

Receiver-Fault Variability and Depth-Dependent Coulomb Stress Changes in the 2019 Mw 7.2 Halmahera Earthquake Sequence

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Manuscript received: 8 September 2025; Received in revised form: 25 April 2026; Accepted: 21 May 2026

Abstract

This study investigates the relationship between fault geometry, Coulomb stress transfer, and aftershock distribution in the Halmahera region after the 2019 Mw 7.2 Halmahera Earthquake. Analysis of focal mechanism solutions reveals two distinct clusters: Cluster 1 is located southwest of the mainshock around Bacan Island and is dominated by normal faulting that suggests local extension, whereas Cluster 2 trends southeast of the mainshock along southern Halmahera and exhibits a mix of strike-slip and normal. Coulomb stress modeling shows that when only the maximum ΔCFS across the depth column is considered, aftershocks appear to occur within positive stress-change zones ($\Delta CFS \geq \sim 0.1$ bar). Evaluation at the actual hypocentral depths reveals that many aftershocks are concentrated within zones of apparent stress-reduction at shallow levels (0–10 km). This observation may be due to mismatches in receiver-fault geometry, spatial heterogeneity in the background stress/strength field, or processes that are not captured by static ΔCFS . By applying a fault-variability approach, we demonstrate that small variations in receiver-fault orientation can substantially alter ΔCFS outcomes and better reproduce the observed aftershock distribution. These results underscore the importance of receiver-fault geometry and segmentation specific to the Halmahera region in interpreting stress transfer.

Keywords: Extensional area; Receiver fault variability; Seismic triggering; Stress shadow; Strike-slip kinematics.

Citation: Wulandari, R., Suhendi, C., & Styawan, Y. (2026). Receiver-Fault Variability and Depth-Dependent Coulomb Stress Changes in the 2019 Mw 7.2 Halmahera Earthquake Sequence. *Jurnal Geoelebes*, 10(2): 145–159, doi: 10.70561/geoelebes.v10i2.47046

Introduction

The Mw 7.2 earthquake that struck south of Halmahera Island, Indonesia, on 14 July 2019 at 09:10:51 UTC (16:10:51 local time, WIB) was one of the most significant seismic events in the North Maluku region (Figure 1 – 2). The seismicity of southern Halmahera is regionally controlled by segments of the nearby fault systems, including the Sorong fault and Sula fault, which extend westward from Papua (Figure 3). Recent high-resolution multibeam bathymetry mapping has defined the detailed strands of the Sorong Fault Zone, including the Molucca-Sorong and

Salawati-Obi segments that trend through the region near Bacan and Halmahera (Watkinson and Hall, 2017). Furthermore, prevailing stress conditions indicate that the northwestern part of Halmahera exhibits significant stress accumulation due to continuous subduction processes, signaling a high potential for large-magnitude earthquakes in this complex tectonic setting (Wajedy et al., 2026). The regional structural context is illustrated in Figure 4b. According to the United States Geological Survey (USGS), the finite-fault solution for this earthquake indicates a left-lateral strike-slip mechanism with a steep fault geometry (strike = 124°, dip = 79°) and

complex rupture characteristics (USGS, 2019). These finite-fault parameters form the structural basis for Coulomb stress change calculations in this study. Tsunami and teleseismic inversion modeling of the

2019 event further suggests that the region is prone to high dip-angle splay faulting, emphasizing its extreme structural complexity (Heidarzadeh et al., 2021).

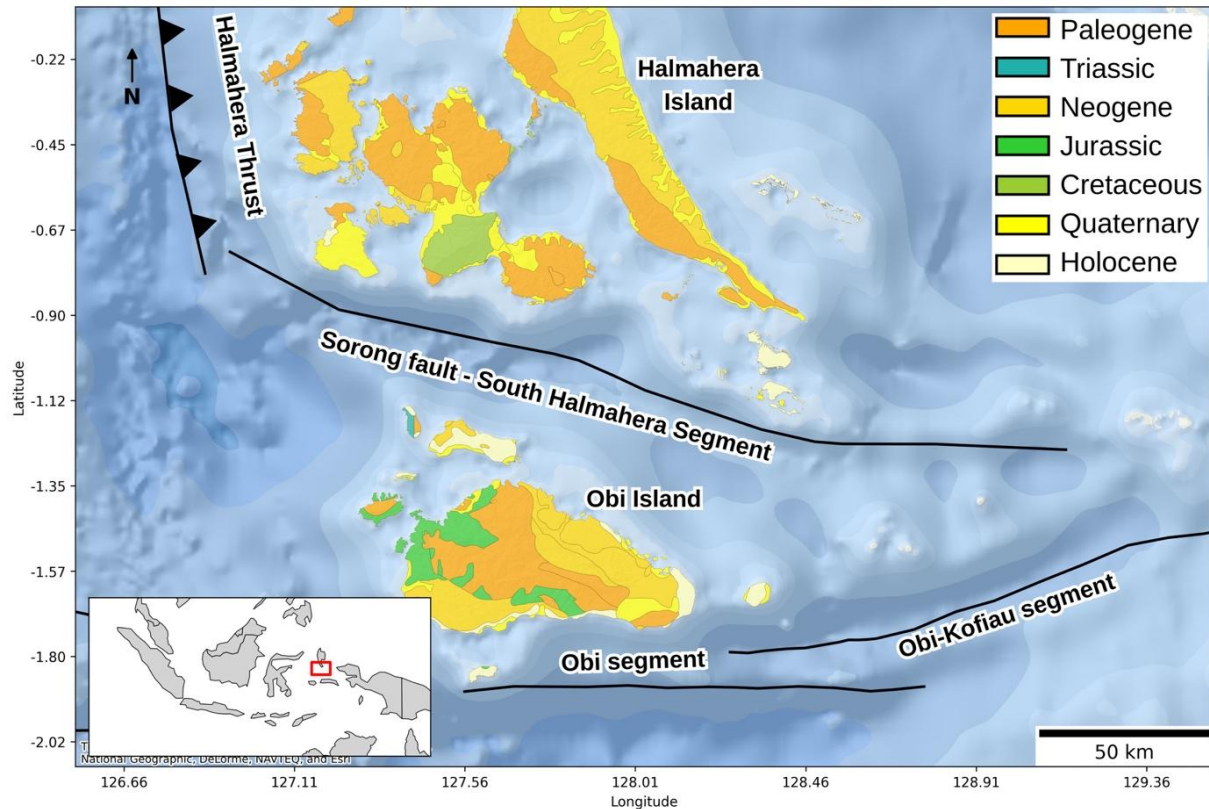


Figure 1. Regional geological map of the Halmahera–Obi area showing the distribution of lithological units by age (Triassic to Holocene) and major tectonic structures, including the Sorong Fault (South Halmahera segment), Obi segment, and Obi–Kofiau segment. The Halmahera Thrust is also identified in the northwestern part of the map. This figure highlights the complex tectonic setting of the region, which plays a significant role in its geological evolution and seismic hazard potential. The inset indicates the location of the study area within Indonesia.

Coulomb stress change analysis has long been used to evaluate static stress transfer between fault segments, which may promote aftershocks or trigger subsequent earthquakes in nearby regions. The core hypothesis posits that a positive value of Coulomb failure stress (ΔCFS) indicates that the earthquake-induced stress changes push the receiver fault closer to rupture (Liu et al., 2023), a mechanism frequently linked to the domino-style triggering of large events on neighboring segments (Altunel et al., 2024). In the Indonesian archipelago, studies have shown that zones of increased Coulomb stress often correlate with aftershock distributions and triggered

events, such as those observed following the 2018 Palu earthquake, the 2006 Yogyakarta earthquake, the Pasaman earthquake 2022, and volcanic-seismic interactions in Halmahera (Supendi et al., 2020; Ramdhan et al., 2025; Wulandari et al., 2023; Sinaga et al., 2021). For example, analysis of the 2023 Türkiye earthquake doublet demonstrated that over 81% of aftershocks occurred in regions of increased Coulomb stress (Dai et al., 2024). However, this correlation is not always consistent: aftershocks have also been observed in areas of low or even negative stress change (Hardebeck & Harris, 2022), which is commonly attributed to

heterogeneity in the background stress field or variations in fault orientation. High-resolution remote sensing studies of recent megathrust and crustal events, such as the optical satellite mapping of co-seismic surface ruptures in the 2023 Türkiye earthquakes by Provost et al. (2024), empirically confirm that actual fault zones exhibit massive geometric complexity, sub-

parallel splays, and variable rupture widths that static models often oversimplify. In the complex submarine terrain of the Molucca Sea and Halmahera, such geometric heterogeneity is highly likely yet inherently obscured, providing a plausible mechanism for why uniform stress models fail to capture localized triggering

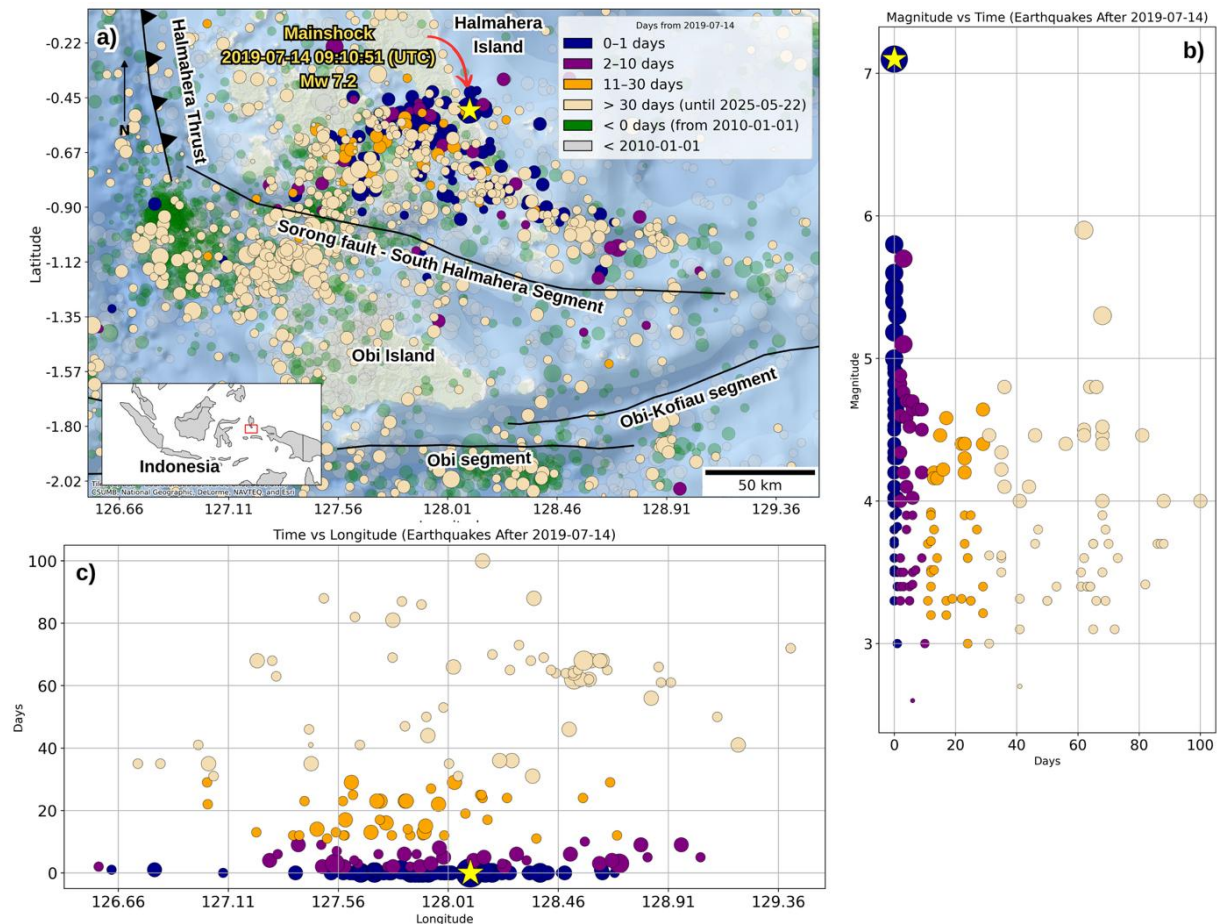


Figure 2. (a) Seismicity in the southern Halmahera region and surrounding areas from the ISC catalog (April 22, 1925 – May 22, 2025). The mainshock location (yellow star) is based on the NEIC preliminary solution, also adopted as the reference for the USGS Finite Fault Solution. (b) Magnitude distribution of aftershocks as a function of time within 100 days. (c) Longitude distribution of aftershocks as a function of time within 100 days.

Despite the importance of the 2019 Halmahera earthquake, no comprehensive study has been conducted to investigate the stress transferred from the earthquake event and its correlation with aftershock distribution in this region. In the context of active Indonesian faults, similar anomalies have been recorded; for instance, post-seismic analysis of the 2016 Mw 6.5 Pidie Jaya earthquake revealed that while stress

increases triggered subsequent events on previously unmapped sinistral faults, numerous aftershocks still occurred within theoretical stress shadow areas (Muzli et al., 2018; Kusumawati et al., 2019). Preliminary seismicity analyses suggest that aftershocks cluster in the north of the South Halmahera segment, part of the Sorong Fault system, and do not extend linearly to the NNW but rather propagate to

the SSW. This pattern may indicate a complex tectonic setting in the region, including the possible involvement of secondary fault structures (Figure 1). Although similar Coulomb stress transfer approaches have been extensively applied in other tectonically active regions (e.g., Siwi et al., 2020; Souisa & Sapulete, 2021; Liu et al., 2023; Dai et al., 2024), no comprehensive analysis has yet addressed the Halmahera region, where detailed assessment of fault interactions and depth-dependent stress changes remains lacking. These observations highlight the need to investigate the spatial relationship between Coulomb stress changes and aftershock occurrence in this tectonically complex region.

This study addresses this gap by utilizing the USGS finite fault model (Figure 4c), to calculate Coulomb stress changes at several key depths using the formulation of Reasenberg & Simpson (1992). By integrating these calculations with aftershock data, the study aims to quantify stress transfer patterns and evaluate their correlation with the aftershock distribution and nearby fault segments. The overarching goal is to provide new insights into fault interactions and aftershock triggering mechanisms associated with the 2019 Mw 7.2 Halmahera earthquake, thereby contributing to a broader understanding of seismic hazard in the North Maluku region.

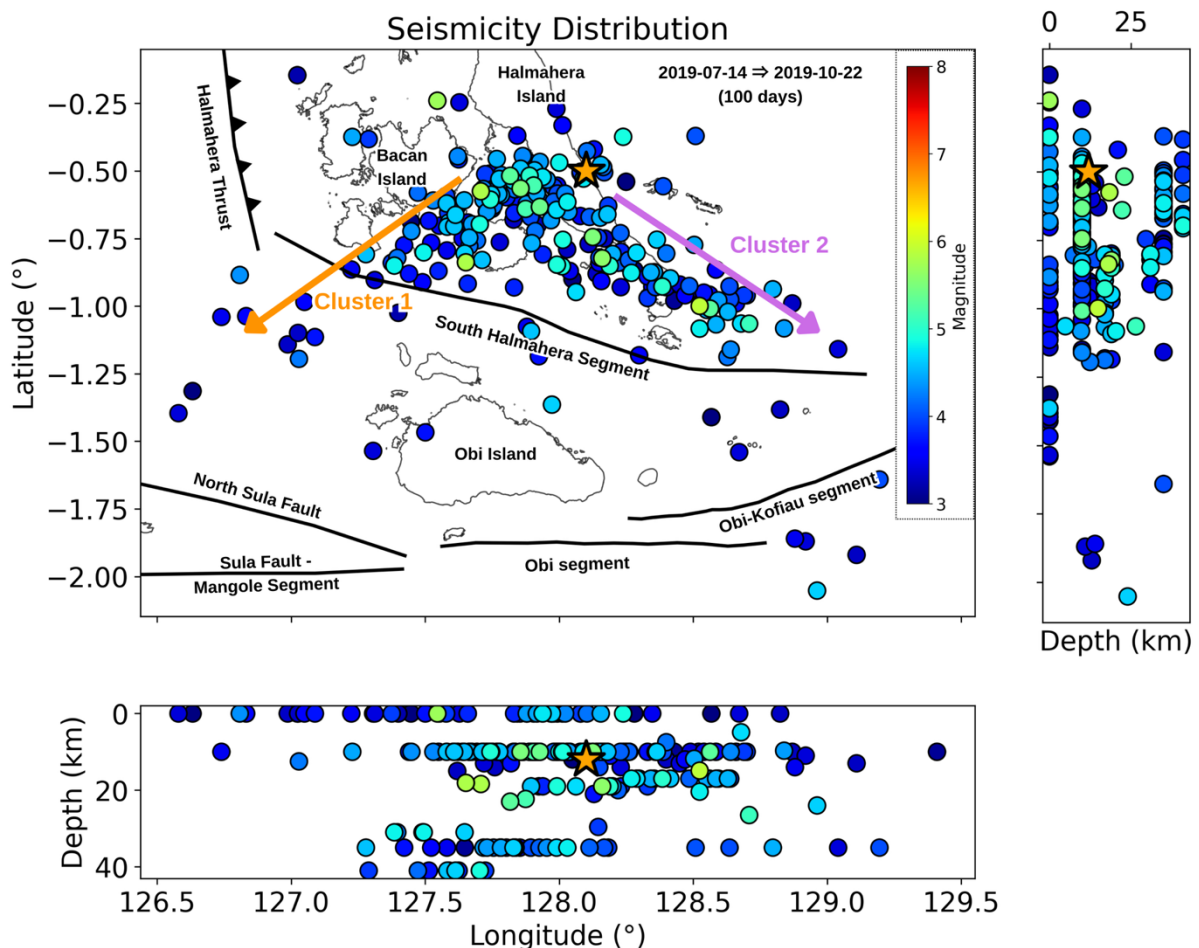


Figure 3. Spatial and depth distribution of seismicity between July 4, 2019 and October 22, 2019 (100 days). The aftershocks extend in two directions, toward the southwest (Cluster 1) and southeast (Cluster 2) from the mainshock.

Materials and Methods

The seismicity data used in this study were obtained from the International Seismological Centre (ISC) catalog (International Seismological Centre, 2026; Storchak et al., 2020), covering the period from 22 April 1925 to 22 May 2025 (Figure 2). For the purpose of Coulomb stress change and aftershock analyses, the dataset was restricted to a 100-day time window following the mainshock, spanning from 4 July 2019 to 22 October 2019 (Figure 3). During this period, seismicity rates were high within the first 10 days after the mainshock, characterized by rapid magnitude releases, and events with magnitudes up to 6 surprisingly occurred after 60 days. This restriction allows for a

focused examination of aftershock activity that is most likely influenced by the static stress perturbations of the mainshock. To decipher the kinematics and orientation of the fault planes driving the Halmahera sequence, complementary focal mechanism data were systematically compiled from the focal mechanism catalog managed by the International Seismological Centre (International Seismological Centre, 2026; Lentas et al., 2019) up to the year 2024 (Figure 4a,b). This repository aggregates diverse moment tensor inversion solutions, including datasets from the Global Centroid Moment Tensor (GCMT) project, providing the high-fidelity structural parameters necessary to construct the ternary diagram analysis.

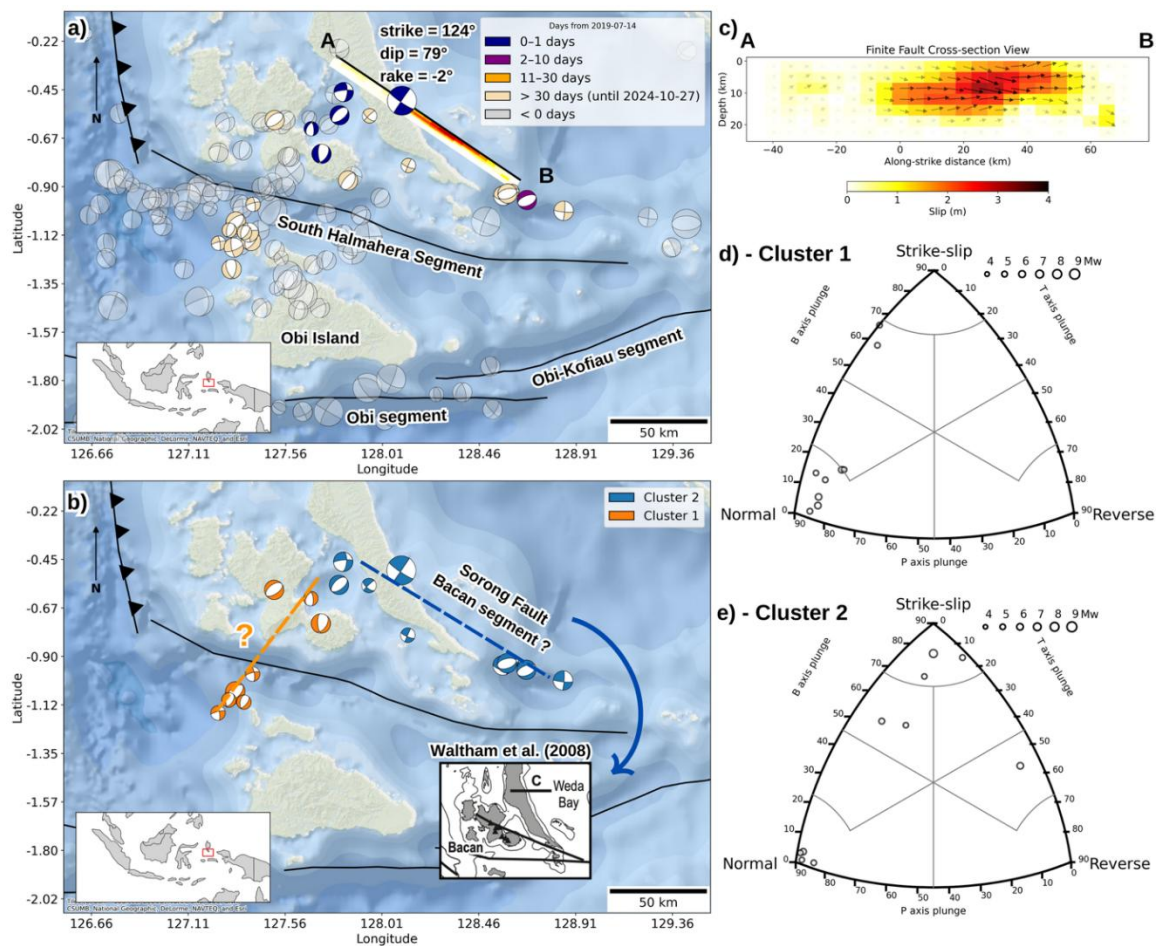


Figure 4. (a) Focal mechanism distribution from available ISC solutions. (b) Focal mechanisms within 100 days of the mainshock, showing two trends, one of which (southeastward) may correspond to the Bacan segment. (c) Slip distribution and orientation from the USGS Finite Fault Solution, with fault location indicated in panel (a) (USGS, 2019). (d–e) Ternary diagrams of focal mechanism types for Cluster 1 and Cluster 2 obtained using FMC (Álvarez-Gómez, 2019), with cluster locations shown in panel (b). Cluster 1 is dominated by normal faulting, whereas Cluster 2 comprises strike-slip and normal faulting events.

For Coulomb stress change calculations, we adopted the finite-fault solution provided by the USGS (2019), which specifies a left-lateral strike-slip mechanism with strike 124° , dip 79° , and rake -2° (Figure 4a,c). These parameters served as the source input for stress transfer modeling in this study.

Information on active fault segments was derived from the 2017 Indonesian Earthquake Source and Hazard Map compiled by Pusat Studi Gempa Nasional (PuSGeN, 2017) (Figure 2). The South Halmahera segment is the closest fault to the mainshock, followed sequentially by the Obi, Obi–Kofiau, North Kofiau, Sagewin, and Dampier segments, all of which are part of the broader Sorong Fault System that dominates the tectonic framework of the region. In addition, the North Sula and Mangole segments, which belong to the Sula Fault, are also present in the surrounding area, underscoring the structural complexity of this tectonic setting.

To begin with, seismic event data were restricted to the maximum depth of 50 km to ensure the analysis focused on shallow

crustal earthquakes. The ISC catalog provides multiple magnitude types for each event; therefore, a magnitude priority scheme was applied, giving preference to Mw, followed by Ms, Ml, and Mb, respectively. This hierarchy was determined based on the reliability of the magnitude type (e.g., degree of saturation). In terms of availability, the majority of magnitudes were reported as MLv, Ms, Mb, Ml, and Mw. The primary contributors were DJA for MLv, IDC for Mb and Ml, and GCMT for Mw, with additional data provided by NEIC, EIDC, and others. To ensure consistency, all magnitudes were converted to Mw using the equations from PuSGeN (2017) shown on Table 1. In these equations, Ml/ MLv was treated as directly equivalent to Mw, as the empirical analysis in the PuSGeN study showed that both magnitude scales exhibit a near-linear relationship with $R^2 = 0.85$. Nevertheless, this assumption may introduce regional uncertainties and could be refined in future studies through updated magnitude calibration analyses specific in the research location. After processing, a total of 3,261 earthquake events were retained.

Table 1. Equations of magnitude type conversion used in this study (PuSGeN, 2017).

Magnitude type	Valid Range	Conversion equation to Mw
mB	$mB \leq 8.2$	$Mw = 1.0107 \times mB + 0.0801$
MS	$MS \leq 6.1$	$Mw = 0.6016 \times MS + 2.476$
MS	$MS \geq 6.2$	$Mw = 0.9239 \times MS + 0.5671$
MLv	All values	$Mw = MLv$ (assumed equivalent)
ML	All values	$Mw = ML$ (assumed equivalent)

Focal mechanism data were primarily obtained from the Global CMT (GCMT) solutions as distributed through the ISC database (Ekström et al., 2012). When GCMT solutions were unavailable, alternative sources were considered. For the mainshock, we adopted the mechanism provided in the USGS finite-fault model, which is based on the NEIC solution (USGS, 2019), to ensure consistency between the mainshock source parameters and the stress modeling framework. The aftershock sequence within 100 days

following the mainshock was analyzed to determine the dominant faulting style. This analysis was conducted using the ternary diagram approach of Álvarez-Gómez (2019), which classifies earthquake focal mechanisms into relative proportions of strike-slip, normal, and reverse faulting. Based on this approach, the events were grouped into two main clusters, corresponding to the Bacan segment and a second area hypothesized to represent an unrecognized fault structure (Figure 4).

The static Coulomb stress change was calculated using the finite-fault model published by the USGS. The computation was performed within the spatial bounds of longitude 125.0931° – 131.0931° and latitude -3.529° – -2.471° , with a grid spacing of 6.67 km. Elastic parameters included a Poisson's ratio of 0.25, Young's modulus of 8×10^5 bar (≈ 80 GPa), and a friction coefficient of 0.4. These values are widely adopted in Coulomb stress modeling as representative of average crustal conditions: a Poisson's ratio of ~ 0.25 reflects typical elastic behavior of crystalline and consolidated sedimentary rocks (Gercek, 2007), a Young's modulus of ~ 80 GPa corresponds to the upper–mid crustal lithologies (Durkin et al., 2019), and a friction coefficient of ~ 0.4 falls within the broader range of $\mu = 0.25$ – 0.80 reported for natural fault zones, reflecting the strength heterogeneity observed in fault rocks (Smith & Faulkner, 2010). Together, these parameters provide a simplified yet realistic approximation for evaluating static stress transfer in the study area. The finite-fault model corresponds to a seismic moment of 6.5×10^{26} dyne·cm, equivalent to a moment magnitude (Mw) of 7.14. The receiver fault geometry was initially defined to be the same as that of the mainshock, consistent with the finite-fault solution reported by the USGS (2019). This assumption was adopted because detailed geological or focal mechanism constraints for individual aftershocks are not available for the study area. While this simplification provides a first-order approximation of the regional stress transfer pattern, it may not fully capture local variations in fault orientation or segmentation. These limitations are further addressed by applying a fault-variability approach in the subsequent analysis. Stress changes were evaluated over a depth range of 0–30 km at 2 km intervals, and the maximum Coulomb stress value was extracted for each grid point. We employed Coulomb 3.4 software, an updated version of 3.3 (Toda et al., 2011) to calculate Coulomb stress change. The

Coulomb failure stress change is calculated using the following equation (Toda et al., 2011):

$$\Delta CFS = \Delta\tau + \mu'\Delta\sigma_n \quad (1)$$

Where:

$\Delta\tau$ = shear stress change on the receiver fault in the slip direction,

$\Delta\sigma_n$ = normal stress change (positive for unclamping),

μ' = effective friction coefficient.

In addition, Coulomb stress changes were evaluated on nearby fault segments by discretizing each segment into smaller receiver elements (hereafter referred to as subfaults). In contemporary finite-fault modeling, the term subfault refers to a discretized fault patch with its own slip amplitude, used to reconstruct complex rupture distributions within active fault systems (Supendi et al., 2023). In this study, however, the term is used more generally to describe the subdivision of larger receiver-fault segments into smaller geometric elements in order to resolve spatial variations in stress changes along the fault. Each subfault was assigned a geometry consistent with left-lateral strike-slip motion, represented by a dip of 90° and rake of 0° . This uniform assumption provides a simplified reference for evaluating regional stress transfer, although local variations in dip and rake may exist and could influence detailed stress patterns. Such variability is beyond the scope of this study but may be explored in future work. As in the main calculation, depths were evaluated from 0–30 km at 2 km intervals, and the maximum ΔCFS value was assigned to each subfault.

Focal mechanism data of aftershocks were used to compute Coulomb stress changes by incorporating the strike, dip, rake, and focal depth of each event. Because it is generally uncertain which nodal plane represents the true fault plane, both nodal planes were evaluated. For classification,

the plane with the smaller strike value was assigned as nodal plane 1, while the other was treated as nodal plane 2.

For aftershocks lacking focal mechanism solutions, a fault-variability approach was employed. In this method, each earthquake was assigned 1,500 random fault geometries, generated with a standard deviation of 30° around the mainshock orientation (Sharma et al., 2020). For each event, the geometry with Coulomb stress change ≥ 0.1 bar was selected as the preferred solution; if no such geometry existed, the configuration with the highest Coulomb stress was chosen instead. The resulting solutions were divided into two clusters and analyzed using ternary diagrams. To further visualize faulting patterns, composite focal mechanism plots (beachballs) were generated for each cluster, highlighting the dominant strike orientations of the aftershock population.

Results and Discussion

Figure 3 and 4b illustrates the contrasting aftershocks and their focal mechanism patterns observed in the two main clusters. Cluster 2, which is interpreted as the Bacan segment and is likely associated with a splay fault system, is dominated by strike-slip and normal mechanisms (Figure 4e). In contrast, Cluster 1, which may represent a newly developed and previously unidentified structure, exhibits dominantly normal faulting (Figure 4d). The occurrence of normal faulting suggests that this area is undergoing extensional deformation, possibly driven by opposing strike-slip faults at its boundaries. This tectonic environment is consistent with the complex zones of distributed crustal deformation and the reactivation of unidentified secondary fault systems documented in northern Sumatra (Muzli et al., 2018). Nonetheless, further investigation is required to validate this interpretation.

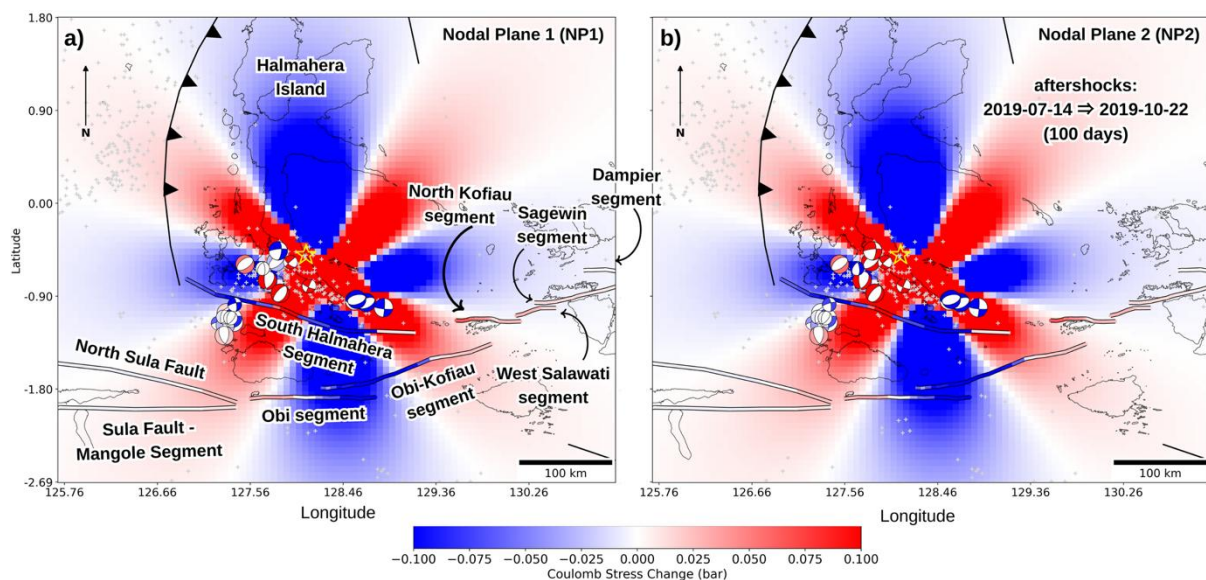


Figure 5. Spatial distribution of maximum Coulomb stress change (0–30 km depth, 2 km intervals) for receiver faults with the same geometry as the source fault. Coulomb stress changes are shown for focal mechanisms in Figure 4b, comparing (a) Nodal Plane 1 and (b) Nodal Plane 2. Nodal Plane 1 exhibits a smaller strike angle than Nodal Plane 2. Grey dots represent aftershock locations (Figure 3). Fault segments also show stress change values consistent with their geometry (strike from subfault orientation, dip = 90° , rake = 0°).

According to Wu et al. (2017), a Coulomb stress change of approximately 0.1 bar can be sufficient to trigger aftershocks. As

shown in Figure 5a-b, regions with positive Coulomb stress change generally coincide with the aftershock distribution. However,

many of the surrounding faults are associated with negative Coulomb stress changes. These negative changes were consistent with the depth-variant stress change on the faults (0-30 km) (Figure 6a-d). These include the nearby South Halmahera segment, most of the Obi segment, and the Obi-Kofiau segment. Although slight stress increases are observed along parts of the North Kofiau

segment, the western Obi segment, and the central portion of the South Halmahera segment, these faults did not host significant aftershock activity (Figure 3). Depth variations further confirm this pattern, as demonstrated in Figure 6a-d, reinforcing the idea that the mainshock did not substantially trigger the adjacent fault systems.

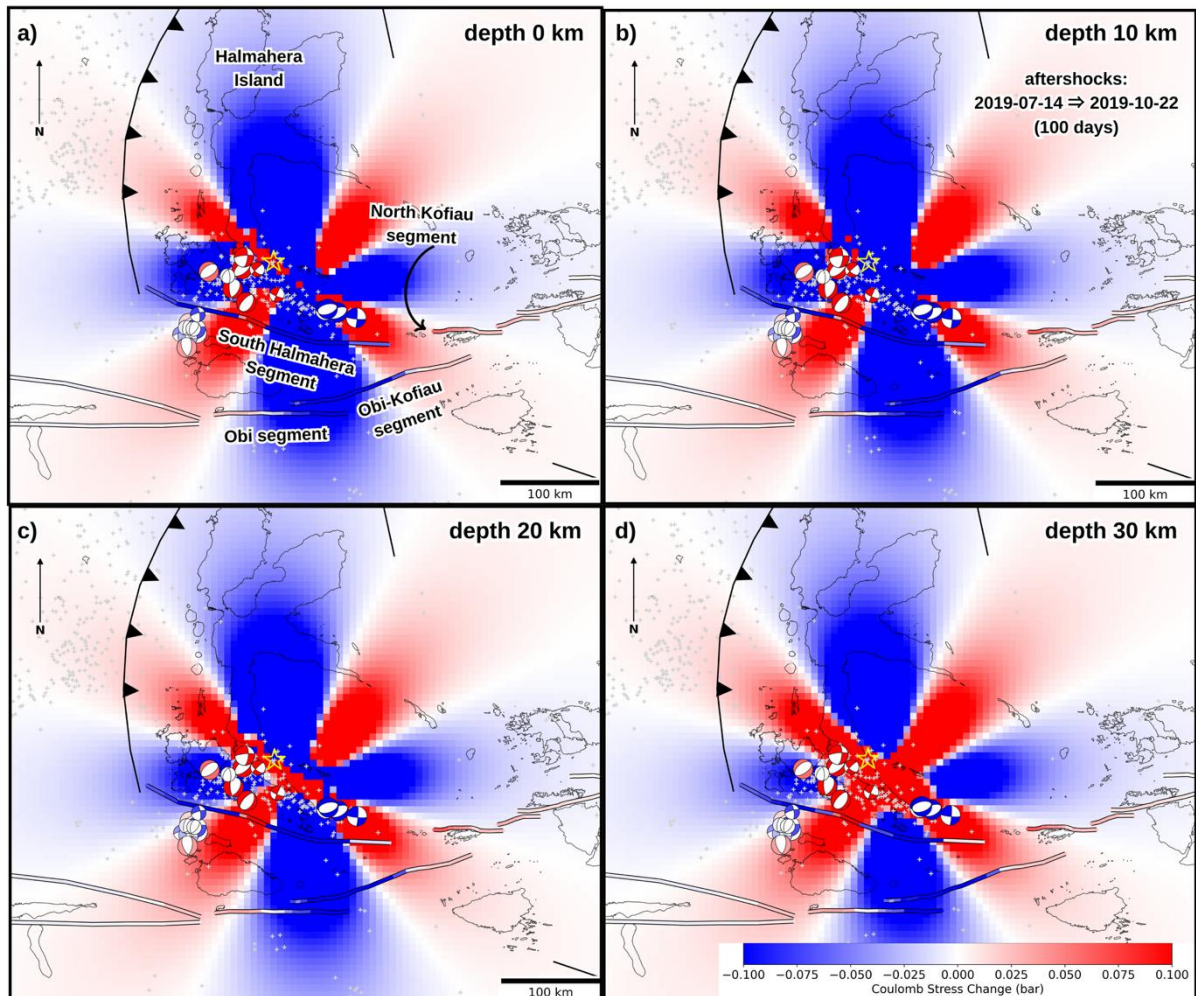


Figure 6. Spatial distribution of Coulomb stress change at depths of (a) 0 km, (b) 10 km, (c) 20 km, and (d) 30 km. Similar stress based on depths are observed in the fault segment closest to the mainshock. The nodal planes shown are selected based on the larger Coulomb stress change value.

The focal mechanisms of aftershocks shown in Figure 5 also reveal intriguing behavior. In the southeastern part of the study area, three aftershocks consistently situated at stress decreases, in contrast with the northwestern and southwestern regions where the distribution of focal mechanisms varies with nodal plane geometry but is

predominantly associated with positive stress changes. This contrast may be linked to differences in local stress orientation and fault plane compatibility with the imposed stress field, suggesting a spatially heterogeneous stress transfer process. The spatially heterogeneous stress transfer documented here aligns with observations

from the contemporaneous 2019 Ambon sequence, where stress redistribution effectively promoted seismicity on specific fault strands with varying source mechanisms (Rohadi et al., 2021). This complexity is consistent with high-resolution satellite observations of recent major strike-slip events, which demonstrate

that rupture zones are not simple linear traces but often consist of multiple sub-parallel strands and diffuse deformation regions. Such physical heterogeneity likely drives the localized variations in stress orientation observed in the Halmahera sequence.

Table 2. Comparison of Coulomb stress change results using identical fault parameters and the fault variability approach in the aftershocks (14/7/2019 – 22/10/2019).

Metric	Same Fault Parameters (N)	Same Fault Parameters (%)	Fault Variability Approach (N)	Fault Variability Approach (%)
Positive Coulomb events	56	23.43	232	97.07
Negative Coulomb events	183	76.57	7	2.93
Total events	239	100.00	239	100.00
Events with $M_w \geq 5.0$	17	7.11	17	7.11
Positive Coulomb events with $M_w \geq 5.0$	3	17.65	17	100.00
Negative Coulomb events with $M_w \geq 5.0$	14	82.35	0	0.00

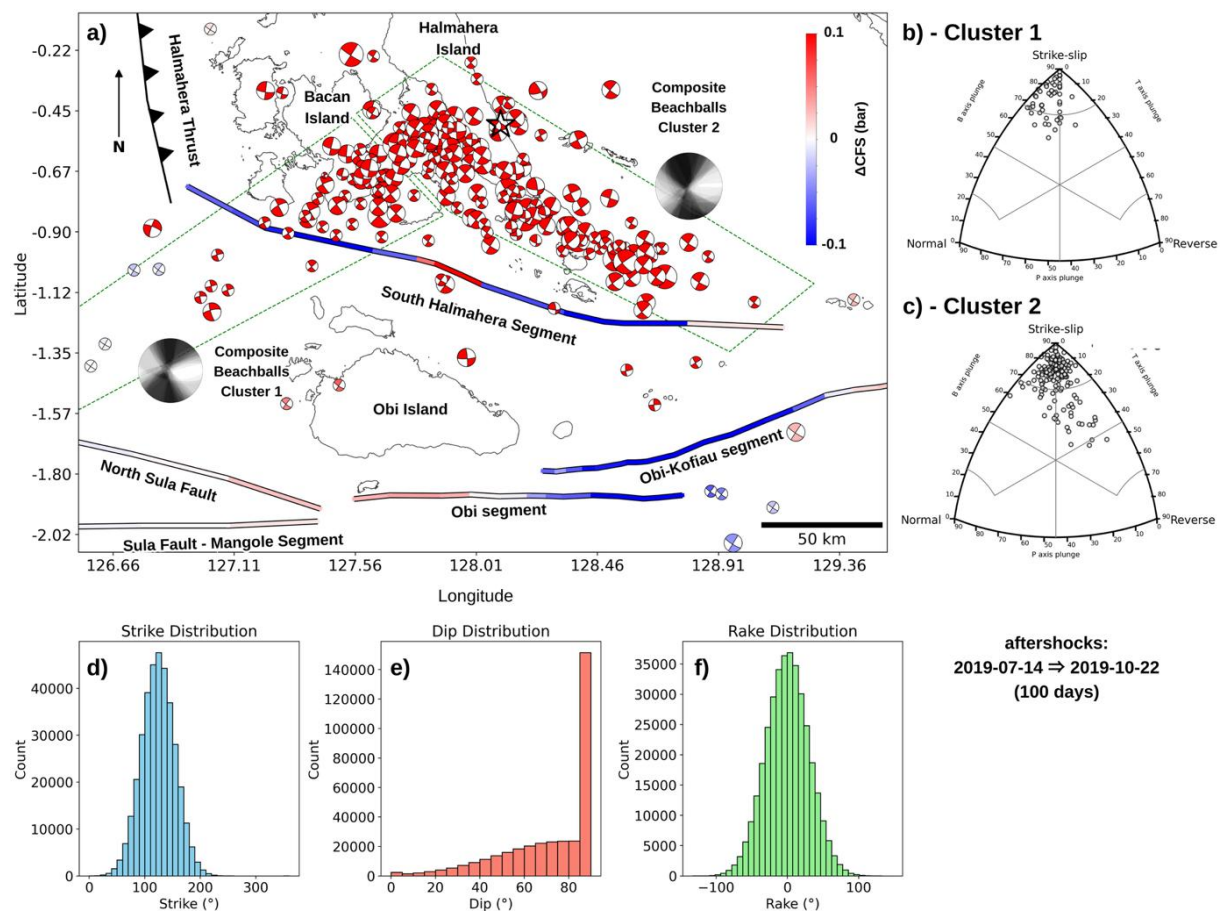


Figure 7. Coulomb stress change distribution for aftershocks using the Fault Variability approach with a normal distribution and 30° standard deviation of the mainshock geometry. (a) Aftershock fault geometries selected based on proximity to the mainshock geometry and showing positive stress changes ≥ 0.1 bar, or alternatively the geometry with the maximum stress change. (b–c) Ternary diagrams of focal mechanism distributions for Cluster 1 and Cluster 2 dominated by strike-slip faulting. Each cluster has a composite of the beachballs in panel (a). (d–f) Strike, dip, and rake distributions for 1500 random geometries of each aftershock, giving a total of 1500 multiplied by the number of aftershocks (within 100 days of the mainshock).

The apparent correlation between aftershock occurrence and regions of increased stress in Figure 5 requires further examination when depth distribution is taken into account. As illustrated in Figure 6, the depth range of 0–10 km is characterized by a reduction in Coulomb stress, yet most aftershocks occurred within this shallow interval (Figure 3). This observation raises the question of whether the aftershock zone corresponds to a shadow stress region. A definitive conclusion cannot be made, since the dominant fault orientations are not well constrained. It indicates further study that focus on the characterization of the complex tectonic in this region is important. The presence of numerous aftershocks in the shallow interval (0–10 km), despite a modeled reduction in Coulomb stress, may be explained by the findings of Provost et al. (2024), who documented that real-world fault zones exhibit an average width of 1 km with a standard deviation of up to 2.5 km. This suggests that localized zone widening or the existence of secondary splays at shallow depths, which are often oversimplified in uniform planar models, could shift these events into positive stress-change environments.

However, one way to address this limitation, we applied a fault variability approach that incorporates uncertainty by assuming aftershocks occur in areas of potential positive stress change shown in Table 2. The results, presented in Figure 7, demonstrate that even minor variations in fault orientation can shift the stress outcome from negative to positive. This is clearly depicted in the ternary diagram, where strike-slip mechanisms dominate, and the composite beachball solutions suggest fault geometries broadly consistent with that of the mainshock. These findings underscore the importance of incorporating receiver fault geometry in Coulomb stress analyses to avoid misinterpretations that place aftershocks in apparent stress shadow

regions. Nonetheless, this approach also has limitations, particularly in cases where independent evidence for shadow stress effects may exist.

Conclusion

The results of this study highlight the complex interaction between fault geometry, stress transfer, and aftershock distribution in the investigated region. The different focal mechanisms observed in the two clusters suggest the coexistence of strike-slip and normal faulting processes, might indicate local extensional regimes possibly driven by surrounding strike-slip faulting activities.

Coulomb stress analysis further reveals that aftershock occurrence is not always consistent with maximum positive stress changes. This emphasizes the limitations of assuming a uniform receiver fault geometry. By applying the fault variability approach, we demonstrate that the proportion of aftershocks falling within positive stress zones ($\Delta CFS \geq 0.1$ bar) increased significantly from 23.43% to 97.07%. These findings underscore the importance of considering geometric uncertainty to avoid misleading interpretations, such as placing aftershocks in apparent stress shadow regions.

However, this study has limitations, as it primarily investigates static stress changes. We do not account for dynamic stress triggering or postseismic effects, which may also influence aftershock distribution. Despite these limitations, our results provide vital insights for improving seismic hazard assessments in Halmahera. Understanding these localized stress interactions is essential for better predicting future fault ruptures and mitigating earthquake risks in North Maluku.

Acknowledgements

The authors would like to thank the editor and reviewers of *Jurnal Gecelebes* for their valuable comments and constructive suggestions that greatly improved this manuscript.

Author Contribution

Rizki Wulandari conducted the data processing, analysis, and manuscript drafting; Cahli Suhendi supervised the research design, provided critical revisions, and coordinated the submission process; while Yudha Styawan contributed to the interpretation of results and refinement of the discussion.

Conflict of Interest

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

References

- Altunel, E., Kozacı, Ö., Yıldırım, C., Sbeinati, R. M., & Meghraoui, M. (2024). Potential domino effect of the 2023 Kahramanmaraş earthquake on the centuries-long seismic quiescence of the Dead Sea fault: Inferences from the North Anatolian fault. *Scientific Reports*, 14(1), 15440. <https://doi.org/10.1038/s41598-024-65906-4>
- Álvarez-Gómez, J. A. (2019). FMC—Earthquake focal mechanisms data management, cluster and classification. *SoftwareX*, 9, 299–307. <https://doi.org/10.1016/j.softx.2019.03.008>
- Dai, X., Liu, X., Liu, R., Song, M., Zhu, G., Chang, X., & Guo, J. (2024). Coseismic Slip Distribution and Coulomb Stress Change of the 2023 MW 7.8 Pazarcik and MW 7.5 Elbistan Earthquakes in Turkey. *Remote Sensing*, 16(2), 240. <https://doi.org/10.3390/rs16020240>
- Durkin, W., Kachuck, S., & Pritchard, M. (2019). The Importance of the Inelastic and Elastic Structures of the Crust in Constraining Glacial Density, Mass Change, and Isostatic Adjustment From Geodetic Observations in Southeast Alaska. *Journal of Geophysical Research: Solid Earth*, 124(1), 1106–1119. <https://doi.org/10.1029/2018JB016399>
- Ekström, G., Nettles, M., & Dziewoński, A. M. (2012). The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors*, 200–201, 1–9. <https://doi.org/10.1016/j.pepi.2012.04.002>
- Gercek, H. (2007). Poisson’s ratio values for rocks. *International Journal of Rock Mechanics and Mining Sciences*, 44(1), 1–13. <https://doi.org/10.1016/j.ijrmms.2006.04.011>
- Hardebeck, J. L., & Harris, R. A. (2022). Earthquakes in the shadows: Why aftershocks occur at surprising locations. *The Seismic Record*, 2(3), 207–216. <https://doi.org/10.1785/0320220023>
- Heidarzadeh, M., Ishibe, T., Harada, T., Natawidjaja, D. H., Pranantyo, I. R., & Widyantoro, B. T. (2021). High potential for splay faulting in the Molucca Sea, Indonesia: November 2019 Mw 7.2 earthquake and tsunami. *Geophysical Research Letters*, 48(10), e2020GL083989. <https://doi.org/10.1029/2020GL083989>
- International Seismological Centre. (2026). *On-line Bulletin*. <https://doi.org/10.31905/D808B830>
- Kusumawati, D., Sahara, D. P., Nugraha, A. D., & Puspito, N. T. (2019). Sensitivity of static Coulomb stress change in relation to source fault geometry and regional stress magnitude: case study of the 2016 Pidie Jaya, Aceh earthquake (Mw =

- 6.5), Indonesia. *Journal of Seismology*, 23, 1391–1403. <https://doi.org/10.1007/s10950-019-09878-3>
- Lentas, K., Di Giacomo, D., Harris, J., & Storchak, D. A. (2019). The ISC Bulletin as a comprehensive source of earthquake source mechanisms. *Earth System Science Data*, 11, 565–578. <https://doi.org/10.5194/essd-11-565-2019>
- Liu, C., Lay, T., Wang, R., Taymaz, T., Xie, Z., Xiong, X., Irmak, T. S., Kahraman, M., & Erman, C. (2023). Complex multi-fault rupture and triggering during the 2023 earthquake doublet in southeastern Türkiye. *Nature Communications*, 14(1), 5564. <https://doi.org/10.1038/s41467-023-41404-5>
- Muzli, M., Umar, M., Nugraha, A. D., Bradley, K. E., Widiyantoro, S., Erbas, K., Jousset, P., Rohadi, S., Nurdin, I., & Wei, S. (2018). The 2016 Mw 6.5 Pidie Jaya, Aceh, North Sumatra, Earthquake: Reactivation of an unidentified sinistral fault in a region of distributed deformation. *Seismological Research Letters*, 89(5), 1761–1772. <https://doi.org/10.1785/0220180068>
- Provost, F., Karabacak, V., Malet, J.-P., Van der Woerd, J., Meghraoui, M., Masson, F., Ferry, M., Michéa, D., & Pointal, E. (2024). High-resolution co-seismic fault offsets of the 2023 Türkiye earthquake ruptures using satellite imagery. *Scientific Reports*, 14(1), 6834. <https://doi.org/10.1038/s41598-024-55009-5>
- Pusat Studi Gempa Nasional (PuSGeN). (2017). *Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017*. Bandung: Pusat Penelitian dan Pengembangan Perumahan dan Permukiman, Kementerian Pekerjaan Umum dan Perumahan Rakyat.
- Ramadhan, M., Palgunadi, K. H., Mukti, M. M., Librian, V., Daniarsyad, G., Muttaqy, F., Hidayat, E., Syuhada, S., Hanif, M., Mursitantyo, A., Lühr, B.-G., Nugraha, A. D., Widiyantoro, S., Setyonegoro, W., & Febriani, F. (2025). Aftershock sequence of the Yogyakarta earthquake 2006 (Mw ~ 6.4), Indonesia, based on analysis of hypocenter relocation, static, and dynamic stress. *Natural Hazards*, 121, 16559–16579. <https://doi.org/10.1007/s11069-025-07440-8>
- Reasenber, P. A., & Simpson, R. W. (1992). Response of regional seismicity to the static stress change produced by the Loma Prieta earthquake. *Science*, 255(5052), 1687–1690. <https://doi.org/10.1126/science.255.5052.1687>
- Rohadi, S., Perdana, Y. H., Herayndoko, N., Sunardi, B., Prakoso, T. A., Suliyanti, S., Sunardi, S., Florida, N., Edison, R., & Karnawati, D. (2021). The M 6.5 Ambon earthquake 26 September 2019: the source mechanism and the aftershock sequence characteristics. *IOP Conference Series: Earth and Environmental Science*, 873(1), 012013. <https://doi.org/10.1088/1755-1315/873/1/012013>
- Sharma, S., Hainzl, S., Zöeller, G., & Holschneider, M. (2020). Is coulomb stress the best choice for aftershock forecasting? *Journal of Geophysical Research: Solid Earth*, 125(9), e2020JB019553. <https://doi.org/10.1029/2020JB019553>
- Sinaga, G. H. D., Zarlis, M., Sitepu, M., Prasetyo, R. A., & Simanullang, A. (2021). Coulomb stress analysis of West Halmahera earthquake Mw=7.2 to Mount Soputan and Gamalama volcanic activities. *IOP Conference Series: Earth and Environmental Science*, 56(1), 012005. <https://doi.org/10.1088/1755-1315/56/1/012005>

- Siwi, P. W., Sriyanto, S. P. D., Rondonuwu, A. T., & Silangen, P. M. (2020). Perubahan Coulomb Stress Akibat Gempa Bumi Laut Maluku 7 Januari 2019. *Jurnal Geosaintek*, 6(3), 137–142.
<https://doi.org/10.12962/j25023659.v6i3.7030>
- Smith, S. A. F., & Faulkner, D. R. (2010). Laboratory measurements of the frictional properties of the Zuccale low-angle normal fault, Elba Island, Italy. *Journal of Geophysical Research: Solid Earth*, 115(B2), 2008JB006274.
<https://doi.org/10.1029/2008JB006274>
- Souisa, M., & Sapulete, S. M. (2021). Analysis of the Impact of Coulomb Stress Changes of Tehoru Earthquake, Central Maluku Regency, Maluku Province. *Jurnal Penelitian Pendidikan IPA*, 7(4), 593–600.
<https://doi.org/10.29303/jppipa.v7i4.975>
- Storchak, D. A., Harris, J., Brown, L., Lieser, K., Shumba, B., & Di Giacomo, D. (2020). Rebuild of the Bulletin of the International Seismological Centre (ISC)—part 2: 1980–2010. *Geoscience Letters*, 7(1), 18. <https://doi.org/10.1186/s40562-020-00164-6>
- Supendi, P., Nugraha, A. D., Widiyantoro, S., Pesicek, J. D., Thurber, C. H., Abdullah, C. I., Daryono, D., Shiddiqi, H. A., & Rosalia, S. (2020). Relocated aftershocks and background seismicity in eastern Indonesia shed light on the 2018 Lombok and Palu earthquake sequences. *Geophysical Journal International*, 221(3), 1845–1855.
<https://doi.org/10.1093/gji/ggaa118>
- Supendi, P., Rawlinson, N., Prayitno, B. S., Sianipar, D., Simanjuntak, A., Widiyantoro, S., Palgunadi, K. H., Kurniawan, A., Ash Shiddiqi, H., Nugraha, A. D., Sahara, D. P., Daryono, D., Triyono, R., Adi, S. P., Karnawati, D., Daniarsyad, G., Ahadi, S., Fatchurohman, I., Anugrah, S. D., Heryandoko, N., & Sudrajat, A. (2023). A previously unidentified fault revealed by the February 25, 2022 (Mw 6.1) Pasaman earthquake, West Sumatra, Indonesia. *Physics of the Earth and Planetary Interiors*, 334, 106973.
<https://doi.org/10.1016/j.pepi.2022.106973>
- Toda, S., Stein, R. S., Sevilgen, V., & Lin, J. (2011). *Coulomb 3.3 Graphic-rich deformation and stress-change software for earthquake, tectonic, and volcano research and teaching-user guide* (2011–1060). U.S. Geological Survey.
<https://doi.org/10.3133/ofr20111060>
- USGS. (2019). *Finite fault model for the M 7.2 earthquake 155 km SSE of Sofifi, Indonesia (2019-07-14 09:10:51 UTC)*. U.S. Geological Survey. <https://earthquake.usgs.gov/earthquakes/eventpage/us70004jyv/finite-fault>
- Wajedy, M. F., Saaduddin, S., Massinai, M. A., Fahrudin, F., & Thariq, A. (2026). Seismic hazard and tectonic stress in Halmahera, Indonesia based on b-value and apparent stress analyses. *Physics of the Earth and Planetary Interiors*, 372, 107512.
<https://doi.org/10.1016/j.pepi.2026.107512>
- Watkinson, I. M., & Hall, R. (2017). Fault systems of the eastern Indonesian triple junction: evaluation of Quaternary activity and implications for seismic hazards. *Geological Society, London, Special Publications*, 441(1), 71–120.
<https://doi.org/10.1144/SP441.8>
- Wu, J., Cai, Y., Li, W., & Feng, Q. (2017). Strong Aftershock Study Based on Coulomb Stress Triggering—A Case Study on the 2016 Ecuador Mw 7.8 Earthquake. *Applied Sciences*, 7(1), 88.
<https://doi.org/10.3390/app7010088>
- Wulandari, R., Chan, C.-H., & Wibowo, A.

(2023). The 2022 Mw6.2 Pasaman, Indonesia, earthquake sequence and its implication of seismic hazard in central-west Sumatra. *Geoscience*

Letters, 10(1), 25.
<https://doi.org/10.1186/s40562-023-00279-6>