Intrusion and Effusion Processes of Andesite Magma in the 2010-2018 Activities at Sinabung Volcano, Indonesia, Based on Seismic Analyses

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Sinabung, an andesite volcano located Sumatra, Indonesia, reactivated in 2010 after 1200 years of dormancy. Monitoring of its activity was conducted after the phreatic eruption, which marked the end of its dormancy, in August 2010. A comprehensive study on the dynamics of magma movement at Sinabung volcano, focusing on the processes of magma intrusion and effusion, has been conducted. The activity is divided into two periods: pre-magmatic (2010-2013) marked by high volcano-tectonic (VT) seismicity; magmatic (2014-2018) marked by lower VT seismic intensity and dominance of eruption events. The intrusion process in the pre-magmatic period before 2014 and the effusion process in the magmatic period during 2014-2018 for Sinabung volcano were elucidated. The pre-magmatic section aims to clarify the progression of magma intrusion during the pre-magmatic phase by analyzing active seismicity beneath the volcano. Temporal variations in the source characteristics of VT and Hybrid earthquakes are assessed based on hypocenter locations and waveform similarities (as indicated by earthquake families).

Subsequently, a model for the progression of magma intrusion during the pre-magmatic period is proposed. The progression of magma intrusion was clarified through the analysis of source parameters and hypocenter locations for VT and Hybrid earthquakes, as well as the similarity of Hybrid earthquakes. It was found that VT earthquake hypocenters are located north and northwest of the summit, at depths ranging from 1 to 10 km. There was an alternation between widely distributed deep seismicity (4-10 km) and concentrated shallow seismicity (2-4 km). The final shallow seismicity, occurring from July to mid-December 2013, differed from previous seismic activity by exhibiting higher intensity, as indicated by seismic moment, a temporary increase in rupture length, and hypocenter migration toward the summit. In mid-December, the VT seismicity was replaced by a swarm of Hybrid earthquakes. These Hybrid earthquakes were smaller in seismic moment (mostly $< 3\times10^{10}$ Nm) compared to VT earthquakes. Their hypocenters were concentrated at the shallowest depths (-0.5 to 1.5 km) directly beneath the summit. These Hybrid earthquakes have repeatable source processes (grouped into six earthquake families), had a dominant low-frequency peak (2.5-4.5 Hz), and exhibited relatively low stress drops (<0.15 MPa). This indicates that the Hybrid earthquake swarm was caused by frequent, repeated fracturing of fluid-filled cracks due to magma intrusion directly beneath the summit. The transition of earthquake families and the changes in their source parameters, particularly an increase in stress drop before the appearance of a lava dome followed by a slight decrease, may reflect gradual changes in internal pressure in the hypocentral zone during the magma intrusion process.

The magmatic section aims to estimate the temporal changes in the mass eruption rate (*MER*), especially after the lava flow event. The *MER* of each eruption event, both pyroclastic density current (PDC) and Vulcanian, was estimated from seismograms. Additionally, the transition of the dominant eruption style from PDC to Vulcanian in relation to the temporary change in *MER* was discussed. The result has a wide range in the cumulative PDC erupted mass of 1.5×10^{8}–7.5×10^{10} kg due to the wide range of relation between seismic energy and the involved volume of PDC. Meanwhile, the cumulative mass estimates for the Vulcanian events are 7.9×10^{7}–3.2×10^{9} kg. Compared to previous results, the upper range of the result may likely be consistent with the total mass emitted from Sinabung activity in the corresponding period. The occurrence of ten of PDCs in a short period and extruding mass exceeding 5.6×10^{8} kg/day was observed and defined as frequent PDC occurrences (FPDC). The magma intrusion and effusion processes at the shallow conduit accompanying FPDC events were also discussed from the viewpoint of the occurrence of rock-fall events and Vulcanian eruptions.

The long-term trend of *MER* showed an exponential decrease over time from the largest *MER* of 2.8×10^8 kg/day to 0.6×10^8 kg/day in February 2018. The *MER* transition coincided with the eruption style from occurrence of PDC only to PDC and Vulcanian eruptions. This study interpreted it as a result of forming a gas pocket from a solidifying plug due to magma stopping when overpressure is lower than yield strength. The *MER* of PDC was higher than that of Vulcanian eruptions, reflected in the cumulative mass where Vulcanian eruptions accounted for only approximately 10% of the cumulative mass of PDC. The occurrence of FPDC is caused by an increase in the magma intrusion rate that cannot be accommodated by the lava dome at the volcano's summit. As the rate of magma intrusion increases, new magma replaces the old magma in the volcanic conduit, increasing the volume of the lava dome and the mass rate of rockfall. The *MER* declined with an exponential trend, punctuated by temporal fluctuations. These fluctuations contributed to the occurrence of FPDC, which posed a significant danger to nearby residents. We interpreted the fluctuations as being caused by restarting the flow after magma pressure re-exceeded the yield strength of Bingham fluid.

Finally, the start entire intrusion process at Sinabung from the last major eruption was proposed by referring the overall inflation-deflation process associated with eruptions at Shinmoedake and Sakurajima volcanoes. We discussed the possibility that deep intrusion started around 400-500 years ago. The long-lasting effusion process at Sinabung was correlated with the prolonged magma intrusion process, and the low magma intrusion rate was found to correspond to the low eruption rate.