International Journal of GEOMATE, April 2023, Vol. 24, Issue 104, pp.36-43
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.104.3695
Geotechnique, Construction Materials and Environment

ANALYSIS OF CHANGE OF SEISMIC STRESS ALONG THE SUMATRAN ZONE TO PREDICT POTENTIAL EARTHQUAKE ZONES

Abdi Jihad[1,2], *Muksin Umar[3,6], Marwan Ramli[5], Syamsidik[3,4], and Vrieslend Haris Banyunegoro[2]

[1]Graduate School of Mathematics and Applied Sciences, Universitas Syiah Kuala, Banda Aceh, Indonesia
[2]Meteorological, Climatological, and Geophysical Agency (BMKG), Banda Aceh, Indonesia
[3]Tsunami and Disaster Mitigation Center (TDMRC), Universitas Syiah Kuala, Banda Aceh, Indonesia
[4]Civil Engineering Department, Faculty of Engineering, Universitas Syiah Kuala, Banda Aceh, Indonesia
[5]Department of Mathematics, Universitas Syiah Kuala, Banda Aceh, Indonesia
[6]Department of Physics, Universitas Syiah Kuala, Banda Aceh, Indonesia

*Corresponding Author, Received: 05 Feb. 2022, Revised: 29 Jan. 2023, Accepted: 26 Feb. 2023

ABSTRACT: A seismic stress change analysis is a powerful method to investigate the relationship of earthquakes, sequences, aftershocks, and potential seismic zones. In previous studies, the analysis was demonstrated by studying earthquake activity to assess seismic hazards on strike-slip, normal, and collisional thrust faults. Unfortunately, seismic stress changes in complex systems, such as subduction and intraplate earthquakes, have not been fully observed, to our knowledge. The objective of the research is to investigate seismic stress changes and their potential effects on the Sumatra subduction zone by using Colomb Stress Change Analysis (Colomb 3.3). The investigation is focused on high-accuracy major earthquake events, during the period of 2004 to 2019, and 50 major earthquakes within a period of 15 years are taken into account to investigate potential zones. Different from previous work, we included temporal and spatial analysis in order to estimate possible future significant seismic events. The results show that the 2004 Aceh-Andaman earthquake triggered the 2005 Nias earthquake as also suggested by previous study. Meanwhile, the 2008 earthquake (Mw 7.2) triggered the Padang earthquake (2009). Our new finding suggests that the 2008 earthquake also provided a positive impulse for the 2010 Mentawai earthquake. Several potential earthquake zones are found at depths of 20 to 50 km in Bengkulu, of 60 to 80 km in Mentawai. The results of this study can be a key to understanding the probability of seismic and tsunami hazards in Sumatra, which is also applicable to other potentially hazardous areas in Indonesia.

Keywords: Earthquake, Seismic stress change, Potential zone, Sumatra, Subduction.

1. INTRODUCTION

Tectonically, a subduction zone located on the Sumatran west coast is known as one of the most active sources of earthquakes [1]–[3]. Since 2004, the subduction zone has generated a series of major earthquakes (Fig.1), including Aceh-Andaman (Mw 9.2) in 2004 [4], [5], Nias-Simeulue (Mw 8.5) in 2005 [6], Bengkulu (Mw 8.4) in 2007 [7], Mentawai (Mw 7.8) in 2010 [8], and offshore along the west coast of Aceh (Mw 8.8, Mw 8.5) in 2012 [9].

Every earthquake releases seismic stresses that can induce the adjacent earthquake sources to trigger aftershocks and other earthquakes [10]–[13]. The 2004 Sumatra-Andaman earthquake (Mw 9.2), causing 1,600 kilometers of deformation and 25 meters of slip, is believed to have induced the Nias-Simeulue megathrust, which accelerated the release of earthquake energy in 2005 and 2012 [14], [15]. The assumption about the induction caused by the Aceh-Andaman on Nias-Simeuleu earthquake has been verified through an analysis of seismic stress changes. The analysis has shown that the 2004 earthquake activity accelerated the release of the earthquake energy in Nias-Simeulue region, 100 days after the earthquake occurred [12].

Seismic stress changes are physics-based models that are a powerful way to identify the relationship among earthquakes, sequences, aftershocks, and potential earthquake zones, and even for earthquake forecasting [16]–[18]. To exemplify this, spatial distributions of aftershocks and earthquake interactions have been successfully modeled in response to seismic stress changes induced by the previous neighboring earthquakes [16], [19], [20].

Use of seismic stress change analysis has been demonstrated by studying earthquake activity in order to assess seismic and tsunami hazards on faults, i.e., strike-slip [21]–[23], normal [24]–[26], and collusion [27]. However, the seismic stress changes in subduction and intraplate earthquakes, especially in complex systems, and their potential effects on regional seismic activity, have not been comprehensively investigated.

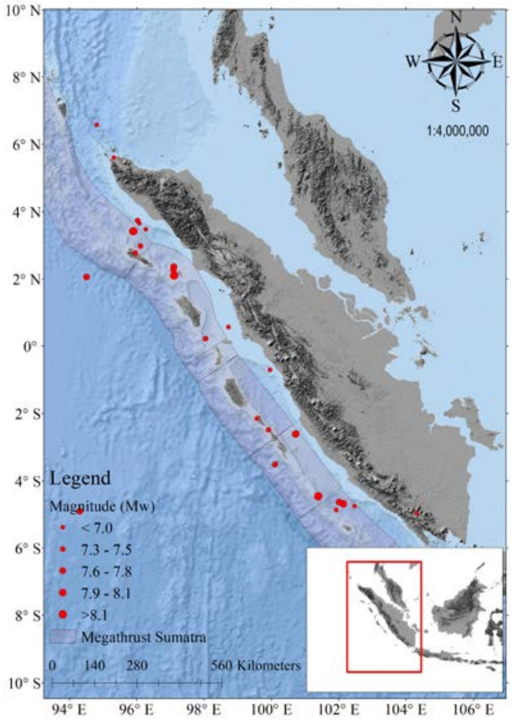


Fig.1 Distributions of major earthquakes on the West Coast of Sumatra. The size of the red circles distinguishes the magnitude of an earthquake

This study aimed to investigate potential earthquake zones on the west coast of the Sumatran subduction zone based on an analysis of seismic stress changes. The seismic stress change analysis was based on large earthquakes (M>7), mainly from 2004 to 2019, and 50 major earthquakes within the 15-year period were taken into account to generate the zones of seismic stress increase and decrease. In brief, the stress changes can be used to specify locations of the zones of increase and decrease. In addition, the high-accuracy hypocenter locations from the previous studies support and validate the identification of potential zones for future earthquakes and tsunamis [28], [29].

2. RESEARCH SIGNIFICANCE

This research is significantly critical as a contribution to existing and ongoing earthquake and tsunami disaster risk reduction efforts in Sumatra. Based on the previous studies, the analysis of seismic stress changes was carried out based on a major earthquake event to identify its effects on the local region or earthquake source. In the present study, the calculation of temporal seismic stress changes is carried out based on a series of major earthquakes that occurred during the period of 2004 to 2019. The corrected focal mechanism and high-accuracy earthquake hypocenter data serve to reinforce the research output, which is set to be a reference for local governments that are developing regional disaster mitigation action plans. Further, the study, provides possible opportunities for prospective researchers to conduct more profound observations that are useful in analyzing the seismic stress changes of subduction earthquakes in other regions.

3. DATA AND METHODS

Research data included the focal mechanisms of earthquakes with a magnitude of M ≥ 7.0 which are potential precursors for tsunamis. In addition, focal mechanisms were obtained from the United States Geology Survey (USGS) earthquake catalog from 2004 to 2019 (https://www.globalcmt.org/). The distribution of earthquakes based on the focal mechanism used in the analysis is shown in Fig. 2.

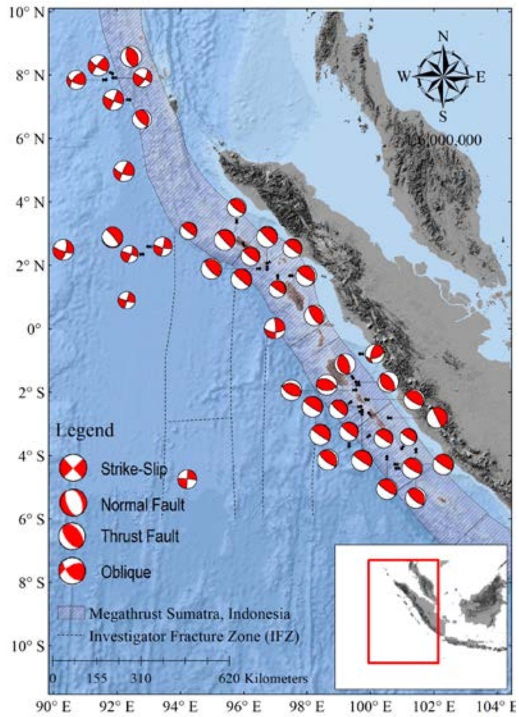


Fig. 2 Distribution of focal mechanisms along the subduction zone on the Sumatran West Coast (https://www.globalcmt.org/CMTsearch.html)

3.1 SEISMIC STRESS CHANGE

Generally, an earthquake occurs when the change in shear stress exceeds the normal stress on the fault, which causes deformation in the direction and shape of the fault plane. However, the seismic stress change on the fault is difficult to measure, but it can be estimated by identifying the difference or change in shear and normal stress from the earthquake. This method is considered effective for defining the seismic stress changes of earthquakes. Seismic stress changes caused by earthquakes can be expressed by Eq.1:

$$\Delta\sigma_f = \Delta\tau_\beta - \mu(\Delta\sigma_\beta - \Delta p) \quad (1)$$

Denoting the shear stress, $\sigma\beta$ is normal stress, p is pore fluid pressure, and μ is the shear coefficient. We used the COULOMB 3.3 code [30] in order to calculate the stress change from the estimated slip and viscous strain in a homogeneous medium [17]. In addition, we also modified the approach of Catalli and Chan (2012) [16] to identify the seismic stress changes in the Sumatran subduction zone. The approach, moreover, classifies the subduction zone into a layered computational grid at depths of 10-100 km. We set the friction coefficient to 0.4 for all calculations. The maximum seismic stress change in each time period and depth range per grid was used for further interpretation.

3.2 FAULT PLANE ANALYSIS

In a fault plane analysis, the magnitude (Mw) was expressed by the length (L) and width (W) of the fault. Empirical conversion of earthquake magnitudes to fault planes is based on the scaling law equations [31] expressed by Eq. 2 and Eq. 3.

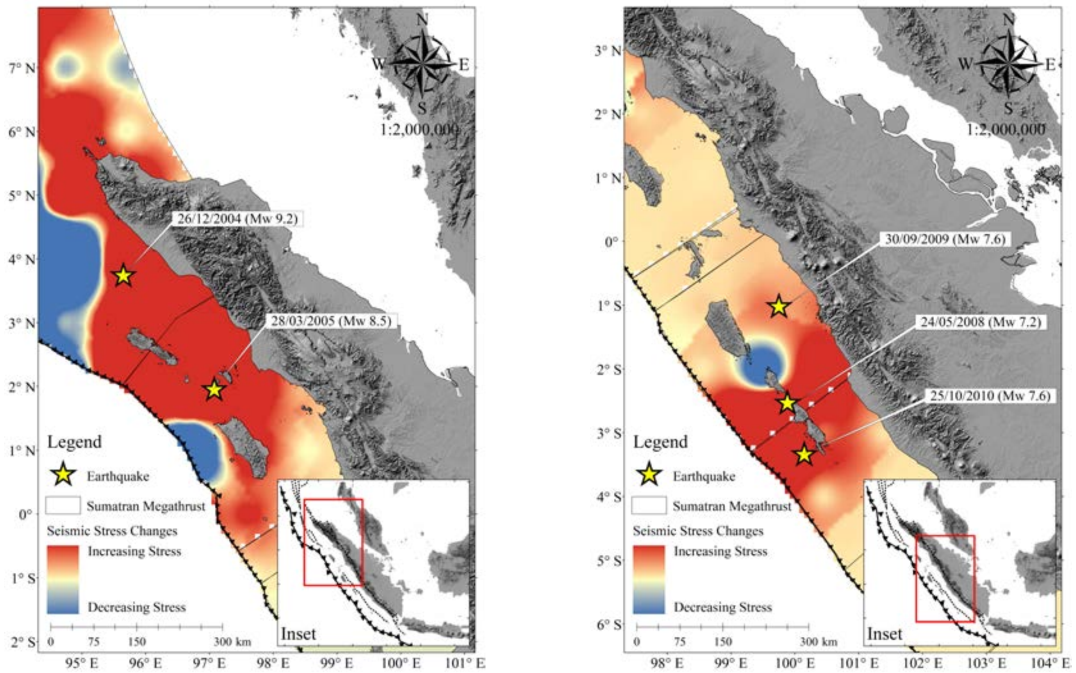
$$log(L) = 0.5 \times Mw - 1.9\ (km) \quad (2)$$
$$log(W) = 0.5 \times Mw - 2.2\ (km) \quad (3)$$

4. RESULTS AND DISCUSSION

The pattern of seismic stress changes in the subduction zone of the Sumatran West Coast is defined by positive values that represent an increase in seismic stress, shown in red. In contrast, the negative values were encoded in blue, indicating the stress decrease.

In 2004, there was a massive earthquake, known as the largest earthquake of the 21st century, the Aceh-Andaman, with a magnitude of Mw 9.2. As shown in Fig. 3a, consistent with the previous studies, the results of the 2004 seismic stress change analysis confirmed that the earthquake was a triggering earthquake preceding the Nias earthquake in early 2005 [14], [32]. Moreover, the earthquake had also induced movement of part of the intraplate zone [5], [10], [14], [33]. Eight years later, a series of earthquakes known as "doublet earthquakes" with magnitudes of Mw 8.5 and 8.8 occurred [10], [34].

Meanwhile, in 2008 the earthquake off the west coast of Western Sumatra (Mw 7.2) caused a dominant effect on the seismic stress pattern of changes in the Sumatran subduction zone, located mainly offshore along the western coast of Sumatra (Fig. 3b). The pattern, in fact, demonstrated that the zone of increased seismic stress had triggered the Padang earthquake (30/09/2009, Mw 7.6) [35], [36].



(a) (b)

Fig. 3 (a) The seismic stress increase in Nias that occurred in 2005 was caused by the 2004s earthquake with magnitude of Mw 9.2. (b) The 2008 earthquake had probably triggered earthquakes in Padang and Mentawai

In addition, the analysis of the seismic stress changes in 2008, as shown in Fig. 3b, highlights a Mentawai seismic gap zone. The pattern of the increased seismic stress in the gap zone will not only trigger major earthquakes in Mentawai islands, but also tsunamis that are assumed to bring about effects upon the densely populated cities and coastal areas around West Sumatra within about 30 minutes [8], [37]–[40].

In addition, the seismic stress change analysis had specified the seismic stress change zones per depth. According to the results of the seismic stress change analysis, shown in Fig. 4, there are several potential earthquake zones, including along the west coasts of Aceh, Nias, and Bengkulu, in addition to the Mentawai seismic gap zones [37], [38], [41], [42]. In more detail, it shows that the seismic stress zone has consistently increased by the depth of 30–50 kms for the Bengkulu west coast. Meanwhile, for the west coasts of Aceh and Nias, and the Mentawai seismic gap zones, signs of the seismic stress increase occur at depths of 60–80 km. Historically, seismic zones with increased stress are those that had undergone massive earthquakes that triggered tsunamis [11], [43], [44].

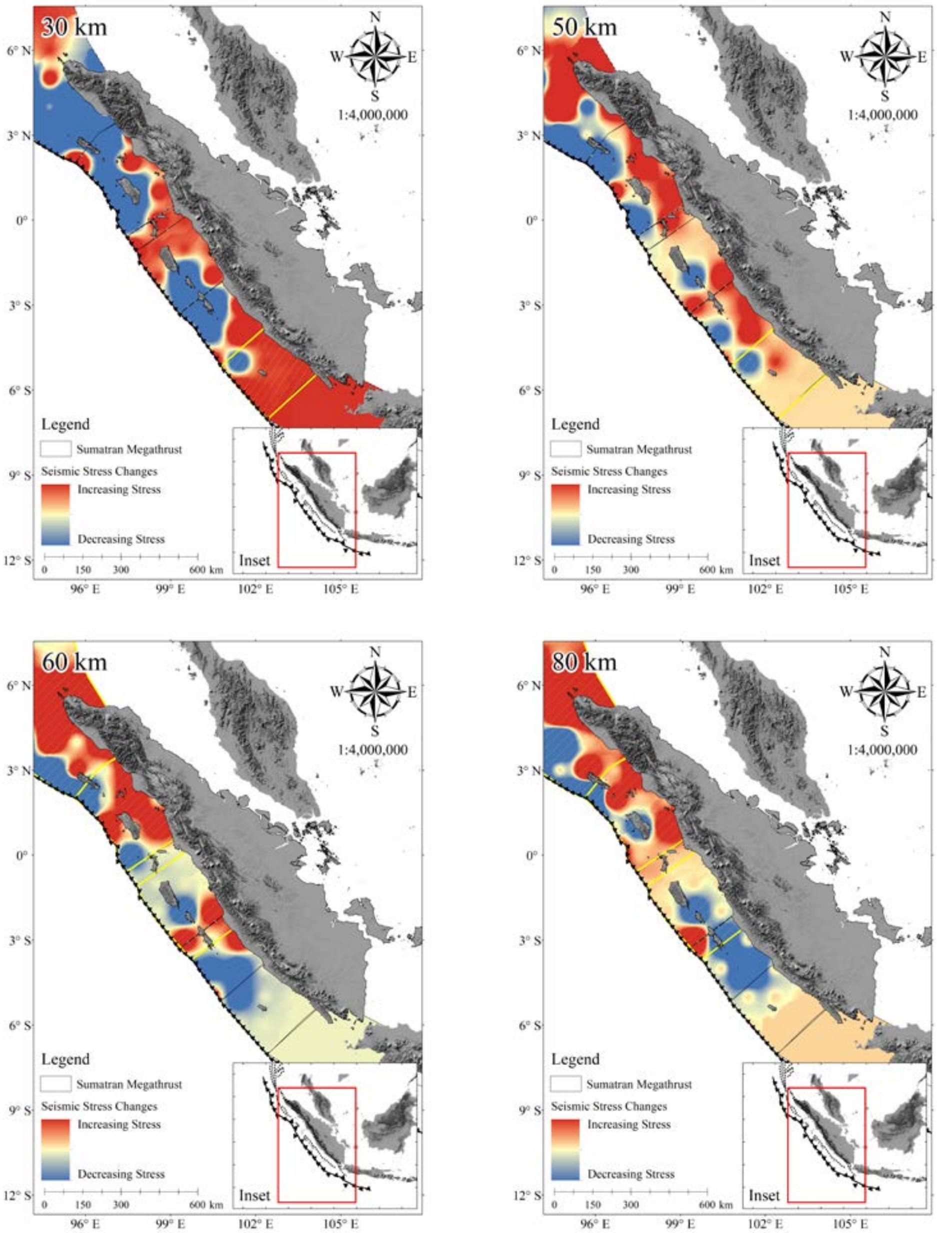


Fig. 4 Earthquake potential zones (indicated by red and yellow boxes) identified based on the spatial analysis of seismic stress changes at depth. The earthquake potential zone in Bengkulu ranges from 20 to 50 km in depth. While in Aceh, Nias, and the Mentawai seismic gap zone, the depths are 60 to 80 km.

We, furthermore, specifically investigated the earthquake activity on Aceh West Coast. Jihad et al. (2020) reported that 20 years after the 2004 earthquake, the area would be possessing potential energy that was equivalent to Mw 8.7. The impact of the Mw 8.7 earthquake was further studied and included tsunami modeling. The results of the study concluded that the impact of the Mw 8.7 earthquake had a potential to trigger a tsunami with a maximum of more than 18 m in height [45]. As shown Fig. 5, after 2019, zones of potential or increased seismic stress had triggered earthquakes (M > 5.5).

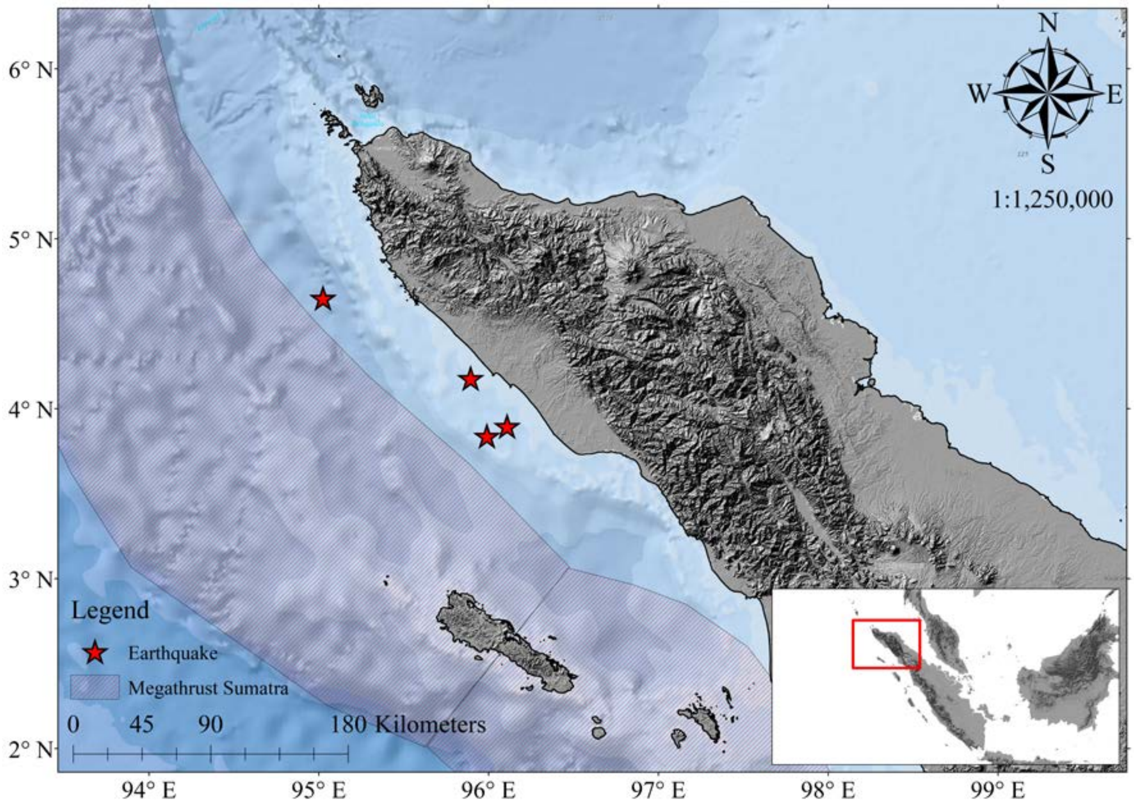


Fig. 5 Seismic activity on Aceh West Coast after 2019. The zone with increased seismic stress has triggered numerous significant earthquakes (M > 5.5).

5. CONCLUSIONS

This study of seismic stress changes in Sumatra has strengthened our understanding of a seismic-triggering process. Major earthquakes in Sumatra have already been proven to trigger some earthquakes located in the increased stress zones. The triggering process was indicated when the 2004 process triggered the 2005 earthquakes, and the 2008 process triggered the 2009 earthquakes. In addition to the spatial analysis, the depths based on the seismic stress changes were also calculated to provide extra details in the present study. Certain zones are indicated to hold stress at a particular depth. Offshore along the Bengkulu West Coast is seen to hold stress at depths in the range of 20 to 30 km, while Aceh, Nias, and Mentawai are holding stress at greater depths in the range of 70 to 80 km. Regarding the seismic triggering process, the stress-holding zones can be useful to forecast the most probable locations for the next earthquakes.

6. ACKNOWLEDGMENTS

We would like to express our sincerest gratitude to the Geophysical Station of Aceh Besar (BMKG), University of Syiah Kuala, and Tsunami Disaster Research Mitigation Center (TDMRC) for the endless support in the completion of this research.

7. REFERENCES

[1] Barber, A. J., Crow., M. J., and Milsom, J. S., Sumatra: Geology, Resources, and Tectonic Evolution, in Geological Society Special Publication, vol. 312005, London: Geological Society, 2005, pp. 1–290.

[2] McCaffrey, R., The Tectonic Framework of the Sumatran Subduction Zone, vol. 37, Issue 1, 2009, pp. 345–366.

[3] Newcomb, K. R. and McCann, W. R., Seismic history and seismotectonic of the Sunda arc, vol. 92, Issue b1, 1987, pp. 421–439.

[4] Ammon, C. J., Ji, C., Thio, H. K., Robinson, D., Ni, S., Hjorleifsdottir, V., Kanamori, H., Lay, T., Das, S., Helmberger, D., Ichinose, G., Polet, J., and Wald, D., Rupture process of the 2004 Sumatra-Andaman earthquake, Science, vol. 308, Issue 5725, 2005, pp. 1133–1139, 2005.
[5] Chlieh, M., Avouac, J. P., Hjorleifsdottir, V., Song, T. R. A., Ji, C., Sieh, K., Sladen, A., Hebert, H., Prawirodirdjo, L., Bock, Y., and Galetzka, J., Coseismic slip and afterslip of the great Mw 9.15 Sumatra-Andaman earthquake of 2004, vol. 97, Issue 1A, 2007, pp. 152–173.
[6] Konca, A. O., Hjorleifsdottir, V., Song, T. R. A., Avouac, J. P., Helmberger, D. V., Ji, C., Sieh, K., Briggs, R., and Meltzner, A., Rupture kinematics of the 2005 Mw 8.6 m Nias-Simeulue earthquake from the joint inversion of seismic and geodetic data, vol. 97, Issue 1A, 2007, pp. 307–322.
[7] Konca, A. O., Avouac, J. P., Sladen, A., Meltzner, A. J., Sieh, K., Fang, P., Li, Z., Galetzka, J., Genrich, J., Chlieh, M., Natawidjaja, D. H., Bock, Y., Fielding, E. J., Ji, C., and Helmberger, D. V., Partial rupture of a locked patch of the Sumatra megathrust during the 2007 earthquake sequence, vol. 456, Issue 7222, 2008, pp. 631–635.
[8] Hill, E. M., Borrero, J. C., Huang, Z., Qiu, Q., Banerjee, P., Natawidjaja, D. H., Elosegui, P., Fritz, H. M., Suwargadi, B. W., Pranantyo, I. R., Li, L. L., Macpherson, K. A., Skanavis, V., Synolakis, C. E., and Sieh, K., The 2010 Mw 7.8 Mentawai earthquake: Very shallow source of a rare tsunami earthquake determined from tsunami field survey and near-field GPS data, vol. 117, Issue 6, 2012, pp. 1–21.
[9] Duputel, Z., Kanamori, H., Tsai, V. C., Rivera, L., Meng, L., Ampuero, J. P., and Stock, J. M., The 2012 Sumatra great earthquake sequence, vol. 351–352, Issue january, 2012, pp. 247–257.
[10] Guo, L., Lin, J., Zhang, F., and Zhou, Z., Transfer of stress from the 2004 Mw9.2 Sumatra subduction earthquake promoted widespread seismicity and large strike-slip events in the Wharton Basin, vol. 33, Issue 1, 2021, pp. 74–85.
[11] Heidbach, O., Rajabi, M., Cui, X., Fuchs, K., Müller, B., Reinecker, J., Reiter, K., Tingay, M., Wenzel, F., Xie, F., Ziegler, M. O., Zoback, M. Lou, and Zoback, M., The World Stress Map database release 2016: Crustal stress pattern across scales, vol. 744, Issue august, 2018, pp. 484–498.
[12] Ishibe, T., Ogata, Y., Tsuruoka, H., and Satake, K., Testing the Coulomb stress triggering hypothesis for three recent megathrust earthquakes, vol. 4, Issue 5, 2017, pp. 1–11.
[13] Cattania, C., Hainzl, S., Wang, L., Enescu, B., and Roth, F., Aftershock triggering by postseismic stresses: A study based on Coulomb rate-and-state models, vol. 120, Issue 4, 2015, pp. 2388–2407.
[14] Cattin, R., Chamot-Rooke, N., Pubellier, M., Rabaute, A., Delescluse, M., Vigny, C., Fleitout, L., and Dubernet, P., Stress change and effective friction coefficient along the Sumatra-Andaman-Sagaing fault system after the 26 December 2004 (Mw = 9.2) and the 28 March 2005 (Mw = 8.7) earthquakes, vol. 10, Issue 3, 2009, pp. 1–21.
[15] Shearer, P. and Roland, B., Lessons Learned from the 2004 Sumatra-Andaman Megathrust Rupture, in Annual Review of Earth and Planetary Sciences, 2010, 2010, pp. 103–131.
[16] Catalli, F. and Chan, C. H., New insights into the application of the Coulomb model in real-time, vol. 188, Issue 2, 2012, pp. 583–599.
[17] Qiu, Q., Moore, J. D. P., Barbot, S., Feng, L., and Hill, E. M., Transient rheology of the Sumatran mantle wedge revealed by a decade of great earthquakes, vol. 9, Issue 995, 2018, pp. 1–13.
[18] Rosid, M. S., Ali, Y. H., and Ramdhan, M., Characterization of the Mamasa Earthquake Source Based on Hypocenter Relocation and Gravity Derivative Data Analysis, vol. 23, Issue 97, 2022, pp. 220–227.
[19] Chan, C. H. and Stein, R. S., Stress evolution following the 1999 Chi-Chi, Taiwan, earthquake: Consequences for afterslip, relaxation, aftershocks and departures from Omori decay, vol. 177, Issue 1, 2009, pp. 179–192.
[20] Freed, A. M., Earthquake Triggering by Static, Dynamic, and Postseismic Stress Transfer, in Annual Review of Earth and Planetary Sciences, Issue 33, 2005, 2005, pp. 335–367.
[21] Li, Y., Huang, L., Ding, R., Yang, S., Liu, L., Zhang, S., and Liu, H., Coulomb stress changes associated with the M7.3 Maduo earthquake and implications for seismic hazards, vol. 1, Issue 2, 2021, pp. 95–101.
[22] Kusumawati, D., Sahara, D. P., Widiyantoro, S., Nugraha, A. D., Muzli, M., Imran, I., Puspito, N. T., and Zulfakriza, Z., Fault Instability and Its Relation to Static Coulomb Failure Stress Change in the 2016 Mw 6.5 Pidie Jaya Earthquake, Aceh, Indonesia, vol. 8, Issue february, 2021, pp. 1–13.
[23] Taufiqq Rafie, M., Sahara, D. P., Cummins, P. R., and Triyoso, W., Stress Accumulation and Earthquake Activity on the Great Sumatran Fault, Indonesia, 2022, pp. 1–31. [Online]. Available: https://doi.org/10.21203/rs.3.rs-1195020/v1

[24] Song, C., Yu, C., Meldebekova, G., and Li, Z., Normal Fault Slips of the March 2021 Greece Earthquake Sequence from In-SAR Observations, vol. 5, Issue 1, 2022, pp. 50–59. [Online]. Available: http://jggs.sinomaps.com/EN/10.11947/j.JGGS.2022.0106

[25] Gunawan, E., Meilano, I., Abidin, H. Z., Hanifa, N. R., and Susilo, Investigation of the best coseismic fault model of the 2006 Java tsunami earthquake based on mechanisms of postseismic deformation, vol. 1172016, pp. 64–72.

[26] Gunawan, E., Kongko, W., Kholil, M., Widyantoro, B. T., Widiyantoro, S., Supendi, P., Hanifa, N. R., Anjasmara, I. M., Pratama, C., and Gusman, A. R., The 2019 Mw 7.0 Banten, Indonesia, intraslab earthquake: investigation of the coseismic slip, tsunami modelling and Coulomb stress change, vol. 9, Issue 14, 2022, pp. 1–12.

[27] Supendi, P., Rawlinson, N., Prayitno, B. S., Widiyantoro, S., Simanjuntak, A., Palgunadi, K. H., Kurniawan, A., Marliyani, G. I., Nugraha, A. D., Daryono, D., Anugrah, S. D., Fatchurochman, I., Gunawan, M. T., Sadly, M., Adi, S. P., Karnawati, D., and Arimuko, A., The Kalaotoa Fault: A Newly Identified Fault that Generated the Mw 7.3 Flores Sea Earthquake, vol. 2, Issue 3, 2022, pp. 176–185.

[28] Jihad, A., Muksin, U., Syamsidik, and Ramli, M., Earthquake relocation to understand the megathrust segments along the Sumatran subduction zone, vol. 630, Issue 012002, 2021, pp. 1–8.

[29] Syukri, M., Anda, S. T., Umar, M., Meilianda, E., Saad, R., Fadhli, Z., and Safitri, R., Identification of Tsunami Deposit At Meulaboh, Aceh (Indonesia) Using Ground Penetrating Radar (Gpr), vol. 23, Issue 96, 2022, pp. 171–178.

[30] Toda, S., Stein, S. R., Sevilgen, V., and Lin, J., Coulomb 3.3 Graphic-rich deformation and stress-change software for earthquake, tectonic, and volcano research and teachin, 2011, pp. 1–63.

[31] Wells, D. L. and Coppersmith, K. J., New Empirical Relationships among Magnitude , Rupture Length , Rupture Width , Rupture Area , and Surface Displacement, vol. 84, Issue 4, 1994, pp. 974–1002.

[32] Wiseman, K. and Bürgmann, R., Stress and Seismicity Changes on the Sunda Megathrust Preceding the 2007 Mw 8.4 Earthquake, vol. 101, Issue 1, 2015, pp. 313–326.

[33] Rafie, M. T., Cummins, P. R., Sahara, D. P., Widiyantoro, S., Triyoso, W., and Nugraha, A. D., Variations in Forearc Stress and Changes in Principle Stress Orientations Caused by the 2004–2005 Megathrust Earthquakes in Sumatra, Indonesia, vol. 9, Issue august, 2021, pp. 1–14.

[34] Delescluse, M., Chamot-rooke, N., Cattin, R., Fleitout, L., Trubienko, O., and Vigny, C., April 2012 intra-oceanic seismicity off Sumatra boosted by the Banda-Aceh megathrust, Nature, vol. 4902012, pp. 240–243, 2012.

[35] Wiseman, K., Banerjee, P., Bürgmann, R., Sieh, K., Dreger, D. S., and Hermawan, I., Source model of the 2009 M w 7.6 Padang intraslab earthquake and its effect on the Sunda megathrust, vol. 190, Issue 3, 2012, pp. 1710–1722.

[36] McCloskey, J., Lange, D., Tilmann, F., Nalbant, S. S., Bell, A. F., Natawidjaja, D. H., and Rietbrock, A., The September 2009 Padang earthquake, vol. 3, Issue 2, 2010, pp. 70–71.

[37] Lifen, Z., Wulin, L., Jinggang, L., and Qiuliang, W., Estimation of the 2010 Mentawai tsunami earthquake rupture process from joint inversion of teleseismic and strong ground motion data, vol. 6, Issue 3, 2015, pp. 180–186.

[38] Qin, Y. and Singh, S. C., Insight into frontal seismogenic zone in teh Mentawai locked region from seismic full waveform inversion of ultra-lon offset streamer data, vol. 19, Issue 11, 2018, pp. 4342–4365.

[39] Wang, X., Bradley, K. E., Wei, S., and Wu, W., Active backstop faults in the Mentawai region of Sumatra, Indonesia, revealed by teleseismic broadband waveform modeling, vol. 4832018, pp. 29–38.

[40] Syamsidik and Catur, D., Tsunami mitigation measures for tsunami prone small island: lesson learned from the 2010 tsunami around the Mentawai island of Indonesia, vol. 7, Issue 1, 2013.

[41] Meng, Q., Duan, B., and Luo, B., Using a dynamic earthquake simulator to explore tsunami earthquake generation, vol. 229, Issue 1, 2021, pp. 255–273.

[42] Prawirodirdjo, L., McCaffrey, R., Chadwell, C. D., Bock, Y., and Subarya, C., Geodetic observations of an earthquake cycle at the Sumatra subduction zone: Role of interseismic strain segmentation, vol. 115, Issue 3, 2010, pp. 1–15.

[43] Zaccagnino, D., Telesca, L., and Doglioni, C., Different fault response to stress during the seismic cycle, vol. 11, Issue 20, 2021, pp. 1–17.

[44] Sahara, D. P., Widiyantoro, S., and Irsyam, M., Stress heterogeneity and its impact on seismicity pattern along the equatorial bifurcation zone of the Great Sumatran Fault,

Indonesia, vol. 164, Issue december 2017, 2018, pp. 1–8.

[45] Jihad, A., Muksin, U., Syamsidik, Suppasri, A., Ramli, M., and Banyunegoro, V. H., Coastal and settlement typologies-based tsunami modeling along the northern Sumatra seismic gap zone for disaster risk reduction action plans, vol. 51, Issue 101800, 2020, pp. 1–13.