JPPIPA 7(4) (2021)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Analysis of the Impact of Coulomb Stress Changes of Tehoru Earthquake, Central Maluku Regency, Maluku Province

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DOI: 10.29303/jppipa.v7i4.975

Article Info
Received: September 20th, 2021
Revised: October 9th, 2021
Accepted: October 10th, 2021

Abstract: The Tehoru earthquake occurred due to the release of stress in rocks. There is a release of energy as an earthquake as a result of the rock elasticity limit has been exceeded because the rock is no longer able to withstand the stress. One method to determine the distribution of earthquake stress is the Coulomb stress change method. The study aimed to determine the ∆CS of the Tehoru earthquake, Seram Island, and the effect of the main earthquake stress release on aftershocks. The research results show that the ∆CS distribution of the Tehoru June 16, 2021 earthquake is shown with negative lobes and positive lobes. The negative lobe is found in an area that is perpendicular to the fault plane and has been identified as having experienced relaxation, so there may be still aftershocks with stress values ranging from (0.0 – 0.3) bar. The dominant positive lobe occurs next to the southern end of the fault plane, too much located in the area of increasing Coulomb stress with values ranging from (0.2 - 0.6) bar.

Keywords: Tehoru earthquake; fault; Coulomb stress change; aftershock.

Citation: 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. doi:https://doi.org/10.29303/jppipa.v7i4.975

Introduction

The Maluku Islands are an area of eastern Indonesia that is prone to tectonic earthquakes. Maluku lies within a highly complex tectonic region resulting from the collision of the Australian and Sunda blocks and the interaction of the Pacific- Caroline and Philippine Sea plates (Souisa, 2018; Supendi et al., 2020). These three tectonic plates collide with each other, so the Maluku Islands often experience high seismic activity. The seismicity in the Banda Sea is a result of collisions between the Australian continental plate and the Banda Arc (Souisa, 2018). The collision between the plates resulted in faults that made Maluku and its surroundings tectonic earthquakes (Bock et al., 2003). Therefore, every year seismicity is increasing in the Maluku islands.

One of the areas of the Maluku islands that are prone to earthquakes is Seram Island. There are two systems that limit Seram Island, namely the fault system in the north of Sorong and the Tarera-Aiduna fault in the south. Seram Island is formed from rising faults with sharp angles to horizontal faults, which are generally in the form of rising faults and anticline axis trending northwest-southeast (Kumparan, 2019). Evidence in the field of this horizontal fault is a change in the direction of river flow. This horizontal fault is a change in the direction of river flow controlled by a horizontal fault and an offset from the existing rock.

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BMKG noted that the Tehoru earthquake, Central Maluku Regency, occurred on June 16, 2021, at 13:43 WIB with a magnitude of 6.1 Mw. The epicenter of the earthquake was at coordinates -3.39°N, 129.56°E at a depth of 14.4 km. The impact of this earthquake on the community reached an intensity scale of IV MMI (Modified Mercalli Intensity). The impact of the Tohoku earthquake caused damage to houses, liquefaction, ground motion, and the potential for a tsunami (Figure 1). The Tehoru earthquake resulted in no casualties, and the community fled to a safe area. Recorded aftershocks, latest first (49 quakes).

The location of the epicenter is an area with active tectonics. This tectonic activity causes volcanic rocks in

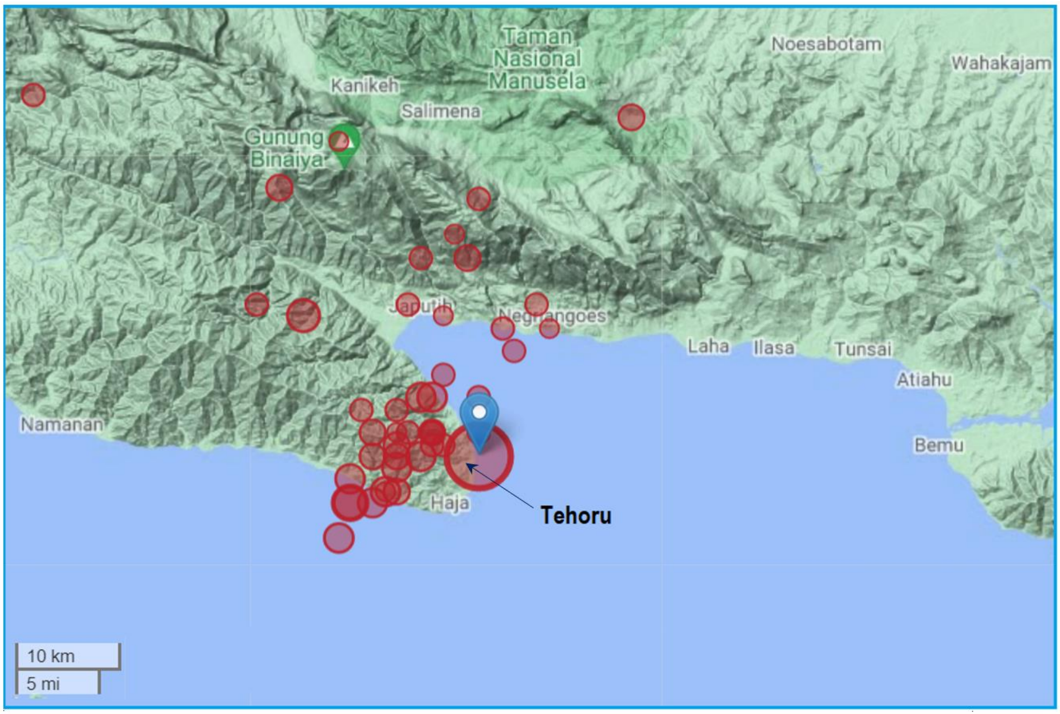


Figure 1. The updated intensity map of the Tehoru earthquake (Anonymous, 2021)

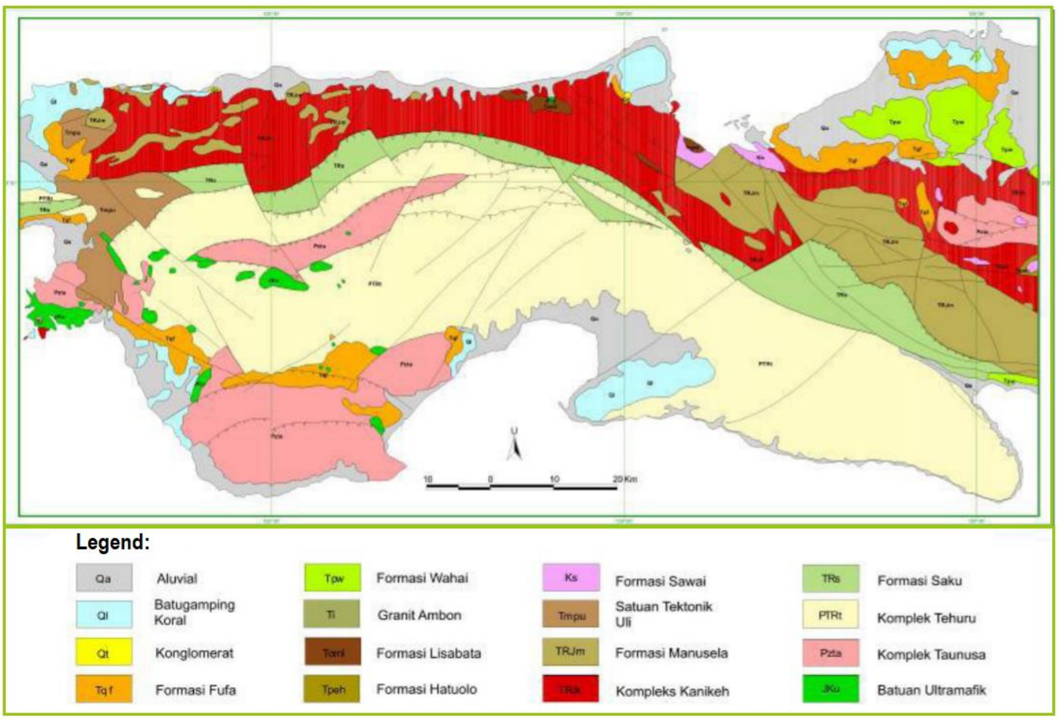


Figure 2. Regional geological map of the study area (Sumardi et al., 2011)

the path above the Benioff line, the emergence of ultrabasic rocks, and the formation of the Salas Complex in Sheet Masohi (Tjokrosapoetro et al., 1994). The Tehoru stratigraphy (Figure 2) covers the Tehoru Complex (PTrt) consisting of phyllite, slate, marbled limestone, and some schist; Taunusa Complex (Pzta), which consists of schist, quartzite, genes, amphibolite, marble, and phyllite; Then there is surface sedimentary rock or Alluvium (Ql). Seram Island and its surroundings are located close to the Seram Trench, so it is easy to generate large thrust earthquakes. A more detailed explanation of the source of this earthquake is not yet available. If viewed from the moment tensor of the earthquake, this earthquake could occur from a horizontal fault in the northeast-northwest direction with an almost horizontal dip with left-lateral movement. This earthquake generator could be a structure that crosses the Tehoru area from the southwest to the northeast, which generally corresponds to the normal fault lineation in the Taluti Bay section.

The occurrence of earthquakes is caused by the release of stress in the rock. There is a release of energy as an earthquake as a result of the rock elasticity limit has been exceeded because the rock is no longer able to withstand the stress. One method to determine the distribution of earthquake stress is the Coulomb stress change method(ΔCS) (King, 2014). In addition, there is considerable evidence that the transfer of ΔCS (either coseismic or postseismic) caused by major earthquakes may contribute to changes in seismicity or even trigger large earthquakes (e.g., Gomberg et al., 2021, Kilb et al., 2002, Hiwa et al., 2019). ΔCS modeling may help understand the stress distribution and explain fault interactions in Seram Island. ΔCS can be used to determine the distribution of aftershocks (King, 2014). ΔCS has been widely used to describe the interaction of earthquakes in their stress fields. For this reason, the research was conducted to determine the ΔCS of the Tehoru earthquake, Seram Island, and the effect of the main earthquake stress release on aftershocks.

When the earthquake occurred, the community around the coast immediately evacuated independently because the Central Maluku District Government and the Regional Disaster Management Agency (BPBD) have provided socialization of earthquake and tsunami mitigation to the community before the earthquake. After the Tohoku earthquake, the local government carried out a review and assessment. The government coordinates and assists in the form of necessities for people who are temporarily displaced. The assistance provided was in the form of necessities, as well as assistance for repairing damaged houses.

Methods

The seismic data

Seismicity data taken from the Global CMT catalog combined with the USGS catalog was then confirmed with the BMKG catalog. The data entered into this catalog is from June 16, 2020, until June 16, 2021. The seismicity coordinates are 2.62° South Latitude and 130.28° East Longitude with a radius of 70.0 km around it. Then fourth aftershocks above 3.5 Mw were recorded in the catalog. The input data for ΔCS used a 6.1 Mw earthquake on June 16, 2021, calculated on two nodal planes.

The Calculation of Coulomb stress change model

The Mohr-Coulomb failure criterion states that the shear stress τ on a fault that ruptures must surpass the critical value τ_f (Figure 3), which is a linear function of the normal stress (Souisa, 2018; Navas-Portella et al., 2020),

$$\tau_f = c + \mu' \sigma_n \quad (1)$$

with c the cohesion and μ' the effective fault friction coefficient (including the contribution of the pore pressure). Care must be taken with the convention of signs in the normal stress, which is not the same in geophysics than in solid mechanics (Cocco and Rice, 2002). Figure 3 shows the Mohr circle as the potential position of the crack plane, with the formula as,

$$\left(\sigma - \frac{\sigma_1 + \sigma_3}{2}\right)^2 + \tau^2 = \left(\frac{\sigma_1 - \sigma_3}{2}\right)^2 \quad (2)$$

or $$\left(\sigma - \sigma_{avr}\right)^2 + \tau^2 = r^2 \quad (3)$$

Eq. (2) and (3) are Mohr's circle equations as the potential position of the crack plane (Souisa, 2018).

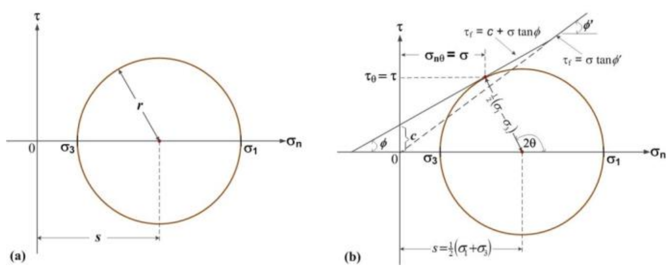


Figure 3. Mohr's stress circle. (a) Geometry and (b) stress representation (Souisa, 2018).

One of the most straightforward and powerful physics-based methods to forecast the distribution of triggered seismicity is Coulomb stress change modeling (Cocco and Rice, 2002; Toda et al., 2005). The Coulomb stress change model is commonly written as,

$$\Delta CS = \Delta\tau + \mu(\Delta\sigma_n - \Delta P) \quad (4)$$

where Δτ is the shear stress change along with slip on the fault, $\Delta\sigma_n$ is the normal stress change on the fault, ΔP is the pore pressure changes, and μ is the friction coefficient. The pore pressure changes ΔP is usually proportional to the volumetric stress changes under undrained conditions, as:

$$\Delta P = -B\frac{\Delta\sigma_{kk}}{3} \quad (5)$$

where B is the Skempton coefficient (Cocco and Rice, 2002) with a range between 0.5 and 1 depending on the rock material, $\Delta\sigma_{kk}$ is the value of normal stress. In the isotropic case, $\Delta\sigma_{11} = \Delta\sigma_{22} = \Delta\sigma_{33}$ and $\Delta\sigma_{kk}/3 = \Delta\sigma$ (average stress), thus (Lin et al., 2019):

$$\Delta P = -B\Delta\sigma_n \quad (6)$$

which B *is* the Skempton coefficient that varies between 0 and 1. Substituting Eq. (6) in Eq. (4) gives the following equation:

$$\Delta CS = \Delta\tau + \mu'\Delta\sigma_n \quad (7)$$

where $\Delta\sigma_n$ is the normal stress (positive unclamping) and $\mu' = \mu(1\text{-}B)$ is the apparent coefficient of friction of the fault rupture plane. The values for the effective friction coefficient range from 0.0 to 0.8. In this calculation, I take the coefficient of friction $\mu'=0.4$ (Stein et al. 1992 in (Lin et al., 2019). The value of $\Delta\tau$ in Eq. (7) must always be positive, but the stress calculation process on a fault can be positive or negative depending on the potential slip directly to the right or the left.

The calculations of ΔCS on rock faults due to earthquakes depend on the geometry and distribution of the slip, the assumed magnitude, regional stress orientation, and the value of the assumed coefficient of friction. In some earthquakes, the ΔCS uncertainty is always dominated by the slip distribution uncertainty.

In the coordinate system (Figure 4), it is shown that the failure plane is subject to the primary stress component (σ_n), which will produce shear stress on the failure plane. The primary stress orientation towards the angle (β) on the failure plane will increase (σ_1) and decrease (σ_3) the stress on the failure plane.

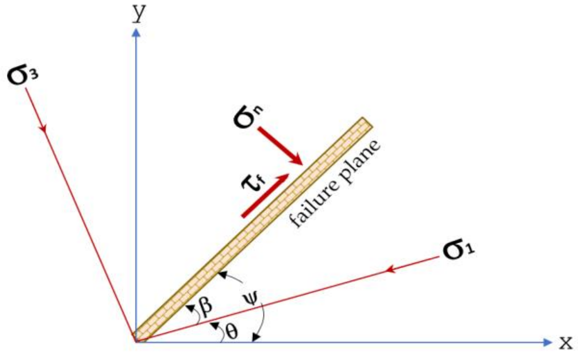


Figure 4. The coordinate system used for calculations of Coulomb stresses on optimum failure planes (King, 2014).

Result and Discussion

The Tehoru earthquake on June 16, 2021, has two types of fault parameters from Global CMT and USGS calculations and then synchronized with BMKG data (Table 1). This parameter is used to calculate ΔCS and display the ΔCS cross-section caused by an earthquake or display the ΔCS dispersion pattern of rocks vertically based on depth. The earthquake source mechanism issued by the three institutions shows compatibility with one another, namely, the earthquake is caused by active fault activity in the form of a normal fault trending northeast-southwest with shallow depth in the crustal earthquake.

Table 1. Parameters of the Tehoru earthquake

Time	Episenter (⁰)	Depth (km)	Mag (Mw)	Strike (⁰)	Dip (⁰)	Rake (⁰)
June 16, 2021	129.56 -3.39	14,4	6,1	246 14	45 58	-48 -124

Calculation of ΔCS and the effect of stress release of the Tehoru earthquake, two different types of fault parameters are used, namely strike angle, dip, and rake. The modeling uses two different nodes with a depth of 14.4 km. The first nodal plane is a horizontal fault in a northeast-southwest direction with a nearly horizontal dip with a left lateral movement, and the second nodal plane is the result of a right-lateral movement in a north-south direction. This calculation uses a friction coefficient value of 0.4.

After processing, the ΔCS distribution of the primary earthquake varies spatially. In Figure 5, a negative ΔCS value or there is a decrease in rock stress at the fault plane location. Rock stress in the fault plane area decreases because it has been released in the form of earthquakes. Horizontally, the ΔCS distribution appears to have three dominant positive lobes occurring at the side end of the fault plane or in the direction of the fault plane and spreading in the northeast-southwest direction with stress values ranging from (0.1 to 1.0) bar. While the two dominant-negative lobes occur in the area perpendicular to the fault plane and spread in the northwest-southeast direction with stress values ranging from -0.1 bar to -1.0 bar. The negative lobe appears dominant and spreads around the fault plane for approximately 67.5 km to reach the eastern part of Masohi City. Meanwhile, the positive lobe spread to Negeri Saunulu, Negeri Yaputi, and Negeri Haya.

If the ΔCS distribution of rock is modeled vertically concerning depth, then it is carried out by cross-section at a depth of 50.0 km and a length of 100.0 km (Figures 6(b) and 7(b)). When viewed from the cross-section, aftershocks occurred at a distance of < 60.0 km with a depth of ≤ 40.0 km below the earth's surface. The cross-section shows that this earthquake is in a relaxation area with the potential for failure so that the number of earthquakes that may occur in the relaxation area tends to increase. According to the cross-section, this earthquake is located in an area of increased Coulomb stress (positive lobe) which is possible that the earthquake was triggered by the main earthquake, which caused aftershocks (faults), and another aftershock can occur again in the future in the area. with positive stress with depth ≤ 40.0 km and DCS distribution ranging from (0.1 - 1.0) bar or (0.01 - 0.1) MPa. Aftershock activities may be promoted or triggered when the Coulomb stress on the fault plane is increased by as little as 0.1 bar (Toda et al., 2005; Wu et al., 2015). The Mw > 3,5 aftershocks distribution are well explained by the seismic coulomb stress changes caused by the Tehoru Mw 6.1 primary shock. Three in four M > 3.5 aftershocks occurred in the positive coulomb stress area with stress values ranging from (0.2 – 06) bar.

Figures 6 and 7 show that the vertical coulomb stress distribution pattern showing the hypocenter of an earthquake with a depth of 14.4 km has a large enough increase in coulomb stress of about 1 bar (0.1 MPa). This means that aftershocks are likely to occur with a fairly high frequency and large magnitude. This is indicated by the positive lobe, which is an area that still has high stress and tends to generate aftershocks. While in the negative lobe, identified stress has been released and experienced relaxation, and the possibility of aftershocks is very small. For fault, areas with decreased stress (negative lobe) tend to provide balance in areas of increased stress (positive lobe).

The Tehoru earthquake had a significant impact on the surrounding area (Toda et al., 2005; Parsons et al., 2006; Parsons et al., 2008). The increasing Coulomb stress changes will promote the occurrence of shallow focus aftershocks outside of the Taluti bay. Since shallow aftershocks are expected to have a higher damage potential, this is a valuable constraint for post-mainshock mitigation efforts (Madlazim, 2015). In addition, ΔCS calculations show that the Tehoru earthquake only occurs in areas of positive stress change from the primary earthquake. Of course, it is ΔCS calculation on the slip model, receiver error, and other parameters, such as depth and effective friction coefficient, which causes some discrepancies in displaying results (Wan et al., 2000; Miao and Zhu, 2012).

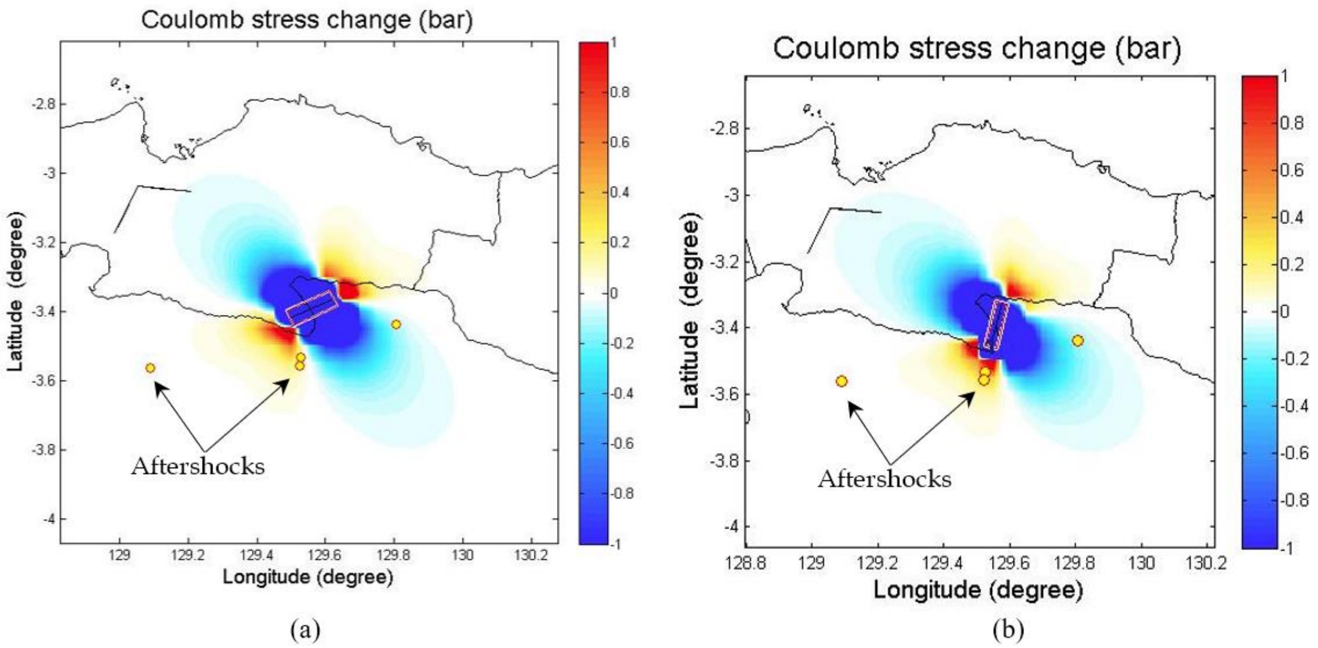


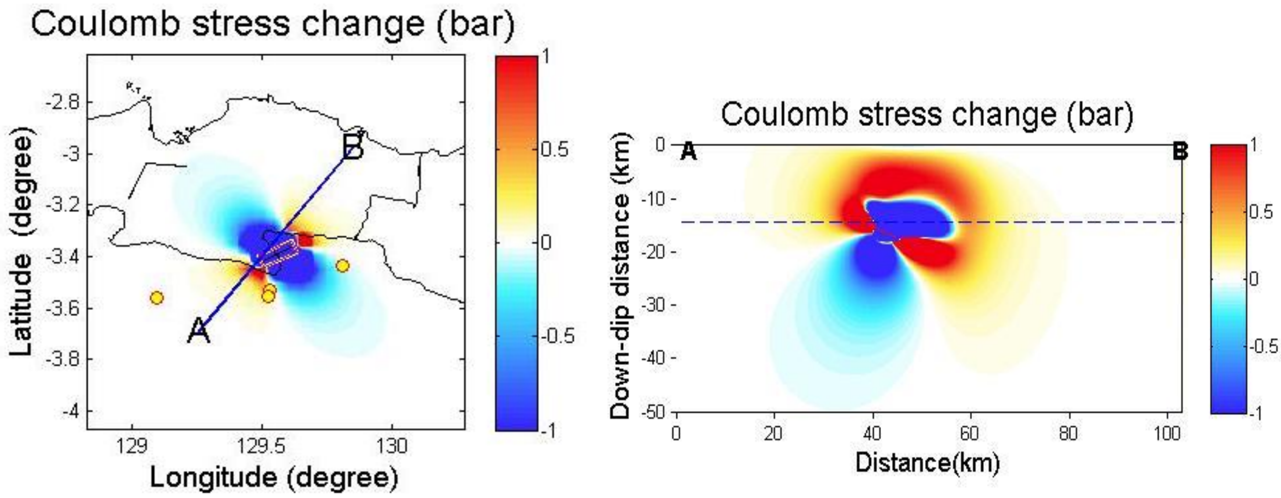
Figure 5. The Coulomb distribution of the primary earthquake stress overlaid with the distribution of the epicenter of the aftershocks (red circle). (a) The Coulomb stress distribution uses the first nodal plane, and (b) the ΔCS distribution uses the second nodal plane.

These aftershocks took place continuously for approximately two months, from June 16, 2021, to September 9, 2021. This indicates that the main earthquake, which has a low-stress drop value (≤ 1.0 bar) as shown in Figure 5, tends to produce more aftershocks because the energy released is large enough (0.1 MPa) to cause a widespread increase in stress on the rock. This illustrates that the closest location to the epicenter of the earthquake is Tehoru, located in Taluti Bay. The location is predominantly composed of coastal and river alluvial deposits. Most of the hills are composed of the Tehoru Complex Formation in the form of metamorphic rocks of

Pre-tertiary age and the OH Formation of Neval and Naval Tufan of Tertiary ages (ESDM, 2021). Some Pre-Tertiary and Tertiary rocks have undergone weathering and are decomposed, soft, loose, unconsolidated so that they are easy to shift when stress is distributed. Weathered rock will generally amplify the effects of earthquake shocks so that earthquake shocks will be more pronounced when exposed to large amounts of energy through the distribution of stress on the rock.

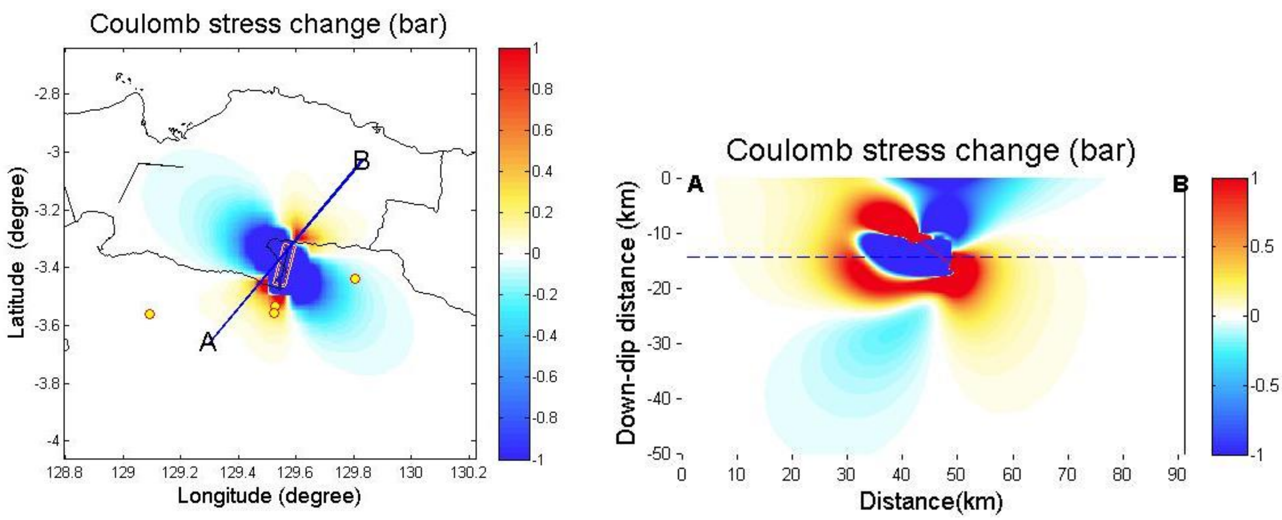
structural mitigation such as planting mangrove trees, constructing breakwater buildings along the coast, constructing houses that can absorb earthquakes, and improving evacuation route signs and assembly points. In addition to structural mitigation, the public also needs to be given education about non-structural mitigation such as periodic earthquake mitigation socialization, making earthquake and tsunami hazard maps and getting earthquake information through social media.

The 2021 Tehoru (Seram Island) earthquake when



(a) (b)

Figure 6. (a). Coulomb stress with fault parameter in the first nodal plane, (b). Cross-section with fault parameters in the first nodal plane.



(a) (b)

Figure 7. (a). Coulomb stress with fault parameter in the second nodal plane, (b). Cross-section with fault parameters in the second nodal plane.

In the study area, the potential for earthquakes can occur at any time, and based on the DCSC analysis, this area is prone to faults and can cause underwater landslides. Therefore, the community needs to obtain compared with data on the Kairatur (Seram-Ambon) earthquake on September 26, 2019. The Kairatu earthquake originated from a dextral and bilateral horizontal fault with a south-north orientation. The total seismic moment of this earthquake is equivalent to a moment magnitude of 6.5. The Kairatu earthquake had a relatively low-stress drop (Sianipar et al., 2019). Aftershocks have a slow decay rate. The ΔCS of the rock caused a large number of Kairatu aftershocks in the area surrounding the main earthquake, similar to the Tohoku earthquake. This identifies that the energy released is large enough to be able to generate the aftershocks of the Tehoru and the aftershocks of Kairatu.

Conclusion

Based on the discussion that has been stated previously, it can be concluded that: the distribution of the Coulomb stress change (ΔCS) of the Tehoru June 16, 2021, earthquake is described by the dominant-negative lobe occurring in an area perpendicular to the fault plane which has been identified to have relaxed, but there may be still aftershocks with stress values ranging from (0.0 - 0.3) bar. Furthermore, the dominant positive lobe occurs at the side end of the fault plane due to the influence of the dominant earthquake source mechanism in the form of normal faults. The location of the epicenter distribution of the aftershocks concentrated in the south of the fault plane is mostly located in the area of increasing Coulomb stress with values ranging from (0.2 - 0.6) bar.

Acknowledgements

Thank you to the Geoscience Center, Faculty of Mathematics and Natural Sciences, Pattimura University, which has prepared facilities for data analysis, and all parties who have supported the completion of this research.

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