Coulomb Stress Changes in the 2004 Aceh Earthquake on the Mount Sibualbuali and Mount Lubukraya

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Abstract - *The great Aceh earthquake on December 26, 2004, had a magnitude of 9.2 Mw for 10 minutes with coordinates 3,316°N 95,854°E. had a tremendous impact on changes in geological conditions and disasters in Aceh and Asia, especially Southeast Asia and South Asia. Changes in geological conditions have resulted in Aceh and its surroundings becoming more prone to earthquakes, including volcanoes in North Sumatra. This research aims to determine the value of changes in coulomb stress that occur on Mount Sibualbuali and Lubukraya. This research uses the coulomb stress method presented in Coulomb 3.4 software. This research produces positive coulomb stress changes in 2021 which are marked by the red lobe, namely 0.197 bar on Mount Sibualbuali and 0.187 bar on Lubukraya. The highest increase in chwerees in coulomb stress was in 2015, namely 0.319 bar in Sibualbuali and 0.262 bar in Lubukraya. This research also resulted in the highest coulomb stress changes at a depth of 90-100 km so that it does not affect the volcanic activity of the two mountains.*

Keywords: *Earthquake; Coulomb; Stress; Sibualbuali; Lubukraya*

INTRODUCTION

The large earthquake that occurred in Aceh on December 26, 2004, with a magnitude of 9.2 Mw for 10 minutes with coordinates 3,316°N 95,854°E. had an extraordinary impact on changes in geological conditions and disasters in Aceh and Asia, especially Southeast Asia and South Asia. The earthquake resulted in a large tsunami that hit the surrounding area and affected the geological conditions in Aceh and its surroundings. The earthquake also caused the west coast of Sumatra such as Nias and Mentawai to become more earthquake-prone areas. The occurrence of earthquakes that occurred in Indonesia is inseparable from the fact that Indonesia is geologically located between the world's three major tectonic plates, namely Eurasia, the Indo-Australia, and the Pacific. This geological location also affects the phenomenon of volcanism in Indonesia. Indonesia is also known as one of the countries in the world with a very high level of volcanism around 30% of the active volcanoes in the world. Among the 129 active volcanoes, 79 are classified as type A, 29 are classified as type B, and 21 are classified as type C. (Pratomo, 2006) Mount Sibualbuali is an active volcano of type B, as there are no records of eruptions since the 17th century. Sibualbuali Volcano is part of the Barisan Mountains which stretches from north to south of the island of Sumatra on the geological map side of Padangsidempuan and Sibolga. The shape of the body of the Sibualbuali Volcano which is not patterned is dominated by the shape of a fault that is in the northwest-southeast direction. Mount Sibualbuali is a type of stratovolcano in North Sumatra, Indonesia. (Hendrasto et al., 2012)This mountain has two fumaroles in the south The activity of Mount Sibualbuali is characterized by geothermal manifestations such as hot tubs, hot springs, hot regions, and steaming earth. (Juliani, 2013)The mountain has two fumaroles in the southern part of the mountain. The lava dome comes from the Toru-Asik fault transfer. Mount Sibualbuali consists of andesite lava flows to dazzites that are generally Holocene in age (Hidayat et al., 2023).

Mount Lubukraya has a shape that is still shown in the shape of a clear volcanic cone accompanied by a crater wall, while the shape of the cone of the Sibualbuali volcano is no longer recognizable, because its shape has changed to an oval. Seismic characteristics as a reference for the development of the Padangsidempuan area, South Tapanuli Regency, North Sumatra Province (Lumbanbatu et al., 2009) (Ariyani, 2018) (Lumbanbatu, 2009) Characteristically, the eruptions of the Sibualbuali and Lubukraya volcanoes produced zeolite, bentonite, kaolin, andesite lava and tras. Mount Lubukraya and Sibualbuali cover the pre-tertiary rocks which are the Sihapas formation and the Telisa formation of the Kampar Group. Mount Lubukraya and Sibualbuali underwent geanticline erosion accompanied by a brief subsidence and rapid sedimentation in the surrounding basin and have formed an accumulation of paralytic to fluvial sediments (Minas Formation). The eroded material begins to fill the graben that is ready to accommodate and form a "piedmont" fan. Mount Lubukraya and Sibualbuali produce the youngest volcanic rocks in this area of Upper Plistocene age. Dasitan and andesite tufa, lava and lava are scattered on Mount Lubukraya. Mount Lubukraya and Sibualbuali also spew out magmatism of the Plicocene-Holocene age. The center of Lubukraya consists of dasitan and andesite tufa, lava and lava. This volcanic petrology has a porphyritic texture composed of plagioclase and quartz. The Sibualbuali and Lubukraya volcanoes produce zeolite, bentonite, kaolin, andesite lava and tras. (Sulistyawan & Harahap, 2013)

In addition to volcanism, Indonesia's geological location also affects earthquakes with several events that may have correlation with volcanoes with ΔCFS criteria. The earthquake event is the result of the release of rock tension that presses on each other. When the elastic limit of the rock is exceeded, there is an energy release as an earthquake due to the inability of the rock to withstand pressure. This will cause a change in the rock stress level both at the epicenter location and in the surrounding area. The occurrence of subsequent earthquakes can be known from the main earthquake that triggered it. One method to see the distribution of rock tension due to major earthquakes is the ΔCFS method (Weatherley, 2006)(Siwi et al., 2020) Some cases of aftershocks triggered by the main earthquake occurred in areas that are faults in Sumatra, Java, Sulawesi, Nusa Tenggara, Maluku) (Siwi et al., 2020) and Papua.

Several cases of mountain eruptions are suspected of triggering earthquakes such as the volcanoes Mount Sinabung, Mount Soputan and Gamalama (Sulawesi and Maluku). Based on the research of Pande et al., (Nursalam, 2016 & Fallis, 2013) from the Aceh earthquake resulted the transverse wedge that splits Mount Sinabung along 275 km with ΔCFS to a depth of 85 km with lobes reaching 5 x 10^{-3} bar. Meanwhile, in the study Walter, there was an increase in ΔCFS by 0.1-1 KPa which affected the increase in the fumarole of Mount Merapi in 2001.(Walter et al., 2007) Research on Mount Soputan and Gamalama, the results showed that Mount Gamalama experienced an increase in stress of 0.007 bar at a depth of 8 km while Mount Soputan experienced an increase in stress of 0.023 bar at a depth of 8 km where this increase in stress affected the occurrence of eruptions in the two volcans. (Sinaga et al., 2017) However, there are cases of volcanic eruptions that are not influenced by major earthquakes, such as Mount Rinjani which experiences increased stress but does not cause eruptions but uplift and subsidence in the northern part.(Utama et al., 2020) Based on the differences that occur in Rinjani and other volcanics, it is necessary to conduct research on changes in coulomb stress in Sibual-buali and Lubukraya.

RESEARCH METHODS

This study uses the same method as the previous research method, namely the descriptive analysis research method. This method uses the Coulomb Stress model calculated in the Coulomb 3.4 software of the USGS. The model presented in Coulomb 3.4 produces a calculation of the value of stress/strain change as well as its distribution resulting from the main earthquake. (Figure 1)

However, to see more clearly the distribution area, it is necessary to use GMT (Global Mapping Tools) to see in more detail the areas and coordinates that experience stress/strain changes in 3D. The stress/strain distribution map will also be presented in 3D on google earth. The data used in this study are the main earthquake parameters, namely the Aceh earthquake of December 26, 2004, to the 2022 earthquake. The parameters used are data on earthquake magnitude and coordinates, earthquake depth, earthquake type (strike, slip, dip), and tensor moment. (Shinji Toda, Ross S. Stein, Volkan Sevilgen, 2011)

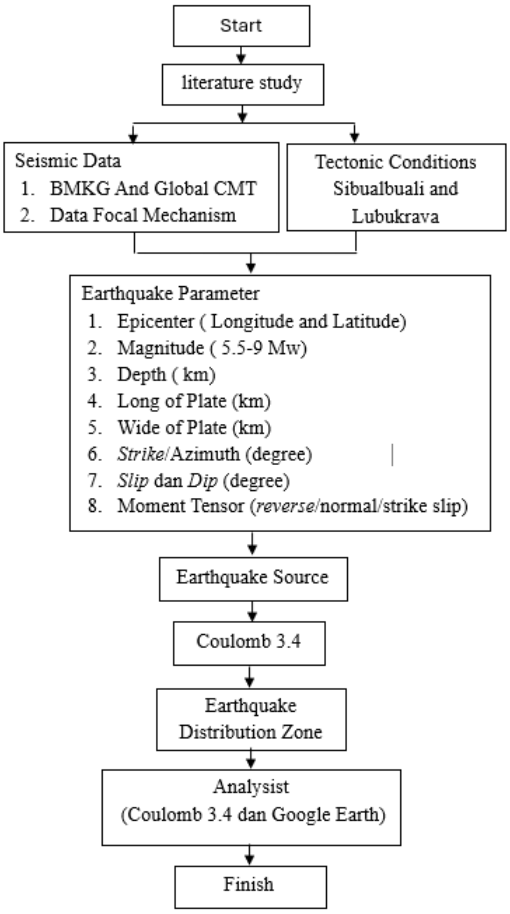

Figure 1. Flow Chart

Considering the collapse of the fracture as a combined cause between normal (reduced) and shear stress conditions, it is measured as a static stress coulomb stress stress criterion (King et al., 1994) Changes in static coulomb stress caused by earthquakes can help explain the distribution of aftershocks (Parsons et al., 1999), as aftershocks will occur when coulomb stress exceeds the collapse force of the fault surface. The change in voltage of the Coulomb state (ΔCFF) is defined as

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

$\Delta\tau$ represents the change in shear stress on the fault (positive in the slip direction), $\Delta\sigma$ is the change in normal stress (positive for unsqueezed faults), Δp is the change in pressure pore, and μ is the coefficient of friction, which ranges from 0.6 to 0.8 for most intact rocks (Harris, 1998). In Oklahoma, where fluid injection is 1-2 km deep near the epicenter, and this has been used for disposal since 1993 (Keranen et al., 2013). In addition, the effect of pore pressure cannot be ignored either. The change in pore pressure after the change in tension occurs and there is no fluid flow (undrained condition), is

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

where β is Skempton's coefficient and σkk is the sum of the diagonal elements of the stress tensor (Rice, 1992). Skempton's coefficient describes the change in pore pressure resulting from an externally applied voltage change, and often ranges in value from 0.5 to 1.0 (Green & Wang, 1986)(Hart & Wang, 1995)(Hart & Wang, 2010)(Cocco, 2002). For fault zone rheology, where the fault of the zone material is tougher than the surrounding material, $\sigma_{xx} = \sigma_{yy} = \sigma_{zz}$ (Rice, 1992) (Parsons et al., 1999) (Harris, 1998); so, $\frac{\Delta \sigma_{kk}}{3} = \Delta_{\sigma}$. Equations (1) and (2) combined with this assumption, making

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

where μ′ = μ (1-ℬ), the effective coefficient of friction. The effective coefficient of friction generally ranges from 0.0 to 0.8, but it is usually found 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 the calculation of coulomb voltage changes to minimize uncertainty. The location and geometry of the fault source, as well as the division of the slip over the plane source, play an important role in calculating the change in coulomb stress. (ΔCFS) Based on the magnitude of the earthquake, we model the source geometry with empirical relationships for strike-slip errors (Wells, Donald L.Coppersmith, 1994), which is built into Coulomb Software 3.3 (Shinji Toda, Ross S. Stein, Volkan Sevilgen, 2011)

RESULTS AND DISCUSSION

Results

ΔCFS modeling is performed to calculate and determine the static voltage distribution by major earthquakes. In addition, this modeling is also used to see the correlation of earthquakes that can trigger the next earthquake as well as the relationship between tectonic and volcanic earthquakes (Utama et al., 2020) Since the Aceh earthquake, December 26, 2004, the island of Sumatra has become an area that has experienced an increase in earthquake intensity than before. Several researchers have evaluated the stress of subduction zone changes, in the Sumatran fault and in 13 active volcanoes on the mainland of Sumatra. Most of the earthquakes that broke out since 2004 have modified stress levels during the entire subduction tectonic region. (Qiu & Chan, 2019)The Great Sumatra Fault (GSF) is one of the active faults that is continuously monitored. The high value of instability, makes it more susceptible to slippage movements, stress buildup, and eventually fault collapse (earthquakes), which can occur in later periods (Kusumawati et al., 2021) (Hardebeck & Okada, 2018)

Table 1. Average Normal, Shear, and Stress values in Mount Sibual-buali in 2004-2015

	2004-2011	2004-2012	2004-2013	2004-2014	2004-2015
Normal	0,068	0,069	0,086	0,119	0,033
Shear	0,169	0,165	0,164	0,194	0,305
Coulomb	0,196	0,193	0,198	0,201	0,319

Table 2. Normal Values, Shear, and Stress on Mount Sibual-buali in 2004-2021

	2004-2016	2004-2017	2004-2018	2004-2019	2004-2020	2004-2021
Normal	0,121	0,143	0,153	0,150	0,127	0,086
Shear	0,139	0,142	0,152	0,079	0,156	0,163
Coulomb	0,188	0,199	0,209	0,139	0,207	0,197

Table 3. Average Normal, Shear, and Stress values in Mount Lubukraya in 2004-2015

	2004-2011	2004-2012	2004-2013	2004-2014	2004-2015
Normal	0,099	0,102	0,136	0,176	-0,029
Shear	0,155	0,155	0,120	0,111	0,273
Coulomb	0,195	0,196	0,182	0,181	0,262

Table 4. Normal Values, Shear, and Stress on Mount Lubukraya in 2004-2021

	2004-2016	2004-2017	2004-2018	2004-2019	2004-2020	2004-2021
Normal	0,185	0,205	0,215	0,150	0,187	0,130
Shear	0,086	0,095	0,105	0,079	0,111	0,135
Coulomb	0,160	0,177	0,187	0,139	0,185	0,187

Table 5. ΔCFS in Sibualbuali and Lubukraya at a depth of 0-100 km

	Sibualbuali			**Lubukraya**		
Depth	shear	normal	coulomb	shear	normal	coulomb
0	-0,251	0,214	-0,203	-0,260	0,192	-0,183
10	-0,170	0,256	-0,068	-0,197	0,069	-0,170
20	0,265	-0,214	0,179	-0,205	0,051	-0,185
30	0,038	-0,156	-0,024	-0,031	0,050	-0,011
40	0,092	-0,023	0,083	0,109	0,025	0,119
50	0,174	0,042	0,191	0,204	0,058	0,233
60	0,244	0,103	0,284	0,285	0,114	0,331
70	0,293	0,157	0,355	0,334	0,168	0,400
80	0,323	0,200	0,403	0,358	0,210	0,442
90	0,335	0,232	0,428	0,362	0,238	0,457
100	0,333	0,250	0,433	0,351	0,251	0,452

Discussion

Coulomb Stress Change (ΔCFS) in Mount Sibual-buali

ΔCFS modeling through coulomb 3.4 was carried out to determine the static voltage distribution of earthquake events. The earthquake parameters used are magnitude moment, depth, longitude, and latitude obtained from the website of the Geophysical Meteorology and Meteorology Agency (BMKG) while the focal mechanism is downloaded from the United States Geological Survey (USGS). The input data analyzed is earthquakes that occurred during the December 26, 2006, to December 2022 earthquakes with a minimum moment magnitude of 5.5. An increase in ΔCFS is characterized by a red lobe while a decrease in ΔCFS is characterized by a blue lobe

Based on table 1, it can be seen that the average values of normal, shear, and ΔCFS that occur on Mount Sibualbuali at a depth of 0-100 km. The highest average normal value occurred in 2014 at 0.119 bar while the lowest average normal value occurred in 2015 at 0.003 bar. The highest average shear value occurred in 2015 at 0.305 bar while the lowest average shear value occurred in 2013 at 0.164 bar. The largest average ΔCFS value occurred in 2015 at 0.319 bar while the smallest average ΔCFS value occurred in 2012 at 0.193 bar. The largest average ΔCFS value that occurred in 2015 was triggered by an earthquake that occurred on March 3, 2015, with a magnitude moment criterion of 5.7 with a depth of 32.2 km and was located at a longitude of 97.72 and latitude of 1.58 with a normal focal mechanism type.

Table 2 is the result of ΔCFS analysis from 2004-2021 which includes the average values of normal, shear, and ΔCFS that occur on Mount Sibualbuali at a depth of 0-100 km. The highest average normal value occurred in 2018 at 0.153 bar while the lowest average normal value occurred in 2021 at 0.086 bar. The highest average shear value occurred in 2021 at 0.163 bar while the lowest average shear value occurred in 2019 at 0.079 bar. The largest average ΔCFS value occurred in 2018 at 0.209 bar while the smallest average ΔCFS value occurred in 2019 at 0.139 bar.

Coulomb Stress Change on Mount Lubukraya

This study uses the same model with the aim of determining the static voltage distribution of earthquake events. The earthquake parameters used are magnitude moment, depth, longitude, and latitude obtained from the website of the Geophysical Meteorology and Meteorology Agency (BMKG) while the focal mechanism is downloaded from the United States Geological Survey (USGS). An increase in ΔCFS is characterized by a red lobe while a decrease in ΔCFS is characterized by a blue lobe

Based on table 1, it can be seen that the average values of normal, shear, and ΔCFS occur on Mount Lubukraya at a depth of 0-100 km. The highest average normal value occurred in 2014 at 0.176 bar while the lowest average normal value occurred in 2015 at -0.029 bar. The highest average shear value occurred in 2015 at 0.273 bar while the lowest average shear value occurred in 2014 at 0.111 bar. The largest average ΔCFS value occurred in 2015 at 0.262 bar while the smallest average ΔCFS value occurred in 2014 at 0.181 bar. The average value of the largest ΔCFS that occurred in 2015 was also the same as Mount Sibual-buali which was triggered by the March 3, 2015 earthquake with a magnitude moment criterion of 5.7 with a depth of 32.2 km and was located at a longitude of 97.72 and latitude of 1.58 with a normal focal mechanism type.

Table 2 is the result of ΔCFS analysis from 2004-2021 which includes the average values of normal, shear, and ΔCFS that occur on Mount Lubukraya at a depth of 0-100 km. The highest average normal value occurred in 2018 at 0.215 bar while the lowest average normal value occurred in 2021 at 0.135 bar. The highest average shear value occurred in 2021 at 0.135 bar while the lowest average shear value occurred in 2016 at 0.086 bar. The largest average ΔCFS value occurred in 2018 and 2021 at 0.187 bar, while the smallest average ΔCFS value occurred in 2019 at 0.139 bar.

Distribution of Coulomb Stress 0-100 km in Mount Sibual-buali and Lubukraya

In addition to ΔCFS from 2011-2021, this study also calculates ΔCFS at a depth of 0-100 km. This calculation is needed to determine the volcanic geological conditions of Sibualbuali and Lubukraya. The value of ΔCFS over time is constantly changing both in depths of 0-100 km.

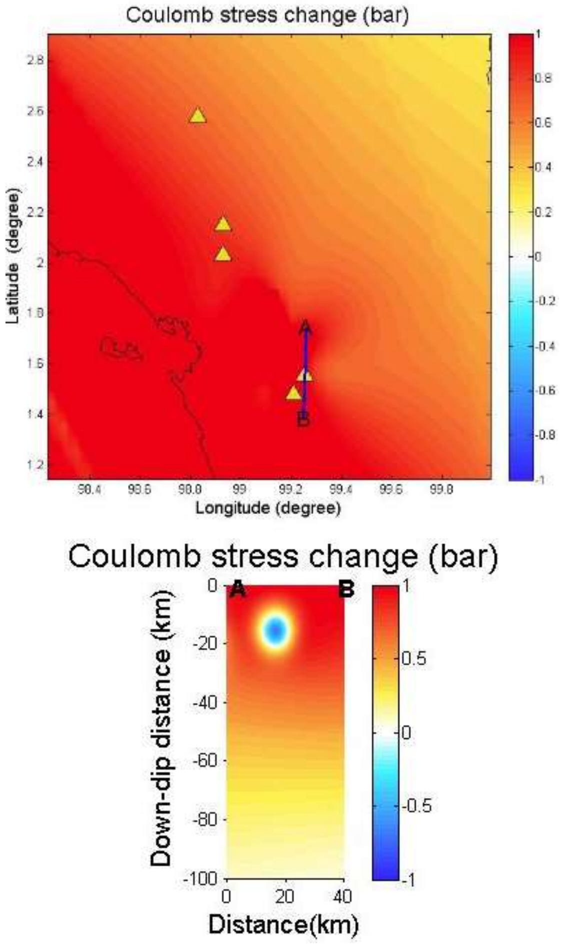

Figure 2. a)Cross Section ΔCFS in Sibualbuali Mount (north-south) b) cross section on depth

If you look at figures 2.a and 3.b, the distance between the Sibualbuali and Lubukraya volcanoes is still categorized as close with a distance of about 10.1 km. The location of Sibual-buali is in the north while

Lubukraya is in the south, so the geological conditions on the two mountains do not have too significant differences.

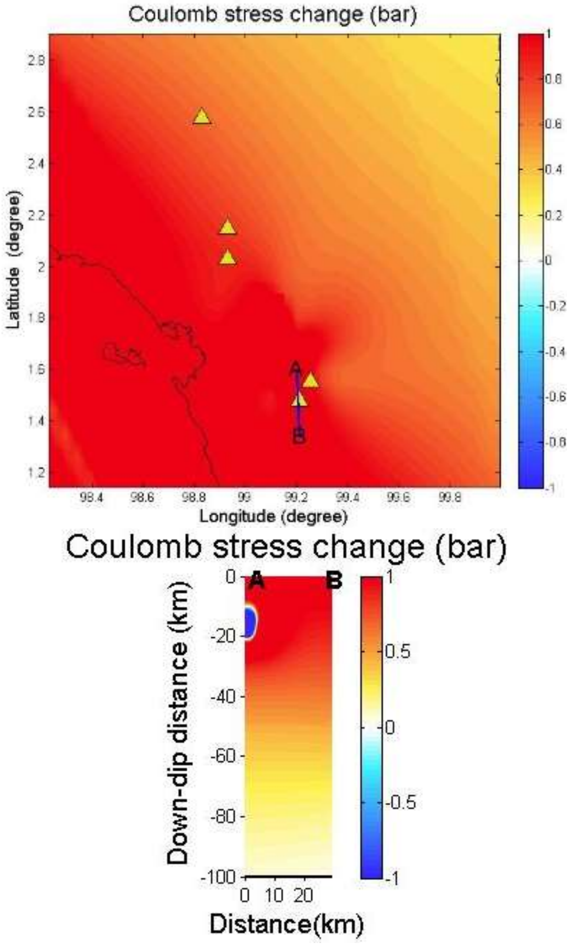

Figure 3. a)Cross Section ΔCFS in Lubukraya Mount (north-south) b) cross section on depth

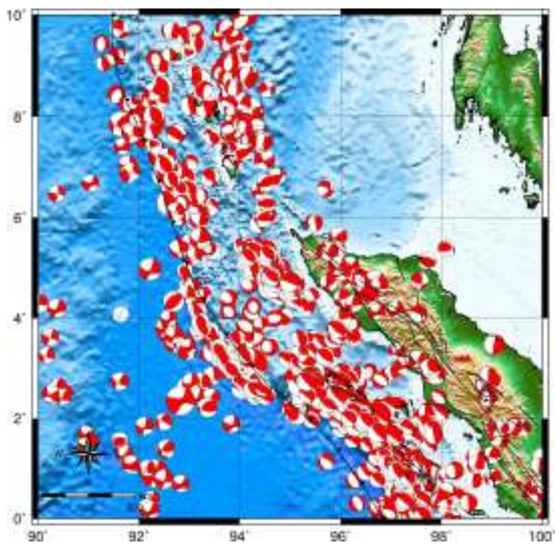

Figure 4. Focal Mechanism of Eartquake 2004-2021 on Northside Sumatera

Based on table 5, the highest ΔCFS value on Mount Sibualbuali is at a depth of 100 km with a value of 0.433 bar. The highest ΔCFS depth level in Sibualbuali is also similar to that in Lubukraya, which is at a depth of 90 km with a value of 0.457 bar. The ΔCFS values in Sibualbuali and Lubukraya are in stark contrast to the red lobes that should be in figures 2 and 3. However, due to the limitations of calculations and mapping from software 3.4, which is only 127 calculations (Sinaga et al., 2017) Other evidence can also support that the highest ΔCFS value is at a depth of >100 km based on earthquakes in southwest Sumatra, namely Nias, Sibolga, and its surroundings. (Figure 4)

From the ΔCFS value that occurred in these coordinates, it did not affect the eruption activity of Sibualbuali and Lubukraya. This may be because the ΔCFS values on the two mountains are still too low to affect the eruption. This incident is similar to the ΔCFS that occurred in Rinjani (Utama et al., 2020) There is not much information about seismic activity in Sibualbuali and Lubukraya so that the seismic relationship to volcanic activity of the two mountains is still unresolved. It is different from some seismic information about eruptions such as Sinabung, Sibayak (Sinaga et al., 2022) Toba (Sinaga & Nainggolan, 2023), and Sorikmarapi (Sinaga et al., 2021).

If the value of the change in coulomb stress on these two mountains is compared to Sibayak, the results will be different, namely 0.107 bar in 2020 and then decrease in 2021 by 0.059 bar.(Sinaga et al., 2022) Likewise with the comparison of changes in coulomb stress in Sorikmarapi, namely 0.144 bar in 2020 and then increasing to 0.157 bar in 2021.(Sinaga et al., 2021) There is a clear difference between the comparison of Sibayak and Sorikmarapi, where the change in coulomb stress in Sibayak decreases while in Sorikmarapi it increases. This is because Sorikmarapi's position is closer to the earthquake source than Sibayak, so Sorikmarapi has darker red lobes than Sibayak.

CONCLUSION

The Aceh earthquake, December 26, 2004, with a magnitude of 9.2 Mw provided positive coulomb stress changes in Sibualbuali and Lubukraya mountains with 0.197 bar and 0.187 bar respectively with an average depth of 90-100 km. This change in Coloumb stress does not affect the volcanic activity of the two mountains.

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