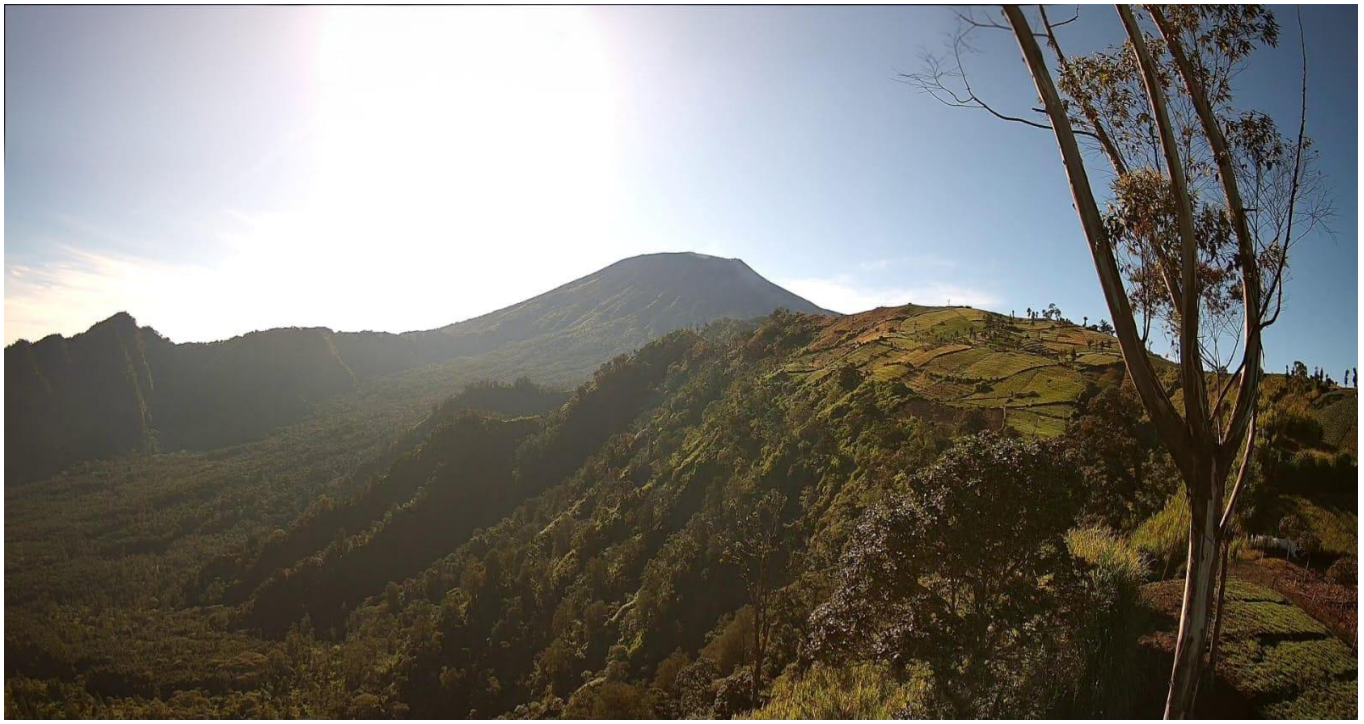
Seismic Unrest at Mount Slamet: Signals of Magma Movement Beyond The Expected Eruption Interval



Novianti Indrastuti, C. Widiwijayanti, *A. Basuki, H. D. Purnamasari, D. K. Syahbana, M. Rusdi, A. G. P. Kastawa, D. Al Hidayat, A. C. Purnomo, S. A. Manaf, I. Mulyana, A. Mathovanie, H. Triastuty, S. Hidayati, N. Haerani, Kristianto, M. Surmayadi Sulistiyani, Mukijo, Martanto*

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Geological Agency

Center For Volcanology and Geological Hazard Mitigation

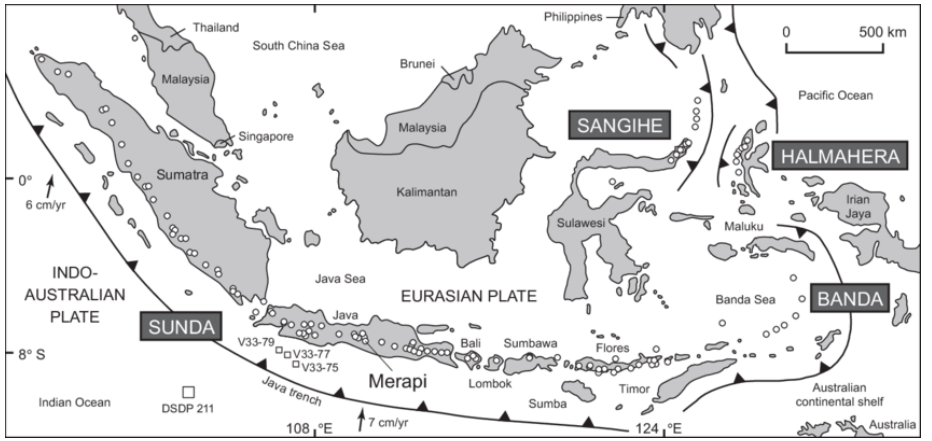
Introduction

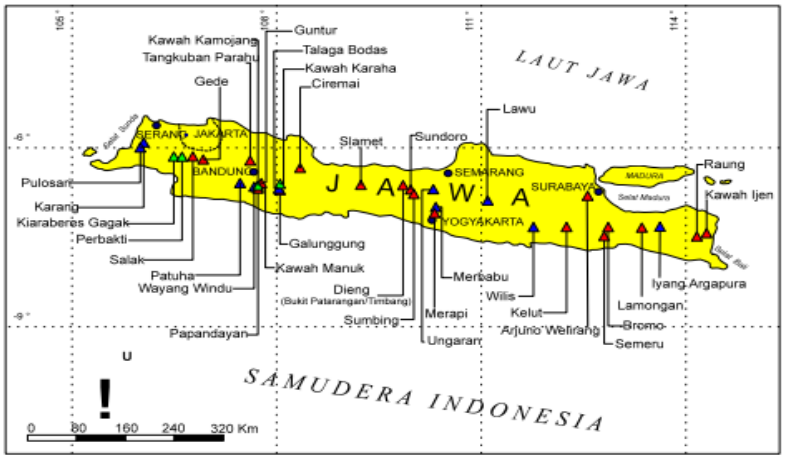
Mount Slamet

- Location : Central Java, Indonesia
- Elevation : 3432 meters (4th highest in Indonesia), after Kerinci, Rinjani, Semeru.
- Type : Stratovolcano
- Tectonic setting : part of sunda volcanic arc

- formation : due to the subduction of the Indo-Australian Plate under the Eurasian Plate

- Crust : sits on a continental crust 20 – 25 km thick



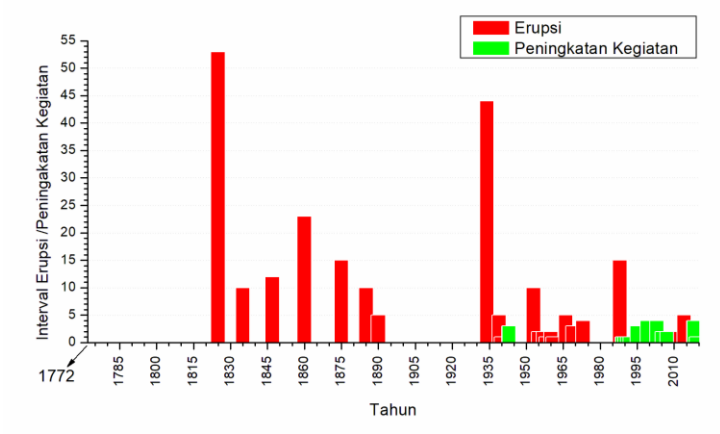


Historical Eruption and Eruption Characteristic

Mount Slamet is one of Java's most active volcanoes, with over fifty eruptions since 1772.

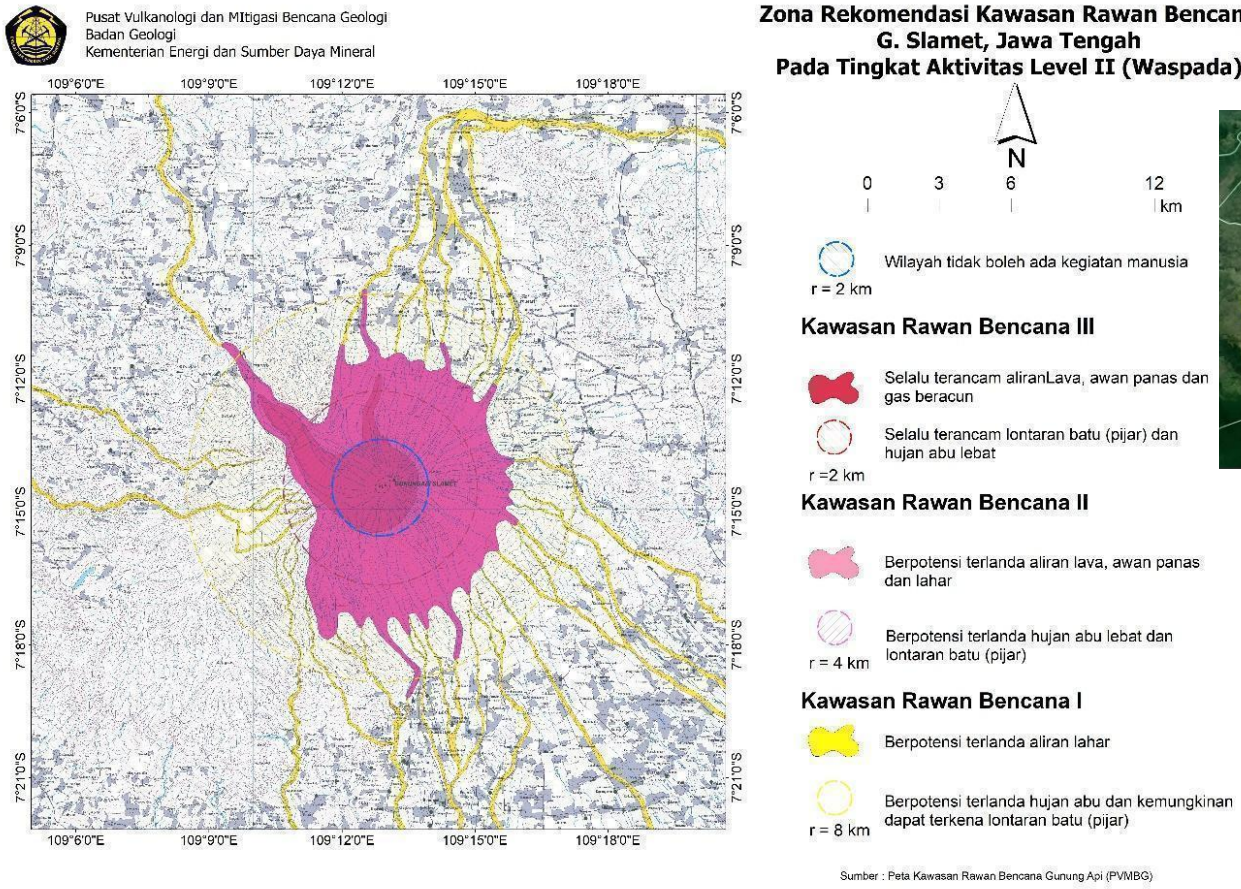
Most events are VEI 1–2, producing small to moderate volumes and plume heights up to 5 km.

The eruptions are generally characterized by Strombolian activity, accompanied by the ejection of incandescent rocks and lava flows. The volcano erupts frequently, on average every three years, with the latest eruption in 2014."



Eruption interval and increase in volcanic activity

Volcanic hazards



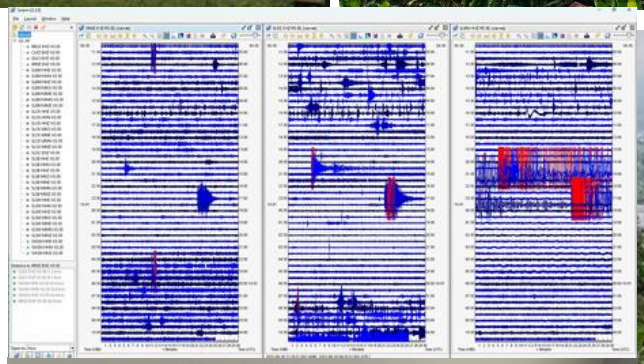
Slamet's flanks span five districts, with around 15,000 people living within a 10 km radius of the summit.

The Slamet Volcano hazard map defines three zones:

- KRB III & (0–2 km): Highest danger zone, permanently exposed to PDCs, lava flows, toxic gas, incandescent ejecta, ballistics, and heavy tephra fall.
- KRB II & (2–4 km): Potentially affected by PDCs, lava flows, lahars, and also at risk from incandescent ejecta, ballistics, and heavy tephra fall.
- KRB I & (4–8 km): Outer hazard zone, mainly threatened by lahars and tephra fall, with occasional impact from incandescent ejecta.

Monitoring System

Slamet Volcano Observatory is ~9km north of the summit, located in Desa Gambuhan, Kab. Pemalang.



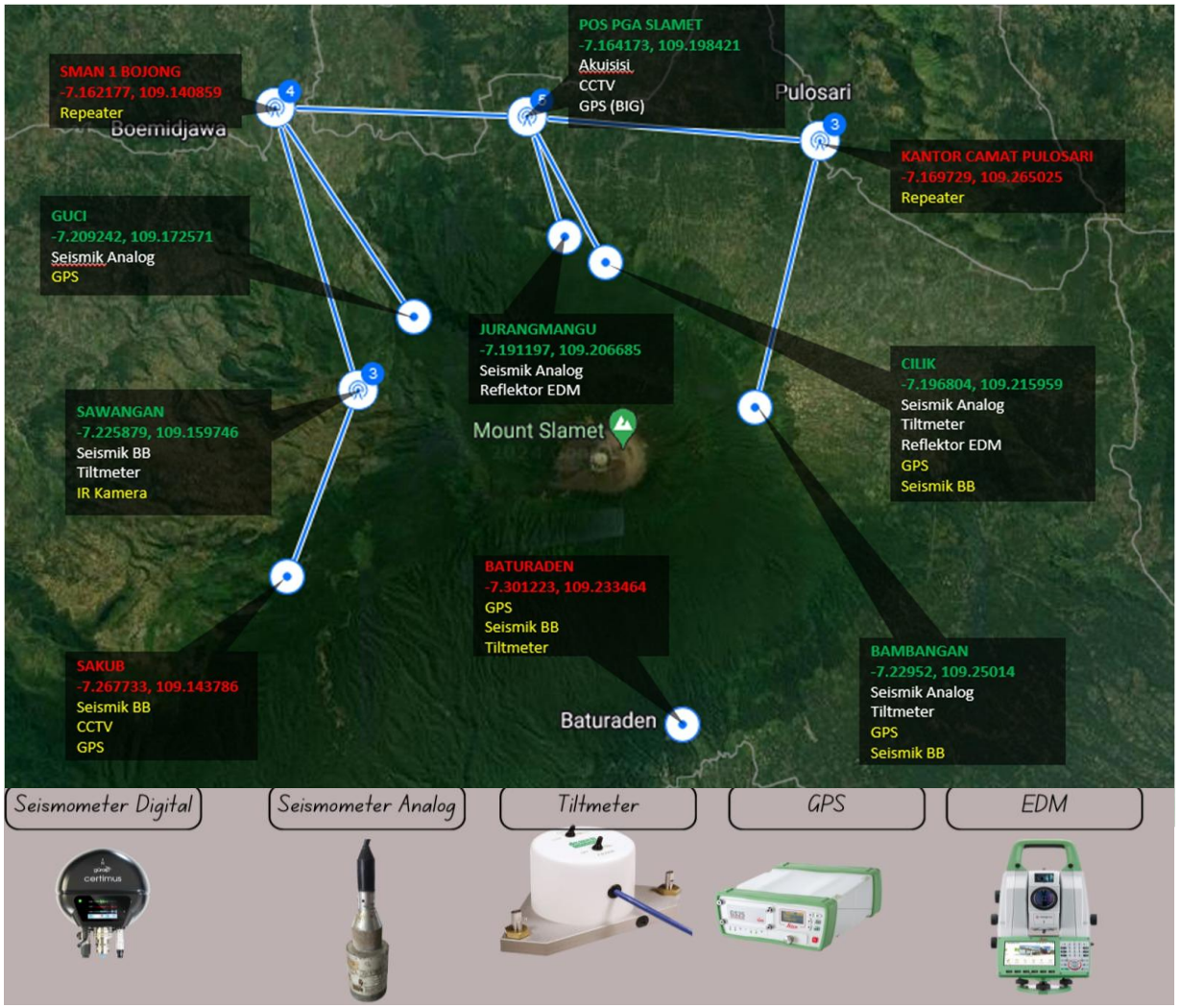
Monitoring network

The Slamet Volcano monitoring network consists of 2 repeater and 7 monitoring stations, equipped with:

- 4 analog seismometers,
- 1 broadband sensor,
- 2 tiltmeters,
- 2 EDM units,
- CCTV, and
- GPS (BIG) stations.

Planned upgrades will add:

- 4 broadband seismometers,
- 5 GPS stations,
- 1 tiltmeter,
- 1 IR camera, and
- 2 repeaters.



Monitoring is designed to detect early anomalies indicating unrest or potential eruption, using:

- Seismic data: earthquake types, tremor, and other signals.
- Visual observation: crater observations via CCTV and drones.
- Ground deformation: EDM, GPS, and tiltmeter.

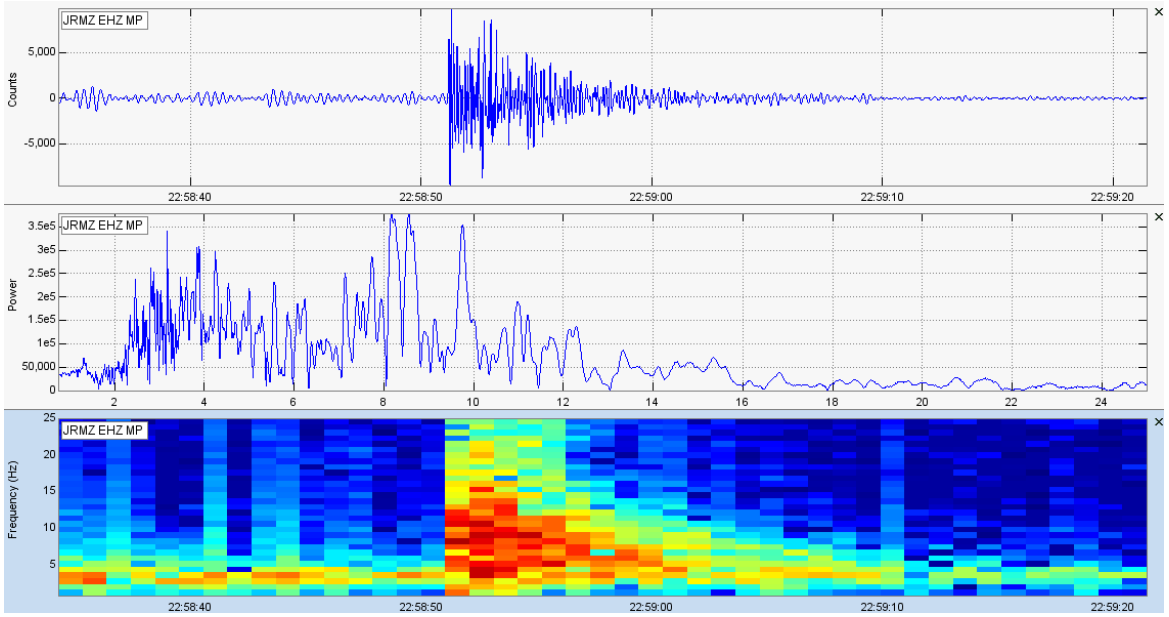
Seismic Event Type Classification

Based on the source mechanism, seismic events at Slamet can be divided into two groups

1. Earthquakes caused by brittle failure or rock fracture, which include Deep VT (VA), Shallow VT (VB), dVT, Local Tectonic (TL) and Regional (TJ).

2. Earthquakes caused by the movement or flow of fluids (gas, water, water vapor) within the conduit system (Harmonic Tremor, Long Periode/Tornilo/Low-Frequency)

When fluid pressure within conduit exceeds the strength treshold of the cap rock, magma may fragmented and escape, eventually reaching the surface as an eruption.



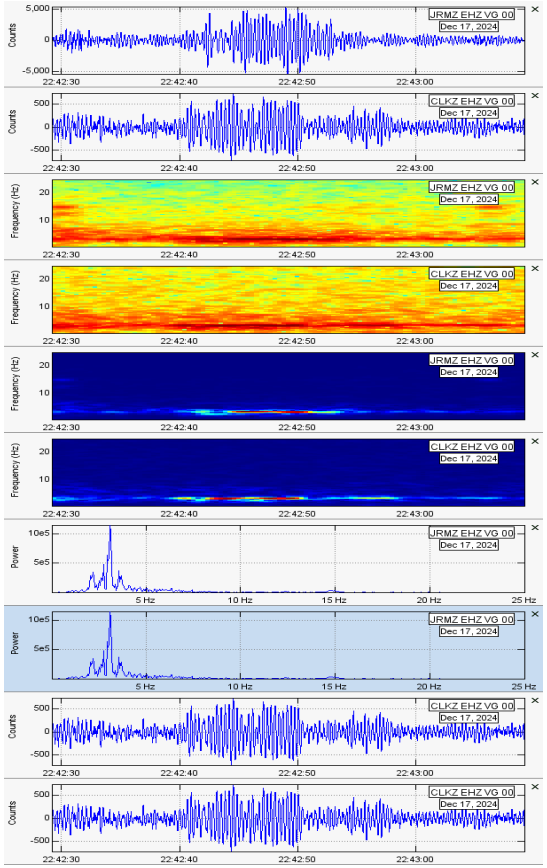
some examples of earthquakes recorded by the JRMZ (Jurang Mangu) seismic station

Deep VT (VA)

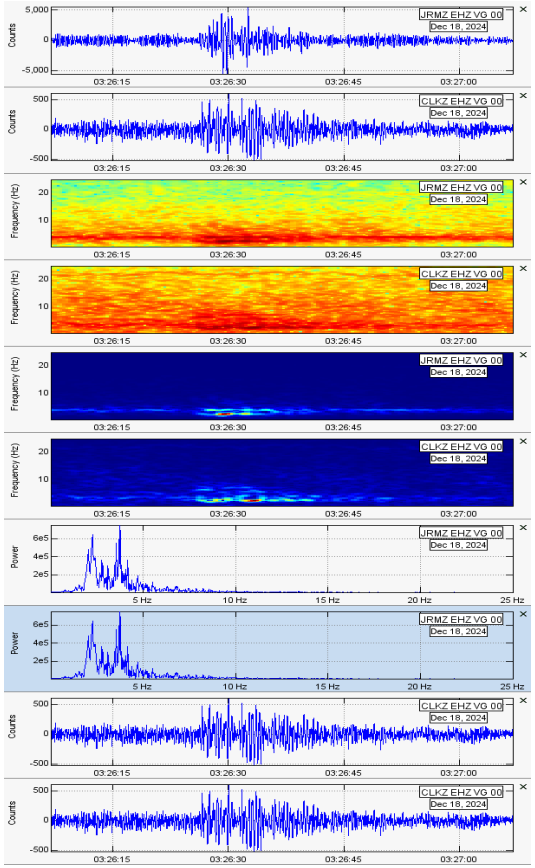
occurs directly under the volcano edifice

- has high frequency content (> 6 Hz)
- display an impulsive onset
- S-P waves arrival (S-P 0.5 – 2 s)

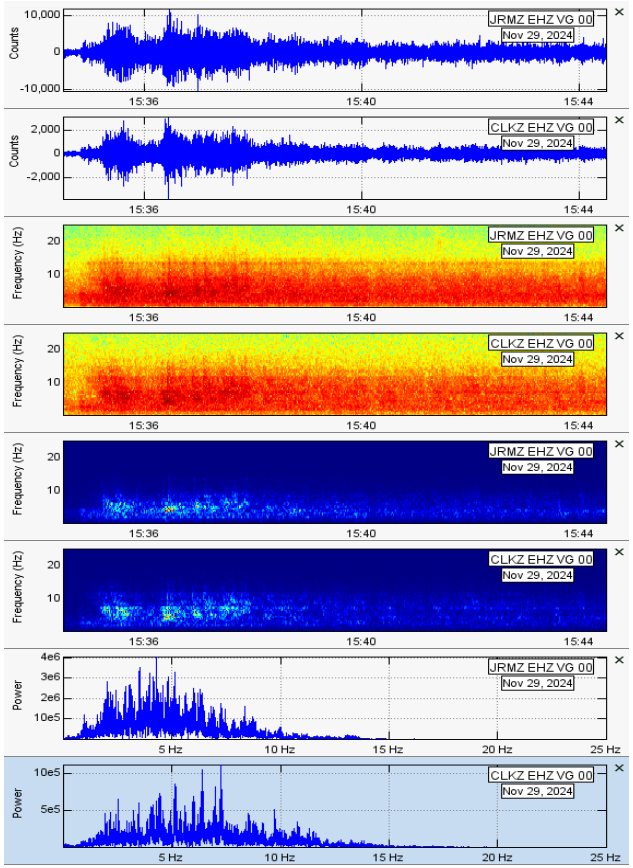
Low Frequency/ LP



Hembusan



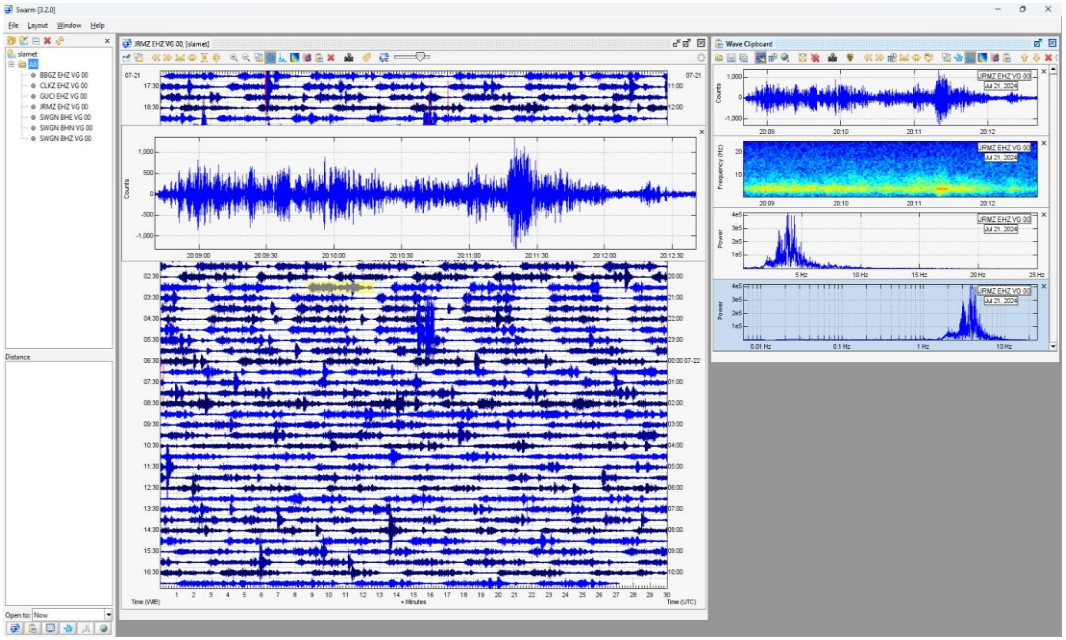
Non Harmonic Tremor

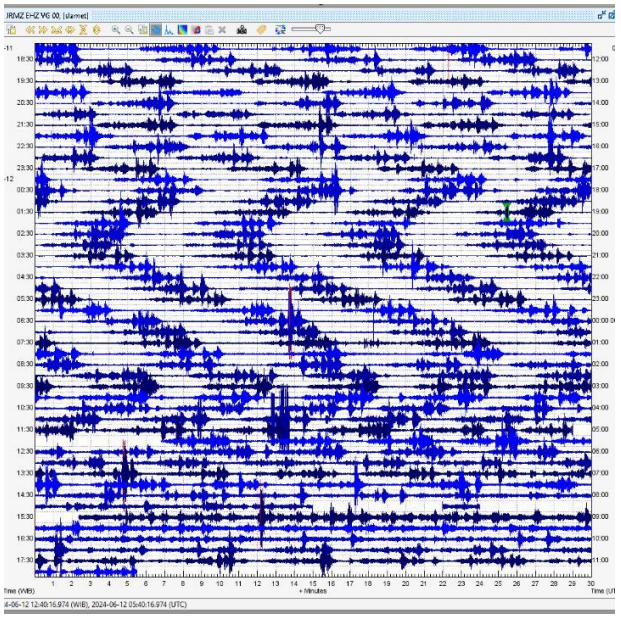


Both LP and non Harmonic tremor share a similar source mechanism, but tremor has a longer duration. In some volcanoes, these events are not always followed by eruptions, such as at Papandayan and Kusatsu Shirane (Japan) (Syahbana et al., 2014).

- occurs directly under the volcano edifice
- low frequency content (1-5 Hz)
- LF duration < 25 seconds, Hembusan 25-60 seconds, Non Harmonic Tremor > 60 seconds
- emergent onset

We refer to this event as a “Batik Earthquake,” recorded on July 24, 2025 classified as a Hembusan/Low-Frequency type.





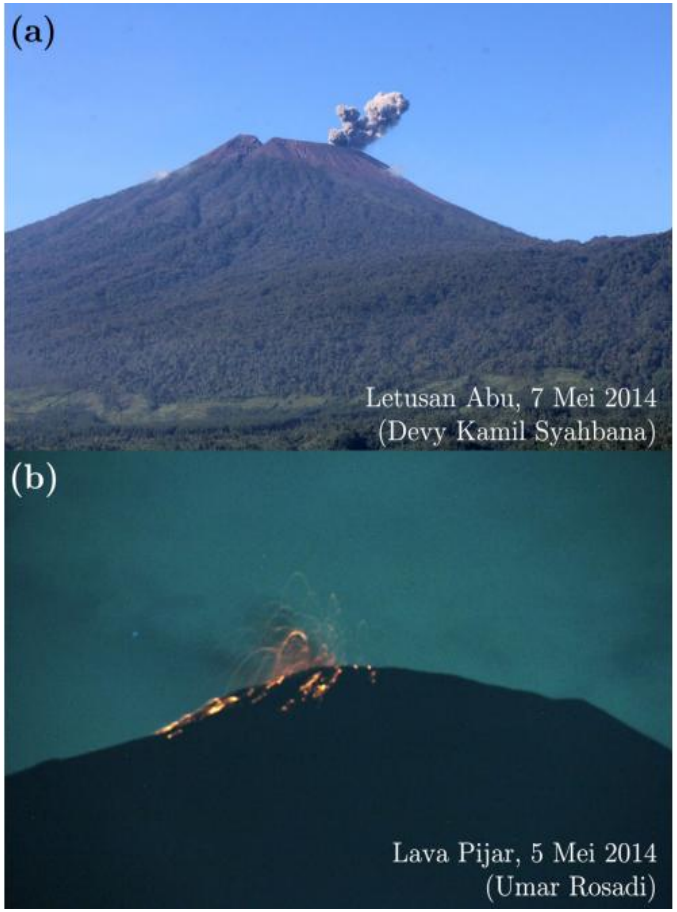
In the historical record of the Slamet Volcano, precursory activity typically follows a characteristic sequence.

Long term precursors : gradual increase in Hembusan or Low Frequency earthquakes (indicates gas release and fluid movement in the conduit), develops over weeks to months.

Short term precursors : appearance of LP earthquakes and tremor, including harmonic tremor, occurs minutes to tens minutes before the eruption (refleks rapid pressurization and upward movement of gas-rich magma or hydrotermal fluids)

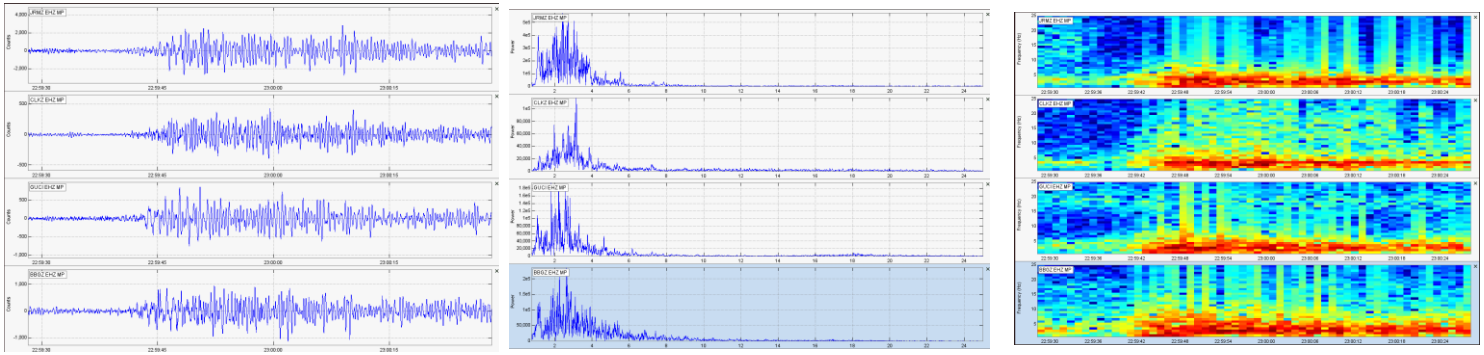
In summary, precursors at Slamet generally begin with a slow build-up of hembusan/LF activity, followed by a short-term spike in LP events and tremor immediately before eruptive onset.

Latest Eruption : March – September 2014 Eruption



(a) Visual observations from the Slamet Volcano Observatory on **7 May 2014** showed an ash eruption from the summit crater.

(b) Visual observations from Baturraden on **5 May 2014** capture a strombolian type eruption, marked by the ejection of incandescan lava



Eruption chronology (2014 – 2015)

10 March 2014: First eruption; ash column reached 1,000 m above the summit. Activity status raised to Level II (Alert).

30 April 2014: Activity increased; status raised to Level III (Alert). Ash column reached 100 – 1,500 m.

12 May 2014: Activity level lowered to Level II (Alert).

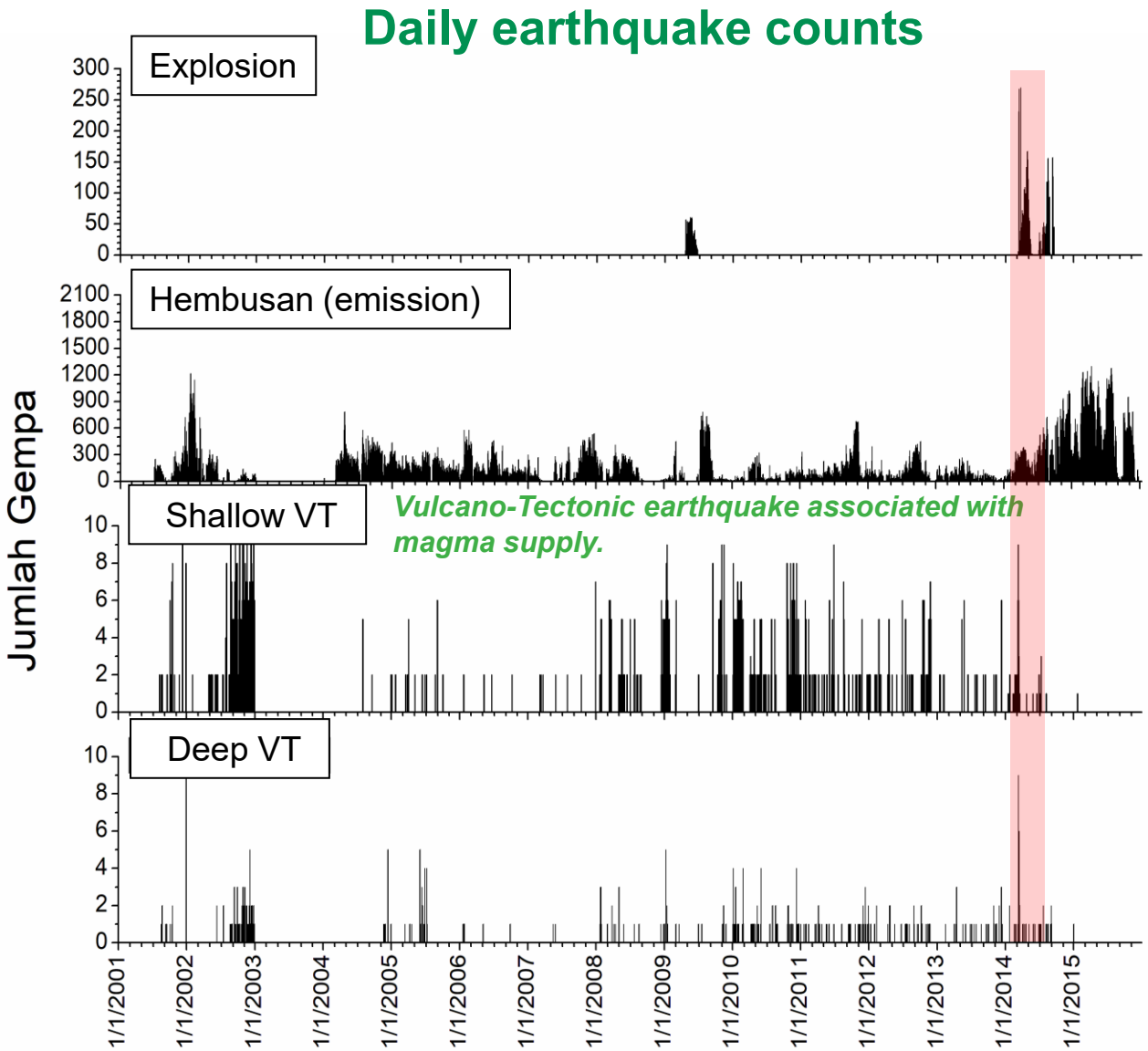
18 May 2014: Eruptive activity continued.

29 June – 28 August 2014: Sustained eruption period; ash columns up to 2,000 m.

12 August 2014: Status raised again to Level III (Alert).

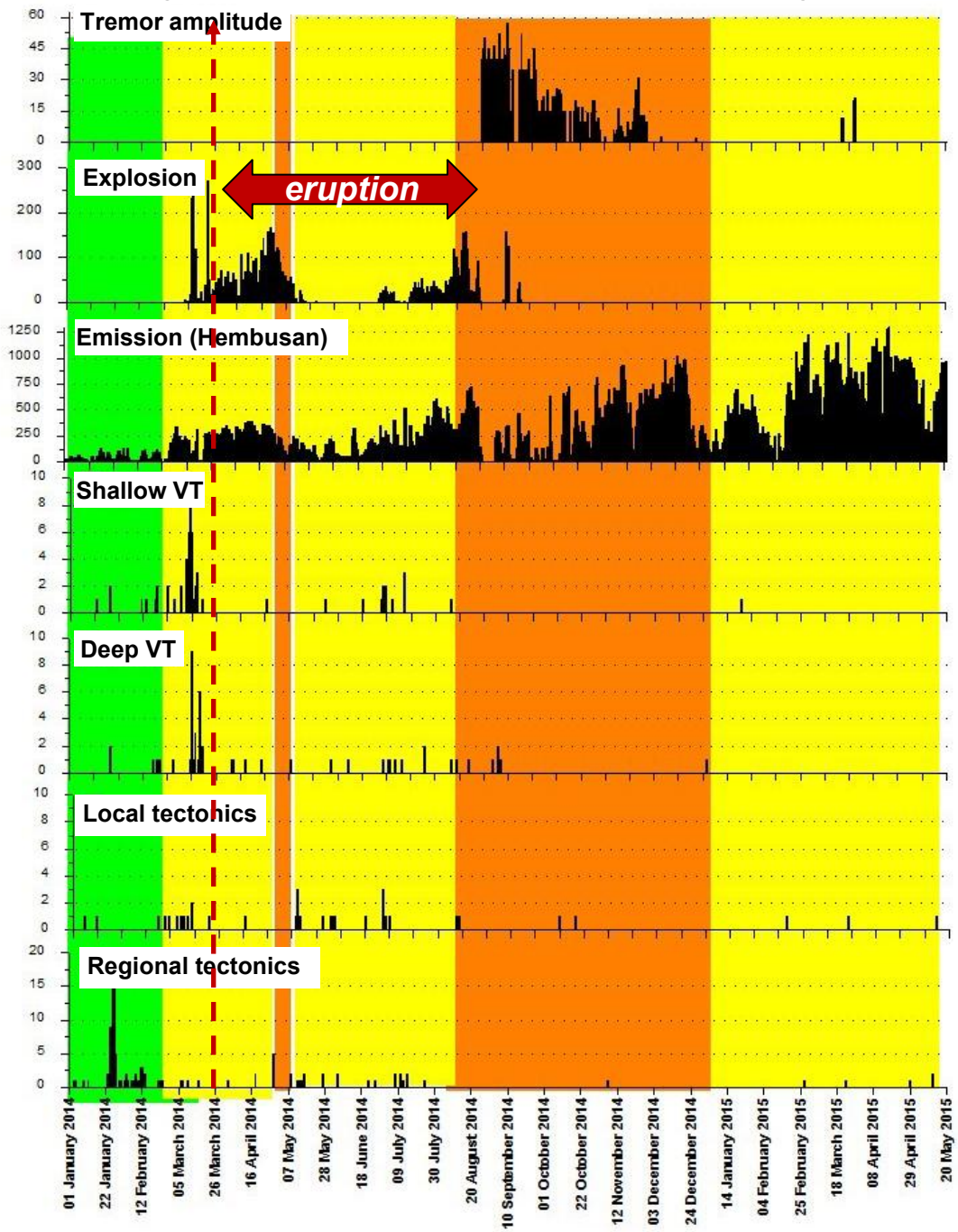
9–12 September 2014: Eruptions continued.

17–19 September 2014: Final eruptive phase; incandescent lava flows observed.



5 January 2015: Status lowered to Level II (Alert).

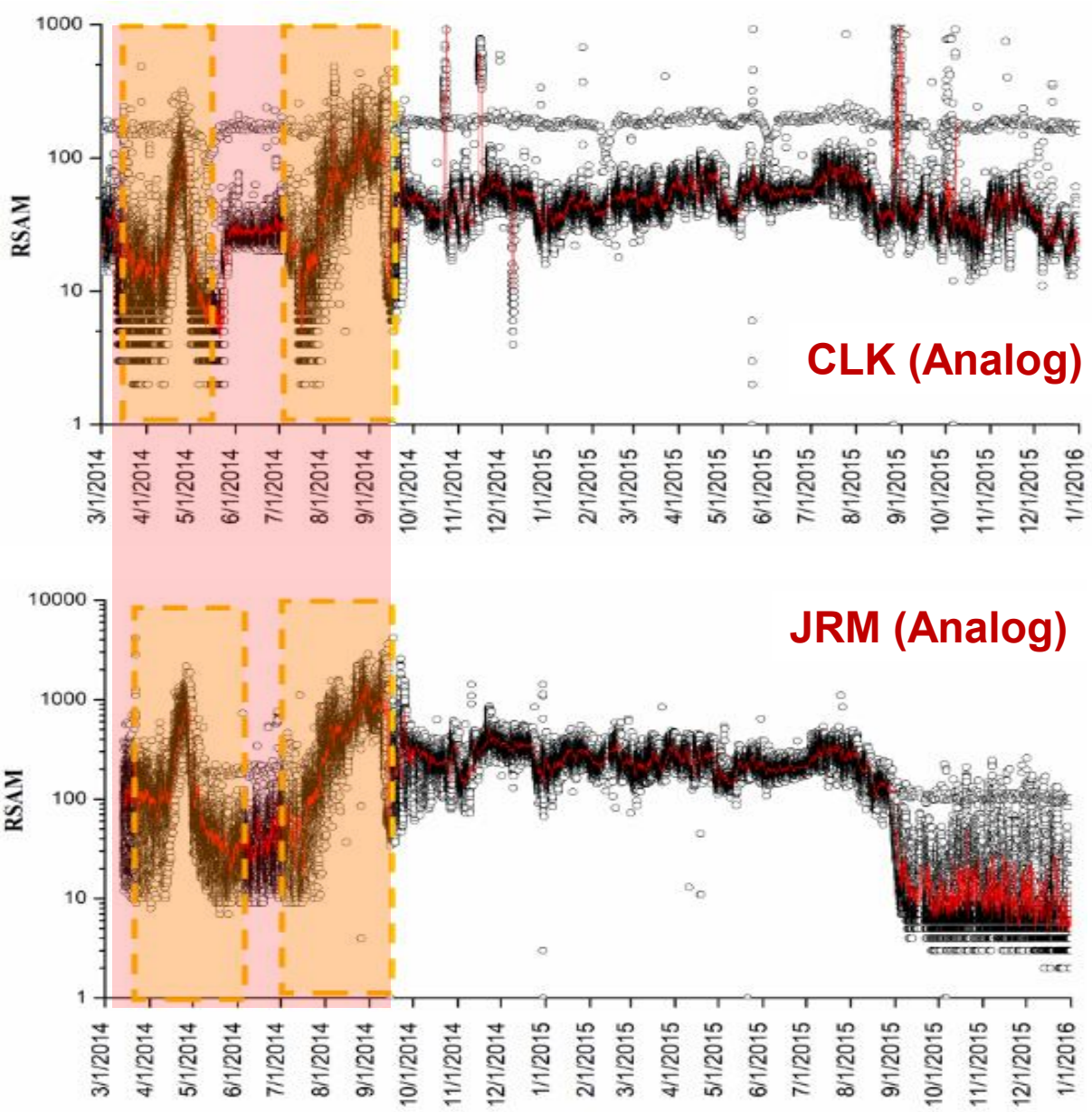
9 September 2015: Activity level lowered to Level I (Normal).

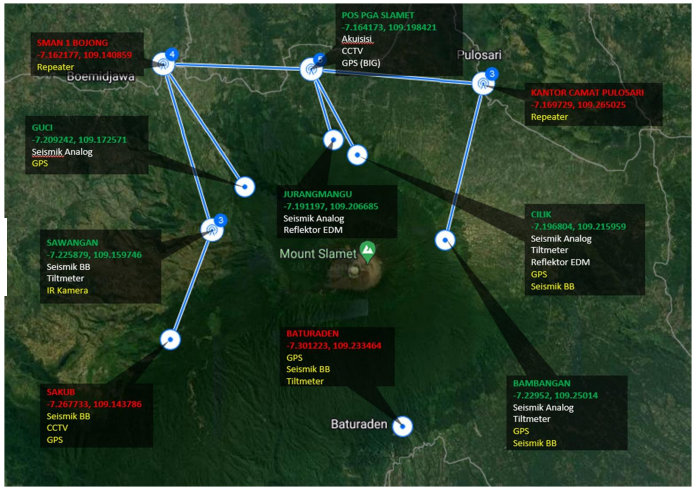


Earthquake counts for Slamet volcano for the period 1 January 2014 to 20 May 2015.
The graph portrays several types of seismic activity: tremors, explosions (letusan), ash/steam emissions (hembusan), VB – shallow volcanic earthquakes, VA – deep volcanic earthquakes, TL – local tectonic earthquakes, and TJ – far tectonic earthquakes.

The vertical color bands show the changes in the Alert Level during the period: Green, Level 1 (normal); Yellow, Level 2 (alert); and Orange, Level 3 (standby).
On 10 March 2014 the Alert increased from Level 1 to Level 2, and on 30 April 2014 increased to Level 3, then lowered on 12 May back to Level 2.
On 12 August 2014 the Alert was raised to Level 3, then lowered back to Level 2 on 5 January 2015.

RSAM (Real-time Seismic Amplitude Measurements) Mar 2014 – Jan 2016





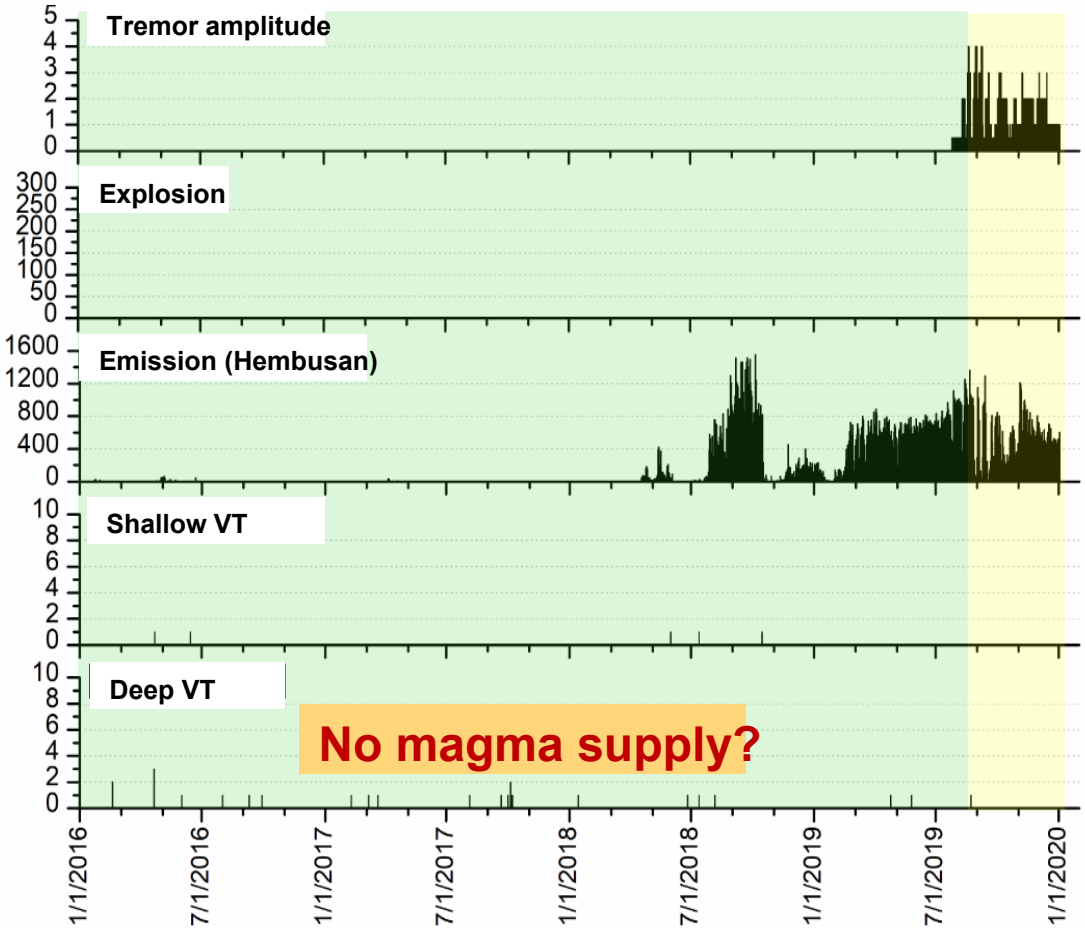
Seismic energy levels began increasing in March 2014. The energy recorded at Station CLK is lower than at Station JRM, reflecting differences in the sensitivity and type of seismometers installed at the two stations.

CRISIS August 2019 – October 2020

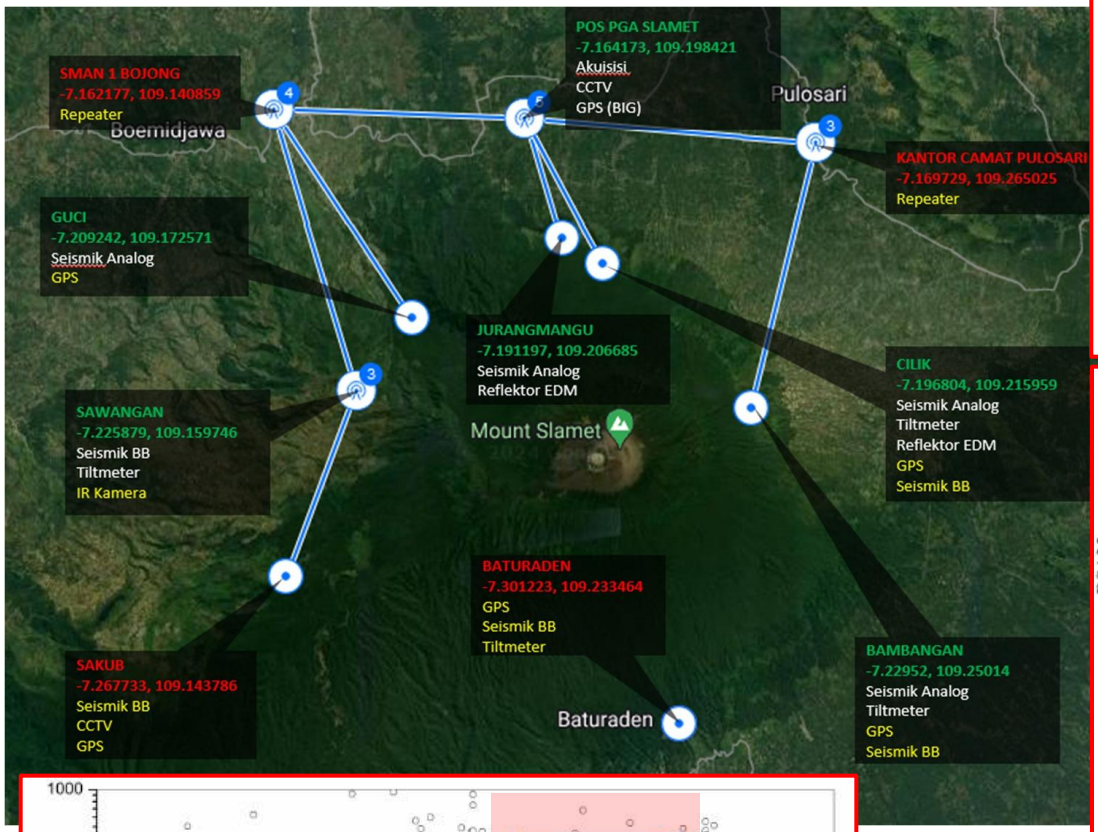
Increased Seismic Activity

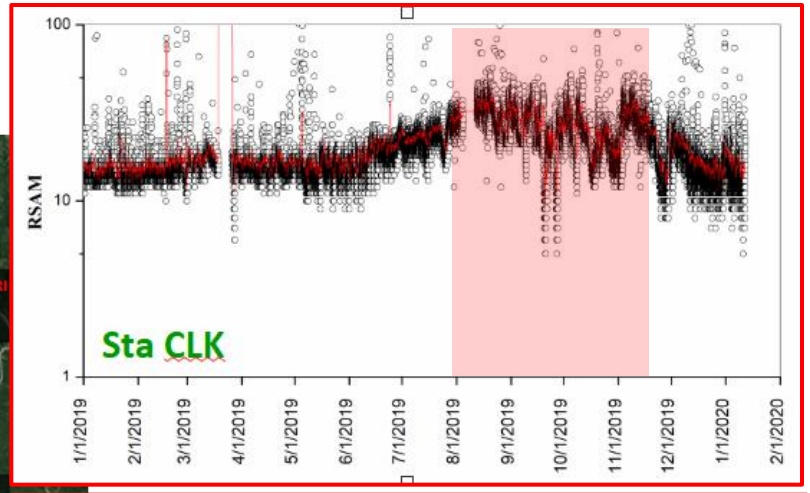
- February 2019: Hembusan earthquakes began to increase.
- Late July 2019: Continuous tremor appeared.
- Seismic energy showed a gradual rise.
- Tiltmeter measurements detected inflation at the end of July.
- 9 August 2019: Activity level raised from Level I (Normal) to Level II (Alert).
- White crater plumes were observed with varying intensity, reaching 25–300 m above the summit.

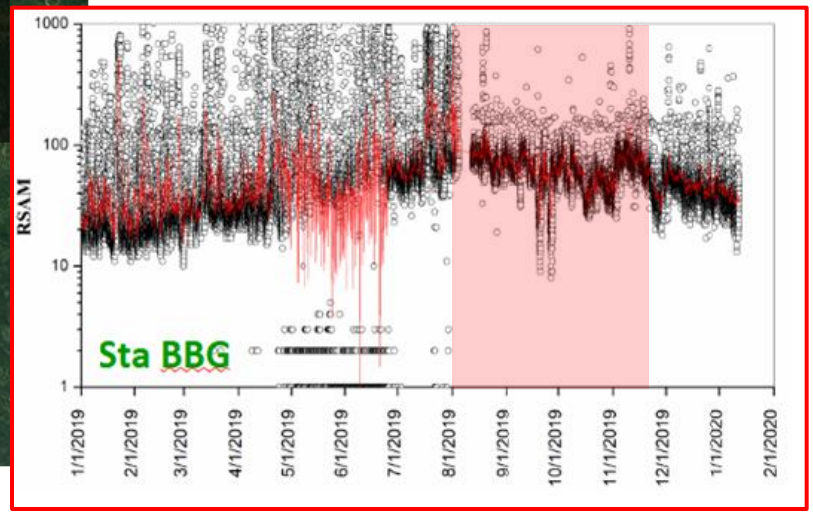
Daily earthquake counts 1 Jan 2016 – 1 Jan 2020

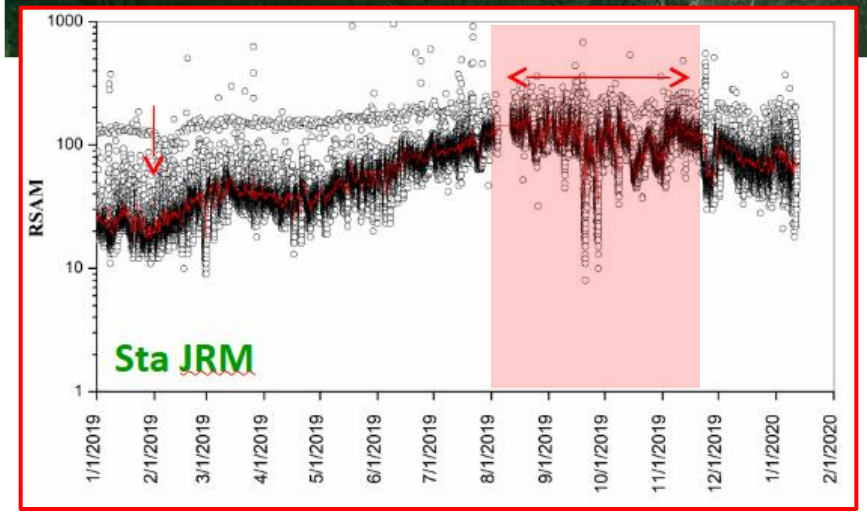


RSAM (*Real-time Seismic Amplitude Measurements*) Jan 2019 – Feb 2020





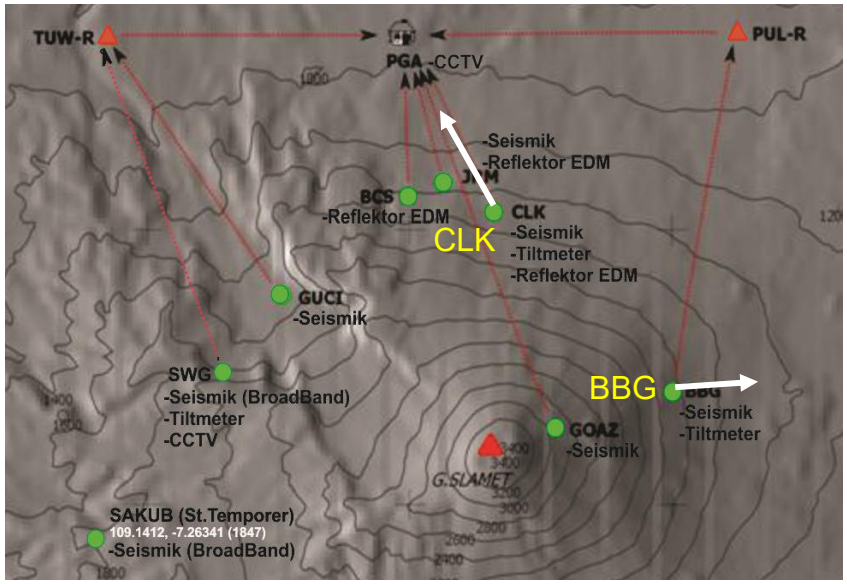




Seismic Energy Trends

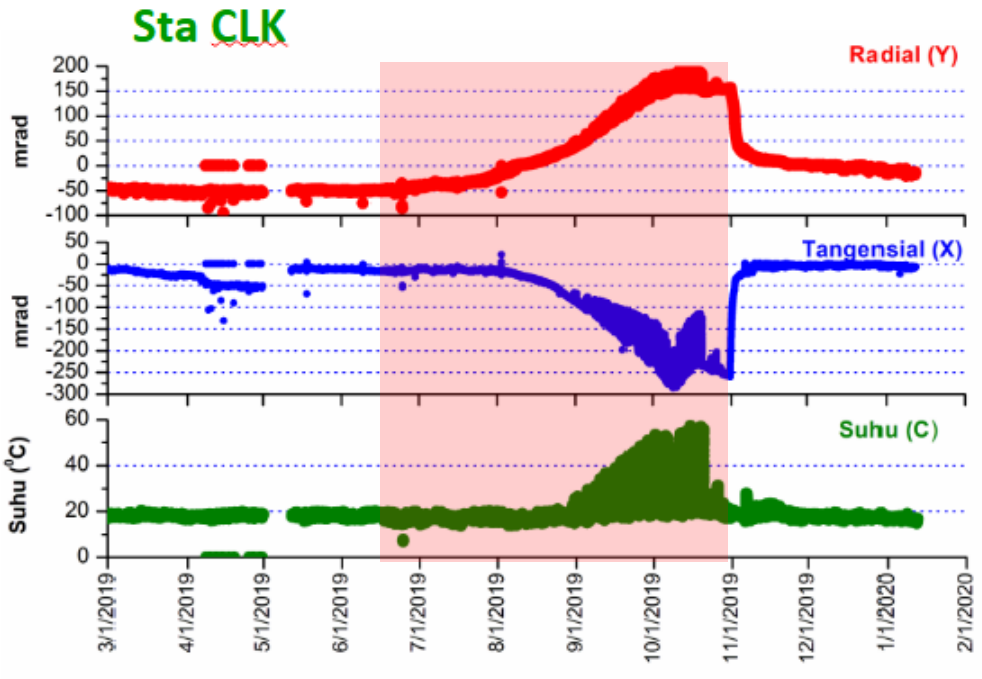
- Seismic energy began increasing in February 2019.
- It reached a peak between August and November, then gradually declined.
- Energy recorded at Station CLK was lower than at Stations JRM and BBG, reflecting differences in seismometer sensitivity and instrument type.

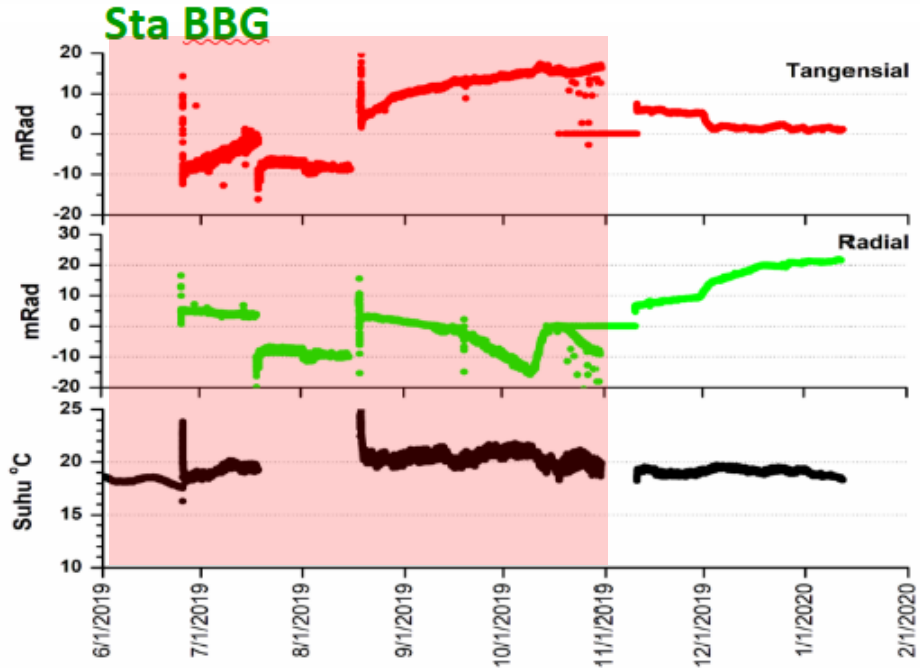
Tiltmeter: Jun 2019 – Feb 2020



Tiltmeter Data:

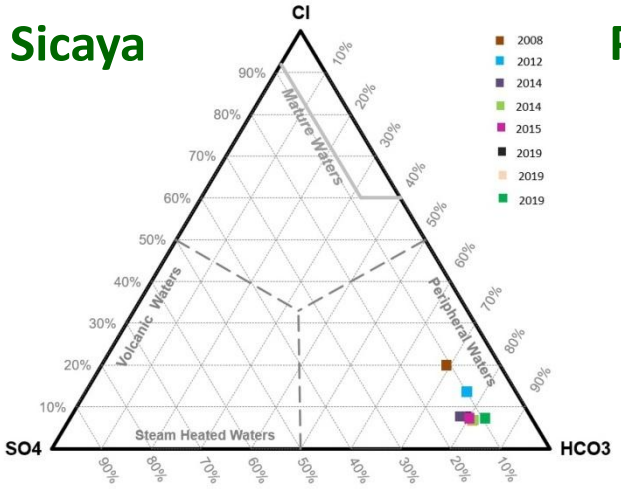
- CLK and BBG stations showed inflation at the end of June 2019
- Trend shifted towards deflation in November 2019



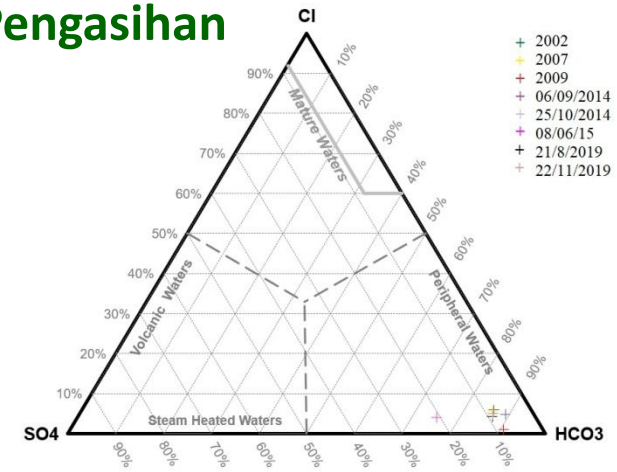


Chemical composition of hot springs

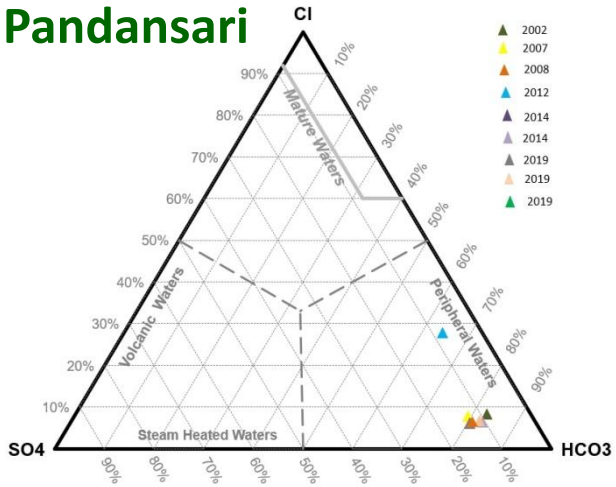
Sicaya



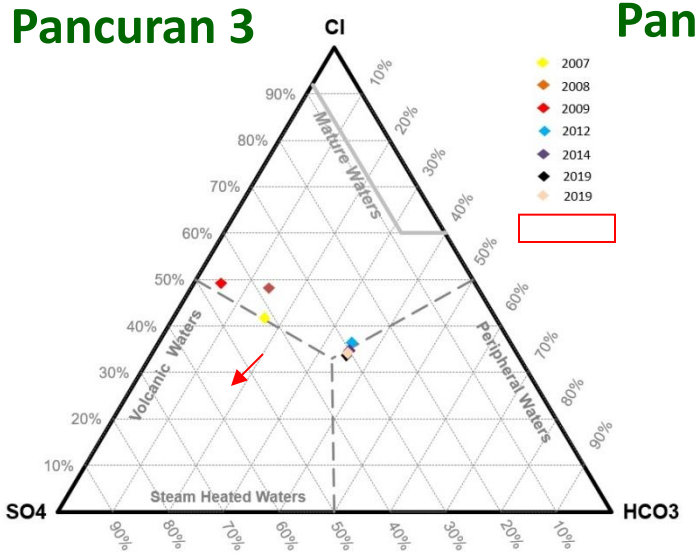
Pengasihan



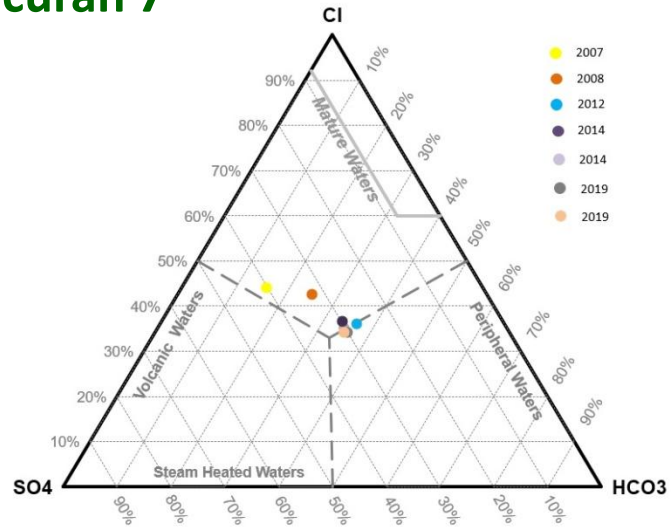
Pandansari



Pancuran 3

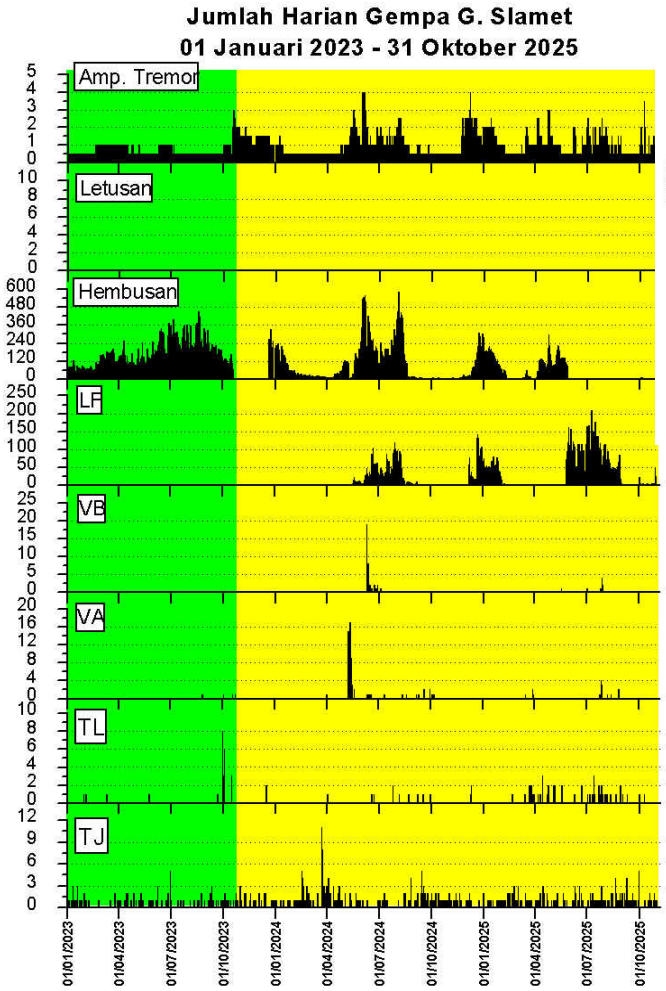


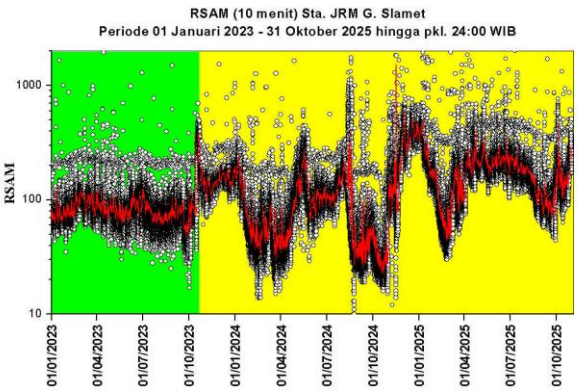
Pancuran 7

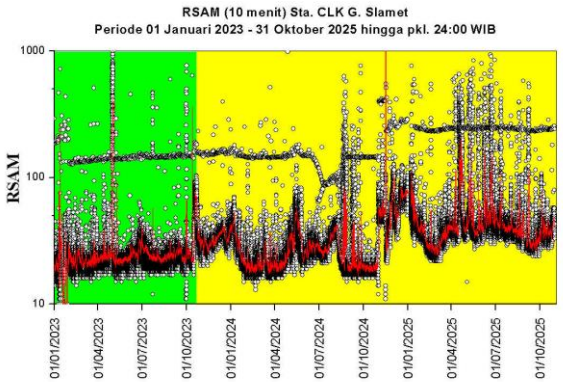


MAP-Guci showed **no significant changes** in chemical composition associated with the increased activity at Mount Slamet. The chemical composition of MAP-Baturaden also remained **relatively consistent** between the **2014 eruption** and the **2019 crisis**.

2023 – 2025 Unrest







RSAM data (Januari 1 – Nov 2, 2023) relatively constant seismic energy with minor fluctuations. sudden increase (Oct 18 – 23, 2023), 19 October 2023 - The status of Mount Slamet was raised from Normal to Waspada.

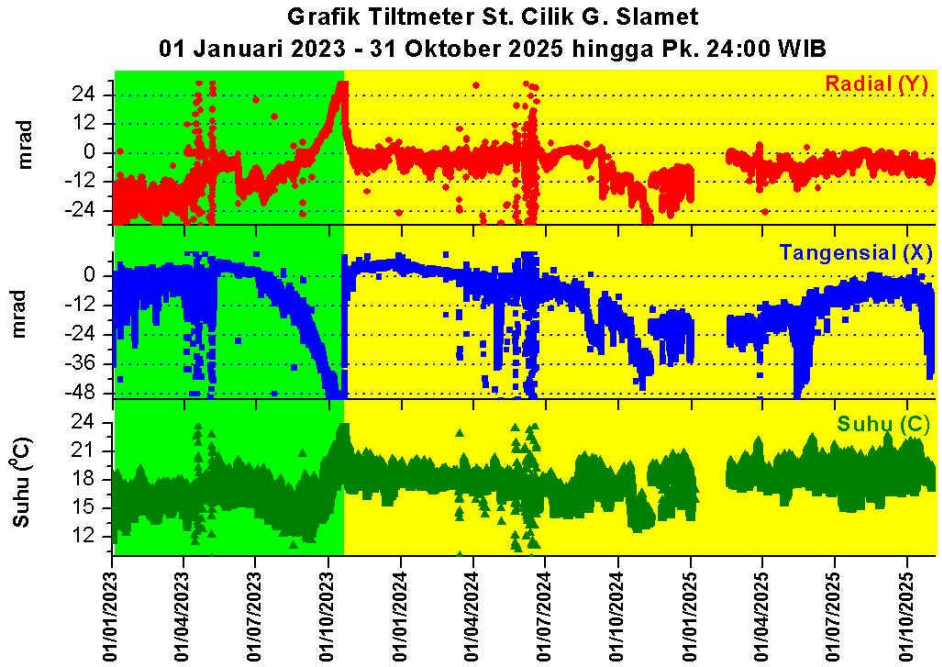
2023 :

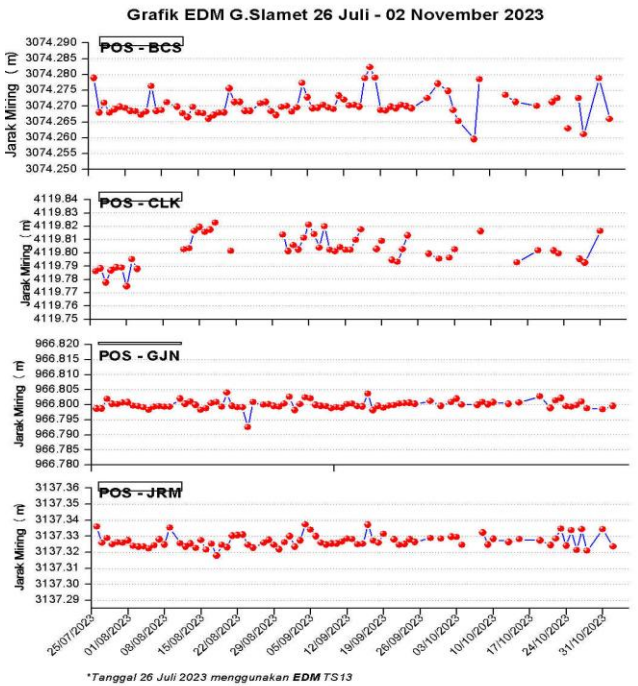
Increase in Local Tectonic Earthquakes from late September 2023

- Rise in tremor amplitude
- Continuous tremor amplitude increase and was followed by Harmonic Tremor in October 2023
- Distal VT earthquakes and harmonic tremor linked to hydrotermal heating and degassing

2024 : Deep VT precursor followed by shallow LP and Hembusan earthquakes, non harmonic tremor recorded in November indicating pressurization

Deformation 1 Januari 2023 – 31 Oktober 2025



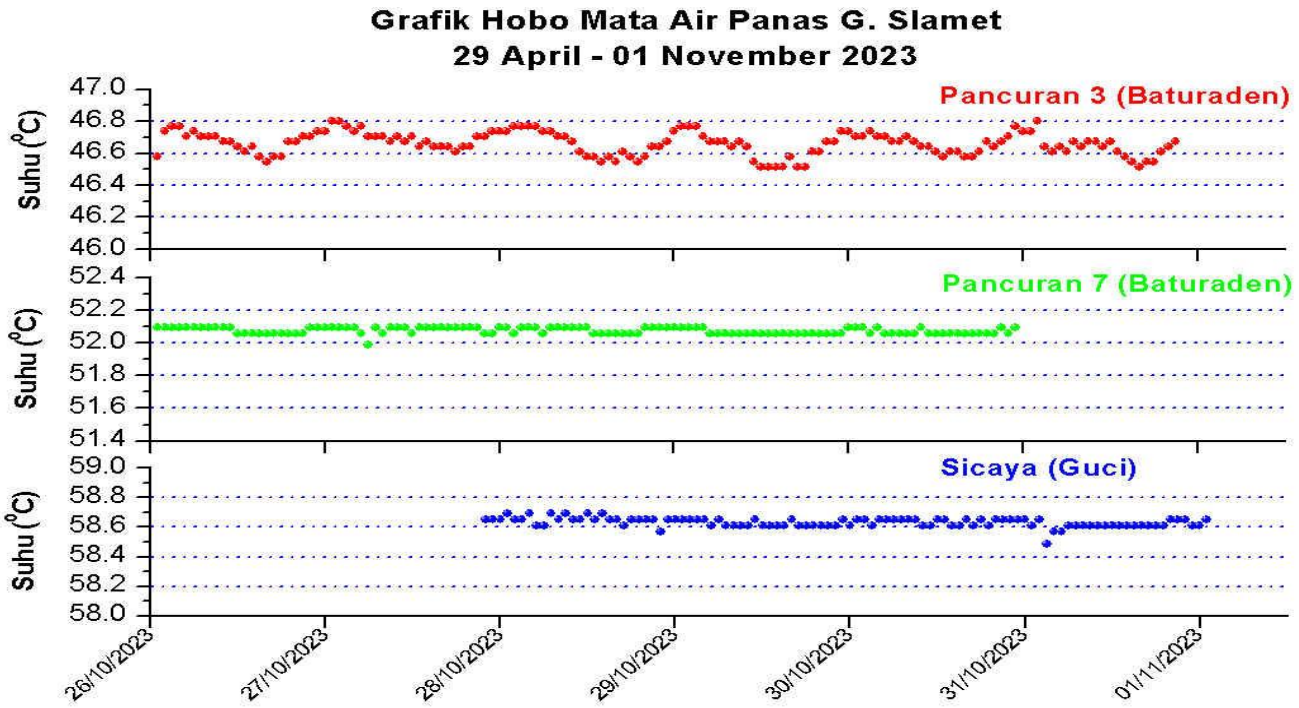


In 2023,

EDM results were mixed: inflation was detected at the Cilik Station, deflation was observed at Buncis Station. No clear pattern appeared at the Jurangmangu station, suggest a small deformation source located closer to Cilik

tiltmeter data showed inflation at two stations, indicating a small intrusion likely located to the northwest of Mount Slamet.

HOT SPRING TEMPERATURE (2023)



The temperatures of the hot springs at Pancuran 3, Pancuran 7, and Sicaya showed no significant variations and remained stable throughout the monitoring period.

Spring temperature measurements have not been conducted since November 2023 because Pandansari is frequently drained, Pengasihan has been walled off by the owner, and Sicaya is likely affected by increasing hotel development in the area.

CONCLUSION

2014 ERUPTION

- Strombolian eruption
- Larger and faster increase in VT earthquakes followed by shallow seismicity associated with release of gases and heating of the hydrothermal system
- Earthquake source relatively shallow
- Deformation center Northwest of Mt. Slamet
- Hot spring chemical composition similar to 2019

2019 CRISIS and 2023 UNREST

- Gas/steam emissions, but no eruption
- No Vts in 2019, only shallow low frequency seismicity
- Vts in 2023 were smaller magnitude and had slower increase
- Deformation smaller and source cannot be modeled
- Unrest was slower and smaller, provided enough heat and gases to cause gas and steam emissions, and shallow seismicity (LFs, tremor and hembusan), but neither intrusion was large enough or fast enough to cause an eruption
- The volcano may be entering a new magmatic phase despite exceeding its recurrence interval
- Continuous, integrated monitoring essential for timely warning and risk reduction

Thank you

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