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EARTHQUAKE CLUSTERING ANALYSIS IN NORTH SUMATRA REGION BASED ON DOUBLE-DIFFERENCE RELOCATION

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ABSTRACT
North Sumatra is an active tectonic zone influenced by the complex interaction between the subduction of the Indo-Australian plate and the movement of the Sumatra Fault. Accurate determination of earthquake hypocenter locations is crucial for seismotectonic modeling and disaster mitigation. This study aims to improve the precision of earthquake hypocenter location in this region through the implementation of the Double-Difference (HypoDD) relocation method and to analyze clustering based on the spatial distribution of earthquakes to identify active fault segments. The earthquake data used came from local seismic station catalogs during the period 2008–2024. The application of the HypoDD method significantly reduced the Root Mean Square (RMS) value of the average seismic phase arrival residual from 0.79373 to 0.33888, indicating an increase in the accuracy of the hypocenter location. Earthquake clustering analysis identified a total of 10 clusters that showed a strong correlation with the surrounding geological structure. The shallow earthquake cluster in the Tarutung region was dominated by a strike-slip fault mechanism, which definitively confirmed that the Renun Segment is an active segment of the Sumatra Fault with intense activity. In addition, a swarm pattern with low magnitude and very shallow depth (<15 km) was identified in the Toba Basin (Cluster 2), indicating the contribution of tectonic-magmatic processes. The cluster of medium- to deep-depth earthquakes (70–150 km) is strongly associated with subduction activity in the Sumatra intraslab megathrust zone. Overall, this study successfully mapped the spatial distribution pattern of earthquake sources in greater detail, contributing significantly to the updating of earthquake hazard maps and the determination of active fault zones in North Sumatra.

Keywords: *Earthquake clusters, Double-Difference, North Sumatra, Seismotectonics, Active faults.*

INTRODUCTION

Sumatra island, particularly North Sumatra, is a region in Indonesia with a high level of seismic activity. North Sumatra is located within the convergence zone between the Indo-Australian Plate and the Eurasian Plate. The convergence between these plates is manifested by the presence of the Sumatra Fault, an active fault that extends along the entire island. The tectonic activity in this region is highly complex and generates various types of earthquakes, including shallow, intermediate, and deep events. The Sumatra Fault is an active strike-slip fault that has produced several major earthquakes (Muksin et al., 2023, 2025; Sieh & Natawidjaja, 2000).

The presence of the Sumatra Fault is one of the main factors contributing to the high level of seismic activity in North Sumatra (see Figure 1). This active fault has generated several destructive earthquakes over the past decade, such as the Central Aceh earthquake (2013), Pidie Jaya (2017), Pasaman (2022), and Tarutung (2022) events (BMKG Catalog, 2023). However, damaging earthquakes have also occurred on unidentified faults, including the 2023 Karo earthquake and the swarm between 2022 and 2023 in the Samosir.

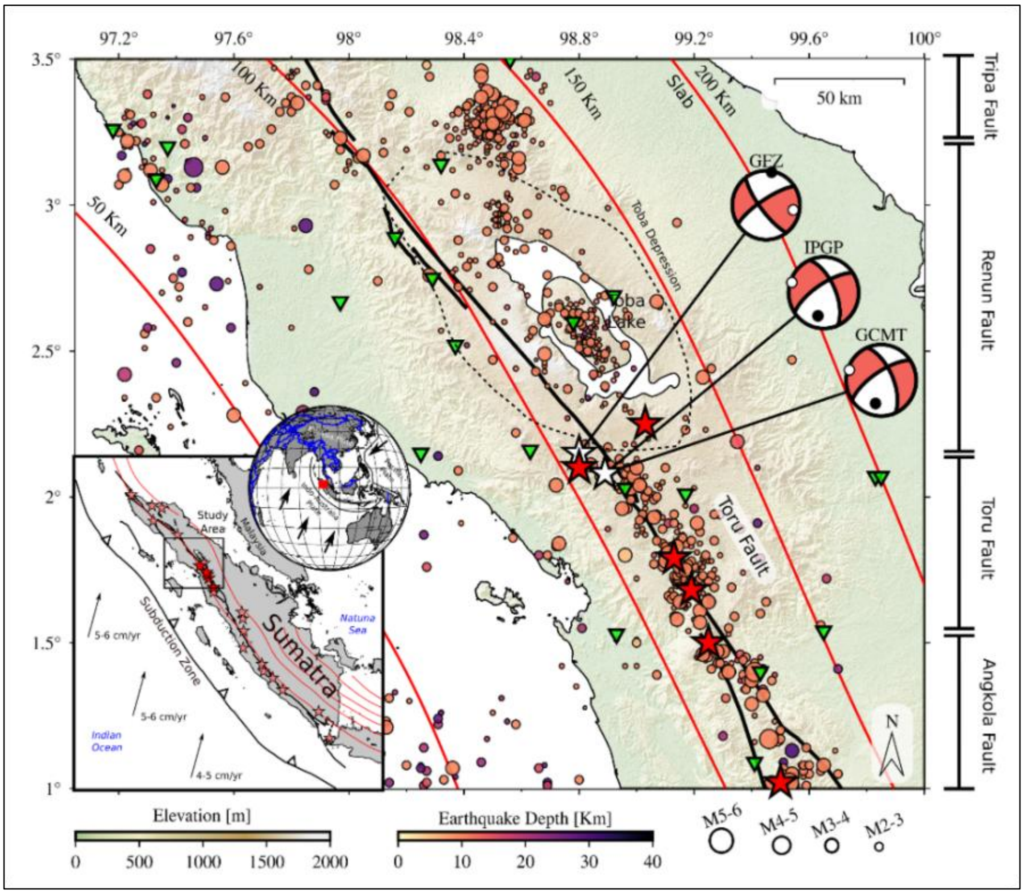

Figure 1. Seismicity map of the North Sumatra for the period 2019–2024, showing several earthquake cluster locations and an example of a damaging earthquake that occurred in the Tarutung on October 1, 2022.

To improve the accuracy of clustering results, a more precise determination of hypocenter locations is required. Several studies have also demonstrated the effectiveness of the double-difference method and the development of local velocity models in enhancing earthquake relocation accuracy. Stabile et al., (2024), conducted a study in the Aswan region of Egypt, analyzing 7.833 earthquake events using the double-difference method and a newly developed 1-D velocity model (Kissling et al., 1995). Aritonang et al., (2021) applied the double-difference (HypoDD) method and demonstrated its effectiveness in improving hypocenter location accuracy, as indicated by more focused earthquake clusters along the Toru, Angkola, and Barumun segments. Furthermore, the results of double-difference (HypoDD) relocation and focal mechanism analysis showed a significant improvement in location precision, with depth distributions ranging from 2–15 km for inland clusters and 3–13 km for offshore clusters in the Inner Northern Apennines region, and revealed clearer NE–SW striking (Kaerger et al., 2024).

In this study, we apply the double-difference relocation method to refine the hypocenter and distribution of earthquakes in the North Sumatera region. The main objectives of this research are to analyze the spatial distribution of shallow earthquake clusters in North

Sumatra, to characterize these clusters in detail after relocation using the Double-Difference method, and, most importantly, to identify the potential existence of previously unmapped active fault segments based on precise clustering patterns (Zaliapin & Ben-Zion, 2013). The contribution of this study lies in providing high-precision details of crustal earthquake sources, strengthening the understanding of local seismotectonic structures, and supplying highly relevant data for updating seismic hazard models and mitigation in the North Sumatra region.

DATA AND METHODS

This study utilizes earthquake event data recorded by the BMKG seismic network in the North Sumatra region during the 2019–2024 period. The data were obtained from the digital catalog of the Regional Earthquake Center I Medan (PGR I). A total of 1,339 earthquake events were used, comprising 21,467 P-wave and 12,816 S-wave arrival times, recorded by 51 active seismic stations in a radius of $\leq 2°$.

Data selection was carried out based on recording quality, with the following criteria: (1) azimuthal gap $\leq 180°$, (2) hypocentral depth ≤ 40 km, (3) recorded by at least four stations, and (4) clearly detectable P- and/or S-wave signals. Data that met these criteria were then converted into numerical format (.cnv) for use in velocity modeling and hypocenter relocation.

Hypocenter relocation was carried out using the Double-Difference (HypoDD) method developed by Waldhauser & Ellsworth, (2000). The principle of this method is to compare the travel times between pairs of closely spaced earthquakes recorded by the same station, allowing corrections for errors caused by local velocity heterogeneity. The differential travel time between two earthquakes i and j at station k is defined in Equation (3).

$$dt_k^{ij} = \left(T_k^i - T_k^j\right)^{obs} - \left(T_k^i - T_k^j\right)^{cal} \quad (3)$$

The difference in travel time is related to the change in hypocenter position (δm) through a linear relationship, as shown in Equation (4).

$$\delta t = G\delta m \quad (4)$$

where G is the partial derivative matrix of travel time with respect to the hypocenter coordinates. The parameter δm is estimated by solving the linear system using the Least Squares QR (LSQR) method to minimize the objective function given in Equation (5)

$$\|W\,(G\delta m - \delta t\,)\|^2 \quad (5)$$

where W is the weighting matrix based on the quality of the P- and S-phase data (ranging from 0 to 1). The iteration continues until the Root Mean Square (RMS) residual value becomes less than 0.5 seconds. The clustering was performed using a nearest-neighbor graph approach, which groups events based on spatial distances between them (<10 km) and similarities in their travel-time patterns. The clustering criteria include:

1. A minimum of eight events per cluster.
2. Distances within a cluster of less than 10 km.
3. Each cluster contain one master event connected to four or more other events.
4. Each event must be recorded by at least four seismic stations.

The results of the relocation and clustering analysis were visualized using Generic Mapping Tools (GMT) to examine the spatial and depth distribution of hypocenters. The identified clusters were then compared with previously mapped active fault structures.

RESULTS AND DISCUSSION

The clustering process was conducted based on the initial relocation hypocentre data using a 1-D local velocity model, then further refined using the Double-Difference method (HypoDD). Before relocation, the hypocenter distribution appeared to be more widespread and showed a distribution pattern that was less focused on the main geological structure. This can be seen in the initial cluster distribution map (Figure 3a), indicating that several spatially adjacent earthquake groups had not yet formed a clear path following the Great Sumatra Fault system.

Subsequent to the application of the HypoDD relocation process, the hypocentre distribution exhibited a more organised and linear pattern following the main fault segments such as Renun, Toru, and Angkola, as well as the deformation zone around the Toba Basin (Figure 3b). The narrowing of this cluster pattern indicated an increase in the accuracy of the hypocentre position as a result of the correction of the travel time residuals (Kenntt & Engdahl, 1991).

The relocation results show 10 main clusters that meet the spatial criteria, inter-event connectivity, and the feasibility of the number of recording stations. This relocation also shows a significant decrease in Root Mean

Square (RMS) travel time, from an average value of 0.79 to 0.33, reflecting an increase in the accuracy of hypocentre determination. A comparison of the RMS values before and after relocation is shown in Figure 2, which shows a consistent decrease in RMS across all clusters. These results indicate that the subsurface structure is better represented by the local velocity model used, and demonstrate the success of the HypoDD method in correcting location uncertainties originating from the initial catalogue.

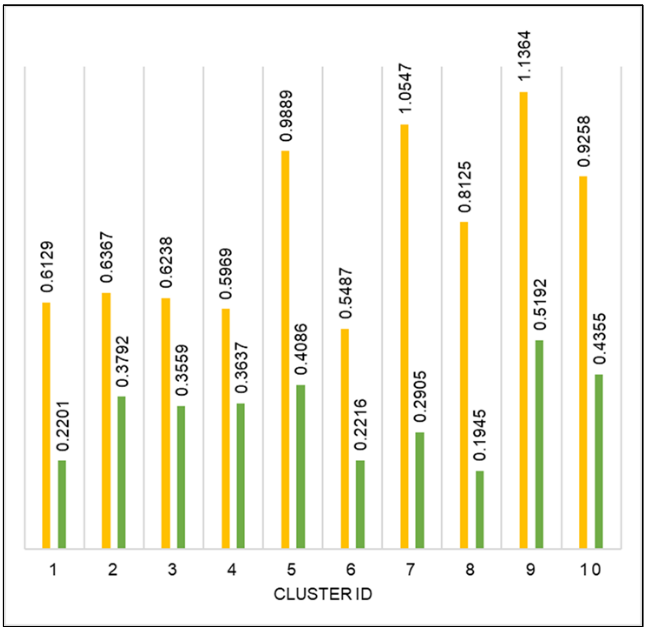

Figure 2. RMS values before (green) and after (yellow) relocation in each cluster.

The temporal magnitude distribution of each cluster provides an overview of the dynamical development of seismic activity in each zone. Figure 3 shows the temporal visualisation of magnitude and frequency variations throughout the observation period. Cluster 1, located in the Renun–Tarutung segment, shows a continuous series of earthquakes from 2022 to 2024. This pattern resembles an earthquake sequence triggered by gradual stress release along the fault plane, where several main earthquake events are followed by aftershock activity that occurs repeatedly along the same deformation path.

In contrast to cluster 1, cluster 2, located in the Karo–Toba region, exhibits a pattern of swarm seismicity with relatively small magnitudes occurring in time intervals not triggered by a single main earthquake. The swarm pattern is generally associated with fluid migration or shallow magmatic activity in a volcano-tectonic environment, thus confirming the link between seismic activity and the Toba Caldera magmatic system. However, clusters in the Angkola segment and southern regions generally exhibit lower event frequencies but with relatively larger magnitudes, indicating fault conditions that are more likely to be locked and store higher accumulations of elastic energy (Adi et al., 2024; Pasari et al., 2021).

Implications for Active Fault Structures

The improved hypocentre distribution pattern through HypoDD relocation provides a clearer picture of the geometry and activity of fault structures in North Sumatra. The results are also consistent with those of Idha et al., (2023), which show that the Tarutung earthquake (Mw 5.8) had a dextral strike-slip source mechanism with a northwest–southeast (NW-SE) direction, with strike values ranging from 138° to 158°. In this study, aftershock activity was distributed in the pull-apart system in the southeast and indicated a transfer of static stress towards the southern part of the Toru segment. The proposed model describes a negative-flower structure controlled by the main fault and secondary extensional faults.

The consistency of this pattern with the clustering and relocation results in this study reinforces the interpretation that tectonic deformation in the Tarutung area is controlled not only by the horizontal movement of the main fault, but also by locally acting fracture systems and pull-apart structures.

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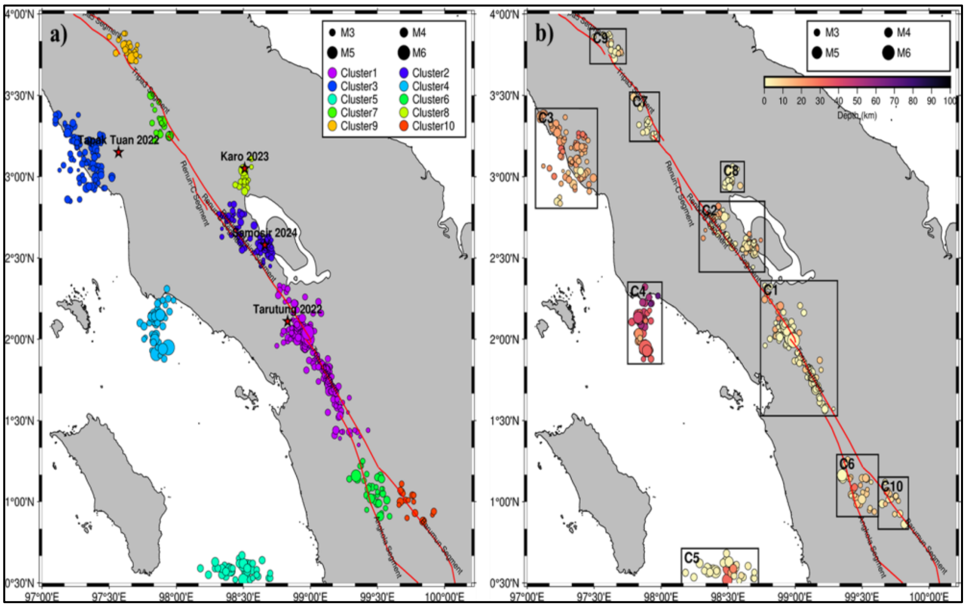

Figure 3. (a) Results of 10 earthquake clusters that have not been relocated in the Sumatra region. Earthquakes outside the clusters have been removed. (b) The distribution of earthquakes relocated from each cluster. The black boxes indicate the cluster boundaries.

Thus, these results have direct implications for earthquake hazard assessment, in which the Renun–Toru segment should be considered an active earthquake source zone with the potential for recurrent events and inter-segment stress transfer capacity (Khalqillah et al., 2025).

Meanwhile, cluster 2 shows a more scattered distribution of shallow hypocentres without a clear single fault plane pattern. This indicates that seismic activity in the Toba region is likely not controlled by a single continuous fault, but is influenced by fluid pressure or geomechanical responses from the Toba Caldera's hydrothermal and magmatic systems. Southwards, the cluster in the Angkola segment shows a more linear and consistent distribution of earthquakes with the fault zone, but with low temporal activity, indicating that this fault segment is relatively locked and has the potential to store greater seismic energy. In general, the results of this relocation and clustering confirm that seismic dynamics in North Sumatra are controlled by a combination of strike-slip tectonic processes on the Great Sumatra Fault and magmatic-hydrothermal processes around the Toba system. The findings make an important contribution to updating earthquake source maps and identifying more focused seismic hazard zones (Pristiwantoro et al., 2025; Simanjuntak et al., 2023).

CONCLUSION

The identification of the clusters provides a deeper understanding of active fault zones and earthquake hazards in North Sumatra. The cluster in the Renun–Tarutung segment shows an earthquake sequence pattern associated with repeated stress release along the fault plane, while the cluster in the Karo–Toba area shows a seismic swarm that is likely triggered by fluid-magmatic processes in the caldera system. Meanwhile, the cluster in the southern part of Angkola shows relatively locked fault activity and has the potential to store greater elastic energy, which could be a source of medium to large earthquakes in the future. Thus, the results of this relocation and clustering are directly relevant to mapping active earthquake sources and are very important as a basis for seismic hazard mitigation planning, risk-based spatial planning, and improving earthquake preparedness strategies in North Sumatra.

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