Preliminary Result of The Influence of Earthquake Stress Change and The Implication for Soputan Volcano and Lokon Volcano

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Abstract. On February 6, 2016, an eruption occurred on the Northern Sulawesi arm, particularly Soputan volcano. One day earlier, Lokon volcano located close to Soputan volcano was decreased its status from standby to alert level by the Center for Volcanology and Geological Hazard Mitigation (CVGHM). The different reactions of two volcanoes proposed the question why the increment activity just happened in Soputan volcano. This uniqueness made us to suggest that static stress of earthquake may control the magmatic systems. We investigate here the earthquake-volcanism interaction through static stress changes by using Coulomb failure stress associated with an earthquake occurred in the Northern Molluca Sea on 25 November 2015. We slice the same dip for the each region in vertical cross sections. Therefore, the Coulomb failure stress pattern can be investigated beneath the study area. Our results suggest that Coulomb failure stress was increased by $0.3 \times 10^{-3}$ to $0.4 \times 10^{-3}$ bar below the Soputan’s region. Lokon’s region, the stress was reduced by $-0.1 \times 10^{-3}$ to $-0.4 \times 10^{-3}$ bar. The positive change may perturb magma overpressure leading to eruption and promoted volcanic earthquakes. The situation was very different that Lokon volcano ran into reduction activity and volcanic earthquakes were discourage due to stress shadow. We show that the difference volcanic response were likely controlled by static stress of the earthquake.

1. Introduction
The Sulawesi island lies near the triple junction between of the Sunda, Australia, and Philippines plates [1,2,3,4]. The collision caused the subduction of the Molluca Sea Plate which has an inverted U shape subduction. The plate dive to the east of Halmahera arc and to the west of Sangihe arc [5]. One of the consequence of the activity is volcanic arcs in Northern Sulawesi Arm, such as Lokon volcano and Soputan volcano.

An unusual phenomenon between two volcanoes were occurred in Northern Sulawesi arm. According to national news, Soputan volcano and Lokon volcano have a difference response at almost the same time. The day before the eruption of Soputan volcano on 6 February 2016, Lokon volcano was decreased its status set by Center for Volcanology and Geological Hazard Mitigation (CVGHM) due to reduction activity.

Numerous studies were conducted to examine the link of some processes to volcanic eruptions. The activity are generally preceded by measurable indications, one of which is the influence of earthquake occurrence [6,7,8,9]. In this study, we investigate how this interaction works, between earthquake and
volcano. We analyze the stress change caused by an earthquake which occurred close to the volcanoes before Soputan volcano’s erupted. Based on these result, we point out that the earthquake may promote the difference responses of two volcanoes by analyzing Coulomb failure stress distribution.

![Figure 1](image1.png)

**Figure 1.** Regional tectonic features of Sunda-Australia-Philippine plates. The dark line indicate the fault line [1]

2. **Data**

To obtain stress change pattern on the study area, we utilized the Coulomb failure stress distribution. We used an earthquake data archived from the Global Harvard Centroid Moment Tensor (CMT Global Harvard) (figure 2 and table 1). Nodal plane II was used which is consistent with the tendency of the 25 November earthquake’s aftershocks based on the mainshock stress change in which the determination already applied with the same method by previous workers [10].

![Figure 2](image2.png)

**Figure 2.** An earthquake in Northern Molluca Sea reported by Global CMT. Red star shows the epicenter of the 25 November 2016 (Mw 5.7) and focal mechanism (blue and white ball) with the fault plane (strike = 1°, dip = 52°, rake = 64°). Triangles indicate Soputan volcano (▲) and Lokon volcano (▲). Map was created using the Generic Mapping Tool (GMT) [11].
Table 1  Focal mechanism of the 25 November 2015 earthquake

| Mw | Nodal plane I (˚) |  | Nodal plane II (˚) |  | Source |
|----|------------------|---|------------------|---|--------|
|    | Strike | Dip | Rake | Strike | Dip | Rake |        |
| 5.7 | 219 | 45 | 119 | 1 | 52 | 64 | Global CMT |

We also used 3102 events which were obtained from Meteorology Climatology and Geophysics Agency (MCGA) from 2009 to 2016 to conduct tomographic inversion in Northern Sulawesi Arm area and its vicinity (figure 3). The events were recorded by 13 stations and AK 135 was used velocity model.

Figure 3. The seismicity between 2009 to 2016 of Northern Sulawesi Arm area and its vicinity. The colors of circle indicates the depth of event (red = 0-100 km, yellow = 100-300 km, and green > 300 km). Map was created using the Generic Mapping Tool (GMT) [11]

3. Theory and Methodology

3.1 Coulomb Failure Stress

We examined whether coulomb failure stress change of the earthquake related to the Soputan eruption and the Lokon volcano. In this equation, geometry information, slip direction, and coefficient of friction are utilized into stress change calculation using Coulomb 3.3 software [12,13]. The equation can be represented as:

\[
\Delta CFF = \Delta \tau + \mu' \Delta \sigma
\]

where \(\Delta CFF\) is Coulomb stress increment, \(\Delta \tau\) is the change in the shear related to the slip distribution (positive in slip direction), \(\mu'\) is the apparent coefficient of friction correspond to the change of pore pressure and \(\Delta \sigma\) is the changes in the normal stress (positive when the fault is unclamped) [12] [14,15]. If \(\Delta CFF > 0\), the stress are loaded into medium or fault plane and brought closer to failure. If \(\Delta CFF < 0\), the fault plane is relaxed or stress shadow. It means the medium lost the stress after the first earthquake occurred [15]. The spatial pattern of stress changes is displayed into map with value of \(\Delta CFF\) using the software.

3.2 Tomographic inversion

To reconstruct the medium or to determine the tectonic pattern beneath Northern Sulawesi Arm whether the existence of volcanoes are influenced by tectonic activity, here we applied delay time tomography algorithm. This method able to minimalize the difference between calculation time (Tcal)
using ray tracing pseudo-bending method [16] and observation time (Tobs). The method is applied in a packet program which is simulps 12 [17].

4. Results and Discussion
To confirm the volcanoes existence are influenced by the Molluca Sea Plate, here we made seismic tomography (figure 4).

![Figure 4](image)

**Figure 4.** (a) The location of Soputan volcano and Lokon volcano, solid lines and triangles depict cross section line and the volcanoes, Soputan volcano (▲) and Lokon volcano (▲). (b) and (c) The results of tomographic inversions below the volcanoes and its vicinity with contour scale of perturbation or anomaly value of seismic wave velocity in percentage between -5% to +5% correspond to AK 135 velocity model.

The tomograms for the structure below the volcanoes are shown in figure 4. According to figure 4, we consider that the opposing subduction of the Molluca Sea plate was defined by positive perturbation (blue color). On the other hand, negative perturbation dominated beneath volcanoes.
which indicated partial melting or magma chamber. So we infer that both volcanoes are located on subduction zone and the existence of the volcanoes are close ties of the tectonic process. Moreover, we presume that the earthquake occurrence which is one of effect of tectonic activity may influence the activity of those volcanoes.

To understand how the earthquake may affect the volcanoes condition, we calculated the stress change into maps. The map of stress distribution of 25 November 2015 earthquake shown in figure 3. Positive change ($\Delta CFF > 0$) and negative change ($\Delta CFF < 0$) in maps are represented with red and blue colors, respectively. The pattern of the Coulomb stress change increased in the SW-NE, while a lobe of stress reduction or stress shadow dominated in the SE-NW. The stress pattern were imaged laterally and vertically at a depth of 50 km (figure 5 and figure 6).

Figure 5. A map of Coulomb stress changes of the 25 November 2015 earthquake. Triangles indicate Soputan volcano (▲) and Lokon volcano (▲).

Figure 6 shows that the positive stress (warm colors, $0.1 \times 10^{-3}$ - $0.3 \times 10^{-3}$ bar) slightly impacted the Soputan volcano’s zone, but another was influenced slightly by the negative stress (blue colors, from $-0.1 \times 10^{-3}$ to $-0.4 \times 10^{-3}$ bar). The models show that the zone of yellow-red and blue was distributed through the cross-section. The positive stress which was distributed beneath Soputan Volcano at a depth $\geq 15$ km may affect the magma chamber, changed the magma overpressure and triggered volcanic earthquakes where the magma chamber was approximately at $> 8$ km [18] and the possibility to impress the magma overpressure was close enough.

On the other hand, the reduction stress was dominant beneath Lokon volcano at a depth 0 km - 30 km which influenced the volcano’s medium to be relax. Moreover, the magma chamber was detected at a depth 2 km – 3 km [19]. So, the magma chamber of Lokon may be undisturbed and the volcanic earthquakes occurrence may be discourage. These analyses resolve this unusual phenomenon and we consider that the enhancement and reduction in stress change able to control the volcanoes circumstance.
Figure 6. Change in Coulomb stress at profiles along the Soputan volcano and Lokon volcano triggered by Mw 5.7 earthquake. Triangles indicate Soputan volcano (▲) and Lokon volcano (●). The left shows the location of the volcanoes and slice lines (solid line). The right shows the cross-section along volcanoes lines at a depth of 50 km and the location magma chamber each volcano which is represented by dashes circle (black and red are the magma chamber of Soputan volcano and Lokon volcano, respectively).

5. Conclusions
The activity between Soputan volcano and Lokon volcano are coupled with distribution of Coulomb failure stress of the earthquake. Moreover, our study perhaps provide new information for controlling volcanic activity from this unusual phenomenon and this study will be clearly seen if several studies are combined to figure it out how this phenomenon works.
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