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Key Points:

- A new 3-D P-wave model of Sulawesi from teleseismic tomography shows three distinct slabs beneath North Sulawesi
- A deep low-velocity anomaly beneath the East Arm suggests the presence of deep mantle inflow responding to lithospheric extension
- A low-velocity anomaly beneath the Tambarana Fault suggests that it is a major lithospheric structure extending beyond the crust

Supporting Information:

Supporting Information may be found in the online version of this article.

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Evidence of Multiple Subducting Slabs Beneath Sulawesi From Teleseismic P-Wave Tomography

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Abstract

The tectonic evolution of Sulawesi is shaped by complex subduction processes, yet the geometry and extent of its slabs remain debated. Using teleseismic P-wave tomography, we present a new 3-D model of the lithosphere and underlying upper mantle beneath Sulawesi, based on passive seismic data from 89 seismic stations. Our results reveal three distinct slabs beneath North Sulawesi: a south-dipping Celebes Sea slab, a westward-subducting Sangihe slab, and a north-dipping structure that likely represents the Sula slab. We also identify a prominent low-velocity anomaly beneath the East Arm of Sulawesi (~200–500 km depth), which we interpret as the inflow of deep mantle required as extension occurred. Furthermore, a separate low-velocity anomaly beneath the Tambarana Fault suggests it to be a major lithospheric-scale structure that extends down into the upper mantle. These findings provide new constraints on subduction dynamics and highlight the role of deep mantle processes in driving surface magmatism.

Plain Language Summary

The surface geology of Sulawesi is shaped by the movement of tectonic plates, where some plates sink into the Earth's mantle while others collide or stretch apart. To better understand these deep processes, we used earthquake data recorded by 89 sensors to create a 3-D velocity image from the surface down to 500 km depth. Our study reveals three distinct tectonic plates that are sinking beneath North Sulawesi and interacting over a remarkably small area. We also identify a large zone of partially molten rock deep beneath the East Arm of Sulawesi (200–500 km depth), which may be linked to the extensional mechanism in the Gulf of Tomini. Another deep anomaly to the east of the Palu-Koro Fault suggests a link between mantle processes and surface deformation. These results are important for the understanding of the connections between deep Earth structures, earthquakes, and volcanoes.

1. Introduction

Sulawesi, located at the triple junction of the Australian, SE Asian, and Philippine Sea plates in eastern Indonesia (Figure 1), is key to understanding how closely spaced subduction zones interact, deform, and compete for space, while also influencing regional tectonics, mantle circulation, volcanism and deep-focus earthquake mechanisms. Indeed, Sulawesi exhibits a complex tectonic setting shaped by collisional events, rifting, accretion, and the dynamic opening and closing of ocean basins (Hall, 1996, 2011, 2012; Liu et al., 2020), which has resulted in diverse deformation styles and geological features. These features include multiple subducting slabs beneath North Sulawesi, the development of a major left-lateral strike-slip fault zone (Palu-Koro Fault Zone), and an isolated active volcano in the Gulf of Tomini (Cottam et al., 2011; Hall, 2012; Hall & Spakman, 2015; Handyarso et al., 2023; Katili et al., 1963; Zhang et al., 2022). Despite significant advances in our understanding of the tectonic evolution of Sulawesi, key questions remain unresolved. The geometry and kinematics of the subducting slabs beneath North Sulawesi are still debated, with contrasting interpretations regarding their extent and segmentation (e.g., Gudmundsson & Sambridge, 1998; Hall & Spakman, 2015; Walpersdorf et al., 1998). The geodynamic drivers of the only active volcano in the Gulf of Tomini remain elusive, raising fundamental questions about the influence of subduction-induced mantle flow and lithospheric deformation (Advokaat et al., 2017; Cottam et al., 2011; Effendi et al., 1997; Hall & Spakman, 2015; Handyarso et al., 2023; J. A. Katili, 1975; Pholbud et al., 2012; Sendjaja et al., 2020; I. Watkinson et al., 2012). Similarly, the Palu-Koro and Tambarana Fault Zone, a key lithospheric-scale structure with a potential connection to asthenospheric flow (Cao et al., 2024), remains poorly constrained.

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Several seismic tomographic studies have been conducted across eastern Indonesia to produce global (Hall & Spakman, 2015), regional (Wehner, Blom, et al., 2022; Wehner, Rawlinson, et al., 2022), and local 3-D models (Jayadi et al., 2023). At the global scale, Hall and Spakman (2015), using the UUP07 global P-wave velocity model, identified several high-velocity anomalies in the region beneath North Sulawesi, suggesting the existence of multiple subducted slabs. However, their tomographic images had limited spatial resolution (100–200 km) in the upper mantle, which hindered detailed insights into mantle processes. At the regional scale, Wehner, Blom, et al. (2022) produced the first continental-scale 3D seismic model of Southeast Asia using adjoint waveform tomography, followed by a refined model for eastern Indonesia (Wehner, Rawlinson, et al., 2022) that incorporates topography, bathymetry, and ocean loading. Both tomographic models reveal a high-velocity anomaly beneath the North Sulawesi Trench, pointing to the presence of a subducting slab reaching depths of ~400 km, although they do not specify whether this corresponds to the Celebes Sea slab or a north-dipping slab. Despite the advanced inversion methods, these models mainly resolve the North Sulawesi subduction zone, with limited resolution beneath the rest of Sulawesi. At the local scale, Jayadi et al. (2023) conducted a local earthquake tomography experiment that was limited to areas of active seismicity and relied on a sparse seismic network. As a result, there is still a lack of high-resolution 3-D imaging that could offer crucial insights into the upper mantle structure beneath Sulawesi.

This study builds on the recent expansion of broadband seismic networks in Sulawesi to develop a 3-D velocity model of the lithosphere and underlying upper mantle. In particular, the new model presented here mitigates the spatial limitations associated with local seismicity, and achieves better resolution than broader-scale models, thereby providing fresh insights into the number and geometry of subducting slabs, key tectonic structures and possible mantle circulation.

2. Data and Methods

We exploit teleseismic earthquake data recorded between January 2020 and October 2023 by 89 broadband seismic stations (Figure 1) operated by BMKG. Source origin time and location of teleseismic events are obtained from the Incorporated Research Institutions for Seismology (IRIS) catalog. The data set includes primarily earthquakes selected to target direct P-wave arrivals, with a criterion of mb > 5 at any depth or mb > 4.6 for events deeper than 150 km, within an epicentral distance range of $27° \leq \Delta \leq 98°$. Direct P phases are complemented by core and reflected phases to improve ray coverage.

P-wave arrivals are extracted from the vertical component of continuous seismograms, following Pilia et al. (2020), Pilia, Davies, et al. (2023), and Pilia, Rawlinson, et al. (2023). Seismic traces corresponding to the arrival of various global phases were selected and cut with a window of ±60 s around the predicted arrival time, calculated using the global reference velocity model ak135 (Kennett et al., 1995). The waveforms are subsequently resampled to 20 Hz and corrected for instrument response, after which a bandpass filter (0.05–4.0 Hz) is applied. To remove errors related to source origin time and minimize the potential influence of large-scale mantle heterogeneities, we subtract the average residual of each source from their respective residual times, ultimately yielding relative arrival-time residuals. The results of the stacking procedure are visually inspected to ensure consistency within each event region and to eliminate noisy or incoherent data. Following these steps, the data set used for tomographic inversion consisted of 46,171 residual times from 985 events (Figure 1), all of which provided direct P-phases, as well as four PKiKP and four PP phases.

We used the Fast-Marching Tomography (FMTOMO) package (Rawlinson, 2006; Rawlinson & Urvoy, 2006) to invert the relative arrival-time residuals for 3-D velocity structure beneath Sulawesi. FMTOMO solves the traveltime prediction problem using a 3-D grid-based eikonal solver (Sethian, 1999). For the inversion step, a subspace inversion scheme is applied, incorporating damping and smoothing regularization (Kennett et al., 1988). The model is parameterized using a regular grid of points on which the velocity is defined, with cubic B-splines applied to create a smooth, continuous representation of the velocity field. For interfaces within the model, a regular grid of points in latitude and longitude defines variations in depth, with cubic B-splines used to create a continuous surface. The model spans by a latitudinal range from 4.5°N to 7.5°S, a longitudinal range from 117.5°E to 127.5°E, and a depth range from 1.7 km (top) to 500 km (bottom). The grid spacing for the velocity model is set to 35 km for latitude and longitude, and 31 km for depth.

Traveltime residuals are strongly affected by lateral velocity heterogeneities in the crust, which cannot be constrained by the teleseismic data set. To combat this problem, we incorporate a 3-D crustal velocity model derived

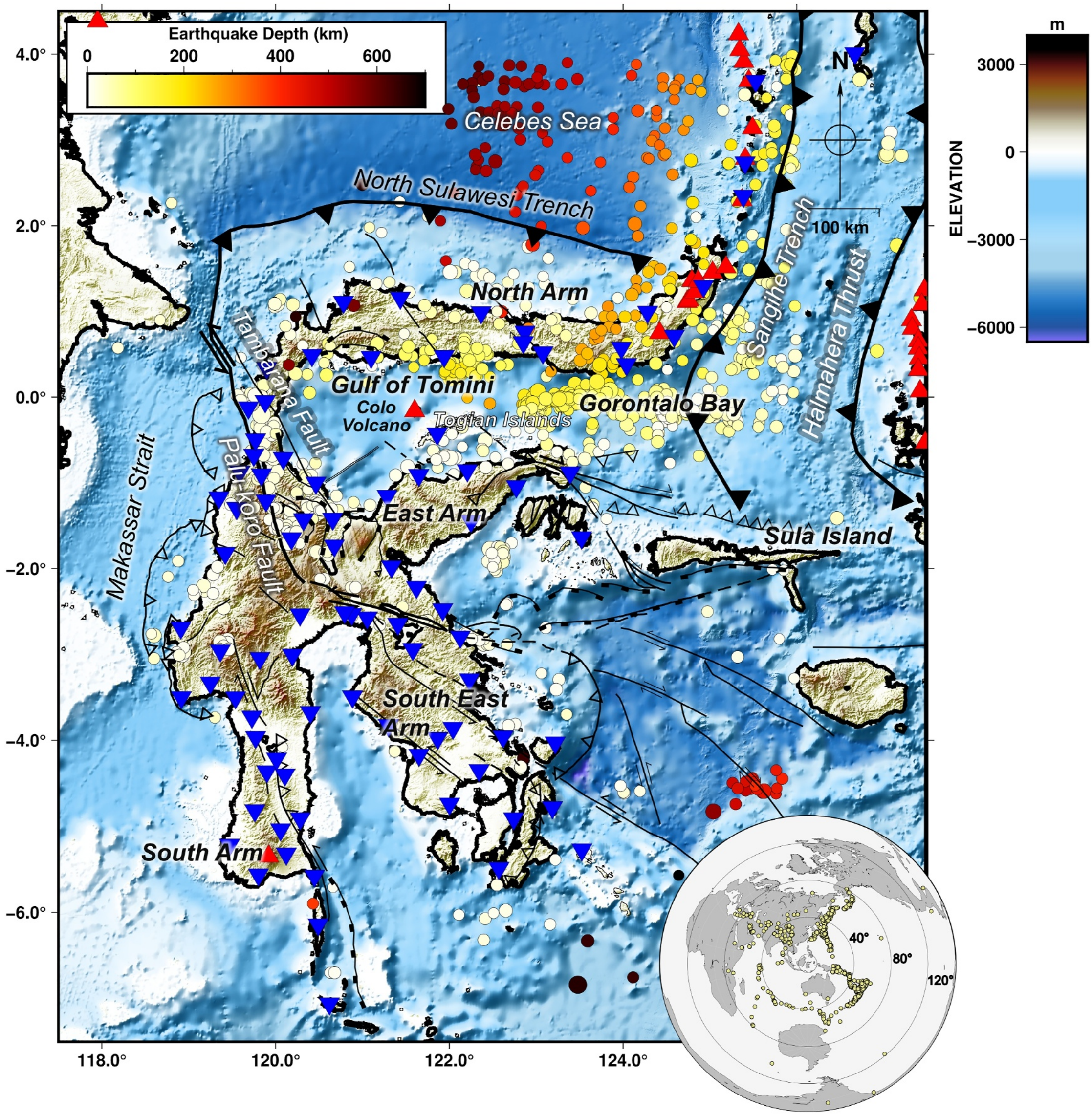

Figure 1. Map of the study area. Blue inverted triangles indicate BMKG (Indonesian Agency of Meteorology, Climatology, and Geophysics) seismic stations used in this study, while red triangles represent active volcanoes based on the Smithsonian Institution Global Volcanism Program (Siebert & Simkin, 2013). Colored dots represent seismic events with mb > 5.0 over the past 10 years from the BMKG catalog. The tectonic structures were taken from Hutchings and Mooney (2021) and Irsyam et al. (2020). Elevation is from Tozer et al. (2019). The inset map shows the distribution of teleseismic source used in this study. Dips of the Sangihe and Halmahera thrusts beneath the Molucca Sea are opposite in polarity to the subducting slabs they are associated with.

from ambient noise data (Heryandoko et al., 2024) as prior information in the inversion. Shear-wave velocities from the ambient noise model are converted to P-wave velocities following Brocher (2005). In a similar fashion, crustal thickness constraints from Linang (2023) are also incorporated in the inversion. The Moho depth beneath Sulawesi, as constrained by receiver function analysis, varies from 15 to 44 km, with an average uncertainty of less than 2 km. In our inversion, the Moho is not treated as a free parameter and is therefore not explicitly inverted for. However, we do invert for velocity values within the crust. For the second layer, the global 1-D velocity model ak135 developed by Kennett et al. (1995) is used. A two-step inversion process is implemented: an initial inversion is performed to estimate residual patterns, followed by a refined inversion after excluding outliers with the largest residuals ($\pm$1.0 s). The final models reduced the data variance by 68%, which corresponds to an RMS reduction from 894 to 508 ms. Figure S1 in Supporting Information S1 shows histograms of the distribution of relative arrival-time residuals for the initial and final model, respectively.

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3. Results

3.1. Resolution Tests

Synthetic tests were conducted following recommendations by Rawlinson and Spakman (2016) to evaluate model resolution. The first synthetic test is the checkerboard test with three different sizes (Figure S2 in Supporting Information S1): coarse (210 km), intermediate (140 km), and fine (70 km), to assess the resolution of the model across varying spatial scales. Gaussian noise (standard deviation of 77 ms) is added to the synthetic data to simulate observational noise. One issue when applying these tests to teleseismic data is that velocity anomalies can become smeared along the dominant ray paths. As expected, areas with dense raypath coverage exhibit improved resolution, while smearing is evident near model edges and beyond the horizontal bounds of the seismic network (Figures S3 to S6 in Supporting Information S1). Overall, these findings suggest that the raypath coverage is sufficient to accurately detect larger-scale velocity anomalies of 140 km or greater from the surface down to about 500 km depth. Our smallest checkerboard wavelength of 70 km represents a conservative but realistic estimate of the minimum resolvable scale for features in well-sampled parts of the model (Figure S6 in Supporting Information S1).

A synthetic test involving a sparse distribution of spikes is conducted to assess smearing effects (Rawlinson & Spakman, 2016). In this test, synthetic spikes are distributed at five locations with maximum positive or negative velocity perturbations of 0.5 km/s (Figure 2). Most input spikes are well-resolved, with their positions and amplitudes closely matching the input model (Figure 2). Some smearing is present, likely due to uneven ray coverage, with most rays arriving from the north and east, consistent with the teleseismic event distribution (Figure 1). To further test resolution, we introduced a set of closely spaced synthetic slabs resembling the observed structures. As shown in Figure S7 in Supporting Information S1, their geometry is generally recovered in well-sampled regions, supporting the reliability of our interpretation. Overall, the tests confirm that 3D velocity structures are robustly resolved across most of the model domain.

3.2. Tomographic Model

Figure 3 shows a horizontal slice at 150 depth, and a series of vertical profiles taken from the final 3-D tomographic model (additional horizontal and vertical profiles, with and without interpretation, in Figures S8–S14 in Supporting Information S1). P-wave velocity anomalies are illustrated as perturbations from the reference model ak135. One prominent feature revealed by our new tomographic model is a region of relatively fast wavespeed in the northern part of the study area, clearly visible in the vertical slices that cross-cut the northern arm of Sulawesi (Figure 3). This high-velocity body shows a maximum velocity perturbation of +0.4 km/s and spans approximately 500 km from east to west. Inspection of the vertical profiles along a number of great-circle lines exhibit further complexity; indeed, three spatially separated high-velocity anomalies, labeled as H1, H2, and H3 in Figure 3, dominate the upper mantle beneath northern Sulawesi.

An intriguing blob-like feature, labeled as L1, is observed in horizontal slices at depths of 200–500 km, revealing a broad low-velocity anomaly beneath the East Arm of Sulawesi and its surrounding region (Figure 3 and Figure S8 in Supporting Information S1). Results from resolution tests confirm that this is an area where tomographic anomalies are recovered with confidence. Vertical profiles across L1 (Figure 3 and Figures S9–S10 in Supporting Information S1) confirm the anomaly exhibits vertical continuity. A strong high-velocity anomaly appears adjacent to L1 at 300–500 km depth. Although visually prominent and of higher amplitude than H3, it lies near the model edge, where resolution is limited. We therefore consider that it may partly reflect an inversion artifact compensating for the adjacent low-velocity anomaly L1. Additionally, low velocity anomalies are detected in the crust and upper mantle down to 100 km depth beneath the eastern side of the Palu-Koro and Tambarana Fault (L2 in Figure 3 and Figures S9–S10 in Supporting Information S1).

4. Discussion

4.1. Multiple Subducting Slabs Beneath Northern Sulawesi

Seismic studies have long debated the subduction architecture beneath northern Sulawesi, with evidence pointing to at least two slabs: the Sangihe slab and the Celebes Sea slab (e.g., Gudmundsson & Sambridge, 1998; Kopp et al., 1999; Walpersdorf et al., 1998). These slabs have been inferred to bend by approximately 90° within the upper 200 km of the mantle beneath North Sulawesi (Di Leo et al., 2012a, 2012b; Gudmundsson &

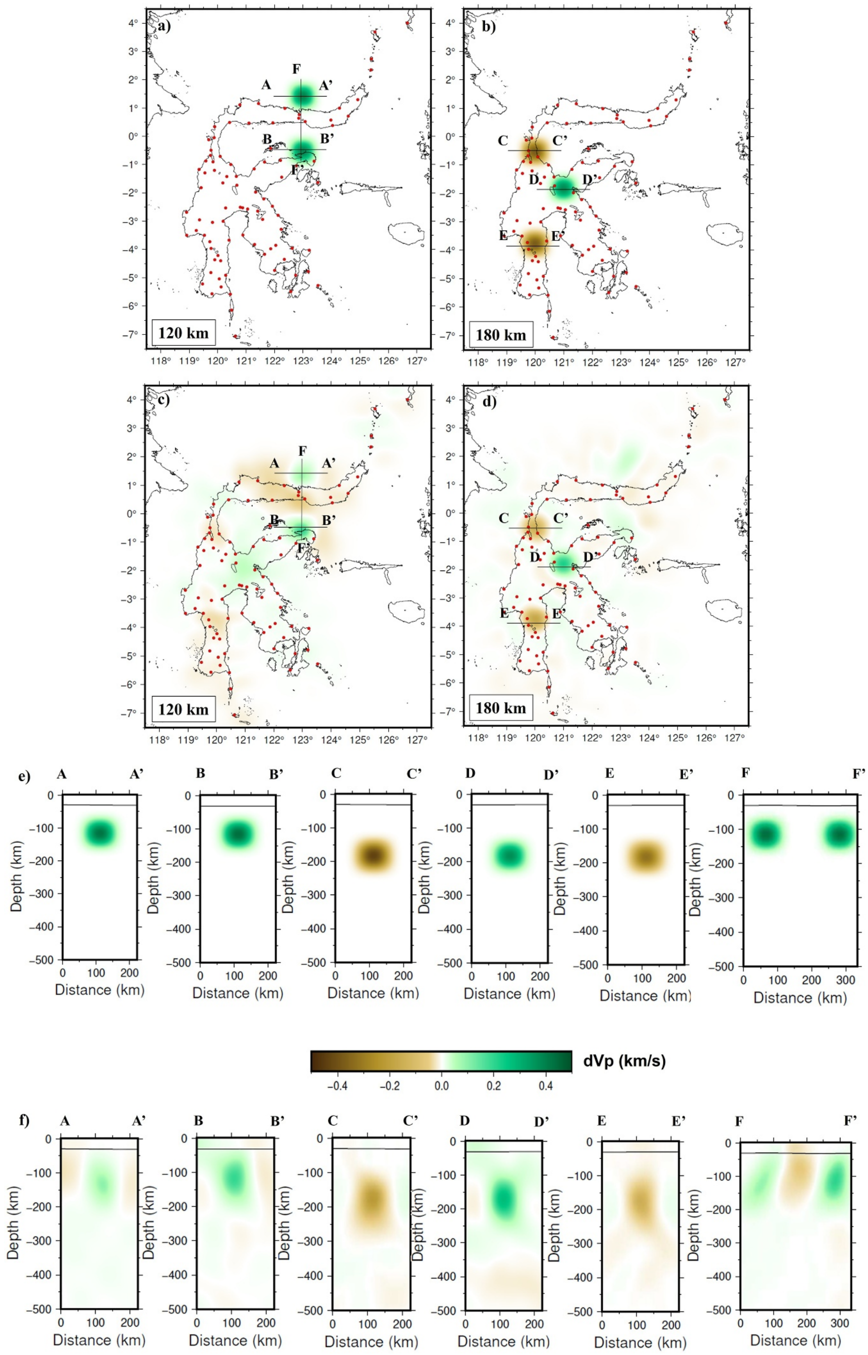

Figure 2. Synthetic test involving the recovery of spike structures. (a) and (b) are horizontal slices at 120 and 180 km depth through the input model. (c) and (d) are the corresponding output models. (e) Shows vertical slices through the input synthetic spikes, and (f) is the corresponding output model.

Sambridge, 1998). Walpersdorf et al. (1998) and Kopp et al. (1999) suggested that the westward-subducting Sangihe slab is kinematically linked to a northward-dipping structure extending from the northern edge of the Sula microcontinent. In contrast, Hall and Spakman (2015) proposed the existence of an additional, separate north-dipping slab, termed the Sula slab, which they argued is separate from the Sangihe slab. Earlier observations by Silver et al. (1983) tentatively identified a north-dipping Benioff zone beneath Gorontalo Bay that extends northward from the Sula microcontinental block. Similarly, Ferdian et al. (2010) and Watkinson et al. (2011) support the presence of a north-dipping thrust north of the Sula Islands. However, it remains unclear

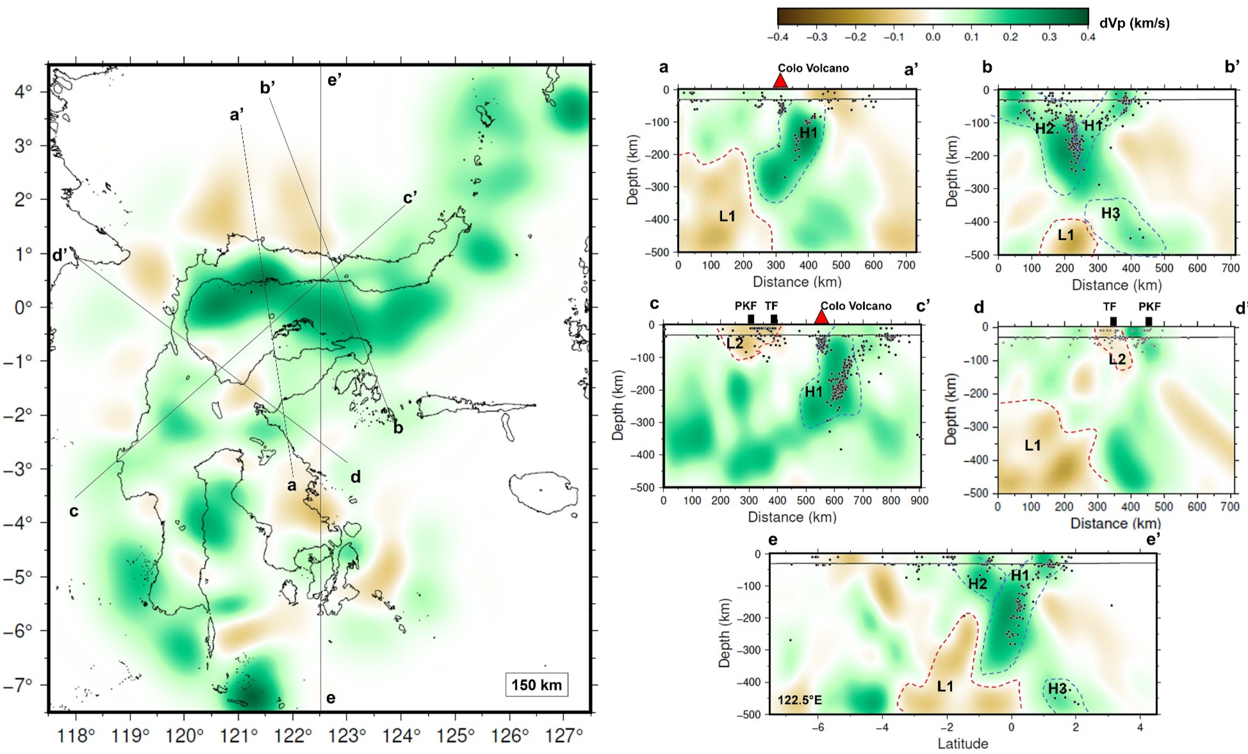

Figure 3. Horizontal slices taken through the final tomographic model at 150 km depth (left) with black lines illustrating the locations of the tomographic profiles (a to e). H1, H2, and H3 represent the Celebes Sea slab, Sula slab, and Sangihe slab, respectively (TF = Tambarana Fault, PKF = Palu-Koro Fault).

whether the observed slab is a continuation of the Sangihe slab or a distinct structure, such as the proposed Sula slab. Our tomographic model reveals several prominent high-velocity zones beneath northern Sulawesi: a south-dipping slab (H1), likely representing the Celebes Sea slab; a north-dipping slab (H2), possibly linked to either Sangihe slab bending or a separate Sula slab; and a west-dipping slab (H3), consistent with the Sangihe slab (Figures 3 and 4).

The Celebes Sea slab represents the subduction of the Celebes Sea lithosphere beneath the North Sulawesi Trench. This slab follows a distinctive west-to-east depth pattern, transitioning from shallow to deep before shallowing again (Hall & Spakman, 2015; Hayes et al., 2018; Song et al., 2022), consistent with the hypothesis that subduction along passive margins could initiate at a point and subsequently propagate laterally (Hall, 2019). However, we realize that the resolution of the slab diminishes in its eastern extent (Figure S7 in Supporting Information S1). Seismicity suggests that the slab extends to a maximum depth of ∼250 km, but our tomographic model (Figure 3h1) offers a different perspective, highlighting significant differences in its depth extent. Notably, at ∼122.5°E, the tomographic image reveals a south-dipping high-velocity anomaly reaching ∼350–400 km depth, exceeding previous depth estimates from Hall and Spakman (2015) and Hayes et al. (2018), with no seismicity in the lower section. We acknowledge that seismicity may provide a direct indication of slab presence, but it typically diminishes at depth due to thermal and rheological conditions. While vertical smearing could extend anomalies artificially, our resolution tests (Figure S7 in Supporting Information S1) show it is insufficient to account for a coherent high-velocity structure extending over 150 km below the seismogenic zone. Additional details on depth variations along the slab are provided in Figure S11 in Supporting Information S1 and illustrated in Figure 4.

Our tomographic images provide critical new constraints on the geometry of the north-dipping slab beneath North Sulawesi. Hall and Spakman (2015) suggested that the north-dipping (Sula) slab spans from 120°E to 124°E. However, our model finds no evidence of such a north-dipping slab west of 122.5°E. The resolution test in Figures S5 and S7 in Supporting Information S1 confirms that the model should be capable of capturing such a feature, if present. To further investigate this discrepancy, we extracted a profile (profile a–a′ in Figure 3) across the proposed trench location of the Sula slab (Hall & Spakman, 2015). Rather than identifying a high-velocity

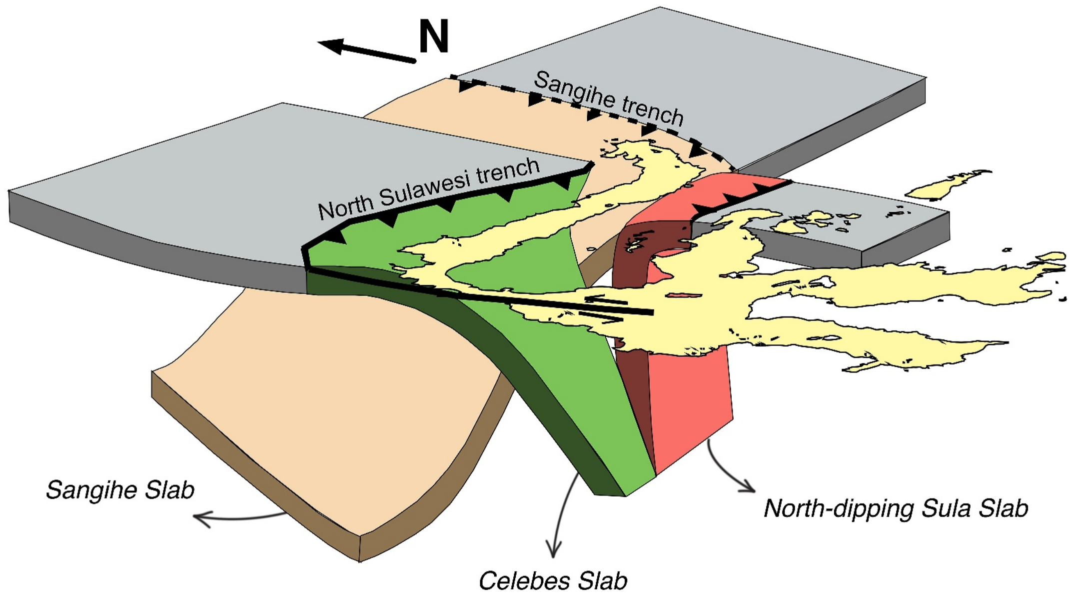

Figure 4. Illustration of slab configuration in North Sulawesi region based on the new tomographic model and pre-existing constraints from Hall and Spakman (2015). The Sangihe trench is dashed because it no longer has a surface expression.

anomaly consistent with an independent Sula slab, our model confirms its absence west of 122°E. This result suggests two possible scenarios: (a) northern Sulawesi hosts three distinct slabs, with the north-dipping Sula slab limited to the region east of 122.5°E, or (b) there are only two slabs, with the north-dipping structure instead representing a deflected continuation of the Sangihe slab, as previously proposed by Walpersdorf et al. (1998) and illustrated by Di Leo et al. (2012a). Considering the geological observations presented by Hall and Spakman (2015), we favor the three-slab interpretation but revise the inferred extent of the north-dipping Sula slab, confining it to the east of 122.5°E. The slab configuration shown in Figure 4 builds on the regional framework of Hall and Spakman (2015), but the specific geometries, depth extents, and lateral terminations are constrained by our new tomographic results.

In the northeastern part of our study area, limited seismic station coverage restricts our ability to accurately map the geometry of the Sangihe slab. However, high-velocity anomalies and the seismicity patterns (Figure 3) suggest interactions between the Sangihe, Celebes Sea, and north-dipping slabs. These findings support the shear-wave splitting analysis of Cao et al. (2024), which indicates that the complex mantle flow pattern in North Sulawesi is influenced by interactions among the Celebes Sea, Sangihe, and Sula slabs, as well as the adjacent Palu-Koro fault.

Cao et al. (2024) also observed N–S trending fast polarization in the western Sula block, subparallel to the Palu-Koro Fault, and proposed lithosphere-asthenosphere coupling. The low-velocity anomaly (L2) beneath the eastern Palu-Koro Fault, extending to 100 km depth (Figure 3, Figures S9 and S10 in Supporting Information S1) suggests a strong connection between the lithosphere and asthenosphere. Additionally, Supendi et al. (2025) detected a low-velocity anomaly in the same region extending to 150 km depth, reinforcing the interpretation of a large lithospheric structure that is not only limited to the crust. Although anomaly L2 lies east of the Palu-Koro Fault, its proximity to the Tambarana Fault suggests a deeper connection to older tectonic structures. The Tambarana Fault, active during the Miocene–Pliocene (Pholbud et al., 2012), exhibits over 7 km of vertical displacement, separating exhumed granitic and metamorphic basement rocks in the west from thick sedimentary sequences beneath Gorontalo Bay in the east (Hennig et al., 2017). This structural contrast points to a major lithospheric boundary and suggests that the Tambarana Fault may have played a dominant tectonic role before the Palu-Koro Fault became active in the last ~2 Ma. Thus, L2 likely reflects a deep-seated structure associated with the Tambarana Fault.

4.2. Low-Velocity Anomalies Beneath the East Arm of Sulawesi

Our tomographic model reveals low-velocity anomalies beneath the East Arm of Sulawesi, including the isolated active Colo volcano in the back-arc region of Celebes Sea subduction (Gulf of Tomini). While this region experienced subduction-collision processes and extensional tectonism (Cottam et al., 2011; Pholbud et al., 2012; Sendjaja et al., 2020; White et al., 2014), the origin of local volcanism remains controversial, largely due to the lack of geochemical analyses. Two end-members have been proposed to explain the enigmatic volcanism, or lack thereof, of northern Sulawesi: (a) subduction-related (Effendi et al., 1997; J. A. Katili, 1975; Sendjaja et al., 2020), and (b) extension-related volcanism (Advokaat et al., 2017; Cottam et al., 2011; Hall & Spakman, 2015; Handyarso et al., 2023; Pholbud et al., 2012; Watkinson et al., 2012).

In the subduction-based explanations, several factors are thought to influence the volcanic activity in the region. These include the southeastward dipping subduction of the Celebes Sea (J. A. Katili, 1975), the Sangihe subduction that produced a volcanic belt extending southwestward (Effendi et al., 1997), and the shallow-angle subduction of the Celebes Sea plate (Sendjaja, 2013). Vroon and Van Bergen (2000) identified adakites at Colo with distinctive Sr and Nd isotopic ratios, linking them to the southward-subducting Celebes slab and distinguishing them from the Sangihe and Halmahera arcs. However, Cottam et al. (2011) argued that subduction-related volcanism should have occurred before the East Sulawesi–Banggai Sula collision (∼5 Ma), whereas volcanic rocks in the Togian Islands and surrounding areas are younger, suggesting a different origin. Earthquakes beneath Colo are also shallow, unlike typical subduction-related seismicity (Cottam et al., 2011; Hall & Spakman, 2015). Hall and Spakman (2015) proposed that Colo formed through localized melting driven by extension, crustal thinning, and delamination. Geochemical analyses indicate a medium-K to shoshonitic magmatic affinity (Cottam et al., 2011). Supported by Willson (1989), Cottam et al. attributed the high-K compositions to rapid extensional thinning beneath Gorontalo Bay. While such volcanism is often linked to subduction zones (Campbell et al., 2014; Leslie et al., 2009), it is also associated with lithospheric thinning in extensional settings where subduction is active (Gläser et al., 2022; Im et al., 2021). Advokaat et al. (2017) further suggested that this extension results from northward slab rollback of the southward-subducting Celebes Sea since the Pliocene.

A pronounced low-velocity anomaly stemming from the MTZ, and reaching up to 200 km depth (referred to as L1) has been identified beneath the East Arm of Sulawesi. L1 appears strongest at depths below 350 km (Figures S8–S10 in Supporting Information S1) and is located south of the main volcanic centers. Therefore, its role as a direct melt source remains uncertain. Recently, Supendi et al. (2025) conducted a local earthquake tomography study of Sulawesi, which provides greater resolution of shallower structures, and detected a low-velocity anomaly beneath the Togian Islands in the Gulf of Tomini down to 200 km depth. This feature lies spatially closer to the magmatism in the region, which is more consistent with partial melting of the mantle during extension. In this context, L1 may represent deeper mantle inflow responding to lithospheric extension rather than being directly implicated in melting. Further integration of tomographic, geochemical, and tectonic data is essential to better constrain the processes driving magmatism in the Gulf of Tomini.

5. Conclusions

Using P-wave teleseismic arrival-time residuals, we constructed a new 3-D tomographic model of the lithosphere and upper mantle beneath Sulawesi. Our results reveal three different high-velocity anomalies associated with different subducting slabs beneath North Sulawesi, with significant differences in the geometry of the north-dipping (Sula) slab and the depth extent of the Celebes Sea slab when compared to previous studies. The observed slab configurations suggest complex subduction dynamics active on a remarkably small scale, consistent with mantle flow patterns inferred from anisotropy studies. Additionally, we identify a pronounced low-velocity anomaly beneath the East Arm of Sulawesi at 200–500 km depth, which we interpret as deep mantle inflow associated with lithospheric extension. A separate low-velocity zone beneath the eastern side of the Palu-Koro Fault near Tambarana Fault suggests a deep-seated lithospheric structure influencing regional deformation.

Data Availability Statement

All arrival-time residuals used in this study are available in the repository of Pilia (2025). The tomographic inversion was carried out using the FMTOMO package, which is freely available from https://github.com/

nrawlinson/FMTOMO. Data visualization was performed using Generic Mapping Tools version 6 (Wessel et al., 2019).

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