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Hypocenter Relocation using Teleseismic Double Difference Method (Case Study: West Sulawesi, Indonesia)

Harmita Lestari[1]*, Pepen Supendi[2], Andri Dian Nugraha[3], Wira Hadi Kusuma[1]

[1]Civil Engineering, State University of Makassar, Makassar, 90224, Indonesia
[2]Meteorology, Climatology and Geophysics Agency (BMKG), Jakarta, 10610, Indonesia
[3]Geophysics Engineering, Bandung Institute of Technology, Bandung, 40132, Indonesia

*Corresponding author. Email: harmita.lestari@unm.ac.id

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Abstract

This study analyzes seismicity in West Sulawesi through earthquake hypocenter relocation using the teleseismic double-difference (TeletomoDD) method. P-wave arrival times recorded by local, regional, and teleseismic stations from the Meteorology, Climatology, and Geophysics Agency (BMKG) were analyzed for the period January 2017 to January 2021. The hypocenter relocation results show a significant reduction in residual time, with most values concentrated between −10 and 10 before relocation and more than 50% near zero after relocation. The epicenters shifted toward the northwest and southeast, driven by the complex tectonic conditions and the presence of shallow faults, particularly along the Mamuju–Mamasa at depths of 5 km to 10 km. The average horizontal hypocenter shift was approximately 4.9 km relative to the routine BMKG catalog, with maximum corrections reaching approximately 17.7 km, and roughly 37.5% of events showing shifts 4–5 km, indicating a substantial improvement in the spatial accuracy of the original catalog. The seismicity analysis results indicated that the fault area was dominated by shallow earthquakes with an average earthquake magnitude of M > 4. The local tectonic regime, mainly controlled by an active shallow crustal thrust fault, suggests that the majority of seismic events are related to local faulting, although some mechanisms remain uncertain. The relocated hypocenter distribution obtained in this study indicates relatively high seismicity in the region. These findings provide improved constraints on seismicity patterns and fault geometry in West Sulawesi, which are important for understanding regional tectonics in more detailed.

Keywords: double difference; hypocenter relocation; Mamasa; Seismicity; West Sulawesi.

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Introduction

The tectonic setting of the southern arm of Sulawesi is characterized by two major groups: the Makassar Strait Thrust (MST) to the west and the Walanae Fault System (WFS) to the south (Jaya et al., 2023; Serhalawan & Chen, 2024). In the West Sulawesi, tectonic deformation had identified as a fold-and-thrust belt affecting Pliocene-aged rock units located offshore to the west of Mamuju (Brackenridge et al., 2020). This fold-and-thrust belt is interpreted to consist of a series of imbricated synthetic thrust faults, commonly referred to as the floor thrust (Yan et al., 2016). This structural system propagates westward and is bounded by the MST, which is subdivided into four distinct segments: Mamuju (MSTM), Central (MSTC), and North (MSTN), including a newly identified segment between the northern and central parts of the Makassar Strait Thrust (MST Central-North) (Hutchings & Mooney, 2021).

In the southern arm of Sulawesi (approximately 2°S to 4.5°S), seismic activity has increased following the 2018

Palu earthquake (Supendi et al. 2019), particularly in the Mamasa region, where earthquake swarm activity has been observed. This swarm is characterized by a sequence of clustered earthquakes with relatively small magnitudes (M < 5) (Figure 1). Between 2017 and 2021, earthquake data from the Meteorology, Climatology, and Geophysics Agency (BMKG) further indicate that West Sulawesi exhibits relatively high seismicity, especially along the Mamuju–Mamasa region (Figure 1).

The potential for a major destructive earthquake remains a significant threat to the Sulawesi region, which is charac-terized by an extensive network of active faults and a high prevalence of tra-ditional structures with limited seismic resistance (Widiyanto et al., 2019; Omira et al., 2019; Pasari et al., 2021). This concern is further supported by geophysical and geodetic evidence highlighting the region's complex tec-tonic setting. Tectonic complexity is evidenced by a three-dimensional shear-wave velocity model showing pro-nounced depth-dependent lateral heter-ogeneities, including a shallow low-velocity zone (≤ 14 km) and a high-velocity anomaly at depths of 20–30 km beneath the North Makassar Strait (Heryandoko et al., 2024). Moreover, interseismic GPS data indicate elevated crustal strain rates in the Mamuju and Majene regions compared to adjacent areas, suggesting heightened seismic vulnerability (Meilano et al., 2023). Additionally, Zenonos et al. (2020) identify Sulawesi as a transition zone with high Vp/Vs anomalies, re-flecting fluid-rich mantle conditions that promote mechanical weakening and strain localization, as evidenced by clustered seismicity in the region.

Over the last five decades, two significant and destructive earthquakes have occurred in the Mamuju–Majene region (indicated by red stars in Figure 1). Several destructive earthquakes have been historically recorded in the West Sulawesi region, including the Mw 7.0 event on 23 February 1969, the Mw 7.0 earthquake on 8 January 1984 (Supendi et al, 2021), and the more recent Mw 6.2 event on 14 January 2021 (Figure 1) in West Sulawesi, caused extensive building damage within approximately 30 km of the epicenter and was associated with a partial rupture of an east-dipping offshore fault west of Mamuju (Meilano et al., 2023). This indicates that extensive seismicity studies are needed to understand the earthquake patterns in West Sulawesi. To characterize seismic activity in Sulawesi, it is essential to analyze hypocenter relocation data in the context of the tectonic region and active fault systems.

Previous relocation studies in Sulawesi have demonstrated the importance of improving hypocenter accuracy for understanding local fault systems using the BMKG network data. For example, in Poso, Central Sulawesi (Supendi et al., 2018), Palu and Mamasa (Supendi et al., 2019), Palu Koro Fault (Ismullah et al., 2017), Mamuju-Majene (Supendi et al., 2021), Mamasa (Rosid et al., 2022), Central Sulawesi (Jayadi et al., 2023), which still uses a 1D velocity model. In contrast, the implementation of 3-D velocity models significantly reduces travel-time residuals and improves the resolution of subsurface structures, particularly in subduction and active faults. (Nugraha et al., 2018).

Previous studies on hypocenter relocation using the teleseismic double-difference (TeletomoDD) method have been conducted in entire Indonesia including West Sulawesi (Nugraha et al., 2019), Palu earthquake sequences (Supendi et al., 2020), and also in East Sulawesi (Lestari et al., 2022). However, previous studies have not provided detailed hy-pocenter relocation focusing on the Mamuju-Mamasa region using a

3D ve-locity model integrated with teleseismic observations, limiting the resolution of local fault geometry.

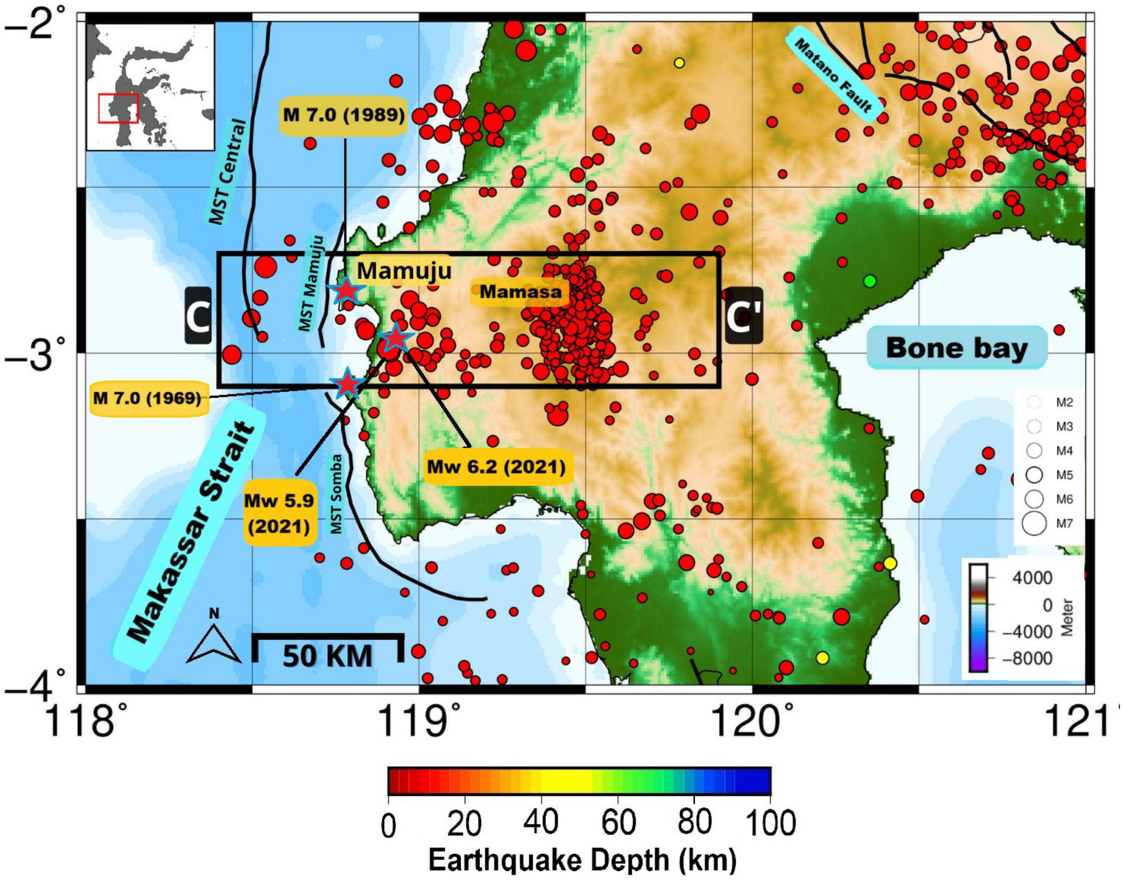

Figure 1. Seismicity map of Sulawesi (earthquake period: January 2017-January 2021 from the BMKG catalog). Earthquake data of M 7.0 in 1970 and M 7.0 in 1969 were taken from Supendi et al. (2021).

The teleseismic double-difference (TeletomoDD) method was proposed by Pesicek et al. (2010) to improve earthquake location accuracy and subsurface imaging. The advantage of this method is its ability to improve earthquake locations by jointly utilizing body-wave arrival times and differential time data observed at various distances (Pesicek et al., 2014). Hypocenter relocation using the TeletomoDD method improves the accuracy of earthquake locations and provides a clearer delineation of regional tectonic structures along the Sunda Arc (Nugraha et al., 2018).

Therefore, this study aims to improve the precise of earthquake hypocenter locations in West Sulawesi and delineate the spatial distribution of seismicity in relation to active fault systems using a 3D velocity model. In addition, this study evaluates the uncertainty of relocated hypocenters to ensure that the results can be interpreted within a robust tectonic framework.

Materials and Methods

Data used

The data used in this study are the arrival times of earthquakes from Indonesian Agency of Meteorology, Climatology, and Geophysics (BMKG) catalog from January 2017 to January 2021. The spatial extent of the study area covers approximately 118°E to 121°E in longitude and 4°S to 2°S in latitude, focusing on the Mamuju–Mamasa region and using earthquake data in those areas.

The earthquake data were then selected based on a minimum of six P-phases to reduce mis-location errors during the relocation process, resulting in 427 events. The S-wave phase was excluded from this study because most events were characterized by fewer than six recorded phases, which is insufficient to satisfy the minimum observational requirements for obtaining a stable and well-constrained hypocenter solution.

Teleseismic Double Difference

The basic equation of the double-difference method relates the residuals between the observed and predicted phase differences of travel times, dr_k^{ij}, for a pair of earthquakes i and j observed at the same station, k, to the change in the vector connecting the two hypocenters through the partial derivative of the travel time t, for each earthquake event with respect to the unknown model parameter, **m**, which is written in Equation 1 (Waldhauser & Ellsworth, 2000):

$$\frac{\partial t_k^i}{\partial m}\Delta m_i - \frac{\partial t_k^j}{\partial m}\Delta m_j = dr_k^{ij} \qquad (1)$$

Similar to the local scale double-difference tomography method, the teleseismic double-difference method (Pesicek et al, 2010) can represent its extension to teleseismic distances using the following equation:

$$r_k^i = \sum_{l=1}^{3}\frac{\partial T_k^i}{\partial x_l^i}\Delta x_l^i + \Delta\tau^i + \sum_{n\epsilon G} w_n^G\delta u_n^G + \sum_{n\epsilon L} w_n^L\delta u_n^L + S_k \qquad (2)$$

Where, r_k^i and r_k^j is residual arrival times for earthquakes i and j at station k, dr_k^{ij} is residual from *double-difference*, $\Delta\tau^i$ is the perturbation of the origin time for earthquakes i, $\Delta x_l^i (l = 1,2,3)$ is a location perturbation in three coordinate directions, δu_n^G and δu_n^L are slowness perturbations for global (G) and local (L) models. w_n^G and w_n^L is the ray lengths with respect to the global and local model nodes (n), S_k is a station correction.

The velocity models used in this study are the 3-D velocity model for Indonesia (Widiyantoro & van der Hilst, 1997) and the 1-D global velocity model AK135 (Kennett et al., 1995) for areas outside Indonesia, following previous studies (Nugraha et al., 2019). The background velocity model comprises 72 × 36 × 18 grid nodes along longitude, latitude, and depth, respectively, spanning global spherical coordinates from −180° to 180° longitude and −90° to 90° latitude, with depth nodes ranging from −50 km to 6000 km. This setup enables consistent ray tracing for phases from regional to teleseismic distances. Ray paths were calculated using the spherical pseudo-bending method, which incorporates Earth curvature and 3D velocity heterogeneity.

One of the important parameters that needs to be considered in the TeletomoDD inversion process is damping. The attenuation parameters depend on the amount of data and the condition number (CND). In this study, the CND value used was between 65 and 80 to balance data misfit reduction and model stability. The inversion adopts an L2-norm (least-squares) formulation, minimizing the squared residuals between observed and calculated travel times. This approach ensures stable convergence and produces a smooth model, although it may be sensitive to outliers in the data.

The inversion solver with three sequential iteration sets, resulting 11 iterations. The inversion process exhibits a rapid and consistent convergence, as indicated by the reduction of weighted RMS from an initial value of 0.955 s to approximately 0.62–0.65 s in iterations (1–3), followed by a more pronounced decrease to ~0.07 s in iterations (4–7). This represents an overall reduction of more than 90%, demonstrating a substantial improvement in the fit between observed and calculated travel times, where early iterations correct major inconsistencies in the initial model.

The stations used in the relocation process are 284 seismic stations spread across and outside Indonesia, including teleseismic stations (Figure 2). In addition to local and regional data, this study utilizes teleseismic stations, defined as stations located at large epicentral distances from the earthquake source. The seismic stations used in this study are distributed across Southeast Asia and surrounding regions, approximately within 11°S to 11°N and 105°E to 132°E, ensuring broad azimuthal coverage. This wide distribution of stations enhances the stability and resolution of hypocenter relocation using the TeletomoDD method.

This study is limited to hypocenter relocation based on seismic travel-time data. The analysis is therefore focused on improving earthquake location accuracy and interpreting regional seismicity patterns.

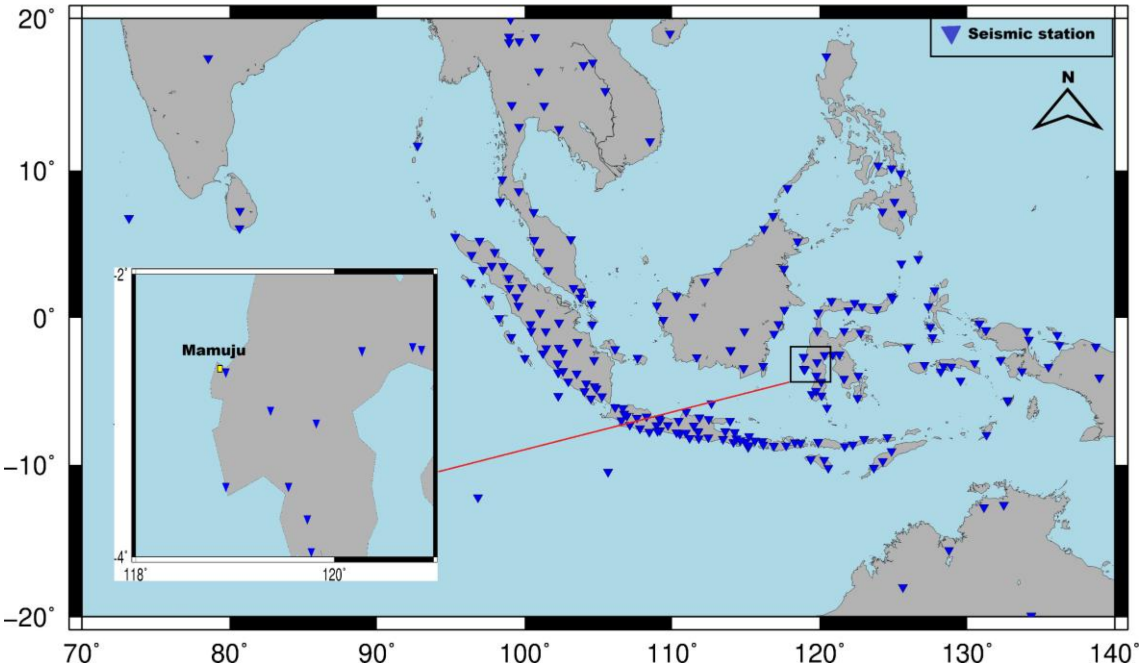

Figure 2. The distribution of seismic stations used in hypocenter relocation within and outside Indonesia, shown by the blue inverted triangles, and the black box, is the study area. Teleseismic stations are distributed over a distance of >1.000 km from the study area.

Results and Discussion

The mean of hypocenter shift is initially on the order of 4–5 km, reflecting substantial corrections to the initial catalog locations. This value progressively decreases to less than 1 m in the final iteration, suggesting a stable and well-constrained solution.

Figure 3 shows that the dominant direction of the relocation vectors is northwest-southeast, with some vectors oriented northeast-southwest. This is consistent with the orientation of the Makassar Strait Thrust, which generally trends northwest-southeast, as also mentioned in Meilano (2023).

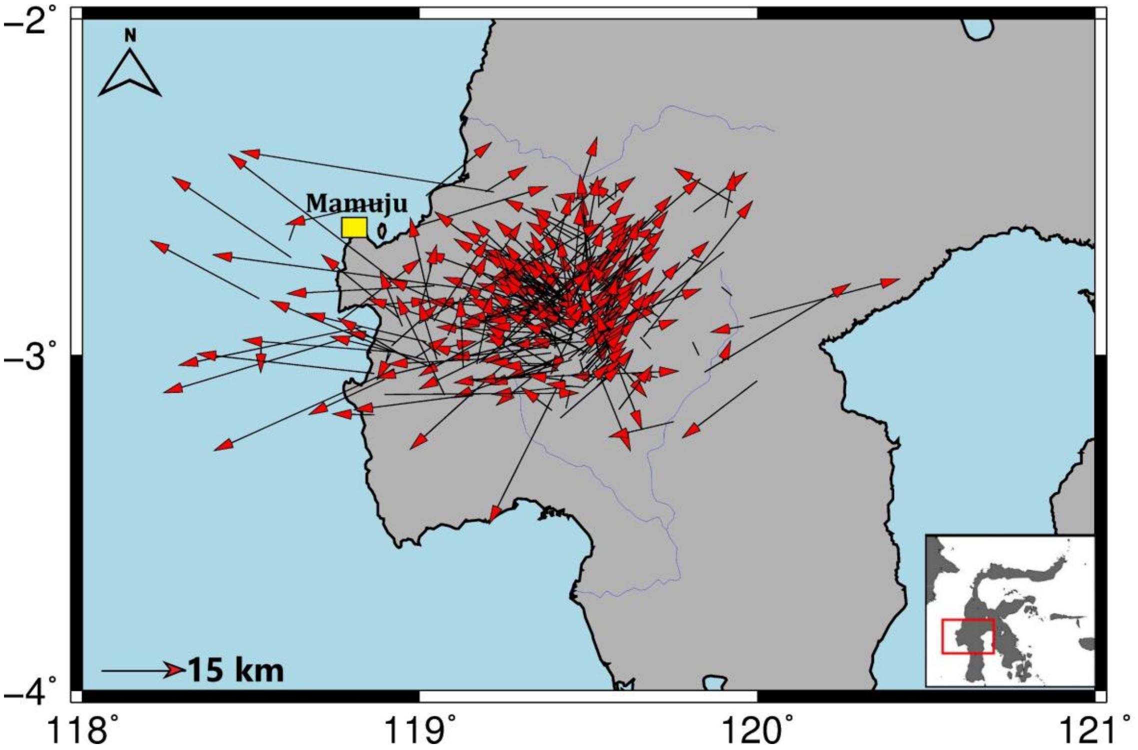

Figure 3. Hypocenter shift vectors from relocation results, where red arrow direction indicates displacement orientation and arrow length represents the magnitude of the shift, highlighting systematic corrections from initial to improved earthquake locations.

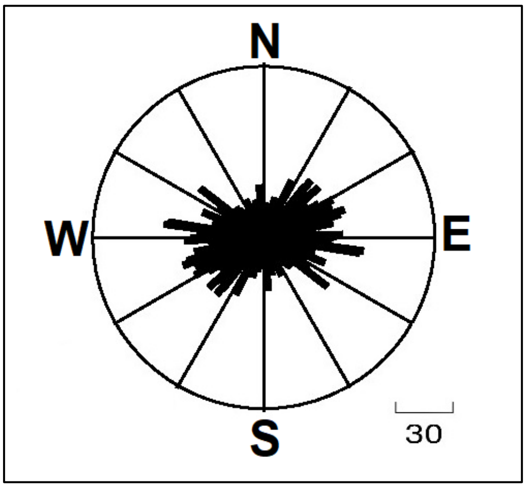

Figure 4. Rose diagram of epicenter shifts resulting from relocation in the Sulawesi region. It appears that direction of epicenter shifts is predominantly northwest and southeast due to the greater distribution of stations in the southeastern and western parts of Sulawesi.

The rose diagram analysis (Figure 4) further supports these findings, showing that the dominant earthquake directions are within ±20° of E–W. It appears that the earthquake epicenters predominantly moved toward the northwest and southeast. This pattern is likely controlled by the uneven station distribution in the southeastern and western parts of Sulawesi and the complex tectonic conditions in these areas. This is also due to the fact that earthquakes in Sulawesi are generally caused by land faults and are shallow earthquakes.

From Figure 5, the residual travel time obtained from the TeletomoDD results shows a significant reduction. In the TeletomoDD, the distance between the earthquake hypocenters is smaller than the distance between the earthquake and the station, so the raypaths of the two earthquakes can be considered the same. This can reduce the difference in residual travel times between the two earthquakes. The relocation results can be considered satisfactory if the residual time value approaches zero.

The depth distribution before relocation (Figure 6a) shows a relatively broad range of earthquake depths, with events extending to approximately 50 km and a peak at approximately 8–15 km. This wide distribution likely reflects uncertainties in the initial hypocenter locations. After relocation (Figure 6b), the depth distribution becomes more concentrated at shallow depths (< 20 km), with a significant reduction in deeper events. This indicates an improvement in hypocenter accuracy and suggests that seismicity in the study area is dominated by shallow crustal earthquakes.

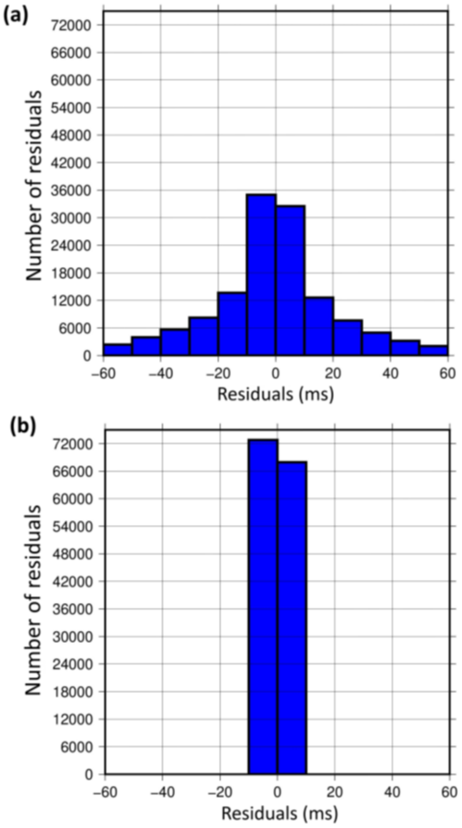

Figure 5. Residual time before (a) and after relocation (b) using the program TeletomoDD in the Sulawesi region. The relocation results show residual values approaching zero.

The horizontal distribution of hypocenters (Figure 7) shows a dominance of shallow crustal earthquakes (< 50 km). The distribution of earthquakes forms a cluster around Mamuju–Mamasa and follows the structure of active faults, including the Makassar Strait Fault, which reflects tectonic control of seismic activity. In this study, the Mamasa earthquake swarm is interpreted to be associated with a previously unidentified local fault system, as its relatively large distance from the MSTM suggests limited direct stress interaction. Previous studies indicate that the swarm is related to a shallow thrust fault mechanism and likely controlled by local fault activity, while also potentially influenced by subsurface fluid migration or hydrothermal processes (Supendi et al., 2019; Rosid et al., 2022; Serhalawan & Chen, 2024).

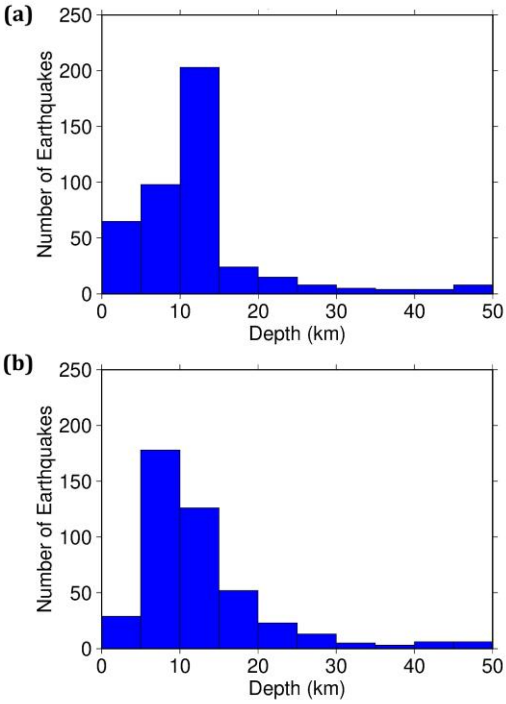

Figure 6. Histogram of the distribution of earthquake depth against the number of events, where panel (a) shows data before relocation, while panel (b) after hypocenter relocation.

In addition, beneath the MSTM (Figure 8b), two earthquakes with M>5 occurred on January 14, 2021 (Mw 5.9) and January 15, 2021 (Mw 6.2). Based on the hypocenter relocation results from this study, Figure 8b shows that Mw 6.2 events occurred beneath the MSTM. Analysis of the focal mechanism solutions (Supendi et al., 2021) indicates that the event was most likely related to activity within the Majene-Mamuju fold and thrust belt system. This interpretation is in line with previous findings from Gunawan et al. (2022), where the Mw 6.2 earthquake occurred along the bending fault plane of MSTM, although this conclusion is based on geodetic inversion and stress analysis.

There were more than 10 earthquake events with magnitude ≥ M4 that occurred along the MSTM at depths of 5–15 km. These earthquakes form a southeastward alignment, indicating the direction of the MSTM, consistent with the findings of Supendi et al. (2019). This condition warrants attention due to the high seismicity in this shallow-depth region.

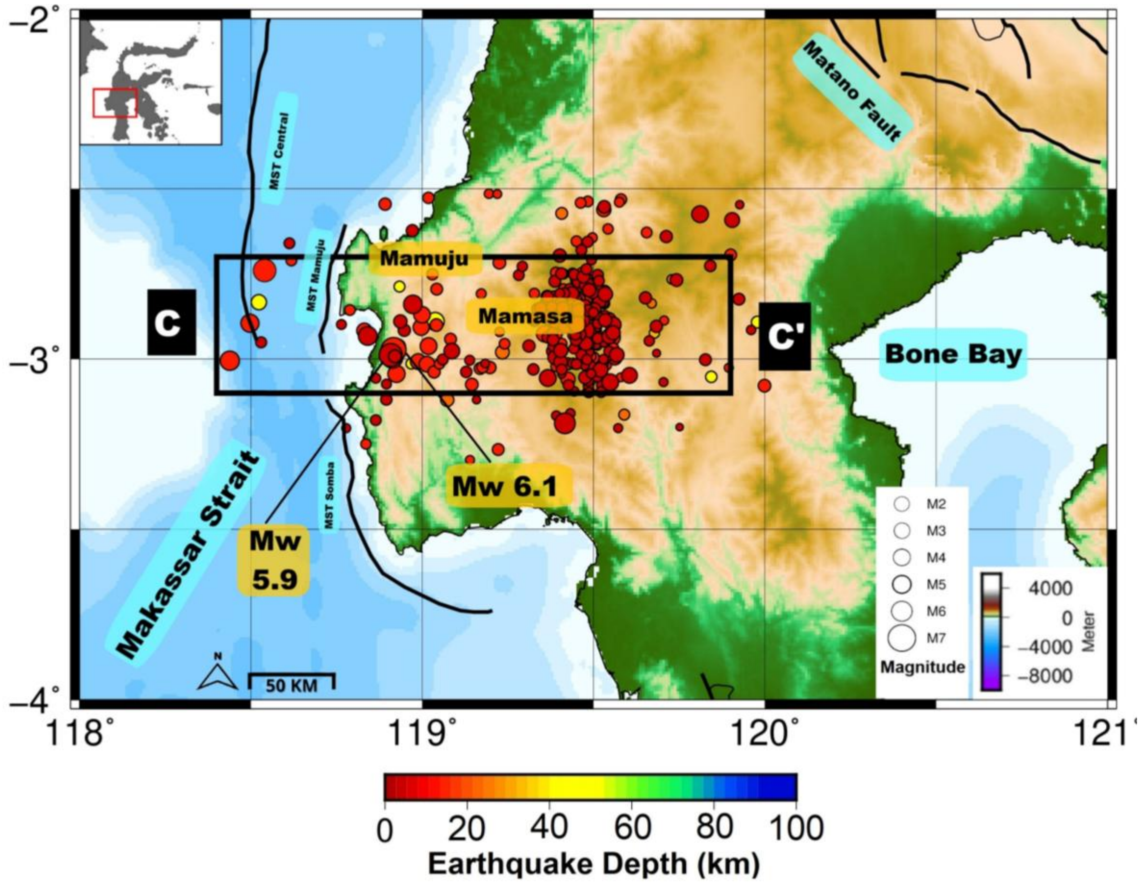

Figure 7. The seismicity map of West Sulawesi shows the distribution of earthquake hypocenters represented by circle symbols, with color indicating depth (±0–100 km). Significant earthquake events (M 5.9, and M 6.2). The horizontal cross-section (C–C') line indicates the location of the cross-section for depth distribution analysis. Black box is the area that is the focus of interpretation. The black lines are faults lines from the Geological Agency.

In addition, an earthquake swarm (Figure 7) is observed as a distinct cluster located approximately 30–40 km from the main seismic activity, with events predominantly characterized by magnitudes of M 3–4 and occurring at shallow depths of 0–10 km beneath Mamasa Regency. This cluster is therefore identified as the Mamasa earthquake swarm. The swarm, which persisted for approximately 30 days (Supendi et al., 2019), is consistent with the interpretation of Sallarès & Ranero (2019) that shallow seismicity often exhibits prolonged duration and low-frequency radiation, indicating sustained rupture processes within the shallow crust. In this context, direct dynamic triggering from distant seismic sources (~230 km) is unlikely, as it exceeds the typical timescale of dynamic stress transfer (O'Malley et al., 2018).

Figure 8b shows the distribution of hypocenters is dominated by shallow to intermediate depths (±5–25 km), with a main cluster identified in the eastern part (~100–130 km) and a secondary cluster in the central part (~50–80 km). The presence of scattered shallow earthquakes and several outliers at greater depths reflects the uncertainty of the location before the relocation process.

Figure 8b shows the epicenter locations in West Sulawesi, specifically in Mamuju and Majene. It appears that some earthquake epicenters are located around the MSTM. However, focal mechanism calculations using the global CMT (Ekström et al., 2012), available at https://www.globalcmt.org, indicate that these events are predominantly characterized by a thrust faulting mechanism. This finding suggests a strong association between the observed seismicity and the Mamuju Thrust, which is known to exhibit a thrust fault-ing mechanism.

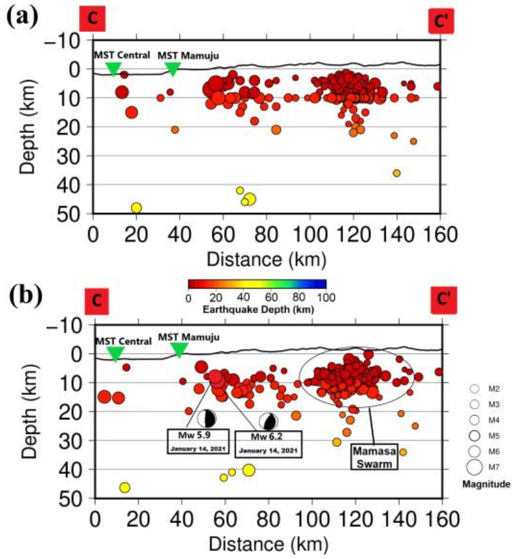

Figure 8. The vertical cross-section of seismicity along the C–C’ (west–east) before hypocenter relocation (a) and after relocation (b) shows the distribution of earthquakes with respect to depth (0–50 km) and horizontal distance. Each circle represents an earthquake event, with the size of the symbol indicating the magnitude (M2–M7) and colors indicating depth variations.

The results of the earthquake relocation show that the earthquake hypocenter depth ranges from 5 to 10 km, with the hypocenter becoming deeper as it moves farther west, reaching 40 km (Figure. 8b). The dominant seismicity cluster was identified at shallow to intermediate depths (±10–30 km), particularly in the eastern part (~100–130 km), known as the “Mamasa swarm” zone. Significant earthquake events (Mw 5.9; and Mw 6.2) occurred. The more focused distribution pattern compared to before the relocation indicates a clearer earthquake source geometry.

The shallow earthquakes along the Mamuju-Mamasa area indicate that the source of the earthquakes originates from shallow crustal faulting. Analysis of the hypocenter relocation performance using the TeletomoDD method (shows significant results, where the fixed-depth issue (Figure 8a) was resolved (Figure 8b), and provide a new description about the sequence of earthquakes along the MSTM and MSTC.

Conclusion

relocation was performed using TeletomoDD method applied to the BMKG catalog for the period January 2017 to January 2021, resulting in 465 relocated events in West Sulawesi. The relocation results demonstrate a significant reduction in travel-time residuals and produce a more coherent clustering of seismic events that better correlates with known geological structures. Earthquakes in Mamuju are dominated by shallow crustal earthquakes. Earthquakes occurring along the Mamuju-Mamasa region are likely associated with the MSTM. The Mamasa swarm indicates stress redistribution rather than activity on a single fault plane as in the Mamuju earthquakes.

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We thank the Meteorology, Climatology, and Geophysics Agency (BMKG), Region IV Makassar, Indonesia, which provides the catalog data. All map figures in this study were made using Generic Mapping Tools (GMT) (Wessel et al., 2019) which is available online at www.soest.hawaii.edu/gmt.

Author Contribution

Harmita Lestari: Conceptualization, Methodology, Data curation, Formal analysis, Software, Visualization, Writing original draft.
Pepen Supendi: Supervision, Methodology, Validation, Writing - review and editing.
Andri Dian Nugraha: Investigation, Resources, Validation.
Wira Hadi Kusuma: Data curation, Visualization, Software.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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