Indonesian Physical Review
Volume 9 Issue 02, May 2026
P-ISSN: 2615-1278, E-ISSN: 2614-7904

Deep Intraslab Deformation Offshore Northern Java Revealed by Time-Domain Moment Tensor (TDMT) Inversion

Muhammad Nurul Fahmi[1*], Yuni Indrawati[2], Arie Realita[1], Madlazim[1]
[1]*Physics Department, Faculty of Mathematics and Natural Sciences, Universitas Negeri Surabaya, Surabaya, Indonesia*
[2]*National Research and Innovation Agency (BRIN), Jakarta Pusat, Indonesia*

Corresponding Author's E-mail: muhammadfahmi@unesa.ac.id

Article Info

Article info:
Received: 23-08-2025
Revised: 14-02-2026
Accepted: 04-03-2026

Keywords:
Centroid Moment Tensor (CMT) Inversion; Deep-focus Earthquakes; Java Subduction Zone; Intraslab Deformation; Tectonic Stress Regime

How To Cite:
M. N. Fahmi, Y. Indrawati, A. Realita, Madlazim. "Deep Intraslab Deformation Offshore Northern Java Revealed by Time-Domain Moment Tensor (TDMT) Inversion", Indonesian Physical Review, vol. 9, no. 2, p 176-189, 2026

DOI:
https://doi.org/10.29303/ipr.v9i2.564

Abstract

This study investigates deep-focus intraslab deformation offshore Northern Java by analyzing two recent major earthquakes: 6 July 2020 (M_w 6.67) and 14 April 2023 (M_w 6.96), occurring at centroid depths of ~500–600 km. The objective is to constrain the source mechanisms and infer the prevailing deformation regime within the subducting Indo-Australian slab. We perform time-domain moment tensor (TDMT) inversion of broadband waveforms (GE/GEOFON network) using MTTime, with standard preprocessing (instrument correction and band-pass filtering) and Green's functions computed from the 1-D ak135 velocity model. Centroid depth is refined via a grid search that maximizes waveform variance reduction (VR). The preferred solutions show good waveform agreement (VR = 82.0% for the 2020 event and 71.6% for the 2023 event) and are consistent with Global CMT solutions (Kagan angles = 7.04° and 6.31°, respectively). Both earthquakes exhibit oblique normal faulting with a persistent dextral strike-slip component, indicating a dominantly extensional stress regime at depth, likely driven by slab pull/gravitational sinking, while the consistent trench-parallel shear suggests more complex internal slab deformation. These results provide quantitative constraints on deep intraslab kinematics beneath Java and motivate expanded event sampling for a more robust regional interpretation.

Copyright (c) 2026 by Author(s), This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

Introduction

Indonesia lies at the junction of three major tectonic plates: the Eurasian, Indo-Australian, and Philippine Sea plates. This complex plate interaction results in high seismicity, making the region particularly prone to tectonic hazards [1]. Beneath Java Island, this subduction zone is characterized by the steeply dipping Indo-Australian plate, which creates an active Wadati-Benioff seismic zone extending to depths of hundreds of kilometers [2, 3]. Recent studies

indicate that the densely populated northern coast of Java is increasingly exposed to tectonic earthquake hazards, particularly widespread ground shaking from regional seismic sources, including deep-focus intraslab events [4-6]. For example, the 6 July 2020 deep earthquake (depth ~594 km) produced maximum reported shaking of approximately MMI IV, while the 14 April 2023 deep earthquake (depth ~594 km) reached about MMI V, demonstrating that deep events can still generate perceptible to moderate shaking despite their large source depths. In contrast, tsunami hazard along Java is primarily associated with shallow megathrust earthquakes or other near-surface sources; deep-focus events are generally not tsunamigenic. Because deep-focus earthquakes can be felt over broad areas, constraining their source mechanisms and stress regimes remains important for regional seismic hazard assessments. Moreover, the mechanisms of deep intraslab earthquakes provide direct constraints on the state of stress within the subducting slab (e.g., slab pull, unbending, and internal shear). These considerations motivate the use of centroid moment tensor (CMT) analysis to robustly characterize deep earthquake sources beneath Java.

Understanding the fault mechanisms and stress orientations of earthquakes is essential for improving seismic hazard assessments. One of the most widely used approaches for characterizing the seismic source is the Centroid Moment Tensor (CMT) inversion [7-11]. This method allows researchers to determine key source parameters such as strike, dip, rake, depth, and fault type. While frequency-domain techniques have been extensively applied in global catalogs like the Global CMT [12], time-domain methods are increasingly gaining attention due to their simplicity, computational efficiency, and compatibility with regional seismic networks [13-15].

Prior applications of time-domain moment tensor (TDMT) inversion methods in Indonesia remain quite scarce, particularly for deep earthquakes within the Java subduction zone. These deeply seated seismic events, typically found at depths exceeding 500 km, exemplify intricate deformation mechanisms within the subducting plate. Although global models [12] commonly depict tensile stress conditions in deep subducting slabs, the exact direction of these stress forces and the specific geodynamic processes at play (such as slab pull versus gravitational sinking) that govern deformation in the deep Indo-Australian plate beneath Java remain poorly understood. Obtaining a comprehensive understanding of these processes is of utmost importance, as the resultant stress distribution can influence both regional tectonic activity and potential seismic threats.

To address this gap, this research investigates the two most important recent intermediate-depth earthquakes ($M_w > 6.5$) that occurred off the northern shore of Java: the occurrence on July 6, 2020 (M_w 6.67), and the occurrence on April 14, 2023 (M_w 6.96). These occurrences were selected because they are well documented and supported by publicly available, high-quality waveform data, making them ideal examples for this investigation. Utilizing a TDMT inversion based on Python (MTTime software [15]) on information from the GEOFON network, our aim is to (i) establish reliable CMT solutions and (ii) utilize these updated mechanisms to offer fresh restrictions on profound tectonic operations. We are particularly interested in determining whether the observed normal faulting corresponds with extensional faulting that runs parallel to the slab, which would offer compelling proof that slab pull forces are the primary influence on the subducted Indo-Australian plate at this depth. This investigation immediately adds to a more thorough regional geodynamic model and illustrates the capacity of contemporary, open-source methods to characterize complex seismicity.

Experimental Method

This study applies the Time-Domain Moment Tensor (TDMT) method to determine the Centroid Moment Tensor (CMT) solutions for two intermediate-depth earthquakes located off the northern coast of Java Island. The TDMT workflow is summarized in a conceptual flowchart (Figure 1).

The study focuses on two deep-focus seismic events. The first occurred on July 6, 2020, with a moment magnitude (M_w) of 6.67 at coordinates 5.60°S and 110.70°E, at a centroid depth of approximately 500 km. The second event occurred on April 14, 2023, with M_w 6.96, centered at 6.02°S and 112.03°E, and a depth of about 594 km (Figure 2). Both earthquakes occurred within the Benioff zone of the subducting Indo-Australian plate, consistent with previously identified deep intraslab activity in the Java region [5, 16].

Seismic waveform data for both events were retrieved from the GE network, operated by the GEOFON Program (GFZ Potsdam, Germany). Data and metadata were accessed via the IRIS Wilber3 platform (https://ds.iris.edu/wilber3/find_event). Station selection was based on three criteria: (i) azimuthal coverage in at least three quadrants around the epicenter, (ii) high signal-to-noise ratio (SNR), and (iii) epicentral distances less than 30°, which are optimal for moment tensor analysis [17]. Data downloading and handling were automated using the ObsPy Python library [18], which integrates well with the MTTime inversion workflow.

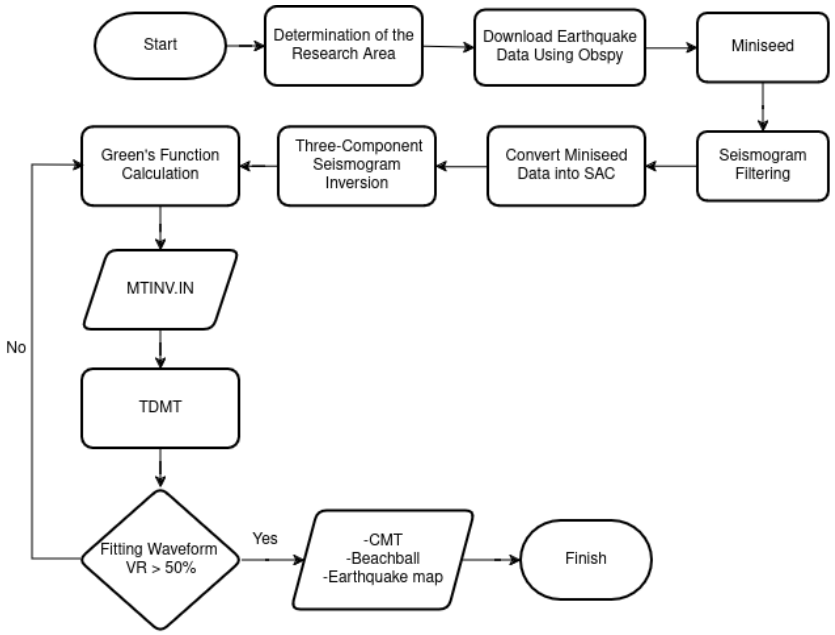


Figure 1. Flowchart of CMT solution determination using the Time-Domain Moment Tensor (TDMT) method.

Preprocessing of the waveform data followed standard seismological procedures [19, 20]. Waveforms, originally in MiniSEED format, were detrended, tapered, and bandpass-filtered to 0.02–0.1 Hz to suppress noise and enhance signal clarity. Instrument response was removed using poles-and-zeros (PAZ) metadata to obtain ground velocity in physical units. The processed data were then converted into SAC format. Each seismogram was decomposed into

three orthogonal components: vertical (Z), radial (R), and transverse (T) to be used in Green's function generation and inversion.

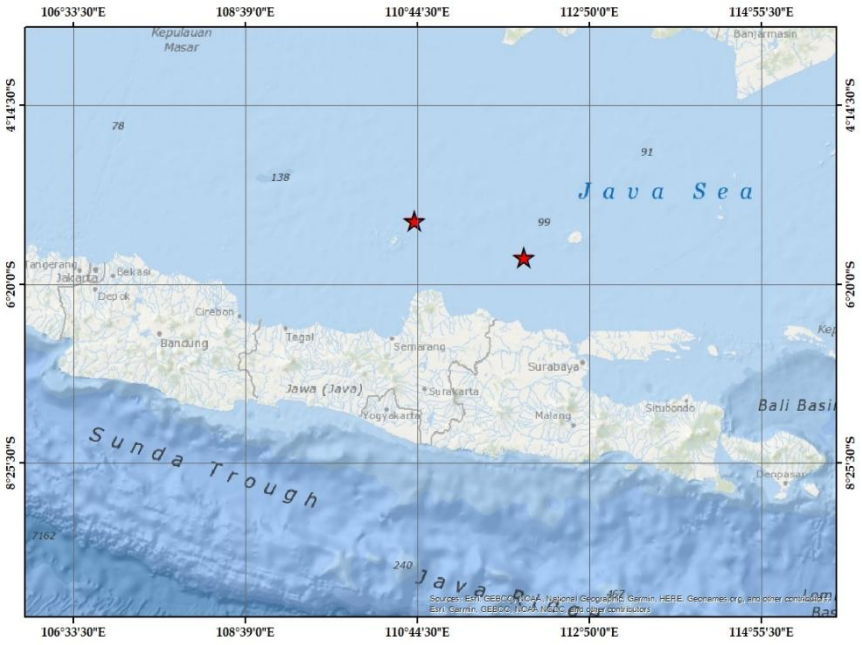


Figure 2. Epicentral locations of the two intermediate-depth earthquakes analyzed in this study. The July 6, 2020 event (M_w 6.67; centroid depth of the April 14, 2023 event (M_w 6.96; centroid depth ~594 km) was located offshore Tuban, East Java.

Centroid moment tensor inversion was conducted using MTTime, a Python-based implementation of the TDMT method [15]. MTTime employs time-domain convolution of Green's functions, precomputed from a 1D layered velocity model (ak135), with observed seismograms. The inversion solves for six independent moment tensor components (Mxx, Myy, Mzz, Mxy, Mxz, Myz) by minimizing the L2-norm misfit between observed and synthetic data. A grid search over centroid depths was performed to determine the optimal source depth. Solutions with variance reduction (VR) values greater than 50% were considered acceptable, as this threshold typically reflects good waveform agreement [8].

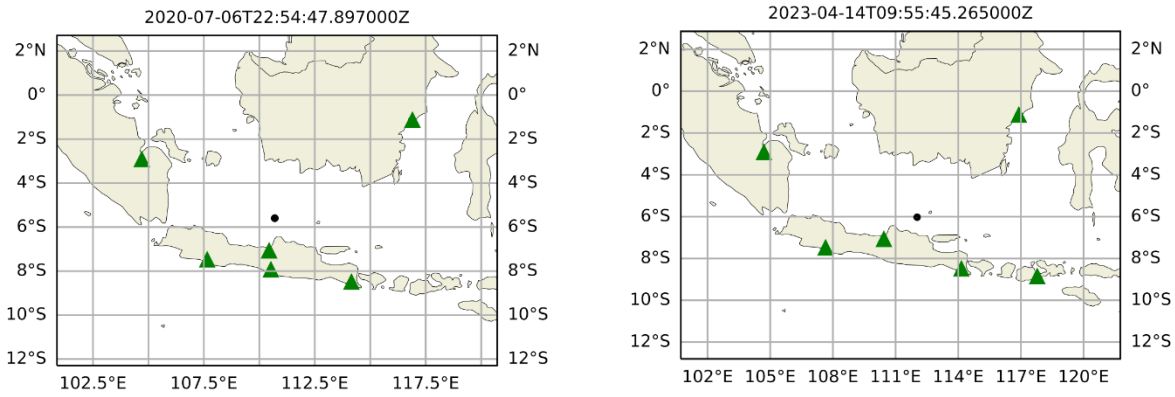
To validate the focal mechanism solutions, a comparison was made with the Global Centroid Moment Tensor (GCMT) catalog using the Kagan angle method [21]. This technique calculates the smallest rotation angle required to align two double-couple solutions in 3D orientation space. Focal mechanisms are considered consistent when the Kagan angle is less than 60°, as supported by regional studies such as [22] and [23], which applied similar validation to Indonesian seismicity.

Results and Discussion

Centroid moment tensor (CMT) inversion results

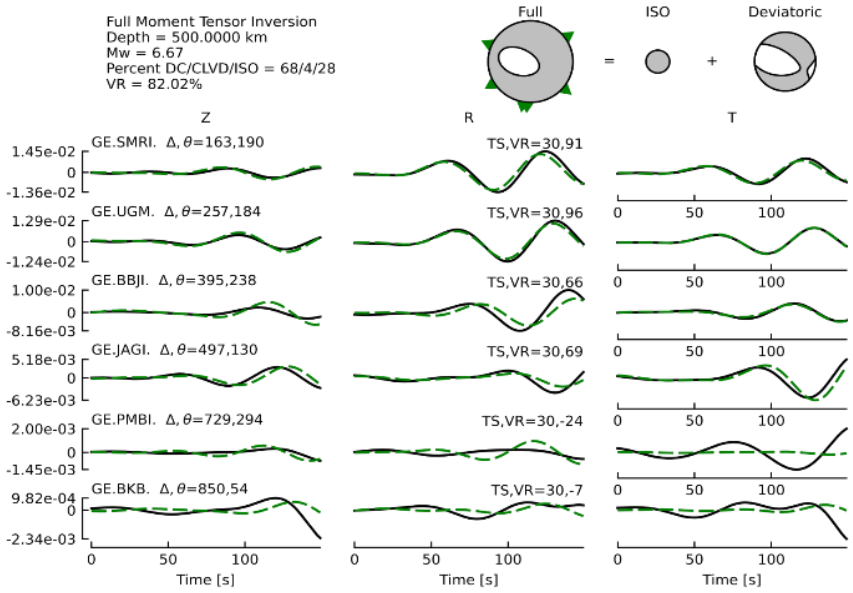
The Time-Domain Moment Tensor (TDMT) inversion for the two intermediate-depth earthquakes yielded reliable centroid moment tensor (CMT) solutions, supported by high waveform fitting quality. For the July 6, 2020 event (M_w 6.67), the optimal centroid depth was

500 km, whereas for the April 14, 2023 event (M_w 6.96), the best-fitting depth was 594 km. Both events occurred within the subducting Indo-Australian slab beneath Java, consistent with previously identified Benioff zone seismicity [5, 16].

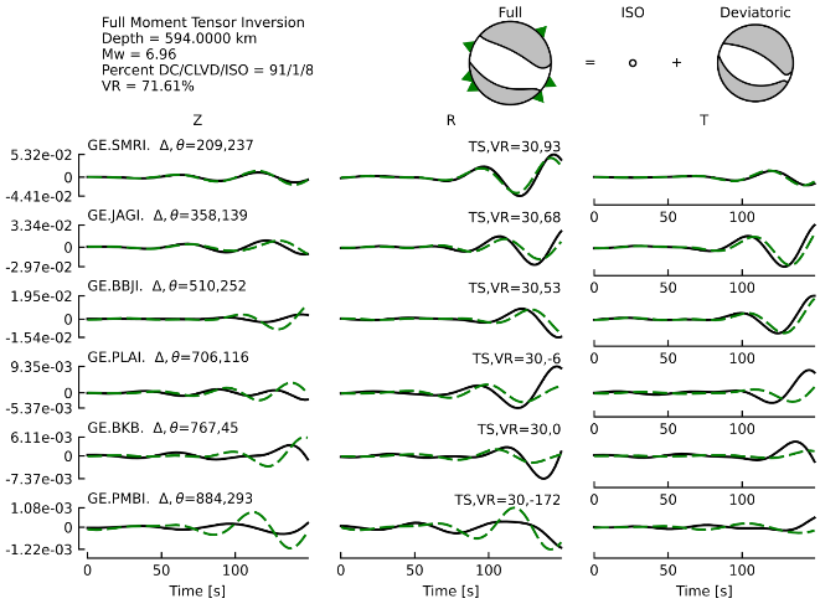


(a) (b)

Figure 3. Geographic distribution of seismic stations from the GE (GEOFON) network used in the TDMT inversion. Green triangles indicate the selected broadband seismic stations utilized for waveform analysis. Panel (a) shows stations recording the July 6, 2020 earthquake (M_w 6.67), and panel (b) corresponds to stations used for the April 14, 2023 earthquake (M_w 6.96).



(a)



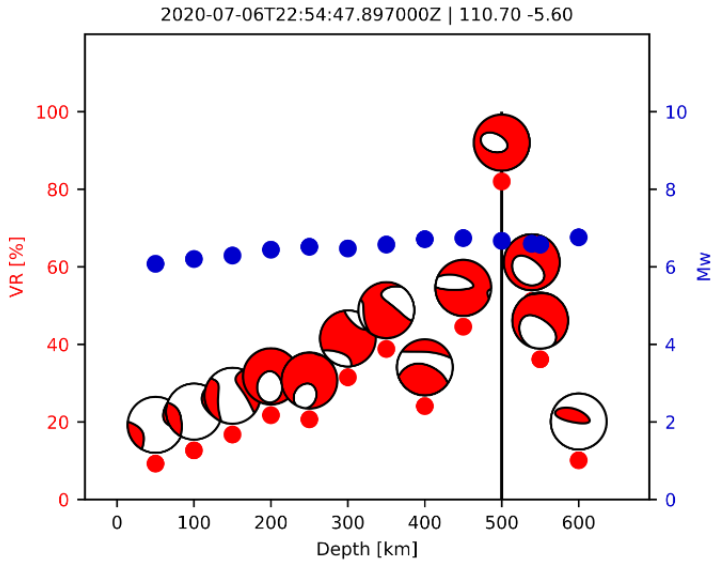
(b)

Figure 4. Full moment tensor inversion results for the two intermediate-depth earthquakes analyzed in this study. Panel (a) displays the inversion output for the July 6, 2020, event (M_w 6.67, depth ~500 km), and panel (b) shows the results for the April 14, 2023 event (M_w 6.96, depth ~594 km). Each panel shows the waveform fit between observed (black) and synthetic (green) seismograms across multiple stations and components (Z, R, T), along with the corresponding focal mechanism (beachball) and moment tensor decomposition.

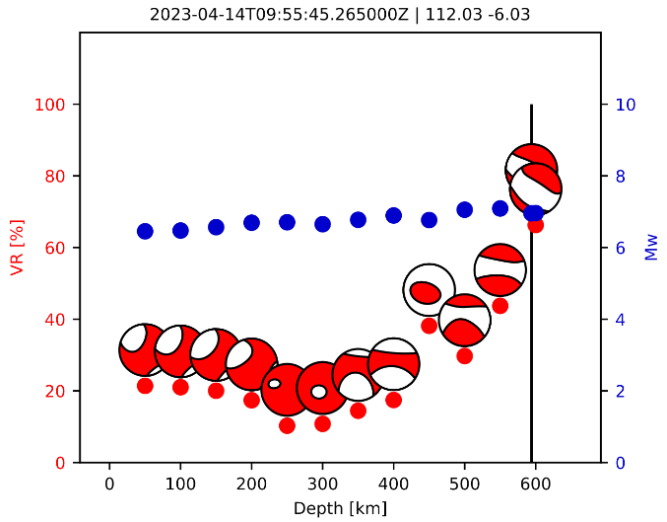
The reliability of the inversion results was supported by the availability and configuration of seismic stations that recorded the two events. Figure 3 displays the station distribution used in the analysis, where green triangles represent seismic stations from the GE (GEOFON) network. Although the distribution is relatively sparse, the selected stations provide sufficient azimuthal coverage from multiple directions, including western Sumatra, central Java, Kalimantan, and Sulawesi. This configuration ensures adequate geometric constraints for the waveform inversion process and helps stabilize the moment tensor solutions by reducing azimuthal bias. The time-domain inversion benefited from the strategic positioning of these stations, which, despite their limited number, captured clear broadband waveforms with acceptable signal-to-noise ratios. This is particularly important for deep earthquakes, as waveform clarity and spatial coverage are critical for accurate Green's function fitting and moment tensor decomposition.

The retrieved moment tensor solutions are predominantly double-couple (DC), indicating that the main source process for both earthquakes is tectonic shear faulting within the slab. The DC fractions reach 68% for the July 6, 2020 event and 91% for the April 14, 2023 event, supporting a fault-slip interpretation as the primary mechanism. The remaining non-DC components (CLVD and isotropic terms) are comparatively smaller and are treated as secondary. In particular, the relatively larger isotropic fraction in the 2020 solution should be interpreted with caution, as non-DC energy can be amplified by limited station coverage/azimuthal gaps,

noise, and modeling simplifications (e.g., the 1-D velocity structure used for Green's functions), rather than reflecting a physically dominant volumetric source.



(a)



(b)

Figure 5. Correlation graph between Variance Reduction (VR), moment magnitude, and depth of the two earthquake events; (a) Earthquake event on July 6, 2020, (b) Earthquake event on April 14, 2023.

The quality of waveform fitting is illustrated in Figure 4, which displays both the CMT solution parameters and the synthetic versus observed waveforms for multiple seismic stations. The variance reduction (VR) values of 82.02% for the 2020 event and 71.61% for the 2023 event indicate high consistency between observed and synthetic seismograms. These values exceed the commonly accepted threshold of 50% for reliable inversions [8], thereby validating the stability of the moment tensor solutions. Most waveform components, particularly the vertical (Z) and radial (R) traces, show excellent phase and amplitude alignment. Slight mismatches

observed in the transverse (T) component likely reflect the limitations of the 1D ak135 velocity model employed in the Green's function computation, which does not fully account for lateral heterogeneities in the subduction zone structure.

Figure 5 presents the relationship between centroid depth and variance reduction (VR) for both earthquake events, derived from the grid search process during moment tensor inversion. The plots display VR values (in red) and moment magnitude (M_w, in blue) as functions of trial depth, with corresponding focal mechanisms (beachball diagrams) at each depth level. The optimal centroid depths of 500 km for the July 6, 2020 event (Figure 5a) and 594 km for the April 14, 2023 event (Figure 5b) coincide with the peaks in VR, indicating strong waveform matching and stable convergence during inversion at those depths.

The graphical distribution further reveals that VR values sharply increase near the optimal depth and decrease symmetrically above and below, forming a bell-shaped trend that suggests sensitivity to depth variation. This pattern confirms the reliability of the depth estimation and supports the physical plausibility of the inversion results. Additionally, the consistent focal mechanism patterns near the VR peaks, with minor depth variation, indicate structural coherence and reinforce the identification of a normal-faulting regime at both locations.

The moment magnitude estimates derived from the inversion M_w 6.67 and M_w 6.96 are plotted alongside VR and remain stable across a wide depth range, showing only minor fluctuations. These values are in close agreement with the Global CMT (GCMT) catalog estimates, further validating the inversion process. The combination of high VR, consistent focal mechanisms, and stable magnitude estimates suggests that both events represent robust, deep intraslab faulting within the subducting Indo-Australian plate.

Furthermore, these moderate-to-large magnitude events at depths exceeding 500 km reflect significant elastic strain accumulation and release, likely linked to slab pull, unbending, or tearing processes. Their centroid locations and fault orientations are consistent with regional slab geometry derived from seismic tomography [16], underscoring the geodynamic significance of such events within the broader context of the Java subduction system.

To enhance consistency between the graphical and tabulated results, we emphasize that Figure 5 is primarily used to determine the preferred centroid depth via a depth-grid search that maximizes variance reduction (VR). Once the VR peak is identified (500 km for the July 6, 2020 event and 594 km for the April 14, 2023 event), the corresponding best-fitting TDMT solution at that depth is selected as the preferred mechanism. The numerical source parameters of these preferred solutions (strike–dip–rake, centroid depth, Mw, and Kagan angle) and their comparison with the GCMT catalog are then summarized in Tables 1 and 2.

Validation and comparison of CMT solutions

After identifying the optimal centroid depths from the depth grid search (Figure 5), we summarize the preferred TDMT solutions and their key parameters in Tables 1 and 2. We then compare these solutions with the GCMT catalog to validate the mechanisms and to clarify how the selected depth controls the final tabulated results. The TDMT inversion results consistently indicate an oblique normal-faulting mechanism for each earthquake. Regarding the

earthquake on July 6, 2020, the fault plane parameters were 83°/40°/−128°, whereas those of the April 14, 2023, earthquake were 104°/30°/−103°. It is evident that both mechanisms are largely influenced by a normal-faulting component, indicating an extensional stress environment, accompanied by a notable dextral (right-shear) component.

These findings offer noteworthy perspectives concerning the geodynamics of deep plates. The strong presence of normal faulting confirms that the Indo-Australian plate, at depths of around 500 to 600 km, is experiencing a substantial extensional stress environment, most likely resulting from slab pull as the plate descends further into the Earth's mantle, as referenced in sources [24, 26]. Perhaps of greater significance, the consistent dextral, or right-shear, component observed in both earthquakes suggests that this stretching is not occurring at a uniform rate. This suggests the presence of intricate internal deformation within the plate, potentially including slab tearing or rotation/twisting, as indicated in source [27]. This provides important regional observational evidence supporting global models, demonstrating that the plate is not just being pulled downward but is also undergoing lateral internal deformation.

Comparing the findings with the Global Centroid-Moment Tensor (GCMT) solution showed that the results were robust and reliable. The extremely small Kagan angles, measuring 7.04° in 2020 and 6.31° in 2023, suggest that the mechanisms are highly similar and remain far below the 60° limit specified in references [21, 22]. The slight variations observed in centroid depth, such as 500 km versus 535 km for the 2020 earthquake, and in rake, with measurements of −128° versus −124°, are within acceptable limits and are likely due to differences in methodology. For our regional analysis, we employed the ak135, a computationally effective one-dimensional (1D) velocity model, in contrast to the GCMT's use of a three-dimensional (3D) global model and low-frequency data [12].

The precision with which our 1D model identifies the primary mechanisms, including the oblique component, underscores its reliability in promptly defining the characteristics of deep earthquake sources in this area. The consistent presence of the oblique normal faulting mechanism in these two significant earthquakes highlights that this type of extensional stress regime is a long-standing trait, not an isolated occurrence, within the deep tectonic plate underlying Java. Identifying this specific mechanism is of utmost importance when creating seismic hazard models. Deep earthquakes exhibiting this type of normal faulting, characterized by extensional forces, have the capacity to efficiently transmit seismic waves upwards, potentially resulting in considerable ground movement in the heavily populated areas situated along Java's northern coastline, in spite of the great depths at which these earthquakes originate [3, 26].

Table 1. Comparison of MTTime CMT parameters with Global CMT for the July 6, 2020 earthquake.

Parameters		TDMT	Global CMT
Origin time		22:54:47	22:54:48
Centroid Depth (Km)		500	535
Magnitude Moment (M_w)		6.67	6.7
Fault Plane 1	Strike	83	92
	Dip	40	37
	Rake	-128	-124
Fault Plane 2	Strike	308	313
	Dip	59	60
	Rake	-63	-67
Kagan Angle		7.04°	
Beachball			
Fault types		Normal Fault	Normal Fault

Table 2. Comparison of MTTime CMT parameters with Global CMT for the July 14, 2023 earthquake.

Parameters		TDMT	Global CMT
Origin time		09:55:45	09:55:51
Centroid depth (Km)		594	606.8
Magnitude moment (M_w)		6.96	7.1
Fault Plane 1	Strike	104	94
	Dip	30	31
	Rake	-103	-108
Fault Plane 2	Strike	299	295
	Dip	61	61
	Rake	-82	-80
Kagan Angle		6.31°	
Beachball			
Fault types		Normal Fault	Normal Fault

Seismotectonic context and geodynamic interpretation

The focal mechanisms and centroid depths derived in this study provide valuable insights into the deep seismotectonic regime beneath northern Java. Both earthquakes occurred within the subducted Indo-Australian slab, which dips northward beneath the Eurasian plate at steep angles. At depths exceeding 500 km, the dominant stress regime transitions to extensional, as a result of slab pull and gravitational sinking of the cold, dense slab material [28, 29].

The oblique-normal faulting pattern observed in this study is consistent with slab-parallel extension documented in other parts of the Sunda subduction zone. These events may reflect either internal slab deformation (flexure, unbending, or tearing) or shear localization near stagnant slab edges. The fault plane orientations are broadly aligned with the trench-parallel direction, reinforcing interpretations of lateral slab stretching and segment boundary dynamics.

These findings contribute to the growing body of knowledge regarding deep-focus earthquakes in Southeast Asia. While such events do not generally pose tsunami hazards due to their depth, they may still result in ground shaking across wide areas and pose structural risks, particularly when amplified by sedimentary basins in northern Java [30]. Furthermore, incorporating these TDMT results into regional stress field models may enhance the accuracy of long-term seismic hazard maps.

In addition to confirming the faulting mechanism and intraslab origin of both events, the results of this study have broader implications for seismic hazard characterization in Java and similar tectonic regions. The successful application of time-domain inversion using MTTime underscores the potential for real-time or near-real-time moment tensor determination in Indonesia. Integrating such regional CMT solutions into national seismic monitoring systems, such as those used by BMKG or BRIN, can improve earthquake source identification and provide better input for probabilistic seismic hazard assessments. This is particularly relevant for northern Java, where deep intraslab events may still generate significant ground motion due to local amplification in coastal sedimentary basins [30].

Comparable studies in other deep subduction systems, such as the Molucca Sea and the southern Philippines, have reported similar slab-parallel extensional faulting at depths >500 km, reinforcing the global consistency of such deformation regimes [23, 24]. These parallels highlight the importance of continuing regional moment tensor analysis to constrain deep lithospheric processes and their seismic implications. Future studies may also explore model sensitivity by applying multiple velocity models, including regional 3D tomography (e.g., [16]), to evaluate inversion robustness and refine centroid depth estimation.

Conclusion

This study provides quantitative constraints on deep intraslab deformation beneath offshore Northern Java based on two recent major deep-focus earthquakes (Mw > 6.5) that occurred in 2020 and 2023. The preferred time-domain moment tensor (TDMT) solutions indicate oblique normal faulting with a persistent dextral strike-slip component at centroid depths of approximately 500–600 km, implying a dominantly extensional stress regime within the descending Indo-Australian slab, likely driven by slab pull/gravitational sinking, while the trench-parallel shear component suggests more complex internal slab deformation. The robustness of the preferred mechanisms is supported by good waveform fits (VR = 82.0% and 71.6%) and close agreement with the Global CMT catalog (Kagan angles = 7.04° and 6.31°). Despite these consistent results, our interpretations are currently based on a limited number of events and a 1-D velocity model, which may affect the resolution of secondary (non-DC) components. Future work will expand the event set across the Java region and test model

sensitivity (e.g., alternative frequency bands and velocity structures) to further strengthen the regional geodynamic interpretation and its implications for seismic hazard assessment.

Acknowledgment

The authors would like to extend their deepest gratitude to Andrea Chiang for creating the MTTime software, without which this research would not have been possible. We also thank and acknowledge Universitas Negeri Surabaya for providing us with all the support and facilities needed to carry out the present study.

References

[1] S. J. Hutchings and W. D. Mooney, "The seismicity of Indonesia and tectonic implications," *Geochemistry, Geophysics, Geosystems*, vol. 22, no. 9, e2021GC009812, 2021.

[2] B. Reynard, J. Nakajima, and H. Kawakatsu, "Earthquakes and plastic deformation of anhydrous slab mantle in double Wadati-Benioff zones," *Geophysical Research Letters*, vol. 37, no. 24, p. L24309, 2010.

[3] A. Rietbrock and F. Waldhauser, "A narrowly spaced double-seismic zone in the subducting Nazca plate," *Geophysical Research Letters*, vol. 31, no. 10, p. L10608, 2004.

[4] A. Koulali, S. McClusky, S. Susilo, Y. Leonard, P. Cummins, P. Tregoning, I. Meilano, J. Efendi, and A. B. Wijanarto, "The kinematics of crustal deformation in Java from GPS observations: Implications for fault slip partitioning," *Earth and Planetary Science Letters*, vol. 458, pp. 69–79, 2017.

[5] P. Supendi, A. D. Nugraha, N. T. Puspito, S. Widiyantoro, and D. Daryono, "Identification of active faults in West Java, Indonesia, based on earthquake hypocenter determination, relocation, and focal mechanism analysis," *Geoscience Letters*, vol. 5, no. 1, p. 31, 2018.

[6] E. Gunawan and S. Widiyantoro, "Active tectonic deformation in Java, Indonesia inferred from a GPS-derived strain rate," *Journal of Geodynamics*, vol. 123, pp. 49–54, 2019.

[7] E. Sokos and J. Zahradník, "Evaluating Centroid-Moment-Tensor uncertainty in the new version of ISOLA software," *Seismological Research Letters*, vol. 84, no. 4, pp. 656–665, 2013.

[8] J. Vackář, J. Burjánek, F. Gallovič, J. Zahradńik, and J. Clinton, "Bayesian ISOLA: New tool for automated centroid moment tensor inversion," *Geophysical Journal International*, vol. 210, no. 2, pp. 693–705, 2017.

[9] Q. Bai, S. Ni, R. Chu, and Z. Jia, "gCAPjoint, A software package for full moment tensor inversion of moderately strong earthquakes with local and teleseismic waveforms," *Seismological Research Letters*, vol. 91, pp. 3550–3562, 2020.

[10] A. Steinberg, H. Vasyura-Bathke, P. Gaebler, M. Ohrnberger, and L. Ceranna, "Estimation of seismic moment tensors using variational inference machine learning," *Journal of Geophysical Research: Solid Earth*, vol. 126, no. 10, 2021.

[11] B. Xu and Y. Zhang, "Joint inversion of centroid moment tensor for large earthquakes by combining teleseismic P-wave and W-phase records," *Geophysical Journal International*, 2023.

[12] G. Ekström, M. Nettles, and A. M. Dziewoński, "The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes," *Physics of the Earth and Planetary Interiors*, vol. 200–201, pp. 1–9, 2012.

[13] D. S. Dreger, "TDMT_INV: Time domain seismic moment tensor inversion," in *International Geophysics*, W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger, Eds., vol. 81, p. 1627. Academic Press, 2003.

[14] A. Chiang, D. S. Dreger, S. R. Ford, W. R. Walter, and S. Yoo, "Moment tensor analysis of very shallow sources," *Bulletin of the Seismological Society of America*, vol. 106, no. 6, pp. 2436–2449, 2016.

[15] A. Chiang, R. Gök, Y. M. Tarabulsi, S. Y. El-Hadidy, W. W. Raddadi, and A. D. Mousa, "Seismic source characterization of the Arabian Peninsula and Zagros Mountains from regional moment tensor and coda envelopes," *Arabian Journal of Geosciences*, vol. 14, no. 1, p. 9, 2021.

[16] S. Widiyantoro, P. Supendi, A. Ardianto, A. W. Baskara, C. A. Bacon, R. Damanik, N. Rawlinson, E. Gunawan, D. P. Sahara, Z. Zulfakriza, Y. M. Husni, and A. Lesmana, "Implications for fault locking south of Jakarta from an investigation of seismic activity along the Baribis fault, northwestern Java, Indonesia," *Scientific Reports*, vol. 12, no. 1, p. 10143, 2022.

[17] G. Ekström, A. M. Dziewoński, N. N. Maternovskaya, and M. Nettles, "Global seismicity of 2003: Centroid–moment-tensor solutions for 1087 earthquakes," *Physics of the Earth and Planetary Interiors*, vol. 148, no. 2–4, pp. 327–351, 2005.

[18] M. Beyreuther, R. Barsch, T. Krischer, L. Megies, Y. Behr, and J. Wassermann, "ObsPy: A Python toolbox for seismology," *Seismological Research Letters*, vol. 81, no. 3, pp. 530–533, 2010.

[19] K. Aki and P. G. Richards, *Quantitative Seismology*, 2nd ed. University Science Books, 2002.

[20] A. M. Dziewonski, T.-A. Chou, and J. H. Woodhouse, "Determination of earthquake source parameters from waveform data for studies of global and regional seismicity," *Journal of Geophysical Research: Solid Earth*, vol. 86, no. B4, pp. 2825–2852, 1981.

[21] Y. Y. Kagan, "3-D rotation of double-couple earthquake sources," *Geophysical Journal International*, vol. 106, no. 3, pp. 709–716, 1991.

[22] S. Pondrelli, S. Salimbeni, G. Ekström, A. Morelli, P. Gasperini, and G. Vannucci, "The Italian CMT dataset from 1977 to the present," *Physics of the Earth and Planetary Interiors*, vol. 159, no. 3–4, pp. 286–303, 2006.

[23] A. D. Prasetio, M. Hasib, A. Amran, Syuhada, F. Febriani, C. N. Dewi, and T. Anggono, "Local seismotectonic analysis of the July 2019 Molucca Sea earthquake sequence based on moment tensor solutions," *Geoscience Letters*, vol. 8, no. 1, p. 33, 2021.

[24] H. Yang, K. H. Chen, Y. M. Wu, and Y. J. Hsu, "Deep slab deformation and rupture in the southern Philippine Sea," *Geophysical Journal International*, vol. 227, no. 1, pp. 525–540, 2021.

[25] M. Madlazim, M. Nurul Fahmi, D. Permata Sari, E. Meilianda, and S. Koesuma, "Implementing and evaluating an automatic centroid moment tensor procedure for the

Indonesia region and surrounding areas," *Earth and Planetary Physics*, vol. 8, no. 4, pp. 609–620, 2024.

[26] A. Tibaldi, N. Corti, E. De Beni, F. Bonali, S. Falsaperla, H. Langer, M. Neri, M. Cantarero, D. Reitano, and L. Fallati, "Mapping and evaluating kinematics and the stress and strain field at active faults and fissures: A comparison between field and drone data at the NE rift, Mt Etna (Italy)," *Solid Earth*, vol. 12, pp. 801–816, 2021.

[27] A. Faucher, F. Gueydan, M. Jolivet, M. Alsaif, and B. Célérier, "Dextral strike-slip and normal faulting during middle Miocene back-arc extension and westward Anatolia extrusion in Central Greece," *Tectonics*, vol. 40, 2021.

[28] G. I. Marliyani, J. R. Arrowsmith, and H. Helmi, "Evidence for multiple ground-rupturing earthquakes in the past 4,000 years along the Pasuruan fault, East Java, Indonesia: Documentation of active normal faulting in the Javan backarc," *Tectonics*, vol. 38, no. 4, pp. 1489–1506, 2019.

[29] S. Aribowo, L. Husson, D. H. Natawidjaja, C. Authemayou, M. R. Daryono, A. R. Puji, P. G. Valla, A. Pamumpuni, D. D. Wardhana, G. de Gelder, D. Djarwadi, and M. Lorcery, "Active back-arc thrust in North West Java, Indonesia," *Tectonics*, vol. 41, no. 7, 2022.

[30] M. N. Fahmi, A. Realita, H. Risanti, T. Prastowo, and M. Madlazim, "Vulnerability in the Java northern region in association with earthquake sources of tectonic origin," *Journal of Physics: Conference Series*, vol. 2596, no. 1, p. 012041, 2023.