Phi: Jurnal Pendidikan Fisika dan Terapan
Vol. 13, No. 1 (2027) 31-45
ISSN: 2460-4348, e-ISSN: 2549-7162
https://jurnal.ar-raniry.ac.id/index.php/jurnalphi/index
Article Type: *original research*

Integrated Seismotectonic Analysis of the West–Central Java Subduction System Based on Seismicity, Focal Mechanisms, and Seismic Tomography

Deanne Ardelia Zahrani[1], Sinta Caenur Winusda[1], Mia Uswatun Hasanah[2*]
[1]Study Program of Geophysics, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Sumedang, Indonesia
[2]Department of Geophysics, Faculty of Mathematics and Natural Sciences, Universitas Padjadjaran, Sumedang, Indonesia

Correspondence E-mail: hasanah@geophys.unpad.ac.id

ARTICLE INFO

Article History:
Received: 06 June 2026
Revised: 29 July 2026
Accepted: 08 August 2026
Published: 09 August 2026

Keywords:
Seismicity; Focal mechanism; Slab deformation; Java ubduction one; Seismic hazard

ABSTRACT

Java Island lies along the convergent boundary between Indo-Australian and Eurasian plates, making it one of the most seismically active regions in Indonesia. Numerous studies have investigated seismicity, focal mechanisms, and seismic tomography beneath West and Central Java. However, these datasets are commonly interpreted separately, and integrated assessments of slab geometry and deformation variations along subduction zone remain limited. This study combines data from ISC-EHB (1964–2022), BMKG (2009–2020), and Global CMT (1976–2022) catalogs, together with records of damaging earthquakes and tsunamis. A total of 7,746 earthquakes were analyzed and integrated with a published seismic tomography model based on the AK135 velocity model through spatial mapping and vertical cross-sections constructed at 1° longitude intervals. The results show a continuous subduction system extending beneath southern Java from west to east. Shallow earthquakes (<100 km) are concentrated near megathrust interface, intermediate-depth events (100–300 km) delineate Wadati–Benioff zone, and deep earthquakes (>300 km) indicate continued slab descent into the upper mantle. Cross-sectional analysis reveals along-strike variations in slab geometry, with relatively shallow slab configurations in the western segment and steeper geometries toward the central segment. Tomographic images show high-velocity anomalies associated with the subducting slab and low-velocity anomalies interpreted as mantle wedge regions. Focal mechanism solutions are dominated by thrust faulting at shallow depths, whereas normal and strike-slip faulting become more common at intermediate depths. These observations provide additional constraints on the relationship between slab geometry, deformation processes, fault activity, and seismic hazards in West and Central Java.

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License

1. INTRODUCTION

Java Island is one of the most seismically and tectonically active regions in Indonesia due to its location at the confluence of three major plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. Along the southern edge of Java, the Indo-Australian Plate subducts beneath the Eurasian Plate at a convergence rate of approximately 6–7 cm/year (Kopp et al., 2009). This

subduction system forms a northeast-dipping slab that extends to depths of over 600 km, as demonstrated by the Wadati–Benioff seismicity pattern (Hutchings and Mooney, 2021). Therefore, the South Java subduction zone is a major source of large megathrust earthquakes, with the potential for tsunamis and significant impacts on densely populated land areas in southern Java.

Previous studies have provided important constraints on the tectonic processes of the Java subduction system. The subduction of seamounts and oceanic ridges can influence plate deformation and the geometry of the plate interface, potentially contributing to megathrust segmentation (Xia et al., 2023). Accretionary prism deformation also accommodates tectonic stress through shortening and faulting within the wedge (Kopp et al., 2011). In addition, variations in megathrust coupling and active fault systems indicate that deformation associated with subduction is not restricted to the plate interface but also affects the overriding plate and back-arc region (Supendi et al., 2018). Seismic tomography and focal mechanism studies have further provided constraints on slab geometry, mantle heterogeneity, and deformation styles beneath Java (Dziewonski et al., 1981; Ekström et al., 2012; Hutchings and Mooney, 2021).

West–Central Java deserves particular attention because this segment of the Java subduction system exhibits pronounced spatial variations in seismicity, slab geometry, and deformation patterns over a relatively short along-strike distance. Earthquake hypocenters range from shallow megathrust events offshore to intermediate- and deep-focus seismicity beneath the island, while deformation within the overriding plate is also expressed by active crustal fault systems. In addition, this region has experienced damaging earthquakes and tsunami events associated with both offshore subduction processes and onshore fault activity. These characteristics make West–Central Java an important setting for examining how along-strike variations in slab geometry are related to earthquake distribution and deformation within both the subducting and overriding plates.

Previous studies have established the broad geometry and along-strike tectonic heterogeneity of the Java margin. However, these studies have addressed different spatial scales and tectonic components, ranging from Indonesia-wide analyses of seismicity and slab structure to local investigations of forearc deformation and individual crustal fault systems. Consequently, the seismotectonic expression of the transition from West to Central Java remains insufficiently constrained, particularly in terms of how along-strike changes in slab geometry correspond to variations in earthquake depth distribution and deformation style within a consistent spatial framework.

We therefore test the hypothesis that along-strike variations in the apparent geometry of the subducting Indo-Australian slab across West–Central Java are accompanied by systematic changes in earthquake depth distribution and focal-mechanism style. To evaluate this hypothesis, a total of 7,746 earthquake events from the ISC-EHB (1964–2022) and BMKG (2009–2020) catalogs were analyzed together with focal mechanism solutions from the Global CMT catalog (1976–2022). Historical damaging earthquake and tsunami records from the BMKG catalog (1881–2024) were incorporated to place the observed tectonic patterns in a regional hazard context, while a published seismic tomography model based on the AK135 reference velocity model was used as an independent structural constraint on the interpreted slab geometry.

The hypothesis is evaluated using five consistently spaced vertical sections at 1° longitude intervals (106°–110°E), enabling direct comparison of the subduction system from West to Central Java. The analysis reveals a west-to-central transition from relatively shallow apparent slab configurations toward steeper geometries characterized by progressively deeper seismicity, accompanied by a depth-dependent shift from predominantly shallow thrust faulting to more complex intermediate- and deep-slab deformation. By linking these observations with independent tomographic constraints and the spatial distribution of historical damaging earthquakes and tsunamis, thereby providing a more spatially resolved understanding of how slab geometry, seismicity, and deformation vary across this transition while complementing previous Indonesia-wide and forearc-focused studies. The spatial distribution of seismic activity in the study area is shown in Figure 1.

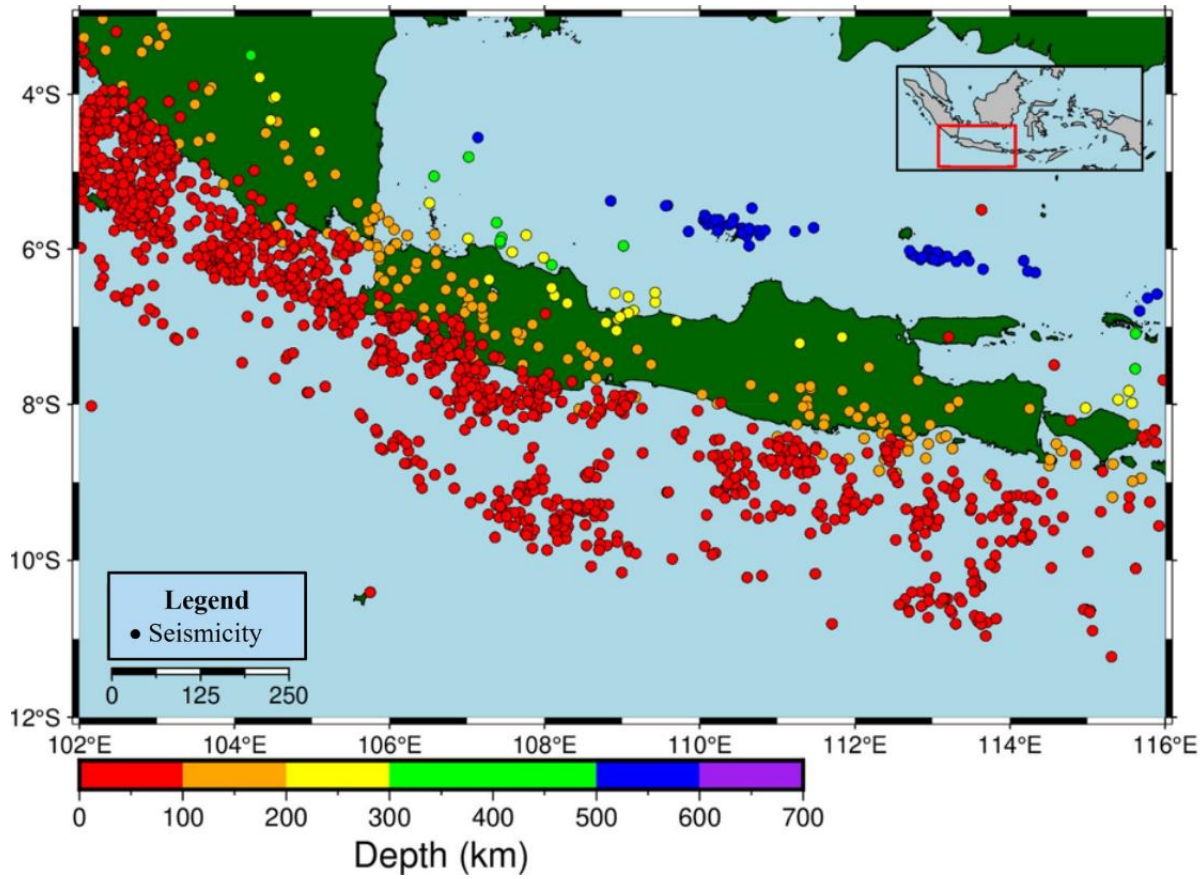


Figure 1. Seismicity Distribution Map Based on ISC-EHB Catalog (1964–2022) and BMKG Catalog (2009–2020) Data. Earthquake epicenters are shown along the southern Java subduction zone, with color gradation representing hypocenter depth..

2. METHODS

This study uses earthquake data from the ISC-EHB catalog (1964–2022) and the BMKG catalog (2009–2020), including origin time, hypocenter location, focal depth, and magnitude (Mw ≥ 3.0), with a maximum depth of 700 km. A magnitude threshold is used to ensure that the dataset represents tectonically relevant seismicity, while the depth range is restricted to capture the full spectrum of subduction-related earthquakes beneath Java. To quantitatively evaluate the depth distribution of seismicity, earthquake hypocenters were grouped into shallow (0–100 km), intermediate (>100–300 km), and deep (>300–600 km) depth intervals. The number and relative proportion of earthquakes within each depth interval were calculated and compared among the vertical sections to evaluate systematic variations in seismicity with depth and along strike.

Focal mechanism solutions were obtained from the Global CMT catalog (1976–2022) for events with Mw ≥ 5.0. The catalog provides moment tensor solutions, nodal-plane parameters (strike, dip, and rake), and the orientations of the principal P, B, and T axes. Focal mechanisms were quantitatively classified using the orientations of the principal axes following the classification approach of Frohlich (1992). The resulting mechanisms were grouped into thrust, normal, strike-slip, and other/mixed mechanisms. The number and percentage of each mechanism type were calculated for the shallow (0–100 km), intermediate (>100–300 km), and deep (>300–600 km) depth intervals to quantitatively evaluate depth-dependent changes in deformation style.

Uncertainty was evaluated using the errors reported in the source catalogs. For the Global CMT dataset, reported uncertainties in origin time, latitude, longitude, CMT depth, and moment-tensor components were examined to assess the reliability of event locations and focal-mechanism solutions. The ISC-EHB dataset has traveltime residuals ranging from −7.5 to 15 s, which were considered as descriptive information on the fit between observed and calculated arrival times.

These uncertainty measures were considered when interpreting hypocenter distributions, focal mechanisms, and slab-related patterns.

Additionally, a dataset of destructive earthquakes and tsunami events from the BMKG catalog (1881–2024) was included. This dataset contains event locations, magnitudes, and reported impacts and was used to examine the spatial relationship between historical damaging events and the regional seismotectonic patterns identified in this study.

Seismicity mapping and visualization were performed using Generic Mapping Tools (GMT) version 6 to generate spatial distribution maps and vertical sections. Five consistently spaced vertical sections at 1° longitude intervals (106°–110°E) were constructed to provide a common spatial framework for comparing earthquake depth distributions, focal-mechanism characteristics, and the apparent geometry of the subducting slab from West to Central Java.

The seismic tomography model used in this study was adopted from Hasanah et al. (2024), who developed a regional seismic tomography model using the FMTOMO package (Rawlinson et al., 2006). FMTOMO employs finite-difference solutions of the eikonal equation combined with an iterative nonlinear inversion scheme to model seismic wave propagation and estimate subsurface velocity structures. The inversion utilized 69,705 earthquake events recorded by 1,185 seismic stations and 2,943,974 P-wave traveltime observations from the ISC-EHB catalog (1964–2020). The model was parameterized relative to the AK135 reference velocity model and provides information on P-wave velocity (Vp) anomalies. Model reliability was evaluated through checkerboard resolution tests using multiple grid configurations, with the optimal resolution obtained for a grid spacing of approximately 100 km × 100 km × 80 km. The resolution tests indicate reliable recovery of velocity anomalies across the study area to depths of approximately 600–650 km. In the present study, the published tomography model is used solely as an independent supporting constraint for interpretation with seismicity, focal mechanisms, and historical earthquake–tsunami data.

Velocity anomalies are interpreted relative to the reference model, where high-velocity anomalies indicate cool, dense material associated with the subducting plate, while low-velocity anomalies correspond to warmer regions potentially influenced by fluids or partial melting within the mantle wedge.

The final analysis integrates the quantitative earthquake-depth distribution, focal-mechanism classification, reported data uncertainties, seismic tomography, and historical earthquake–tsunami records within the same cross-sectional framework. This approach allows the interpretations of slab geometry and deformation patterns to be evaluated using quantitative observations in addition to visual comparison. The overall research workflow is illustrated in Figure 2.

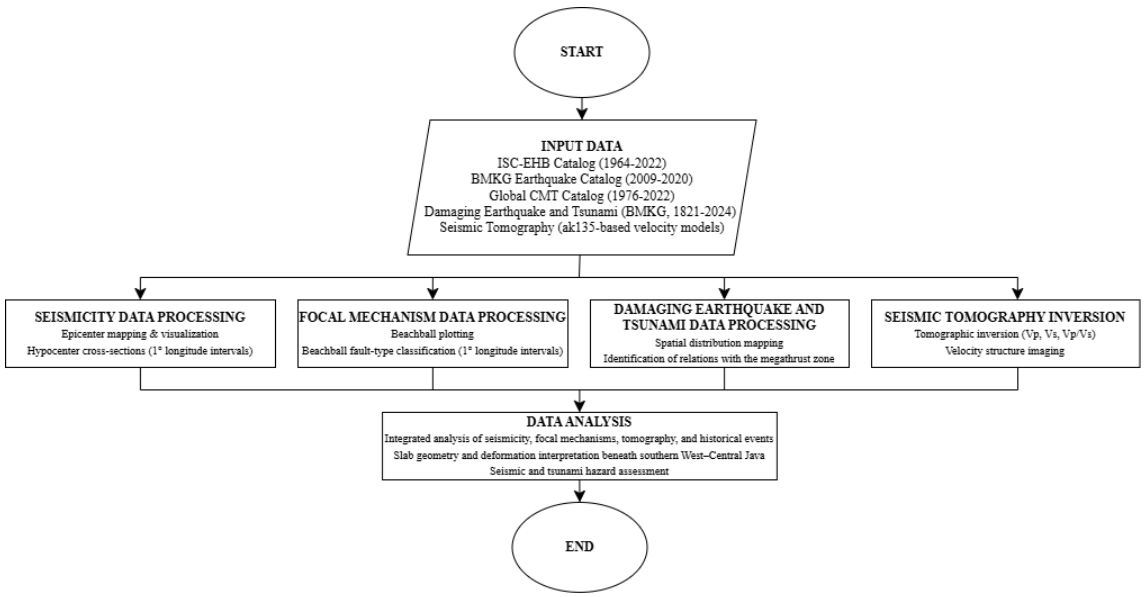


Figure 2. Research workflow encompassing data input, seismicity processing, focal mechanism analysis, seismic tomography, and damaging earthquake and tsunami analysis, culminating in an integrated interpretation of the West–Central Java subduction zone.

3. RESULT AND DISCUSSION

Characterization of seismicity, focal mechanisms, damaging earthquakes and tsunamis, and seismic tomography provide fundamental insights into tectonic deformation and fault activity within the subduction system. In this study, these analyses are used to describe the spatial distribution of earthquake events and to infer the relationship between hypocenter patterns and the underlying tectonic framework of the South Java subduction zone.

3.1 Seismicity Analysis

The distribution of seismicity in the study area, as shown in Figure 3, reveals a clear spatial pattern that reflects the tectonic framework of the South Java subduction system. Earthquake epicenters are largely aligned with a belt extending from west to east parallel to the trench, depicting the subduction of the Indo-Australian Plate beneath the Eurasian Plate. This pattern indicates that seismic activity is primarily controlled by the megathrust interface, consistent with previous regional studies (Hall, 2012; Widiyantoro and van der Hilst, 1997). Furthermore, the occurrence of seismicity on the Java mainland, particularly in the western to central regions, indicates that tectonic deformation is not limited to the plate boundary but extends to back-arc fault systems such as the Kendeng and Baribis zones.

Based on the depth distribution, seismicity shows a clear vertical segmentation associated with the subduction process. Earthquakes with shallow depths ranging from 0 to 100 km are concentrated along the southern boundary and correspond to deformation along the megathrust interface. Earthquakes with intermediate depths ranging from 100 to 300 km form the north-dipping Wadati–Benioff zone, representing progressive subduction of the subducting plate. In contrast, earthquakes with deep depths greater than 300 km, predominantly observed in the western to central segment, indicate that the plate is penetrating into the deeper upper mantle and the mantle transition zone. This depth-dependent distribution is consistent with the continuity of the subducting slab and its influence on seismicity across different depth regimes (Widiyantoro and van der Hilst, 1997; Hutchings and Mooney, 2021).

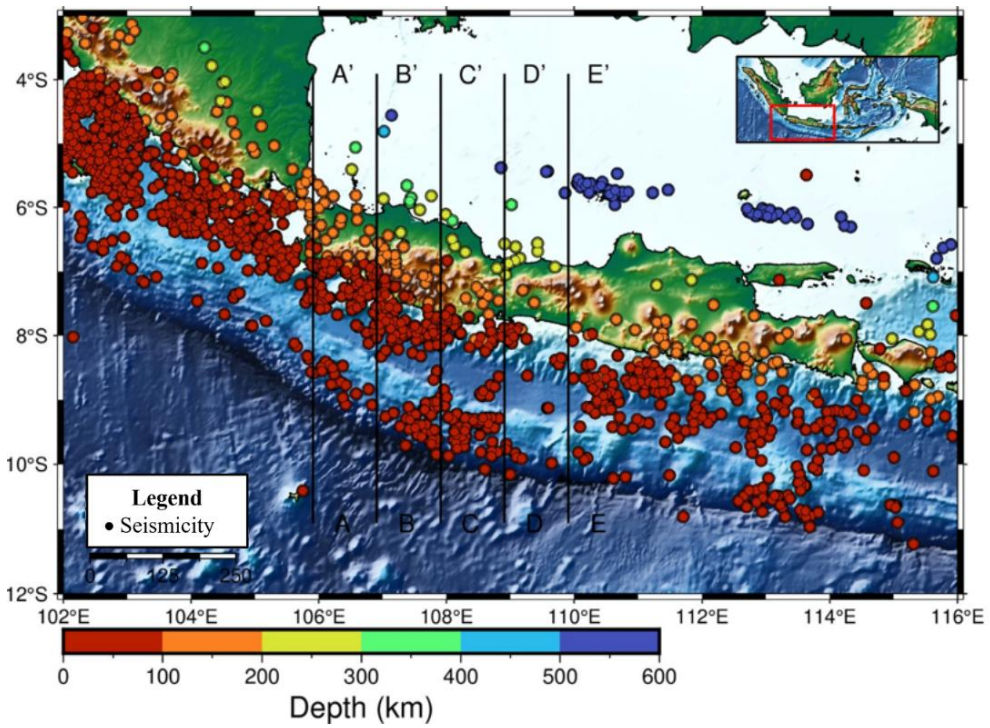


Figure 3. Seismicity distribution map derived from the ISC-EHB (January 1964–December 2022) and BMKG (January 2009–December 2020) catalogs. Dots represent earthquake epicenters, with color gradation indicating hypocenter depth. Vertical lines from A–A′ to E–E′ mark the locations of vertical cross-sections used to analyze subduction structure based on the spatial and depth distribution of earthquakes.

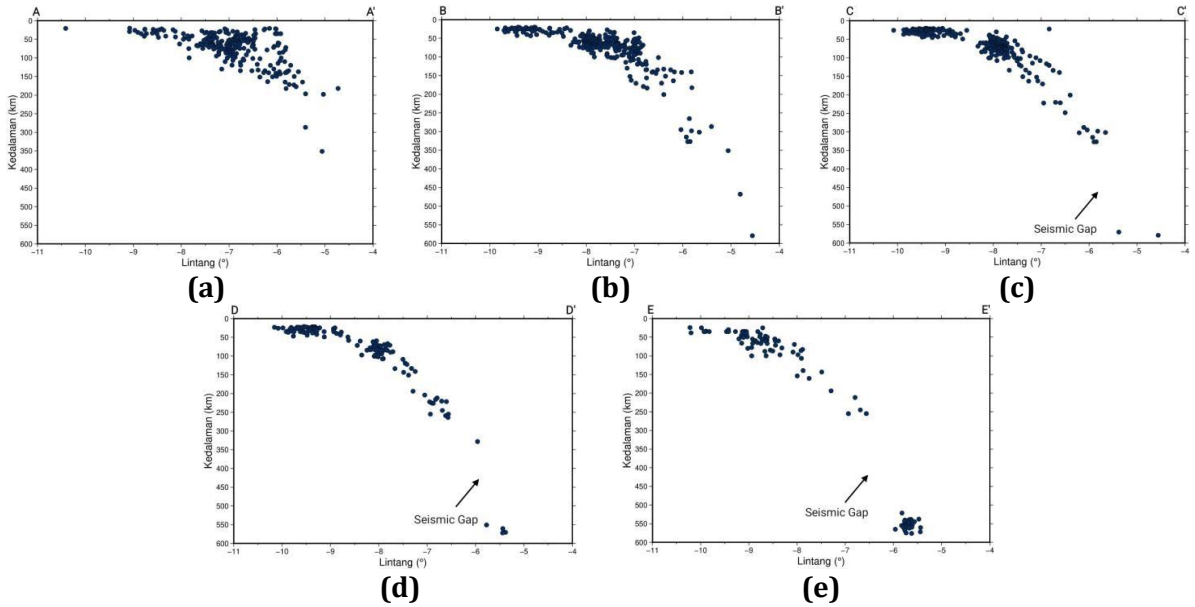


Figure 4. Vertical cross-sections of seismicity along profiles A–A′ to E–E′ at 1° longitude intervals: (a) 106°E; (b) 107°E; (c) 108°E; (d) 109°E; and (e) 110°E. The vertical axis represents hypocenter depth (km), while the horizontal axis represents latitude (°). Dots indicate earthquake epicenters along the southern Java subduction zone.

Vertical cross sections, as shown in Figure 4, highlight significant along-strike variations in the geometry of the subducting slab beneath southern Java. The western segment (A–A′ to B–B′) is characterized by a relatively shallow slab dip and predominantly shallow seismicity, indicating limited plate penetration at depth. In contrast, the central segment (C–C′) exhibits a steeper slab geometry, with seismicity extending beyond 400 km depth. The eastern segment (D–D′ to E–E′) shows an even steeper configuration, where earthquakes reach depths greater than 500 km, onsistent with deeper penetration of the slab into the mantle. These observations indicate substantial heterogeneity in slab geometry and deformation along the Java subduction zone.

Furthermore, several cross sections, particularly along profiles C–C′ to E–E′, reveal zones of reduced seismic activity at intermediate depths that may be interpreted as seismic gaps. These features indicate localized decreases in earthquake occurrence relative to the surrounding regions and may reflect variations in stress distribution or mechanical properties within the subduction system. However, additional geodetic constraints are required before inferring megathrust locking conditions or future seismic potential.

The apparent steepening of the slab geometry from west to east suggests significant along-strike variations in subduction geometry beneath southern Java.The relatively shallow geometry observed in profiles A–A′ and B–B′ contrasts with the steeper slab configurations identified in profiles C–C′ to E–E′, where earthquake hypocenters extend to greater depths. Similar variations in slab geometry have been reported in previous studies of the Java subduction system and may be related to differences in slab properties and tectonic conditions along the margin (Widiyantoro and van der Hilst, 1997; Kopp et al., 2011). Variations in slab geometry may influence the distribution of seismicity and deformation patterns throughout the region. In addition, the occurrence of intraplate seismicity beneath mainland Java suggests that subduction-related stresses are transmitted into the overriding plate, potentially contributing to deformation within back-arc fault systems such as the Kendeng and Baribis fault zones (Supendi et al., 2018; Marliyani et al., 2021).

The interpretation of seismicity patterns should also consider differences in location quality and catalog characteristics. The ISC-EHB catalog provides relocated hypocenters specifically developed to improve the consistency of earthquake locations for global and regional tectonic studies, whereas the BMKG catalog is derived from the Indonesian seismic monitoring network and provides denser regional coverage for the more recent period. Because the two catalogs differ in temporal coverage, network configuration, and location procedures, their hypocentral distributions

may contain different levels of location uncertainty. The ISC-EHB dataset used in this study has traveltime residuals ranging from −7.5 to 15 s, which provide descriptive information on the fit between observed and calculated arrival times but are not treated as a complete statistical measure of hypocentral uncertainty. In addition, differences in network development and detection capability through time may affect the completeness of the BMKG catalog, particularly for smaller-magnitude and older events. Therefore, variations in earthquake density are interpreted primarily in terms of regional spatial and depth patterns rather than as direct measures of temporal changes in earthquake occurrence.

3.2 Focal Mechanism Analysis

Focal mechanism analysis was conducted to identify faulting styles and characterize regional deformation patterns operating within the southern Java subduction system. The spatial distribution of focal mechanisms in Figure 5 shows that earthquake sources are predominantly aligned along the megathrust zone, with additional events distributed onshore, indicating deformation within the back-arc region.

At shallow depths (<100 km), focal mechanisms are dominated by thrust faulting, reflecting compressional stress associated with interplate coupling along the megathrust interface (Kopp et al., 2011; Hutchings and Mooney, 2021). This indicates that the dominant deformation style in the southern Java forearc is associated with convergent plate interaction.

Quantitative classification of the Global CMT focal mechanism solutions further supports the depth-dependent variation observed in Figure 6. Among the shallow events (0–100 km), 391 of 723 events (54.1%) are classified as thrust mechanisms. At intermediate depths (>100–300 km), the mechanisms are more heterogeneous, with 21 of 67 events (31.3%) classified as thrust, 12 (17.9%) as normal, 7 (10.4%) as strike-slip, and 27 (40.3%) as other mechanisms. At deep levels (>300–600 km), normal faulting becomes dominant, accounting for 20 of 28 events (71.4%). These results quantitatively indicate a depth-dependent change from predominantly compressional deformation at shallow depths toward more heterogeneous intermediate-depth deformation and predominantly extensional deformation at greater depths.

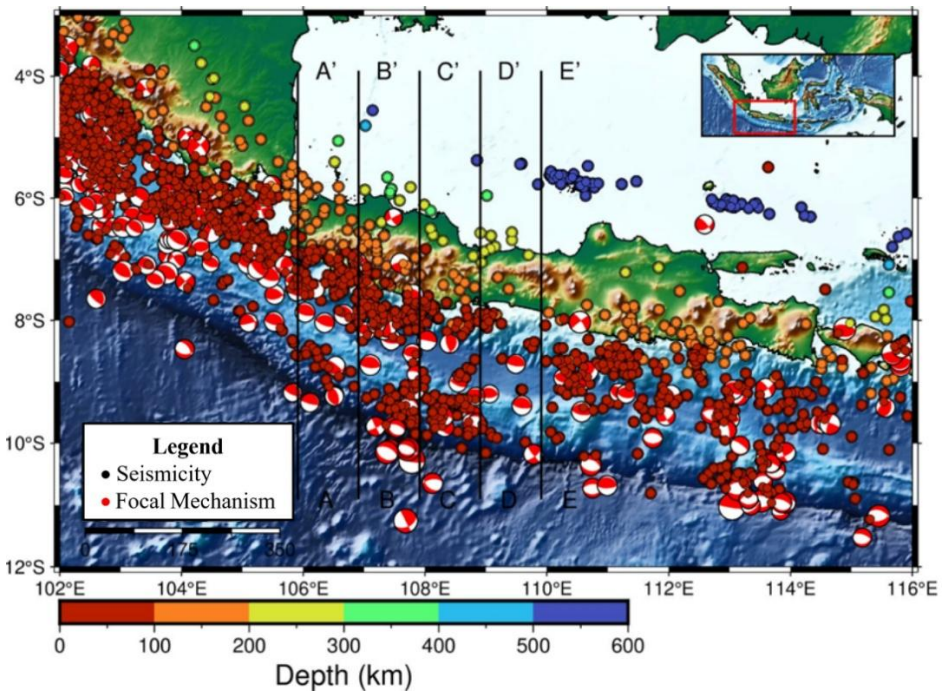


Figure 5. Combined map of seismicity and focal mechanisms derived from the ISC-EHB, BMKG, and Global CMT catalogs (January 1976–December 2022). Dots represent earthquake epicenters, with color gradation indicating hypocenter depth, while beachball symbols denote focal mechanism locations along the southern Java subduction zone. Vertical lines from A–A′ to E–E′ indicate the locations of vertical cross-sections used for subduction structure analysis.

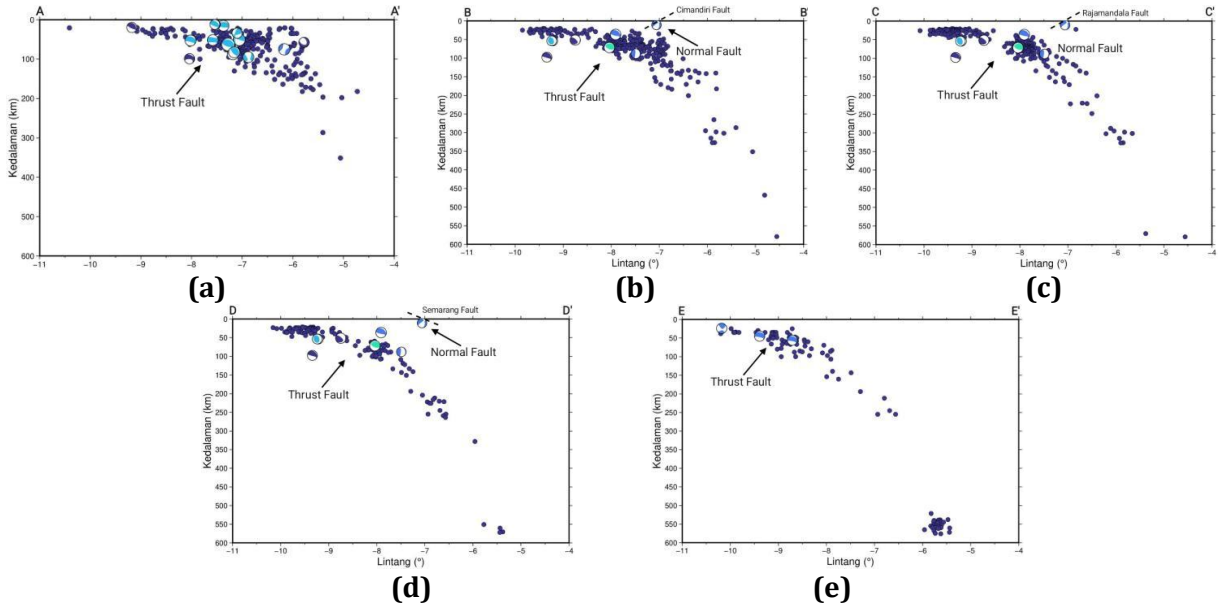


Figure 6. Combined vertical cross-sections of seismicity and focal mechanisms along profiles A–A′ to E–E′ at 1° longitude intervals: (a) 106°E; (b) 107°E; (c) 108°E; (d) 109°E; and (e) 110°E. The vertical axis represents hypocenter depth (km), while the horizontal axis represents latitude (°). Dots indicate earthquake epicenters, and beachball symbols represent focal mechanisms along the southern Java subduction zone.

Vertical cross-sections shown in Figure 6 reveal a systematic variation in faulting mechanisms with depth. In the western segment (A–A′ to B–B′), shallow seismicity is largely characterized by thrust mechanisms, consistent with a relatively low-angle subduction geometry. In contrast, the central segment (C–C′) shows the occurrence of normal faulting alongside thrust mechanisms at intermediate depths (100–300 km), indicating more heterogeneous deformation within the subducting plate. Further east (D–D′ to E–E′), normal faulting becomes more prominent at greater depths (>300 km), consistent with extensional deformation within the deeper slab that may be influenced by slab-pull forces (Widiyantoro and van der Hilst, 1997).

In addition to subduction-related deformation, several focal mechanisms indicate the influence of active crustal faults in onshore Java. Along profile B–B′ (~107°E; ~7°S), normal fault mechanisms are associated with the Cimandiri Fault, an active structure exhibiting complex kinematics including strike-slip and reverse components (Haryanto et al., 2017; Badan Geologi, 2022). Similarly, along profile C–C′ (~108°E), focal mechanisms are linked to the Rajamandala Fault zone, which accommodates deformation through a combination of reverse, strike-slip, and normal faulting under compressional stress from subduction.

Further east, along profile D–D′ (~109°E), normal faulting is interpreted to be associated with the Semarang Fault system, indicating intraplate deformation within northern Java. These observations demonstrate that deformation in Java is not solely controlled by megathrust processes but is also strongly influenced by stress transfer into the overriding plate.

The focal mechanism results are also subject to the uncertainties and sampling characteristics of the Global CMT catalog. The Mw ≥ 5.0 threshold adopted in this study means that the focal mechanism dataset primarily represents moderate-to-large earthquakes and does not capture the complete population of smaller earthquakes within the region. The Global CMT solutions used here also provide reported uncertainties in origin time, epicentral coordinates, CMT depth, and moment-tensor components, which are used to characterize the reliability of individual solutions. Consequently, the focal mechanisms are interpreted primarily as indicators of regional deformation style rather than as precise constraints on local stress conditions or individual fault-plane geometry.

Overall, the integration of spatial, cross-sectional, and quantitative focal-mechanism analyses indicates that the southern Java subduction system exhibits a depth-dependent variation in deformation style, from predominantly compressional thrust faulting at shallow depths to more

heterogeneous deformation at intermediate depths and predominantly extensional normal faulting at greater depths. This variation is consistent with changes in the mechanical behavior of the subducting slab with depth and the interaction between the subducting and overriding plates, highlighting the complex tectonic regime of the region.

3.3 Damaging Earthquakes and Tsunami Analysis

The spatial distribution of damaging earthquakes and tsunami events derived from the BMKG catalog is shown in Figure 7, with their vertical distribution along profiles A–A′ to E–E′ presented in Figure 8. The results indicate that destructive seismic events in southern Java are primarily concentrated along the offshore subduction zone, with additional clusters observed in onshore regions.

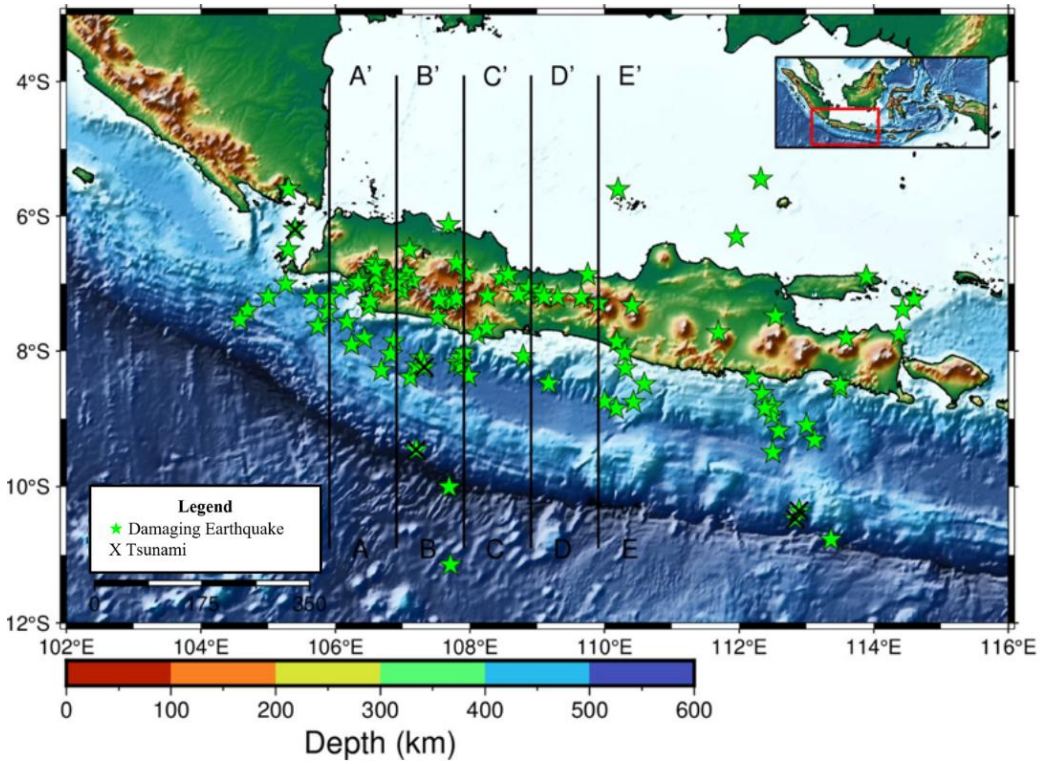


Figure 7. Spatial distribution map of damaging earthquakes and tsunami events based on the BMKG catalog for the period 1881–2024. Green star symbols indicate the locations of damaging earthquakes, while cross (×) symbols denote tsunami events. Vertical lines from A–A′ to E–E′ represent the locations of vertical cross-sections used to analyze subduction structure and the spatial distribution of seismic events in southern Java.

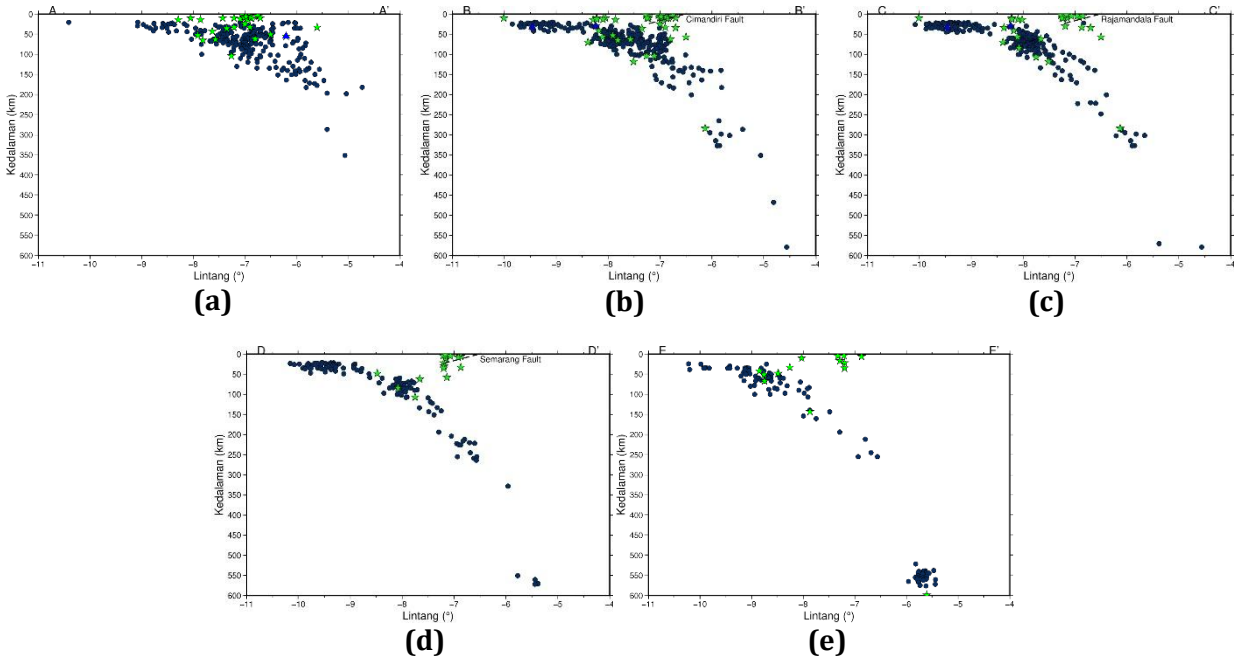


Figure 8. Vertical cross-sections of damaging earthquakes and tsunami events along profiles A–A′ to E–E′ at 1° longitude intervals: (a) 106°E; (b) 107°E; (c) 108°E; (d) 109°E; and (e) 110°E. Dots represent earthquake epicenters, green star symbols indicate damaging earthquakes, and blue star symbols denote tsunami events. The vertical axis represents event depth (km), while the horizontal axis represents latitude (°) along each profile.

Tsunami-generating earthquakes are predominantly located along the southern Java trench and occur at shallow depths (<60 km), indicating their origin within the upper portion of the megathrust interface. Historical records show that numerous large earthquakes (Mw 7.0–8.0) have originated from this zone since the 19th century, several of which generated tsunamis. These events demonstrate the importance of the southern Java megathrust as a major source of tsunami hazard in the region.

Representative historical events further illustrate this relationship. For example, a tsunami-generating earthquake in 1963 (Mw 6.6; depth ~55 km) occurred within the shallow megathrust interface, demonstrating that even moderate-magnitude earthquakes can produce tsunami impacts when rupture occurs at shallow depths (BMKG, 2025). Similarly, major events in 2006 (Mw 6.8; depth ~33 km) and 2009 (Mw 7.3; depth ~30 km) originated from shallow segments of the subduction zone and generated significant tsunami impacts along the southern coast of Java (BMKG, 2025). The concentration of these events within a narrow depth range highlights the importance of shallow megathrust segments in controlling tsunami generation.

In addition to offshore sources, damaging earthquakes are also observed in onshore regions of West Java. These events are spatially correlated with major active fault systems, particularly the Cimandiri and Rajamandala Faults, indicating that crustal deformation in the back-arc region contributes significantly to seismic hazard. The spatial association of these earthquakes with mapped fault systems is consistent with deformation of pre-existing crustal structures under the regional tectonic stress field.

Further east, a deep-focus earthquake (Mw 6.9; depth ~643 km) is identified beneath the Java Sea. This event is not associated with tsunami generation and instead reflects internal deformation within the subducting slab, likely related to slab pull processes. The contrast between shallow tsunamigenic earthquakes in the south and deep non-tsunamigenic earthquakes in the north highlights a clear vertical segmentation of seismic sources.

The interpretation of the historical damaging-earthquake and tsunami record should consider variations in catalog completeness and data quality over time. The BMKG dataset used in this study spans 1881–2024, covering periods with substantial differences in seismic instrumentation, network

coverage, and event-reporting capability. Consequently, the locations, depths, magnitudes, and reported impacts of older historical events may be less well constrained than those of modern instrumentally recorded earthquakes. The apparent spatial distribution of historical damaging earthquakes and tsunamis should therefore not be interpreted as a temporally homogeneous record of seismic activity. In this study, the historical catalog is used primarily to provide regional hazard context and to examine broad spatial relationships between damaging events, the subduction zone, and crustal fault systems.

Overall, the distribution of damaging earthquakes and tsunami events shows a clear spatial association with the regional subduction system and active crustal fault zones. Tsunami hazards are primarily associated with shallow offshore earthquakes near the megathrust, whereas damaging onshore earthquakes demonstrate the additional contribution of active crustal structures to regional seismic hazard. Together, these observations highlight the importance of considering both offshore subduction sources and onshore fault systems in evaluating seismic and tsunami hazards in southern Java.

3.4 Seismic Tomography Analysis

Seismic tomography analysis is used to image variations in P-wave velocity (Vp), which provide information on subsurface velocity heterogeneity beneath the southern Java subduction zone. The tomography results in Figure 9 are interpreted to characterize regional velocity variations and to provide an independent constraint on the geometry of the subducting slab, with anomalies defined relative to the AK135 reference model.

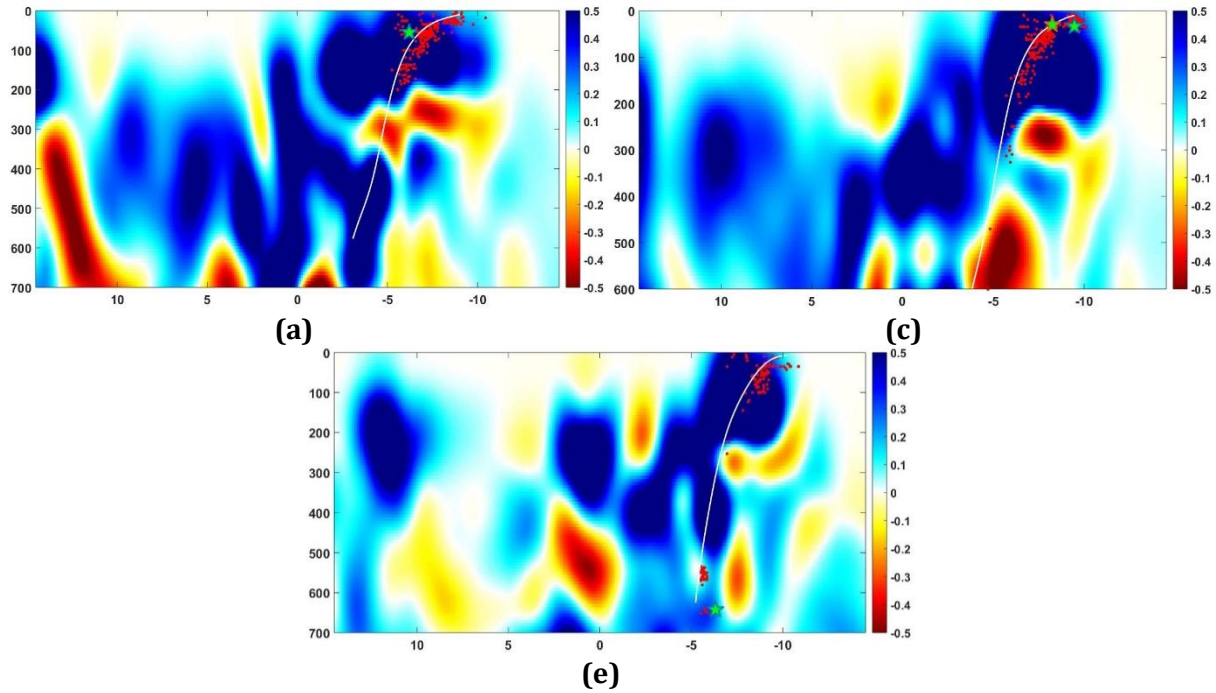


Figure 9. Seismic tomography cross-sections along profiles A (106°E), C (108°E), and E (110°E) showing P-wave velocity (Vp) anomalies relative to AK135 reference model. Color scales represent velocity anomalies, where warm colors indicate low-velocity zones and cool colors indicate high-velocity zones. Red dots represent earthquake hypocenters and star symbols indicate damaging earthquake events.

In general, the tomographic sections along profiles A (106°E), C (108°E), and E (110°E) reveal a clear contrast between the subducting slab and the surrounding mantle. High-velocity anomalies that spatially correspond with the Wadati–Benioff seismicity are interpreted as being consistent with the subducting Indo-Australian slab, which is expected to be colder than the surrounding mantle (Widiyantoro and van der Hilst, 1997). Similar interpretations have been reported in regional

tomographic studies, where subducting slabs are commonly expressed as high-velocity bodies due to their higher density and elastic rigidity (Zhao, 2004).

By contrast, low-Vp anomalies observed above the inferred slab may reflect variations in temperature, fluid content, composition, and/or partial melting within the mantle wedge. In subduction environments, fluids released from the descending slab may modify the physical properties of the overlying mantle and contribute to reductions in seismic velocity. However, the interpretation of low-Vp anomalies is non-unique, and the available Vp tomography alone cannot uniquely distinguish among thermal, compositional, fluid-related, or partial-melting effects. Therefore, these anomalies are interpreted as possible indicators of mantle-wedge modification rather than direct evidence of a specific physical process.

Furthermore, the relationship between seismic velocity anomalies, earthquake distribution, and damaging earthquake events provides important insight into the geodynamic processes beneath southern Java. In all tomographic sections, earthquake hypocenters (red dots) are predominantly concentrated along the boundary between high-velocity and low-velocity anomalies. This spatial correspondence suggests that seismicity is concentrated within or near the inferred subducting slab and its boundaries.

The high-velocity anomalies interpreted as the Indo-Australian slab represent relatively cold, dense, and rigid lithospheric material descending into the mantle. The occurrence of intermediate-to-deep earthquakes within or adjacent to the high-Vp anomalies is spatially consistent with internal deformation of the subducting slab. In contrast, low-velocity anomalies above the slab are interpreted as hotter and weaker mantle wedge regions that may contain fluids and partial melts generated by slab dehydration processes.

Damaging earthquakes represented by green star symbols are generally concentrated in the shallower parts of the subduction system, particularly near the megathrust and major crustal fault zones. Their distribution relative to the velocity structures provides additional spatial context for regional seismic hazards. However, the tomography alone does not directly constrain earthquake-generation processes or local stress accumulation.

Along profile A, the slab shows a relatively shallow geometry, with dominant high-velocity anomalies at shallow to intermediate depths. Earthquake hypocenters are concentrated near the velocity-gradient boundary, suggesting that seismic activity is concentrated along the megathrust interface and the upper part of the Wadati–Benioff zone. The presence of damaging earthquakes in this segment indicates that shallow deformation may contribute significantly to seismic hazard in the western part of Java. Compared with the other profiles, low-Vp anomalies above the inferred slab appear relatively limited. However, their physical origin cannot be uniquely determined from the Vp model alone.

Along profile C, the slab becomes steeper and the high-velocity anomaly extends to greater depth. Low-velocity zones above the slab are also more developed, which may indicate a stronger thermal or hydrous modification of the mantle wedge. This pattern is consistent with slab bending and internal deformation at intermediate depths, and it may also be related to the transfer of deformation to onshore fault systems such as the Rajamandala Fault. The broader low-velocity anomalies in this segment may indicate more intense fluid circulation and partial melting processes within the mantle wedge, reflecting a more active subduction-related thermal regime.

Along profile E, the slab appears steeper and extends to greater depths, indicating continued slab penetration into the upper mantle. The persistence of high-velocity anomalies supports the interpretation of a well-defined subducting slab, whereas the more limited low-velocity anomalies above it may suggest a comparatively weaker influence of fluid-rich or partially molten material. The steeper slab geometry in this segment is associated with deeper earthquake hypocenters, reflecting stronger slab pull forces and deeper internal slab deformation beneath central Java.

The tomographic interpretation should also be considered within the spatial resolution of the adopted model. Model resolution was evaluated through checkerboard resolution tests by Hasanah et al. (2024), with the optimal recovery obtained at a grid spacing of approximately 100 × 100 × 80 km. The tests indicate that regional velocity anomalies within the study area can be reliably recovered to depths of approximately 600–650 km. These resolution results support the use of the model for interpreting regional-scale velocity structures and broad slab geometry. However,

structures smaller than the effective grid resolution and sharp boundaries between velocity anomalies cannot be resolved with the same level of confidence. Therefore, the tomographic interpretation in this study focuses on regional-scale patterns rather than fine-scale structural details.

Overall, the tomography results demonstrate that variations in slab geometry strongly influence earthquake distribution, deformation style, and mantle processes beneath Java. The combination of high-velocity slab anomalies, low-velocity partially molten mantle wedge regions, concentrated seismicity, and damaging earthquake distribution supports the interpretation of an active and laterally heterogeneous subduction system beneath West–Central Java.

4. CONCLUSION

This study integrates seismicity, focal mechanism, seismic tomography, and historical damaging earthquake and tsunami data to improve understanding of the geometry and deformation characteristics of the southern Java subduction system. The combined datasets indicate substantial along-strike variations in slab geometry, with relatively shallow slab configurations in the western segment and steeper geometries toward the central segment, accompanied by progressively deeper seismicity. Quantitative focal mechanism analysis further reveals a depth-dependent variation in deformation style, with thrust mechanisms dominating shallow earthquakes (54.1%), more heterogeneous mechanisms at intermediate depths, and normal faulting becoming dominant at greater depths (71.4%). These results indicate a transition from predominantly compressional deformation at shallow depths toward more heterogeneous intermediate-depth deformation and predominantly extensional deformation within the deeper subducting slab.

Comparison with the published seismic tomography model shows a spatial correspondence between seismicity and regional P-wave velocity anomalies, with high-Vp anomalies consistent with the inferred subducting slab. The tomography model, supported by checkerboard resolution tests, provides an independent regional-scale constraint on the interpreted slab geometry, although the physical origin of individual velocity anomalies remains non-unique. Historical damaging earthquake and tsunami records further demonstrate the important role of shallow offshore megathrust earthquakes in tsunami hazard, while damaging onshore earthquakes indicate the additional contribution of active crustal faults to regional seismic hazard.

Overall, this integrated multi-dataset approach provides additional constraints on the tectonic framework of southern Java and a more spatially resolved characterization of the West–Central Java transition by linking along-strike variations in apparent slab geometry with earthquake depth distribution and deformation style. The results contribute to a better understanding of the relationships among subduction geometry, deformation, and regional seismic hazard and may serve as a useful reference for future tectonic studies and earthquake and tsunami hazard assessments in the region. From a physics education perspective, the integration of seismicity, focal mechanisms, and seismic tomography provides a contextual example for teaching fundamental physics concepts such as seismic-wave propagation, wave velocity, stress, strain, and deformation, and the relationship between physical properties and Earth structure. The spatial maps and cross-sectional visualizations presented in this study may also be used as supporting learning materials to connect these concepts with real geophysical phenomena in Indonesia.

REFERENCES

Abidin, H. Z., Andreas, H., Gumilar, I., Sidiq, T. P., & Fukuda, Y. (2009). Land subsidence and urban development in Bandung Basin (Indonesia). *Environmental Geology*, 57(4), 873–887.

Badan Geologi. (2022). Atlas peta tematik patahan aktif kabupaten/kota di Indonesia. *Kementerian Energi dan Sumber Daya Mineral.*

Badan Penanggulangan Bencana Daerah. (2023). Kajian dampak gempa yang berpusat di Tuban Jawa Timur. *PPID Pemerintah Kabupaten Jember.*

Direktorat Gempabumi dan Tsunami Kedeputian Bidang Geofisika. (2025). *Katalog gempabumi signifikan dan merusak tahun 1881–2024*. Badan Meteorologi, Klimatologi, dan Geofisika.

Dziewonski, A. M., Chou, T.-A., & Woodhouse, J. H. (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *Journal of Geophysical Research: Solid Earth*, 86(B4), 2825–2852. https://doi.org/10.1029/JB086iB04p02825

Ekström, G., Nettles, M., & Dziewoński, A. M. (2012). The Global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors*, 200–201, 1–9. https://doi.org/10.1016/j.pepi.2012.04.002

Hall, R. (2012). Late Jurassic–Cenozoic reconstructions of the Indonesian region and the Indian Ocean. *Tectonophysics*, 570–571, 1–41. https://doi.org/10.1016/j.tecto.2012.04.021

Handayani, L., Supendi, P., & Nugraha, A. D. (2017). Audio-Magnetotelluric Modeling of Cimandiri Fault Zone at Cibeber, Cianjur. *Indonesian Journal on Geoscience*, 4(1), 27–36.

Haryanto, I., Hutabarat, J., Sudradjat, A., Ilmi, N. N., & Sunardi, E. (2017). Tektonik Sesar Cimandiri, Provinsi Jawa Barat. Bulletin of Scientific Contribution, 15(3), 255–274.

Hasanah, M. U., Supendi, P., Nugraha, A. D., Widiyantoro, S., & Syaifuddin, F. (2024). The new insight of tectonic setting in Sunda–Banda transition zone using tomography seismic: Case study: 7.1 M deep earthquake 29 August 2023. Open Geosciences, 16, 20220710. https://doi.org/10.1515/geo-2022-0710

Hutchings, L. & Mooney, W. D. (2021). The seismicity of Indonesia and tectonic implications. *Journal of Geophysical Research: Solid Earth*, 126(2). https://doi.org/10.1029/2020JB021515

Irsyam, M., et al. (2020). *Peta sumber dan bahaya gempa Indonesia tahun 2017*. Pusat Studi Gempa Nasional (PUSGEN).

Kopp, H. (2011). The Java convergent margin: Structure, seismogenesis, and subduction processes. In D. Brown & P. D. Ryan (Eds.), Arc–continent collision (Geological Society, London, Special Publications, Vol. 355, pp. 111–137). *Geological Society of London.* https://doi.org/10.1144/SP355.6

Marliyani, G. I., Arrowsmith, J. R., & Whipple, K. X. (2016). Characterization of slow slip-rate faults in humid areas: Cimandiri fault zone, Indonesia. *Journal of Geophysical Research: Earth Surface*, 121(8), 1453–1474.

Munandar, R. A., & Sulsaladin, R. (2022). Karakteristik Tektonik dan Periode Ulang Gempa Bumi pada Sesar Cimandiri Jawa Barat*. Buletin Meteorologi, Klimatologi dan Geofisika,* 2(4), Mei 2022.

Mustika, I., M. (2014). *Tsunami Earthquake 17 Juli 2006 di Pangandaran Jawa Barat.*

Natalia, H. C., Harbowo, D. G., & Ikhram, R. (2021). Potensi geodiversity di sekitar kawasan Anak Krakatau–Way Kambas, Provinsi Lampung, sebagai kandidat geopark Indonesia. *Journal of Science and Applicative Technology, 5*(1), 47–57.

Pusat Vulkanologi dan Mitigasi Bencana Geologi. (2023). *Katalog tsunami Indonesia tahun 416–2021*. Kementerian Energi dan Sumber Daya Mineral.

Pusat Studi Gempa Nasional. (2017). *Peta sumber dan bahaya gempa Indonesia tahun 2017*. Pusat Penelitian dan Pengembangan Perumahan dan Permukiman, Kementerian Pekerjaan Umum dan Perumahan Rakyat.

Risnawati, R., Ihsan, I., Wahyuni, A., & Muh. Said L. (2021). Pola Sesar Saddang Berdasarkan Tingkat Seismisitas dan Fokal Mekanisme (Studi Kasus Januari 2010 - Juli 2020). *JFT: Jurnal Fisika dan Terapannya*, 8(1), 57–64.

Ryanto, T. A., Suntoko, H., & Setiaji, A. B. W. (2019). Pendugaan awal patahan di Pulau Jawa menggunakan anomali gravitasi dan riwayat kegempaan [Preliminary fault prediction in Java Island using gravity anomaly and earthquakes history]. *Eksplorium,* 40(1), 43–52. https://doi.org/10.17146/eksplorium.2019.40.1.5470.

Sapiie, B., Asikin, S., & Suryana, E. (2010). *3D palinspastic reconstructions of Rajamandala carbonate complex as implication of paleogeography in the Western Java, Indonesia. In Proceedings of the 34th Indonesian Petroleum Association Annual Convention. Jakarta: IPA.*

Supendi, P., Nugraha, A.D., Puspito, N.T., Widiyantoro, S., & Daryono. (2018). Identification of active faults in West Java, Indonesia, based on earthquake hypocenter determination, relocation, and focal mechanism analysis. Geosci. *Lett.* 5, 31. https://doi.org/10.1186/s40562-018-0130-y.

T. Muliawati, & Harbowo, D. G. (2023). A statistical review of the dates and patterns of volcanic activity of Lewotolo Volcano, East Nusa Tenggara, Indonesia. *IOP Conference Series: Earth and Environmental Science, 1245*(1), 012006.

Vermata, A. (2021). Analisis Struktur Geologi Daerah Rajamandala Kulon, Kabupaten Bandung Barat, Jawa Barat. *Universitas Padjadjaran.*

Widiyantoro, S., & van der Hilst, R. D. (1997). Mantle structure beneath Indonesia inferred from high-resolution tomographic imaging. *Geophysical Journal International*, 130(1), 167–182. https://doi.org/10.1111/j.1365-246X.1997.tb00996.x

Widiyantoro, S., Gunawan, E., Muhari, A., Rawlinson, N., Mori, J., Hanifa, N. R., Supendi, P., Shiddiqi, H. A., Nugraha, A. D., & Putra, H. E. (2020). Implications for megathrust earthquakes and tsunamis from seismic gaps south of Java Indonesia. Scientific Reports, 10, 15274. https://doi.org/10.1038/s41598-020-72142-z

Xie, F., Wang, Z., Zhao, D., Gao, R., & Chen, X. (2023). Seismic imaging of the Java subduction zone: New insight into arc volcanism and seismogenesis. *Tectonophysics,* 854, 229810. https://doi.org/10.1016/j.tecto.2023.229810

Xia, Y., Kopp, H., Klaeschen, D., Geersen, J., Ma, B., & Schnabel, M. (2023). Seamount and ridge subduction at the Java margin, Indonesia: Effects on structural geology and seismogenesis. *Journal of Geophysical Research: Solid Earth,* 128(2), e2022JB026272. https://doi.org/10.1029/2022JB026272