

Magma intrusion process during pre-magmatic period (2010–2013) of Sinabung volcano as revealed by seismicity of volcano-tectonic and hybrid earthquakes

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ABSTRACT

Sinabung volcano in Indonesia reactivated, with a series of phreatic eruptions, in August and September 2010. These eruptions were followed by various types of magmatic eruption at the summit, including lava dome growth, pyroclastic density currents, lava flow, and vulcanian eruptions, starting in December 2013. Prior to the magmatic eruptions, Sinabung exhibited two sequences of phreatic eruption and an increase in the seismicity of volcanic earthquakes. This study clarifies the progress of magma intrusion during the pre-magmatic period based on the hypocenter distribution, waveform similarity, seismic moment, rupture length, and stress drop for volcano-tectonic (VT) and hybrid earthquakes. It was found that the hypocenters of VT earthquakes are distributed north and northwest of the summit at a depth range of 1–10 km below sea level. Deep seismicity (4–10 km) alternated with shallow seismicity (2–4 km). The last shallow seismicity, from July to mid-December 2013, was different from previous seismicity in terms of higher intensity, as determined from the seismic moment, a temporary increase in the rupture length, and the migration of hypocenters towards the summit. The seismicity of VT earthquakes was altered by a swarm of hybrid earthquakes in mid-December. The hybrid earthquakes were smaller, in terms of seismic moment (mostly $<3 \times 10^{10}$ Nm), than the VT earthquakes. Their hypocenters were concentrated in the shallowest depth range (–0.5 to 1.5 km below sea level) directly below the summit, their source process was repeatable (they could be grouped into six earthquake families), their dominant peak was in a low-frequency range (2.5–4.5 Hz), and they had a relatively low stress drop (<0.15 MPa). This suggests that the swarm of hybrid earthquakes was induced by a frequent repeated fracture of fluid-filled cracks due to the intrusion of magma up to directly below the summit. The transition of the earthquake family and the change in its source parameters, namely an increase in the stress drop prior to the appearance of a lava dome and then a slight decrease, may reflect a gradual change in internal pressure in the hypocentral zone through the magma intrusion process.

1. Introduction

Sinabung volcano is situated in Sumatra, Indonesia. It reactivated, with phreatic eruptions, on August 27, 2010, after a long hiatus of 1200 years (Iguchi et al., 2012). After the first phreatic eruptions, Sinabung volcano went through an abnormal period (hereafter referred to as the pre-magmatic period) for three years prior to the violent magmatic

eruptions in January 2014 (Gunawan et al., 2019).

Based on observations conducted by the Center for Volcanology and Geological Hazard Mitigation (CVGHM), the seismicity of volcano-tectonic (VT) earthquakes decreased after the phreatic eruptions in August–September 2010. In addition, in December 2013, one month before the magmatic period began, hybrid earthquakes started, followed by the appearance of a new lava dome at the summit.

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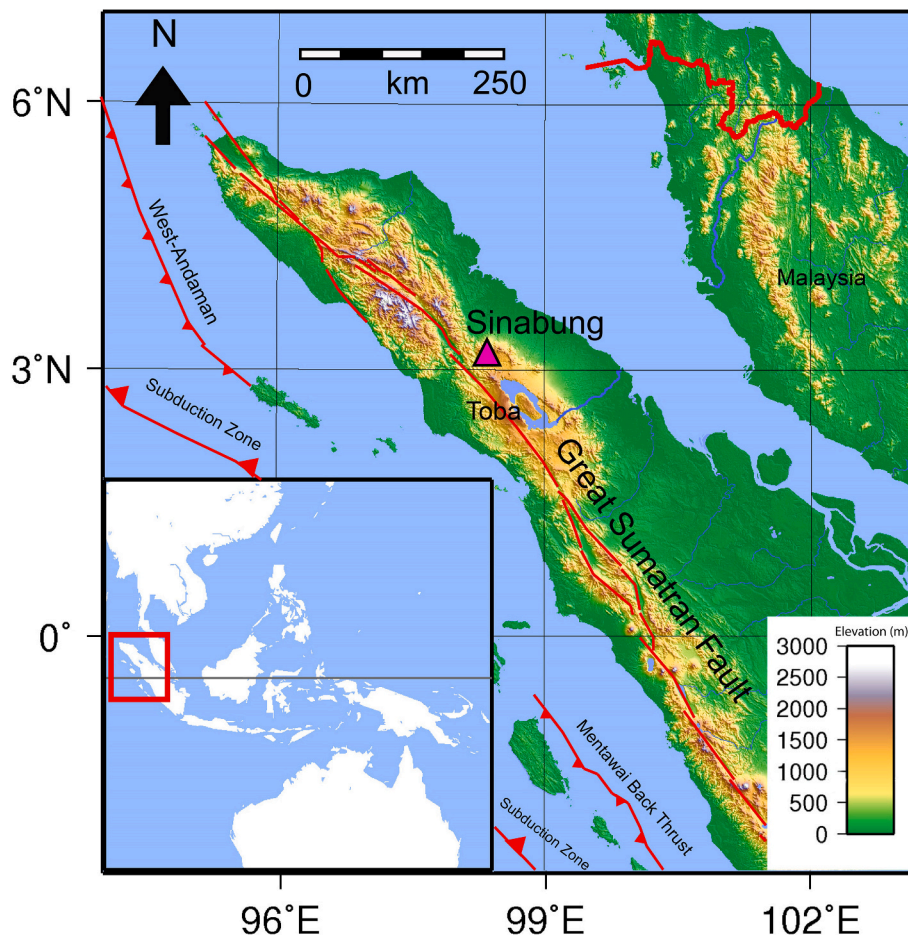


Fig. 1. Location of Sinabung volcano (magenta triangle) in north Sumatra, Indonesia (modified from [Sadalmelik \(2007\)](#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The occurrence of VT earthquakes prior to eruptions has been frequently reported ([Bell and Kilburn, 2012](#); [Roman and Cashman, 2006](#); [White and McCausland, 2016](#)). This type of earthquake releases energy by fracturing the volcanic medium, which is unable to accommodate the stress that accumulates prior to fracture. It has high-frequency characteristics (5–15 Hz) ([Battaglia et al., 2004](#); [Sanchez, 2004](#)) and clear P- and S-wave onsets. The hypocenters of VT earthquakes provide information on the location of fracture caused by magma intrusion ([Bell and Kilburn, 2012](#); [Kato et al., 2015](#); [White and McCausland, 2016](#); [Almendros et al., 2018](#)).

Records of hybrid earthquakes have an initial high-frequency wave similar to that for VT earthquakes, followed by a low-frequency wave ([Chouet, 1996](#); [Miller et al., 1998](#); [Neuberg, 2000](#); [Ottemöller, 2008](#)). Hybrid earthquakes result from brittle fractures of ultrahigh-viscosity magma in fluid-filled conduits; the generated seismic wave is trapped in the conduits, creating a low-frequency wave ([Neuberg, 2000](#); [Neuberg et al., 2006](#)). The low-frequency vibration of hybrid earthquakes at Mount St. Helens resulted from low rupture velocities combined with strong path effects due to their shallow sources without fluid ([Harrington and Brodsky, 2007](#)).

Hybrid earthquakes occur in close succession (i.e., as a swarm), as observed at Mount St. Helens ([Morgan et al., 2008](#)), Soufriere Hills ([Miller et al., 1998](#); [White et al., 1998](#); [Ottemöller, 2008](#)), Mount Redoubt ([Power et al., 2013](#)), and Sinabung volcano ([Gunawan et al., 2019](#)). Hybrid earthquake swarms, which are often followed by lava dome growth, are associated with pressurization within the volcano ([Chouet et al., 1994](#)). It has also been hypothesized that they result from repetitive stick-slip between the plug and conduit caused by internal

pressure variations in the volcano ([Iverson et al., 2006](#)). Increased hybrid seismicity correlates with increased degassing levels and deformation ([Watson et al., 2000](#)) and is a sign of major dome collapse events ([Ottemöller, 2008](#)).

Earthquake swarms can be classified into several families based on the similarity of their waveforms ([Okada et al., 1981](#); [Umakoshi et al., 2008](#); [Battaglia et al., 2016](#)). An analysis of swarms provides information on the volcano's internal conditions and can be used for determining the source location ([Battaglia et al., 2004](#)). [Neuberg et al. \(2006\)](#) found pressure fluctuation cycles and [Statz-Boyer et al. \(2009\)](#) reported differences in the response to magma among degassing, groundwater heating, and new magma intrusions.

Several studies have investigated the seismicity of Sinabung volcano. [Afnimar et al. \(2020\)](#) derived equations for the magnitude and energy of pre-magmatic VT earthquakes to accurately describe seismicity. [Afnimar et al. \(2022\)](#) determined the source mechanisms for VT earthquakes and delineated three faults. Based on a comparison of three-dimensional tomography results for compressional (Vp) and shear wave (Vs) velocities for VT earthquakes from October 2010 to July 2013 with those obtained immediately before the magmatic eruption ([Nugraha et al., 2019](#)), [Indrastuti et al. \(2019\)](#) suggested that magma ascends from the lower region towards the surface. This is supported by pressure source migration from deep to shallow regions during the pre-magmatic period, as determined from ground deformation obtained using global navigation satellite system (GNSS) data ([Hotta et al., 2019](#)).

[McCausland et al. \(2019\)](#) utilized the seismicity of Sinabung volcano to forecast eruptions using a process-based model of pre-eruptive seismic patterns. This model is considered to have successfully

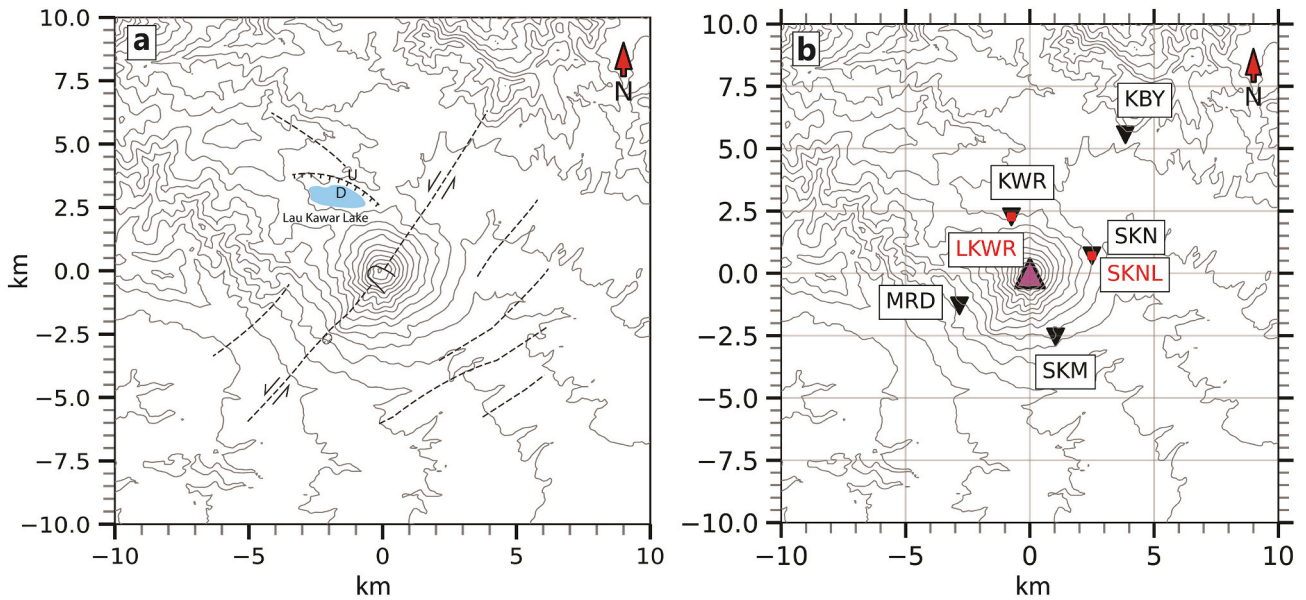


Fig. 2. a Lineaments around Sinabung volcano (modified from [Prambada \(2010\)](#)). b Location of seismic (black labels) and GNSS stations (red labels). The seismic and GNSS stations are equipped with short-period (1-s) seismometers and GNSS receivers (Leica GR10, 1-s sampling rate), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

forecasted eruptions and to indirectly describe the intrusion process. However, the seismicity was not analyzed in detail; for example, the analysis of non-VT earthquakes was limited to daily counts and the real-time seismic amplitude measurement (RSAM) analysis covered the entire frequency range without consideration of the source mechanisms that produce frequencies in specific ranges.

Previous research (excluding that by [McCausland et al. \(2019\)](#)) primarily focused on the spatial variations in the internal structure and the existence of concealed faults. The relationship between internal conditions during the pre-magmatic period and the temporal change in seismicity was not considered. [McCausland et al. \(2019\)](#) found temporal changes in the seismicity and intrusion progress but did not provide detailed explanations, especially regarding seismic source parameters. In particular, the seismicity of hybrid earthquakes that occurred at the

end of the pre-magmatic period was not analyzed in detail or discussed.

In the present study, we elucidate the progress of internal processes during the pre-magmatic period by analyzing the seismic moment, rupture length, and stress drop for VT and hybrid earthquakes observed at Sinabung volcano. The temporal change in the source parameters is examined based on the hypocenter locations and the similarity of waveforms (as shown by earthquake families). Finally, a model for the progress of magma intrusion in the pre-magmatic period is proposed.

2. Geological setting

Sinabung volcano, located northwest of Toba ([Fig. 1](#)), is a strato-volcano that formed during the Pleistocene and Holocene eras and has basal-andesitic to andesitic lava types ([Prambada, 2010](#); [Iguchi et al.,](#)

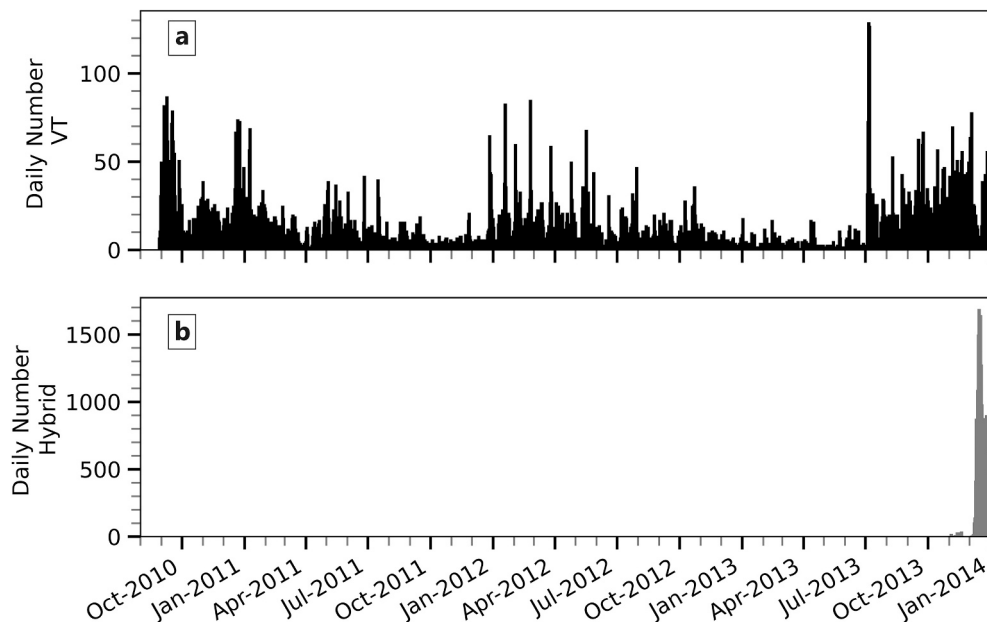


Fig. 3. Time series of daily numbers of volcanic earthquakes starting from August 29, 2010. a VT and b hybrid earthquakes.

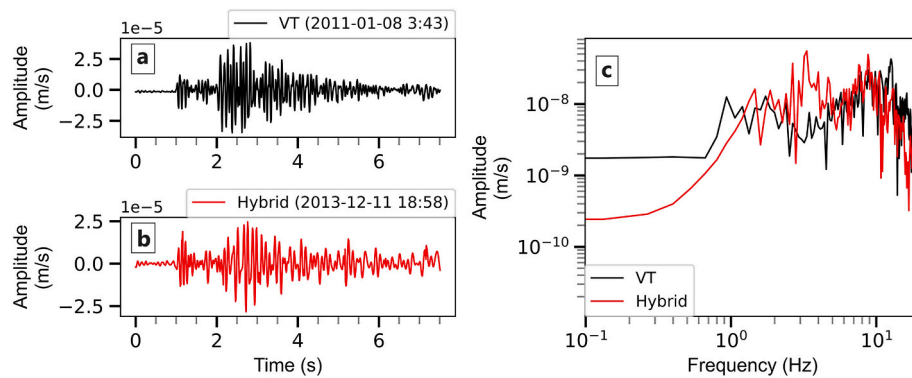


Fig. 4. Waveforms of a VT earthquakes and b hybrid earthquakes. c Spectra of VT (black line) and hybrid earthquakes (red line). Times are given in UTC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2012). A left-lateral strike-slip fault crosses its summit (Fig. 2a, Pramada, 2010). Another normal fault lies near Lau Kawar Lake to the northwest (Fig. 2a). The region's topographic lineaments typically follow a southwest-northeast orientation, perpendicular to the broader structural pattern of the terrain of the Great Sumatran Fault (Gunawan et al., 2019). Younger volcano deposits are mainly in the central and eastern regions, while older ones are primarily in the west (Iguchi et al., 2012). The younger part lacks pumice fall, suggesting effusive eruptions forming lava domes and flows rather than Plinian eruptions. The last significant eruption occurred in the 9th or 10th century, with pyroclastic density currents (PDCs) extending approximately 4.5 km from the summit (Nakada et al., 2019), resembling the 2014–2018 eruptions.

3. Activity in pre-magmatic period

3.1. Overview of eruptive activity in 2010–2018

Since 1600 CE, Sinabung volcano had remained dormant until a phreatic eruption occurred at its summit on August 27, 2010. The activity ceased temporarily in September 2010, with the dormant period lasting until September 15, 2013, when a second phreatic eruption occurred. A new lava dome appeared at the summit on December 18, 2013, gradually growing until it collapsed at the end of the month, triggering PDCs that destroyed the 3-Mm³ lava dome (Gunawan et al., 2019; Nakada et al., 2019; Pallister et al., 2019).

Lava effusion in the form of flows began on January 10, 2014, reaching the volcano base by March 2014 (Nakada et al., 2019). From the end of September 2014 to February 2018, lava effusion alternated with dome growth, rockfall, and PDC events. Vulcanian eruptions occurred in the latter half of 2015, coinciding with decreased PDC activity. A paroxysmal eruption on February 19, 2018, marked by increased VT seismicity at the end of January 2018, produced a PDC that traveled 4.9 km and volcanic plume that reached 7.7 km, dispersing 0.8 Mton of volcanic ash (Syarifuddin et al., 2019).

3.2. Pre-magmatic period in 2010–2013

Next, we give the details of the activity prior to the magmatic eruption that started in January 2014. Seismic activity, particularly VT seismicity, peaked during and immediately after the first phreatic eruptions, followed by a decreasing trend until December 2011 (Fig. 3). Another spike in VT seismicity occurred in February 2012, followed by a decline in early 2013. A tiltmeter did not show significant change, suggesting a pressure stabilization process with a low rate (Gunawan et al., 2019).

Subsequent to the dormant period post-October 2010, low-rate inflation was observed from June to October 2013, suggesting a deep-seated intrusion of magma (Hotta et al., 2019). This inflation

coincided with increased VT seismicity starting in July 2013, with the first spike (129 events/day) on July 6 (Fig. 3), followed by a second sequence of phreatic eruptions starting on September 15, 2013 (Gunawan et al., 2019). These eruptions lacked juvenile material and were characterized by SO₂ emission rates of around 430 tons/day, with an S/Cl ratio in the ash leachates that reached 12, suggesting deep-sourced magma and/or the incorporation of hydrothermal sulphur-bearing phases (Primulyana et al., 2019). The deep-sourced magma migrated to a shallower depth, as indicated by ground deformation observations. The pressure source, with a volume increase of 0.39 Mm³, was estimated to be at a depth of 0.4–2.1 km below sea level (bsl), which is shallower than that for the previous source (which inflated starting in June 2013) (Hotta et al., 2019).

By November 2013, the eruption transitioned from phreatic to magmatic, with ash that contained juvenile material. This trend continued until mid-December 2013 (Nakada et al., 2019), accompanied by a shift in seismicity from VT to hybrid earthquakes. The appearance of a new lava dome on December 18, 2013 (Gunawan et al., 2019) coincided with a decrease in the number of hybrid earthquakes and a lower S/Cl ratio in ash leachates, indicating the degassing of a shallower magmatic source (Primulyana et al., 2019). The growing lava dome eventually collapsed by December 31, 2013, generating a PDC (Pallister et al., 2019).

4. Seismic data

Seismic data have been acquired by the CVGHM since the end of August 2010, immediately after the first phreatic eruption. A total of 8 stations (Fig. 2b), equipped with a short-period (1-Hz) seismometer, were operated during the period from 2010 to 2013. The installation locations and types of seismometers were updated according to eruptive activity and equipment availability. The installation specifications can be found in the study of Gunawan et al. (2019). Most of the stations were equipped with only vertical-component, but two horizontal-components were added to the MRD station to clearly detect S waves. The seismic signals at the stations were transmitted to the Sinabung Volcano Observatory via frequency modulation (FM) telemetry. Large-amplitude signals are sometimes saturated due to the low dynamic range of FM telemetry. The signals were digitized at a sampling rate of 100 Hz by data loggers (LS-7000, Hakusan Corporation). Generally, only eruption-related signals, such as signals from PDC, are saturated; few VT and hybrid earthquake signals are saturated. Events with saturated signals were not used in the analysis.

5. Waveform characteristics of VT and hybrid earthquakes

The waveforms and spectra of VT and hybrid earthquakes recorded at Sinabung volcano are shown in Fig. 4. The VT earthquakes began with

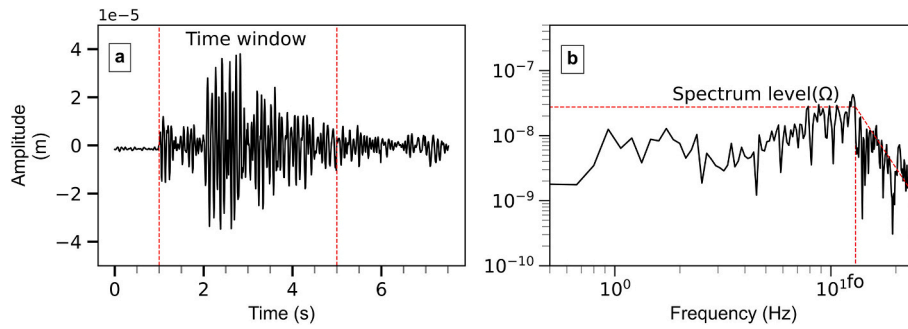


Fig. 5. Analysis used to obtain spectrum level Ω and corner frequency f_0 . a Time window (4 s) from onset of P wave. Spectrum was obtained using the fast Fourier transform. b Spectrum of waveform in a. Ω was obtained from the peak spectrum level in the frequency range 5–15 Hz. f_0 is the frequency at which the spectrum starts to decline.

a distinct onset of P waves, followed by S waves within 0.8–3.2 s. The spectrum of VT earthquakes has a flat frequency response from 0.8 to 12 Hz. Hybrid earthquakes are different from VT earthquakes in terms of S-wave and spectrum content. It is difficult to discriminate S waves from P waves. The spectrum of hybrid earthquakes has two peaks (at 2.5–4.5 Hz and 7–11 Hz, respectively). The time difference between P and S waves indicates the depth of the earthquake. This suggests that the hybrid earthquakes occurred at shallower depths than those of VT earthquakes and its high-frequency peak related to the fracture and its low-frequency peak related to viscous magma in fluid-filled conduits.

6. Methods

6.1. Clustering of earthquakes into families

The phylogenetic tree method was applied to earthquake families within populations of VT and hybrid earthquakes to examine relations among the families. A phylogenetic tree is a graphical representation that shows the proximity among families of earthquakes. Each family is connected by a line at a certain height indicating the proximity distance (D) to other families. The clustering of earthquakes into families was based on the cross-correlation value (CCV) between two events among N events. CCV is defined as the maximum cross-correlation value between two discrete signal points:

$$(f^*g)[m] = \sum_{n=-\infty}^{\infty} f[n] \cdot g[n-m] \quad (1)$$

where $f[n]$, $g[n]$ are sequences of data points and m is a lag parameter that represents the displacement between the two sequences. $(f^*g)[m]$ is CCV value at lag m . The CCVs range from 0 to 1, where a value of 1 indicates an exact match between two events and a value of 0 indicates complete dissimilarity. The CCVs were calculated for all combinations and then used to construct matrix $\mathbf{M}$. Each element in $\mathbf{M}$ indicates the similarity between two events. We sorted the events in chronological order. We set a threshold of 0.9 to exclude low-similarity elements in matrix $\mathbf{M}$ (threshold values of 0.6, 0.7, and 0.8 were also tested) (Umakoshi et al., 2008). A higher threshold gives better results but decreases the number of included events. A threshold of 0.9 provides a better concentration of data and better separation power compared to those obtained with a lower threshold while retaining a sufficient number of events.

For each row in matrix $\mathbf{M}$, the number of elements that exceeded 0.9 were counted. The rows were then sorted according to the number of elements that exceeded the threshold to produce a new matrix $\mathbf{M}^*$. The first row in $\mathbf{M}^*$ represents the first earthquake family, which has the highest number of elements that exceed the threshold. After sorting, an event that produces the first row consisting of the highest number of elements that exceed the threshold is referred to as a reference event. Events that generate elements in the first row that exceed the threshold

are referred to as members of the first earthquake family. To identify the second earthquake family, elements in the second to N^{th} rows were examined to find non-members of the first family (i.e., members of the first family were excluded). The row with the highest number of non-members of the first earthquake family was identified as the second earthquake family. With the elements in previously identified earthquake families excluded, the procedure for finding a new family was repeated until no events remained in $\mathbf{M}^*$. An earthquake family with >50 members is hereafter considered to be an earthquake family.

To evaluate the proximity among the families, hierarchical/agglomerative clustering was performed by applying the shortest distance method to the reference events that represented the characteristics of each earthquake family (Gordon, 1987). The proximity distance (D) between two families is defined as 1 minus the CCV between reference events:

$$D = 1 - \text{CCV}. \quad (2)$$

A smaller D value implies higher similarity between the families. The results of the hierarchical clustering analysis were chained using a phylogenetic tree. In the tree diagram, the length of a vertical line indicates the smallest D value or shortest proximity distance between the two families.

6.2. Hypocenter location

Geiger's method with adaptive damping (Nishi, 2005) was applied to determine the hypocenter locations of the VT and hybrid earthquakes. The one-dimensional P-wave velocity in a stratified layer modeled by CVGHM (Nugraha et al., 2019) was assumed for the calculation, with the velocity ratio of P to S waves fixed at 1.73. The ratio is calculated from bulk and shear modulus of the medium. In general, in Earth's crust, the ratio is typically around 1.7 to 1.8. At least four P-wave arrival times collected from five seismic stations (SKN, KWR, SKM, MRD, and KBY; see Fig. 2b) and one S-wave arrival time at the MRD station were used to calculate the hypocenter locations. Stacking waveforms among high-similarity events (CCV > 0.9) at the MRD station increased the visibility of the S-wave arrival times of hybrid earthquakes. The difference of S–P-wave arrival times of hybrid earthquakes for the horizontal components were < 0.5 s. To enhance the accuracy of the relative locations among the hypocenters, we relocated the hypocenters using the joint hypocenter determination method with the program VELEST (Kissling et al., 1994). In addition to relocating earthquake event coordinates, VELEST also updates the velocity models and provides station corrections.

6.3. Source parameters

The circular fault model (Brune, 1970) was applied to the VT and hybrid earthquakes to derive their source parameters, namely the

Table 1

List of earthquake families (times are given in UTC).

Family	First event	Last event	Duration (days)	Number of events
F1	2013-12-10 00:12	2013-12-10 13:48	0.6	68
F2	2013-12-11 13:11	2013-12-14 15:22	3.1	58
F3	2013-12-11 15:55	2013-12-13 14:40	1.9	54
F4	2013-12-11 18:09	2013-12-19 03:39	7.4	196
F5	2013-12-15 07:16	2013-12-19 01:14	3.7	55
F6	2013-12-20 16:39	2013-12-28 16:56	8.0	70

seismic moment M_0 , the radius of equivalent dislocation r , and the stress drop $\Delta\sigma$ from the corner frequency f_0 , and the level Ω of the spectrum. The parameters are expressed as

$$M_0 = \frac{4\pi\rho\beta^3 d\Omega}{2R(\theta, \phi)} \quad (3)$$

$$r = \frac{2.34V_s}{2\pi f_0} \quad (4)$$

$$\Delta\sigma = \frac{7M_0}{16r^3} \quad (5)$$

where ρ and V_s are the density and S-wave velocity for the medium, respectively, d is the hypocenter distance, and $R(\theta, \phi)$ is the root-mean-square (RMS) of the shear displacement radiation over the entire focal sphere. The values of f_0 and Ω were obtained as shown in Fig. 5. The time window for the spectral analysis was 4 s from the onset of a P wave. Within the time window that encompassed P and S waves, it was

assumed that there is no difference in the spectra between P and S waves (Iguchi et al., 2001; Triastuty et al., 2009; Kwiitek et al., 2011). We set the density at 2360 kg/m³ (Afnimar et al., 2020) and the S-wave velocity at 1.36 km/s, which is the top-layer value for the one-dimensional model (Indrastuti et al., 2019) under a velocity ratio of P to S waves of 1.73. Due to the limited number of stations, the focal mechanism could not be obtained with sufficient accuracy; hence, $R(\theta, \phi)$ was assumed to be 0.63 (Boore and Boatwright, 1984). The rupture length L is defined as (Hanks and Wyss, 1972)

$$L = 2r \quad (6)$$

To apply the Brune model, it is necessary for the S wave to arrive vertically. This requirement can be assessed using the concept of impulsivity, as introduced by Farge et al. (2020) for determining the source parameters of low-frequency earthquakes. Impulsivity (I) is defined as the ratio of signal energy to background signal energy, written as

$$I = \frac{\int s(t)^2 dt}{\int b(t)^2 dt} \quad (7)$$

Its value ranges from 0 (least impulsive) to 1 (most impulsive). Here, $s(t)$ denotes the signal being analyzed, which has a 4-s time window, and $b(t)$ denotes the background signal, whose duration is three times longer than the $s(t)$ time window, spanning from 4-s before to 4-s after the analyzed signals. We rejected events that do not satisfy the condition $I > 0.5$.

7. Results

7.1. Earthquake families

Based on the calculation of CCVs, six earthquake families were identified for hybrid earthquakes and no families were identified for VT earthquakes, for which the highest member count was only 14. The

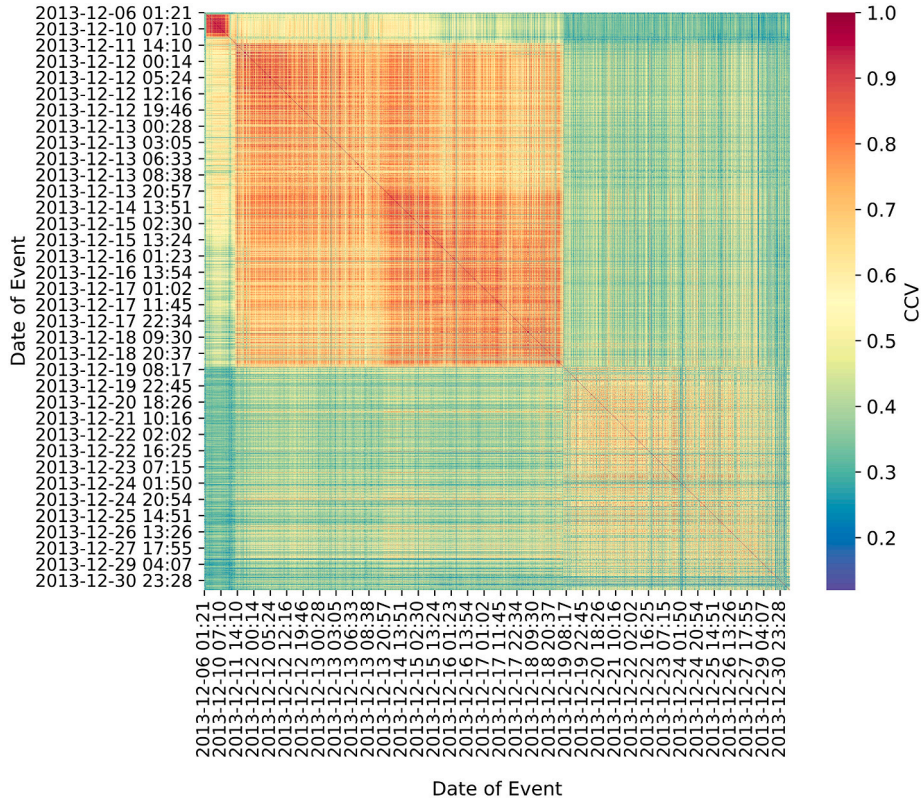


Fig. 6. Heat map of CCV values for each hybrid earthquake event with respect to other events.

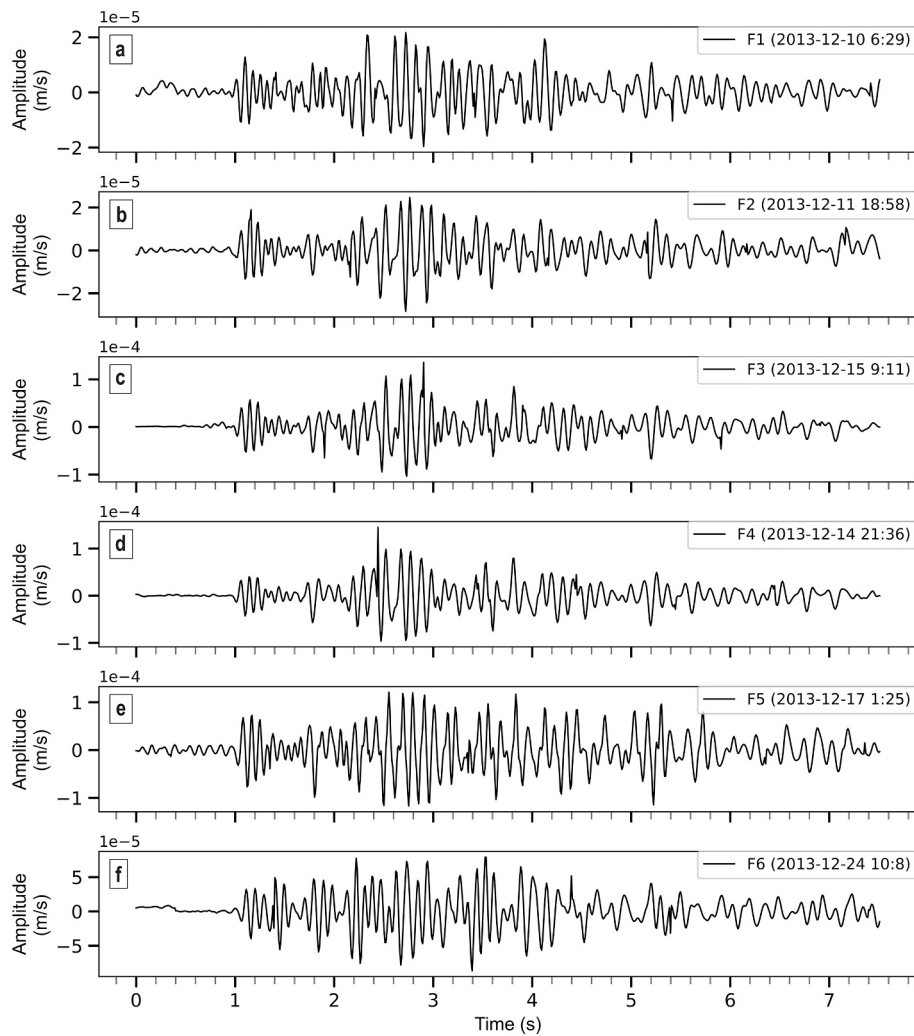


Fig. 7. Waveforms of reference events in six earthquakes families. a F1, b F2, c F3, d F4, e F5, and f F6. Times are given in UTC.

earthquake families, denoted as F1, F2, F3, F4, F5, and F6, are listed in Table 1 in order of the occurrence of their first event. F4 is the largest family (196 events).

A heat map of the CCV values for each hybrid earthquake event with respect to other events and the waveforms for the reference events for the six families are shown in Figs. 6 and 7, respectively. The waveforms are only slightly different (Fig. 7). The first wave packet vibrates for 0.4 s and the second wave packet appears around 0.7 s from the onset. The third wave packet is the largest and contains low-frequency components.

The similarity among the six families was evaluated using D (Eq. 2). The families were arranged in a phylogenetic tree (Fig. 8). The smallest D value (0.1) is between F3 and F4. The second-smallest D value (0.15) is between F5 and set of {F3, F4}. The third-smallest D value (0.16) is between F2 and set of {F3, F4, F5}. The D values are <0.24 among F2, F3, F4, and F5. These families have high similarity. In contrast, F1 has a D value of 0.42 to set of {F2 – F5} and F6 has a D value of 0.57 to set of {F1 – F5}. Therefore, the six families can be reclassified into F1, F2 – F5, and F6. Hybrid earthquakes that belong to F4 occurred during the period from December 11 to December 19 (Table 1). The seismicity of F2 and F3 commenced at almost the same time as that of F4 and overlapped the initial part of the seismicity of F4. F2 and F3 were replaced by F5 in the latter part of F4. In contrast, hybrid earthquakes that belong to F1 occurred before F4. F6 seismicity began after that of F4. Fig. 9 shows the temporal change in CCV for each hybrid earthquake during the seismicity of F2 – F5 in relation to the F4 reference event. The CCVs for earthquakes become larger and closer to the F4 reference event (CCV =

1) and decrease with increasing occurrence time from the reference event. After the appearance of the F4 reference event, the waveforms change gradually over time. The waveforms for earthquakes that occur closer in time are more similar to each other.

7.2. Renewed velocity model and station corrections

Comparisons between the initial velocity model and the renewed P- and S-wave models are shown in Fig. 10a and b, respectively. There were no significant updates in the values of V_p and V_s . Updates of V_p , which were in the range of 0.01–0.04 km/s, occurred at depths of 1–6 km bsl and those of V_s , which were in the range of 0.01–0.02 km/s, occurred at shallower depths, namely –2 to 3 km. This indicates that the velocity model is stable.

Station corrections, represented by P-wave arrival time delays, are shown in Fig. 10c. All stations show negative delays. The smallest delay value is for the MRD station (–1.21 s) and the largest delay is for the SKM station (–0.11 s). The KBY station is installed on the Toba regional deposit and all other stations are installed above Sinabung eruption deposits. A more negative (positive) delay value indicates harder (softer) rock.

7.3. Hypocenter locations

A plot of the hypocenters of the VT and hybrid earthquakes before and after relocation using the joint hypocenter determination method is

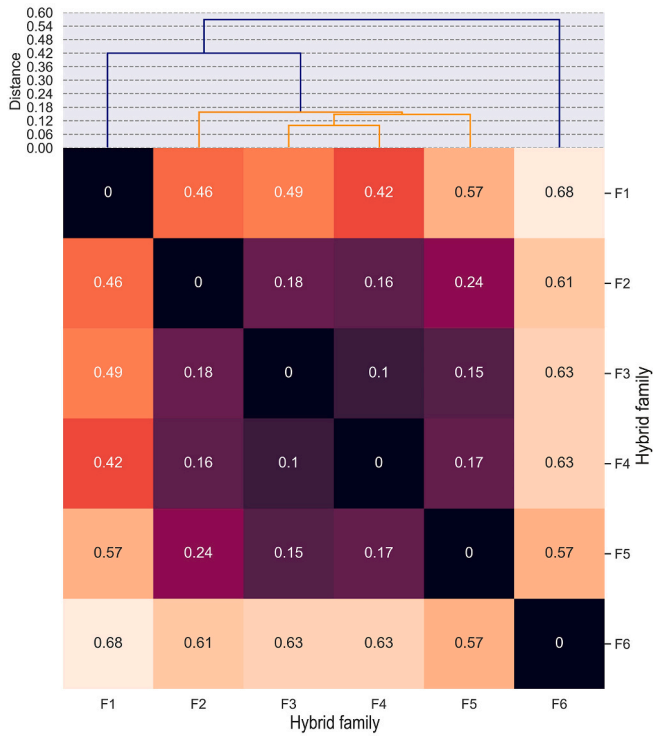


Fig. 8. Phylogenetic tree of earthquake families and proximity distance (Eq. 2) among six families. The heat map represents the proximity distances between families. Darker (lighter) colors indicate shorter (longer) distance. The phylogenetic tree above the heatmap displays the level of similarity between the families. Orange lines indicate the closer-distance families F2 – F5.

shown in Fig. 11. The initial root-mean-square error of 0.65 lower to 0.34 in the final output. The relocated hypocenter locations of the VT and hybrid earthquakes are plotted in Fig. 12. Enlarged views of the hypocenter locations of the hybrid earthquakes are shown in Fig. 13. Most of the hypocenters of the VT earthquakes are north of the summit at a depth that ranges from 1 to 10 km bsl (Fig. 12a). The epicenter zone extends to the north and then its orientation rotates towards the northwest. The northwestern alignment in the direction of NW-SE coincides with the faults near Kawar Lake (Fig. 2a). The hypocenters with a northwestern alignment are deep; they become shallower as they approach the summit (Fig. 12a).

The hypocenters of the hybrid earthquakes are separated from the hypocentral zone of the VT earthquakes and are concentrated at depths of $-0.5 - 1.5$ km bsl beneath the summit. The hybrid earthquakes have shallower depths than those of the VT earthquakes and are located

directly below the summit, whereas the VT earthquakes are shifted to the NE at the top depth of the hypocentral zone (Fig. 9c). The hybrid earthquakes can be divided into six families. It is confirmed that the events in each family occupy the same location in a horizontal range of ± 0.2 km and a vertical range of ± 0.4 km. The families F1 – F5 occupy the same zone at depths of 0.5 to 1.5 km below the summit. The family F6 is slightly shallower and shifted to the east (Fig. 10).

The temporal changes in the locations of the VT earthquakes, divided into east-west, north-south, and depth components, are shown in Fig. 14. The depth of the VT earthquakes fluctuates in the range of 1 to 10 km (Fig. 14c). It is possible to separate the analysis period into six sub-periods according to the depth and its variation. Three sub-periods have deep hypocenters (denoted by D for “deep”) and three sub-periods have shallow hypocenters (denoted by S for “shallow”). The hypocenters in the sub-periods D1, D2, and D3 are deeper (4–10 km) and more widely distributed vertically (Fig. 14c) and horizontally (Figs. 14a and b). The hypocenters in the sub-periods S1, S2, and S3 are shallower and distributed in a narrower range (2–4 km). The deep and shallow seismicity alternated. It is noteworthy that the hypocenters migrated in S3. The hypocenters remained at 2.8 km north of the summit in October 2013 and then moved south to a position 2.2 km from the summit (on average) in November–December 2013 (Fig. 11b). This indicates that the hypocenters approached the summit crater.

7.4. Impulsivity test

Impulsivity tests were applied to the VT and hybrid earthquakes. Using the criterion $I > 0.5$, we rejected 13 VT and 45 hybrid earthquake events. The average impulsivity was found to be 0.73 (standard deviation: 0.12) for VT earthquakes and 0.71 (standard deviation: 0.10) for hybrid earthquakes.

7.5. Source parameters

The time series of the seismic moment, rupture length, and stress drop for the VT earthquakes are plotted in Fig. 15. The seismic moments for the VT earthquakes range from 0.02×10^{10} to 13.9×10^{10} Nm, with most values being $< 0.5 \times 10^{10}$ Nm (Fig. 15a). The cumulative seismic moment increased rapidly from July 2013, reaching 1.7×10^{13} Nm in December. The rupture lengths for most of the VT earthquakes range from 70 to 80 m (Fig. 15b). It is noteworthy that the rupture length increased to 95 m in July 2013, when the seismicity of the VT earthquakes began to increase. Although there are no digital data immediately before July 2013, we can estimate the increase from the common range values observed before this date. Then, the rupture length returned to 70 m. The time series of the stress drop ranges from 0.01 to 1.32 MPa, with most values < 0.3 MPa, and shows a similar pattern to that of the seismic moment (Fig. 15c) because the rupture length has a

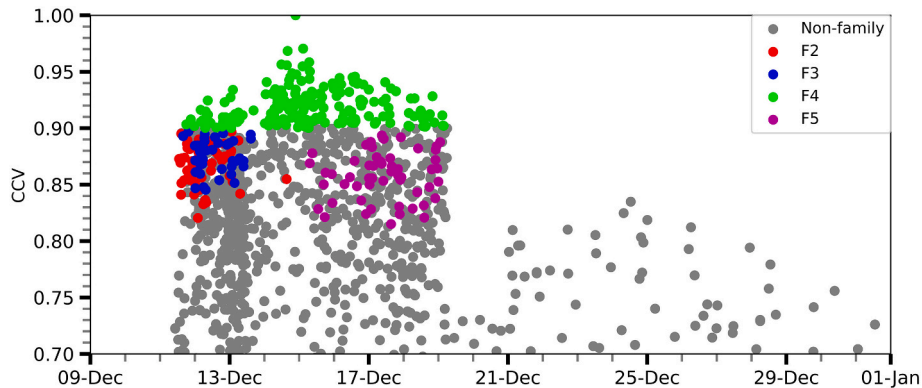


Fig. 9. Temporal change in CCV during hybrid earthquake swarm (December 11 to 31, 2013). The CCV of each hybrid earthquake is plotted in relation to the F4 reference event.

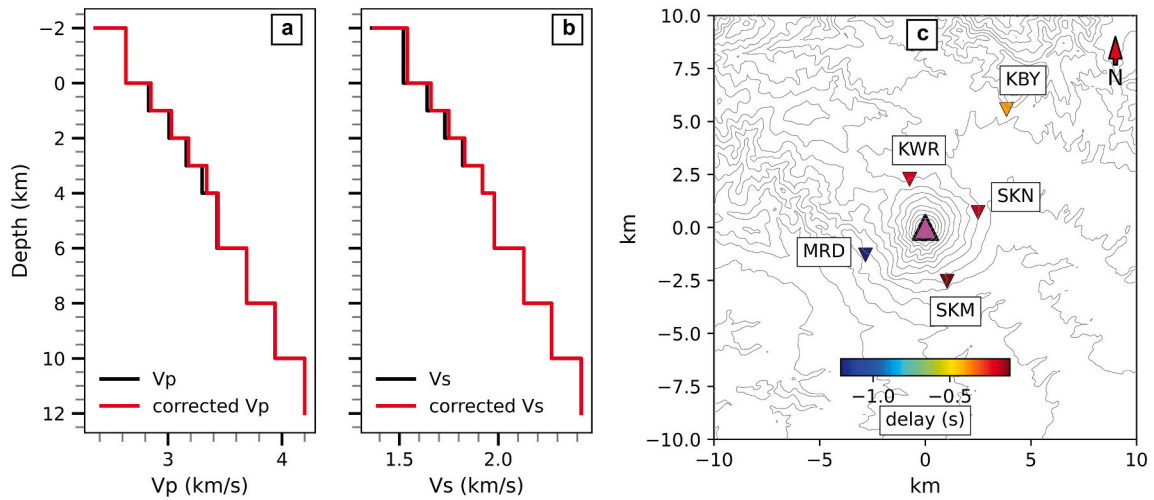


Fig. 10. Comparisons of initial and renewed 1D velocity model of a V_p and b V_s . c Station corrections represented by delays of P-wave arrival times.

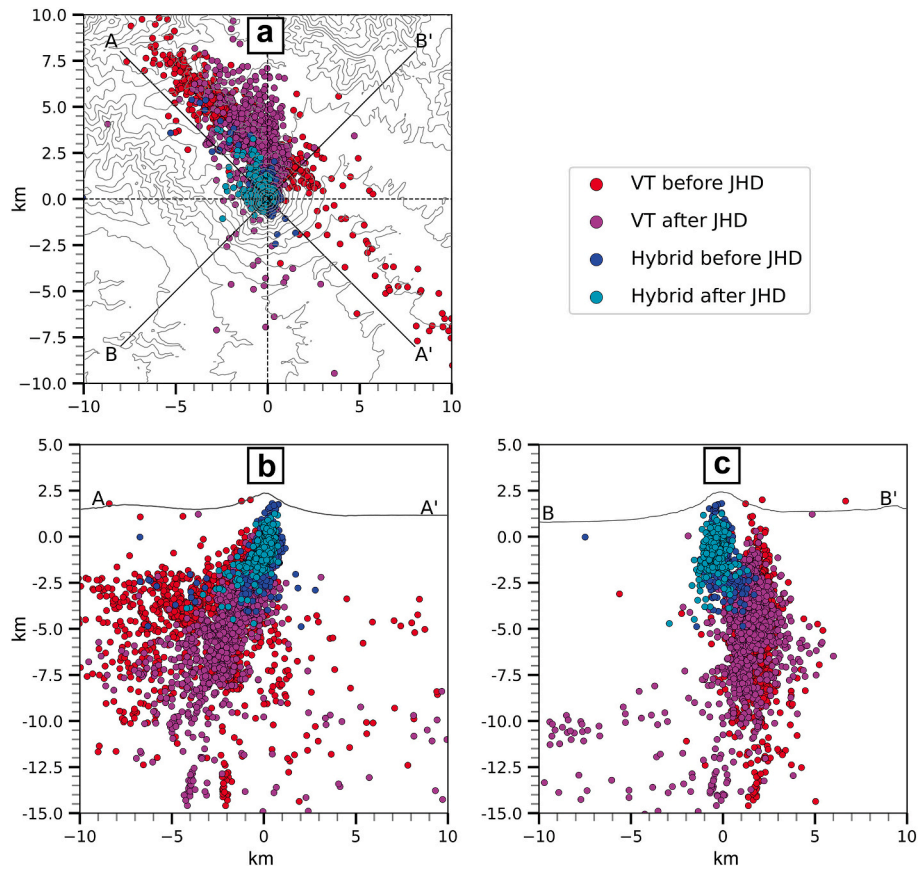


Fig. 11. a Plot of epicenters before and after relocation process of VT and hybrid earthquakes. b Similar to a, but projected in A-A' cross-section plane. c Similar to a, but projected in B-B' cross-section plane. The origin of the coordinates is set at the summit (3.171233°N, 98.39172°E).

narrow range (70 to 80 m). The rupture length increased in July 2013; however, the stress drop did not decrease significantly due to an increase in the seismic moment.

The seismic moments of the hybrid earthquakes, which range from 0.1×10^{10} to 3.4×10^{10} Nm, are smaller than those of the VT earthquakes (Fig. 16a). The time series of the seismic moments of the hybrid earthquakes show an increase-decrease pattern starting from December 11. The seismic moment was 0.4×10^{10} Nm on December 11 and gradually increased to 0.6×10^{10} Nm on December 13. The seismic

moment then accelerated, reaching 1.7×10^{10} Nm on December 16, and peaked at 3.2×10^{10} Nm on December 18, when a lava dome was visually observed at the summit. After the appearance of the dome, the seismic moment rapidly decreased, dropping to 1.3×10^{10} Nm on December 21. It then had a gradual decreasing trend until the end of December. The rupture lengths for the hybrid earthquakes were in a narrow range of 82 to 92 m (Fig. 16 b); they are slightly larger than those for the VT earthquakes. The time series pattern for the stress drop for the hybrid earthquakes (Fig. 16c) is quite similar to that for the seismic

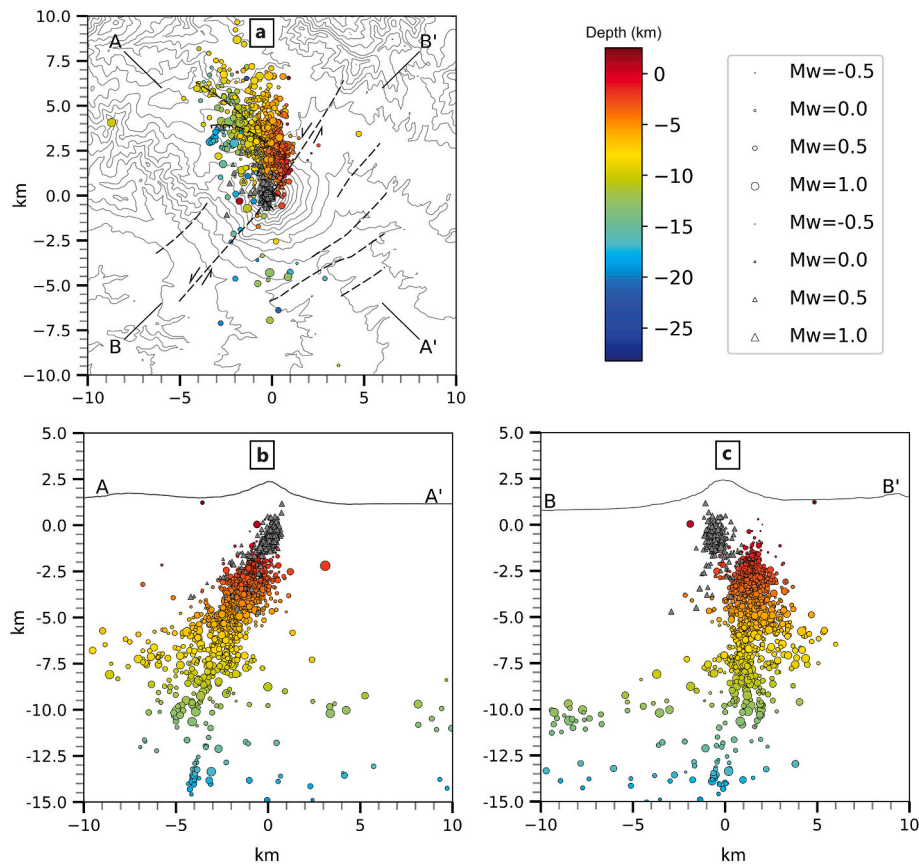


Fig. 12. Hypocenter distribution of VT and hybrid earthquakes during period from September 21, 2010, to end of 2013. a) Epicenters. Cross-sectional views along b) line A-A' and c) line B-B'. Colored circles and gray triangles indicate VT and hybrid earthquakes, respectively. Colour indicates depth and circle and triangle sizes represent the moment magnitude (Mw).

moment (Fig. 16a) from December 11 to 19 because the rupture length has a narrow range. However, the rupture length became shorter after December 19 and then increased starting from December 26, reaching 95 m at the end of December. The stress drop increased from 0.02 to 0.12–0.14 MPa from December 11 to 16, 2013, and remained at that level until December 18. It then decreased to 0.07–0.12 MPa on December 21. A further gradual decrease continued until the end of December. The stress drops for the hybrid earthquakes (<0.2 MPa) are much smaller than those for the VT earthquakes. For a given seismic moment, the stress drops for the hybrid earthquakes are smaller than those for the VT earthquakes because of the longer rupture length for the hybrid earthquakes.

The temporal changes in the source parameters are compared among the families. The short-lived (<3 days) families F1, F2, and F3 have seismic moments of $<1.0 \times 10^{10}$ Nm. The longer-lived families F4, F5, and F6 have larger seismic moments than those for F1, F2, and F3. F4 is the only family for which the seismic moment shows an increase-decrease pattern. Non-family events indicate a similar increase-decrease pattern during the seismicity of F4. F5 has the largest seismic moments, which range from 1.5×10^{10} to 2.5×10^{10} Nm. F6 has the second-largest seismic moment, which remains constant at 1.4×10^{10} Nm. The longer-lived families F4, F5, and F6 have larger stress drops (~ 0.10 MPa) than those for F1 – F3 (<0.05 MPa).

8. Discussion

8.1. VT earthquakes

During the pre-magmatic period, the hypocenters of the VT earthquakes were distributed north and northwest of the summit at a depth

range of 1–10 km bsl. Indrastuti et al. (2019) reported a similar distribution of VT earthquakes, which were primarily concentrated to the north and northwest of the summit. However, Nugraha et al. (2019) reported a slightly different distribution of VT earthquakes for the November–December 2013 period. Although VT earthquakes were distributed in the N–NE area in both studies (Fig. 11a), Nugraha et al. (2019) found that the distribution extends up to 6 km, whereas in the present study, the distribution in the N–NE area extends up to only 3 km. In our results, the VT earthquakes migrated into the N–NE area occurred in November 2013. (Fig. 14a, the epicenters existed in the east of summit during S3 period (coordinate value >0); Fig. 14b, the epicenters migrated from the north to the south (coordinate value towards 0)).

The seismicity of the VT earthquakes alternately increased at deep (4–10 km) locations in the sub-periods D1, D2, and D3 and at shallow (2–4 km) locations in the sub-periods S1, S2, and S3 (Fig. 14). The alternating seismicity at deep and shallow depths is interpreted as an increase in the connectivity of fractures, which facilitated the movement of magma to shallower locations (Scandone et al., 2007). For Sinabung volcano, the epicenters of the VT earthquakes are located north and northwest of the volcano. However, pressure sources during the pre-magmatic and magmatic eruptions after 2014 (Hotta et al., 2019) are not located in the seismic zone. Therefore, it is difficult to interpret the VT earthquakes as being generated by fracture due to the direct intrusion of magma. It is possible to interpret the seismicity of the VT earthquakes, in particular those with a NS orientation of the P-axis, as being triggered by magma pressure from the south (Afnimar et al., 2022). Before the phreatic eruption in 2010, the volcano was inflated (Chaussard and Amelung, 2012); however, no significant ground deformation was detected by GNSS from 2011 to before the S3 sub-period (Hotta et al., 2019). Magma intruded into a deep location,

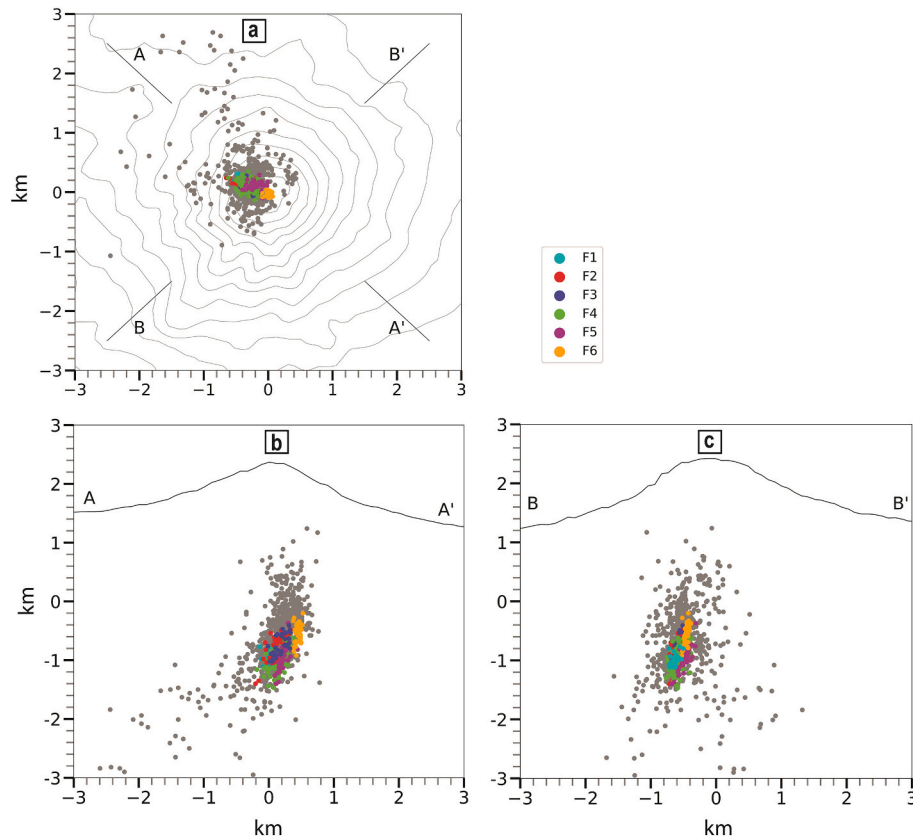


Fig. 13. Enlarged views of hypocenter locations of hybrid earthquakes. Colored circles indicate families. a Epicenters and projection map on cross-section along b line A-A' and c line B-B'.

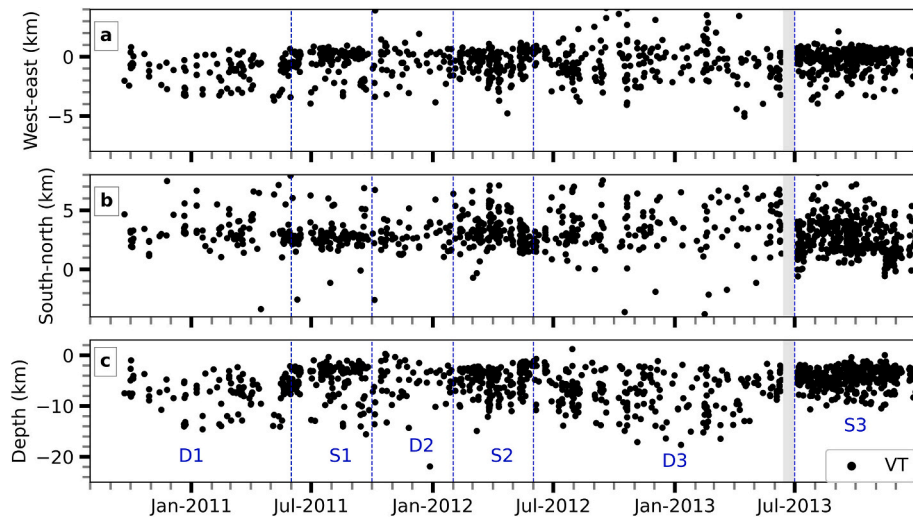


Fig. 14. Time series of hypocenter locations of VT earthquakes in a east-west, b north-south, and c depth directions. D1-D3 and S1-S3 are periods separated based on the distribution pattern of the hypocentral depth. Gray bars indicate period in which no digital data were obtained.

which was pressurized before the 2010 eruption. The magma intrusion is considered to have already started before 2007 because InSAR data show ground inflation from 2007 (Chaussard and Amelung, 2012). Under the highly pressurized condition, the VT earthquakes were triggered in the fragile north and northwest parts due to the fluctuation of the pressure at the deep location.

The seismicity of the VT earthquakes in the S3 sub-period is somewhat different from that in previous sub-periods. The increase in the cumulative seismic moment was the largest in S3. The hypocenters were

concentrated only in the shallow part, showing a trend of approaching the summit. This may indicate an increase in pressure inside the volcano due to a new intrusion of magma towards shallower areas. The extension of the slope distance between the LKWR and SKNL stations starting from June 2013 (Fig. 15d) supports the new intrusion of magma. Hotta et al., (2019) estimated the pressure source has depth of 3–8 km during October to December 2013, similar with our VT depth during that period (2–6 km; Fig. 14c). Other characteristics of S3 include an increase in rupture length and a slight decrease in stress drop in July 2013. The

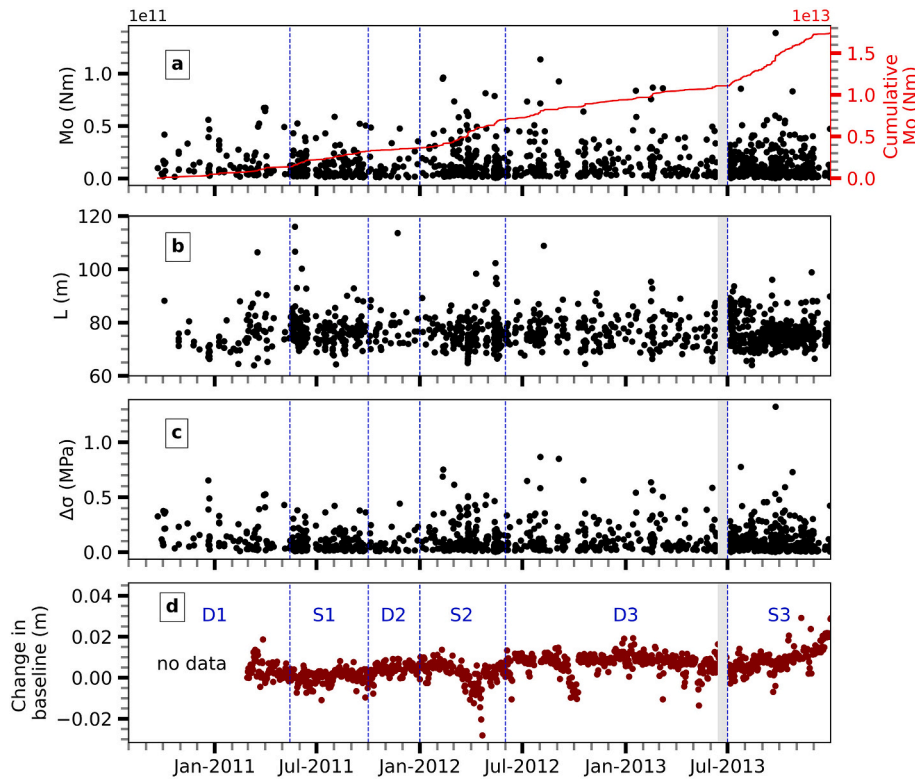


Fig. 15. Time series of source parameters of VT earthquakes. a Seismic moment and its cumulative value (red line), b rupture length, and c stress drop. d Slope distance change between LKWR and SKNL stations. D1-D3 and S1-S3 are periods separated based on the distribution pattern of the hypocentral depth. Gray bars indicate period in which no digital data were obtained. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

decrease in stress drop during repeated earthquake cycles can be attributed to incomplete stress release, changes in stress from earthquakes on nearby faults, or changes in rock strength (Kanamori and Brodsky, 2004). Among these factors, the most likely explanation for the decrease in stress drop at the onset of intrusion in July 2013 is a change in rock strength. Changes in rock strength can result from the influence of migrating fluids within the rock (Kanamori and Brodsky, 2004). In this case, fluids carried through the magma intrusion process may have led to a reduction in rock strength. Possible fluids are volcanic gases from degassed magma.

8.2. Hybrid earthquakes

The seismicity of the VT earthquakes was altered by a swarm of hybrid earthquakes beneath the summit in mid-December 2013. The stress drops for the hybrid earthquakes (Fig. 16c) were smaller than those for the VT earthquakes (Fig. 16c). The low stress drop for the hybrid earthquakes is caused by a reduction in rock strength. The hybrid earthquakes occur at shallow depths (−0.5–1.5 km bsl) directly below the summit. The rock strength at this depth is weaker than that at the location of deeper VT earthquakes. The strength of rock increases linearly with pressure and depth, from 0 km to the brittle-ductile transition zone (~15 km) (Grigull, 2011). Another reason for the reduction in rock strength is fluid migration into the rock (Kanamori and Brodsky, 2004), which can be caused by viscous magma. This suggests that the contribution of fluid to the source process is higher for hybrid earthquakes than for VT earthquakes.

Considering the fluid, the characteristic low-frequency dominant peak of the hybrid earthquakes is examined. The logarithmic spectral ratio of the low-frequency range (LFR, 0–5 Hz) to the high-frequency range (HFR, 2–20 Hz) is plotted on Fig. 13e. From December 11, 2013, the seismic moment and stress drop for the hybrid earthquakes

increased and persisted until just before the beginning of lava effusion on December 18 (Fig. 13a and c). The spectral ratios LFR/HFR at the beginning of the seismicity (December 11 to 13) are smaller in the sequence until the end of December. This suggests that the seismic moment increased due to dominant fracturing caused by pressure buildup due to magma intrusion. The log LFR/HFR ratio suddenly increased to a positive value on December 14, suggesting that the movement of fluid-filled cracks became dominant (rather than fracturing). On December 15, the log LFR/HFR ratio dropped to around 0 and remained at that level. This may reflect the contribution of fracture in the process of magma solidification, as evidenced by the extrusion of solid magma forming a lava dome at the summit on December 18.

After the appearance of the lava dome at the summit, the seismic moment and stress drop decreased, probably due to the release of pressure within the volcano. A further decrease in stress drop was detected from December 25 to the end of the month (Fig. 16c). This decrease corresponds to an increase in the log LFR/HFR ratio to >0 (Fig. 16e). The lower stress drop and dominance of low frequencies is related to fluid migration into the rock (Kanamori and Brodsky, 2004). This means that viscous magma continued to migrate to the summit. According to satellite observations, the dome grew at a rate of 1.4 m³/s and began to collapse, producing pyroclastic flows by December 31, 2013 (Pallister et al., 2019).

The activity of a hybrid earthquake is characterized by the frequent repeating of events with similar waveforms, as indicated by the six families. Each family has its specific rupture length and hypocenter location because of the similarity of its waveforms. A given earthquake family, in particular F4 (Fig. 16a and c), gradually changes its seismic moment and stress drop within narrow ranges, maintaining similar waveforms. The existence of earthquake families indicates that the magma intrusion process proceeds gradually. A further change in internal conditions due to the intrusion of magma allows the seismicity to

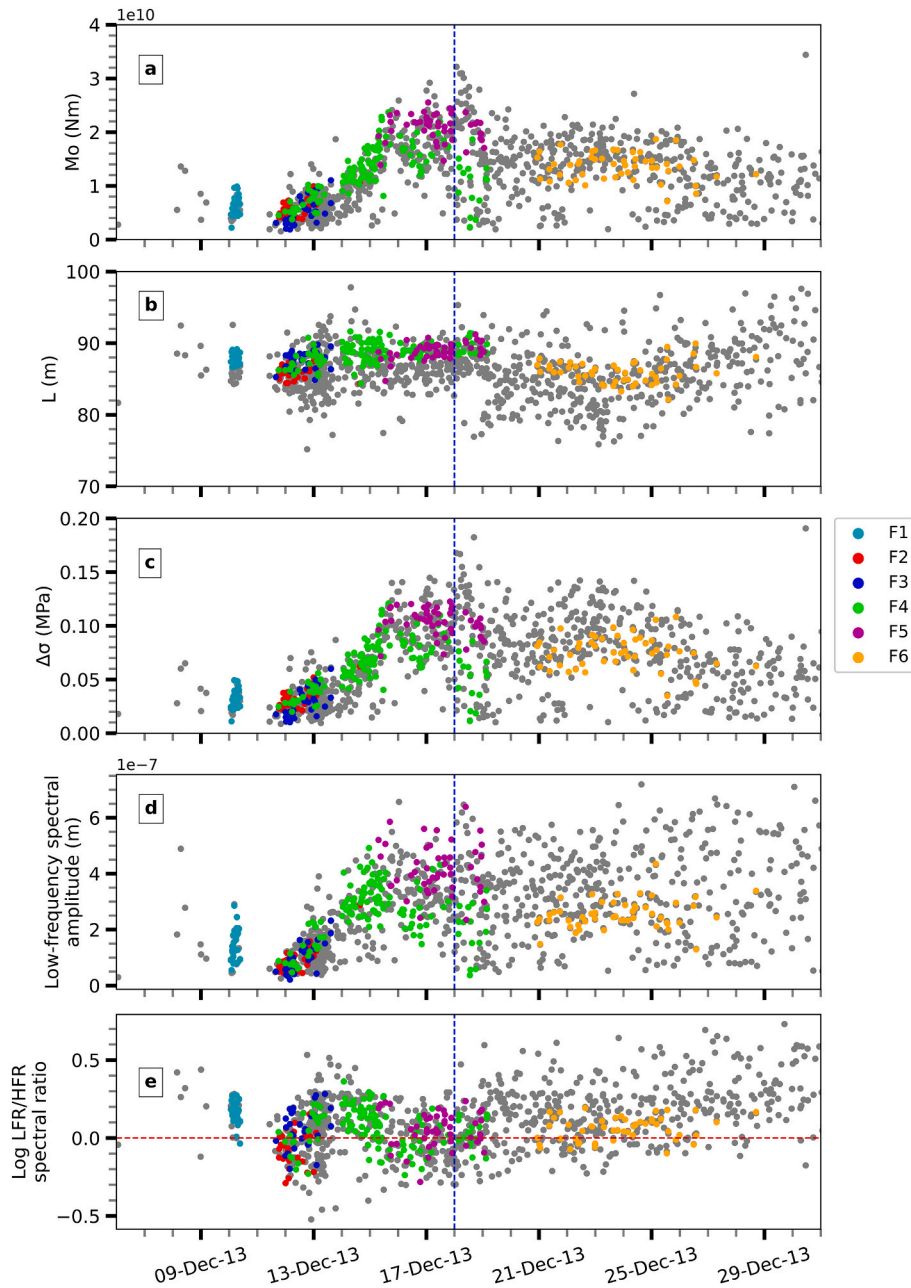


Fig. 16. Time series of source parameters of hybrid earthquakes. Colored dots represent earthquakes that belong to a family and gray dots represent non-family events. a Seismic moment, b rupture length, c stress drop, d spectral amplitude in low-frequency region, and e ratio of spectral peaks in high- and low-frequency regions in logarithmic scale.

transition from one family to another. The waveform evolution from one family to another has been reported for earthquakes in Unzen, Japan (Umakoshi et al., 2008). Before the appearance of the lava dome, five families (F1 – F5) were identified. Only F6 is found after the beginning of lava effusion; mostly non-family events occurred in the periods December 19–21 and December 27–31, 2013. Magma intrusion proceeds gradually as an endogenous process; however, magma moves rapidly as an exogenous process after the conduit opens.

8.3. Process of magma intrusion

A schematic diagram of the process of intrusion of magma is shown in Fig. 17. The shortening of the satellite line of sight, as determined by InSAR analysis (Chaussard and Amelung, 2012), indicates that Sinabung volcano had already inflated before 2007. This suggests that the

intrusion of magma into a deep part of the volcano and the inflation of the ground around the summit are due to an increase in hydrothermal activity (González et al., 2015), probably triggered by heat supply from the deep magma (Stage A). Phreatic eruptions occurred from August 27 to September 7, 2013. As these eruptions did not emit juvenile material, it is inferred that the magma remained in the deep part, with only heat and gas migrating to the summit crater (Stage B). The presence of VT earthquakes with a radius range of 2–5 km (Fig. 14), despite the presence a newly opened conduit due to phreatic eruptions, indicates continued pressure at the depth of the upper crustal magma storage region (McCausland et al., 2019).

Seismic observations conducted after the beginning of the eruptive activity reveal a high seismicity of VT earthquakes (Stage C, October 2010 to June 2013). The VT hypocenters in this stage were distributed northwest and north of the volcano (Fig. 12a), where faults have been

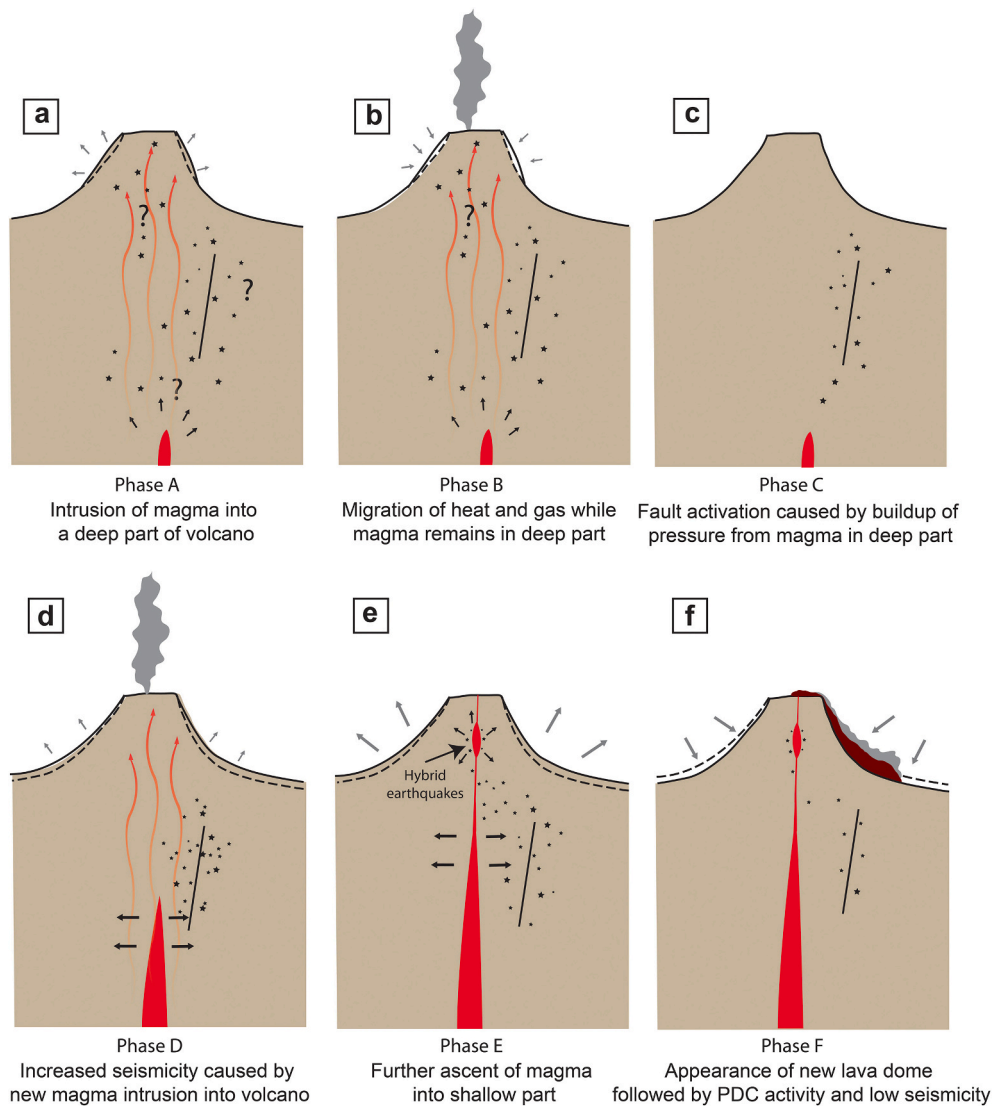


Fig. 17. Schematic diagram of magma intrusion process that induced inflation of volcano, seismicity of VT and hybrid earthquakes, and phreatic eruptions prior to magmatic eruptivity that started in December 2013. a Intrusion of magma into deep part of volcano prior to phreatic eruptions in 2010. b Phreatic eruptions in 2010. Migration of heat and gas while magma remained in the deep part. c Pressurized volcanic body (October 2010–June 2013). d New magma intrusion and second phreatic eruptions (July–November 2013). e Further ascent of magma to shallow part (November–December 2013). f Appearance of new lava dome and subsequent PDC (after December 2013).

identified both geologically (Fig. 2) and seismically (Afnimar et al., 2022). This seismicity might be due to fault activation caused by stress fields due to magma pressure from the south, as inferred from the pressure source location (Afnimar et al., 2022). The pressure already increased in Stage A, as indicated by InSAR analysis. In Stage C, the seismicity of the VT earthquakes repeated as a release of stress due to the buildup of magma pressure in the deep part in the upper crustal magma storage region (McCausland et al., 2019). As ground deformation measured by GNSS did not show a significant change (Fig. 15d), new magma did not intrude in Stage C.

The situation changed in Stage D (July–October; Fig. 14d). The seismicity of the VT earthquakes suddenly increased on July 6, 2013 (S3). This seismicity is different from the seismicity in S1 and S2 in Stage C. The seismicity in S3 is higher than that in S1 and S2, as shown by the cumulative seismic moment (Fig. 15a). The hypocenter zone extended to the south, approaching the summit (Fig. 14b). The rupture length increased to 90 m at the beginning of S3. Moreover, the extension of the slope distance, indicating the inflation of ground deformation, started as a precursor before S3 in June 2013 (Fig. 15d). This indicates new magma

intrusion into the volcano in Stage D. The depth of the pressure source is estimated to be 3–8 km during the period from June to October 2013 (Hotta et al., 2019). Stages A–C within the timeframe before June 2013. The magma depth may be deeper than 8 km. There was no significant inflation in Stages A–C. The magma may migrate to shallower parts in Stage D. During the progress of the seismicity and inflation, a phreatic eruption occurred on September 15, 2013. This indicates that the magma was insufficiently shallow to erupt juvenile material in Stage D.

A further ascent of magma is revealed by a shallower pressure source and hybrid earthquakes directly below the summit in Stage E (November–December 2013, Fig. 16e). The emergence of hybrid earthquakes preceded by low-frequency earthquakes indicates magma ascent and the disruption of the hydrothermal system (McCausland et al., 2019). The extension of the slope distance accelerated (Fig. 16d). The pressure source that induced the deformation is estimated to be at a depth of 0.4–2.1 km (Hotta et al., 2019). The hypocenters of the hybrid earthquakes are at similar depths (–0.5–1.5 km; Fig. 13). The occurrence of hybrid earthquakes indicates the involvement of fluid-filled cracks, as revealed by dominant peaks in the low-frequency range and a low stress

drop. Finally, a new lava dome appeared at the summit on December 18, 2013, followed by PDC activity (Stage F, after the end of December 2013).

9. Conclusion

VT and hybrid earthquakes during the pre-magmatic period (2010–2013) of Sinabung volcano were analyzed to clarify the process of magma intrusion using hypocenter locations, waveform similarity, and source parameters. The seismicity (phreatic eruptions) from 2010 to June 2013 is dominated by VT earthquakes at depths of 1–10 km bsl north and northwest of the summit. These earthquakes were triggered by the pre-pressurization of magma that had intruded into a deep part of the volcano before the 2010 eruption. The VT seismicity that began in July 2013 was caused by a new intrusion of magma into a shallower part. This is different from previous seismicity in terms of higher intensity, a temporary increase in the rupture length, and the migration of hypocenters. In mid-December 2013, the seismicity was altered by a swarm of hybrid earthquakes at shallow depths (–0.5–1.5 km bsl), suggesting a further ascent of magma. The hybrid earthquakes involve fluid-filled cracks, as revealed by dominant peaks in the low-frequency range and a low stress drop. A decrease in the seismic moment for the hybrid earthquakes on December 18, 2013, may indicate a pressure release by the beginning of lava effusion.

CRedit authorship contribution statement

Vico Luthfi Ipmawan: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Masato Iguchi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Takahiro Ohkura:** Writing – review & editing, Supervision, Conceptualization. **Takeshi Tameguri:** Writing – review & editing, Supervision, Conceptualization. **Hetty Triastuty:** Writing – review & editing, Validation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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