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Remote reconstruction of Semeru Volcano December 2020-2022 eruptions using open-access satellite imagery and crowdsourced data

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Abstract

Semeru, one of Indonesia’s most active volcanoes, generated significant pyroclastic density current (PDC) events in December 2020, 2021, and 2022, resulting in varying societal impacts. This study reconstructs the spatial extent and temporal evolution of these PDCs by integrating open-access satellite imagery, official reports, and crowdsourced data from social media and video platforms. Deposits mapping reveals that PDCs primarily affected the southeast sector, with deposits emplacement controlled by topography and prior ravines infilling. Chronological reconstruction shows distinct eruption styles: 2020 and 2022 events developed progressively over several hours, initiated by incandescent rockfalls and culminating in large PDCs, while the 2021 event was abrupt, coinciding with heavy rainfall, exhibiting a shorter duration but greater runout. Crater morphology indicates that all three events were preceded by active lava coulee growth and followed by increased lava extrusion, suggesting gravitational collapse as the primary trigger, with meteorological factors potentially enhancing explosivity in 2021. The integration of multi-source open data addresses gaps in official records and enhances eruption documentation, particularly for well-observed volcanoes with persistent activity. However, challenges remain due to diverse variable data quality and the need for careful validation. This approach supports improved hazard assessment and underscores the value of open and citizen-generated data in volcanic crisis response.

1. Introduction

Mount Semeru, located in East Java between Malang and Lumajang regencies, is the highest volcano in Java and one of the most active volcanoes in Indonesia (Fig.1.A). Its persistent eruptive activity poses significant hazards, particularly from pyroclastic density current (PDC) and lahars, which frequently travel down ravines in the southern to eastern sectors. These flows can extend over 10 km from the summit, threatening residential areas, agricultural lands, and infrastructure. The southeastern drainage, Besuk Kobokan (12 km from the summit), is especially vulnerable due to massive and active sand quarrying activities, which concentrate workers, machinery, and transportation routes directly within the primary PDC pathway. This persistent human and economic exposure significantly increased the potential casualties and complicated evacuation efforts during eruption crises.

In three consecutive years of 2020–2022, Semeru produced three major PDC events on 1 December 2020, 4 December 2021, and 4 December 2022, each with a runout exceeding 10 km (Fig.1.B–D). While these events were comparable in scale, their impacts varied significantly. The 2020 event was relatively underreported, with limited official documentation. In contrast, the 2021 eruption caused over 50 fatalities, displaced more than 10,000 people, and drew national and international attention (Yanuarto, 2021). The 2022 event had no reported casualties, but still prompted large-scale evacuations and significant damage (Arifin, 2022). Despite their societal importance, no comprehensive study has yet documented the full extent of the PDC deposits or reconstructed a detailed chronology for these events, which leave gaps for hazard modelling and risk mitigation.



Figure 1. A. Location map of Mount Semeru. B–D. Documentation of large PDC events in December 2020–2022 taken from social media X (credit to X account @detikcom, @AlertaMundial19, and @BNPB_Indonesia).

In recent years, along with official institution monitoring, volcanic activity documentation has been transformed by the advancements of open-access satellite remote sensing and crowdsourced online resources (Clive et al., 2024; Dewanto et al., 2023; Hickey et al., 2025; Wadsworth et al., 2022). Platforms such as Sentinel-1 and Sentinel-2 provide freely available, high-temporal-resolution imagery suitable for detecting surface changes from volcanic deposits. At the same time, real-time observations shared via social media, YouTube, and news portals have proven valuable for capturing eruption timing, flow dynamics, and ground impacts, especially when official monitoring is overwhelmed or delayed.

This study integrates open-access satellite data, official monitoring reports, and crowdsourced observations to reconstruct the spatial extent, temporal evolution, and triggering conditions of the 2020–2022 PDC events at Semeru. We present deposit maps, detailed event chronologies, and crater morphological changes, and discuss their implication for eruption mechanisms and hazard assessment. By synthesizing diverse public data sources, this work aims to improve eruption documentation in data-scarce environments and support more resilient volcanic risk management.

2. Geological setting

Mount Semeru is a Quaternary stratovolcano located in the eastern segment of the Sunda Arc, formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate. It is part of the Bromo-Tengger-Semeru complex, which comprises Quaternary calderas and volcanic centers overlying Tertiary volcanic and sedimentary basement rocks (Smyth et al., 2008), with active volcanism at Bromo and Semeru (Fig.2.A). While Bromo occupies the interior of the Pleistocene Tengger Caldera, Semeru rises on the southern flank of two older Jambangan and Ajek-ajek calderas (Fig. 2.B). These calderas have diverse volcanic products, including basaltic to dacitic lavas and andesitic pumiceous pyroclastic flows. Meanwhile, Semeru has basaltic to andesitic lavas, lithic-rich pyroclastic flows with minor scoria, and scoria-rich falls (Sutawidjaja et al., 1996).

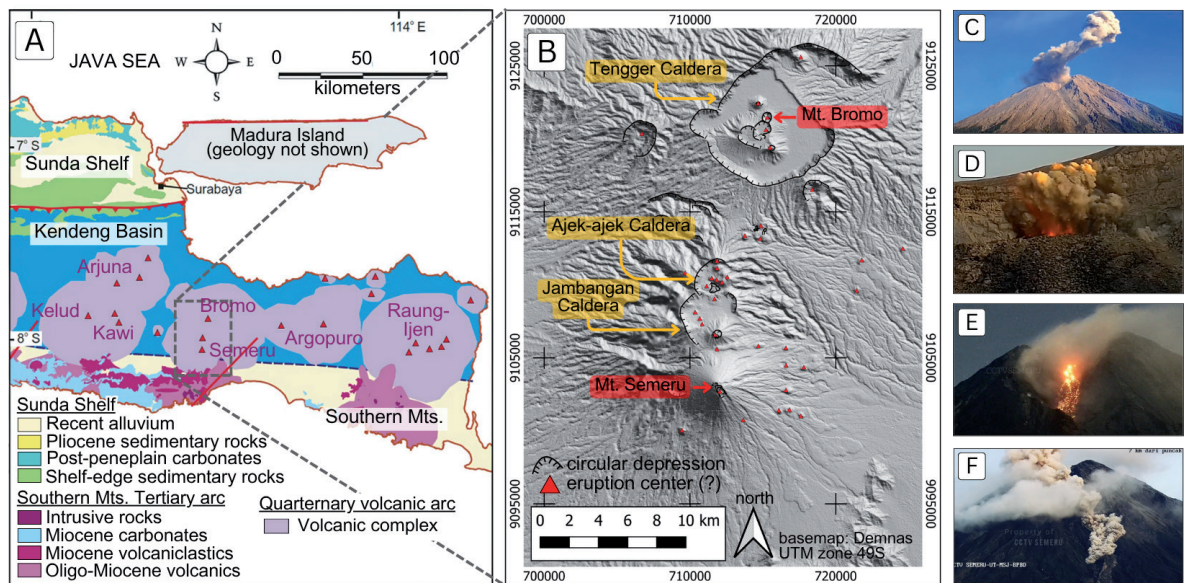


Figure 2. A. regional geology of East Java (adapted from Smyth et al., 2008), B. Bromo-Tengger-Semeru volcanic complex and its features. C-F. Semeru recent eruption style, shown in order: small-scale phreatic eruption, small Vulcanian blast, incandescent rockfall on the growth of coulee, and small PDC flowing down the slope (courtesy of various videos from CCTV Semeru YouTube channel).

Since 1967, Semeru's activity has been characterized by persistent explosive phases, following the last major 6.5 km-long lava flank effusion during 1941–1942 (Dana et al., 1995). As described by Thouret et al. (2007), post-1967 activities have been concentrated at the Jonggring Seloko crater, which opens toward the southeast sector. The activity typically includes daily phreatic blasts (column height 300–1,000 m) and intermittent phreatomagmatic and Vulcanian eruptions (column height 1,000–3,000 m), often accompanied by slow extrusion of a lava dome or coulee and occasional small lava avalanches or glowing rockfalls (Fig 2.C–F). More intense eruptions are related to increased magma extrusion rates, resulting in larger Vulcanian eruptions with higher column height (3,000–7,000 m) and major PDCs generated by gravitational collapse of the lava domes or coulee, with runout distances of 5–12 km. Semeru is also a prominent producer of lahars, with flows predominantly affecting the distal eastern, southeastern, and southern sectors during and after eruptive periods.

3. Datasets and methods

The areal extent of 2020–2022 PDC deposits at Semeru were mapped using ratio images derived from Sentinel-1 Synthetic Aperture Radar (SAR) data, and validated with Sentinel-2 optical imagery. SAR ratio imaging is effective in highlighting surface changes associated with recent volcanic deposits (Macorps et al., 2023).

Level-1 Ground Range Detected (GRD) SAR images from Sentinel-1, which represent pre- and post-events with the same *row* and *path*, were obtained from [ASF Data Search](#), then were preprocessed using the *Sentinel-1 Toolbox* (S1TBX) module within Semi-Automatic Classification Plugin (SCP) in QGIS. The preprocessing steps included orbit files, removal of GRD border and thermal noise, radiometric calibration, and terrain correction (orthorectification). The output consisted of terrain-corrected backscatter coefficients for both VV (Vertical-Vertical) and VH (Vertical-Horizontal) polarization modes. The processed images were clipped to the study area, and ratio images were generated using the Raster Calculator in QGIS. The VH polarization was selected for ratio analysis due to its enhanced contrast, which is more indicative of surface changes of volume scattering caused by newly emplaced volcanic deposits. The ratio was produced by dividing pixel values of the pre-event image by those of the post-event image, effectively highlighting areas affected by new deposits (Fig.3.A–C).

Concurrently, Sentinel-2 optical images, specifically RGB composites of bands 4-3-2 (Fig. 3.D–F) were accessed from SentinelHub EO Browser (<https://apps.sentinel-hub.com/eo-browser>). These were used to generate a time-lapse sequence, prioritizing images with less than 5% cloud cover for clearer visual assessment. Then, the estimated deposit boundaries

for each event were manually digitized based on both the SAR and optical data (Fig. 3.A–C). Additionally, a slope map was generated to assess PDC runout patterns in relation to the volcanic topography.

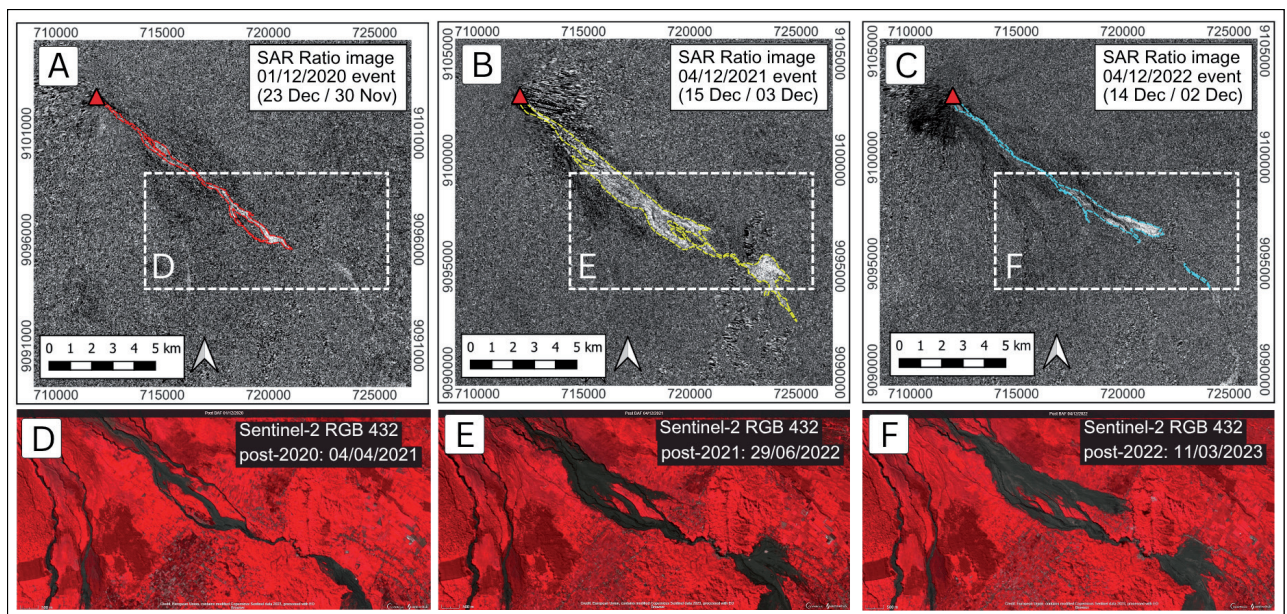


Figure 3. A–C. ratio image from processed Sentinel-1 SAR data of each event and manual delineation of deposit extent. D–F. Sentinel-2 false color composite image (RGB 4-3-2) used for validation of deposit extent.

Chronologies of volcanic activity patterns, event timelines, and crater morphology changes were compiled from publicly available sources. The volcanic activity pattern was based on visual observation, including eruption column height, runout distance of “lava avalanche”, and runout of “hot ash-cloud”. The available eruption column height data did not always distinguish between different eruption types. In this study, “Lava avalanche” refers to small-scale events of hot rockfall or block avalanche, incandescent (glowing) at night, without generation of ash-cloud, and originating from the lava coulee. “Hot-ash-cloud” refers to the events of PDC. Those data were collected from the official website of Center of Volcanology and Geological Hazard Mitigation (CVGHM/PVMBG), specifically MAGMA Indonesia (<https://magma.vsi.esdm.go.id>), weekly bulletin records in Global Volcanism Program (GVP) (Global Volcanism Program | Semeru), and Telegram groups operated by volcano enthusiasts, including “Info Semeru” (t.me/infosemeru), “VolcanoYT” (t.me/VolcanoYT), and “Info GA dan MKG” (t.me/InfoGAdanMKG). All information was cleaned, sorted, and used to construct a timeline diagram of volcanic activity from 1 December 2020 to 31 December 2023. Sentinel-2 optical images (RGB 12-11-4, urban color) accessed from the SentinelHub EO Browser were also used to check the thermal activities associated with the lava extrusion.

Detailed event timelines (days and hours) were primarily compiled from CVGHM official press releases and GVP bulletin reports, particularly for 2021 and 2022 events. Meanwhile, the timeline of the 2020 event is primarily based on Banggur et al. (2024). Additional raw data, including photographs and videos, were collected through manual keyword searches on news portals, Telegram, YouTube, and Facebook. Selected footage was curated and validated based on the availability of timestamps and geolocation context before being integrated into a timeline graph. The complete list of resources for crowdsourcing is provided in the figure captions (Results section) and in a separate list in **Appendix 1**. The changes of crater morphology from 2020 to 2023 were assessed through visual inspection on publicly shared photographs from Øystein Lund Andersen (www.oysteinlundandersen.com) and videos on the internet, as well as Sentinel-2 true-color composites (RGB 4-3-2) accessed via SentinelHub EO Browser.

4. Results

4.1 Areal extent of PDC deposits

PDC deposits from the December 2020, 2021, and 2022 eruptions at Semeru were primarily emplaced in the southeastern sector, with runout distances exceeding 10 km from the

summit (Fig. 4.A). The flows traversed the upper volcanic cone and foot (4–5 km from the summit), where slopes decreased to less than 20°, before propagating across flatter terrain. Beyond 7 km, the ravine system branches and slope diminish further ($\leq 10^\circ$), influencing flow divergence and depositional patterns.

Despite their similar source and general flow direction, the morphological characteristics and emplacement of the PDCs varied significantly among the three events (Fig. 4. A–B).

- **2020 Event:** The PDC deposit has a predominantly channel-confined morphology with relatively narrow cross-sectional extent. It primarily followed the Besuk Wedok channel and ended within Besuk Semut, with a maximum runout of 11 km.
- **2021 Event:** In contrast, the PDC deposit has a broader and more laterally extensive distribution. Its expansion within the first 7 km may be facilitated by eroded, thin, fine-grained deposits on channel banks, preconditioned by rainfall. Beyond this point, the flow diverted and overspilled due to partial infilling of the main channels (Besuk Wedok and Besuk Semut) by the 2020 PDC and associated lahars. The main portion flowed through Besuk Wedok, overspilling into the Summersari and Supiturang areas, while a minor portion flowed into Besuk Lanang and the upstream area towards Kajarkuning, later rejoining Besuk Semut. Subsequently, the PDC flowed into a narrow passage between Tertiary volcanic ridges near Gladak Perak bridge, entered the Besuk Kobokan ravine, and fanned out extensively into the Kamarkajang and Sumberwuluh with a maximum distance of 16 km, the longest of the three events.
- **2022 Event:** The 2022 PDC initially followed a channelized path but began to widen at approximately 6 km from the summit. It passed through the Watukobong area (near the western edge of the 1942 lava flow) and, instead of entering the sediment-choked Besuk Wedok, the main flow was “jumped” and overspilled into the north overbank of Besuk Lanang, then flowed into Kajarkuning, where it formed a fan-shaped deposit that buried much of the village. The total runout distance was 15 km from the crater.

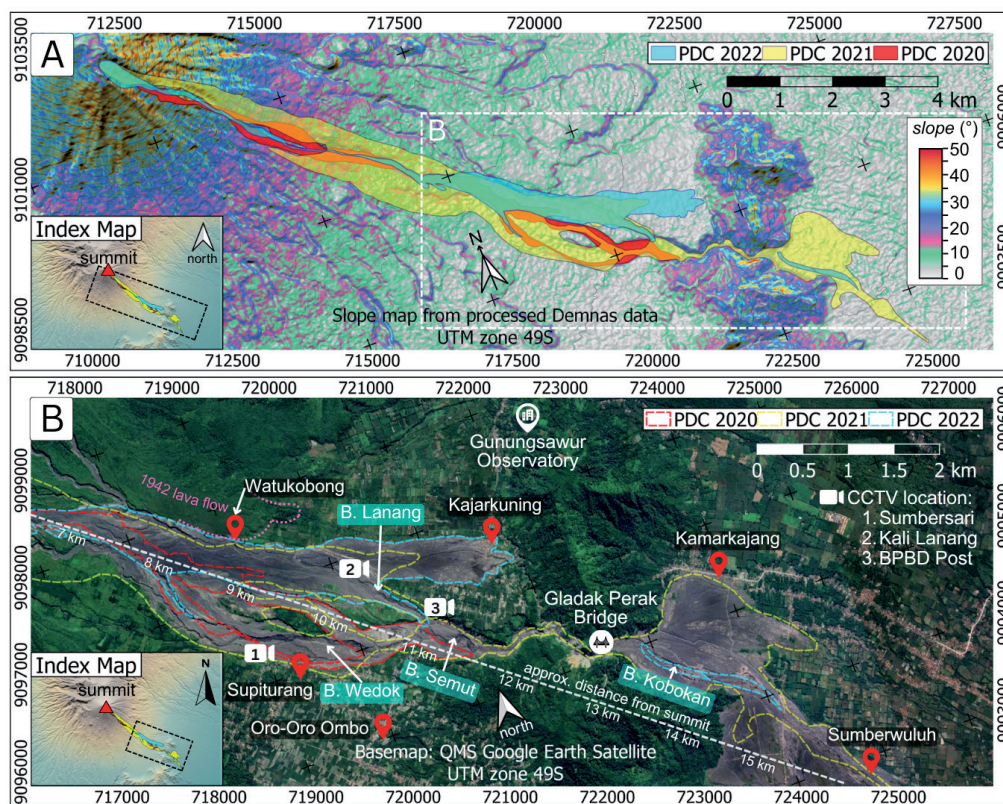


Figure 4. A. Areal extent of Semeru 2020–2022 PDC deposits plotted against the slope map processed from Demnas data. The area inside the white striped-outline rectangle represents the distal area depicted in the Figure. 4.B. **B.** the distal area (primarily residential area) damaged by PDC deposits and its corresponding toponymy mentioned in this study, including the location of CCTVs that can be accessed from *CCTV Semeru* YouTube channel.

4.2 Volcanic activities during 2020–2022

Visual observations at Semeru from 2020 to 2022 (and thus limited by weather-related visibility) were compiled in Figure 5. Nearly daily, eruptions from the central vent produced ash columns ranging 500–1,000 m above the summit, with no significant increase in column height preceding the major December events. Small-scale lava avalanches typically travelled 1,000–1,500 m from the crater, while PDCs remained minor, with runout not exceeding 5,000 m (confined primarily to the upper volcanic cone), except during large December eruptions.

Sentinel-2 optical imagery (Fig.5, A–L) reveals variation of lava coulee activity, identified by yellow-orange thermal signatures. During periods of increased activity, the thermal activity of the coulee extended further down to the southeastern flank. In contrast, during quieter periods, thermal signatures were still detected at the central vent, with reduced activity within the coulee body.

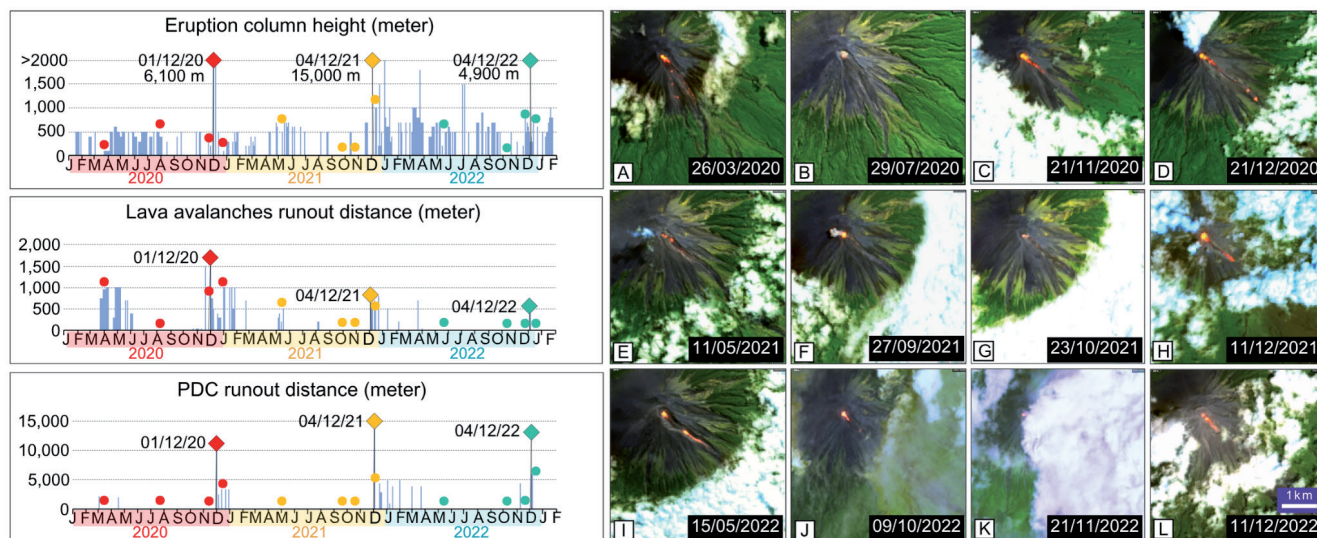


Figure 5. Activities during 2020–2022 (left), diamond symbols depicting large events in December, and circle symbol marks the approximate time of thermal activities detected in Sentinel-2 urban color composite (RGB 12-11-4) (right, A–L).

4.3 Event chronology of December large events

4.3.1 The 1 December 2020 event

The 1 December 2020 event was preceded by increased activity days prior between November 19 and 20, with at least 11 lava avalanche events with runouts of 500–1,500 m (Fig.6). From November 28 to 30, the frequency and intensity of lava avalanches and small PDCs from the tip of the coulee increased significantly, reaching up to 1,000 m in runout. Crater incandescence was clearly observed on November 29.

The main eruptive phase began on November 30 at approximately 11:35 PM local time and lasted until the morning of December 1, with a total duration of 4 hours and 13 minutes (Fig.6). It initiated with small, incandescent lava avalanches, accompanied by minor explosions and sustained crater incandescence. The first PDC was observed at 01:27 AM, followed by continuous crater incandescence and escalating explosive activity. Around 03:00 AM, for the first time, the PDC reached a distance of 11 km, affecting the Besuk Semut area, with associated ashfall reported from Gunungsawur Observatory. The event ended at 05:40 AM, with the hot ash-cloud reportedly reaching Besuk Kobokan. Following this main phase, several smaller lava avalanches and PDCs occurred throughout December 2020. Notably, the official alert level remained at Level II (Waspada), unchanged until 15 December 2021 (one year later), and also no change of alert level around the major eruption on 4 December 2021.

4.3.2. The 4 December 2021 event

The 4 December 2021 event (Fig.7) exhibited a notably different and rapid sequence of events compared to the 2020 event, although it was preceded by similar precursory activity. On December 1, small lava avalanches and PDCs descended approximately 700 m from the coulee tip, and by December 3, runouts had increased to 1,000 m.

The main event occurred on the afternoon of December 4 under rainy conditions, which obscured visibility of the volcanic cone. From the first recorded footage of PDC in Summersari to the end of the main signal, the event had an approximate duration of 2 hours. The onset of 2021 PDC appeared sudden and was preceded by laharc flooding in the ravines. At 01:30 PM, the report mentioned seismic data from Gunungsawur Observatory, indicating the onset of either lava avalanches or lahars. At 01:47 PM, Video footage at the Summersari area (10 km from the summit) shows unusually large lahar, more likely fast-moving grain flow and steamy lahar (Fig.7.A–B). The PDC arrived at the same location at 02:35 PM, followed by a larger pulse at 02:50 PM. From the Oro-oro Ombo area, the advancing PDC front was clearly visible (Fig. 7.D). About 10 minutes later, the flow reached Gladak Perak bridge and entered Besuk Kobokan ravine (Fig. 7.E).

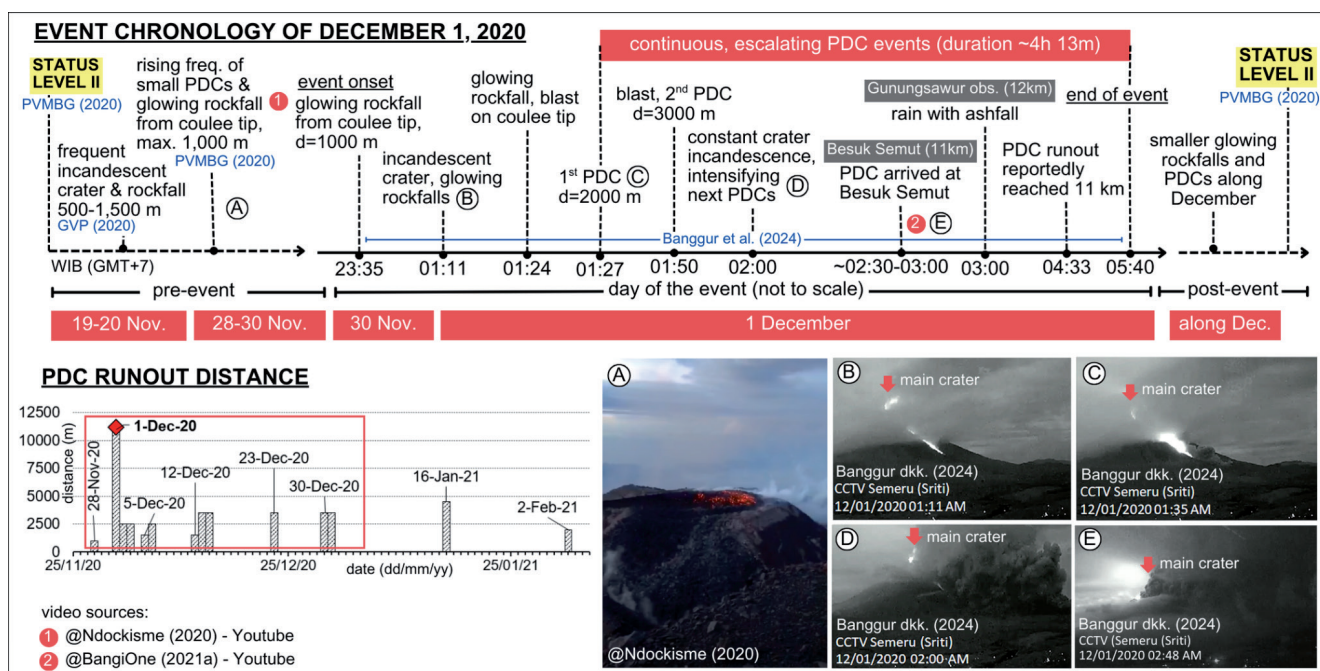


Figure 6. Detailed event chronology of 1 December 2020 event with various data sources. The timeline graph (above) is compiled from various written sources (blue colored letters) such as the official press release of PVMBG (2020) and bulletin report from GVP (2020a, 2020b), but mostly rewritten from Banggur et al. (2024). Also on the timeline graph, letter in circle depicted the corresponding images on the bottom right, and number in circle depicted data sourced from YouTube videos of Ndockisme (2020) and BangiOne (2021a).

A YouTube livestream (BangiOne, 2021c, depicted in Fig. 7.E) captured detailed observations of the PDC front near a sand quarry in the Leprak River (Kamarkajang area), ~1 km east downstream of Gladak Perak bridge. The event began with dark grey plumes rising from the bridge area, accompanied by minor laharc flow at the quarry (note that at the same time, PDC had already reached Summersari). Three minutes later, the sky darkened and ash fall began. At 03:01 PM, a high-speed hot ash-cloud emerged from the narrow gorge below the bridge. By 03:05 PM, ash fall transitioned to pebble fall, prompting panic and evacuation from the site. Moreafter, total darkness and heavy rain reportedly occurred around 04:00 PM in Sumberwuluh (14–15 km from the summit).

The 2021 PDC reportedly reached a maximum runout of 16 km with ash column height reaching 15 km (GVP, 2022), though it was not specified whether this column originated from central magmatic explosion or was a phoenix plume generated by the PDC itself. According to the official report (PVMBG, 2021), seismic signals associated with the largest PDC began at 02:50 PM and lasted 1 hour 26 minutes, ending around 04:40 PM.

The post-event activity included smaller lava avalanches and PDCs on December 5–8, with runouts not exceeding 5 km. Small PDCs (<5 km) remained frequent in the following months. The official alert remained at Level II (Waspada) around the event, then it was raised to Level III (Siaga) on the night of 15 December 2021, following continued PDC activity.

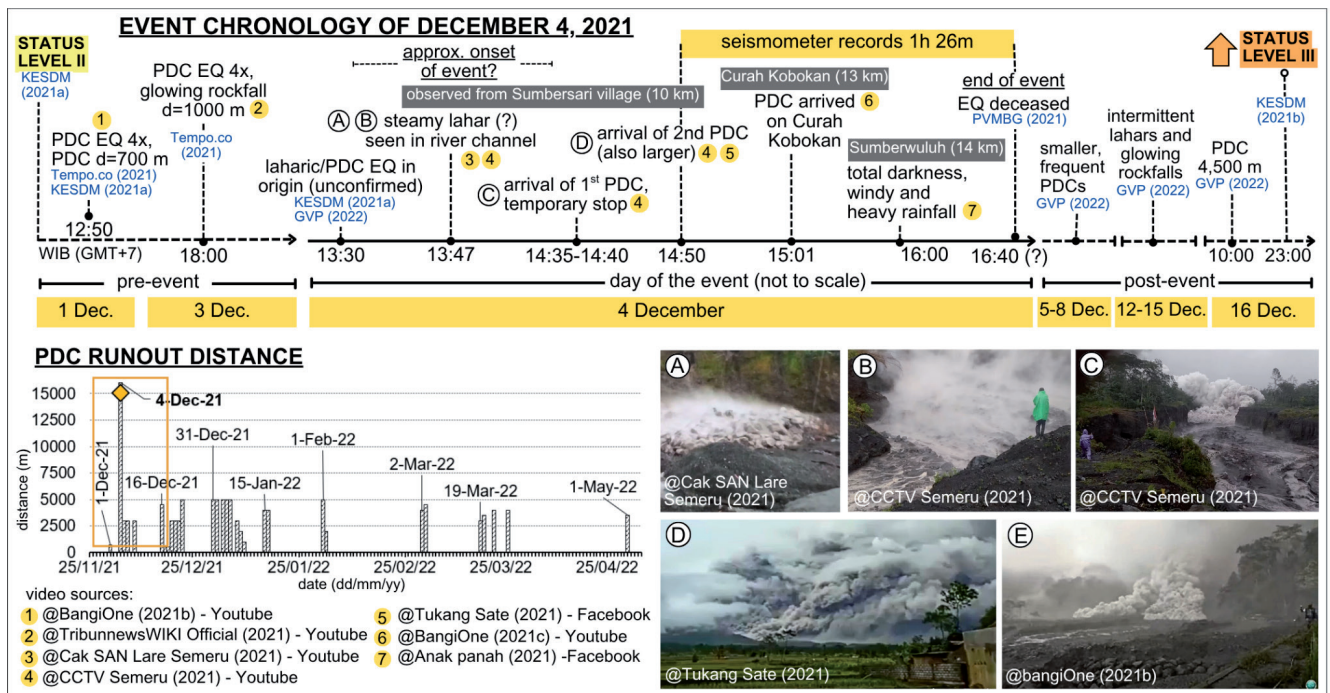


Figure 7. Detailed chronology of 4 December, 2021 event. On the timeline graph (top), written sources shown by blue letters are obtained from official press releases of KESDM (2021a, 2021b) and PVMBG (2021), news portal Tempo.co (2021), and report from GVP (2022). Most information on the exact large events is obtained from various online video resources, shown with number in circle, such as YouTube videos of BangiOne (2021b) and (2021c), TribunnewsWIKI Official (2021), Cak SAN Lare Semeru (2021), and CCTV Semeru (2021). Several videos were also obtained from Facebook, such as from Tukang Sate (2021) and Anak panah (2021). Letter in circle on the timeline graph correspond to the images on the bottom right side.

4.3.3 The 4 December 2022 event

The onset of the 4 December 2022 event resembled that of the 2020, which also occurred under a clear night sky (Fig.8), but its precursory activity was distinct. A key difference from both the 2020 and 2021 events was the absence of observed lava avalanches or small PDCs in the days leading up to the eruption. In the six months prior, only a single lava avalanche was recorded on November 9 (4.5 km runout). In contrast, small phreatic to Vulcanian eruptions (300–1,000 m column height) occurred more frequently, some producing dark plumes.

The 4 December 2022 event (Fig. 8) lasted 10 hours 44 minutes, from pre-dawn to afternoon, which was the longest between 2020 and 2022 events. It was exceptionally well-documented due to CCTV livestreams on the “CCTV Semeru” YouTube channel (see the location of CCTV in Figure 4.B and its corresponding documentation in Figure 8).

The event started around 01:00 AM with incandescence in the crater and along the lava coulee body, accompanied by ash columns and explosive blasts, then kept escalating past the dawn. At 01:19 AM, a small incandescent lava avalanche appeared at a specific point on the lava coulee, likely at its tip. Two incandescent explosions were observed from the main crater at 01:25 and 01:31 AM. Activity intensified at 01:46 AM, marked by continuous incandescent lava avalanches from the coulee, explosions from the main crater, and the first occurrence of PDC. At 02:46 AM, a blast from the incandescent lava avalanche (on the coulee body), followed by another blast from the main crater. Thereafter, PDC generation at the coulee tip became continuous, increasing in size and runout, with fluctuating intensity. For the first time, at 03:00 AM, PDCs reached Semeru’s foot (~4–5 km from the summit). Notably, no significant eruption column was observed from the main crater.

The PDC’s activity intensified throughout the morning. At least 16 distinct PDC pulses were observed between 03:00 and 09:00 AM, with maximum runouts of 9 km. Then, the next wave was observed at the upstream of Besuk Lanang at 09:12 AM, reaching Watukobong (8–9 km from the summit) by 09:30 AM. The largest and longest PDC sequence followed, lasting approximately 3 hours. This phase began with ashfall in Summersari (10 km from the summit) during 10:37 to 10:55 AM and in Besuk Lanang (11 km from the summit)

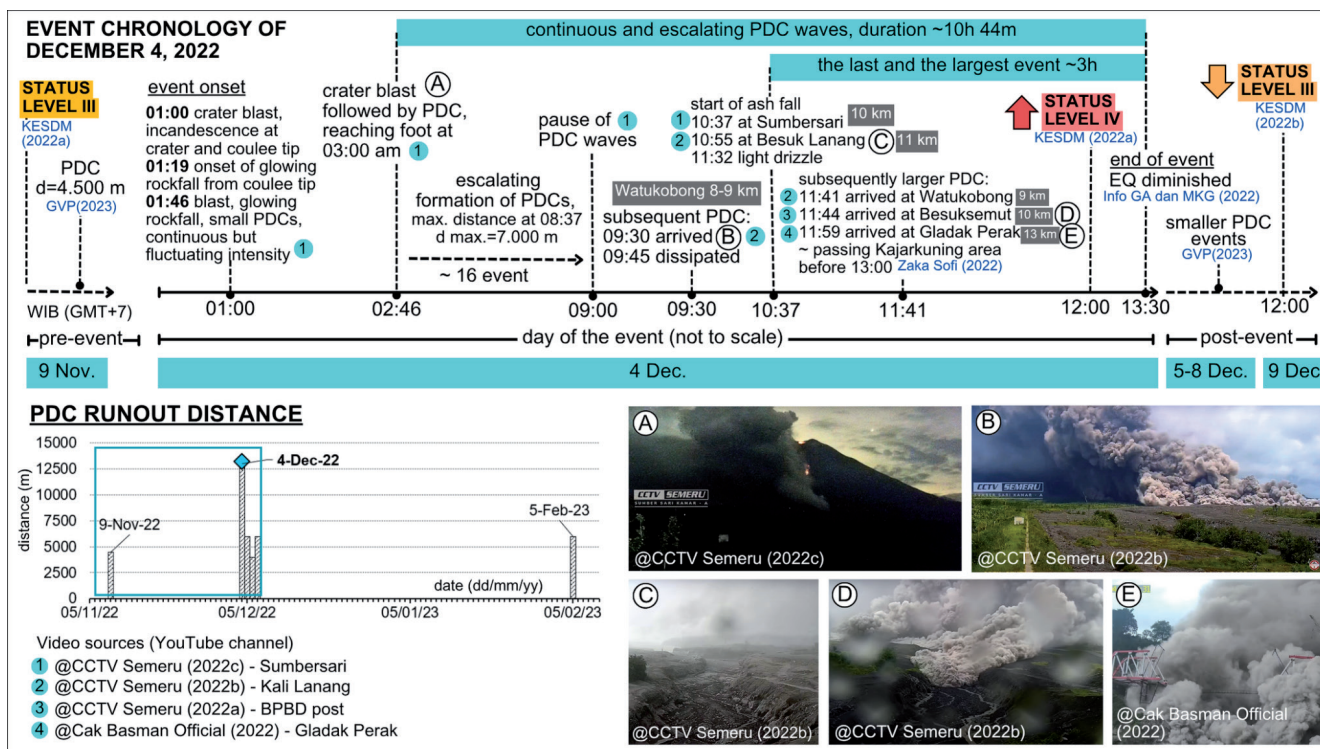


Figure 8. Chronology of December 4, 2022 event. The timeline graph (top) was made from various sources. Written sources, marked with blue letters, were obtained from the official press release of KESDM (2022a and 2022b), GVP (2023) bulletin reports, and Telegram groups such as Zaka Sofi (2022) from Info Semeru group and Info GA dan MKG (2022). Detailed event on 4 December 2022, mostly sourced from YouTube videos from CCTV Semeru channel (2022a, 2022b, and 2022c) and Cak Basman Official (2022b). On the timeline graph, letters in a circle correspond to the photos on the bottom right.

from 10:55 to 11:10 AM, accompanied by drizzle at 11:32 AM (10 minutes). No increase in river flow was observed during this time. The PDC reached Watukobong at 11:41 AM, Besuk Lanang at 11:43 AM (when it destroyed the CCTV camera), crossed Besuk Semut at 11:45 AM, and reached Gladak Perak bridge at 11:59 AM. The Kajarkuning area was likely impacted between 12:00 and 01:00 PM, as it was already covered by the latter time. The official alert level had been at Level III (Siaga) in the preceding days. It was raised to the highest Level IV (Awat) at 12:00 PM. Then, seismic signals decreased by 01:30 PM.

Later that night, incandescent lava flows and smaller PDCs continued, and in the following days. The alert level was lowered back to Level III (Siaga) on December 9, following a reduction in inflation rates and thermal anomalies. Volcanic activity returned to typical background levels with small eruptions ranging in 200–1,000 m column height, until another PDC (6,000 m runout) occurred in February 2023.

4.3.4 Crater morphology change

Semeru's crater and vent morphology evolved significantly during the 2020-2022 period. Prior to the major events, a 2017 photograph (Fig.9.J) shows an intact lava dome at the summit of Jonggring Seloko, with "leak points" on its flanks serving as extrusion sites for incandescent lava avalanches. Throughout 2020-2022, the crater morphology showed the growth and destruction of lava dome and coulee (Fig.9.J-O).

- **The 1 December 2020 event** marked distinct changes: Sentinel-2 images revealed erosion scars on the northern crater rim and southern opening, followed by the emplacement of a fresh black lava coulee (Fig.9.B). The post-event photo (Fig. 9.K) shows partial dome collapse of the eastern portion and new lava extrusion. This morphology remained relatively stable until the next large event (Fig.9.L).
- **The 4 December 2021 event** caused profound changes. Sentinel-2 images show circular erosion scars and significant widening and deepening of the crater (Fig.9.E). Visual evidence indicates complete dome collapse, exposing an underlying circular, dyke-like structure, along with a newly extruded black lava coulee (Fig.9.M). Sentinel-2 images also show a prominent increase of the coulee length (and inferred lava volume) between April and September 2022 (Fig.9.F-G).

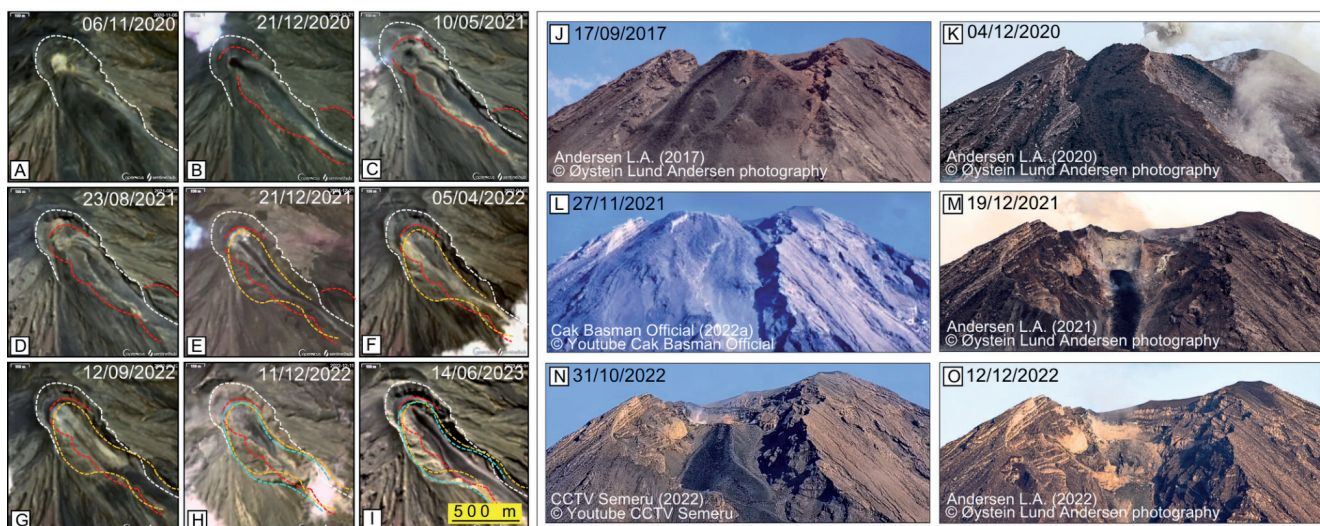


Figure 9. Crater changes during 2020–2022 acquired from Sentinel-2 natural color image (A-I) and photograph from various sources, such as Øystein Lund Andersen photography (2017, 2020, 2021, 2022) and video screenshot from Cak Basman Official (2022a) and CCTV Semeru (2022) (J-O).

- **The 4 December 2022 event** further altered the crater morphology. Sentinel-2 images show continued erosion with wider and longer coulee in the following years (Fig. 4.6.H–I). A post-event photograph (Fig. 4.6.O) reveals the destruction of the 2021-formed coulee, with exposure of underlying dykes, forming fracture-network conduit systems.

5. Discussion

5.1. Role of open-access remote sensing and crowdsourced data in volcanic eruption documentation

Open-access satellite imagery and basic GIS tools offer rapid and effective means for post-event assessment of volcanic eruptions, particularly for preliminary mapping of deposit emplacement (Gouhier et al., 2022; Macorps et al., 2023). In addition, crowdsourced data, particularly from public digital platforms, significantly enhances the documentation of specific eruptive events (Hickey et al., 2025). These data often capture real-time ground-level impacts and event dynamics that might be overlooked during official emergency responses, where decision-making and hazard mitigation take precedence over comprehensive event recording.

Social media posts (e.g., on X) and communities like the Telegram groups, such as Info Semeru, VolcanoYT, and Info GA dan MKG, proved particularly valuable. These groups, including volcano enthusiasts and local observers, frequently share near-real-time updates, often including official information from CVGHM/PVMBG alongside eyewitness observations. The structured format of Telegram, with automatically timestamped message and media, allows for more reliable chronological reconstruction.

Also, an important finding is the growing public engagement with persistently active volcanoes like Semeru. The 2022 event was better documented than the 2020 and 2021 eruptions, likely due to increased awareness following previous large events. This enhanced documentation enabled a more detailed and robust chronology, highlighting how repeated crises can catalyze improved citizen science participation, with a trend that, if harnessed, could support more resilient volcanic risk communication and monitoring.

5.2. Limitations of open-access remote sensing and crowdsourced data

Despite its utility, open-access remote sensing data faces limitations due to the spatial and temporal resolution of satellite imagery, hindering detailed analysis of the eruption center and quantitative assessment of morphological changes (Dewanto et al., 2023, 2025). Furthermore, uncertainties arise when constructing timelines heavily reliant on the accuracy and precision of informal sources, requiring careful validation. Key challenges associated with public data include diverse formats, inconsistent quality, manual compilation requirements, and dependence on sustained public interest (Hickey et al., 2025; Hidayat,

2020; Wadsworth et al., 2022). For instance, much footage on platforms like YouTube often lacks clear timestamps, geolocation, or contextual narration. Some recordings have low resolution, others are duplicates, limiting their analytical value. The usefulness of such media is therefore highly dependent on the awareness, technical ability, and reporting habits of individual citizens. Also, a major limitation of community-driven platforms is the risk of data loss due to platform instability or lack of archiving. For example, the Info Semeru Telegram group was reportedly deleted by June 2025, underscoring the fragility of such data sources.

5.3 Insight into eruption mechanism

Reconstructing the chronology of eruptive events provides valuable insights into the mechanisms driving large, hazardous phenomena such as PDCs. The timelines of the 2020–2022 PDC events reveal slightly varied eruption conditions, all linked to periods of elevated magma extrusion, with gravitational collapse of the growing lava coulee as the primary trigger. The 2020 and 2022 PDCs developed progressively over several hours, initiated by incandescent lava avalanches from the coulee, followed by intensifying explosive activity and larger PDCs. This pattern is consistent with shear lobe failure of an over-steepened coulee, where incandescent material breaches the unstable carapace, leading to cascading collapses (Calder et al., 2002). Increasing gas pressure within the conduit may have further enhanced explosivity and larger PDC generation. In contrast, the 2021 PDC was notably abrupt, with a shorter duration but the longest runout (16 km). It occurred during heavy rainfall and was preceded by laharcic flows, suggesting possible external triggers. Rainfall may have contributed by increasing pore pressure within the volcanic edifice, weakening the coulee structure, or promoting phreatomagmatic interactions, processes documented at other lava dome systems (Matthews, 2004). However, the reported 15 km ash column, which is often cited as evidence of high explosivity, could also represent a phoenix plume generated by the PDC itself, rather than a magmatic explosion. Alternatively, the event may reflect the culmination of internal magmatic overpressure or structural failure within the coulee. Without direct geophysical and/or geochemical data, the role of meteorological factors remains possible but not conclusively demonstrated.

Despite their differing triggers and dynamics, all three events were followed by increased lava extrusion in the days and months afterwards, indicating that the upper conduit was in a critical state of overpressure prior to collapse. This supports the interpretation that large-scale PDCs at Semeru originate from gravitational failure of an actively growing coulee during early phases of increased extrusion (Andronico et al., 2018; Calder et al., 2002).

5.4. Implication for hazard assessment

Even when based on publicly available data, event reconstruction serves as a critical preliminary assessment for further research and hazard evaluation (Oikawa et al., 2016; Mannen et al., 2018; Yute et al., 2021; Hickey et al., 2025). In the case of Semeru, the eruption source, PDC deposit patterns, and their temporal progression reveal key aspects for hazard assessment, emphasizing the need to integrate knowledge of Semeru's unique PDC generation and emplacement behavior as the primary factor driving real-time alerts.

Semeru's large-scale PDCs likely originate from the gravitational failure of an actively growing lava coulee during periods of increased extrusion. This mechanism means that hazard mitigation should prioritize direct monitoring of the coulee's structural stability and extrusion rate. This involves the regular use of satellite-based SAR and high-resolution optical imagery for precise volume and displacement tracking, alongside existing ground-based observation. The documentation also confirms that PDC generation is predominantly linked to lava coulee collapse, not to the magnitude of the eruption column. Crucially, in Semeru, eruption column height alone is an unreliable proxy due to the common occurrence of visually impressive phoenix plumes generated by PDCs. Instead, monitoring runout distances and increased frequencies of small-scale collapse and PDCs provides a more direct and practical indicator of escalating hazard. Finally, the potential role of heavy rainfall (2021 event) highlights the need to integrate real-time meteorological monitoring into volcanic hazard assessments, particularly during periods of heavy precipitation.

The emplacement dynamics of Semeru's PDC deposits reveal notable differences across the 2020–2022 events. For example, the 2022 PDC unexpectedly diverted to the Kajarkuning area, located east of the main drainage (direction to Besuk Kobokan ravine), which had

been largely filled by prior deposits. This phenomenon was also observed in the 2010 Merapi eruption, where PDC deposits obstructed and changed the river's direction (Marfai et al., 2012). Semeru's CCTV footage shows the flow arriving in multiple pulses, suggesting a series of collapse events rather than a single, catastrophic failure. Furthermore, the high mobility of these PDCs, evident in their ability to travel long distances even on gentle slopes ($\leq 10^\circ$), indicates base fluidization and friction reduction, consistent with hot, fine-grained, and highly mobile flow (Breard et al., 2023). Such behavior increases the possibility of flow direction changes and overbank deposition, even when primary channels are not fully obstructed (Cole et al., 2002; Komorowski et al., 2013; Torres-Orozco et al., 2024). This underscores the importance of routine topographic monitoring and updated flow-path modelling for effective hazard mitigation and geotechnical planning (Cappello et al., 2019).

6. Conclusions

This study demonstrates the integration of multiple publicly available data, specifically open-access satellite imagery, official reports, and internet-based crowdsourcing, to reconstruct detailed chronologies of Mount Semeru's large PDC events from 2020 to 2022. The approach provides insights into deposit emplacement and eruption mechanisms. Results indicate that PDCs were primarily driven by gravitational failure of an actively growing lava coulee, with meteorological factors potentially acting as external triggers, particularly during the 2021 event. In addition, eruption column height is shown to be an unreliable indicator for eruption magnitude due to phoenix plume effects. Despite challenges related to data resolution, variable quality, and the need for rigorous validation, combining diverse sources improves documentation. Future efforts should focus on developing automated workflows for data compilation and on increasing public awareness and engagement to foster more reliable, community-informed volcanic monitoring.

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