

Geochemical and Morphometric Characterization of Mt. Ronggo (Scoria Cone), East Java, Indonesia: Insights into Monogenetic Volcanism and Edifice Instability

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ABSTRACT

Mt. Ronggo is a Quaternary monogenetic scoria cone on the western flank of the Mt. Semeru volcanic complex, East Java. This study integrates whole-rock geochemistry (XRF), field stratigraphy, and morphometric reconstruction to delineate its eruptive evolution and structural instability. Geochemical analysis reveals predominantly basaltic products ($\text{SiO}_2 \approx 46\text{--}52 \text{ wt\%}$) with significant compositional overlap with regional calc-alkaline trends of the Tengger-Bromo, Semeru, and Lamongan systems, suggesting the vent taps a shared or similar transcrustal mush reservoir. The field stratigraphic record captures an eruptive transition, evidenced by a pyroclastic density current (PDC) deposit and preserved charcoal fragments suitable for future radiocarbon dating. Morphometric modeling of the original cone ($V \approx 126.6 \times 10^6 \text{ m}^3$) identifies a 120° sector collapse involving $20.4 \times 10^6 \text{ m}^3$ of material. Mass balance calculations show the Western Hill remnant accounts for only 23.7% of the failed mass. This volume discrepancy indicates slope failure was governed by a pre-existing NW-SE structural weak zone that compromised the western flank, determining the collapse azimuth and facilitating distal dispersal or burial of the remaining 76.3% of material. These results highlight the critical role of structural heritage in controlling lateral instability of monogenetic volcanoes in the Java Volcanic Arc.

ABSTRAK

Gunung Ronggo adalah kerucut scoria monogenetik Kuartar di lereng barat kompleks Gunung Semeru, Jawa Timur. Penelitian ini mengintegrasikan geokimia (XRF), stratigrafi lapangan, dan rekonstruksi morfometrik untuk menguraikan evolusi erupsi dan ketidakstabilan strukturnya. Analisis geokimia menunjukkan produk didominasi basalt ($\text{SiO}_2 \approx 46\text{--}52 \text{ wt\%}$) dengan tumpang tindih komposisi yang signifikan terhadap tren calc-alkaline regional sistem Tengger-Bromo, Semeru, dan Lamongan, mengindikasikan pusat vulkanik ini terhubung dengan reservoir magma regional yang sama atau mirip. Rekaman stratigrafi lapangan mengindikasikan transisi erupsi, dibuktikan oleh endapan aliran densitas piroklastik (PDC) dan fragmen arang yang cocok untuk penanggalan radiokarbon di masa depan. Pemodelan morfometrik kerucut asli ($V \approx 126,6 \times 10^6 \text{ m}^3$) mengidentifikasi longsoran sektor 120° yang melibatkan $20,4 \times 10^6 \text{ m}^3$ material. Perhitungan keseimbangan massa menunjukkan sisa Bukit Barat hanya menyumbang 23,7% dari massa yang longsor. Ketidaksesuaian volume ini mengindikasikan kegagalan lereng dikendalikan oleh zona lemah struktural barat-laut-tenggara yang membahayakan lereng barat, menentukan arah longsoran, dan memfasilitasi penyebaran atau penguburan sisa 76,3% material. Hasil ini menyoroti peran penting warisan struktural dalam mengendalikan ketidakstabilan lateral gunung api monogenetik di Busur Vulkanik Jawa.

1 Introduction

Monogenetic volcanoes represent the most widespread type of volcanic manifestation on Earth, occurring across all major tectonic settings. These systems are generally defined by their small eruptive volumes ($\leq 1 \text{ km}^3$), short eruptive lifespans typically ranging from days to decades, and the eruption of discrete, relatively primitive magma batches (Németh and Kereszturi, 2015; Smith and Németh, 2017). While often forming isolated clusters in monogenetic volcanic fields, they frequently occur as parasitic or flank vents on the slopes of larger polygenetic stratovolcanoes. The diversity of their geomorphic forms, ranging from scoria cones and spatter cones to maars and tuff rings, is primarily governed by the interplay between magmatic properties and environmental factors, such as the availability of surface or groundwater (Valentine and Connor, 2015; Gurusinga et al., 2023).

Recent research highlights that these small-volume systems often serve as "petrological windows" into deeper transcrustal mush reservoirs that feed more complex polygenetic complexes nearby (Smith and Németh, 2017; Barber et al., 2023). Despite their perceived structural simplicity, monogenetic edifices are highly susceptible to lateral instability and sector collapse. Such failure events can be triggered by rapid construction, internal hydrothermal weakening, or the intrusion of sheet-like bodies, and often lead to the formation of horseshoe-shaped morphologies (Watt, 2019; Romero et al., 2021; Zhang, 2023). In some instances, segments of the cone are "rafted" away from the vent by concurrent lava effusion, leaving behind a significant mass balance discrepancy between the original edifice and its remnants (Riggs and Duffield, 2008). Furthermore, sector collapse can profoundly alter the underlying magma plumbing system, sometimes triggering high-energy explosive transitions, such as the production of pyroclastic density currents (PDCs), due to system decompression (Walter et al., 2019; Watt, 2019).

This study investigates Mt. Ronggo, a basaltic scoria cone located in the Tajinan District, East Java, Indonesia (Figure 1), which exhibits a distinct 120° sector breach opening toward the west (Figure 2). By integrating volumetric reconstruction, whole-rock geochemistry (XRF), and field stratigraphic observations, we aim to delineate the eruptive history of Mt. Ronggo and evaluate the role of structural heritage in shaping its current geomorphology. These

findings provide new insights into the mechanical evolution of monogenetic volcanoes in the Java Volcanic Arc and their connection to regional magmatic systems shared with the Tengger-Semeru complex.

2 Geological Context

Mt. Ronggo scoria cone is situated within the Tajinan District, Malang Regency, East Java (Figure 1). Geographically, it is located on the western flank of the Mt. Semeru volcanic complex and southwest of the Tengger Caldera. The topography is characterized by hilly terrain on the slopes of the Gunung Buring range. Geologically, Mt. Ronggo is part of the Buring Volcanic Rock formation (Qpvh), a Quaternary unit consisting predominantly of basaltic lavas (containing olivine and pyroxene) and sandy tuffs (Sujanto et al., 1992). Regional magnetic surveys indicate that subsurface structures are consistent with these volcanic deposits, showing varying susceptibility levels associated with basaltic and andesitic fragments (Husna, 2018).

Monogenetic volcanism is a characteristic feature of this segment of the Java Volcanic Arc, where small-volume centers often occur as parasitic vents on the flanks of larger polygenetic systems like Semeru, Tengger, and Lamongan (Carn and Pyle, 2001; Barber et al., 2023; Gurusinga et al., 2023; Zhang, 2023). In the immediate regional vicinity, Ranu Grati Maar is situated in the coastal lowlands, approximately 24 km north of the Tengger-Semeru complex (Gurusinga et al., 2025). Ranu Grati is the largest maar lake in Java, with a mean diameter of 1.6 km and a maximum depth of 126 m (Scharf et al., 2001). Its phreatomagmatic origin is evidenced by its crater morphology and pyroclastic sequence, which records oscillations between phreatomagmatic and magmatic eruptive styles (Scharf et al., 2001; Pirrung et al., 2005; Gurusinga et al., 2025).

Approximately 50 km southeast of Ranu Grati lies the Lamongan Volcanic Field (LVF), which covers an area of 260 km². The LVF comprises a dense cluster of 61 basaltic cinder-spatter cones and 29 prehistoric maars distributed around the central Lamongan volcano (Carn, 2000; Carn and Pyle, 2001; Gurusinga et al., 2023). The distribution of these monogenetic centers is heavily influenced by the regional stress field, with the LVF exhibiting a prominent NW-SE linear orientation consistent with an extensional tectonic regime. This tectonic configuration facilitates the rapid ascent of relatively primitive, basaltic to

basaltic-andesite magma batches (SiO_2 ranging from 41.4 to 52.9 wt.%) from shared transcrustal mush reservoirs (Carn and Pyle, 2001).

Locally, Mt. Ronggo is aligned with a prominent northwest-southeast lineament, which is closely associated with two distinct lava platforms. This structural orientation likely acted as a primary conduit

for magma transport and later governed the plane of instability that led to the 120° sector failure of the edifice. The advanced state of weathering observed across the edifice, resulting in a ubiquitous soil-like bed, reflects a prolonged period of geomorphological stability under humid tropical conditions following the cessation of eruptive activity.

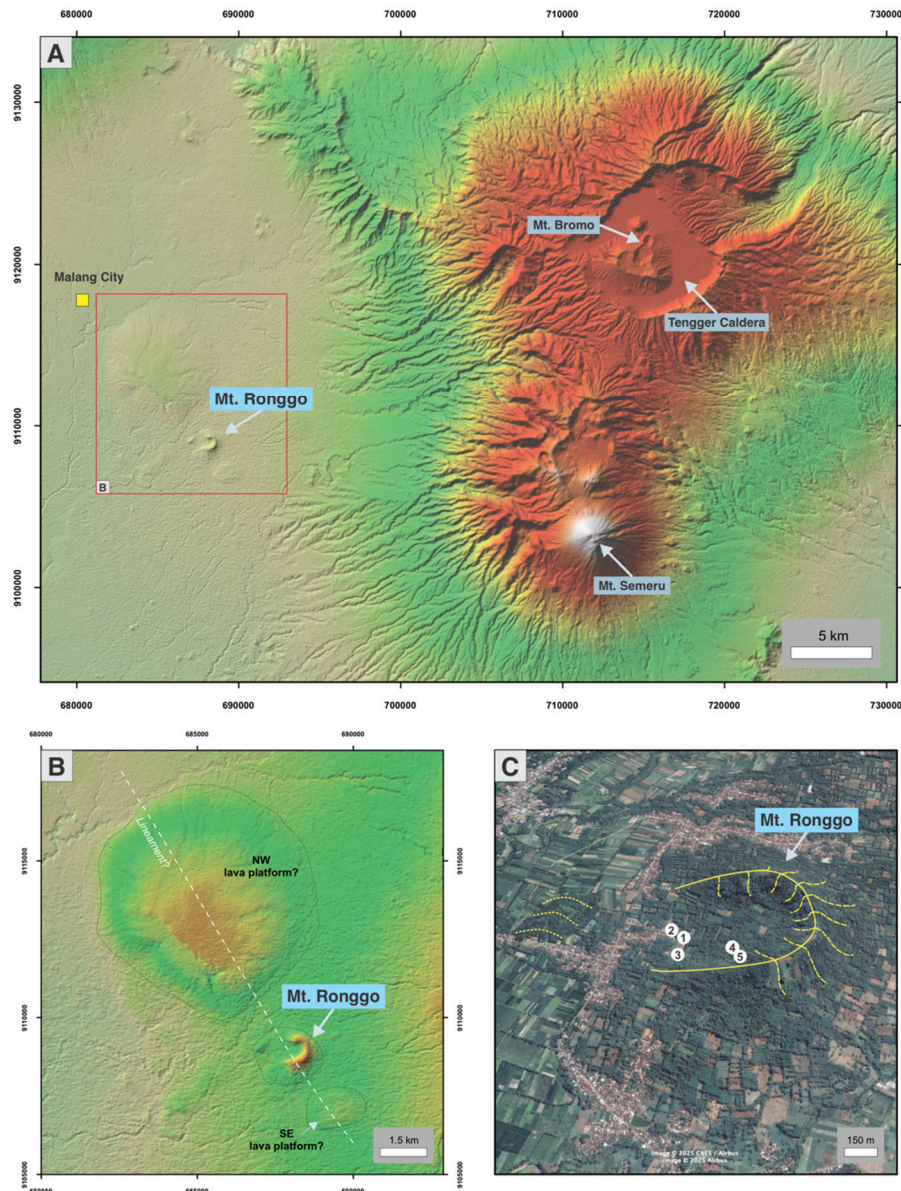


Figure 1 Geographic and structural setting of Mt. Ronggo. (A) Regional topographic map showing the location of Mt. Ronggo relative to the Mt. Semeru volcanic complex, Mt. Bromo, and the Tengger Caldera. (B) Shaded relief map emphasizing the NW-SE lineament that aligns the Mt. Ronggo cone with two distinct lava platforms. (C) High-resolution satellite image indicating the five primary field observation and sampling locations (Loc 1-5). Base map compiled from DEMNAS (Badan Informasi Geospasial, 2018) and satellite imagery (Google Earth, 2024).

3 Methods

3.1 Field Observations and Sample Collection

Fieldwork was conducted in two phases on 8 March 2025 and 25 January 2026 to characterize the Mt. Ronggo scoria cone, situated near the Tengger-

Semeru volcanic complex. Geomorphological observations focused on the distinctive horseshoe-shaped morphology and a significant lineament associated with two lava platforms. Outcrop investigations revealed that the majority of the area is covered by a soil-like bed resulting from intense

weathering. Stratigraphic logging identified a distinct black ash layer situated directly beneath this weathered horizon. Representative clasts, mostly consisting of fragments, were collected from available exposures for petrographic and geochemical analysis.

3.2 Geochemical Analysis

The whole-rock geochemical composition of the collected fragments was determined using X-ray fluorescence (XRF) analysis at Akita University, Japan, following the procedures described by [Gurusinga et al. \(2023; 2025\)](#). Representative fragment clasts were cut into small portions and carefully picked to ensure the selection of the freshest, least-altered material. These samples were dried, crushed, and pulverized into fine powder. To determine loss on ignition (LOI), powders were heated to 900°C. Glass beads were prepared using an alkali flux consisting of a 3:1 ratio of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) to lithium metaborate (LiBO_2) mixed with 0.8 g of sample at a 5:1 flux-to-sample dilution ratio. The mixtures were fused at 1150°C. Major element concentrations were measured using a Rigaku Co. ZsX Primus II spectrometer.

3.3 Geomorphological Modeling and Volume Estimation

To reconstruct the volcanic evolution and mass balance of the Mt. Ronggo edifice, morphometric modeling was employed using geometric approximations of the original structure. The total volume of the original volcanic edifice was modeled as a solid cone, while the internal crater void was represented as a composite cylindrical structure to account for its distinct upper and lower morphology. This cylindrical model was selected based on DEM cross-sections showing steep, near-vertical crater walls, characteristic of welded scoria cone interiors.

All volume calculations were performed using standard geometric formulas as follows:

Cone volume

$$V = \frac{1}{3} \pi r^2 h \quad (1)$$

This formula was applied to determine the initial solid volume of the scoria cone based on a base radius (r) of 725 m and a cone height (h) of 230 m.

Cylinder volume:

$$V = \pi r^2 h \quad (2)$$

The internal crater void was reconstructed by summing the volumes of an upper cylinder ($h = 50$ m) and a lower tube ($h = 120$ m), both maintaining a constant radius (r) of 350 m. The net solid cone volume

was subsequently derived by subtracting the total crater void volume from the initial solid cone volume. Half-ellipsoid volume:

$$V = \frac{2}{3} \pi abc \quad (3)$$

The volume of the western hill remnant was estimated using a geometric approximation for a half-ellipsoid body. In this formula, a and b represent the semi-axes of the base (185 m and 250 m, respectively), and c represents the height (50 m) of the hill.

The volume of the collapsed body was calculated as a $\sim 120^\circ$ sector (representing approximately 1/3 of the total circular edifice) of the net solid cone volume. Finally, a mass balance was established by comparing the western hill volume against the total estimated collapsed mass to determine the proportion of the original edifice remaining in situ versus the material dispersed into the surrounding area by post-collapse processes.

4 Results

4.1 Field Observations and Morphological Features

Mt. Ronggo is a monogenetic scoria cone situated on the distal eastern flank of the Tengger-Semeru volcanic complex. Field observations (Figure 2, Figure 3) reveal that the Mt. Ronggo area is dominated by a thick, weathered soil-like bed resulting from intense tropical weathering. Local quarrying activities (Figure 3f) exposed a well-preserved black ash layer beneath this weathered horizon (Figure 3g). At Location 1, charcoal fragments were found within the soil-like bed (Figure 3a-b), while a pyroclastic density current (PDC) deposit containing black scoria was identified at Location 4 (Figure 3e). The overall morphology (Figure 2) is defined by a large horseshoe-shaped breach opening toward the west, with an isolated Western Hill remnant. The reconstructed cone has a base radius of 725 m and a height of 230 m.

4.2 Outcrop and Field Stratigraphic Description

Outcrop investigations conducted during the March 2025 and January 2026 fieldwork phases indicate that the majority of the Mt. Ronggo area is characterized by intense weathering. This surface process has produced a ubiquitous soil-like bed that covers almost all of the volcanic edifice and the surrounding platforms (Figure 3a-d; f-g). Stratigraphic access was not provided by manual excavation, but rather by cliffs dredged by local residents who utilize the soil-like bed for concrete brick production (Figure 3f).

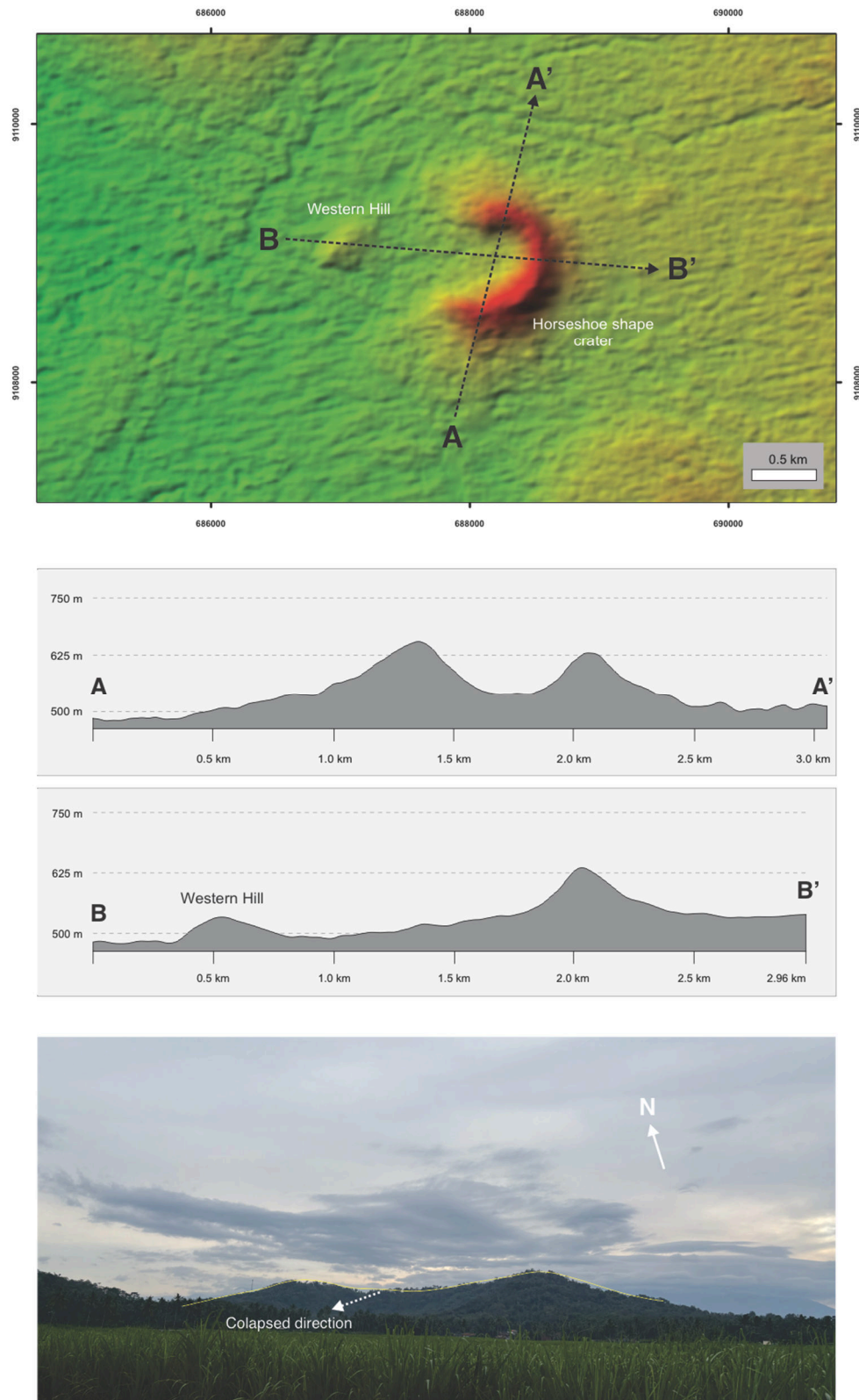


Figure 2 Morphological setting of Mt. Ronggo. The upper panel shows a digital elevation model (DEM) highlighting the horseshoe-shaped crater (120° breach) opening toward the west and the isolated Western Hill remnant. The lower panel shows topographic profiles A-A' (east-west) and B-B' (north-south), illustrating the asymmetric relief created by the sector collapse. Elevations are in meters above sea level (m a.s.l.). DEM source: DEMNAS ([Badan Informasi Geospasial, 2018](#)).

Similar to the quarrying activities that exposed tephra successions at Ranu Grati Maar ([Gurusinga et](#)

[al., 2025](#)), these local industrial activities at Mt. Ronggo revealed that the weathered horizon is directly

underlain by a well-preserved black ash layer (Figure 3g). The primary volcanic materials recovered from these sub-surface layers consist mostly of fragments,

including black and orange scoria, lava boulders, and potential spatter fall fragments (Figure 4).

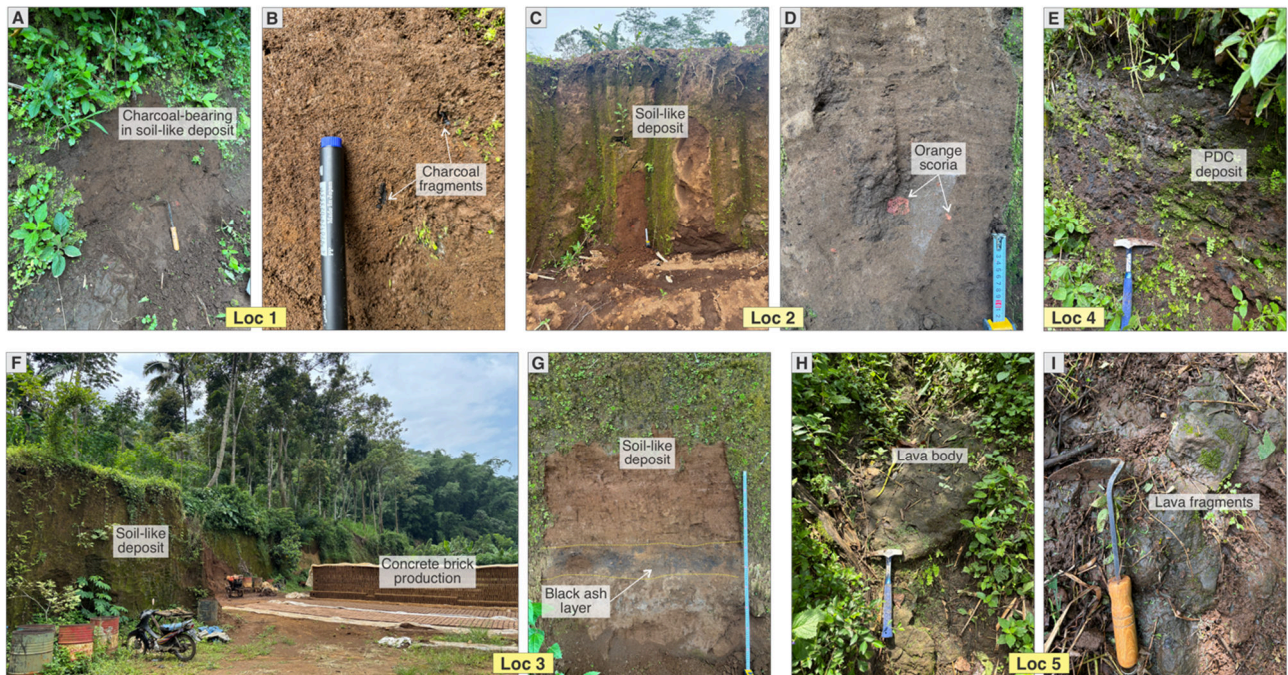


Figure 3 Field photographs of stratigraphic units and outcrops. (A-B) Charcoal fragments preserved within the soil-like deposit at Location 1. (C-D) Weathered soil-like deposit and primary orange scoria fragments at Location 2. (E) Outcrop of a pyroclastic density current (PDC) deposit containing black scoria at Location 4. (F) Local concrete brick production utilizing the highly weathered soil-like deposit at Location 3. (G) Stratigraphic sequence showing the black ash layer underlying the soil-like bed. (H-I) Exposed lava body and associated fragments at Location 5.

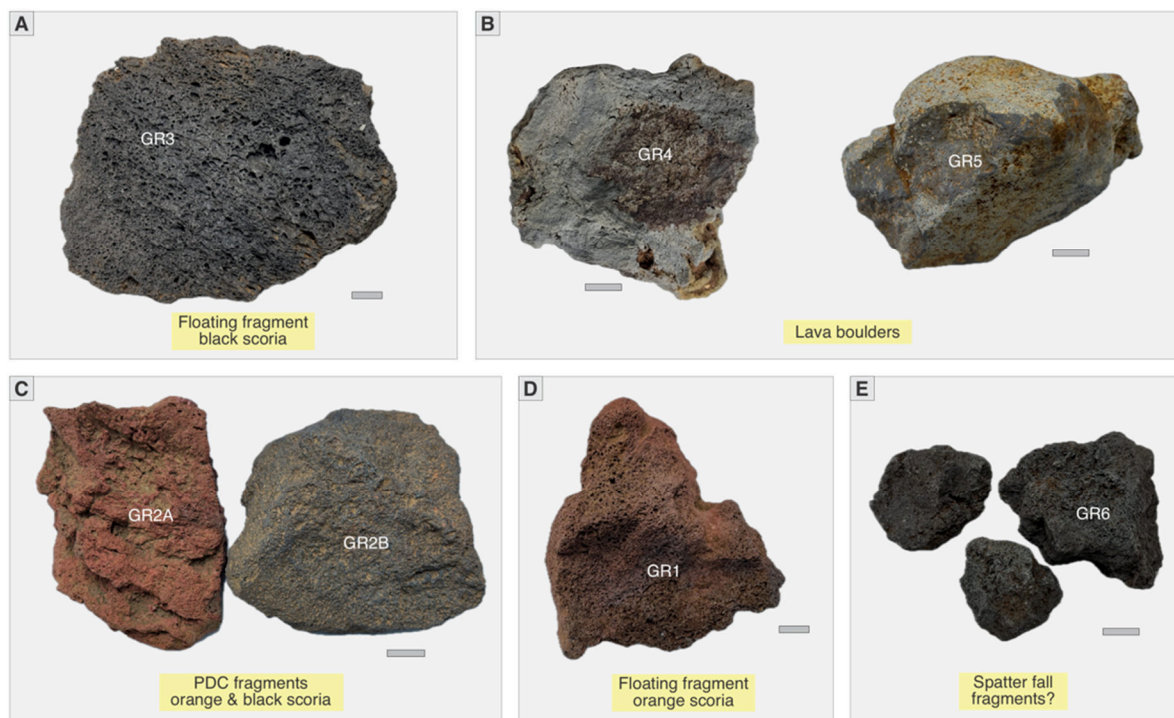


Figure 4 Macroscopic characteristics of volcanic products from Mt. Ronggo. (A) Black scoria fragment (sample GR3). (B) Dense lava boulders (samples GR4 and GR5). (C) Mixed orange and black scoria fragments from the PDC unit (samples GR2A and GR2B). (D) Orange scoria fragment (sample GR1). (E) Spatter fall fragments are characterized by high density (sample GR6). Scale bars represent 1 cm

At Location 1 (Figure 3a-b), this soil-like bed was found to contain charcoal fragments. Additionally, a pyroclastic density current (PDC) deposit was identified at Location 4 (Figure 3e). Although the outcrop at this location is also weathered, primary black scoria fragments can still be found within the unit. Floating fragments of vesicular scoria remain the most prevalent clast type identified within the subsurface sequence exposed by the dredging activities.

4.3 Whole-rock Geochemistry

Whole-rock geochemical analysis conducted via X-ray fluorescence (XRF) indicates that the eruptive products of Mt. Ronggo are compositionally situated predominantly within the basalt field, extending to the lower boundary of the basaltic andesite field (Figure 5). The silica content (SiO_2) for the analyzed samples ranges narrowly around 46–52 wt%. When plotted on a Total Alkali-Silica (TAS) classification diagram, the Mt. Ronggo samples exhibit a significant compositional overlap with the mafic geochemical trends of surrounding regional volcanoes, specifically the Tengger-Bromo-Semeru (Wahyudin, 1991; van Gerven and Pichler, 1995), Lamongan Volcanic Complex (Carn and Pyle, 2001; Gurusinga et al., 2023), and Ranu Grati Maar (Gurusinga et al., 2025). The major element concentrations are consistent with the regional calc-alkaline series typical of the East Java segment of the Sunda Arc.

4.4 Edifice Reconstruction and Volumetric Modelling

Morphometric reconstruction of the original volcanic structure prior to its failure yielded specific volumetric parameters. The original solid cone (R base = 725 m, H_{cone} = 230 m) had an initial volume of approximately $126.6 \times 10^6 \text{ m}^3$ (Figure 6). The internal crater void was modeled as a composite cylindrical structure consisting of an upper cylinder (50 m height) and a lower tube (120 m height), both maintaining a constant radius of 350 m. The total calculated volume of this crater void is $65.4 \times 10^6 \text{ m}^3$ (Table 1). By subtracting the crater void from the solid cone, the net solid edifice volume before collapse is determined to be $61.2 \times 10^6 \text{ m}^3$ (Table 1). The collapsed sector, representing 120° (approximately one-third) of the original cone, has a calculated volume of $20.4 \times 10^6 \text{ m}^3$.

4.5 Sector Failure and Mass Balance Analysis

The failure of the Mt. Ronggo edifice is characterized as a $\sim 120^\circ$ sector collapse, representing approximately one-third of the original circular cone. The volume of this collapsed body is calculated at $20.4 \times 10^6 \text{ m}^3$ (Table 1). Volumetric estimation of the western hill remnant, modeled as a low-dome half-

ellipsoid ($a = 185 \text{ m}$; $b = 250 \text{ m}$; $c = 50 \text{ m}$), results in a volume of $4.84 \times 10^6 \text{ m}^3$. Mass balance calculations indicate that this remnant hill accounts for 23.7% of the total collapsed mass. The remaining 76.3% ($15.6 \times 10^6 \text{ m}^3$) of the failed material is currently unaccounted for in the immediate vicinity of the breach, suggesting it was dispersed into the surrounding landscape by post-collapse transport and erosion processes.

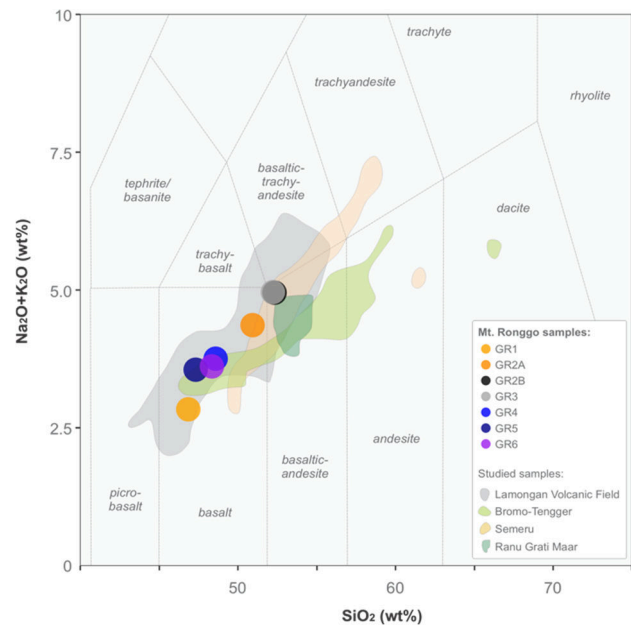


Figure 5 Total Alkali-Silica (TAS) classification diagram (after Le Bas et al., 1986). Mt. Ronggo samples (GR1–GR6) are plotted alongside regional data from the Lamongan Volcanic Field (Carn and Pyle, 2001; Gurusinga et al., 2023), Bromo-Tengger (van Gerven and Pichler, 1995), Semeru (Wahyudin, 1991), and Ranu Grati Maar (Gurusinga et al., 2025). The results indicate that Mt. Ronggo is predominantly basaltic ($\text{SiO}_2 \approx 46\text{--}52 \text{ wt}\%$) and exhibits a significant compositional overlap with the surrounding regional volcanic systems. All compositions are normalized to 100% on an anhydrous basis.

5 Discussion

5.1 Regional Magmatic Provenance and Petrological Links

The whole-rock geochemical data obtained via XRF analysis indicate that the eruptive products of Mt. Ronggo are predominantly basaltic, with some samples plotting at the lower boundary of the basaltic andesite field ($\text{SiO}_2 \approx 46\text{--}52 \text{ wt}\%$) (Figure 5). This compositional range shows a significant geochemical overlap with the regional trends of the Tengger-Bromo, Semeru, and Lamongan volcanic systems (Figure 5). Such uniformity in major element concentrations suggests that Mt. Ronggo acts as a "petrological window" into the deeper magmatic processes of the East Java segment, a concept recently applied to the Slamet-Loyang system in Central Java by Barber et al. (2023). By sampling relatively primitive

magma batches that reach the surface with minimal differentiation, Mt. Ronggo provides a clear view of the regional parental magma that likely feeds the larger polygenetic complexes nearby.

Table 1 Volume calculations for the scoria cone, composite crater, collapsed sector, and western debris hill. The original cone is modeled as a right circular cone (height = 230 m, base radius = 725 m). The crater is modeled as a composite cylinder (radius = 350 m, upper section = 50 m, lower tube = 120 m). The collapsed sector represents ~120° (one-third) of the net solid cone. The western hill is modeled as a half-ellipsoid ($a = 185$ m, $b = 250$ m, $c = 50$ m)

Component	Volume ($\times 10^6$ m ³)	Formula
Original cone	126.6	$(1/3) \times \pi \times 725^2 \times 230$
Upper crater (50 m)	19.2	$\pi \times 350^2 \times 50$
Lower crater (120 m)	46.2	$\pi \times 350^2 \times 120$
Total crater void	65.4	$19.2 + 46.2$
Net solid cone	61.2	$126.6 - 65.4$
Collapsed (~120°)	20.4	$(1/3) \times 61.2$
Western hill	4.84	$(2/3) \times \pi \times 185 \times 250 \times 50$
Unaccounted	15.6	$20.4 - 4.84$

The compositional stability observed in Mt. Ronggo's fragments mirrors the findings of Gurusinga et al. (2025) at Ranu Grati Maar, where texturally diverse scoria types were found to share a nearly identical bulk composition, originating from a single, relatively homogeneous magma batch. As shown in the TAS diagram (Figure 5), monogenetic centers across the East Java segment, including the Lamongan Volcanic Field and Ranu Grati, frequently exhibit overlapping silica and total alkali values with the major stratovolcanoes like Bromo-Tengger. This implies that these monogenetic vents, despite their small volume, tap into a laterally extensive transcrustal mush reservoir that underlies the broader volcanic complex (Barber et al., 2023).

The basaltic nature of Mt. Ronggo suggests rapid ascent of magma from deeper storage regions, with limited crustal residence time compared to the more evolved products of larger systems (Smith and Németh, 2017; Barber et al., 2023). Following the theoretical models of Takada (1994), such monogenetic eruptions occur when the magma supply rate is too low to maintain a permanent, heated conduit, leading to the formation of isolated vents rather than a centralized polygenetic edifice. The occurrence of Mt. Ronggo on the western flank of the

Tengger-Semeru complex represents a "hybrid" system where monogenetic and polygenetic volcanism coexist, driven by the regional stress regimes of the Java Arc (Marliyani et al., 2020; Barber et al., 2023). Consistent with the Lamongan Volcanic Field (Carn, 2000), the placement of Mt. Ronggo was likely facilitated by structural lineaments that provided efficient pathways for small, primitive magma batches to bypass the main polygenetic plumbing system and reach the surface.

5.2 Markers of Eruptive Transition

The identification of a pyroclastic density current (PDC) deposit at Location 4 (Figure 3e), containing discernible black scoria fragments, provides an essential clue regarding the explosive energy and fragmentation history of Mt. Ronggo. In the regional context of East Java, similar deposits are identified in monogenetic systems like Ranu Grati Maar, where they are interpreted as base surges resulting from intense magma-water interactions or rapid conduit transitions (Gurusinga et al., 2025). The presence of these high-energy deposits at Mt. Ronggo suggests a transition from purely effusive growth to a more explosive phase, potentially triggered by the decompression of the magmatic system following the initial stages of edifice instability or sector failure. Such units represent pulses of high fragmentation efficiency that can occur even in predominantly basaltic systems (Ball, 2022; Benamrane et al., 2022).

The occurrence of charcoal fragments within the soil-like bed at Location 1 (Figure 3a-b) serves as a significant stratigraphic discovery that offers a key opportunity for future chronological research. While radiocarbon dating was beyond the scope of this study, the preserved charcoal fragments provide a clear pathway for future work to establish a precise absolute age for the failure event or specific eruptive stages and to correlate Mt. Ronggo's activity with the regional history of the Tengger-Semeru complex.

The ubiquitous soil-like bed covering the majority of the Mt. Ronggo area (Figure 3c, f) and the underlying black ash layer (Figure 3g) reflect a significant period of surface stability following the cessation of eruptive activity. As noted by Ball (2022), the development of mature soil horizons on tephra deposits often requires hundreds to thousands of years, with production rates influenced by local climatic conditions. The advanced state of weathering observed at Mt. Ronggo, exposed by local brick production activities (Figure 3f) that utilize the dredged soil, indicates a substantial interval of post-eruptive geomorphological and pedogenic modification. This aligns with models of edifice degradation where monogenetic landforms gradually lose primary features like sharp crater rims due to

humid-climate weathering (Wood, 1980; Benamrane et al., 2022). Consequently, these stratigraphic layers record a clear transition from high-energy eruptive pulses to a long-term period of environmental stability and degradation.

5.3 Reconstruction and Edifice Instability

Morphometric reconstruction of the original Mt. Ronggo edifice ($R_{base} = 725$ m, $H_{cone} = 230$ m) suggests a transition from a symmetrical "ideal" cone to the current horseshoe-shaped morphology through a significant failure event. The calculated height-to-width ratio (H_{co}/W_{co}) for the reconstructed structure is approximately 0.158, which is slightly lower than the 0.18 value typically proposed for pristine basaltic scoria cones (Benamrane et al., 2022; Zhang, 2023). This deviation, combined with the presence of the 120° sector breach (Figure 4; Figure 6b), indicates that Mt. Ronggo underwent a major structural failure during its growth or immediate post-building phase. Such breaches are characteristic of monogenetic systems where lateral instability is facilitated by rapid construction or the orientation of underlying structural lineaments (Watt, 2019; Romero et al., 2021; Zhang, 2023). The steep conical form ($H/W \approx 0.158$), dominance of scoriaceous and spatter fragments, and basaltic composition ($SiO_2 \approx 46\text{--}52$ wt%) collectively classify Mt. Ronggo as a scoria cone (cinder cone) formed by Strombolian to Hawaiian-style magmatic eruptions, with only subordinate phreatomagmatic episodes evidenced by the PDC deposit.

The orientation of the NW-SE lineament, which aligns two distinct lava platforms (Figure 1b) with the Mt. Ronggo cone, is consistent with the direction of maximum horizontal stress (σ_{Hmax}) frequently observed across the Java Volcanic Arc (Carn, 2000; Barber et al., 2023; Marliyani et al., 2020; Zhang, 2023). As observed at the Lamongan Volcanic Field and other regional centers, the installation of Mt. Ronggo along such crustal weaknesses facilitated the rapid ascent of basaltic magma while simultaneously establishing the primary plane of instability that compromised the western flank, leading to the 120° sector collapse (Carn, 2000; Benamrane et al., 2022; Barber et al., 2023; Marliyani et al., 2020; Zhang, 2023). This structural heritage provided the pathway for magma rise and the preferential direction for the mass transport that shaped the current geomorphology (Martí et al., 2016; Zhang, 2023).

5.4 Volumetric Reconstruction and Edifice Instability

The mass balance calculations provide a quantitative perspective on this failure mechanism. The volume of the collapsed body is estimated at 20.4

$\times 10^6$ m³, while the western hill remnant (Figure 6a-c) represents only 4.84×10^6 m³, or roughly 23.7% of the failed mass (Table 1; Figure 7). This significant discrepancy indicates that the majority of the material (76.3% or 15.6×10^6 m³) is currently unaccounted for in the immediate vicinity of the breach (Table 1; Figure 7). It is important to note that the volume estimates presented here are subject to uncertainties inherent in geometric modeling of natural landforms. The original cone may not be a perfect right circular cone, and the crater walls may not be perfectly cylindrical. Variations in DEM resolution and the interpretation of the crater floor elevation also introduce uncertainty. A sensitivity analysis suggests that the calculated volumes may vary by approximately $\pm 15\text{--}25\%$ depending on the exact geometry of the cone, the crater walls, and the debris deposit.

Nonetheless, the relative volumes and the mass balance discrepancy are robust and remain significant even within this uncertainty range. This "missing" material likely formed a volcanic debris avalanche deposit characterized by hummocky terrain and chaotic breccias that traveled several kilometers beyond the base of the volcano (Romero et al., 2021). However, due to intense weathering and subsequent erosion, the diagnostic hummocky topography may no longer be preserved. Given the humid climate and intense weathering recorded in the soil-like bed (Figure 3f), it is probable that these distal deposits were either buried by subsequent products or dispersed through surface runoff and rill erosion (Pedrazzi et al., 2020; Benamrane et al., 2022; Zhang, 2023). The abrupt removal of this significant mass, effectively acting as a "conduit cork," may have triggered the transition to the explosive energy required to produce the PDC deposit identified at Location 4 (Figure 3e) by suddenly decompressing the shallow magmatic system (Riggs and Duffield, 2008; Romero et al., 2021).

6 Conclusions

Mt. Ronggo acts as a "petrological window" into a regional transcrustal mush reservoir shared with nearby polygenetic complexes. Geochemical analysis shows a significant compositional overlap with the Tengger-Bromo, Semeru, Ranu Grati Maar, and Lamongan Volcanic Field, with stable basaltic products ($SiO_2 \approx 46\text{--}52$ wt%), reflecting rapid magma ascent from a deep source region via structural lineaments that minimized crustal interaction.

The stratigraphic record captures a transition to high-energy explosivity, evidenced by the identification of a PDC deposit likely triggered by system decompression following edifice failure. The

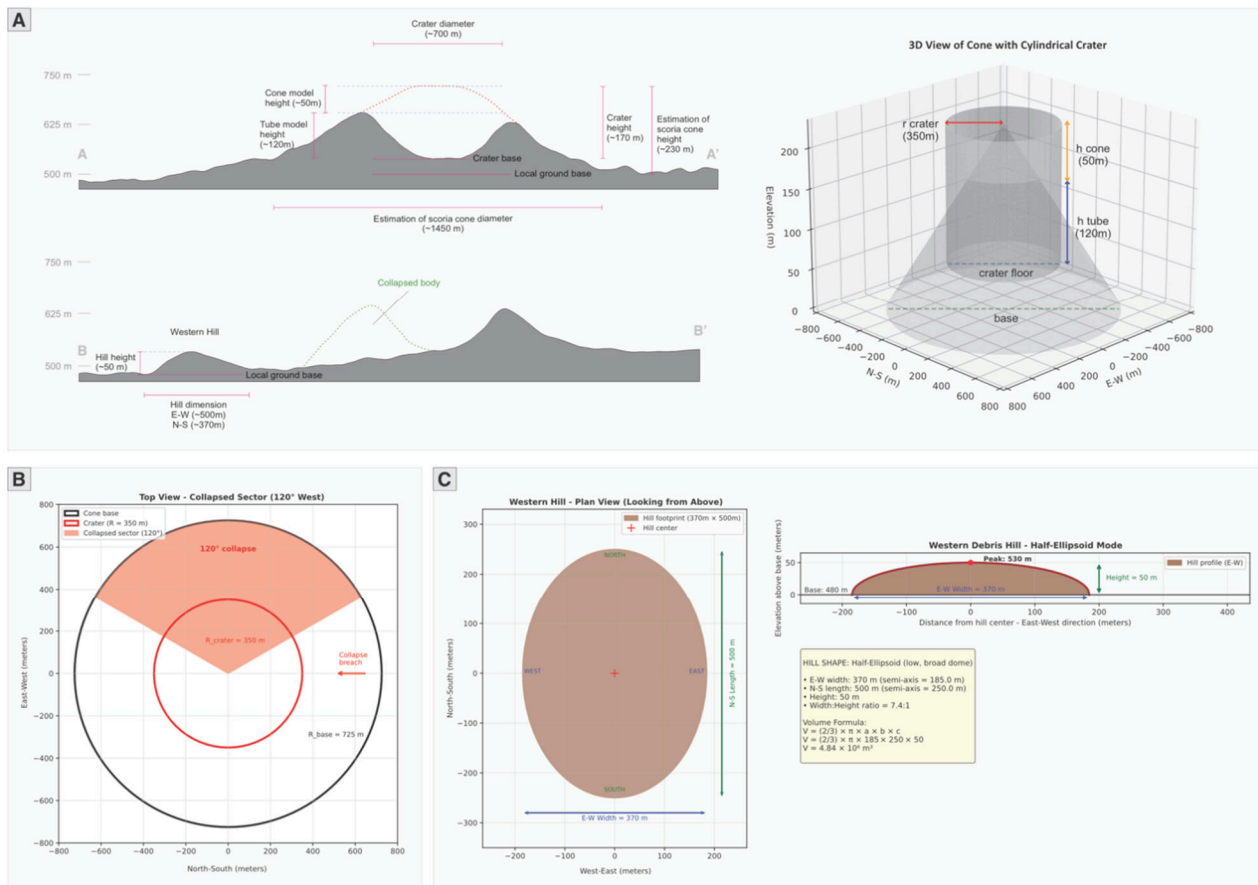


Figure 6 Volumetric reconstruction of the sector collapse at Mt. Ronggo. (A) Geometric modeling comparing current topography with an idealized scoria cone ($R_{base} = 725$ m, $H_{cone} = 230$ m) and cylindrical crater ($R_{crater} = 350$ m, total depth = 170 m). (B) Top-view model of the 120° western sector collapse ($R_{base} = 725$ m; collapsed sector shown in red). (C) Morphometric parameters for the Western Hill remnant modeled as a half-ellipsoid ($a = 185$ m, $b = 250$ m, $c = 50$ m). The net solid cone volume prior to collapse is 61.2×10^6 m³, with a collapsed volume of 20.4×10^6 m³.

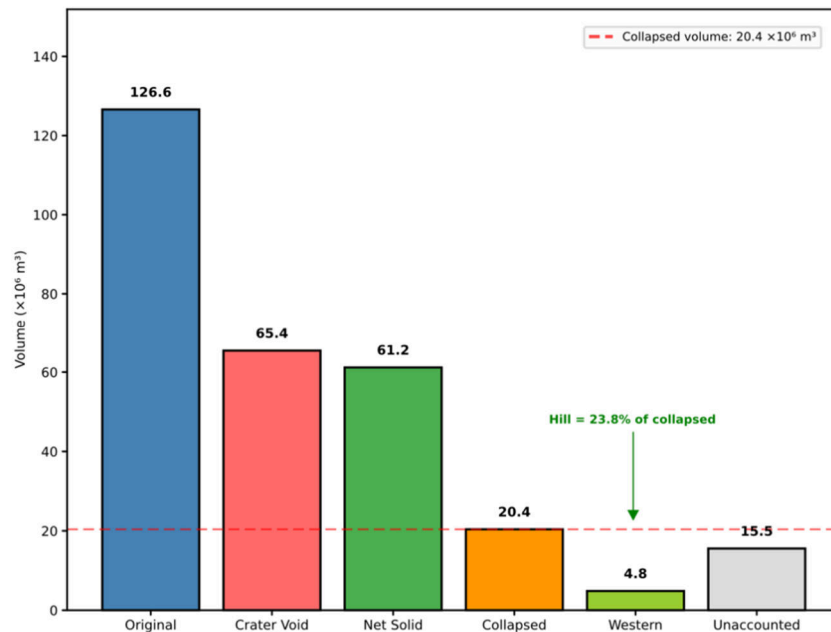


Figure 7 Mass balance of the failed volcanic material at Mt. Ronggo. The bar chart shows that the Western Hill represents only 23.7% (4.84×10^6 m³) of the total collapsed volume (20.4×10^6 m³). The remaining 76.3% (15.6×10^6 m³) of the failed mass is currently unaccounted for in the proximal area, suggesting distal dispersal or burial following failure along the NW-SE structural weak zone. Error bars represent the estimated uncertainty of ± 15 –25% inherent in geometric modeling of natural landforms.

occurrence of charcoal fragments within the weathered sequence provides a critical target for future radiocarbon dating to establish the absolute age of the eruption. Intense weathering across the edifice, currently utilized by local residents for concrete brick production, indicates a substantial post-eruptive interval of environmental stability and geomorphological degradation.

Morphometric reconstruction identifies a major ~120° sector collapse involving 20.4×10^6 m³ of volcanic material. The Western Hill remnant accounts for only 23.7% of this total collapsed volume, a discrepancy suggesting that slope failure was governed by a pre-existing structural weak zone in the basement aligned with a prominent northwest-southeast lineament. This structural heritage likely compromised the western flank, determining the azimuth of failure and facilitating the distal dispersal

or burial of the remaining 76.3% of the mass. The resulting horseshoe-shaped geomorphology highlights the critical role of inherited geological structures in controlling lateral instability and the mechanical evolution of monogenetic volcanoes in the Java Volcanic Arc.

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