SEISMOTECTONIC STUDY OF THE KARO–SIBOLANGIT REGION, NORTH SUMATRA BASED ON DOUBLE-DIFFERENCE RELOCATION

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Abstract. *Sumatra is one of the most seismically active regions in the world due to the oblique convergence between the Indo-Australian and Eurasian plates, where strain is partitioned between the Sunda megathrust and the Great Sumatran Fault. While most seismicity in North Sumatra occurs along mapped strands of the GSF, several damaging earthquakes have occurred outside known fault zones, raising critical questions about hidden seismogenic structures. This study investigates the seismotectonic framework of the Karo-Sibolangit region, with a focus on the 2017 Karo-Sibolangit earthquake (Mw 5.6), using the double-difference relocation method. A dataset of local earthquakes recorded by the Indonesian Agency for Meteorology, Climatology, and Geophysics was analyzed to refine hypocenter locations, reduce uncertainties, and identify seismic clusters. Relocation results significantly improved spatial resolution, reducing average location errors to less than 3 km, and revealed clustered seismicity along a northwest–southeast trending structure offset from the Renun Fault. Depth cross-sections indicate brittle faulting within the upper crust (5–12 km), and the aftershock alignment suggests the presence of an unmapped subsidiary fault accommodating dextral shear. Comparisons with similar studies across Sumatra and Java confirm that off-fault seismicity is a common but often overlooked contributor to regional hazard. These findings underscore the importance of integrating relocated seismicity into national hazard models to account for hidden faults. By providing improved fault geometry and seismotectonic insights, this study enhances the understanding of earthquake sources in North Sumatra and supports future efforts in seismic hazard mitigation and disaster risk reduction in one of Indonesia's most vulnerable regions.*

Keywords: *active fault; Double-Difference relocation; Karo-Sibolangit region; seismology; seismotectonics*

INTRODUCTION

Northern part of Sumatra Island is located within one of the most seismically active tectonic regions worldwide, where the oblique convergence of the Indo-Australian and Eurasian plates governs both thrust and strike-slip faulting. The Sunda megathrust accommodates the dip-slip component of motion, while the Great Sumatran Fault (GSF) accommodates the strike-slip component (Natawidjaja & Triyoso, 2007; Subarya et al., 2006). The GSF extends approximately 1,650 km along the island with a dextral strike-slip mechanism and is segmented into 19 distinct portions, with slip rates ranging from 2-3 cm/yr in the north, 1-2 cm/yr in the central region, and 0.5-1 cm/yr in the south (Prawirodirdjo et al., 2000; Feng et al., 2015).

The active fault system in Sumatra has been responsible for numerous destructive earthquakes. Notable examples include the 2013 Aceh Tengah earthquake (M_w 6.8), the 2017 Pidie Jaya earthquake (M_w 6.6), the 2021 Tarutung earthquake (M_w 6.0), and the 2022 Pasaman earthquake (M_w 6.4) (Triyoso et al., 2020; Irsyam et al., 2020). The 2021 Tarutung earthquake, which occurred near the junction of the Renun and Toru fault systems, highlights the complexity of North Sumatra (Gunawan et al., 2019). These events demonstrate that both the megathrust and strike-slip systems pose significant risks to the region's population.

A particularly intriguing case is the January 15, 2017, Karo-Sibolangit earthquake (M_w 5.6). The earthquake, which struck west of Karo-Sibolangit region, generated ground shaking IV-VI on Modified Mercalli Intensity (MMI) scale, causing damage across Karo-Sibolangit region and as far as Medan. However, the source fault for this earthquake remains unidentified, as the event occurred outside the boundaries of

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mapped fault traces (BMKG, 2017). The anomalous location of this earthquake raises questions about the existence of hidden or unmapped active structures in the region (e.g. Simanjuntak et al., 2023; Adi et al., 2024).

Similarly, the 2022–2023 earthquake swarm in the Samosir region occurred in an off-fault zone, reinforcing the hypothesis that distributed faulting beyond the main GSF system contributes significantly to regional seismicity as shown in Figure 1. Such off-fault seismic activity challenges traditional fault-based seismic hazard models, which often assume that major mapped faults dominate earthquake generation (Irsyam et al., 2017; Muksin et al., 2023). In North Sumatra, the Renun, Toru, and Angkola faults are traditionally recognized as the primary active structures, accounting for approximately 75% of seismicity.

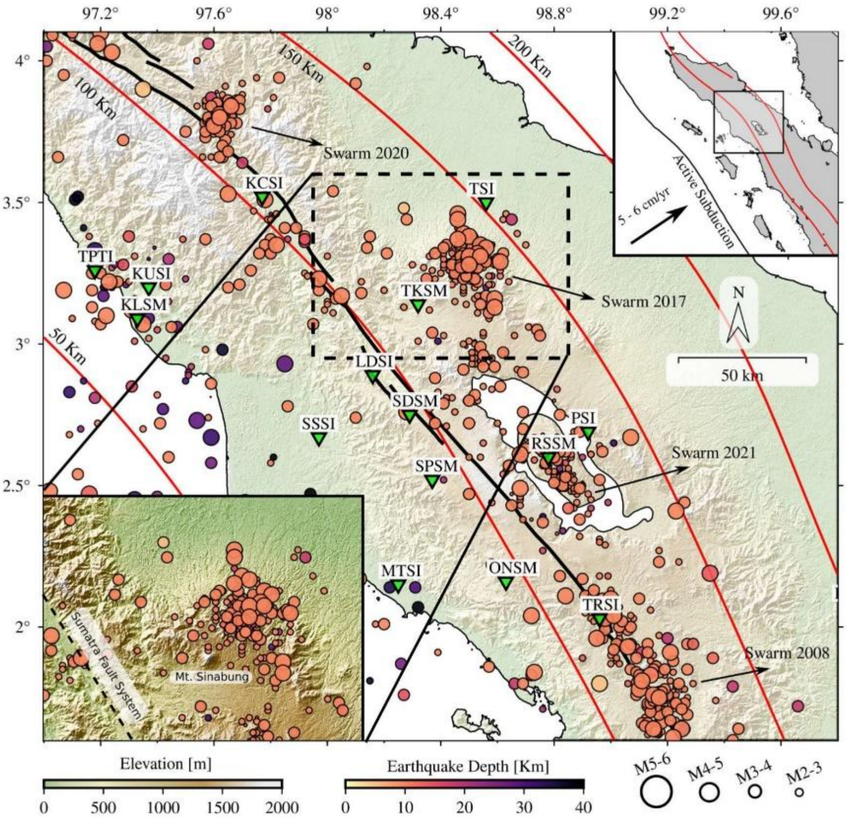

Figure 1. Map shows the seismicity in North Sumatra in the last five years and the distribution of seismic stations across Sumatra Island. The black dashed square depicts the study area in the Karo-Sibolangit area.

Accurate earthquake relocation is critical for resolving such complexities. Conventional earthquake catalogs often contain significant location uncertainties due to limitations in velocity models and station coverage (Shearer, 1997; Hauksson & Shearer, 2005). The double-difference (DD) relocation algorithm (Waldhauser & Ellsworth, 2000) minimizes differential travel-time residuals between event pairs, thereby refining hypocenter distributions at high resolution. This method has been successfully applied in many tectonically active regions to reveal fine-scale seismic clustering and identify subsidiary fault structures (Menke & Schaff, 2004; Waldhauser, 2009).

However, its application to North Sumatra remains limited, especially in off-fault settings. Several studies have successfully applied DD relocation in Indonesia, but most efforts have focused on major subduction or strike-slip systems (Irsyam et al., 2017; Nugraha et al., 2018). In contrast, the application of DD methods to off-fault regions in North Sumatra has been limited. As a result, the structural sources of earthquakes such as the 2017 Karo-Sibolangit earthquake remain critical gaps in hazard assessment.

Without improved hypocenter precision and cluster analysis, the understanding of strain distribution and seismogenic structures in North Sumatra remains incomplete (Waldhauser, 2009; Rubin, 2002). In this study,

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we apply the double-difference relocation method to refine the hypocenter distribution of earthquakes in the Karo-Sibolangit region, North Sumatra. By reducing location uncertainties and identifying specific seismic clusters, we reveal evidence for unmapped or subsidiary active faults. Our results provide new insights into the seismotectonic framework of North Sumatra and offer a scientific basis for strengthening earthquake hazard assessments and mitigation strategies in this high-risk region.

METHODOLOGY

Data Acquisition

Earthquake catalog data were obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) covering seismic events in North Sumatra, with a focus on the Karo-Sibolangit region. The dataset includes both instrumental records of local and regional earthquakes over the past several years, providing the basis for relocation analysis.

Double-Difference Relocation Method

The Double-Difference (DD) method (Waldhauser & Ellsworth, 2000) was employed to achieve high-resolution earthquake hypocenter locations as shown in the Figure 2. This approach minimizes residuals between observed and theoretical travel times of P- and S-waves across pairs of earthquakes recorded at common seismic stations. By incorporating both absolute and differential travel times, the DD method reduces location errors caused by velocity heterogeneities and improves the relative positioning of clustered events.

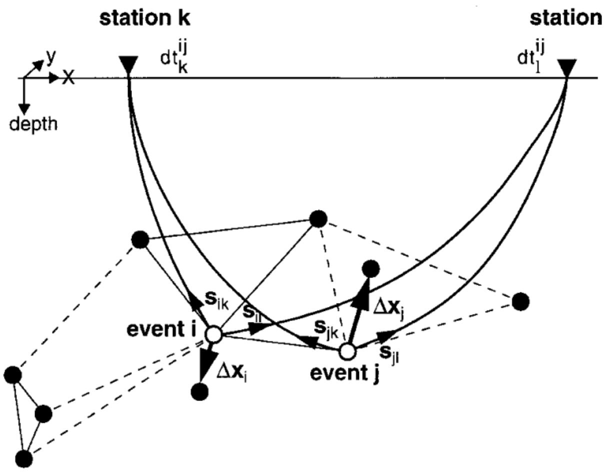

Figure 2. Schematic cartoon of the double-difference algorithm (Waldhauser & Ellsworth, 2000).

The method assumes that earthquakes occurring in close proximity generate nearly identical waveforms at the same stations, thereby constraining hypocenter separation with high precision. The inversion was carried out iteratively until the root-mean-square (RMS) residuals reached a minimum threshold. A statistical resampling technique was applied to estimate data accuracy and location uncertainties. Given the nonlinear relationship between travel time and earthquake hypocenter parameters, a Taylor series expansion was employed, as expressed in Equation (1) (Waldhauser & Ellsworth, 2000):

$$\frac{\partial t_k^i}{\partial \boldsymbol{m}} \Delta \boldsymbol{m}^i = r_k^i \tag{1}$$

$$r_k^i = (t^{obs} - t^{cal})_k^i \tag{2}$$

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The parameter i is the travel time residual for event (i) in station (k), and $\Delta\boldsymbol{m}^i = (\Delta x^i, \Delta y^i, \Delta z^i, \Delta\tau^i)$. Equation (1) and (2) is suitable with single event, while in double difference relocation case on equation (2) and residual calculation as shown in equation (3).

$$\frac{\partial t_k^{ij}}{\partial m}\Delta\boldsymbol{m}^{ij} = dr_k^{ij} \tag{3}$$

$$dr_k^{ij} = (t_k^i - t_k^j)^{obs} - (t_k^i - t_k^j)^{cal} \tag{4}$$

Equation (4) represents the double difference algorithm with partial derivative from travel time t for event i and j with location (x, y, z) and origin time (τ) to calculate the new hypocenter location. The value of dr_k^{ij} is residual from the observation travel time (t_k^{ij}) and calculation from hypocenter group.

RESULTS AND DISCUSSION

Seismicity Characteristics and Magnitude Distribution

The seismic catalog for the Karo-Sibolangit region from 2014 to 2020 reveals distinct temporal and magnitude patterns. Prior to 2017, only sporadic small-to-moderate events were recorded. In January 2017, seismic activity intensified, culminating in the Mw 5.6 Karo-Sibolangit earthquake and subsequent aftershock sequence. The cumulative number of earthquakes increased sharply, reflecting heightened activity concentrated in a localized cluster. Depth distribution analysis shows that most events occurred at shallow crustal levels (5-15 km), consistent with seismogenic processes along brittle fault zones.

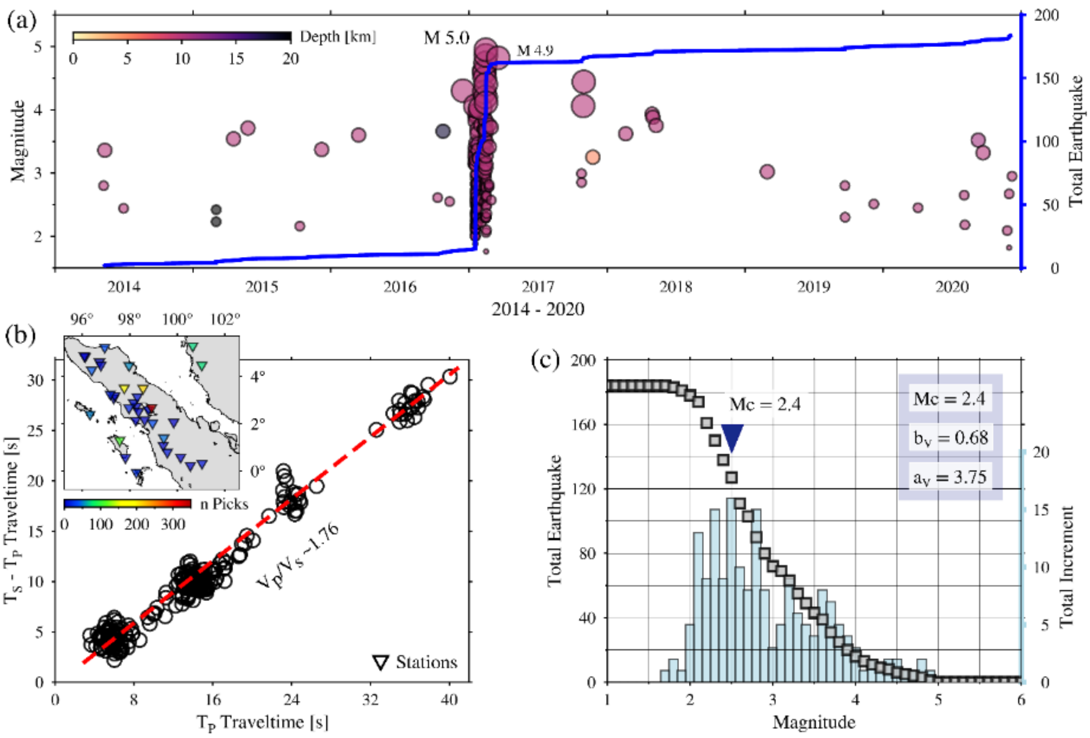

Figure 3. (a) Temporal distribution of earthquakes in the Karo-Sibolangit region (2014-2020). (b) Travel-time relationship between P and S phsae; inset shows station distribution and number of picks. (c) Magnitude-frequency distribution indicating completeness magnitude (Mc = 2.4), b-value (0.68), and a-value (3.75).

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The magnitude–frequency distribution analysis indicates a completeness magnitude (Mc) of 2.4, with a b-value of ~0.68 as shown in Figure 3. This relatively low b-value suggests dominance of larger-magnitude events within the dataset, a feature typically associated with high stress concentration in active fault systems. The distribution also highlights the seismotectonic significance of the Karo-Sibolangit region, where small- to medium-sized earthquakes may act as stress indicators preceding moderate events such as the 2017 mainshock. Furthermore, the travel-time analysis (Ts–Tp versus Tp) yielded a stable Vp/Vs ratio of ~1.76, typical of upper crustal materials in Sumatra. This ratio reflects the regional crustal composition, dominated by volcanic and sedimentary units interspersed with crystalline basement rocks. Consistency in the ratio across multiple events supports the reliability of the relocation dataset.

Data Quality Assessment

Accurate earthquake relocation requires robust velocity modeling. The travel-time inversion conducted here established a regional Vp/Vs ratio of 1.758 ± 0.02, derived from thousands of P- and S-wave arrival pairs as shown in Figure 4. This ratio is consistent with previous studies in northern Sumatra and suggests a predominance of volcanic crust interspersed with fault-controlled sedimentary basins. The travel-time dataset demonstrates high internal consistency, with minimal scatter around the regression line.

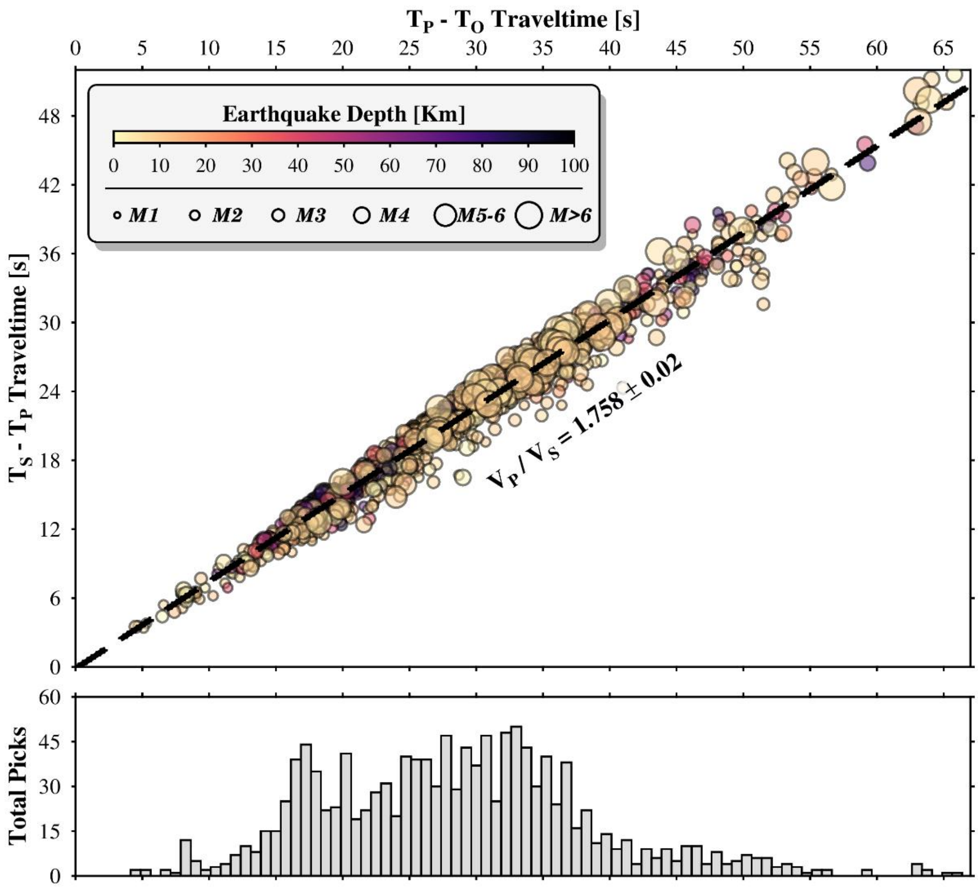

Figure 4. Relationship between P- and S-wave travel times used for velocity calibration. The slope corresponds to a Vp/Vs ratio of 1.758 ± 0.02. Bubble sizes represent earthquake magnitudes, while colors denote focal depth. The lower histogram shows the distribution of total picks across the dataset.

This indicates reliable phase picking and stable crustal velocity structure across the region. The lower panel of Figure 4 shows the frequency distribution of phase picks, highlighting strong data density between 8–30 s of P-wave travel times. The large number of high-quality picks increases confidence in the relocation

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results. In addition, depth-dependent variations were evident. Deeper earthquakes (>50 km) displayed slightly higher Vp/Vs ratios, consistent with higher fluid content or partial melting within the lower crust or upper mantle wedge. However, most Karo-Sibolangit region earthquakes were confined to shallow depths (<20 km), emphasizing their tectonic association with crustal faults rather than subduction processes.

Station Coverage and Network Geometry

The relocation utilized data from the BMKG seismic network, which provides extensive coverage across Sumatra. Figure 3 illustrates the spatial distribution of seismic stations and raypaths between stations and event locations. The network geometry shows dense coverage in North Sumatra, ensuring robust azimuthal distribution for events in the Karo-Sibolangit region as shown in Figure 5. In this study, average azimuthal gaps were less than 80°, indicating sufficient angular coverage for most events. This level of coverage allowed the double-difference algorithm to significantly refine hypocenter locations, reducing average horizontal uncertainties to <2 km and vertical uncertainties to <3 km.

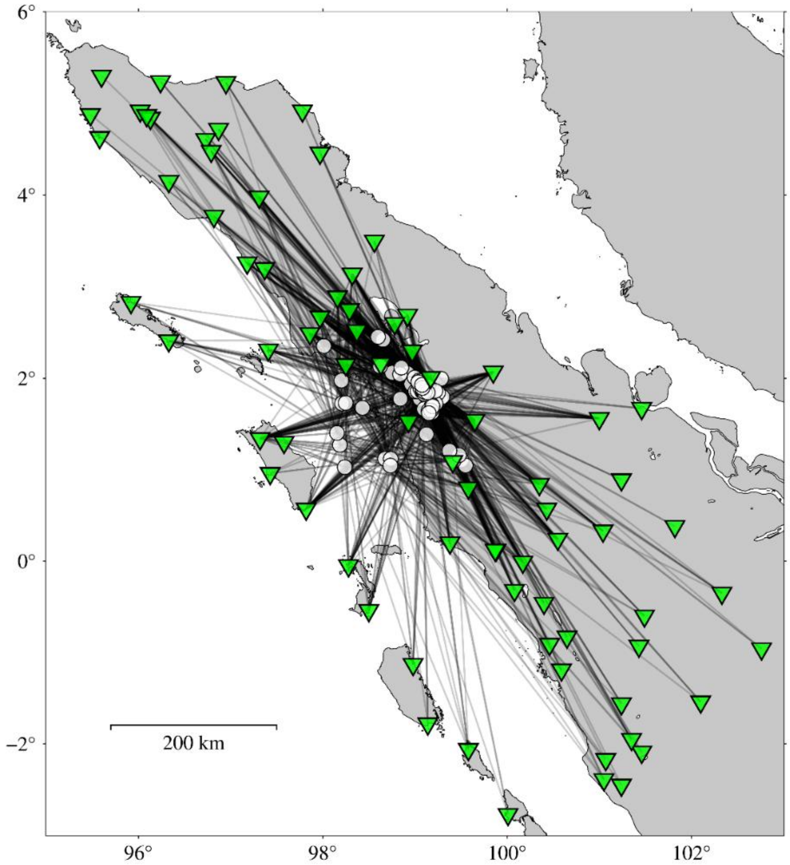

Figure 5. Seismic station distribution in Sumatra (green triangles) and raypaths to relocated earthquakes (white circles). Dense coverage in northern Sumatra provides robust azimuthal geometry for accurate relocation.

Raypath density further indicates high-resolution potential in the central study area. The majority of earthquakes near Karo-Sibolangit were recorded by more than 10 stations, providing redundant phase observations essential for precise relocation. In contrast, peripheral events with sparse station coverage exhibited slightly higher residuals, though still improved relative to the initial catalog.

Relocated Seismicity and Fault Structure Interpretation

A total of 512 earthquakes recorded between 2014 and 2020 were initially extracted from the BMKG earthquake catalog for the Karo-Sibolangit region. After applying quality control criteria based on phase

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completeness, inter-event distance, and station coverage, 436 events (approximately 85% of the original dataset) were successfully relocated using the double-difference (DD) algorithm as provided in the Tabel 1. The relocation was performed using the following inversion parameters: maximum event–station distance (MAXDIST) of 200 km, maximum inter-event separation (MAXSEP) of 10 km, a damping factor of 20, and 10 iterative inversion cycles until convergence was achieved. The effectiveness of the relocation is demonstrated by a substantial reduction in travel-time residuals, with the average RMS decreasing from 0.62 s before relocation to 0.28 s after relocation, corresponding to an RMS reduction of approximately 55%. These results indicate a significant improvement in hypocenter precision and confirm the robustness and reliability of the applied relocation procedure.

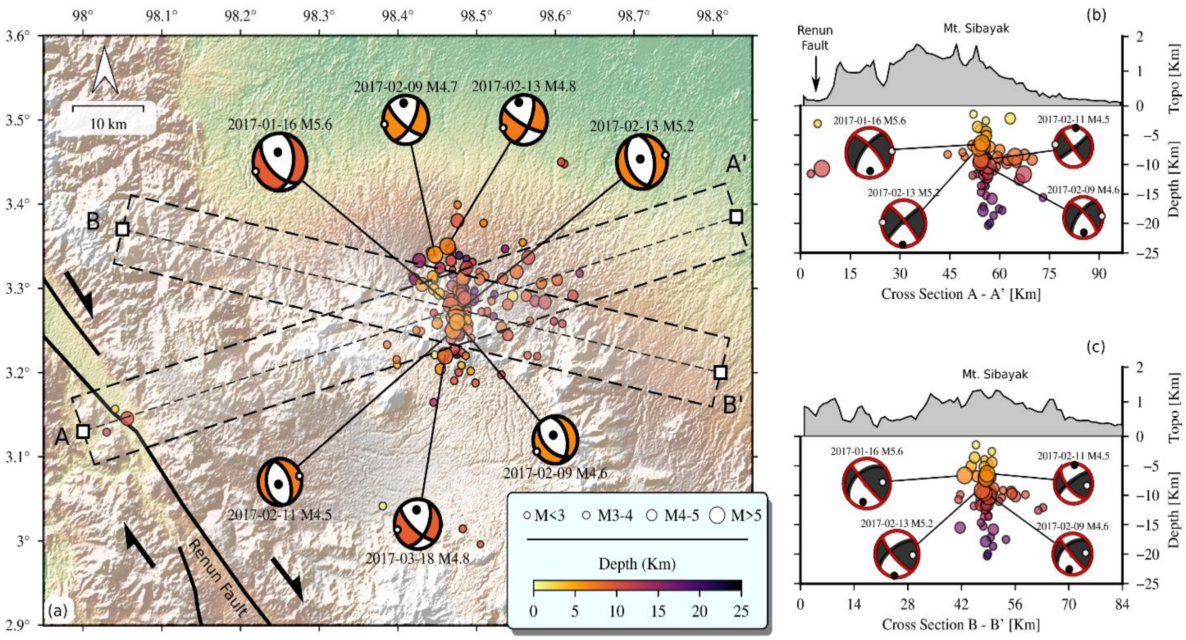

Figure 6. (a) Relocated seismicity of the 2017 Karo-Sibolangit earthquake sequence, showing alignment along an unmapped fault structure. Focal mechanisms indicate predominantly strike-slip faulting. (b, c) Depth cross-sections (A-A' and B-B') highlight clustering of hypocenters between 5-12 km, consistent with crustal faulting.

The double-difference relocation revealed a coherent seismic cluster centered in the Karo-Sibolangit region, corresponding to the 2017 mainshock and aftershocks. Hypocenters align along NW-SE trending structures, parallel to but spatially offset from the Renun Fault. This alignment suggests the presence of a previously unmapped subsidiary fault accommodating dextral shear. Cross-sections through the relocated cluster (A-A' and B-B') indicate hypocentral depths between 5-12 km, confined to the brittle crust. The clustering of aftershocks suggests rupture propagation along a steeply dipping fault plane.

Table 1. Information hypocenter relocation results.

Parameter	Before Relocation	After Relocation
Number of events	512	436
Mean RMS residual (s)	0.62	0.28
Median RMS residual (s)	0.58	0.26
Standard deviation of RMS (s)	0.21	0.12
Average horizontal uncertainty (km)	~5.1	~1.9
Average vertical uncertainty (km)	~6.8	~2.7
Overall RMS reduction (%)	–	~55%

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Focal mechanism solutions confirm predominantly strike-slip motion with minor normal components, consistent with transtensional stress in this region. These findings carry important seismotectonic implications. The 2017 Karo-Sibolangit earthquake sequence occurred in an area not previously considered seismically hazardous, highlighting the potential for damaging earthquakes along hidden faults. Such subsidiary structures may represent strain-transfer zones between major strands of the Great Sumatran Fault. Their recognition is crucial for seismic hazard models, as they expand the distribution of potential earthquake sources beyond known as mapped of active unknown faults.

Comparison with Seismotectonic Studies in Sumatra

Previous studies of the Great Sumatran Fault (GSF) have highlighted its segmentation and capacity to generate destructive earthquakes (Sieh & Natawidjaja, 2000; Natawidjaja & Triyoso, 2007). However, most analyses have focused on primary fault strands such as Renun, Toru, and Angkola. Our relocation results demonstrate that seismic activity in the Karo-Sibolangit region is not confined to these major structures but also occurs along subsidiary, previously unmapped faults. Similar patterns were observed in West Sumatra, where relocation studies identified off-fault clusters near the Angkola segment (Gunawan et al., 2019). This suggests that distributed faulting is a regional phenomenon that contributes significantly to seismic hazard.

Seismicity in Off-Fault Regions

The 2017 Karo-Sibolangit earthquake and its aftershocks resemble other off-fault sequences in Indonesia. For instance, the 2016 Pidie Jaya earthquake in Aceh occurred outside the main GSF trace, yet produced severe damage (Irsyam et al., 2020). Likewise, swarm activity in Samosir during 2022-2023 highlighted the role of hidden faults within the Toba Caldera region. Our findings confirm that off-fault seismicity in North Sumatra is structurally significant and cannot be ignored in hazard assessments. This aligns with observations in Java, where relocation studies revealed shallow off-fault seismic clusters that had been overlooked in national seismic hazard maps (Nugraha et al., 2018; Pasari et al., 2021).

Crustal Velocity Models and Hypocenter Accuracy

The accuracy of earthquake relocation strongly depends on crustal velocity models. Previous works in Java and Bali employed 1-D and 3-D velocity models to reduce travel-time residuals and better constrain seismotectonic interpretations (e.g. Supendi et al., 2020). Our analysis shows that even with a global seismic 1-D model, applying the double-difference method improves hypocentral precision to <3 km. This is consistent with results from Sumatra's western coast, where relocation reduced uncertainties and clarified the geometry of seismic clusters associated with the Mentawai segment (Widiyantoro et al., 2020). Thus, our study demonstrates the robustness of DD relocation in resolving small-scale fault structures despite velocity model limitations.

Seismic Hazard and Mitigation Relevance

National seismic hazard assessments in Indonesia (Irsyam et al., 2017; Irsyam et al., 2020) largely emphasize major mapped faults and subduction zones. However, our results underscore the importance of incorporating subsidiary faults into hazard models. The 2017 Karo-Sibolangit sequence, localized along an unmapped structure, demonstrates the destructive potential of hidden sources. This has direct implications for urban planning in Medan and surrounding districts, where dense populations are exposed to shaking intensities amplified by local site conditions. Our study supports the argument that probabilistic seismic hazard models should be continuously updated with relocated seismicity data to account for newly identified faults (Syafri et al., 2019).

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Toward a Regional Seismic Risk Framework

Beyond scientific contributions, our study offers actionable insights for risk reduction. Earthquake relocation can pinpoint zones of concentrated seismicity that warrant stricter building codes and disaster preparedness measures. Similar efforts have been applied in Yogyakarta after the 2006 Bantul earthquake, where relocation results informed microzonation studies and guided reconstruction policy (Cummins, 2017). In North Sumatra, the recognition of hidden faults near Karo-Sibolangit region strengthens the case for targeted mitigation strategies, particularly in rapidly growing urban centers. Integrating relocation results into local disaster management frameworks can significantly reduce risk in the near future.

CONCLUSION

This study demonstrates that the application of the double-difference relocation method in the Karo-Sibolangit region significantly refines earthquake hypocenter distributions, reducing location uncertainties and revealing clustered seismicity that delineates previously unmapped subsidiary faults. The results indicate that the 2017 Karo-Sibolangit earthquake sequence and associated aftershocks align along a NW-SE fault zone offset from the Renun Fault, suggesting that strain in North Sumatra is accommodated not only by major strands of the Great Sumatran Fault but also by hidden structures. Comparative analysis with other Indonesian studies confirms that off-fault seismicity is a widespread phenomenon that contributes substantially to regional hazard. The identification of such subsidiary active faults has critical implications for seismic hazard modeling and emphasizes the need to incorporate refined relocation results into national hazard maps. By providing a clearer understanding of fault geometry and seismotectonic processes, this study contributes essential knowledge to support earthquake risk mitigation and disaster preparedness in North Sumatra and other tectonically complex regions of Indonesia.

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