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Analysis of Coulomb Stress Changes in Aceh Earthquake on Sibayak Volcano

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Abstract *- Based on geological conditions, Indonesia is located between the Indo-Australian plate, the Eurasian plate, and the Pacific plate, making Indonesia prone to tectonic earthquakes. However, since the big earthquake that occurred in Aceh on December 26, 2004, the geological conditions in Sumatra have undergone significant changes marked by stressful situations in the western to southern regions of Sumatra, especially on Sibayak Volcano. This study used data from BMKG and Global CMT, which included magnitude (Mw), depth, earthquake coordinates (longitude and latitude), type of earthquake, strike, dip, and rake. From the analysis using Coulomb 3.3, the highest coulomb stress value of Sibayak Volcano was obtained in 2015 with an average change in coulomb stress of 0.235 bar, shear 0.1909 bar, normal 0.1106 bar. However, the lowest coulomb stress value occurs in 2021 with a moderate shift in coulomb stress of 0.0593 bar, shear 0.0251, normal 0.0849 bar.*

Keywords: *Earthquake; Coulomb Stress; Sibayak*

INTRODUCTION

Indonesia is an archipelagic country with a high level of seismic activity and is located at the intersection of three very active world tectonic plates (Simandjuntak & Barber, 1996). The three plates are the Eurasian, Pacific, and Indian-Australian, which move to push one another. The meeting of these three tectonic plates causes the emergence of volcanic phenomena and earthquakes throughout Indonesia, where Indonesia is known to have the most significant number of volcanoes in the world that have ever erupted in history (76), with more than 1100 eruption dates (Gasparon, 2005). There are currently 75 types of volcanoes in Indonesia, and 12 are in Sumatra. About one-seventh of the world's recorded eruptions have occurred in Indonesia, and four-fifths of historically active volcanoes have erupted in the last century (Gasparon, 2005).

Sumatra Island is the southwestern part of Southeast Asia where the Indian Ocean lithospheric plate dips at an angle of about 45' down Sumatra Island in the N 20'E direction, with speeds ranging from 5-7 cm per year. Sibayak is a volcano located at 4°15' North Latitude and 97°30'East, Karo Regency, North Sumatra province, Indonesia (Hotta et al., 2019). Sinabung and Sibayak volcanoes have the same straight line as Lake Toba; it is suspected that all volcanic activity and the emergence of these two volcanoes have a close connection with the occurrence of Lake Toba (Trianaputri et al., 2017). The epicentre is a northeast-southwest lineament near the elongated sinistral fault zone between Sinabung and Sibayak volcanoes (Hendrasto et al., 2012). Bedrock in the form of sedimentary rocks from the Tapanuli group and granitic rocks, which are part of the Mergui micro-continent, will affect the genesis of magma in this area so that acidic rocks are more dominant (characterized by the number of lava domes) compared to other places where the bedrock is different. Meanwhile, the oblique subduction effect causes the formation of the Semangko fault. It also causes a tiny number of volcanoes compared to Java Island, where the subduction direction is perpendicular to the magmatic arc (Telles et al., 2019).

Earthquakes often occur around active tectonic and volcanic areas. Recently a swarm event happened around the Sinabung Volcano and Sibayak areas (Nugraha et al., 2018). Apart from the earthquake area, Sibayak Volcano is currently functioning as a geothermal power plant (Muksin et al., 2013; Daud et al., 2001; *Mapping Geothermal Heat Source in Homa Hills Using Gravity Technique*, 2012). Several cases have occurred where earthquakes can be one of the triggers for increased volcanic activity from volcanoes. Although in recent times, Sibayak Volcano has not shown an increase in volcanic activity, it is necessary to know the geological conditions of Sibayak Volcano, especially the stress caused by tectonic earthquakes around it. Several stress conditions affect volcanic activity in volcanoes (Sieh & Natawidjaja, 2000).

The relationship between earthquakes and earthquake activity can be seen through changes in coulomb stress. Several cases of the connection between earthquakes and volcanic activity have occurred in several volcanoes in Indonesia and outside Indonesia. One of them is the change in coulomb stress to the volcanic activity of Sinabung Volcano. The analysis of changes in coulomb stress at Sinabung Volcano resulted in earthquakes in Sumatra affecting Sinabung volcanic activity with a coulomb stress value of 0.118 bar in 2016 (Sinaga et al., 2022). The positive stress direction is opposite to the pyroclastic flow direction (Sinaga et al., 2022). Apart from 2016, the volcanic increase from the Sinabung earthquake has also been studied in 2010 and 2013, where the Aceh earthquake on December 26, 2004, triggered the Sinabung eruption on August 27, 2010, which was influenced by shallow-medium earthquakes and also the epicentre close to Sinabung. (Kototabang & Geofisika, 2013) The same case also occurred on Sorikmarapi Volcano and Rinjani Volcano. The average value of change in coulomb stress in 2021 at Sorik Marapi Volcano is 0.157 bar with an average depth of 90 km below sea level (Sinaga et al., 2021). The static Coulomb stress change model shows an extreme increase in stress distribution when an earthquake occurred on July 28 2018. The earthquake did not directly affect the activities of Rinjani Volcano. Still, based on the results of DInSAR imagery, there was an uplift in the body of Rinjani Volcano and subsidence in the north (Utama et al., 2020). The same thing happened with Merapi Volcano, Soputan Volcano and Gamalama Volcano. Tectonic earthquakes south of Merapi Volcano correlated with increased fumarole temperature in 2001 and increased pyroclastic flow in 2006. The model is shown the mode of stress transfer between the earthquake and Merapi Volcano (Walter et al., 2007). The analysis of coulomb stress data results indicates the increase in coulomb stress distribution at Soputan Volcano at 0.023 bar and 0.007 bar at Gamalama Volcano. An increase followed this stress in the volcanic activity of Soputan Volcano and Gamalama Volcano with a violent eruption type (Sinaga et al., 2017). Even though the status of the mountains is still safe, it is necessary to analyze the coulomb stress at that location to see the geological stress conditions so that it becomes a reference for disaster mitigation.

RESEARCH METHODS

The method used in research on Sibayak Volcano is an analytical-descriptive method. The model used in this study is the Coulomb Stress Model. Earthquake stress/strain will be analyzed in coulomb 3.3 software. The value and distribution of stress/strain from earthquakes will be mapped in 2D and 3D using the Global Mapping Tool Software and Google Earth Software. The data used in this study are earthquake magnitude and coordinate data, earthquake depth, type of earthquake (strike, slip, dip), and moment tensor (Shinji Toda, Ross S. Stein, Volkan Sevilgen, 2011).

By considering the failure of the fracture as the cause of the combined normal (minimized) and shear stress conditions, it is measured as the criterion of static coulomb stress (King et al., 1994). Changes in static coulomb stress caused by earthquakes can help explain the distribution of aftershocks (Parsons et al., 1999) because aftershocks will occur at any time when the coulomb stress exceeds the shear strength of the fault surface. The state Coulomb voltage change (ΔCFF) is defined as

$$\Delta CFF = \Delta_\tau + \mu\,(\Delta_\sigma + \Delta_p) \qquad (1)$$

Δτ represents the change in shear stress at fault (positive in the slip direction), Δσ is the change in normal stress (positive for an uncompressed fracture), Δp is the change in pore pressure, and μ is the coefficient of friction, which ranges from 0.6 to 0.8 for most intact rocks (Harris, 1998). In Oklahoma, where the fluid injection was 1-2 km deep near the epicentre, this has been used for disposal since 1993 (Keranen et al., 2013). In addition, the effect of pore pressure cannot be ignored. The change in pore pressure after a change in stress occurs and there is no fluid flow (undrained condition) is

$$\Delta p = \frac{\beta \Delta\sigma_{kk}}{3} \qquad (2)$$

Where β is Skempton's coefficient, and σkk is the number of diagonal elements of the stress tensor (Rice, 1992). The Skempton coefficient describes the change in pore pressure resulting from a change in externally applied stress and often ranges in value from 0.5 to 1.0. (Green & Wang, 1986; Hart & Wang, 1995; Cocco, 2002) For fault zone rheology, where the fracture zone material is more rigid than the surrounding material, $\sigma_{xx} = \sigma_{yy} = \sigma_{zz}$ (Rice & Cleary, 1976; Parsons et al., 1999; Harris, 1998); so, $\frac{\Delta\sigma_{kk}}{3} = \Delta\sigma$. Equations (1) and (2) combined with this assumption, create

$$\Delta CFF = \Delta_\tau + \mu\,\Delta_\sigma \qquad (3)$$

where μ′ = μ (1- b), Effective friction coefficient. The effective coefficient of friction generally ranges from 0.0 to 0.8, but it is usually around 0.4 (μ = 0,75, b = 0,47) for horizontal faults or faults of unknown orientation (Parsons et al., 1999). These values are commonly used in coulomb change calculations to minimize uncertainty. The location and geometry of the fault source, as well as the distribution of slip over the plane source, play an essential role in calculating the change in coulomb stress. Based on the magnitude of the earthquake, we modelled the source geometry with empirical relationships for strike-slip faults (Wells & Coppersmith, 1994), which was built into Coulomb Software 3.3 (Toda, 2005).

RESULTS AND DISCUSSION

Results

ΔCFS modelling was carried out to determine the static stress distribution by the earthquake event. In addition, this method also can be used to see the relationship between earthquakes that can trigger the next quake and the relationship between tectonic and volcanic earthquakes (Utama et al., 2020). Since the Aceh earthquake on December 26, 2004, the area around Sumatra Island has experienced more frequent earthquakes. Several researchers have evaluated the stress of changes in the subduction zone on the Sumatran fault and 13 active volcanoes on the Sumatran mainland. We have found that the magnitude of the earthquake that broke out since 2004 has modified the stress level during the entire subduction tectonic region. (Qiu & Chan, 2019) The Great Sumatra Fault (GSF) is one of the active faults always well-monitored in Sumatra.

It is shown by the quality instability value, thereby making it more susceptible to slip movement, stress build-up, and fault failure (earthquakes), which could occur in its return period. (Kusumawati et al., 2021; Hardebeck & Okada, 2018). Figure 1 shows the topographical boundaries of the Toba depression are indicated by thick lines with ticks in them, equivalent to the contours of 1500 m and 1000 m where Sibayak Volcano is shown in number 2. (Aldiss & Ghazali, 1984)

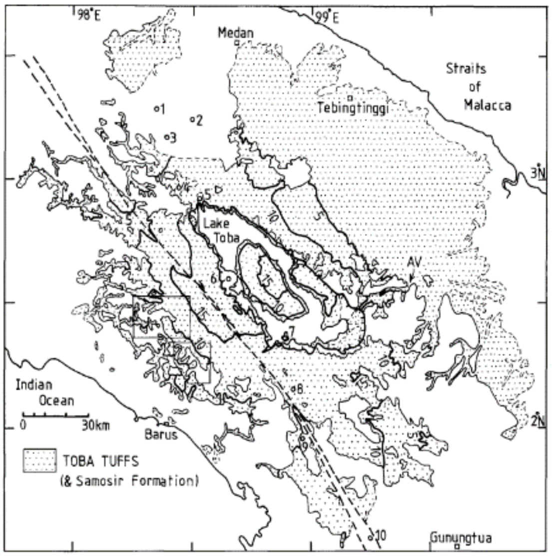

Figure 1. The topographical boundaries of the Toba depression are indicated by thick lines with ticks in them, equivalent to the contours of 1500 m and 1000 m

In addition to the changes in coulombs stress studied from year to year, we also examined changes in coulomb stress at depths of 0-100 km.

Table 1. Normal, Shear and Stress Average Values at Sibayak Volcano in 2004-2015

	2004-2011	2004-2012	2004-2013	2004-2014	2004-2015
Normal	0.0861	0.0863	0.0944	0.1181	0.1106
Shear	0.0418	0.0424	0.0422	0.0505	0.1909
Coulomb	0.0761	0.0770	0.0802	0.0979	0.2350

Table 2. Normal, Shear and Stress Average Values at Sibayak Volcano in 2016-2021

	2004-2016	2004-2017	2004-2018	2004-2019	2004-2020	2004-2021
Normal	0.123	0.135	0.145	0.123	0.125	0.084
Shear	0.037	0.026	0.036	0.054	0.057	0.025
Coulomb	0.086	0.080	0.090	0.104	0.107	0.059

Table 3. Normal, Shear, and Coulomb Stress at Sibayak Volcano 2001-2021 in depth 0-100 km

Depth	shear	normal	coulomb
0	-0.38525	0.27675	-0.27492
10	-0.32858	0.12500	-0.27875
20	-0.21767	0.05800	-0.19475
30	-0.10633	0.00900	-0.10283
40	0.00075	0.00391	0.00208
50	0.10225	0.02175	0.11058
60	0.19025	0.05266	0.21108
70	0.26141	0.08966	0.29675
80	0.31475	0.12875	0.36608
90	0.3515	0.16616	0.41741
100	0.3715	0.19883	0.45091

It is done because changes in coulomb stress also affect the geological and seismic conditions of Sibayak Volcano. Changes in coulomb stress from year to year continue to experience erratic changes within 0-100 km.

Discussion

Changes in Coulomb Stress from 2011-2021

ΔCFS modelling is carried out to determine the distribution of static stress by an earthquake. In addition, this method also can be used to see the relationship between earthquakes that can trigger subsequent earthquakes, both between mainshock-mainshock and mainshock-aftershock, and the relationship between tectonic and volcanic earthquakes. (Utama et al., 2020) Earthquake data in the form of moment magnitude, depth, longitude, and latitude were obtained from the Meteorological and Geophysics Agency (BMKG) website, while the focal mechanism was downloaded from the United States Geological Survey (USGS). The input data analyzed are earthquakes from May 2004 to May 2021 with a minimum moment magnitude of 5.5. An increase in coulomb stress change is indicated by a red lobe, while a blue lobe suggests a decrease in coulomb stress change.

Table 1 shows the average values of normal, shear, and alterations in coulomb stress that occur on Sibayak Volcano at a depth of 0-100 km. The highest average standard value occurred in 2014 at 0.1181 bar, while the lowest average value occurred in 2011 at 0.0861 bar. The highest average shear value occurred in 2015 at 0.1909 bar, while the lowest average shear value occurred in 2011 at 0.0418 bar. The enormous average coulomb stress change occurred in 2015 at 0.2350 bar, while the minor average change occurred in 2011 at 0.0761 bar. The enormous average coulomb stress change in 2015 was triggered by an earthquake that occurred on March 3, 2015, with a moment magnitude criterion of 6.2 with a depth of 23.6 km and located at a longitude of 98.58 and latitude of -0.72 with a reverse fault type focal mechanism. In addition, the distribution of positive coulomb stress increased by 0.01-0.1 bar in 2015 and reached Aceh.

Table 2 is the result of an analysis of changes in coulomb stress from 2004-2021, which includes the average values of normal, shear, and alterations in coulomb stress that occur on Sibayak Volcano at a depth of 0-100 km. The highest average standard value occurred in 2018 at 0.1450 bar, while the lowest average value occurred in 2021 at 0.0849 bar. The highest average shear value occurred in 2020 at 0.0570 bar, while the lowest average shear value occurred in 2021 at 0.0251 bar. The enormous average coulomb stress change occurred in 2020 at 01073 bar, while the most minor average coulomb stress change occurred in 2021 at 0.0593 bar. The average value of changes in coulomb stress in 2021 is a continuation of the earthquakes that occurred in 2020 caused by small earthquakes occurring at an average depth of below 40 km. The change in coulomb stress on Sibayak Volcano is dominated from the west to the south, as shown in Figure 2. The coulomb stress value in this area has also included the calculation from the Deli Serdang earthquake on January 16 2017 (Setiadi et al., 2017). Apart from Sumatra, especially Aceh and North Sumatra, coulomb stress studies have also been carried out in Poso, Sulawesi.

The results of the study of the 2017 Mw 6.6 earthquake in Poso increased coulomb stress changes of >0.2 bar leading to the northwest and southeast of Sulawesi Island. (Sianipar et al., 2021). However, the coulomb stress changes in table 1 compared to table 2; the most significant change occurred in 2015. So, the average value of coulomb stress changes from 2011 to 2021 has experienced increases and decreases that are not constant. Changes in coulomb stress are not constantly caused by earthquakes with moment magnitude, depth, location, and variative focal mechanisms. Primarily the normal fault focal mechanism type occurring in 2016 and the following year, which affects or spreads stress horizontally around Sibayak Volcano.

Due to the high-stress concentration and the proximity to other densely populated cities (e.g. Padang Sidempuan, Bukittinggi, Solok and Padang Panjang), the bifurcation end of the GSF poses a significant potential for earthquake hazard (Sahara et al., 2018).

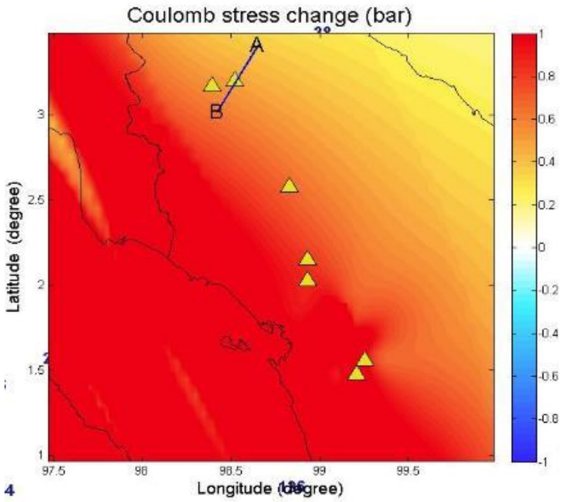

Figure 2. Changes in Coulomb Stress based on the northeast-southwest cross section of Sinabung Volcano 2011-2021

Apart from Sumatra, we also carried out coulomb stress calculations on the island of Java. The result of data processing is that there is an increase in Coulomb stress in the southern region of Java Island with a value range of 0.01-1 kPa and is thought to cause stress accumulation due to tectonic earthquakes that point downward on the peak of Merapi volcano (Puspasari & Wahyudi, 2017).

Changes in Coulomb Stress on depth 0-100 km

Table 3 shows the shear, standard, and coulomb change values at Sibayak from 2001-2021. The change in coulomb stress at Sibayak has a different average value at each depth. The lowest average shear value is found at a depth of 0 km at -0.38525 bar, while the highest average shear value is at a depth of 100 km at 0.3715 bar. The lowest standard mean value is at a depth of 0 km of 0.27675, while the highest standard average value is at a depth of 100 km of 0.19883 bar. The lowest average coulomb change value is at a depth of 10 km at -0.27875 bar, while the highest average coulomb change value is at a depth of 100 km at 0.45091 bar.

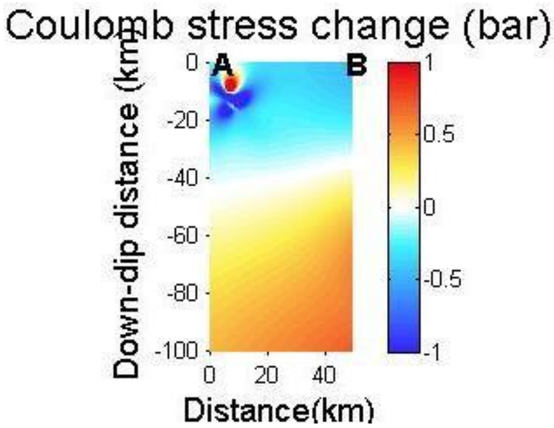

Figure 3. Changes in the Coulomb Stress of Sibayak Volcano at a depth of 0-100 km

Based on Figure 3 shows that the highest average value of coulomb stress change is 100 km, whereas the lowest average value of coulomb stress change (strain) is at a depth of 0 km with a magnitude of 7.6 Mw at a depth of 77.8 km and a longitude of 99.67o latitude. -0.79o, earthquake 22 February 2002 magnitude 6 Mw at depth 50 km and longitude 100.31o latitude -1.68o. Stress changes by the main earthquake affect the location of the emergence of aftershocks in the Sibayak Volcano area (Steacy et al., 2013). The shift in coulomb stress increases by approximately 0.1 bar in the fracture plane increases can trigger aftershocks (Stein, 1999). From the analysis of changes in the increasing coulomb stress, it is obtained that the emergence of small earthquakes, although these are assumed to be volcanic earthquakes distributed at a depth of 2-14 km.

Figure 4 shows the moment tensor of the analyzed earthquakes in western and southern Sumatra. The centroid moment tensor shows slip, reverse, and normal faults. A reverse fault is the centroid tensor moment that most often occurs around Sibayak Volcano. The moment tensor shows that the earthquake formed a path from west to north of Sumatra, which corresponds to the Indo-Australian plate, where the epicentre is parallel to the direction from southwest to northeast, close to the sinistral fault, which is located in the zone extending between Sinabung and Sibayak (Hendrasto et al., 2012).

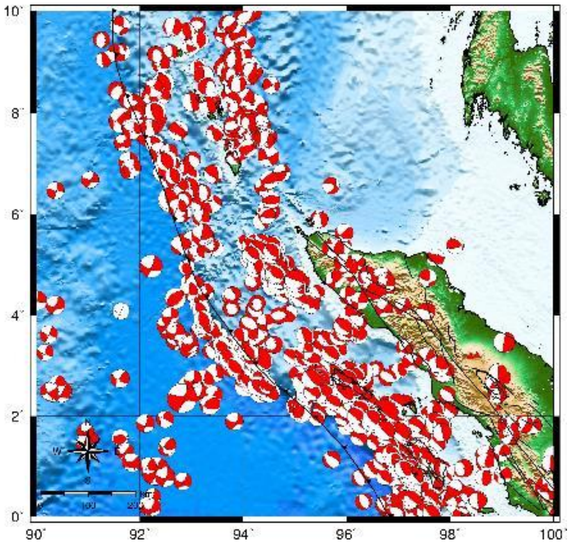

Figure 4. Moment Tensor of the 2011-2021 Earthquakes in western and northern Sumatra

The analysis was done in an area close to Sibayak, namely Bekancan, located 14.6 km away. The result is a hypothesis about the location of the swarm event relative to the Sinabung and Si lot in the Bekancan area, which is thought to be related to changes in stress due to volcanic-tectonic activity (Nugraha et al., 2018).

CONCLUSION

The average value of changes in coulomb stress at Sibayak Volcano constantly changes yearly. The tremendous average change in coulomb stress on Sibayak Volcano occurred in 2015, which was 0.235 bar, while the lowest average change in coulomb stress on Sibayak Volcano occurred in 2021 at 0.0593 bar. The highest average value of coulomb stress change also occurs at a depth of 100 km, while the lowest average value of coulomb stress change (strain) is at a depth of 0 km. Earthquakes around Sibayak Volcano influence the positive and negative changes in coulomb stress.

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