Coulomb stress analysis of West Halmahera earthquake mw=7.2 to mount Soputan and Gamalama volcanic activities

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Abstract. West Halmahera is the convergency of three plates, namely the Philippines plate, the Eurasian plate, and the Pacific plate. The location of the West Halmahera is located in the three plates, so the Western Halmahera potentially earthquake-prone areas. Some events increased activity of Mount Soputan and Mount Gamalama preceded by a massive earthquake. This research was conducted in the BMKG Region I Medan. This research uses Coulomb Stress Model. Coulomb Stress Model was used to show increasing and decreasing stress consequence from earthquake in the area of West Halmahera. Data such as the earthquake magnitude, earthquake depth, and Focal Mechanism required as input models. The data obtained from BMKG, Global CMT, and PVMBG. The result of data analyzed show an increase in the coulomb stress distribution at Mount Soputan 0.023 bar and 0.007 bar in mountain Gamalama. This stress followed by increased volcanic activity of the mount Soputan and mount Gamalama with freatic eruption type.

1. Introduction

Molucca Sea is located in the western Pacific Ocean, located near Molucca province, Indonesia. This limits the Sea Celebes Sea, the Banda Sea in the south, Halmahera, Seram, Buru, and Celebes. Tectonically, Halmahera Island situated between three plates, namely Philippines plate, the plate, the Eurasian plate and the Pacific plate [4]. Australian plate is located at the south and is bounded on the south by a fault system Sorong, which is a complex transpressif zone that extends to the east over 1500 km, from Papua New Guinea along the northern boundary of the Island of Papua until towards the west about 800 km to Celebes. Eurasia has a fracture eastern boundary in the southern Philippines and continue to fault West Halmahera [16]. Eurasian Plate in the region of Southeast Asia and the Philippines is a complex area and involves a lot of small plates that move semi-independent. West Halmahera island's arm mostly covered by younger volcanic products, so that the development tectonic can not be recognized properly. From earthquake research note that there are two seismic zones were intersected below banioff West Molucca Sea section shows the collision of the arc island. One of Benioff zones being tilted westward beneath the Sangihe arc and Celebes Sea, and the other sloping ramps to the east under Halmahera. Because it allegedly plate Sangihe (Eurasia) subducting
eastward and produce mélange in Talaud Island and Halmahera magmatic arc in the west, while to the west subducting plate Halmahera produce mélange in Sangihe Island. Thus becoming the Molucca Sea active earthquake area. Mw=6.6 earthquake that occurred August 26th, 2012, based in northeast Manado. On December 29th, 2013 an earthquake of Mw=5.7. And in the Molucca Sea region are also frequent aftershocks with a magnitude Mw=5 until now. Unique phenomenon also occurred around the Molucca Sea, the continuity of which there are two volcanoes that form an arc contradictory. Two continuity of this volcano is located on the northern arm of Celebes and Halmahera Islands. The appearance of two continuity of this volcano in line with seismotectonic studies that showed two subduction in the area. [2].

Based on PVMBG website, Soputan is one of the active volcano type stratovolcano located in the district. Tombatu, Minahasa North Celebes. With the location coordinates of 01°06’30” north latitude and 124°43’ west longitude. Soputan has an altitude of 1783.7 meters above sea level. Geomorphology Soputan and surrounding mountains can be grouped into three morphological units which include units of volcanic body morphology, morphological units hills and plains morphology. The seismic data that happens, there are similarities seismic activity before the eruption It shows the characteristics of the eruption of the Soputan is always preceded by earthquakes tremors were followed by a swarm of volcanic earthquakes avalanches and earthquakes. The occurrence of tremors indicate that magma is at a stage movement towards the surface. Occurrence of Earthquake Tremor repeated several times to reflect the occurrence of supply of magma to the surface, which in turn leads to accumulation of pressure at the surface.

Gamalama also one type A strato volcano with an altitude of 1715 m sea surface located in the Molucca Islands, Ternate (Ternate Island), North Molucca province. With the coordinates of 0°48’ north latitude and 127°19’30” east longitude. Gamalama is one of the active volcanoes located on Halmahera Island arcs, the northeast Molucca. The area is estimated as the area meeting some of the plates of which the Pacific Plate, Eurasian and Philippines and other small plates. Ternate Island formed by mount Gamalama take place on the path of subduction (subduction zone) sloping to the east with a small angle. Morphology Gamalama general is flat on the coast, but becomes steeper toward the top.

2. Methods

The data used in parameter earthquake is West Halmahera earthquake mainshock with Mw = 7.2 dated November 15th, 2016 and depth of 60 km with longitude/latitude of epicenter are 126.49° E /1.95° N (BMKG). Earthquake focal mechanism data with strike/dip/rake = 42°/35°/110° and the type of fault was reverse (Global CMT). And seismicity and focal mechanism data supporting earthquake from November 2004 until December 2014 with a minimum scale of an earthquake of 5.4 magnitude on the location of the North-South Molucca Sea, Halmahera, and the Minahasa peninsula.

Volcanic activity data was taken from PVMBG website. The volcano eruption type based on phreatic and phreatomagmatic in December 2014. This research use coulomb 3.4 software and analyzed coulomb stress method where it is based on static stress change. Static stress changes, the earthquake which resulted in changes in static stress triggering volcano-tectonic earthquakes 8 km under mount Soputan [3] and mount Gamalama thus increasing fault/fracture at the top of the mountain Soputan and mount Gamalama. If the rainfall is high enough, the rain water will be able to enter through the fault/fracture and meet magma, it will eruption. When an earthquake occurs, it changes the state of stress on nearby faults. In order to estimate the state of stress, the Coulomb failure stress is calculated using elastic dislocations on rectangular planes in a homogeneous and isotropic half-space following [13].

Various criteria have been used to characterize the conditions under which failure occurs in rocks. One of the more widely used is the Coulomb failure criterion, which requires that both the shear and normal stress on an incipient fault plane satisfy conditions analogous to those of friction on a pre-existing surface. In the laboratory, confined rocks approximately obey the Coulomb failure conditions, which also appear to explain many field observations [8]. Our approach is similar to those taken by [18], [14], [7], [15], [11], [5], [9], and [19]. In the Coulomb criterion, failure occurs on a plane when the Coulomb stress $\sigma_f$ exceeds a specific value.
\[ \sigma_f = \tau_\beta - \mu(\sigma_\beta - p) \]  
\hspace{1cm}(1) 

Where \( \tau_\beta \) is the shear stress on the failure plane, \( \sigma_\beta \) is the normal stress, \( p \) is the pore fluid pressure and \( \mu \) the coefficient of friction. The sign of \( \tau_\beta \) must therefore be chosen appropriately. In a system where the x- and y-axes and fault displacements are horizontal, and fault planes are vertical (containing the z direction), stress on a plane at an angle \( \psi \) from the x-axis (Fig. 1) is given by

\[ \begin{align*}
\sigma_{11} &= \sigma_{xx} \cos^2 \psi + 2\sigma_{xy} \sin \psi \cos \psi + \sigma_{yy} \sin^2 \psi \\
\sigma_{33} &= \sigma_{xx} \sin^2 \psi - 2\sigma_{xy} \sin \psi \cos \psi + \sigma_{yy} \cos^2 \psi \\
\tau_{13} &= \frac{1}{2} (\sigma_{yy} - \sigma_{xx}) \sin 2 \psi + \tau_{xy} \cos 2 \psi
\end{align*} \] 
\hspace{1cm}(2) 

We can now write the change of Coulomb stress for right-lateral \( \sigma^R \) and left lateral \( \sigma^L \) motion on planes orientated at \( \psi \) with respect to the x-axis in the following way.

\[ \begin{align*}
\sigma^R_f &= \tau_{13}^R + \mu' \sigma_{33} \\
\sigma^L_f &= \tau_{13}^L + \mu' \sigma_{33}
\end{align*} \] 
\hspace{1cm}(3) 

The effective friction coefficient is assumed to be 0.4 in all calculations. A \( \mu \) of 0.4 minimises the calculation error caused by the uncertainty in \( \mu \) to \( \pm 25\% \) [10]. Failure is facilitated on specified or optimally oriented faults when the Coulomb failure stress, \( \sigma_\phi \), rises. Unless specified, the optimal fault orientation is defined by the given regional stress field [1].

The accuracy of the Coulomb stress changes due to an earthquake depends mainly on the accuracy of the source parameters of that earthquake (i.e. the location and geometry of the fault rupture, and the amount and sense of slip distribution). The more accurate the source parameters the more reliable results, and thus interpretations can be made. A reliable estimate of the slip distribution and fault geometry is therefore very important for stress transfer calculations. Small differences in slip distribution and fault geometry can lead to significant perturbations in the Coulomb failure stress. Further details of the technique can be found in [10].

3. Result

3.1 Coulomb Stress Change West Halmahera November 15th, 2014

From the data of earthquakes in West Halmahera Mw = 7.2 dated November 15th, 2015 obtained from BMKG stations and data from the Global CMT Focal Mechanism processed in software Coulomb 3.4. The results of coulomb stress change of the earthquake in four field lobe consists of two lobe fields positive and two lobe field negative. Lobe positive value marked in red is an area of stress increase of 0.01 bar to 0.05 bar in the southwest and northeast. So that the affected area coulomb stress distribution of positive changes produce aftershocks that caused the stress increases due to the earthquake of Mw = 7.2. While the negative lobe marked with blue color which is an area the stress drop of 0.01 bar to 0.05 bar as shown in Figure 1.

**Figure 1.** Distribution coulomb stress changes earthquake of 7.2 Mw West Halmahera on November 15th, 2014 at a depth of 60 km

**Figure 2.** Cross section A-B Coulomb stress changes at a depth of 120 km
Coulomb stress Changes is positive spread in the depths of 0-120 km. From the results of cross section we can see that the coulomb stress this positive work at a distance of 25-300 km. Regional coulomb increase this stress has a value between 0.01 to 0.05 bar as shown in Figure 1. For areas with decreased coulomb stress is spread in depth at a distance of 0-120 km. From the results of cross section we can see that the positive coulomb stress work at a distance of 0-300 km. The range of values negative coulomb stress is between 0.01 to 0.05 bar as in Figure 2.

3.2 Effects of Changes in Coulomb stress Earthquake West Halmahera December 2004-December 2014 Concerning Volcanic Activity Soputan and Mount Gamalama

From the sum of 112 earthquakes that occurred in the Molucca Sea have red lobe is positive that an increase coulomb stress area of 0.01 bar to 0.05 bar and have a direction east, northeast, south, southwest, and west. While the negative lobe is negative which is a regional decrease in coulomb stress 0.01-0.05 bar to bar.

Figure 3. Distribution coulomb stress change West Halmahera 2004-2014 at depth 10 km.

Coulomb stress changes are positive spread in depth from 0 to 10 km. From the results of cross section we can see that the coulomb stress this positive work at distance of 0 to 300 km. Increased stress this area has a value of between 0.01 to 0.05 bar as shown in Figure 3. For areas with decreased coulomb stress at distance of 150 to 225 km. The range of values coulomb negative stress is between 0.01 to 0.05 bar as shown in Figure 4.

Figure 4. Cross section coulomb stress change West Halmahera Earthquake to depth 10 km

Figure 5. Cross section A-B coulomb stress change under mount Soputan

Figure 6. Cross section A-B coulomb stress change untuk mount Gamalama 2014 in depth 10 km
The cross section of the results obtained coulomb stress distribution changes under Soputan mountain to a depth of 10 km as shown in Figure 5. In the image cross section A-B in the area that increased stress working at a distance of 0 to 10 km. Rated positive Coulomb stress at a depth of 8 km is 0.023 bar.

The cross section of the results obtained coulomb stress distribution changes under Gamalama mountain to a depth of 10 km as shown in Figures 6. In the image cross section A-B in the area has increased coulomb stress. Value coulomb positive stress at a depth of 8 km is 0.007 bar.

Figure 7. The coulomb stress Change graph on the mount Soputan and Mount Gamalama period 2004-2014

Based on Figure 7 it can be seen the value of coulomb stress on Mount Soputan and Mount Gamalama at 2004-2014. At the time the mountain Soputan increased coulomb stress the Gamalama mountain also increased coulomb stress. Likewise, when Mount Soputan decreased coulomb stress the Gamalama mountain coulomb stress also decreased. While the decline in stress coulomb lowest occurred in 2004-2005 due to the number of earthquakes is less than in later years.

For value coulomb stress Changes at a depth of 8 km on the mountain Soputan and Mount Gamalama in 2004-2014 respectively 0.023 bar and 0.007 bar. The value of coulomb stress is caused by the massive earthquake of Mw 7.2 that hit West Halmahera with a strike 42°, dip 35° and rake 110° in the opposite direction to that mountain areas and mountain Soputan Gamalama coulomb stress decreased to 0.023 bar and 0.007 bar.

Based on data, Mount Gamalama have increasing in volcanic activity 34 days after the mainshocks of West Halmahera Earthquake Mw 7.2, while Mount Soputan have increasing in volcanic activity 41 days after the mainshocks of West Halmahera Earthquake Mw 7.2. The Epicenter of west halmahera earthquake mainshocks Mw 7.2 was located ~156 km from mount Gamalama while mount Soputan located ~226 km from the epicenter of west halmahera earthquake mainshocks Mw 7.2.

Although the mountain Soputan and Mount Gamalama coulomb stress has value only 0.023 bar and 0.007 bar but indirectly affect volcanic activity in both the mountain. As a result of the increase in the value of the coulomb stress, physical conditions in the magma rising magma [6]. Among the increasing pressure of the gas bubbles of magma and magmatic system, sehuniga causing cracks widen-fractures or the occurrence of new cracks in the rocks of the magma chamber wall and is characterized by volcano-tectonic earthquakes on Mount Soputan and Mount Gamalama. Based on data from PVMBG that when it mount Soputan and Mount Gamalama is experiencing the rainy season with moderate rainfall. Rainwater that seeps through the cracks-cracks of rocks and mixes with magma to form gas bubbles. The gas bubbles will increase the pressure in the magma chamber that previously had a change of dynamic stress. If the magma dome can not withstand the pressure from the inside due to the density of the walls of the dome was reduced because of rain, the magma dome had collapsed due to the gas pressure teperangkap in the magma chamber, causing phreatic eruption at Mount Soputan and phreatomagmatic on mountain Gamalama [6]. As a result of the earthquake that occurred in West Halmahera/Molucca sea or water it can indirectly affect volcanic activity is
increasing to become status of alert on December 26th, 2014 on Mount Soputan and become status of alert on December 19th, 2014 on Mount Gamalama.

4. Conclusion
In accordance with the purpose of research, the results achieved are 1) Earthquake in West Halmahera indirectly affect mountain Soputan and Mount Gamalama due to long distances to be observed coulomb stress that can transfer stress and affect stress fracture in Soputan and Gamalama. 2) The method coulomb stress can see accumulate value of coulomb stress change correlation with addition earthquake in surrounding West Halmahera. 3) Coulomb stress Changes that comes from the earthquake period November 2004-December 2014 including the west Halmahera 7.2 Mw earthquake happens Mount Soputan generate increased coulomb stress at a depth of 8 km is 0.023 bar while Gamalama mountain coulomb increased stress at a depth of 8 km is 0.007 bar resulted in a mountain of volcanic activity Soputan and Mount Gamalama increased caution status to become alert after ±30 days a major earthquake occurs. Things were discovered from analysis used are 1) the results of this study can be concluded that the Molucca Sea and surrounding waters is a zone prone to earthquakes and volcanic activities, especially mountain Gamalama and Mount Soputan. 2) Based on the historical data from BMKG and Global CMT has earthquakes as much as 112 times the scale of magnitude 5.2 and 7.5 magnitude on the geographical area of 4.95 north latitude-1.05 south latitude and 123.49 east longitude-129.49 west longitude in the period November 2004 to December 2014. With this type of fault that occurred in the waters of West Halmahera dominant fault ride / reverse. 3) The distance and the large magnitude earthquake affecting the value and reach coulomb stress, and volcanic activity of Mount Soputan and Mount Gamalama. 4) Coulomb stress Changes change on Mount Soputan has similarities with the coulomb stress changes on Gamalama mountain although the value is different. 5) The number of earthquakes that can be processed in coulomb 3.4 software just 127 so that only an earthquake with a magnitude 5.4 mw which can be processed.

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