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Paper:

Evaluation of Volcanic Activity at Sinabung Volcano, After More Than 400 Years of Quiet

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Before its 2010 eruption, Sinabung Volcano was a B-type volcano, in its Indonesian classification. A series of explosions featuring 1-5 km high phreatic-ash columns occurred from August 27, 2010 untill September 7, 2010. SO_2 flux measured during the eruptions showed sizeable gas emission and the youngest volcanic product has age of 1200 years BP obtained from ^{14}C dating. At the end of August 2010, four continuous seismic stations were established around the volcano, and 6 additional stations were deployed in October 2010. Deformation monitoring was conducted temporarily till in February 2011, four continuous GPS stations were installed. All were set up through collaboration between Indonesian and Japanese academic and government institutions. Hypocenter calculations using data of 4 seismic stations from September to October 2010 showed two concentrations for shallow volcanic earthquakes (VTB) 0.5-2 km beneath the crater and for deep volcanic earthquakes (VTA) 2.5-14 km beneath the crater. These epicenters defined a northeast-southwest lineament, near an elongated sinistral fault zone between Sinabung and Sibayak volcanoes. Earthquake sources went deeper northeastward. Results using the data of 10 stations from November 2010 to February 2011 showed that earthquakes were concentrated at depths of 4-6 km beneath Lake Lau Kawar. Tilt and Electro-optic Distance Measurement (EDM) measurements from August to September 2010 showed no significant changes We inferred that since the last explosion in 7 September 2010, stabilization process both in pressure and energy were low.

Keywords: Sinabung volcano, the 2010 eruption, phreatic, volcanic earthquakes, deformation monitoring

1. Introduction

Indonesia has 127 active volcanoes which are classified into 3 types : (i) an A-type that has erupted at least once since AD 1600, (ii) a B-type that has not erupted in at least 400 years, and (iii) a C-type that shows only remnants of volcanic phenomena. Until the end of August 2010, 68 of 127 volcanoes were classified as an A-type and Sinabung volcano was classified as a B-type.

Sinabung Volcano is located in Karo Regency, North Sumatera Province (**Fig. 1**). Geographically, the summit lies at 03°10′ North, 98°23.5′ East with a height of 2460 m asl (above sea level) [1]. Geological mapping was done in October-November 2010. The youngest Sinabung deposit is a pyroclastic flow (**Fig. 2**) that lies in the southeastern part. From petrogenetic analysis, it is concluded that the constituent of this deposit had been originated from thin lava flow effused during eruptions of low to moderate intensity. This youngest deposit had occurred at approximately 1200 ^{14}C years BP. The identification of eruption products showed that the 2010 eruption was phreatic [3], based on samples of ash dated September 4, 2010 using X-Ray Diffraction (XRD). These ash contains silicon oxide, iron oxide (magnetite), sodium, calcium, alluminum silicate (anorthite), iron sulfide (pyrite) and potassium alluminum silicate hydroxide (illite). Those mineral contents indicate that the ash has strong hydrothermal alteration.

There had been no monitoring of volcanic activity at Sinabung volcano before the eruption in August-September 2010, and it is difficult to evaluate volcanic activity at Sinabung volcano after its longterm (>400 years) of dormancy. On August 27, 2010, Sinabung started erupting, with the first phreatic eruption and then followed by another series of explosions on August 28, 29, 30,

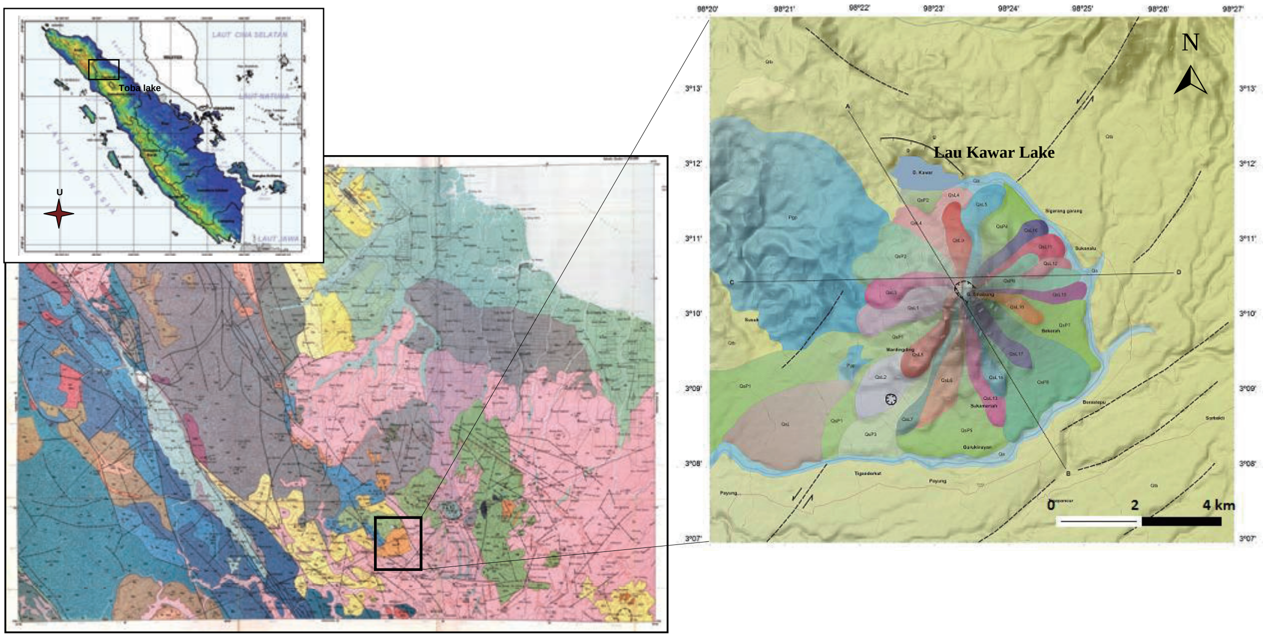

Fig. 1. Location of Sinabung volcano northeast of Lake Toba, North Sumatera (index), a geological map of Medan Quadrangle [2] (left), and a geological map of Sinabung volcano [3] (right).

Fig. 2. Youngest pyroclastic flow deposit of Sinabung. ^{14}C age of charcoal is 1200 BP (= 740 – 880 A.D. at 1 sigma).

Fig. 3. Explosions of Sinabung volcano at 06:23 on August 30 (left) and at 17:59 on September 3 (right), 2010.

September 3 and 7, 2010. The eruption produced 1-5 km high volcanic ash columns (**Fig. 3**). In this paper, we will describe and evaluate the volcanic activity of Sinabung volcano, especially the 2010 eruption and is other recent volcanic activity till July 2011.

The evaluation applies some methods, such as seismic, deformation (EDM, Tilt, GPS), geology and SO_2 observations. Seismic observation is carried out to determine the hypocenter distribution of volcanic earthquakes associated with the magma ascent. Tilt and GPS observations are to detect the movement of subsurface materials precedes volcanic eruptions and to identify the geometry of pressure source location (magma chamber). The calculation applied in Tilt and GPS use some parameters as constraint that obtained from seismic observation. EDM observation is to detect the ascending pressure reflected as the shortening distance among baselines. SO_2 observation is to predict the impending eruption due to gas amount increase.

2. Chronology of 2010 Eruption

The first explosion of Sinabung volcano occurred on August 27, 2010. Center for Volcanology and Geological Hazard Mitigation (CVGHM) sent a quickresponse team to monitor the activity of the volcano. On August 28, weak white ash plume rose up to about 20 meters in high and there was no sign of waxing in activity.

On August 29 at 00:12 WIB, when a 1500 meters ash column was produced CVGHM upgraded Sinabung volcano from B-type to A-type and raised its alert level to Level IV (AWAS). It was also decided to evacuate people within a radius of 6 km from the active crater. At that time, CVGHM had deployed seismic stations around the volcano. Activity continued on August 30, and at 06:23 an explosive eruption occurred and an ash column reached about 2000 meters above the summit This eruption occurred without any clear precursor. After this eruption,

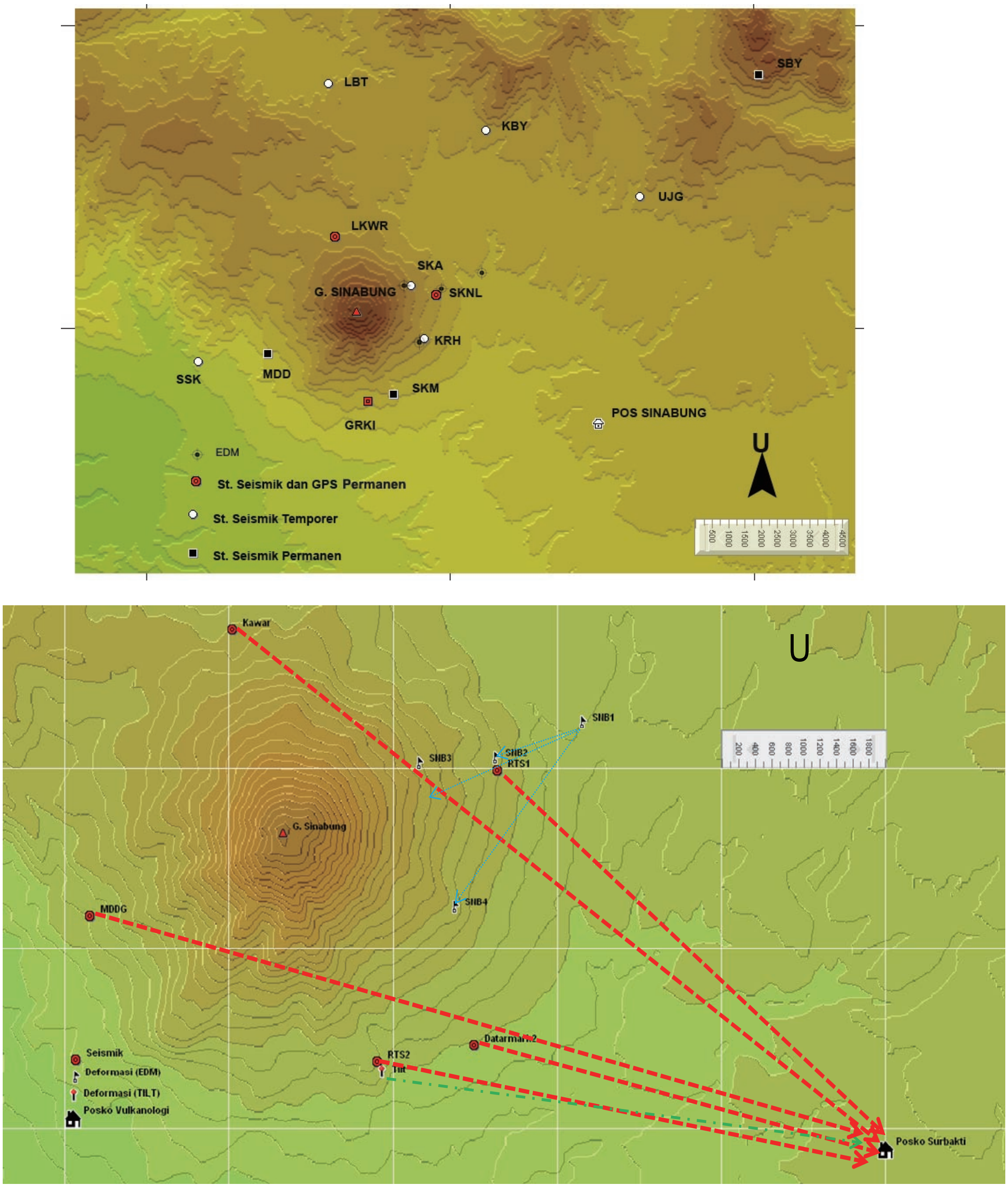

Fig. 4. Monitoring network at and around Sinabung volcano (above) EDM and tilt locations (below).

volcanic activity seemed to decrease and seismicity was dominated by gasemission earthquakes.

Following continuous tremors and tectonic earthquake on September 2, an explosive eruption at 04:38 on September 3 sent an ash column to about 2000 meters above the summit. Tremors occurred continuously until the next explosive eruption at 17:59 on the same day which produced an ash column more than 1000 meter high An explosive eruption preceded by a volcanic earthquake swarm occurred at 00:23 on September 7 with an ash column approximately 5000 meters high. The last eruption observed at 19:03 produced a 500 meters high ash plume. After that volcanic activity decreased. Seismicity remained high, however, with many earthquakes. Continuous tremor occurred on September 9 and 14-15, but no eruption followed. Visual observation marked continuous ash emitted from Sinabung crater and covered about 100 m along the eastern upper slope of Sinabung volcano.

3. Monitoring Method

Monitoring of Sinabung volcano has been conducted since the end of August 2010. Four seismometers were deployed around the volcano (**Fig. 4**). Three stations were

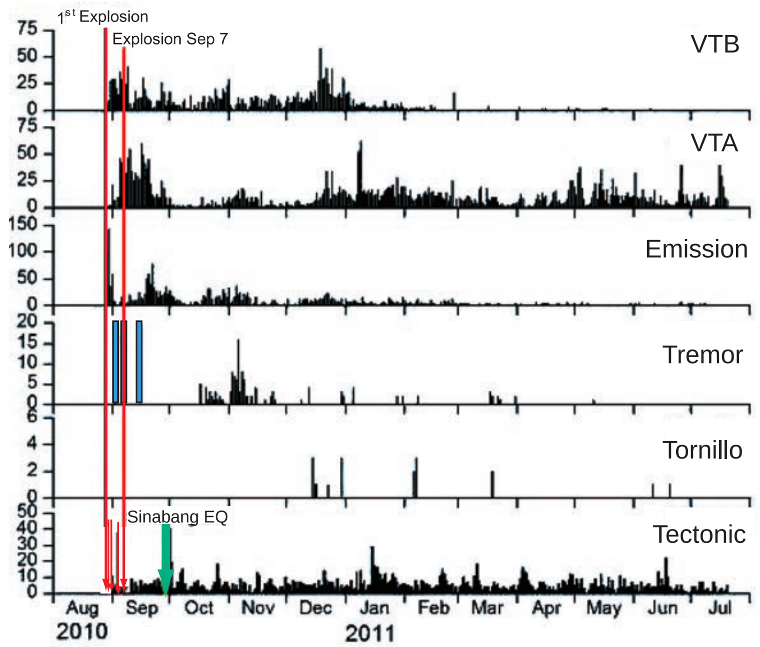

Fig. 5. Daily number of earthquakes from August 2010 to July 2011 with explosions noted by thin arrows and Sinabang earthquake (M5.3) noted by bold arrows. Bars indicates occurrence of continuous tremors.

equipped with a 1-component short-period seismometer L-4C (Mark) and one station using a 3-component seismometer L-22D. Analog data was transmitted continuously to the observatory using radio waves. In October 2010, CVGHM in collaboration with the Disaster Prevention Research Institute (DPRI) of Kyoto University added 6 temporary stations in order to increase the coverage of surrounding tectonic faults and Sibayak volcano (**Fig. 4**). All stations were equipped with 3-component seismometer. Seismic data was digitized using the EDR7000 Kinkei System, with a sampling rate of 250 Hz, and downloaded every month. Other monitoring included one tiltmeter station and five EDM benchmarks as shown in **Fig. 4**. The tiltmeter transmitted continuously while EDM measurements were conducted daily. In February 2011, four continuous GPS stations were established around Sinabung volcano (**Fig. 4**) using a receiver LEICAGR10 with an antenna type LEIAR10. GPS data was transmitted continuously every 1 hour. SO_2 flux was measured during the eruption in August-September by using a Mini-DOAS (Differential Optical Absorption Spectrometer) while the temperatures of hot springs were measured using a thermocouple.

4. Seismicity

Volcanic earthquakes at Sinabung volcano are classified into five-types: deep-VTA-type volcanic earthquakes, shallow VTB-type volcanic earthquake, gasemission earthquakes, tremors, and T-type (Tornillo) earthquakes. VTA-type earthquakes were characterized by clear onset with an interval of S-P time between 1 and 3.5 seconds. VTB-type earthquakes are classified as volcano tectonic earthquake with aninterval of S-P time less than 1 second. The dominant frequency of VTB-type earthquakes is similar to that of VTA-type earthquakes, implying a similar mechanism for both. Gasemission earthquakes are characterized by highfrequency content and accompanied by the emergence of a plume from the crater. Tremor earthquakes appear before and after eruption. The amplitude of seismicity sometimes ranges over the drum recorder and the duration ranges from minutes to days. T-type earthquakes also recorded were characterized by long duration of coda and narrow-band frequency content.

Seismicity of Sinabung volcano (**Fig. 5**) is dominated by VTA, VTB, and gasemission earthquakes. From 8 to 17 VTA earthquakes and 2 to 9 VTB earthquakes were recorded per day. A swarm of VTA and VTB earthquakes still occurr every month. Gasemission earthquakes were also recorded frequently at an average of 10 per day. Occurrence of VT earthquakes in large number makes Sinabung one of the highest risk volcanoes in Indonesia. An increase in VT earthquakes became the precursor of eruptions during the crisis period of August and September 2010.

Their magnitude and hypocenter of the earthquake are determined in order to identify the source of Sinabung volcano earthquakes. Magnitude is calculated based on the coda amplitude of the earthquakes. Calculated magnitude was between 0.1 and 2.32 which showed the high energy of volcanic earthquakes near the volcano that were sometimes felt by people near to the source. In the period of September to October 2010, hypocenters were calculated from the arrival times of P- and S-waves from 4 stations using *GAD* software [4]. Our velocity model use two layers with P-wave velocities (V_p) 2.8 km/second and a

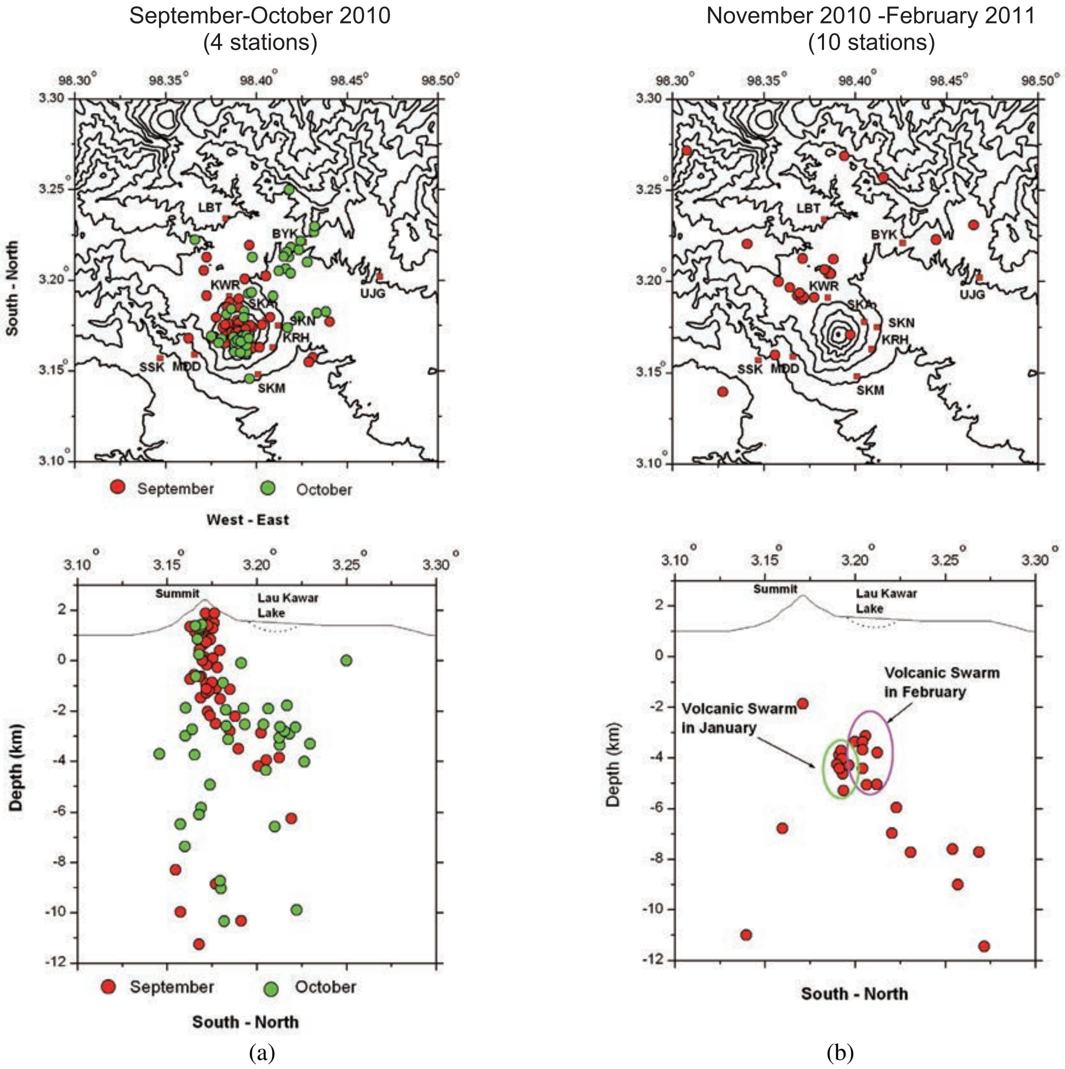

Fig. 6. Hypocenter of volcanic earthquakes from 4 stations during September and October 2010 (a) and 10 stations from November 2010 to February 2011 (b).

thickness of 2.4 km and a second layer 3.9 km/second and a ratio of $V_p/V_s = 1.73$. Residual error in hypocenter calculation is less than 0.1 second for P-waves and 0.2 second for S-waves. Hypocenters in the period from November 2010 to February 2011 were calculated from 10 seismic stations using *Hypomh* software [5], assuming the same velocity structure with those of September-October 2010 The preliminary results of hypocenter were calculated using *Hypomh* software for time saving and overall effective processing. The result of hypocenter calculation was limited by residual error of less than 0.2 second.

5. Evaluation of Volcanic Activity

Hypocenter distribution during the crisis period of September to October 2010 is shown in **Fig. 6(a)**. In September, hypocenters of VTB earthquakes were concetrated at depths of 0.5 to 2 km beneath the crater, while those of VTA earthquakes lies at depths of 2.5 to 14 km. In October, VTB earthquakes were located 1-1.5 km beneath the crater. VTA earthquakes were distributed at depths of 2 to 14 km. Epicenters are aligned in the direction from southwest to northeast, close to sinistral fault that lies in elongated zone between Sinabung and Sibayak volcanoes (see geological map in **Fig. 7**). The locations of earthquakes became deeper northeastward. **Fig. 6(b)** shows the hypocentral distribution from November 2010 to February 2011. Most of the earthquakes were concentrated at depths of 4 to 6 km beneath Lake Lau Kawar (**Figs. 6(b)**, **1** and **7**). A few VTA earthquakes were located at depths of 8 to 14 km beneath the north part of the volcano.

EDM observation from September 2 to October 2 2010 are shown in **Fig. 8**. Both baselines tend to be flat since the last explosion in September 7 2010, but small fluctuation still occur between the time of observation. The baseline of SNB1-SNB3 where located near the eruption point has more rough fluctuation than SNB1-SNB2 baseline where located more distance. It was assumed that this small fluctuation represent a low energy release and the release of energy would have been taken long time. The

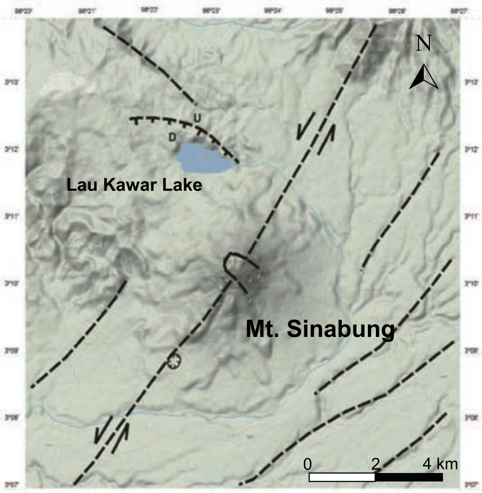

Fig. 7. Map showing the development of the tectonic structure around Sinabung volcano [3].

difference fluctuation among baselines is different due to its distance from the eruption point. All baselines show similar trends.

A graph of tilt (**Fig. 9**) shows 2 trends in the two periods, from 2 to 11 September 2010 (Level IV) and from September 12 to 25, 2010 (levels IV to III). The average tilt changes from September 2 to 11, 2010 is $X = 883.0288$ microradians and $Y = 989.9406$ microradians. Between September 12 and 25, 2010 average tilt is $X = 876.3502$ microradians and $Y = 927.8355$ microradians. The average value of X and Y between these two periods do not show any significant shift. We infer that a pressure stabilization process developed at a low rate, consistent with low gas emission from the eruption point in August 2010. We tried to adopt pressure source calculation that had been applied in Kelud effusive eruption in 2007 [6] and obtained the depth of pressure source to be at 0.7 km beneath the summit and a pressure change of 9×10^6 Pascals. The volume involved during the eruption is estimated 13.05×10^8 m^3 with the radius of magma chamber is 500 m. Total energy calculated from tilt within period of September 2-11, 2010 (alert level IV) is 11.7×10^{21} erg, while from seismic observation is 6×10^{17} erg (period of August 27-September 28, 2010). This means that there are difference between the energy of eruption and the cumulative energy of intrusion approximately of 1.17×10^{22} ergs. This energy remnant will be released continuously in the form of surface activity (gas emission) or volcanic earthquakes.

EDM and tilt data show small fluctuation since the last eruption on September 7 but both in stable manner. On September 29, Sinabang (M5.3) earthquake occurred. Inflation has been recorded in both EDM and tilt measurements (**Figs. 8** and **9**) after the shock, which we attribute to regional block movement, not to a result of volcanic activity. This is because variation in slope distances is not only an indication of energy release, but is also sensitive to regional tectonic activity. There was no extensive delay between the occurrences of earthquake and the inflation,

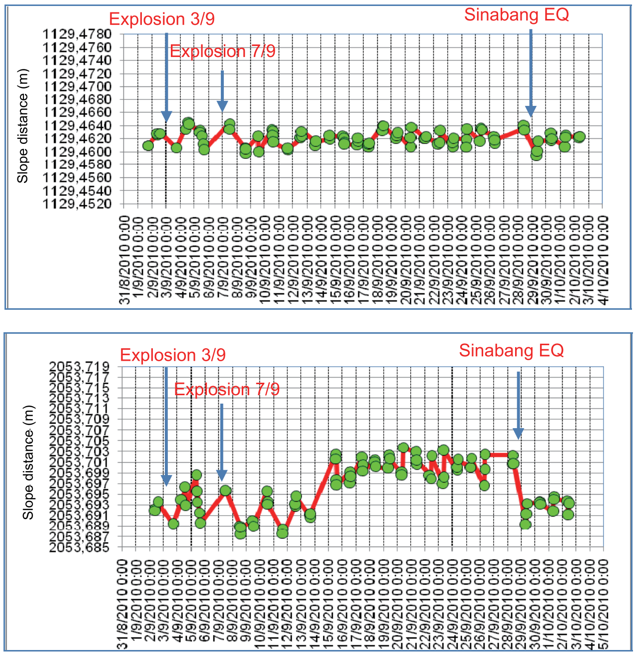

Fig. 8. Slope distance of the SNB1-SNB2 baseline (top) and the SNB1-SNB3 baseline (bottom).

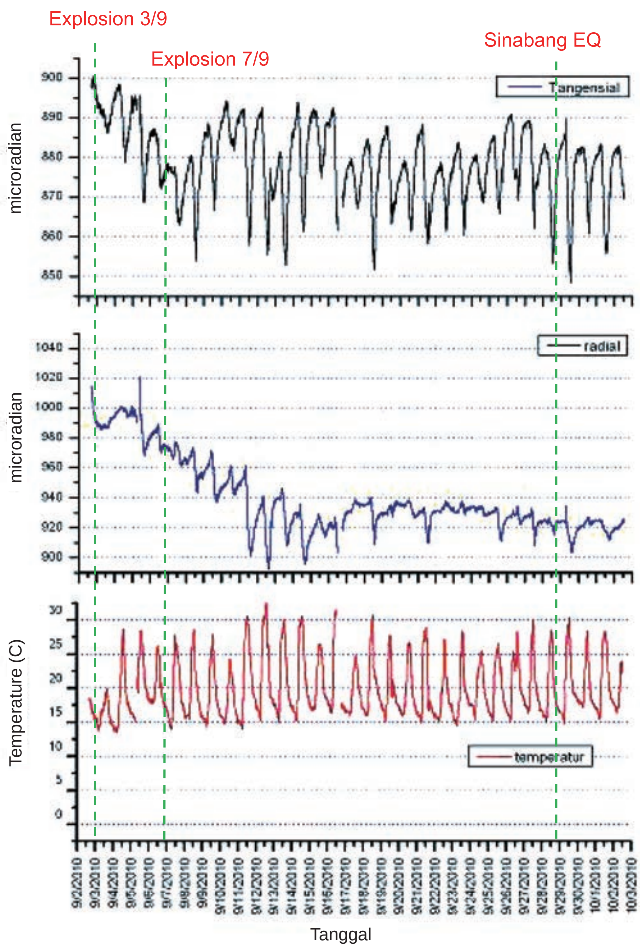

Fig. 9. Tiltmeter results for Sinabung in the period from September to October 2010.

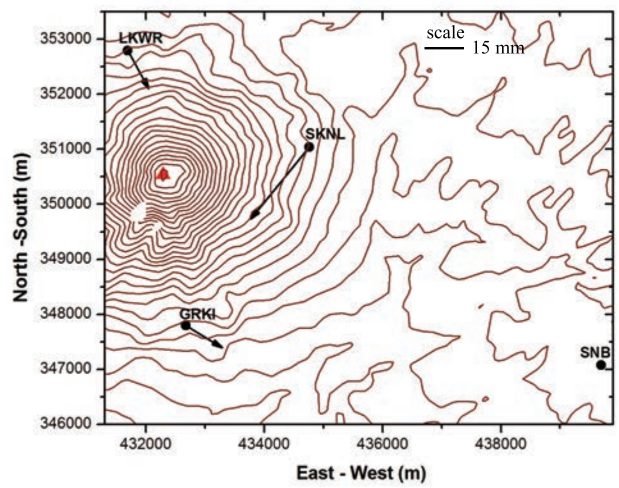

Fig. 10. Vector displacement (in cm) at Sinabung by GPS measurements during the period of March to April 2011.

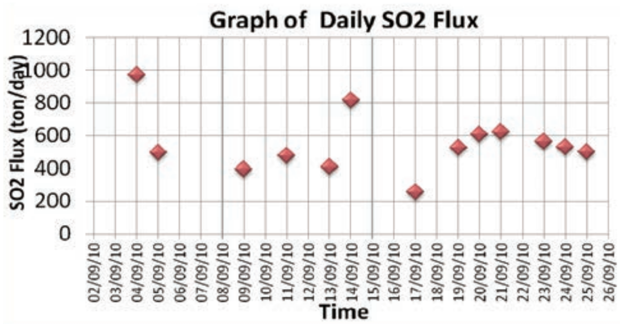

Fig. 11. SO_2 flux during the eruption period in September 2010.

as they occurred on the same day. One day after the Sinabang earthquake, tilt and EDM data returned to indicate stable condition.

Figure 10 shows vector displacement at Sinabung from GPS measurement in the period from March to April 2011 and pressure source calculation was has been carried out based on this GPS data. The result shows that a pressure source was located about 3 km west and 1 km south of the summit at a depth of 6.5 km. This depth corresponds with the aseismic zone derived from seismic data during the same period (4-6 km). The pressure source from March to April 2011 was not beneath the summit, but in the southwestern part of Sinabung volcano, near the MDDG (Mardinding) seismic station (**Fig. 4**). We assume that the location correlated with a fracture zone between two horizontal faults at the southwest part of the volcano (see geology maps in **Figs. 1** and **7**).

The result of observation in **Fig. 11** shows the fluctuation of SO_2 flux with a range between 400 and 600 tons/day while SO_2 flux on September 4 reached 972 tons/day. After that, SO_2 flux tended to decrease. On September 14, SO_2 increased to 800 tons/day and during the same period, a continuous tremor was recorded on September 14-15 (**Fig. 5**). SO_2 flux on September 17 was measured during foggy weather, which caused apparent drastic decrease in SO_2 flux (265 tons/day). SO_2 flux after September 21 tended to decrease along with waning volcanic activity and decrease in the number of volcanic earthquakes.

Sinabung volcano has been at alert level II (WASPADA) since October 7, 2010. Recently, activity at Sinabung volcano is relatively "calm." Gas emission is observed visually from the crater. The seismicity of Sinabung is, however, still high. Ten to sixteen VT earthquakes/day still indicate high pressurization of the reservoir or hydrothermal system. Based on the results of eruptions in 2010, a future increase in VT earthquakes could be an eruption precursor. Calculation of earthquake hypocenters is important to observing the location of sources and contributing to the evaluation of volcanic activity. The seismic network that covers the surrounding region is expected to improve the observation of volcanic activity of Sinabung and of influence to this volcano by tectonic activity. Monitoring of deformation by EDM, tiltmeter and continuous GPS will also enhance the observation of Sinabung activity.

For future eruption to cope with, CVGHM will conduct mitigation efforts, such as the establishment of an Observatory Post of Sinabung Volcano that is fully equipped with monitoring instrumentation. CVGHM will also develop volcano geological and hazard maps. The distribution of information and coordination to local governments will also be conducted periodically.

6. Conclusions

This paper has focuses on the preliminary result of methods applied to monitoring the activity of Sinabung volcano during and after the latest eruption crisis. The data described here has allowed us to understand the basic characteristics of Sinabung volcano and its correlation with regional tectonic activity.

During the crisis period from September to October 2010, volcano-tectonic earthquakes were distributed beneath the summit and a north-south lineation zone. In the period from November 2010 to February 2011, epicenters were concentrated beneath Lake Lau Kawar at depths of 4 to 6 km. This result correspond with the pressure source locations found using GPS data. SO_2 flux correlated with change in volcanic earthquakes.

From the results above, we concluded that tectonic activity affects the volcanic activity of Sinabung volcano, whose recent seismic activity is quite high. For this reason, CVGHM will mantain observation priority of Sinabung volcano to anticipate future eruptions.

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Selected Publications:
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• S. Nakada and T. Druitt, "The 2000 eruption of Miyakejima volcano, Japan," Bulletin of Volcanology, Vol.67, No.3, pp. 203-280, March, 2005.

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