

Spatial Analysis of the Seismic Gap Zone Based on Multiparameter Seismotectonics in Southern East Java as an Indicator of Megathrust Earthquake Potential

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Abstract

The southern region of East Java is located above an active subduction zone, where the Indo-Australian Plate is subducting beneath the Eurasian Plate. This tectonic condition makes the region potentially susceptible to large-scale megathrust earthquakes. This study aims to characterize the suspected seismic gap segments in the southern subduction zone of East Java, with a primary focus on the area between Pacitan and Lumajang. The approach used is based on high-resolution seismotectonic spatial analysis, combining three main parameters: seismicity distribution, earthquake return period estimates, and a-values and b-values as indicators of tectonic activity and stress condition. The analyzed data covers a long period of time, from 1910 to 2025, and was compiled by the BMKG and USGS catalogs. The results of the analysis show that the Pacitan-Lumajang segment experiences a lack of earthquake activity in the plate interface, although this area is tectonically active. In addition, this segment has a very long return period (> 500 years for M_w7 and $> 4,000$ years for M_w8), accompanied by low a-value and b-value, indicating low earthquake frequency and high stress accumulation. These findings indicate that the segment is a locked zone that has the potential to release large amounts of energy in the future. The results of this study provide an initial contribution in understanding the spatial distribution of seismic activity in the southern region of East Java, and can be used as supporting considerations in initial disaster risk assessments, especially in densely populated coastal areas.

Keywords: Earthquake return period; locked segment; subduction; tectonic stress.

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Introduction

Java Island is one of the regions with complex tectonic conditions in Indonesia. This is due to its location above the convergence zone between the Indo-Australian Plate and the Eurasian Plate, which forms an active subduction zone along the southern coast of Java. This zone is known as a source of major earthquakes, including megathrust earthquakes that have the potential to trigger tsunamis (Hutchings & Mooney, 2021; Rakuasa & Pakniany, 2024). In recent decades, tectonic activity

in this zone has continued to be a concern due to its potential to trigger large-scale disasters. Several studies (Rakuasa & Pakniany, 2024; Widiyantoro et al., 2020; Xie et al., 2023) indicate that the southern Java megathrust zone has the potential for large-magnitude earthquakes. Widiyantoro et al. (2020) conducted tsunami modeling based on GPS data inversion results. One of the scenarios used modeled the megathrust segment south of Central to East Java, with an estimated magnitude reaching $M_w8.8$. The modeling results indicate that this scenario could generate a tsunami with a

maximum run-up height of up to 12 meters along the coast of East Java. The high concentration of the population, national economic centers, and strategic infrastructure on the island of Java makes the potential for a major earthquake a serious threat, not only in geological terms but also from a social and economic perspective.

Tectonically, the subduction zone in the south of Java Island is classified as very active (Hutchings & Mooney, 2021). However, several segments in this zone show very minimal seismic activity over a long period. This phenomenon of no earthquake activity is known as a seismic gap, which is a segment at the plate interface that, although located in an active tectonic area, does not show significant release of seismic energy (Xia et al., 2021). This condition indicates the presence of an interlocking process on the subduction plane, which inhibits the slow release of slip. However, the subduction force between the plates continues, causing stress accumulation, which in the long term has the potential to be released suddenly in the form of a large earthquake (Wetzler et al., 2017; Haerudin et al., 2019).

Efforts to identify the existence of a seismic gap in the southern region of East Java have been carried out by Putra et al. (2019), who used seismicity data from the Agency for Meteorology, Climatology and Geophysics (BMKG) for the period 2006–2018. Their study results show that the segment between Pacitan and Lumajang has a low level of seismicity, especially in the plate interface area. This finding is supported by the study of Widiyantoro et al. (2020), which utilized GPS data from 37 observation stations spread across Central Java and East Java. They succeeded in mapping the slip deficit zone, which is the difference between the rate of tectonic plate movement and the actual slip rate on the fault at the plate interface. The results of geodetic data inversion show a high slip

deficit rate in the southern East Java during the 2008–2014 observation period, namely 20–40 mm/yr. This area is then interpreted as a locked segment that has not fully released tectonic energy.

Study by Pasari et al. (2021) examined the earthquake potential in Java Island through an earthquake nowcasting approach, which is based on the statistical analysis of seismicity data from the period 1963–2021. This study showed that on February 18, 2021, Malang and Blitar, East Java, had an Earthquake Potential Score (EPS) of more than 90% for $M \geq 6.5$ earthquakes. Although this score is not a precise prediction of earthquake occurrence time, the value indicates significant tectonic stress accumulation. This study also reinforces the idea of the existence of a locked segment in the subduction interface. This zone is considered a seismic gap and is a seismogenic zone that can consistently generate large earthquakes within the subduction zone.

The existence of a seismic gap identified by Putra et al. (2019), along with the slip deficit zone mapped by Widiyantoro et al. (2020) on the same segment, and further reinforced by the findings of Pasari et al. (2021), collectively strengthens the suspicion that the Pacitan–Lumajang region is an area with high megathrust earthquake potential. However, previous studies have not integrated high-resolution seismotectonic spatial parameters and generally only use limited data up to 2021. This limitation has the potential to cause locked segment mapping to be less than optimal because it ignores the recent earthquake activity, which is important in estimating earthquake risk more accurately.

To strengthen our understanding of the seismic potential in this segment, this study integrates three main approaches: seismicity analysis, earthquake return period estimation, and seismotectonic evaluation through a- and b-value. This

study aims to characterize the suspected seismic gap zone in the southern subduction zone of East Java, to obtain an overview of the potential accumulation of unreleased seismic energy. The method used is based on a spatial approach with a high-resolution grid that has not been widely applied in this region. In addition, the use of a long-term earthquake catalog (1910–2025) allows for the development of a more representative regional seismic model. Through this approach, the study is expected to provide an initial contribution in mapping the potential seismic hazards in the southern region of East Java.

Tectonic Setting of Java Island

Java Island, which is part of the Sunda Arc, formed in response to the interaction between the Indo-Australian Plate and the Eurasian Plate as depicted in Figure 1 (Gunawan et al., 2017; Godang et al., 2024). Tectonically, this region is located in an active convergent boundary zone, where the Indo-Australian Plate subducts north-northeastward beneath the Eurasian Plate at an average subduction rate of about 6–7 cm per year based on GPS observations and tectonic modeling (Gunawan & Widiyantoro, 2019; Widiyantoro et al., 2020). This subduction forms a system consisting of several main components: trench, forearc basin, volcanic arc, and backarc basin (Sribudiyani et al., 2003; Gunawan & Widiyantoro, 2019).

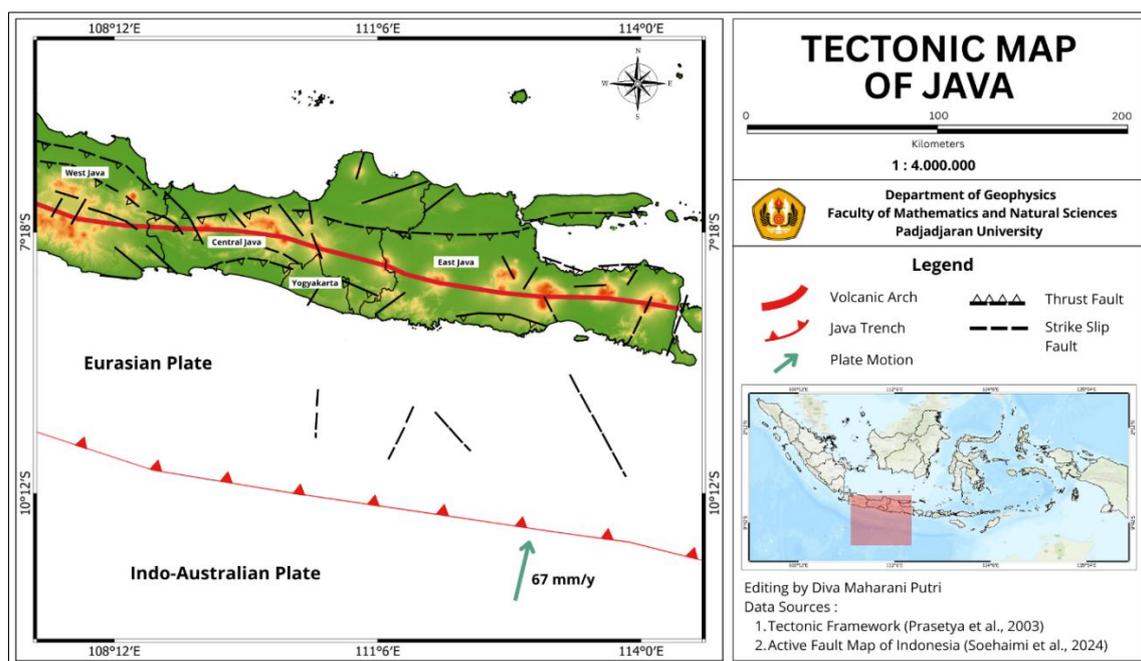


Figure 1. Regional tectonic map of Java Island showing active faults (Soehaimi et al., 2021), main tectonic plate boundaries (Indo-Australia and Eurasia), the direction and plate motion of Java subduction, the position of the Java Trench, and the morphology of the tectonic arc (modified from Sribudiyani et al., 2003).

In the southern part of Java Island lies the Java Trench, which represents the surface expression of an active subduction zone, appearing as a linear depression on the seafloor (Godang et al., 2024). Based on the Slab2.0 model, the subducting slab's dip steepens northward, reaching depths of more than 600 km beneath the Java Sea (Hayes et al., 2018). Around this trench

zone, numerous normal faults are found, formed due to the bending of the subducting oceanic plate (Patria & Aulia, 2020). In East Java, the dominant structures are normal faults, such as the Pasuruan, Probolinggo, and Baluran Faults. Meanwhile, Central to East Java is more dominated by reverse faults, including the

Kendeng Fault Zone and the Semarang Fault (PuSGeN, 2022).

Between the Java Trench and the volcanic arc, there is a geological feature known as a forearc basin (Mukti, 2018; Noda, 2016). The Western and Eastern Java arcs are classified as compressional accretionary, where the presence of the forearc basin is closely related to the accretionary body surrounding the trench. The accretionary body in a subduction zone is formed through the accumulation of sediments dragged from the subducting plate. The sedimentary layers at the seaward edge of this forearc basin show a landward dip and undergo structural folding (Noda, 2016).

Marine seismic studies in the East Java forearc structure, particularly around the 1994 (M_w 7.8) tsunami earthquake rupture zone offshore Banyuwangi, have identified splay faults branching from the landward flank of a subducting seamount beneath the forearc basin (Xia et al., 2021). These faults accommodate deformation in the overriding plate, triggered by compressional forces and the subduction motion of the oceanic plate (van Zelst et al., 2022; Xia et al., 2021).

Splay faults can trigger significant displacement on the seafloor or land surface. This displacement not only causes direct earthquake shaking but can also generate complex and intense seismic waves, as seen in cases like the 2018 Palu, Sulawesi, and 2016 Kaikoura, New Zealand earthquakes (Hollingsworth et al., 2017; Xia et al., 2021). In subduction zones, splay faults are also frequently associated with megathrust earthquakes, such as the 2004 Sumatra earthquake (van Zelst et al., 2022).

A volcanic arc is a chain of volcanoes that forms as a result of tectonic plate subduction. According to data from the Ministry of Energy and Mineral Resources (2025), there are 35 active volcanoes

distributed along Java Island. When an oceanic plate subducts beneath a continental plate, it reaches depths where high pressure and temperature cause dehydration of the subducting plate. The water released from the plate then migrates into the overlying mantle wedge, thereby lowering the melting point of the mantle rocks and leading to magma generation (Dong et al., 2024; Widagdo et al., 2018). Morphologically, volcanic arcs are generally arranged in a linear pattern and are parallel to the subduction trench (Adam et al., 2022).

A backarc basin is a sedimentary basin that forms on the overriding plate, located behind a volcanic arc and away from the subduction trench. These basins form due to extensional forces in the Earth's crust, which can be triggered by the thermal influence of magmatic activity within the volcanic arc. This heat weakens the backarc crust, making it more susceptible to stretching. This stretching process leads to crustal thinning and subsidence, which then forms a basin that is subsequently filled with sedimentary material over time (Aribowo et al., 2022; Artemieva, 2023; Lupi et al., 2022). Although generally formed in an extensional tectonic context, some backarc basins in Java show secondary compressional phase, resulting in the formation of active thrust faults. These fault structures have the potential to be sources of seismic activity. One example is the Java Backarc Thrust in northwest Java, which has been identified as seismogenic, generating earthquakes (Aribowo et al., 2022).

Java Island, from a seismotectonic perspective, is divided into two main settings: the highly active arc seismotectonic settings in the western part and the active arc seismotectonic settings covering the West Java to East Java region (Godang et al., 2024). This tectonic setting is associated with a variety of seismic activities, ranging from megathrust

earthquakes at the interface to intraplate slab earthquakes and upper crustal earthquakes due to internal slab deformation and lithospheric fragmentation (Zhou & Xia, 2020).

Data and Methods

Data

This study focuses on the southern Java East subduction zone, covering geographic coordinates between 7.87° S to 11.63° S, and 110.52° E to 115.00° E. The data used are secondary data from two sources, both are open-access and available to the public. First, the hypocenter data from the BMKG amount to 6,927 events recorded during the period 2022–2024. This data includes information on the epicenter, depth, magnitude, and origin time. The geometry of the subduction slab refers to the Slab 2.0 model developed by Hayes et al. (2018). BMKG data and the subduction slab model are used for seismicity mapping and cross-section. The second source comes from the United States Geological Survey (USGS), covering 1,930 earthquake data with a magnitude $M_w > 3.2$ during the period 1910–2025. This data is used for statistical analysis purposes, including the estimation of earthquake return period, as well as the calculation of a-value and b-value parameters based on the frequency-magnitude distribution. The earthquake catalog used includes records of earthquakes from subduction zones, fault zones, and from scattered earthquake activity without any connection to clearly mapped faults (background seismicity) (Bazrafshan et al., 2024).

a- and b-value

Earthquakes are complex phenomena that cluster in space and time (Hisyam et al., 2024; Zaliapin & Ben-Zion, 2020). To avoid bias in seismic catalogs, a declustering process is necessary to separate dependent earthquakes (foreshocks and aftershocks) from

independent earthquakes (mainshocks) (Maiti & Kim, 2025; Zaliapin & Ben-Zion, 2020). In this study, declustering was applied using the empirical Gardner & Knopoff (1974) method, which utilizes a magnitude-based spatio-temporal window approach. This method aims to produce an earthquake catalog that approximates stationary Poisson behavior for more representative seismotectonic statistical analysis (Gardner & Knopoff, 1974; Zaliapin & Ben-Zion, 2020).

The analysis of seismotectonic parameters is conducted based on the Gutenberg–Richter relation, which describes how the number of earthquakes decreases with the increase in the magnitude of the earthquakes. This relationship is expressed in Equation (1), where N is the number of events with a magnitude $\geq M$, and the terms a and b are seismic and tectonic parameters (Gutenberg & Richter, 1944)

$$\log N = a - bM \quad (1)$$

The analysis was conducted using the Maximum Likelihood Estimation (MLE) method as formulated by Utsu (1966), which is statistically considered more stable than the linear regression method. To improve spatial resolution, the analysis was conducted using a spatial grid of size $0.1^\circ \times 0.1^\circ$ with minimum events are 50 events. In each grid, the a-value and b-value are calculated using Equation (2) (Utsu, 1966) and (3) (Pakiding et al., 2025; Rehman & Zhang, 2024).

$$b = \frac{\log e}{\bar{M} - M_0} \quad (2)$$

$$a = \log N + \log(b \ln 10) + M_0 b \quad (3)$$

With \bar{M} being the average magnitude and $\log e$ being 0.4343 (da Costa et al., 2024; Pakiding et al., 2025). M_0 being Magnitude of Completeness (M_c), which in this study is valued at 4.9. This value was obtained through the MLE method (Utsu, 1966) based on the Frequency-Magnitude Distribution (FMD) of the declustered

earthquake catalog (Figure 2). This value was chosen because it represents the threshold where the magnitude distribution begins to follow a linear pattern. Thus, the m_c value indicates the minimum limit for well-documented data (Rehman & Zhang,

2024). An accurate m_c estimation is crucial for the application of Equation (1). An m_c that is too high will significantly reduce the number of data samples, whereas an m_c that is too low can potentially yield biased a- and b-values (da Costa et al., 2024).

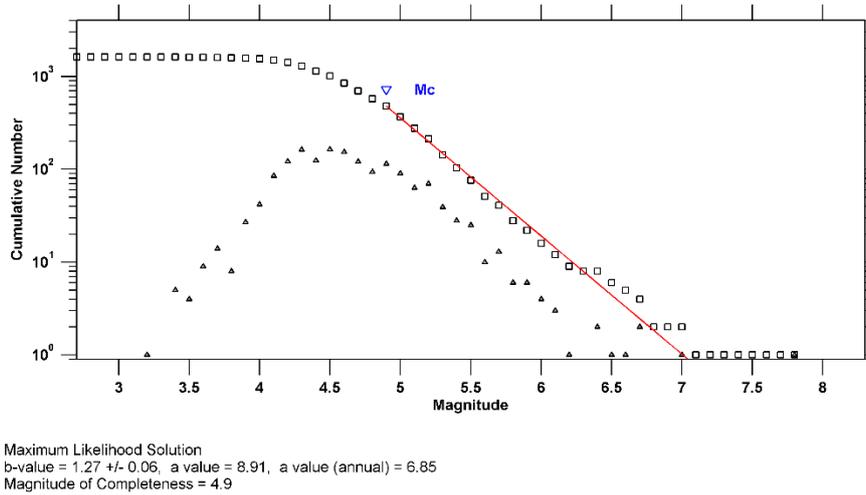


Figure 2. Frequency-Magnitude Distribution (FMD) based on the USGS Catalog 1910-2025.

Earthquake Return Period

The estimation of earthquake return periods in this study was conducted based on statistical analysis for three magnitude categories, which are M_w6 , M_w7 , and M_w8 . This estimation aims to identify how often earthquakes of such magnitudes occur spatially in the research area. The return period (θ) for each grid cell is calculated using Equation (4) (Munandar & Salsaladin, 2022; Rehman & Zhang, 2024; Siregar et al., 2023).

$$\theta = \frac{1}{N_1(M \geq M_0)} \quad (4)$$

Where $N_1(M \geq M_0)$ is a seismicity index that reflects how often earthquakes with a magnitude of $M \geq M_0$ occur in the region during the observation period.

Software

Data analysis and visualization in this study were conducted using several main software packages tailored to the needs of each stage. ZMAP version 6 (Wyss et al., 2001), based on MATLAB version 7.8

(Pratap, 2010), was used for the calculation and spatial visualization of seismotectonic parameters a-value and b-value, as well as earthquake return periods. ZMAP supports the use of the MLE method in calculating seismic statistical parameters (Ernandi & Madlazim, 2020; Hisyam et al., 2024; Rehman & Zhang, 2024). Spatial visualization of hypocenters was performed using Generic Mapping Tools (GMT) version 6 (Wessel et al., 2019), which allows for the creation of cross-sections based on slab model references. This visualization was combined with QuantumGIS version 3.43 (Menke, 2022), which functions in geospatial data processing, such as overlaying seismicity data, geological structures, and administrative boundaries. All visualization processes are based on geographic coordinates referring to the World Geodetic System 1984 (WGS84) reference system. Additionally, Microsoft Excel was used as a tool for data alignment, format conversion, and earthquake catalog filtering.

Results and Discussion

Seismicity Distribution

The seismicity map of the southern region of East Java during the period 2022-2024, as shown in Figure 3, indicates the spatial distribution of earthquake epicenters forming a linear pattern-oriented West-East and aligned with the subduction zone, rather than local faults. This linear pattern represents the continuity of seismic activity that geometrically follows the direction of plate subduction, extending parallel to the Java Trench. However, the seismicity map shows a seismic anomaly, which is a zone of less seismic activity in the southern sea region from Pacitan to Lumajang, indicated by the dashed line on the map as a seismic gap zone. This area is spatially located directly above the projection of the Indo-Australian Plate slab that subducts beneath the Eurasian Plate, but it does not show significant energy release in the form of earthquakes over a long period based on BMKG catalog data. This pattern indicates the presence of a seismic gap due to the less earthquake activity during the observation period (Rakuasa & Pakniany, 2024; Megawati et al., 2024).

The indication of a seismic gap zone in southern East Java is supported by a study by Hutchings & Mooney (2021), which used the USGS earthquake catalog for events with magnitudes $> M4.6$ during the 2000–2020 period. Based on cross-section analysis, this study indicates that the southern region of East Java lies above a seismic gap zone that extends laterally for ~400 km. This confirms that the region has the potential for earthquakes originating from the megathrust zone and also from processes within the mantle due to the complex subduction structure beneath it.

Further analysis was conducted through three cross-sections, which are cross-section A–A', B–B', and C–C', to provide an overview of the vertical distribution of the hypocenter, as shown in Figure 3 (b–d).

This cross-section shows the distribution of hypocenters relative to the position of the slab modeled based on the geometric curve. The distribution of hypocenters shows a consistent tilt towards the north, corresponding to the subduction of the Indo-Australian plate. In cross-sections A–A' and B–B', it is evident that very few earthquakes occur precisely at the plate interface. Most earthquakes are distributed above the slab, specifically in the Eurasian Plate (overriding plate) with a depth range of 20–60 km or within the slab at depths > 60 km, which are referred to as intraslab earthquakes (Xie et al., 2023; Wickham-Piotrowski et al., 2024). The earthquakes that occur in the overriding plate are likely shallow crustal earthquakes related to the structural adjustment of the lithosphere due to the pressure from the subduction of the plate or local fault activity that forms above the interface. On the other hand, intraslab earthquakes indicate tectonic activity occurring within the slab body due to internal deformation during subduction (Haerudin et al., 2019).

The B–B' cross-section, which traverses the Pacitan-Lumajang region as a suspected seismic gap zone, shows relatively less seismic activity and is not distributed along the plate interface. The less seismic activity strengthens the hypothesis that the B–B' profile crosses a seismic gap zone that is currently locked. These results are in line with the research by Muttaqy et al. (2022), which identified a seismic gap in the southern region of East Java, covering the southern coast up to the trench. This is supported by the results of tomography and slip deficit modeling, which indicate that this area is part of a locked slab segment with the potential for megathrust (Muttaqy et al., 2022).

Unlike the B–B' cross-section, which shows a lack of seismic activity at the plate interface, the C–C' cross-section, which covers the southern Banyuwangi region, shows relatively higher seismic activity

with hypocenters at depths of 10-100 km, and some earthquakes occur right at the plate interface at depths of 30-60 km. This distribution represents the slab's response to the convergence forces that have been partially released seismically. This supports the differences in tectonic behavior between megathrust segments (Bilek &

Lay, 2018). Such segmentation patterns are a common feature in subduction zones, where slip behavior is not uniform across segments, and locked segments are the primary candidates for megathrust earthquake sources (Wetzler et al., 2017; Muttaqy et al., 2022).

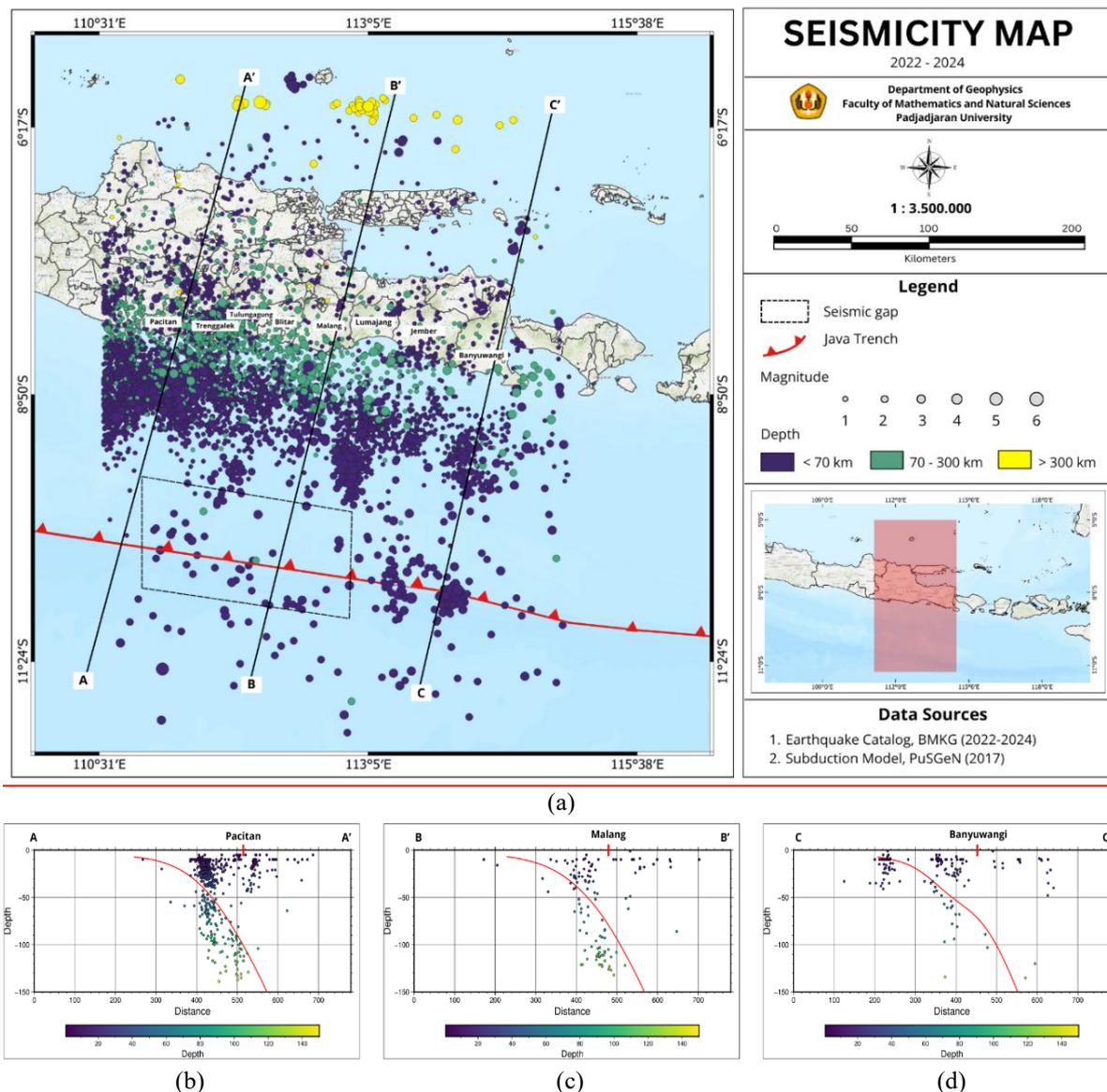


Figure 3. Seismicity map of the southern East Java region (2022–2024). The distribution of earthquake epicenters forms a linear pattern parallel to the Java Trench (red line), representing subduction activity. Three lines (A-A', B-B', and C-C') indicate the location of vertical cross-sections shown in Figure 3. The dashed line indicates the seismic gap zone of Pacitan–Lumajang, which has less earthquake activity. Three lines indicate the location of vertical cross-section (b) A–A', (c) B–B', and (d) C–C', which show the distribution of hypocenters relative to the subducting plate.

Earthquake Return Period

The estimation of the earthquake return period is conducted for earthquakes with

magnitudes M_w 6, M_w 7, and M_w 8 based on the earthquake catalog. This parameter is very important in understanding the dynamics of seismic energy release in

subduction zones. In general, the results of return period mapping show that the greater the magnitude of the earthquake analyzed, the longer the estimated return period. The return period of earthquakes does not provide a precise time prediction, but rather offers a long-term probability (Sandhu et

al., 2022). In the context of the megathrust zone, the longer the return period, the greater the likelihood that the segment has not released energy for a long time, thus storing significant potential (Rehman & Zhang, 2024).

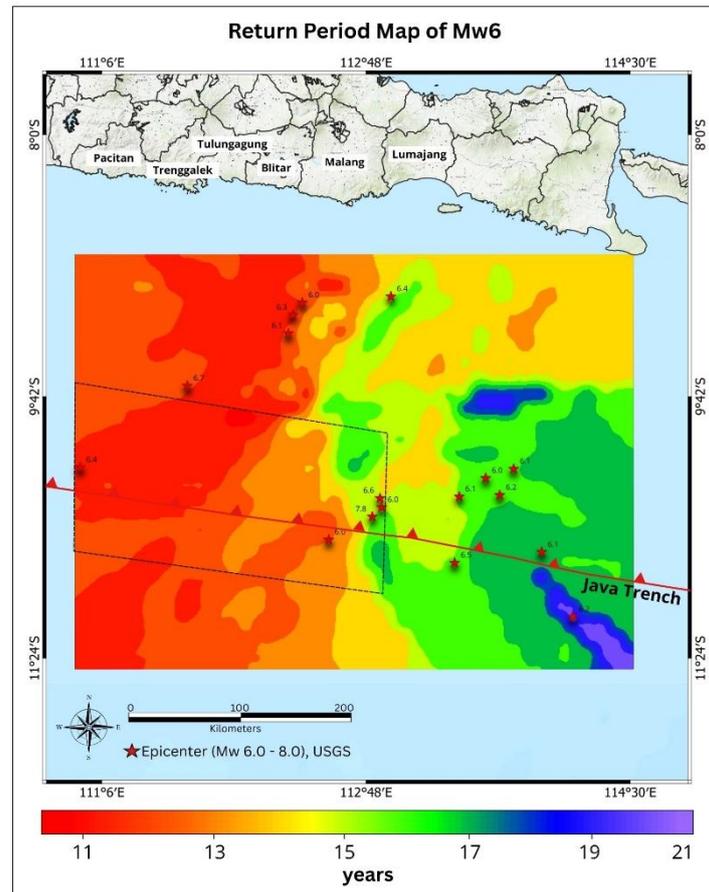


Figure 4. Spatial map of earthquake return period estimates for M_w6 .

Figure 4 shows that most of the southern East Java subduction zone exhibits a short return period for M_w6 earthquakes, ranging from 11 to 21 years. This indicates that M_w6 earthquakes occur quite frequently in this zone due to the gradual release of energy. However, in the Pacitan–Lumajang segment, although the return period for M_w6 is in 10–15 years, the hypocenter location is outside the plate interface, tending to be in the overriding plate (Figure 3). According to Wickham-Piotrowski et al. (2024), earthquakes outside the plate interface generally reflect the release of energy due to crustal deformation against tectonic forces from the subduction slab.

Therefore, although it appears statistically active, this segment has not yet experienced a major energy release.

The return period map of M_w7 earthquakes in Figure 5 shows that the Pacitan–Lumajang segment has a return period between 260 to >500 years, which is considered long on the major earthquakes scale. The long return period indicates that it is very rare for M_w7 earthquakes to occur in that zone during the observation period. This condition describes a slip deficit and the accumulation of stress that has not yet been released at the plate interface (Widiyantoro et al., 2020).

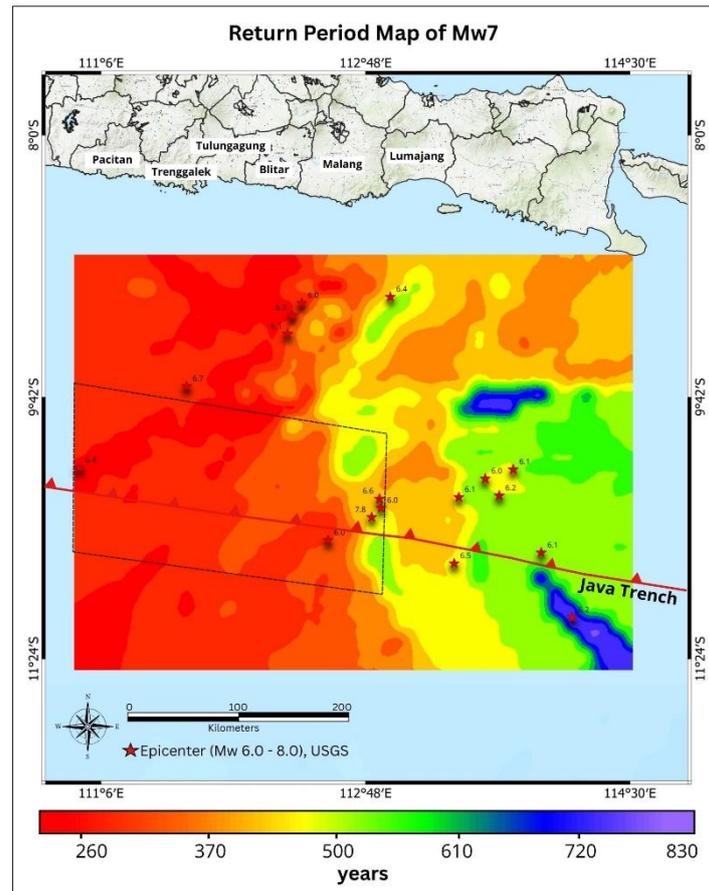


Figure 5. Spatial map of earthquake return period estimates for M_w7 .

The return period map for M_w8 earthquakes (Figure 6) shows that the Pacitan–Lumajang zone is estimated to have a return period ranging from 4,000 to <16,000 years. This area is marked from red to yellow. The long return period indicates that no M_w8 earthquake events were recorded in the region during the observation period (1910-2025). According to Scholl et al. (2015), $M_w \geq 8$ earthquakes are rare but destructive events, usually occurring in highly locked subduction zones with minimal seismic history. This characteristic corresponds to the Pacitan-Lumajang zone observed on this map. This is a common characteristic of megathrust zones that have the potential to produce "great megathrust earthquakes" such as those in Chile (1960, M9.5), Alaska (1964, M9.2), and Sumatra (2004, M9.1), which originate from subduction zones with similar characteristics (Scholl et al., 2015).

The long return period for these large earthquakes is consistent with the elastic rebound theory, which posits that plate movements undergo a phase of energy accumulation over a prolonged period and are released during a major earthquake (Lowrie, 2007). Additionally, this phenomenon is also supported by the Gutenberg-Richter Law in the frequency-magnitude relationship, which states that the frequency of earthquakes is inversely proportional to their magnitude. Thus, large earthquakes occur less frequently compared to small earthquakes (Aslamia & Supardi, 2022).

Seismotectonic Parameters a-value and b-value

The statistical parameters a-value and b-value based on the Gutenberg–Richter law are often used to interpret seismotectonic conditions. In several studies that have been conducted (Aslamia & Supardi, 2022;

Ernandi & Madlazim, 2020; Pakiding et al., 2025), both values are analyzed together because they can indicate the potential for significant earthquakes in a given area. a-value is a seismicity constant that describes the number of earthquake occurrences within a certain period, without considering the magnitude (Suwandi et al., 2017). Meanwhile, the b-value reflects the

frequency distribution between large and small earthquakes. According to Pakiding et al. (2025), b-value is also related to tectonic conditions, as it reflects the magnitude of differential stress and the brittleness of rocks. A low b-value usually indicates high stress accumulation in relatively homogeneous and brittle zones (Taroni et al., 2021).

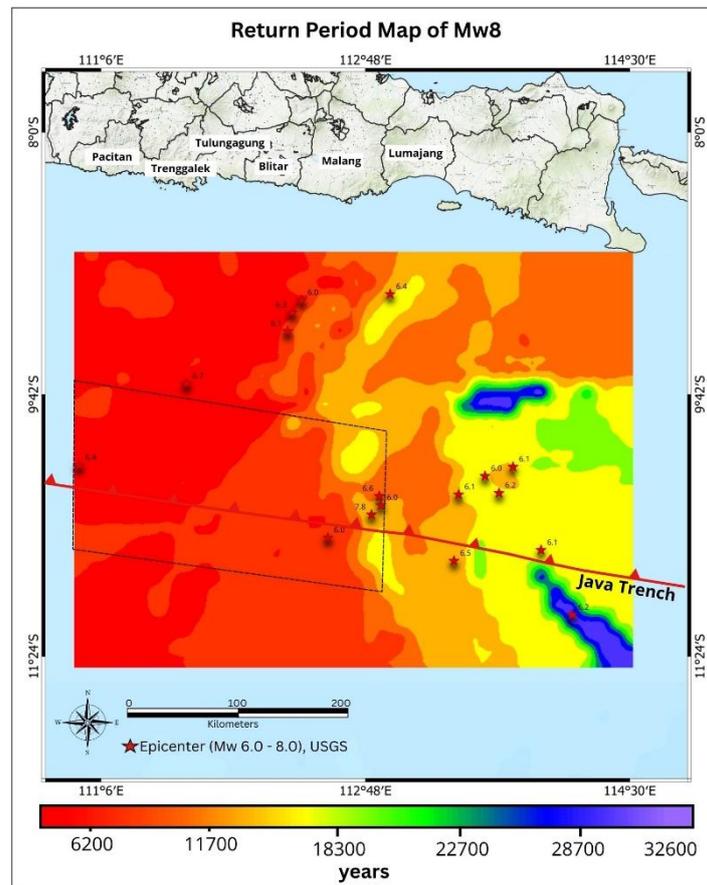


Figure 6. Spatial map of earthquake return period estimates for $M_w 8$.

Based on the spatial distribution map of a-value and b-value produced, it appears that the Pacitan-Lumajang segment has a similar pattern, both being relatively lower compared to the surrounding segments. Regions with low a-values and low b-values are generally associated with locked megathrust zones, that is, zones where accumulated stress has not been released (Pakiding et al., 2025; Sandhu et al., 2022).

In Figure 7, the a-value in this segment mostly falls within the range of <9.5 , with some areas reaching a minimum value close

to 9. The low a-value reflects the generally low level of seismic activity in the area, as shown in the seismicity map (Figure 2) and the seismic cross-section B–B' (Figure 3 (b)). The spatial decrease in a-value can also indicate the presence of a "seismic quiescence" zone, which is often associated with areas storing high stress (Katsumata & Nakatani, 2021).

Similarly, the b-value shown in Figure 8, the Pacitan-Lumajang segment is in the low range, which is <1.4 , even reaching a minimum value of ~ 1.2 in several areas.

This characteristic is consistent with the area of minimal earthquake activity at the plate interface, as shown in the previous seismic cross-section results. This interpretation strengthens the suspicion that

the segment is a locked segment with a high potential for the accumulation of unreleased seismic energy.

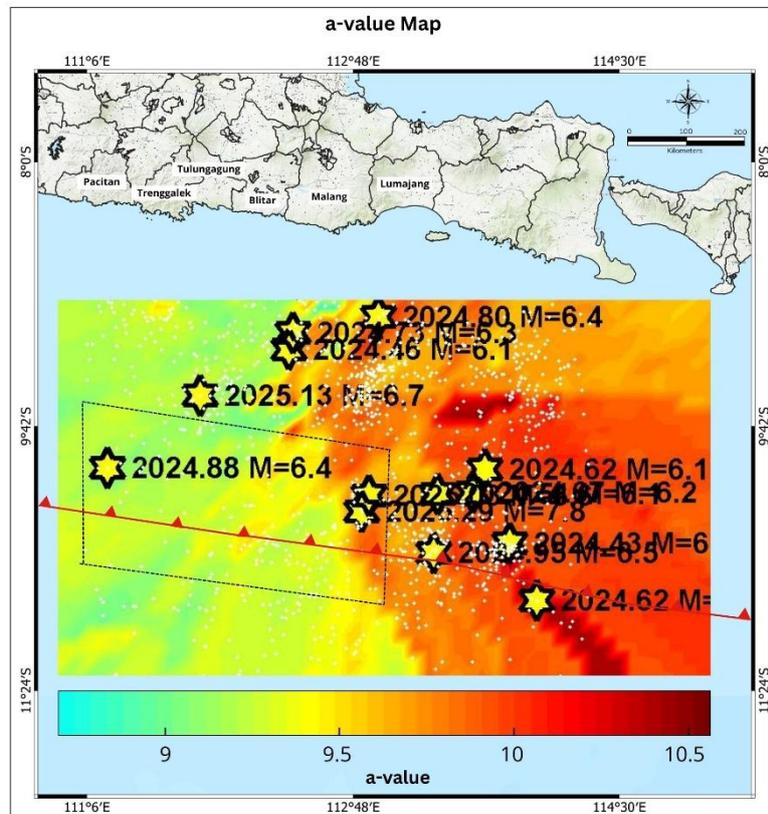


Figure 7. Spatial map of a-value reflecting the earthquake frequency in the research area.

These results are consistent with the study by Hisyam et al. (2024), which asserts that in East Java, the majority of significant earthquakes from 2002 to 2022 were preceded by a temporal decrease in b-value. The study also identified that the major earthquake on April 10, 2021 (M_w 6.1) in Malang occurred in an area with a low b-value (~ 0.9), indicating that zones with low b-values are closely associated with the locations of major earthquakes. The low b-value in the Pacitan–Lumajang segment represents the potential for a major earthquake due to the high level of stress accumulation at the plate interface. Patterns like this are often associated with locked megathrust zones, as recorded in the Nankai, Chile, and Sumatra zones before major events (da Costa et al., 2024).

The correlation results between spatial parameters indicate that the Pacitan–Lumajang segment exhibits consistent seismotectonic characteristics, consistent with those of the seismic gap zone. The distribution of seismicity (Figure 2 and 3) shows that seismic activity in this region is very low, especially at depths of less than 70 km. Furthermore, the return period estimation map (Figure 4–6) reinforces this indication, dominated by shades of red to green in this zone. The long return period of major earthquakes, more than 200 years for M_w 7 and more than 4,000 years for M_w 8, indicates that significant seismic energy release has not occurred for a long time. This condition is further reinforced by the relatively low a-value distribution (< 9.5), as well as the low b-value (< 1.4), even approaching 1.2 at some points. The

combination of these two parameters indicates a low frequency of earthquake

occurrences and a high accumulation of stress in the zone.

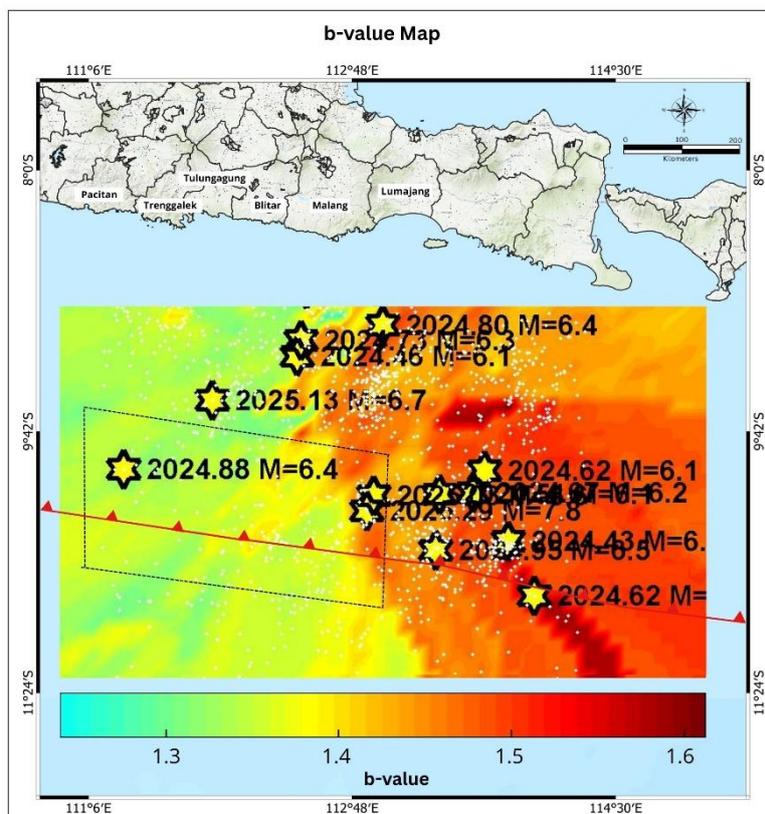


Figure 8. Spatial map of b-value reflecting the tectonic conditions in the research area.

The results of this study are consistent with Widiyantoro et al. (2020), which identified a slip deficit of 20–40 mm/year in a suspected seismic gap zone off the southern coast of East Java during the 2008–2014 geodetic observation period. This slip deficit serves as an indicator of a locked segment, which is likely experiencing significant accumulation of tectonic stress that has yet to be released. According to the study, if this segment were to release its stored energy suddenly, it could generate an earthquake with a potential magnitude of M_w 8.8.

The integration of the three parameters, which include low seismicity, long return periods, and relatively low a-value and b-value, supports the interpretation that the Pacitan–Lumajang segment is a seismic gap zone. Suppose a megathrust earthquake occurs in this segment, the southern coastal areas of East Java, including Pacitan,

Trenggalek, Tulungagung, Blitar, Malang, and Lumajang, are at risk of experiencing significant impacts on infrastructure and population.

Conclusion

This research successfully characterized spatially the Pacitan–Lumajang segment in the southern subduction zone of East Java, which is suspected to be a seismic gap zone. The integration of three main approaches, which are seismicity analysis, return period estimation, and evaluation of seismotectonic parameters such as a-value and b-value, results in a consistent spatial picture. The seismicity distribution map and cross-section show less earthquake activity on the interface, a long return period for major earthquakes, which is >200 years for M_w 7 and >4,000 years for M_w 8, as well as relatively low a-value and b-value. The high-resolution spatial

approach used, along with the integration of long-term data (1910–2025), significantly contributes to mapping the seismic potential in greater detail. Although this study is limited to instrumental earthquake data, the results of this study are expected to provide an initial contribution to mapping the spatial distribution of seismic activity and serve as initial considerations in megathrust and tsunami disaster risk assessments in the southern coastal areas of Java.

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Author Contribution

Diva Maharani Putri contributed to the study through Conceptualization, Formal Analysis, Investigation, and Writing – original draft. Nanda Maharani was responsible for Data curation and Visualization. Ilham and Riska Yulinda contributed to Validation, Supervision, and Writing – review & editing.

Conflict of Interest

The authors declare no conflict of interest.

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