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Relocation of the Hypocenter of an Earthquake with the Double Difference Method in the Mentawai

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Abstract

This research aimed to accurately relocate the hypocenter of earthquakes in the Mentawai region to enhance precision in hypocenter determination. The arrival time data used were secondary data recorded in the seiscomp4 software at BMKG Class I Padang Panjang. The dataset comprised 66,979 arrival time data point form 2,380 earthquakes that occurred between September 2023 and September 2024. The Double-difference method, utilizing the Crust 2.0 velocity models, was employed for the relocation process. This method evaluated two hypocenters using a single recording station, provided that the distance between the hypocenters was less than the distance to the recording station. The HypoDD program was used for data processing. The relocation results indicated that the hypocenter had shifted and exhibited an increasing tendency toward cluster formation. The hypocenter depth was adjusted from an initial average of approximately 41.05 km to 51.05 km. This shift suggested am improvement in the quality of residual distribution. The enhancement of earthquake hypocenter resolution supported disaster mitigation by accelerating early warnings, improving construction safety in earthquake-prone areas, and optimizing emergency response. The relocation results in the Mentawai region identified 89 earthquake hypocenter points out of the 94 points recorded before relocation.

Keywords: double difference; HypoDD; residual histogram.

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Introduction

The Mentawai region is highly seismically active and prone to earthquakes due to the subduction of the Indo-Australian tectonic plate beneath Sumatera. This Subduction progresses at an estimated rate of 45 mm per year, affecting the mentawai Islands. These islands, situated off the west coast of Sumatera, lie at the intersection of the Sumatran Fault and the Sumatran Subduction Zone (Naim, 2018).

The Tuba Ridge (TR) is formed by the convergence of the Mentawai Fault (MF) and the West Andaman Fault (WAF) in the northern Sumatra forearc area. The kinematics of this zone are characterized by backthrust and strike-slip movements (Marzuki et al., 2022). TR is defined as an anticline that induces uplift and progradation, resulting from deformation in the restraining bend. South of Sumatra, the WAF marks the boundary between the arc besin and the primary accretionary complex (Le Béon & Lu, 2023).

The MF serves as the boundary between the acctionary prism and the forearc basin, acting as a backthrust in southern Sumatra.

The extension of this fault into the arc has led to the formation of the MF zone, with recent structural developments concentrated in the eastern region. The extent of the Mentawai Fault in this area remains uncertain. The anticline structure delineates the boundary between two geological zones. An accretionary prism was identified as being indented in the Sunda Strait region and parts of the southern Java Islands (Pusgen, 2017).

An earthquake is a natural disaster that occurs suddenly and rapidly, causing devastation to various entities on Earth, including individuals, property, and artifacts (Wijaya, 2024). An earthquake as a ground perturbation resulting from the rapid release of energy. Which propagates outward form the epicenter in all directions (Kammer et al., 2024). Indonesia, located at the convergence of three tectonic plates, frequently experiences earthquake due to the resultant volcanic and seismic activity, significantly influencing their distribution. The impact of an earthquake, including fatalities, is influenced by social factors such as population density, the timing of the event, and community preparedness. Despite advancements, the ability to accurately forecast earthquake impacts remain limited. Earthquake are classified into three categories based on hypocenter depth. Shallow earthquakes occur at depths of less than 60 kilometers from the Earth's surface. Moderate earthquake has hypocenter ranging from 60 to 300 kilometers while deep earthquakes are those with hypocenters exceeding 300 kilometers (Bulo, 2020).

Tectonic earthquakes are significant due to their destructive consequences. Understanding the frequency, energy output, and impact of tectonic earthquakes in relation to tectonic plates is essential. Displacements along fault planes caused by tectonic earthquake typically range from 0.2 to 0.8 meters (Gomberg & Ludwig, 2017). The epicenters of tectonic earthquake are generally located along faults and subduction zones, where frequent movements occur. Shallow earthquake epicenters are often found in regions where magma migration leads to the gradual thinning of the oceanic plate and the formation of faults. This phenomenon, known as seafloor spreading, contributes to the generation of the shallow earthquakes. Additionally, a submarine fault traversing the central mountains of Sumatra further influences tectonic activity in the region. A multitude of faults emerge from the subduction zones formed by the interaction of two tectonic plates (Gomberg & Ludwig, 2017).

Earthquake sources are classified into three categories. The first category consists of subduction earthquake sources, which are defined as zones of seismic activity located near the boundary where an oceanic plate descends beneath a continental plate. The second category includes fault earthquakes, which originate from the movement of superficial faults or fissures. Finally, the third category, known as background earthquake sources, refers to earthquake that occur in a target location despite the absence of identifiable seismogenic data (Kumala, 2016).

The precise determination of earthquake hypocenter relocation is essential for global and local seismicity analysis, fault zone identification, microfracture distribution and orientation, and velocity structure analysis. A seismic relocation method is necessary to ascertain a more precise hypocenter location. The Double Difference method is a method for relocating the hypocenter of an earthquake. Earthquakes can be relocated simultaneously via the Double Difference method. This method links earthquakes to achieve a more accurate hypocenter location by utilizing the differences in their travel periods (Apdila, 2015).

Identifying the hypocenter of an earthquake, a crucial earthquake parameter, plays a significant role in seismology. The accurate determination of earthquake hypocenter locations is essential for comprehensive tectonic structure studies, particularly in detecting fault zones and subduction zone patterns. Several factors influence the accuracy of predicting earthquake hypocenter sites, including seismic station network layout, earthquake data distribution, arrival time readings, and velocity structure models (Dewi, 2018).

The benefits of hypocenter relocation include :
1. Reducing disaster risks and impacts
By determining the accurate location of the hypocenter, authorities can provide faster and more precise warnings to the public, thereby minimizing the risk of damage and casualties.
2. Safer construction planning
Accurate hypocenter data enables better and safer infrastructure development, particularly in earthquake-prone areas.
3. More efficient emergency response
Emergency response teams can promptly reach the most affected areas, improving the effectiveness of relief efforts (Ramdhan et al., 2023).

Parameters of the earthquake hypocenter released by BMKG (Meteorological Agency Climatology and Geophysics) are still lacking optimal in terms of accuracy because it is more focuses on the speed of information for tsunami early warning for the community (Sabonbali, 2020).

This investigation was conducted in the Mentawai region, located between the coordinates 0.7235°N to 3.9263°S and 97.3142°E to 100.98°E. The study examines disparities in earthquake hypocenter depths in the Mentawai region before and after relocation, along with a comparative analysis of hypocenter positions pre- and post –relocation. The objective is to apply the twofold difference approach to accurately relocate the hypocenter in the mentawai region, evaluate he changes in hypocenter locations due to relocation, and determine the average depth of earthquakes in area.

Materials and Methods

The principal location of the study was the Mentawai region in western Sumatera, Indonesia. is the Mentawai region in western Sumatra, Indonesia. The investigations utilized arrival time data of seismic waves from seismic stations near Mentawai. Data from both P (primary) and S (secondary) waves were utilized. The double difference (DD) method was employed to ascertain the migration of the hypocenter using arrival time from September 2023 to September 2024. The Position of the earthquake hypocenter was refined using the Double Difference (DD) method.

The initial data used in this study were obtained from BMKG Padang Panjang (PGR-VI), comprising a total of 2,380 records from all observation areas. However, for the Mentawai region, only 94 data points were selected as the initial dataset. After the relocation process using the Double Difference method, the final dataset for the Mentawai region was reduced to 89 data points. This reduction resulted from a data filtering process aimed at enhancing the accuracy of the relocation results.

The hypoDD program was utilized to relocate the seismic hypocenter. Waldhauser & Ellsworth (2000) introduced this method, derived from the Geiger method, which utilizes residual transit time data from each pair of hypocenters to the earthquake recording station. It is suggested that the distance between the two hypocenters should be shorter than the distance from a hypocenter to the earthquake recording station. Thus, the objective is to compare the two hypocenters with the station. This is accomplished by modeling the waves from the two hypocenters as propagating through the same ray path or medium. Errors can be minimized by determining the new hypocenter's location based on the differential travel time between the two hypocenters (Serhalawan, 2018).

Determining the location of the hypocenter of an earthquake hypocenter has been widely conducted and developed using various approaches and methods. One of these is the Double Difference method (Baskoro et al., 2024). This method is a technique for hypocenter relocation derived from the Geiger approach, utilizing travel time residuals from two adjacent earthquake hypocenters to each seismograph station (Dewi, 2018).

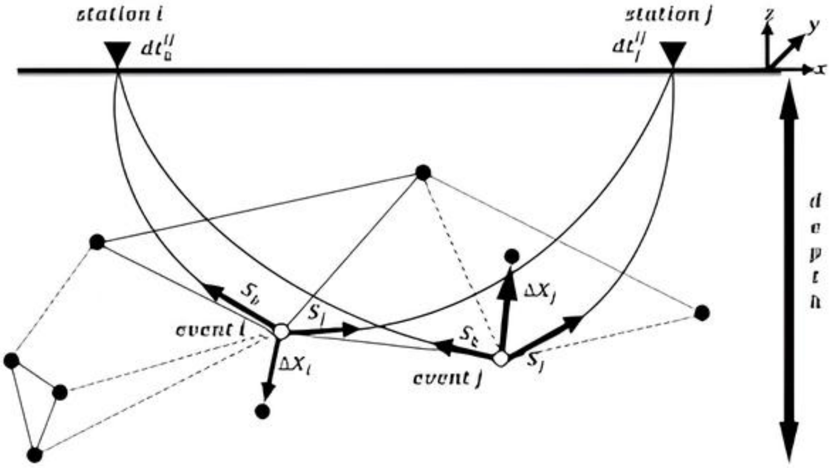

Figure 1. Illustration of the double difference methods (Waldhauser & Ellsworth, 2000).

Figure 1 illustrates the Double Difference algorithm. The white circles, recorded at stations k and l with a travel time differential (dt_k^{ij}) and its slowness vector s, represent the hypocenters of adjacent earthquake events. These events are analyzed using cross-correlation data (solid lines) or earthquake catalogs (dashed lines) for events i and j. The ray path remains consistent as the two events are significantly closer to the earthquake recording station than to each other. Δx_i and Δx_j denote the relocation vector (Powell & Lamontagne, 2017). The velocity model plays a crucial role in determining hypocenter relocation. If the velocity model does not align with geological conditions, the relocation results may not accurately reflect tectonic conditions. The velocity model itself is influenced by the geological structure of a region. According to Powell & Lamontagne (2017), in identifying the precise position of an earthquake hypocenter, the velocity model is a key priority. Hypocenter determination often relies on global velocity models, which can produce significant residuals. One of the primary requirements for obtaining accurate earthquake locations is the availability of a high-precision seismic wave velocity model at a local or regional scale. Based on the relationship between earthquake positions, velocity models, and complex geological conditions (Tumangkeng, 2020), the Crust 2.0 model (Zheng et al., 2022) at depths of 0–80 km in the Mentawai Islands region serves as the reference model for the P-wave velocity used in this study. Table 1 displays the values for each layer of the crust 2.0 model.

Table 1. Model for the P-wave velocity (Zheng et al., 2022).

Depth (km)	Velocity (km/s)
0.00	1.45
3.00	1.65
8.30	5.80
10.00	6.80
18.00	8.35
80.00	8.45

The difference in travel time between two seismic events, as expressed in the following equation, is referred to as the residual time between observation and calculation (Jannah, 2016).

$$d_k^{ij} = (t_k^i - t_k^j) - (t_k^i - t_k^j)^{cal} \quad (1)$$

Where:
i and j = two contiguous hypocenters.
k and l = recorded both earthquake events.
d_k^{ij} = residual travel time between earthquake pairs I and J at station K.
t_k^i = travel time of earthquake I recorded by station K.
t_k^j = travel time of earthquake J recorded by station K.
t^{obs} = Recorded travel time of observation (as noted by the receiving station).
t^{cal} = calculated trip time (derived from computations based on ray tracing in accordance with the employed velocity model).

The phase with the observed arrival time can be determined using either the relative travel time difference through cross-adjustment or the absolute travel time, as indicated by Equation (1) (Jannah, 2016). The differential variation between events I and J for each parameter is used to calculate the residual travel time between two seismic events. Equation (1) can be expressed as follows (Jannah, 2016):

$$\Delta d = \left(\frac{\partial t_k^i}{\partial m}\right)\Delta m^i - \left(\frac{\partial t_k^i}{\partial m}\right)\Delta m^j \quad (2)$$

Upon deconstructing the parameters for modifying the hypocenter model (Δm), Equation 2 can be articulated as follows (Powell & Lamontagne, 2017):

$$\Delta d = \frac{\partial t_k^i}{\partial x}\Delta x^i + \frac{\partial t_k^i}{\partial y}\Delta y^i + \frac{\partial t_k^i}{\partial z}\Delta z^i + \Delta t_0^i - \frac{\partial t_k^j}{\partial x}\Delta x^j + \frac{\partial t_k^j}{\partial y}\Delta y^j + \frac{\partial t_k^j}{\partial z}\Delta z^j + \Delta t_0^j \quad (3)$$

Equation (3) is applicable to an earthquake cluster (Powell & Lamontagne, 2017). The recorded number of n earthquakes at station k is arranged into a matrix according to Equation (2). The matrix equation for each station can be expressed as follows (Powell & Lamontagne, 2017):

$$WGm = Wd \quad (4)$$

Where:
W = A diagonal matrix used to weight each equation (containing values of 0 and 1).
G = A matrix of partial derivatives of travel time with respect to hypocenter parameters (M × 4N).
m = A vector representing relative position changes between hypocenter pairs concerning the predicted hypocenter's relative position $[dx, dy, dz]^T$ within a single cluster (2N × 1).
d = Residual travel time data for all hypocenter pairs (M × 1).
M = The number of double-difference observations.
N = quantity number of hypocenters.

G represents the travel time in relation to the partial derivative residual matrix of hypocenter parameters, with dimensions M × 4N. N denotes the number of hypocenters within a cluster, while M refers to the number of equations derived from each hypocenter pair within that cluster. d represents the residual double difference of all hypocenter pairs, whereas m is the vector of relative position changes between hypocenter pairs and the estimated (initial) hypocenter locations $[dx, dy, dz, dt]^T$ within a single cluster.

Each equation is assigned a weight using a diagonal matrix, W, to account for variations in the signal-to-noise ratio for each event at every station. The W matrix assigns weights based on the quality of event selection (Mahendra et al., 2016). Iterative calculations are conducted to refine the hypocenter position until the residual travel time between computed and observed data approaches zero.

Results and Discussion

This investigation was conducted in the Mentawai region, located between the coordinates 0.7235°N to 3.9263°S and 97.3142°E to 100.98°E. A total of 2,380 earthquake events recorded between September 2023 and September 2024 served as the initial input for the hypocenter relocation methodology. After applying the Ph2Dt filtering tool, 94 earthquake events were selected. The HypoDD program further refined this selection, identifying 89 earthquake events based on hypocenter displacement distribution.

Figure 2 illustrates the cross-section. The red color (Before) and yellow color (After) cross-section before and after relocation, respectively. While the overall cross-section remains similar before and after relocation, the depth of earthquake sources generally shows a shallower trend after relocation. Earthquakes occurring at depths of 0 to 60 kilometers tend to form clusters. According to Raharjo et al (2023), the activity of the Sumatran fault has triggered shallow earthquakes at depths of around 40 km, observed at 300 kilometers. Additionally, the data indicate the presence of a subduction zone at a depth of approximately 150 km directly beneath the Sumatran fault, also identified from 300 km.

This study identifies a cluster of earthquakes distributed at depths below 60 km, primarily occurring along the Mentawai fault. Furthermore, the subduction zone is characterized by a high frequency of earthquakes. Before relocation, approximately 82 shallow earthquakes, 9 medium-depth earthquakes, and 2 deep earthquakes were recorded. After relocation, the distribution changed to 72 shallow earthquakes, 18 medium-depth earthquakes, and 4 deep earthquakes. The correlation between earthquake origins and depth was derived from the analysis of cross-section maps shown in Figures 5 and 6.

The parameters obtained from data processing differ from the original dataset, illustrating variations in longitude and latitude when applying the double-difference method. These adjustments indicate that the relocation process aligns with the expected relocation requirements. Before relocation, the average hypocenter depth was approximately 41.05 km, which increased to around 51.05 km after relocation.

In a geotechnical context, relocation often affects the depth of soil layers or subsurface structures. Before relocation, the soil and geological strata beneath the original area were relatively stable, having undergone natural compression over time. However, post-relocation, changes in structural load and alterations in soil pressure distribution may influence the depth of existing soil layers (Feng, 2024).

Depth alterations may also result from load redistribution, leading to increased pressure on deeper soil strata or shifts within soil layers. In some cases, the thickness of a soil layer may increase due to the compaction of deeper soil or the displacement of previously shallower layers.

Figure 4 presents the seismicity map of the Mentawai region after relocation, based on processing results. The earthquakes primarily consist of shallow seismic events occurring at depths between 0 and 60 km, with a few moderate-depth earthquakes. Compared to Figure 3, which displays the original hypocenter locations, several notable changes are evident. Both the hypocenter and epicenter of the earthquakes have shifted. Following the relocation, many epicenter distributions now form clusters that appear closer to the Mentawai fault.

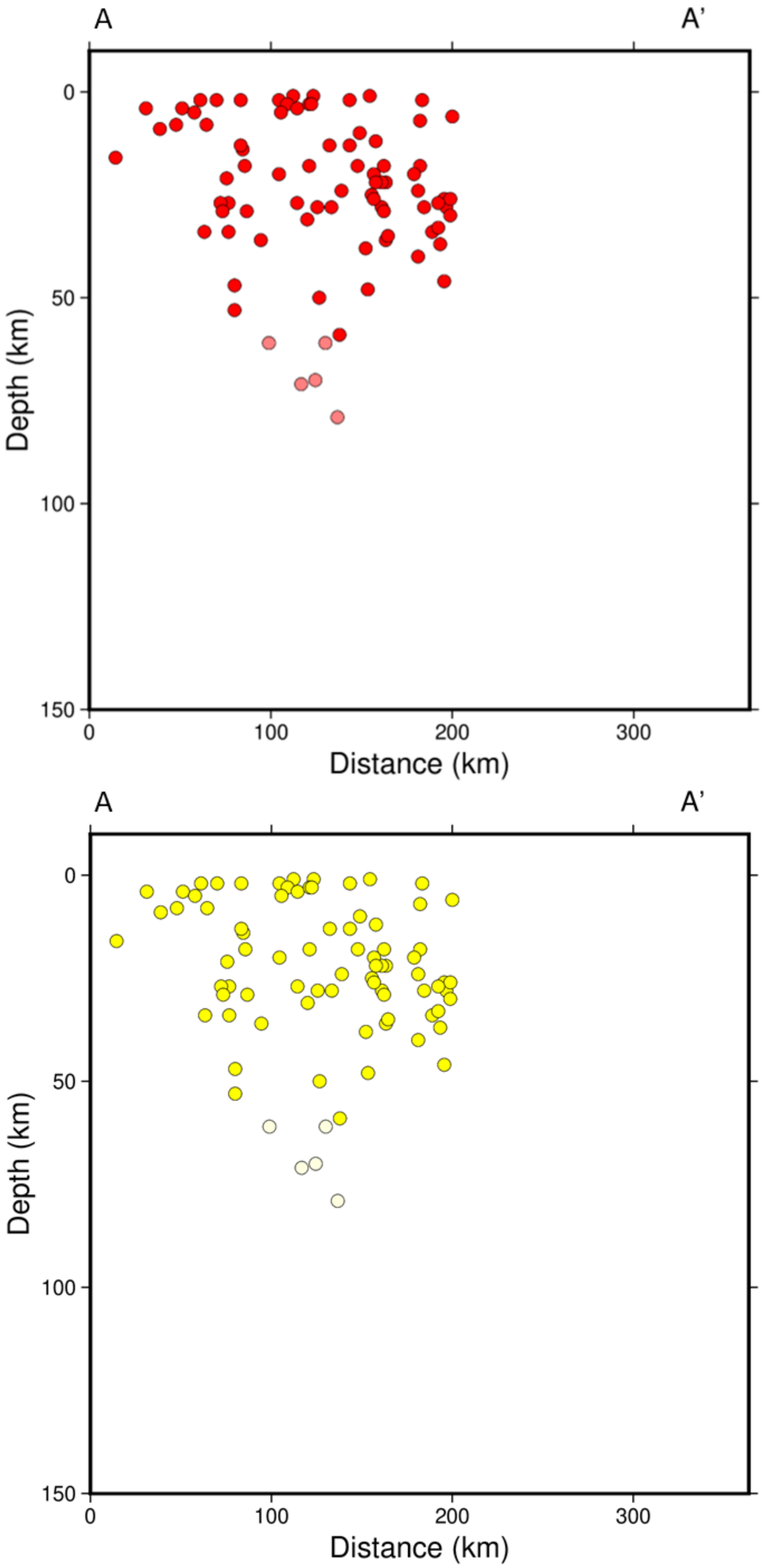

Figure 2. Cross-Section Before (red) and After (yellow) Relocation.

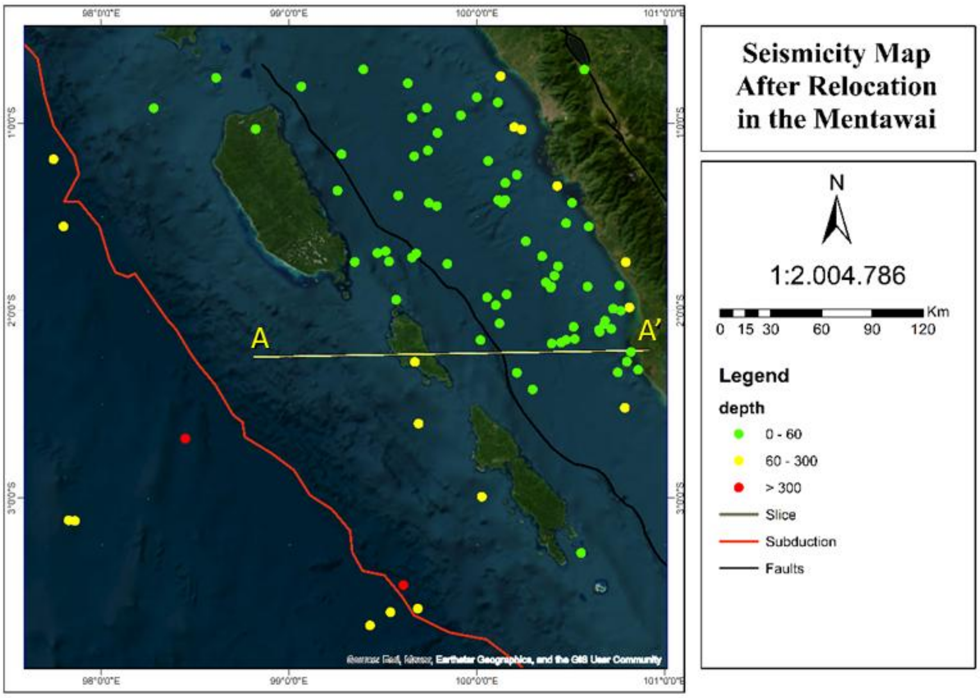

Figure 3. Seismicity map after relocation.

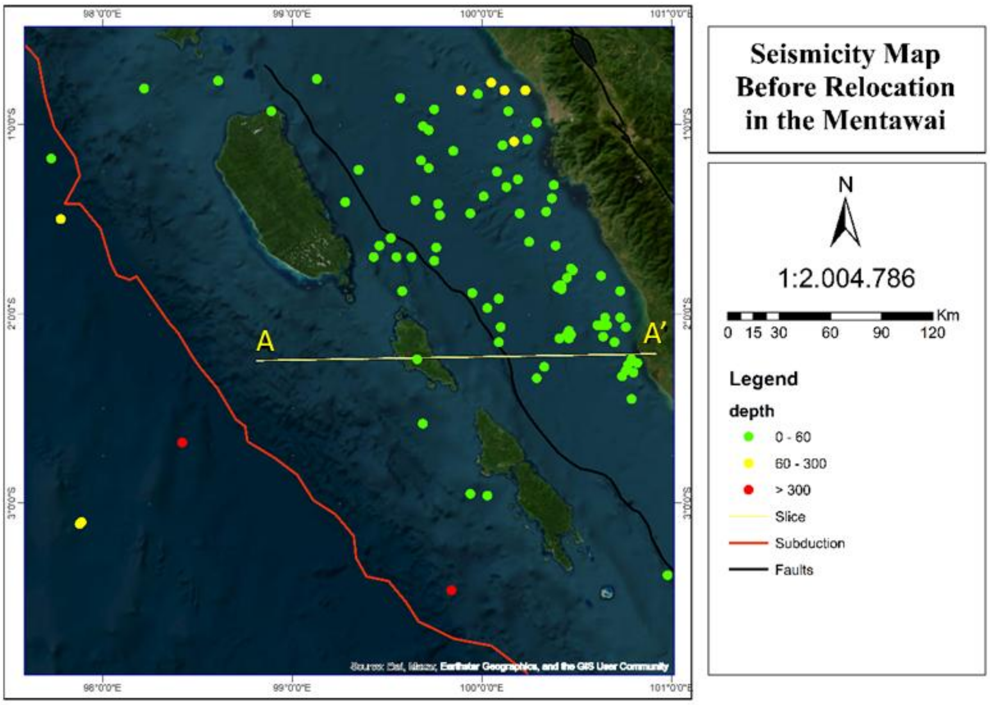

Figure 4. Seismicity map before relocation.

Un-relocated data refers to events or event pairs that do not meet the predefined criteria. These criteria are applied during the processing of earthquake occurrences using the Ph2dt program. The author sets the following parameters: minimum picking weight (MINWGHT) = 0, maximum distance between earthquake pairs and stations (MAXDIST) = 450 km, maximum distance between earthquake pairs (MAXSEP) = 210 km, maximum number of neighbors (MAXNGH) = 8, minimum number of links for a neighbor (MINLNK) = 2, minimum number of links for an earthquake pair (MINOBS) = 2, and maximum number of links for an earthquake pair (MAXOBS) = 20. Additionally, iterative adjustments to the earthquake hypocenter during relocation may lead to further modifications.

The relocation process led to a reduction in the number of data points from 94 to 89. This reduction was due to a data filtering process that prioritized quality and accuracy in the analysis. Data that did not meet the quality criteria during the relocation process were automatically eliminated to prevent biased analytical outcomes.

The relocation data reveal distinct clusters, suggesting a significant level of seismic activity along the Mentawai fault. It is hypothesized that minor faults are triggered by earthquakes occurring along the main Mentawai fault, particularly in areas with high seismic density. According to Lange et al (2018), the Mentawai fault, the Andaman fault, and several smaller faults exhibit notable activity within the region between the subduction zone and the Sumatran fault zone.

Constructing a histogram of the residual travel time after relocation enables an evaluation of the accuracy of the Double Difference method applied in the relocation process. The research findings are categorized based on quality (Q), as outlined by Utama & Garini (2022), and can be defined in Table 2.

Table 2. Hypocenter RMS Quality

Q (quality)	*RMS*
A	*<0.15*
B	*<0.30*
C	*<0.50*
D	*others*

The RMS parameters in Figure 7 shows that, compared to the pre-relocation RMS value, the post-relocation RMS value is decreasing (approaching zero). In this study, RMS represents residual error or inaccuracy measured in seconds. Therefore, when converted into hypocenter quality (Q), the data results can be considered to meet a relatively high standard. The primary objective of the Double Difference approach, applied to two consecutive earthquake events recorded by the same seismic stations, is to minimize residual discrepancies between calculated and observed travel times (Dahlia, 2022). The results of the earthquake hypocenter relocation using the Double Difference method are considered satisfactory, as the computation yields an average RMS value of 0.665.

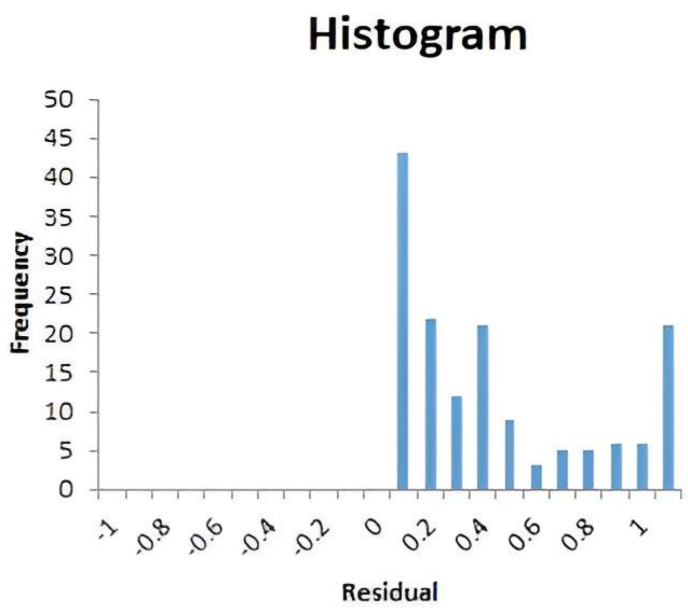

Figure 5. Histogram of travel time residual.

Conclusion

The distribution of seismic hypocenters before and after relocation exhibited several changes. Prior to relocation, data from 94 earthquake events were collected, whereas post-relocation, 89 events were identified using the hypoDD software. The relocation process adjusted both the hypocenters and epicenters, revealing a clustering of events primarily along minor faults, particularly around the Mentawai fault.

The average depth of seismic events before relocation was 41.05 km, whereas after relocation, it increased to 51.05 km. Based on this depth, it can be inferred that most of the earthquakes remain classified as shallow.

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Author Contribution

Siti Hannifah Maulani: Formulated the research concepts, designed the methodology, and conducted data analysis using the double difference method with HypoDD.

Refrizon: Provided expertise in geophysical analysis and contributed to the interpretation of results.

Rida Samdara: Managed the technical aspects of equipment setup and reviewed and revised the manuscript for intellectual content.

Lori Agug Satria: Supervised the research process, assisted with data processing, and edited the publication for intellectual clarity.

Suaidi Ahadi: Provided research resources and assisted in data compilation.

Conflict of Interest

The authors declare no conflicts of interest regarding this study. There are no personal or financial affiliations that could influence the findings and conclusions of this research. All authors have conducted this study independently.

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