IDENTIFICATION OF EARTHQUAKE AND TSUNAMI RISK ZONES IN SOUTHERN JAVA USING GRAVITY METHOD

IDENTIFIKASI ZONA RISIKO GEMPA BUMI DAN TSUNAMI DI SELATAN JAWA MENGGUNAKAN METODE GAYA BERAT

Isna Karima[1*], Agustya Adi Martha[2], Nurul Hudayat[2*], Tati Zera[1]

[1] Physics, Faculty of Science and Technology, UIN Syarif Hidayatullah Jakarta, Jakarta
[2] National Research and Innovation Agency - BRIN, Jakarta

*Corresponding author: nurul.hudayat@brin.go.id

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ABSTRACT: The southern part of Java has a high level of disaster risk because it is affected by a subduction zone where the Indo-Australian plate thrusts beneath the Eurasian plate. Six tsunami events occurred in the southern part of Java, caused by earthquakes in the area, based on BMKG catalogue data from 416 to 2023. Given the very large population on the island of Java, the possibility of causing more casualties is greater. Therefore, it is very necessary to have thorough mitigation preparation to estimate the possibility of areas experiencing a large earthquake that triggers a tsunami. This study aims to determine areas with a high level of earthquake and tsunami risk distribution using the gravity method with data from the TOPEX satellite in the form of free air anomaly data and topographic data. After data processing and an anomaly map were obtained, it showed that areas with a high level of earthquake risk were located around the subduction zone and Java Trench. This is due to the geological conditions of the southern part of Java, located in the subduction zone where many active faults were found.

Keywords: Earthquake, tsunami, gravity, subduction zone, Southern Java

ABSTRAK*: Wilayah selatan Jawa memiliki tingkat risiko bencana yang tinggi karena terletak pada zona subduksi yang terbentuk akibat aktivitas tumbukan lempeng Indo-Australia yang menunjam ke lempeng Eurasia. Sebanyak enam kejadian tsunami terjadi di wilayah selatan Jawa yang disebabkan oleh gempa bumi di wilayah tersebut berdasarkan data katalog BMKG dari tahun 416 sampai dengan tahun 2023. Mengingat jumlah penduduk di Pulau Jawa yang sangat banyak, maka kemungkinan menimbulkan korban jiwa yang lebih banyak menjadi lebih besar. Oleh karena itu, sangat diperlukan persiapan mitigasi yang matang untuk memperkirakan kemungkinan wilayah mengalami gempa bumi besar yang memicu tsunami. Penelitian ini bertujuan untuk mengetahui wilayah dengan tingkat sebaran risiko gempa bumi dan tsunami yang tinggi menggunakan metode gayaberat dengan data dari satelit TOPEX berupa data anomali udara bebas dan data topografi. Setelah dilakukan pengolahan data dan diperoleh peta anomali, menunjukkan bahwa wilayah dengan tingkat risiko gempa bumi yang tinggi berada di sekitar zona subduksi dan palung Jawa. Hal ini berdasarkan kondisi geologi wilayah selatan Jawa yang berada pada zona subduksi dan banyak ditemukan patahan aktif.*

Kata Kunci: *Gempa bumi, tsunami, gaya berat, zona subduksi, Selatan Jawa*

INTRODUCTION

Java Island has complex geological conditions and is characterized by high seismic activity due to the influence of an active seismotectonic arc system, resulting in a high level of disaster risk (Anggarajati et al., 2024). Earthquakes arise from seismic processes associated with the sudden release of accumulated energy within the Earth, which is characterized by the rupture of rock layers (Prananda et al., 2022).

The released energy is generally generated by the accumulation of stress along the plate boundary, which progressively increases until it exceeds the strength of the rocks and induces rupture. In Java, seismicity is commonly categorized into earthquakes originating from the southern Java subduction zone and those associated with the active Java fault zone. Earthquakes within the subduction zone occur at shallow to deep depths and typically have magnitudes greater than 4 Mw. Large-magnitude events of up to 8.5 Mw have been recorded in western Java, whereas earthquakes of 5–6 Mw are common along the southern part of the island. Subduction-zone earthquakes generally exhibit thrust and normal-fault mechanisms, while horizontal (strike-slip) mechanisms are rarely observed in this subduction (Jayadi et al., 2023).

Earthquakes with thrust-fault mechanisms have been documented along the Cimandiri Fault, including the Gandasoli Sukabumi (1982) and Cibadak Sukabumi (2000) events. A similar thrust-fault mechanism was identified for the 1990 Majalengka earthquake on the Baribis Fault. Right-lateral strike-slip fault was recorded during the 1995 Bumiayu earthquake along the Bumiayu Fault, whereas the 2006 Yogyakarta earthquake exhibited a left-lateral strike-slip mechanism. Normal-fault earthquakes, meanwhile, are associated with extensional processes within the seismic gap zone (Soehaimi, 2008).

The gravity method is a geophysical technique used to detect subsurface density. This method has been applied to identify fault structures (Martha et al., 2023), hydrocarbon exploration (Juwita et al., 2024; Wibowo et al., 2024) and evaluate geothermal prospects (Hudayat et al., 2024). For earthquake and tsunami mitigation, gravity data can support regional assessments by delineating structurally vulnerable zones in southern Java and identifying areas with elevated seismic and tsunami hazard potential.

Geological Setting

Java Island is characterized by complex tectonic conditions resulting from the convergence between the Indo-Australian Plate, which is subducting beneath the Eurasian Plate (Haryanto, 2006). This convergent interaction produces recurrent episodes of tectonic compression and extension, generating frequent seismicity associated with several active fault systems (Helmi and Haryanto, 2008). Three major active surface-expressed faults—the Cimandiri, Baribis, and Lembang faults—were formed through tectonic processes operating from the Cretaceous to the Quaternary (Haryanto, 2006).

The southern margin of Java constitutes a convergent plate boundary forming an active subduction zone driven by the motion of the Indo-Australian Plate. As a result, Java is situated within a region of elevated seismicity due to its location along this subduction corridor (Indriana, 2008). This subduction pathway is part of a shallow megathrust system extending approximately 5,500 km from south of Bangladesh and continuing along the western and southern margins of Sumatra, Java, Bali, and into eastern Indonesia (Saraswati and Anjasmara, 2014).

The geological setting of Java within the megathrust zone confers a high level of geohazard potential, particularly the possibility of large earthquakes occurring within existing seismic gap segments. Such major seismic events may influence volcanic activity and can generate tsunamis, given that large offshore earthquakes are one of the primary tsunami-generating mechanisms (Ashar, 2017). Considering Java's dense population relative to other regions, the potential impacts are substantial. Consequently, comprehensive mitigation planning is essential to anticipate areas that may experience significant seismic events (Erlangga, 2020).

METHODS

The data used in this study consist of secondary gravity and topographic datasets totaling 87,966 measurement points. These datasets were obtained from the TOPEX satellite altimetry database (TOPEX, 2025). The gravity anomalies are derived from satellite radar altimetry, in which satellites such as TOPEX/Poseidon, GEOSAT, and ERS-1—operating at altitudes of approximately 800 km—emit microwave pulses toward the ocean surface. The recorded two-way travel time yields precise sea surface height (SSH) relative to a reference ellipsoid. Because the ocean surface closely conforms to the geoid, SSH reflects variations in the Earth's gravitational field.

Along-track SSH profiles are differentiated to obtain sea surface slopes (vertical deflections), which are resolved into north–south and east–west components. These slope components are subsequently transformed into gravity anomalies using Fourier-based processing techniques designed to reduce long-wavelength errors and enhance short-wavelength signals that are attenuated by ocean depth (~4 km). The effective resolution is constrained by altimeter noise arising from ocean-surface roughness, with a typical measurement precision of 10–20 mm after averaging. This supports along-track resolutions of approximately 20–30 km (e.g., ~24 km for combined GEOSAT/TOPEX global coverage) and gridded products at ~2 arc-minutes (~3.7 km at the equator). However, upward continuation effects limit the reliability of wavelengths shorter than ~20 km, and comparisons with shipborne gravity measurements indicate anomaly accuracies on the order of 4–7 mGal (Sandwell and Smith, 1997).

The acquired gravity data were processed using conventional gravity-method procedures. This method measures spatial variations in gravitational acceleration produced by density contrasts within the subsurface. Its fundamental basis follows Newton's law of universal gravitation (Telford et al., 1990), which states that the attractive force between two masses m_1 and m_2 separated by distance r is: (Equation 1)

$$\boldsymbol{F} = \gamma \frac{m_1 m_2}{r^2} \hat{r} \quad (1)$$

F is the force generated between two particles of mass m_1 and m_2, r is the distance between the two particles, $\hat{r}$ is the unit vector of m_1 and m_2, and γ is the universal gravitational constant (6.6732×10^{-11} N m^2/kg^2).

Measurements of gravitational acceleration at the Earth's surface are affected by variations in latitude, topography, elevation, Earth–Sun positional effects, and subsurface density heterogeneity (Basid and Hidayat, 2011). To quantify these density contrasts, gravity anomalies are obtained by comparing observed gravity values with corresponding theoretical gravity at the same location. In this study, the complete Bouguer anomaly was calculated using Equation 2 (Telford et al., 1990):

$$CBA = FAA - BC + TC \quad (2)$$

where CBA denotes the complete Bouguer anomaly, FAA is the free air anomaly, BC represents the Bouguer Correction, and TC is the Terrain Correction, all expressed in mGal.

RESULTS AND DISCUSSION

The study area extends from West Java to Central Java, within coordinates 107.010°E to 111.70°E and 9.00°S to 5.00°S. This research utilizes topographic data and gravity anomaly data retrieved from the Topex website. Following initial preprocessing, a topographic map was generated, as presented in Figure 1. Based on the resulting topographic map, high-elevation regions are represented by red to pink zones, with elevation values ranging from approximately 0.228 m to 3014.34 m. These areas correspond to the upland physiographic domains of West Java and Central Java, consistent with the mountainous terrain along the southern segment of Java Island, including prominent ranges such as the Dieng Complex Volcano. Medium elevations are depicted by yellow to orange zones, spanning –1075.18 m to 0.228 m. Low-elevation zones, indicated by blue to green ranges from –6645.07 m to –1075.18 m, represent the Indian Ocean bathymetry and are associated with the southern Java subduction system.

Overall, the integrated topographic and bathymetric map delineates the major physiographic gradients across Java Island—from highland regions to the deep oceanic basin. When interpreted in the context of regional tectonics, these morphological patterns indicate the convergent interaction between the Eurasian Plate and the Indo-Australian Plate along the southern margin of Java.

corrections applied to the Free-Air Anomaly and topographic data yield the Bouguer anomaly map as shown in Figure 2 reveals subsurface density variations in the study area. The Bouguer anomaly values rangebetween -175 mGal to 171.52 mGal and are categorized into three groups. The high anomaly values, ranging from 51.89 mGal to 171.52 mGal, are represented by red to pink colors. Moderate anomalies, spanning from 20.53 mGal to 51.89 mGal, appear as yellow to orange zones. The low anomalies, have values between -175.00 mGal to 20.53 mGal, are indicated by blue to green colors. The distribution pattern shows high anomalies around the Java Island and the Java Trench, while low anomaly values dominate the Indian Ocean area.

The transition from blue to green on the map suggests the location of the Java subduction zone.

The Bouguer anomaly map shown in Figure 2 range from –175 mGal to 171.52 mGal, are classified into three main categories. High anomaly values between (51.89–171.52 mGal) are represented by red to pink color, moderate anomalies (20.53–51.89 mGal) are depicted in yellow to orange, and low anomalies (–175.00–20.53 mGal) appear in blue to green.

The spatial distribution indicates that high anomalies are concentrated around Java Island and the Java Trench, while low anomalies are predominant in the Indian Ocean region. The gradational change from blue to green on the anomaly map marks the transition zone associated with the Java subduction system, reflecting contrasts in crustal density between the overriding and subducting plates.

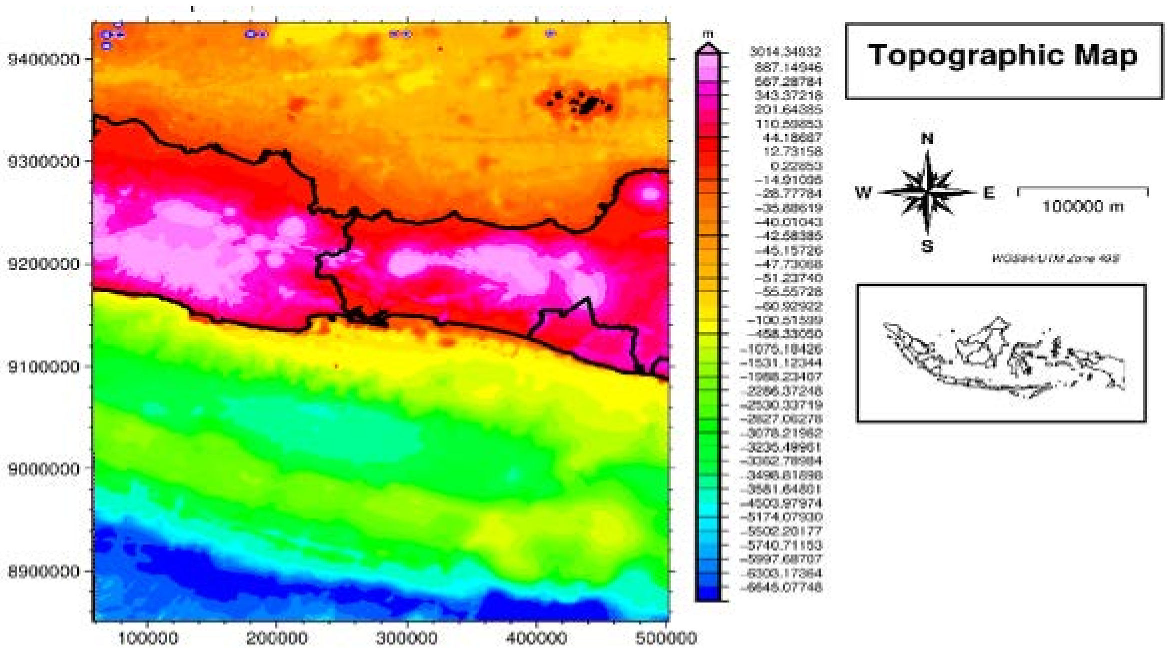

Figure 1. Topographic and bathymetric map of the study area showing elevation variations from Onshore Java to the Java Trench.

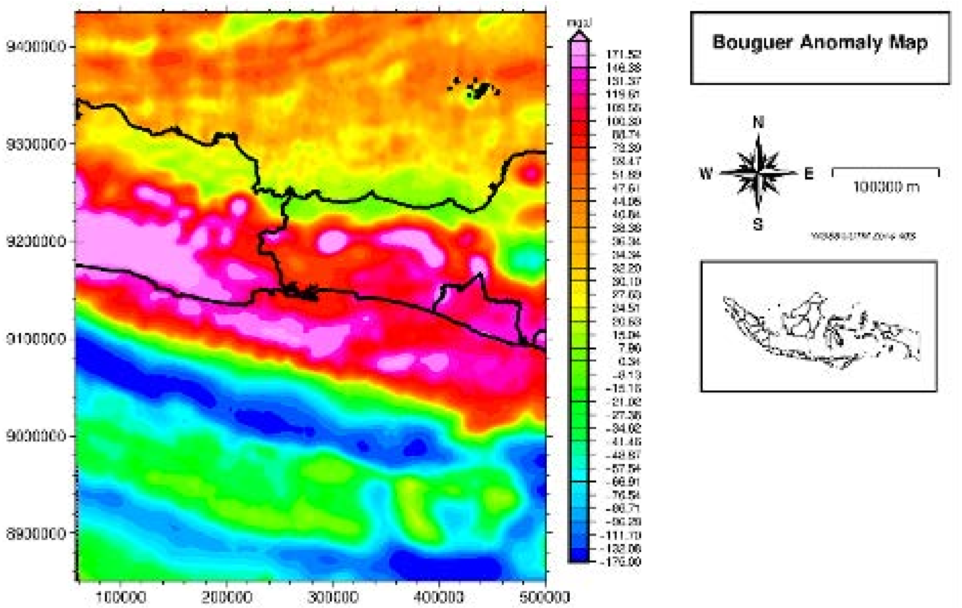

Figure 2. Complete Bouguer anomaly map presenting the gravity field, used to delineate density contrasts and regional structural trends.

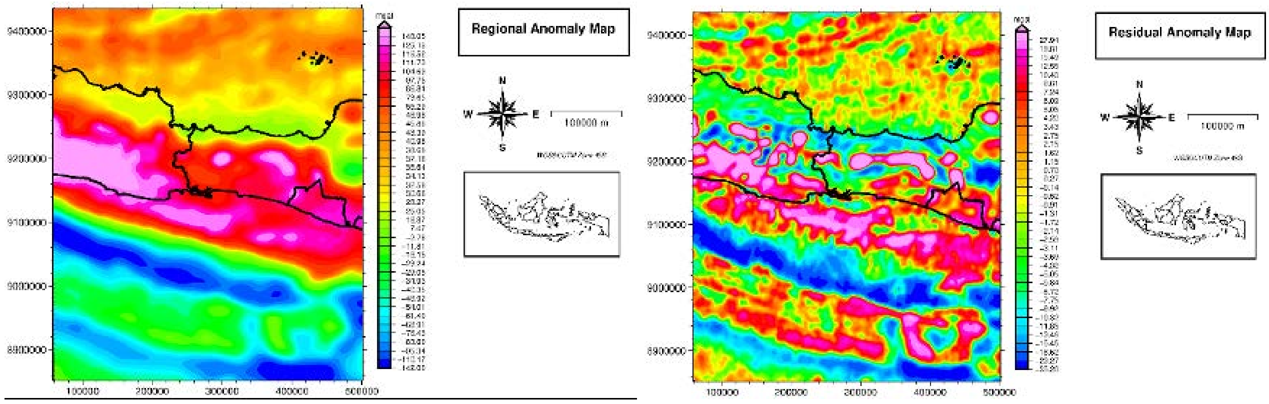

Figure 3. Regional gravity anomaly; (b) residual gravity anomaly derived from separation of long and short wavelength components.

The gravity anomalies were filtered to minimize noise and suppress unwanted interference. In this study, an upward continuation filter was applied to the gravity data, extending the field to an elevation of 5 km. This technique effectively transforms gravity observations at the surface into their equivalent response at a higher measurement level. The resulting upward-continued field yields a regional anomaly map with a smoother character, implying a more homogeneous distribution of long-wavelength anomalies. As shown in Figure 3a, the regional anomaly map reveals that high-gravity values are concentrated across Java, whereas the low-gravity zones, depicted in green, delineate the subduction system south of Java.

In contrast, the residual anomaly map (Figure 3b) exhibits a more heterogeneous, high-frequency anomaly pattern, reflecting density contrasts within the shallow subsurface. High residual anomalies are distributed across Java Island and within the Java Trench. However, several localized high-residual anomalies also occur in areas interpreted as part of the subduction zone, deviating from the expected pattern. Under typical conditions, low-gravity anomalies are anticipated in such settings due to the presence of thick sedimentary sequences or relatively low-density crustal materials. The occurrence of high anomalies in these regions may instead be attributed to local geological structures, such as uplifted crustal blocks, magmatic intrusions, or shallow, dense lithologies (Novitri et al., 2025).

The second vertical derivative (SVD) map was performed to enhance the characterization of subsurface density variations by amplifying short-wavelength gravity gradients. This method is effective for delineating major geological structures such as faults, lithological contacts, and potential indicators of natural resources or geohazards.

In the SVD map shown in Figure 4, the anomalous values exhibit a distinct distribution, divided into positive (red–yellow) and negative (blue–green) zones. Positive SVD values represent

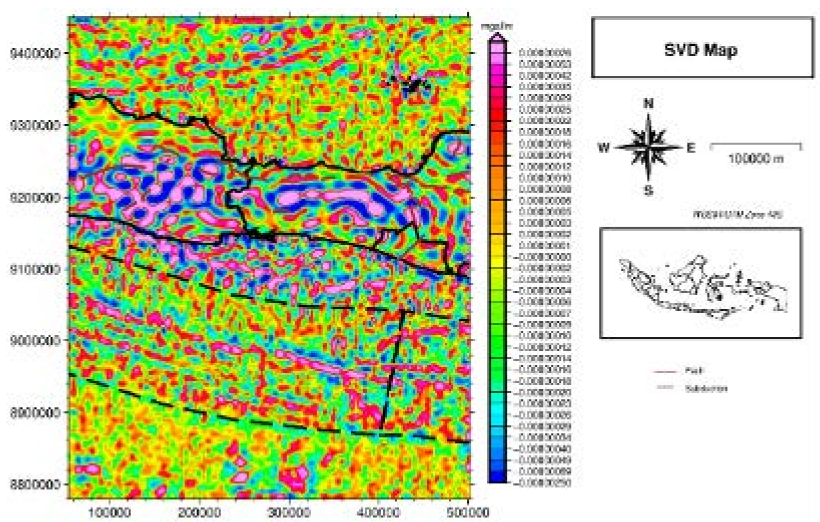

Figure 4. SVD representation of gravity gradients across the study area.

short-wavelength, high-frequency anomaly zones commonly associated with sharp lithological boundaries or near-surface structural discontinuities. These positive values, however, do not directly indicate higher-density rocks and must be interpreted in relation to local geological conditions.

Negative SVD values correspond to short-wavelength, low-frequency anomalies that may delineate structural depressions such as sedimentary basins or normal-faulted blocks. Similar to the positive anomalies, these values do not inherently signify lower-density rocks but instead emphasize the geometry of subsurface structures.

The sharp transitions between positive and negative SVD zones likely represent major structural boundaries, including fault systems or fold hinges, reflecting zones of significant lateral density variation.

SVD also reveals a contrast between high and low anomalies over short distances toward the southwestern and southern parts of the study area. When qualitatively analysed and correlated with regional geological data, the anomaly pattern is consistent with features that may be associated with the subduction zone. However, as SVD enhances high-frequency components related to shallow density contrasts, interpretations regarding deeper structures such as subduction zones must be made cautiously and supported by additional geophysical evidence. The observed patterns include linear trends that may indicate active faults and major tectonic boundaries. A dominant anomaly trend aligns with the subduction direction in the southern part of Java, suggesting the influence of subduction-related crustal deformation due to interactions between oceanic and continental plates. Additionally, anomaly patterns oriented west-east and southwest-northeast likely correspond to the regional fault system in West Java and Central Java, further supporting the presence of significant active faulting and crustal deformation.

On the tsunami distribution map shown in Figure 5 a) there are six events that have occurred on the island of Java based on data from the BMKG catalog from 416 to 2023. It is important to note that records before the modern instrumental period are historical reconstructions with high uncertainty and should be interpreted cautiously. Point 1 corresponds to the Pangandaran tsunami, which occurred on July 17, 2006, at longitude 107.314° E and latitude 9.672° S, associated with an earthquake of magnitude 7.0 Mw. Point 2 marks the tsunami event near Pelabuhan Ratu, on September 2, 2009, located at longitude 107.32° E and latitude 8.24° S, triggered by the 7.3 Mw Tasikmalaya earthquake. Point 3 (blue) denotes an earthquake that occurred in the Java Sea in 1823 with a magnitude of 6.8 Mw. Point 4 represents an earthquake whose shaking reached the Semarang region of Central Java in 1840, although its magnitude remains unknown. Point 5 marks the October 20, 1859 event, during which a tsunami was reported in Pacitan. Point 6 corresponds to the September 11, 1921 earthquake, which had a magnitude of 7.5 Mw and generated a tsunami observed at Parangtritis, Yogyakarta.

The earthquake distribution map in Figure 5(b) shows seismic events that occurred in the southern part of Java from 2004 to 2024 with magnitudes exceeding 2.5 Mw. The analysis indicates that earthquake clusters are concentrated along the subduction zone, the Java Trench, and onshore Java. This pattern corresponds with the distribution of active fault segments documented in the 2017 active fault database compiled by PusGEN, an agency under the Ministry of Public Works and Housing responsible for earthquake mitigation. The high seismicity in these regions reflects

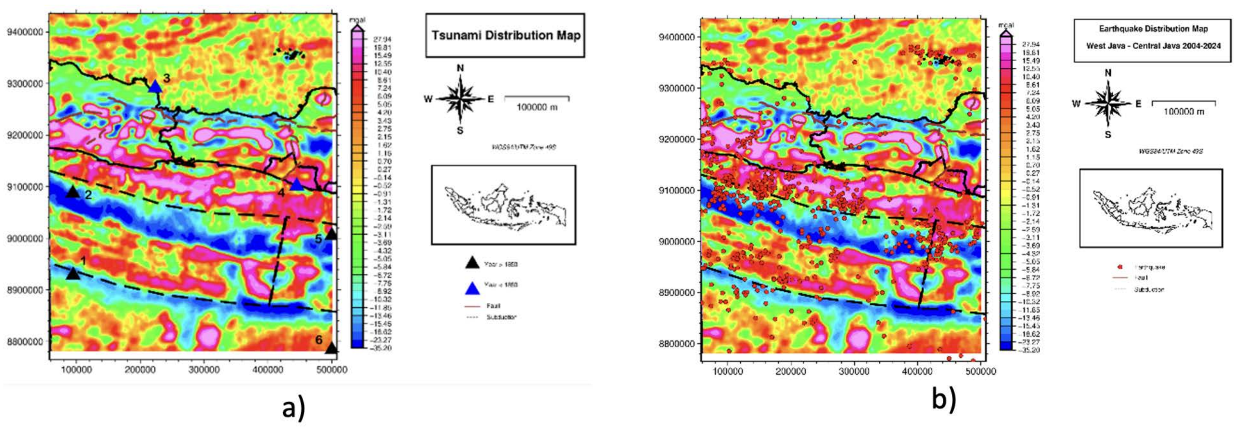

Figure 5. (a) Map showing the locations of tsunami events recorded around Java. (b) Earthquake distribution map illustrating seismic activity in the southern Java region between 2004 and 2024.

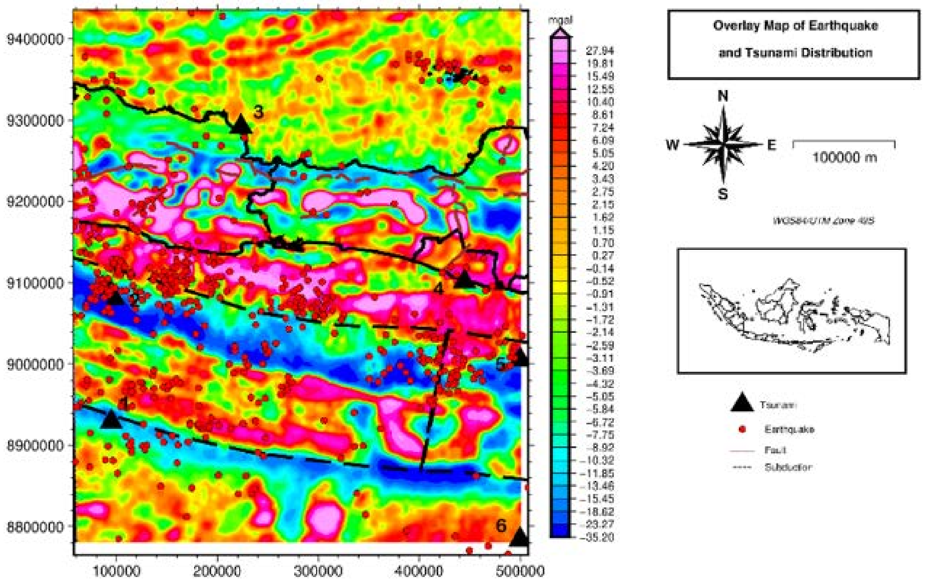

Figure 6. Overlay Map of Earthquake and Tsunami Distribution

ongoing tectonic processes associated with deformation along these active fault systems.

Tsunami occurrences in the study area are generally concentrated near earthquake epicenters and active fault segments, as illustrated in Figure 6. The map shows the distribution of seismic events alongside tsunami-generation points (indicated by black triangles) across southern Java. The presence of these points suggests that certain earthquakes meet the conditions necessary to generate tsunamis. However, tsunami generation is controlled not only by earthquake magnitude but also by fault mechanism, focal depth, event location (offshore vs. onshore), slab geometry, and the extent of seafloor deformation.

The Java subduction zone south of the island is a well-known source of large interplate thrust, or megathrust, earthquakes capable of producing significant tsunamis along the southern coast. A notable example is the Mw 7.7 Pangandaran earthquake in 2006, which triggered a destructive tsunami in West and Central Java due to its shallow thrust mechanism and associated seafloor displacement. It is important to emphasize that not all earthquakes in southern Java generate tsunamis; tsunamigenic events predominantly arise from shallow megathrust earthquakes occurring along the subduction interface.

Red to yellow colors denote high-elevation regions, representing mountainous terrain on land or bathymetric highs such as submarine ridges. In contrast, green to blue colors indicate lower elevations, encompassing coastal lowlands and the seafloor. This pattern shows that much of the southern coast of Java is characterized by low-lying topography, making these areas generally more susceptible to tsunami inundation should a major earthquake occur along the subduction zone.

Higher-elevation areas, such as the mountainous regions of Central Java, are comparatively less exposed to tsunami hazards, provided they lie sufficiently inland or away from steep coastal slopes. Nonetheless, these elevated zones remain seismically active due to the presence of inland fault systems, although not all faults in Central Java produce large earthquakes; several generate only shallow, small-to-moderate magnitude events.

CONCLUSSIONS

Based on the findings of this study, high residual anomaly values are distributed across onshore Java, the Java Trench, and the adjacent subduction zone. The Java subduction system is marked by intense seismicity along the convergent interface between the Indo-Australian and Eurasian plates. The overlay of earthquake and tsunami distributions demonstrates that most seismic events cluster near the subduction boundary, where plate convergence generates substantial tectonic stress. Shallow megathrust earthquakes in this zone are particularly capable of producing tsunamis that pose hazards to the southern coast of Java.

In addition, several earthquake epicenters are dispersed across Java Island, reflecting the presence of active inland fault systems capable of generating tectonic earthquakes within the region.

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