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The 2021 Semeru volcano eruption: An insight from visual, seismic, and deformation monitoring data

Kristianto[1], Ahmad Basuki[1], Heruningtyas Desi Purnamasari[1], Devy Kamil Syahbana[1]

[1]Center for Volcanology and Geological Hazard Mitigation (CVGHM), Jl. Diponegoro 57, Bandung 40122, Indonesia

kristianto@esdm.go.id

Abstract. Semeru is the highest volcano on the island of Java and one of Indonesia's volcanoes that has a potential threat of pyroclastic flows. The eruption of Semeru often shows a transition pattern between explosive and effusive styles. An increased eruptive activity occurred in 2021 with series of explosions dominated the first two thirds of the year and then transition to series of pyroclastic flows in December 2021. On 4 December 2021, a dome collapse triggered significant pyroclastic flows that reached a maximum distance of 16 km from the crater and resulted in 51 casualties. In this paper, we aimed to study the dynamics of magma movement from depth to the surface and assessing the style transition of the eruptions between explosive and effusive activity from visual, seismic and deformation monitoring data. We analyzed Semeru volcano monitoring data throughout the year 2021. The volcanic activity monitoring system of Semeru volcano consists of 4 seismic stations, 5 deformation stations (2 tiltmeters and 3 GPS stations), and 2 Web Camera/CCTV. Our analysis on seismic data indicates that the series of large pyroclastic flows were triggered by excess pressure at shallow depths a few hours before the events. Deep volcanic earthquakes are relatively increased after the collapse of the lava dome or pyroclastic flows, possibly caused by the sudden decrease in hydrostatic pressure of the rock mass around the magma pocket, thus triggering gas expansion. Deformation monitoring using a tiltmeter at Argosuko and Jawar stations indicates inflation of a deep source since 15 August 2021. Since 7 November 2021, tiltmeter measurement has shown deep source deflation patterns which indicate magma movement from the deep reservoir to a shallower reservoir. After 21 November, inflation of the deep source was observed again, indicating an increase in magma supply from the deep pocket. The results of the pressure source modeling from GPS vector data in the period before the eruption, 1 November – 4 December 2021, showed an anomaly in the form of an increased volume at a depth of > 1.7 km of about 0.84 million/m3. Between 5 December and 31 December 2021, after the 4 December pyroclastic flow, the deformation modeling indicates the transition of the pressure source from a depth of 1.7 km to 8 km. In addition, we also observed a decrease in volume of 5.6 million/m3. The deformation pattern at shallow depths showed a deflationary pattern indicating a decrease in magma overpressure.

Keywords: Semeru Volcano, Pyroclastic Flow, Seismic, and Deformation

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1. Introduction

Semeru is a stratovolcano characterized by the growth of a lava dome in its crater. Geographically, it is located at 08°06'30" S and 112°55'00" E. Semeru volcano, referred to as the Mahameru summit, which has a height of 3676 m above sea level, is the highest summit among the volcanoes on Java island. Administratively, Semeru belongs to the Lumajang and Malang Regencies, East Java. Semeru is one of the most active volcanoes in Indonesia. The most significant volcanic hazard of the Semeru eruption is pyroclastic flow that often causes loss of life and property.

Semeru volcano frequently shows eruptive activity, it is known as a restless volcano; ash eruptions occur on average every 20-30 minutes. Mount Semeru is known to have erupted in historical records starting in 1818, with the most prolonged repose period of 28 years. The eruptive activity of Semeru is characterized by lava dome growth, ash eruptions accompanied by lava flows, lava avalanches, and pyroclastic flows originating from the edge of the lava flow deposit or the lava dome on the summit crater.

The current eruptive activity occurs in Jonggring Seloko Crater, formed in 1913. From 1946 until now, the eruptive activity has never stopped; eruptions occur every 15- to 1-hour intervals. Besides eruptive activity and lava flows, lava dome formation is also typical in Jongring Seloko Crater. Hence, the potential for pyroclastic flow mainly occurs from the direction of this lava dome. Several pyroclastic flow events that have occurred up to a distance of more than 5 Km occurred in 1963 (8 Km), 1977 and 1981 (10 Km), 1994 (11.5 Km), 2002 (11 Km), and 2003 (11 km) which enters the Besuk Sat, Besuk, Bang, Besuk Kembar, and Besuk Kobokan rivers (Solikhin, et al., 2012, Thouret, J. C., et al., 2014). On 3 February 1994, the pyroclastic flow reached a distance of 11.5 km towards Besuk Kobokan, resulting in 7 deaths. (Data Dasar Gunungapi, 2011). On 1 December 2020, there was a pyroclastic flow from the lava dome reached a distance of 2 to 11 Km in the direction of Besuk Kobokan, resulting in a volume of 5,265,421 meter^3 of pyroclastic flow material deposits (Kristianto et al. 2021) which could trigger lahar flow during the rainy season. On 4 December 2021, the pyroclastic flow reached a distance of 16 km in the direction of Besuk Kobokan (Triastuty et al., 2022), resulting in 51 fatalities, 2,970 houses damaged, 10,395 people displaced, and the Gladag Perak bridge, the main bridge connecting between Malang and Lumajang Regency, destroyed (https://bnpb.go.id/berita/).

Previous research showed that changes in seismicity prior to eruptions can be seen from spectral properties of the seismic signals. Changes in the spectral properties can be associated with changes in the dimensions or physical conditions (physical boundary conditions) of the magma chamber and mixing (coupling) between magma and gas (Triastuty, 2011). Previous research using tiltmeter measurement showed deformation on Semeru Volcano prior to it's eruptions (Nishi et al., 2007, Nishimura et al., 2012). The use of seismic and deformation method can be used to better estimate the state of volcanic activities at Semeru and to estimate the potential hazards. These can contribute to a better early warning system.

2. Monitoring System

The primary method of monitoring the hazard of this eruption is the seismic method; however, we also incorporate the deformation in analyzing the level of volcanic activity. The seismic monitoring system of Semeru volcano currently consists of 5 seismic stations (St. Kepolo, St. Leker, St. Bang, St. Kamar A, and St. Argosuko); the distance of each seismic station from Jonggring Seloko Crater, namely: St. Kepolo 3.3 km, St. Leker 7.2 km, St. Bang 7.4 km, St. Room A 8 km, and St. Argosuko 9 km. Another monitoring method used is the deformation method consisting of 3 GPS stations (Leker, Argosuko, Pos), the distance of each GPS station to Jonggring Seloko Crater are: Leker 7.2 km, Argosuko 9 km, and Pos 11.5 km, and 2 Tiltmeter stations (St. Argosuko and St. Jawar), respectively 9 km and 6.5 km from Jonggring Seloko Crater, and 2 CCTV cameras placed at the PGA Post at Gunung Sawur and the Mount of Sriti Repeater 11.7 km and 11.5 km from Jonggring Seloko Crater. This CCTV camera helps assist with visual monitoring from the east and southeast.

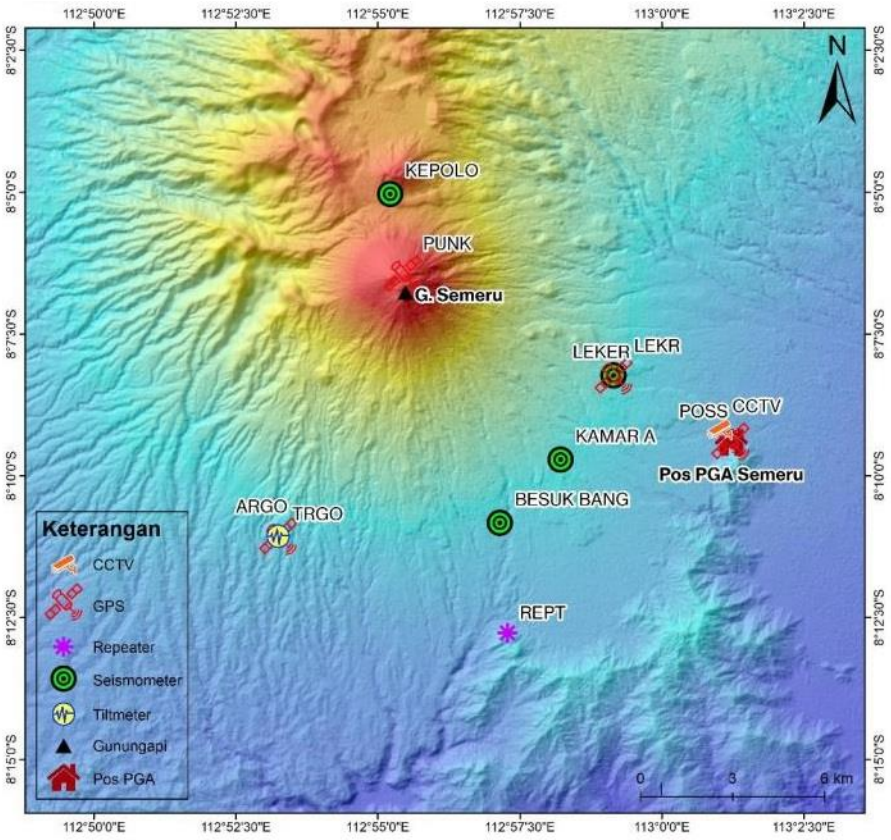

Figure 1. The network of volcanic activity monitoring equipment at Semeru Volcano has five seismic stations, 3 GPS stations, 2 Tiltmeter stations, and 2 CCTV cameras.

3. Data and Methods

This paper used continuous visual, seismic, and deformation monitoring data from the Semeru Volcano Observation Post on Mount Sawur in 2021. Visual observations provide the results of the eruption column height, flow direction, and estimated range of pyroclastic flow. Continuous data from 5 seismic stations are used to classify recorded seismic signals. We also used the REDPy (Repeating Earthquake Detector in Python) method (Hotovec-Ellis and Jeffries, 2016) to analyze continuously archived data and automatically generate a catalogue of seismic signals using the Short-time-average-STA/long-time-average-LTA algorithm. We also examined the Global Navigation Satellite System (GNSS) data to produce baselines, vectors, and modeling of the pressure source causing the deformation using Webobs (Beauducel, 2020). Tiltmeter data provides information on the transition pattern of the pressure source of magma movement from the deep reservoir to the shallower reservoir

4. Visual Monitoring

The volcanic activity of Semeru Volcano, which was visually monitored during 2021, was dominated by explosive eruption activity with an average of 50 events per day. The eruption column height ranged from 100 - 1000 meters from the summit. Dominant winds spread volcanic ash from the eruption to the north, northeast, east, south, and southwest. Lava avalanches activity directly to the Besuk Kobokan river channel. There are four periods of significant lava avalanches: 1 January - 28 February, May 3 - 12, May 12 - 18, and December 1 - 31, 2021.

Pyroclastic flow events were observed on 16 January 2021 and 2 February 2021, with a flow distance of 4 km and 2 km to Besuk Kobokan. In January - February 2021, there was an increase in lava avalanches and a decrease in the incidence of explosive eruptions. On 4 December 2021, at 14:50 local time, pyroclastic flows were observed towards the Besuk Kobokan river channel with a flow distance of 16 km. The volume of the lava dome destroyed was estimated at 6.2 million m^3 (Triastuty et al., 2022). Until 31 December 2021, 20 pyroclastic flows occurred with a flow distance of 2000 - 5000 meters in the direction of the Besuk Kobokan river channel.

(a) (b) (c)

Photo 1. Pyroclastic flow occurred on 16 January 2021 (a), 2 February 2021 (b), and 4 December 2021 (c) toward the Besuk Kobokan river channel and reached distances of 4 km, 2 km, and 16 km.

5. Seismic Monitoring

In 2021, seismometers recorded several earthquake types that are associated with: volcanic activity on the surface (eruption/explosion, emission, lava avalanches, pyroclastic flow), related to the supply or movement of magma (volcano-tectonic earthquakes (deep/VA and shallow/VB), and harmonic tremors), and associated with tectonic activities (regional and distant). The eruption and emission earthquake types were recorded to be very dominant, indicating the release of energy in the form of intensive volcanic/pyroclastic material releases, especially between 27 January and 30 November 2021. Eruption earthquakes recorded an average of 50 events per day. Avalanche earthquakes increased from 1 January to February 28, 3 to 12 May, 12 to 18 May, and 1 to 31 December 2021. Meanwhile, in the period of 1 - January - February 28 and 1 - 31 December 2021, there was an increase in Pyroclastic flow and Harmonic Tremor earthquakes. The seismicity of Volcano Tectonic Earthquakes throughout 2021 increased in the period 1 January - 12 April and December 7 - 28, 2021. Tectonic earthquake events (Local Tectonic and Distant Tectonic) increased during April and December 2021. An increase in this type of earthquake could disturb magma stability, especially near the surface or volcanoes in crisis conditions (Kriswati et al., 2009).

We analyzed the seismic data of Semeru Volcano for the period 2021 using the REDPy (Repeating Earthquake Detector in Python) method, which can be downloaded on the Github website https://github.com/ahotovec/REDPy (Hotovec-Ellis and Jeffries, 2016). REDPy is designed to analyze real-time or archived data to generate a catalogue of earthquake signals detected using the Short-time-average-STA/long-time-average-LTA algorithm. REDPy performs a cross-correlation on all the detected earthquake signals. Earthquake signals with a cross-correlation coefficient above a certain threshold are grouped into the earthquake repeaters family. Earthquakes from one family are assumed to originate from a similar location and/or source mechanism. Earthquake signals whose cross-correlation coefficients with previous events are below the specified threshold are labelled "Orphans" meaning they have no similarity to other earthquakes. We also use REDPy to calculate the Frequency Index (FI) of each earthquake by comparing the energy in the high-frequency band (5–10 Hz) with energy in the low-frequency band (1–2.5 Hz) (Buurman and West, 2010). The REDPy method can assist seismologists in interpreting physical models of volcanic activity over time (Wellik et al., 2021).

We use seismic data from BANG Station recordings which have continuous and less noise recording data. We divided the activity period of Semeru Volcano into three stages based on our estimation of its physical dynamics.

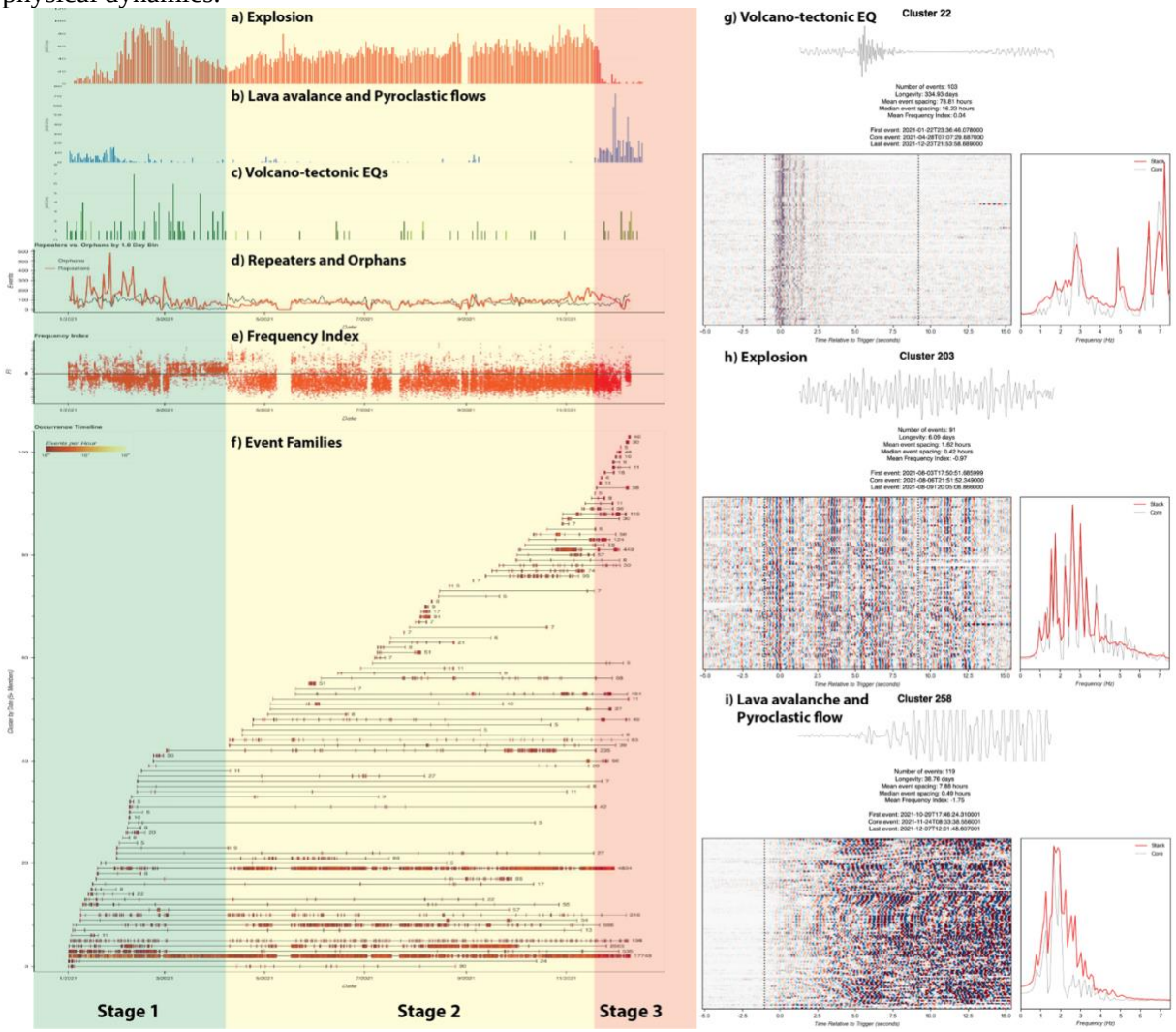

Figure 2. The results of seismic data analysis with REDPy, the activity of Semeru Volcano during 2021 is divided into three stages based on estimates of the physical dynamics that occur in Semeru Volcano.

The first stage is in the period from January to early April 2021. In this period, there is an indication of pressure accumulation due to magma movement, indicated by the high number of volcano-tectonic earthquakes. This earthquake is characterized by an impulsive wave onset and a high dominant frequency content (5-10 Hz) (e.g., cluster 22). The Repeaters-Orphans graph shows an increase in the Repeaters-Orphans ratio over time.

The second stage is in the period from early April to November 2021. Deep magma intrusion activity continues at a much lower rate during this period. Seismicity was dominated by explosion earthquakes (e.g., cluster 203) with dominant low-frequency contents (1-5 Hz). The frequency index shows the dominance of low-frequency earthquakes and fewer high-frequency earthquakes. The explosion quakes in this second stage were gradually increasing. We also saw a significant increase in the number of Repeaters.

The third stage is from the end of November to December 2021. In this period, we found a transition of surface activity from explosions to avalanche activities. In this period, the number of avalanches

increased significantly. From the Repeaters-Orphans chart, the number of Repeaters has decreased, but the number of Orphans has increased. The frequency index shows a widening trend (high-frequency earthquakes were increasing, but low-frequency earthquakes remained high), correlated with the occurrence of pyroclastic flows (e.g., cluster 258).

6. Deformation Monitoring

We use the Webobs application to analyze the GNSS data. Webobs (Beaducel, 2020) is an application that functions to acquire GNSS data in the field, then process it automatically using Gipsy-X, a scientific software for GNSS data processing to analyze deformation data. From data processing using Webobs, the modeling results were obtained from the location of the pressure source causing the deformation.

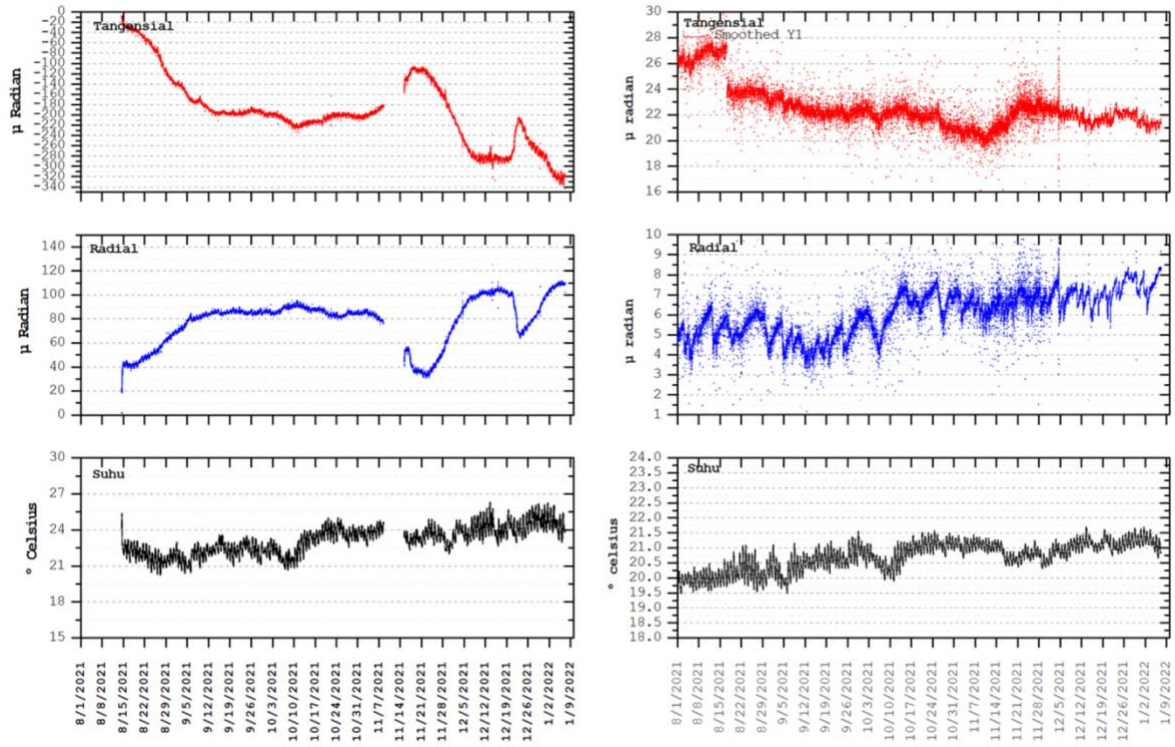

Figure 3. Tiltmeter recording St. Argosuko period of 14 August - 5 January 2022 (left), and St. Jawar the period of 8 January - 6 January 2022 (right).

On 15 August 2021, there was inflation in the deep magma pocket. On 7 November 2021, there was deflation in the deep magma pocket, but an increase in supply was detected; this can be seen in St. Argo and St. Jawar. On 21 November 2021, magma was moving from a shallower pocket. The peak on 4 December 2021 occurred an eruption of pyroclastic flow. After the eruption on 4 December, the tiltmeter looks stagnant again and tends to deflate after another series of eruptions. The tiltmeter starts inflation after 19 December 2021. On 4 December 2021, an eruption occurs after the tiltmeter shows inflation (the peak of inflation) before deflation occurs so that the magma that comes out to the surface is the magma supply before the inflation period.

7. Discussion

The volcanic activity of Semeru Volcano during 2021 is dominated by explosive eruptions with an average of 50 events per day, resulting in an eruption column with a height ranging from 100 - 1000 meters from the summit. The eruption column is generally white to thick grey, indicating volcanic ash's presence. Information on the event time, the eruption column heights, and the direction of the ash

dispersions are beneficial for the stakeholders in the civil aviation sectors, especially to anticipate flight disturbances flying around the Semeru volcano area. The increased explosive eruption activity was observed visually and seismically, especially from 27 January to 30 November 2021. The pattern of changes in the characteristics of explosive eruptions to effusive eruptions began with an increase in pressure and an active hydrothermal system (Kristianto et al., 2021), characterized by the rise in avalanches and harmonic tremors and the decrease in explosion earthquakes occurred in the period of 1 January - 28 February and December 1 - 31, 2021. This pattern must be watched for, especially for the potentially increasing pyroclastic flow activities, which are mainly still toward the Besuk Kobokan River channel.

The results of seismic signal processing with REDPy help us understand the physical processes that occurred before the significant occurrence of pyroclastic flow in Semeru. Some crucial points can be summarized as follows. The first stage is the pressure-building stage, characterized by higher volcano-tectonic earthquakes compared to the period after. During this period, the Repeaters-Orphans ratio increased several times, indicating a rapid shear stress reloading process that causes slippage on the same or similar faults in the body of the volcano due to magma movement. Changes in the number of earthquake families indicate changes in the pressure associated with the movement of magma fluid from deeper to the shallower parts of the volcanic edifice. The second stage is the stage of fluid flow and strombolian explosive eruptions; this is indicated by a significant increase in the number of earthquake families, indicating friction between fluids and rocks at varying depths from time to time (from deep to the surface) and/or changes in eruption energy over time. At the end of this period, the increase in the Repeaters-Orphans ratio is associated with an increase in the magma flow rate to the surface. The third stage is the transition stage from the explosive eruption phase to the lava avalanche and pyroclastic flow. A decreased percentage of Repeaters compared to Orphans during this period indicates changes in the lava avalanche and pyroclastic flow extents.

The results from the pressure source modeling of the GNSS vector data show a mass anomaly at a depth of > 1.7 km of 0.84 million m3. After the eruption, the pressure source modeling showed a volume reduction of 5.6 million $m^{3.}$ The deformation data shows a deflationary pattern related to the pressure and energy releases on 4 December 2021. The results of the tiltmeter analysis indicate that there is magma migration from the deep magma pocket to the shallow depth reservoir, as seen from the periodic changes in the X- and Y-components before and after the 4 December 2021 eruption.

8. Conclusion

Monitoring volcanic activity is vital in estimating the dynamics of magma movement to the surface and assessing the style of the eruptions between explosive or effusive eruptive activity. In 2021, volcanic activity at Semeru volcano was monitored 24h every day visually and instrumentally. We find changing activity characteristics from explosive to effusive eruptions characterized, which is indicated by the decreases in explosion quakes followed by the increases in harmonic tremors and avalanches earthquakes, including the pyroclastic flow. An inflationary deformation pattern preceded the eruptive activity in December 2021.

We postulate three stages of activities indicating progressing physical processes that occurred prior to the significant pyroclastic flow event in December 2021. The first stage is pressure development, characterized by increasing volcano-tectonic earthquakes (deep/VA and shallow/VB). The second stage is the fluid flow activity, characterized by frequent explosive strombolian eruption activities. The third stage is the transition phase from the explosive to the effusive eruption activities, indicated by an increasing number of avalanches and pyroclastic flow earthquakes.

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