phenomenon was also observed in the 2021 Majene earthquake (M_w 6.2) in West Sulawesi,[22] confirming that areas with low *b*-values represent zones with high stress concentration in thrust fault systems in the shallow crust. The brittle and homogeneous rock characteristics in these areas, including those around the Toli-Toli corridor, tend to favor the occurrence of a single large fracture rather than a widespread distribution of microfractures. Conversely, in the deep zone with depths exceeding 70 km, a transition in rock failure mechanisms occurs, characterized by an increase in *b*-values to 0.8-1.0. This phenomenon, particularly in subduction zones such as beneath the northern arm of Sulawesi (Gorontalo), is influenced by high thermal gradients that make the rock more ductile, allowing stress to be continuously released through a series of small-magnitude earthquakes. In addition, increased pore fluid pressure due to dehydration of the subducting plate reduces the rock's shear strength, triggering high background seismicity and mathematically increasing the slope of the Frequency-Magnitude Distribution (FMD) curve.

Compared to the results of Rohadi's study,[1] Previous seismicity analysis in Indonesia has not comprehensively covered the Sulawesi region, especially parts of West Sulawesi and Central Sulawesi. With this study, information on seismicity parameters (*a*- and *b*-values) in both regions can be mapped more accurately. This is very important, considering that the area was once the site of major earthquakes, such as the 2018 Palu-Donggala and the 2021 Majene events. Thus, this study not only fills the gap in seismicity data for Sulawesi but also makes a meaningful contribution to understanding seismic risk in a region that has historically proven vulnerable to earthquakes.

Conclusion

Based on seismicity analysis in the Sulawesi region for the period 1976–2024, earthquake activity was dominated by events with magnitudes 4–5 and depths less than 100 km, indicating a predominance of shallow crustal earthquakes.

An investigation into the spatial distribution of seismic parameters across Sulawesi reveals a marked divergence between crustal and deep-seated activity. The frequency of seismic events in the deep zone is approximately 1.6 times higher than that observed in the shallow crust. These elevated *a*-values indicate robust seismic productivity across the Sulawesi region. Specifically, the highest activity levels, characterized by *a*-values of 4.0 or higher, are predominantly located in Central and North Sulawesi.

Furthermore, within the shallow regime (≤ 70 km), suppressed *b*-values (< 0.8) are prominently concentrated across Gorontalo, West Sulawesi, and various segments of the Central, South, and Southeast arms. This spatial signature suggests significant tectonic stress accumulation within the crust. Conversely, deeper seismic events (> 70 km) exhibit a transition toward more stable *b*-values, ranging from 0.8 to nearly 1.0, indicating a more incremental mode of energy dissipation within subduction zones or the upper mantle.

Thus, this study has succeeded in compiling information on seismicity parameters in previously unreached areas of West and Central Sulawesi and provides an important contribution to understanding the potential for earthquakes and to disaster mitigation efforts in the Sulawesi region.

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