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|Research Article

Evaluating ascent condition during the formation of 723 CE vulcanian eruption of Kelud: Implication for hazard

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ABSTRACT

The 723 CE eruption of Kelud volcano in East Java, Indonesia, provides critical insights into the ascent dynamics and pre-eruptive conditions of explosive vulcanian eruption. This study examines textural and compositional variations in the groundmass and microlite morphologies of lithic-rich pyroclastic density currents (PDCs) and pumice fallout deposits from the different stages of the 723 CE eruption. Petrographic and geochemical analyses reveal contrasting ascent conditions between different clast types and eruptive stages. Lithic clasts, dominated by euhedral microlites and evolved rhyolitic groundmass compositions, crystallized under slow magma ascent and limited degassing within a dense plug or lava dome. In contrast, pumice clasts, characterized by skeletal microlites and dacitic groundmass compositions, reflect rapid magma ascent and fragmentation during explosive eruption phases. These findings highlight the dynamic interplay of crystallization, degassing, and conduit processes that govern vulcanian eruptions, particularly at Kelud. This study underscores the importance of petrological approaches in analyzing the eruptive products of vulcanian eruptions to better understand the magmatic processes responsible for such events and to improve hazard assessments for future similar eruptions.

ABSTRAK

Letusan Gunung Kelud pada tahun 723 M di Jawa Timur, Indonesia, memberikan informasi penting tentang dinamika kenaikan magma dan kondisi pra-erupsi dari letusan eksplosif tipe vulkanian. Penelitian ini menggabungkan kajian pada variasi tekstur dan komposisi massadasar (*groundmass*) serta morfologi mikrolit dari aliran piroklastik (*pyroclastic density currents*/PDCs) kaya litik dan endapan jatuhnya pumis dari berbagai tahap letusan tahun 723 M. Analisis petrografi dan geokimia menunjukkan perbedaan kondisi kenaikan magma pada berbagai jenis endapan dan tahap erupsi. Butiran litik, yang didominasi oleh mikrolit *euhedral* dan komposisi massadasar riolitik yang telah berkembang, mengkristal pada kondisi kenaikan magma yang lambat dan *degassing* yang terbatas sehingga dapat membentuk sumbat magma atau kubah lava. Sebaliknya, butiran pumis, yang dicirikan oleh mikrolit berbentuk *skeletal* dan komposisi massa dasar dasitik, mencerminkan proses fragmentasi akibat kenaikan magma yang lebih cepat selama fase letusan eksplosif. Temuan ini menjelaskan interaksi dinamis antara kristalisasi, *degassing*, dan proses konduit yang menghasilkan letusan jenis vulkanian, khususnya di Gunung Kelud. Studi ini menegaskan pentingnya pendekatan petrologi dalam menganalisis produk letusan tipe vulkanian untuk memahami proses magmatik yang bertanggung jawab atas kejadian tersebut dan meningkatkan evaluasi bahaya untuk potensi letusan serupa di masa depan.

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1 Introduction

Vulcanian eruptions are commonly observed in many subduction-related volcanoes worldwide. They are characterized by a short-lived, explosive nature that may produce an alternation of dense, ash-rich pyroclastic density currents (PDCs) and discrete pumice fallout deposits (Sulpizio et al., 2016; Bernard and de Maisonnette, 2020). These eruptions are often associated with basaltic to dacitic magma and produce a typical mixture of juvenile and lithic materials (Macorps et al., 2018; Bain et al., 2019). Such eruptions pose significant hazards, including the deposition of lithic-rich PDCs capable of devastating proximal areas and pumice fallout that can disrupt regional air traffic and infrastructure (Macorps et al., 2018; Indriyanto et al., 2023). Understanding these hazard potentials is particularly crucial in densely populated volcanic regions, where thorough hazard assessment is essential for mitigating the risks.

Studying the groundmass and microlite compositions in products of vulcanian eruptions provides key insights into the eruptive processes and magma dynamics (Bain et al., 2019; Bernard and de Maisonnette, 2020; Baumann et al., 2023). Groundmass crystallization and microlite textures are strongly influenced by magma ascent rates, degassing efficiency, and conduit processes (Bernard and de Maisonnette, 2020; Popa et al., 2021). Thus, variations in these textures can be directly linked to eruption style and intensity, allowing to reconstruct pre-eruptive conditions and forecast similar future events. Despite their importance, detailed analyses of compositional and textural variations of groundmass for many vulcanian products remain underexplored.

This study investigates the textural and compositional variations of groundmass derived from lithic-rich PDC deposits and pumice fallout of Kelud

723 CE vulcanian eruption. By focusing on these eruptive products, this research aims to elucidate the physical and chemical conditions of magma prior to eruption, contributing to a broader understanding of eruption dynamics and their associated hazards. Such insights are critical for improving hazard assessments in the Kelud and other volcanic regions worldwide.

1.1 Kelud volcano

Kelud (also known as Kelut) is a stratovolcano located in East Java, Indonesia. It is regarded as one of most hazardous volcanoes in Indonesia due to its frequent explosive eruptions and proximity to the densely populated areas such as Kediri, Blitar, and Malang. Situated within Sunda Volcanic Arc and formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate (Hidayat et al., 2021; Ghufrani and Soesilo, 2024), Kelud is part of a prominent volcanic chain that includes Arjuna, Bromo-Tengger, Argopuro, and Ijen (Figure 1).

Kelud's magmatic system primarily comprises high-K basaltic-andesitic to dacitic magmas, characteristic of subduction-related tectonic settings (e.g. Jeffery et al., 2013; Kadarsetia, 2016). Its eruptive products include lava, pyroclastic materials, and lahars, originating from a variety of eruption styles. Despite this variability, Kelud has displayed consistent magmatic evolution from the Pleistocene to the present (Dempsey, 2013; Indriyanto et al., 2023).

During the Holocene, the activity of Kelud was primarily explosive, with a notable dominant type of vulcanian to subplinian eruptions (Goode et al., 2019; Hidayati et al., 2019; Indriyanto et al., 2023). These eruptions have repeatedly reshaped Kelud's morphology over time, leading to notable features such as the formation and diminishment of its crater lake, the periodic development of lava domes and

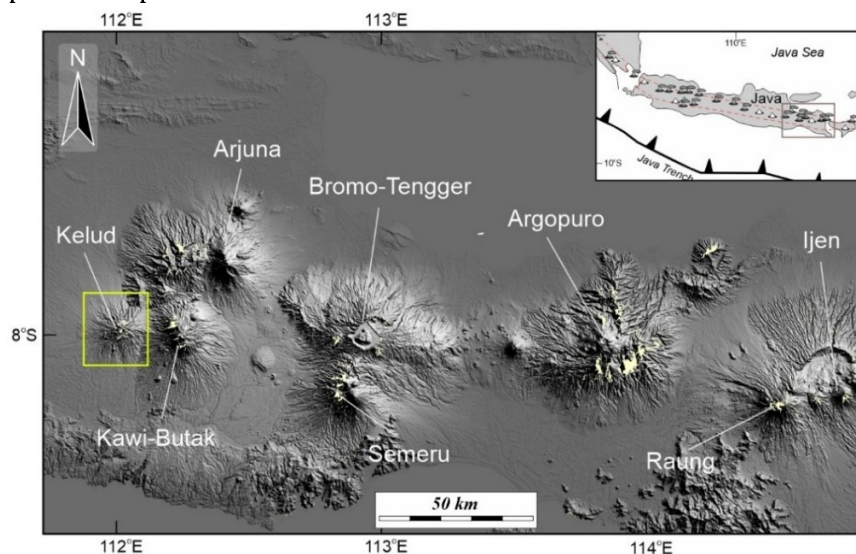


Figure 1 Location of Kelud volcano in Java Island and the relative position of it in the Sunda Volcanic Arc. Yellow square indicates the location of Kelud volcano as studied area.

plugs, and the widespread deposition of pyroclastic materials and lahars (i.e., [Hidayati et al., 2019](#); [Indriyanto et al., 2023](#)). Among its eruptive events, the 723 CE eruption is particularly remarkable, which showcasing complex interactions between high-energy pyroclastic flows, vent dynamics, and eruptive transitions. The deposits from this event offer critical insights into Kelud's behaviours and its implication to the eruptive activity during this period.

1.2 Geology of 723 CE eruption

The stratigraphy of 723 CE eruption (also referred to as Margomulyo 1 episode) has previously been studied in detail by [Indriyanto et al. \(2023\)](#). It contains a sequence of deposits associated with high-concentration pyroclastic density currents (PDCs), dilute PDCs, and tephra fallout layers, formed during an extensive eruptive episode around 1.3 to 1.1 cal. ka B.P. (**Figure 2**).

The 723 CE deposit is characterized by lithofacies transitions from lithic-rich vulcanian-derived PDCs to an alternation of vulcanian fallout and column collapse-derived PDC deposits. The early stage includes poorly to moderately sorted lithic breccia deposits originating from disruption of dome or lava plug and transported as high-energy currents. The

final stage comprises dilute PDCs interstratified with tephra fallout layers, attributed to short-lived vulcanian eruptions. These eruptions generated blocky crystalline ash, juvenile fragments, and lithic components (**Figure 3**), representing a vent instability and partial conduit wall erosion during the eruptive episode ([Indriyanto et al., 2023](#)).

The 723 CE eruptive products highlight a complex interaction between magmatic processes and magma dynamics, which produced distinct eruptive materials. Therefore, examining these eruptive products provide critical insights into the eruptive behaviour and potential volcanic hazards of Kelud volcano.

2 Methods

A total of 8 samples from both lithic rich PDC and pumice fallout deposits with a weight more than 250 g/sample were collected during fieldwork in 2018. Each sample were manually separated using a hand-sieve with 1 ϕ interval and using W-170-ST ultrasonic cleaner before undergone an overnight dried at 40°C. The selected dense lithic and pumice grains were subsequently molded and casted into thin section for further chemical and textural analysis.

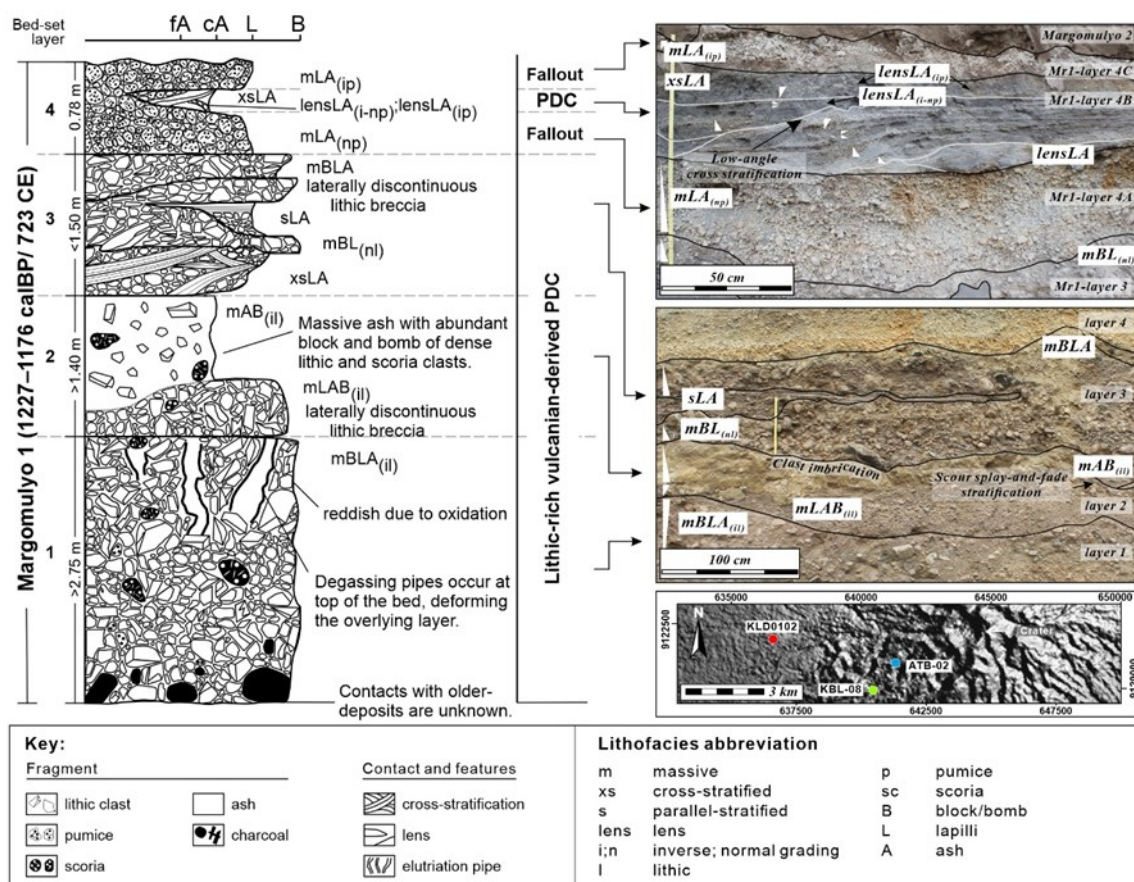


Figure 2 Stratigraphy, field photos, and observation points of 723 CE eruptive products of Kelud volcano (Modified from [Indriyanto et al., 2023](#))

Petrography and geochemical analysis were conducted at microscopy facilities of Faculty of International Resource Sciences, Akita University and Department of Geological Engineering, Institut Teknologi Bandung. Modal mineral proportion analysis was performed using a Nikon ECLIPSE LV100N and Nikon ECLIPSE Ci-POL optical microscopes by counting more than 2000 points at a continuous area. Further, the microlite texture and shape was observed through JEOL JSM-IT300LV scanning electron microscope (SEM). The observation of carbon-coated, polished thin section was carried out under 20 kV accelerating voltage at higher than x1000 magnification to get high-resolution multiple BSE images over continuous area.

Groundmass glass major and minor element compositions were measured using JEOL JSM-IT300LV scanning electron microscope (SEM) coupled with Oxford Instruments X-Ray energy dispersive spectrometer (EDS). Element acquisitions were executed using 15 kV accelerating voltage, a 2.2 nA beam current, a working distance of 10 mm, and applying cobalt (Co) as primary standard. Dwelling time was set to be 30 s to avoid sample damage during measurement.

3 Results

3.1 Petrography results

The clast componentry of 723 CE eruptions uses the classification defined by [Indriyanto et al. \(2023\)](#).

The lithic rich vulcanian-derived PDC deposits are dominated by dense lithic (DL), whereas the fallout mainly consists of pumice grains with minor lithic and crystal clasts (**Figure 3**).

Petrographic observation of 30 selected grains from 8 thin section samples shows that dense lithic and pumice clasts of 723 CE eruption share similar phenocrysts and groundmass assemblages, consisting of plagioclase, clinopyroxene, orthopyroxene, and titanomagnetite (**Figure 4**); although the proportions vary in the lithic and pumice clasts. The groundmass consists of similar mineral assemblages, with the lithic clasts are microlite and volcanic glass dominant, whereas the pumice clasts are mainly dominated by volcanic glass and vesicles. Qualitative observation of the groundmass shows that the lithic clasts are dominated by euhedral prismatic and swallowtail shapes for both plagioclase and pyroxene microlites (**Figure 4**). On the contrary, the pumices have relatively smaller crystals (most populated at the size interval of 10–15 μm) and exhibits skeletal to swallowtail plagioclase microlites with some swallowtail pyroxene microlites.

The quantitative modal proportion of the analyzed samples shows that lithic clasts have a relatively high phenocryst content of 84–93 vol.% and low vesicularity of 3–7 vol.% (**Figure 3**). In contrast, samples from pumice clasts have moderate phenocryst content (37 to 62 vol.%) and high vesicularity reaching the value of 38 vol.%.

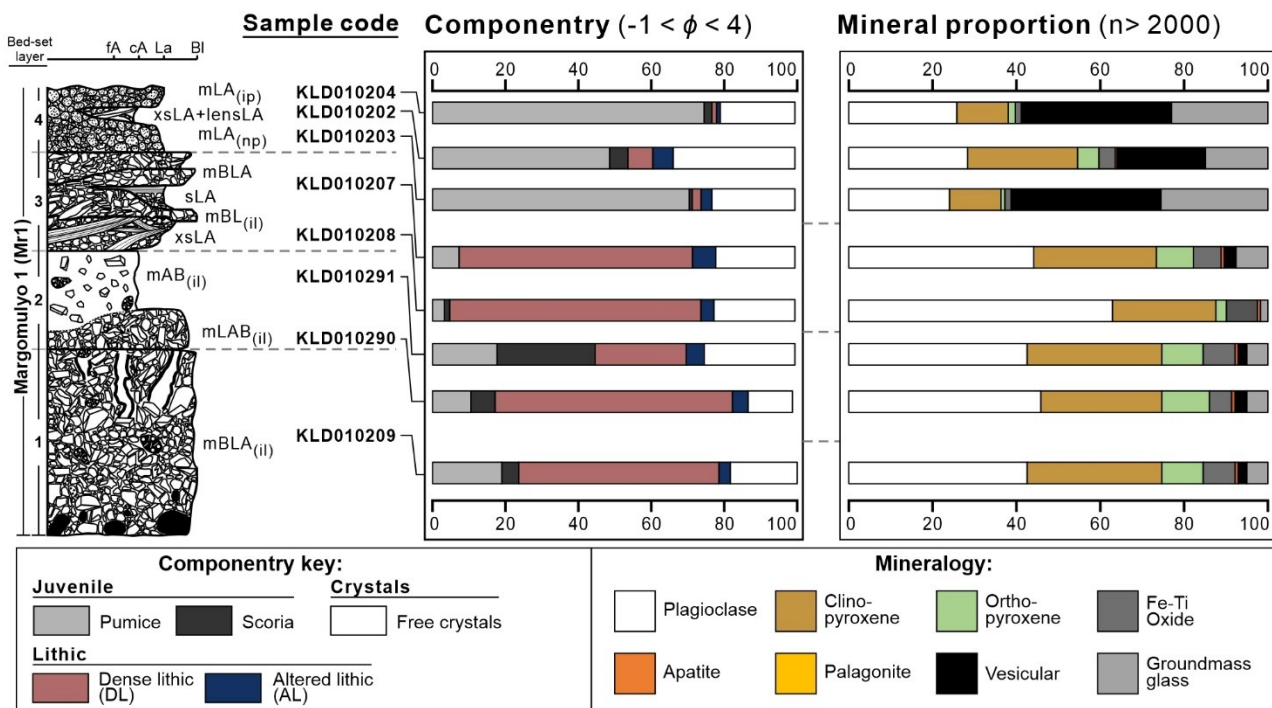


Figure 3 Componentry and modal mineral proportion of the analyzed samples taken from different eruption stages and layers of 723 CE eruption products. The componentry used in this study is based on the results of previous study (See [Indriyanto et al., 2023](#)).

Plot of mineral proportion against eruption stage shows that vesicularity and phenocryst contents have a negative correlation with the eruption stage, with PDC deposits have a higher phenocryst content decrease toward the fallout deposits.

3.2 Groundmass glass composition

The groundmass glass compositions of lithic and pumice clasts are plotted alongside previously published bulk compositions of Kelud products (Dempsey et al., 2013; Jeffery et al., 2013; Kadarsetia, 2016), including the 723 CE eruption (Indriyanto et al., 2023), on a volatile-free basis (Figure 5; see Supplementary Material for full analysis results). Despite having bulk compositions of basaltic andesite

to andesite, most groundmass samples fall within the dacite field, with some lithic groundmass samples are classified as rhyolite. The groundmass compositions show a medium-K calc-alkaline affinity, whereas the bulk compositions are low-K to medium-K calc-alkaline affinities. Both the total alkali values and magma affinities reflect a more evolved nature compared to their respective bulk compositions.

Further, the groundmass compositions are plotted against silica values, showing that Al_2O_3 , Fe_2O_3 , MgO , and CaO have negative correlations with silica concentrations while K_2O and Na_2O are positively correlated. The trends are consistent with those observed in the bulk compositions.

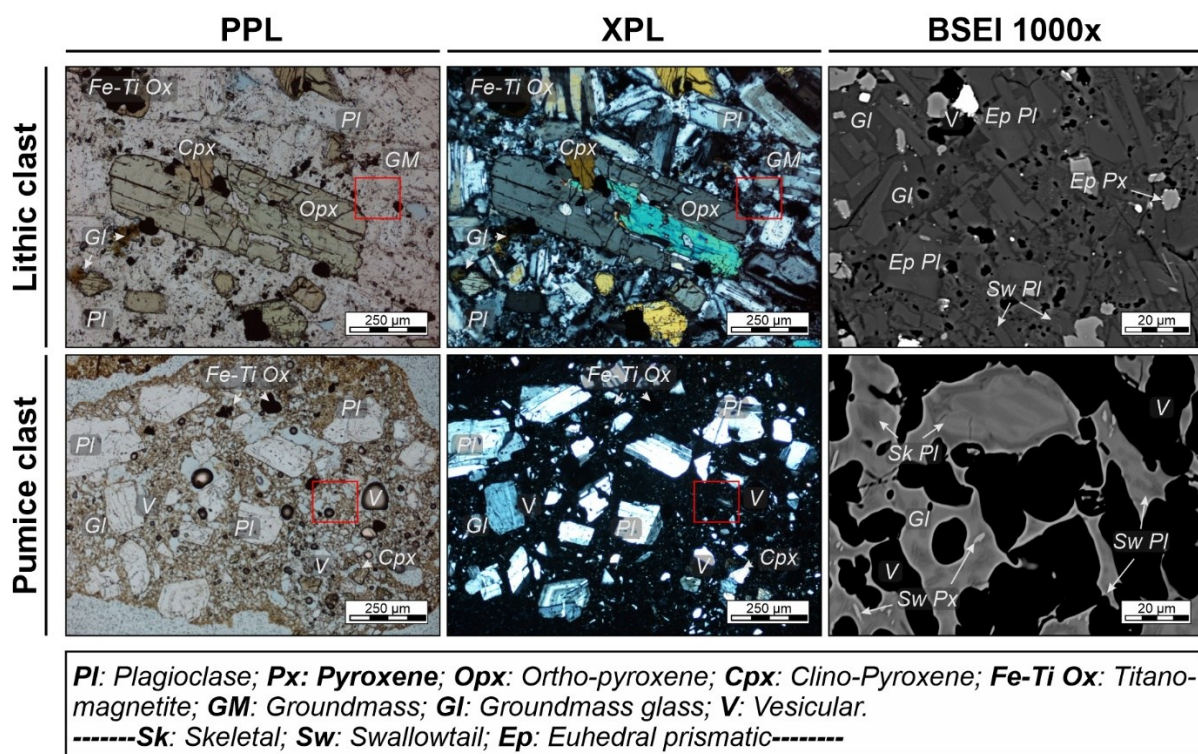


Figure 4 Representative microphotograph images of lithic and pumice clasts taken using polarized and electron microscopes for the 723 CE vulcanian products of Kelud. The red rectangles are area used for higher resolution observation using SEM. Note that the blue stain is caused by pigment color applied during the sample preparation.

4 Discussion

4.1 Morphological variation of plagioclase microlite

The morphological and textural variations of microlites offer valuable information on the crystallization environments and magma degassing processes during certain volcanic eruption. Microlite morphology is primarily influenced by the degree of undercooling (ΔT), which depends on the cooling and decompression rates experienced by the magma during ascent (e.g., Burkhard, 2005; Shea and Hammer, 2013). Higher ΔT , rapid decompression, and

shorter crystallization times favor the formation of skeletal morphologies, while lower ΔT and slower rates promote euhedral growth. In vulcanian eruptions, contrasting the eruption and cooling processes reflected from the microlite textures is essential to evaluate the magmatic condition prior and during the eruption.

The microlites in the 723 CE eruptive products exhibit two distinct trends (Figure 6). The predominance of euhedral microlites in lithic clasts suggests a slower cooling rate and a more stable crystallization condition at the early stage of lava dome or plug development, which occurred within a

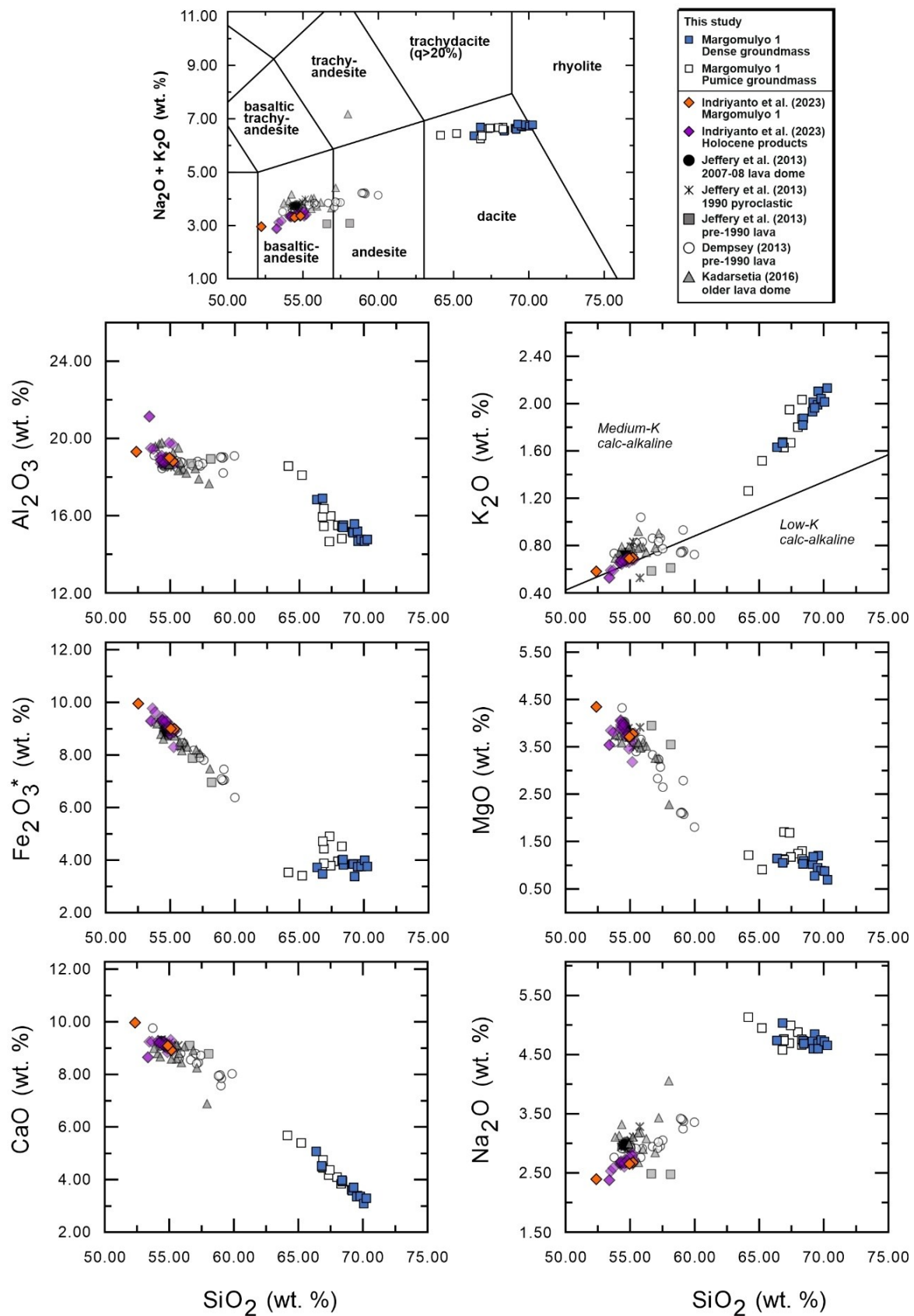


Figure 5 Groundmass composition and major mineral variations of the analyzed lithic and pumice clasts plotted alongside the bulk-compositions from previous studies.

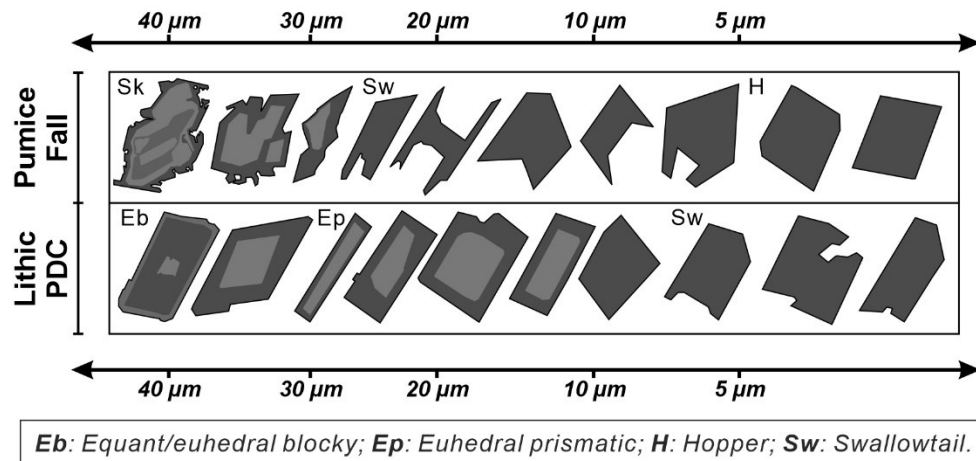


Figure 6 Morphological variation of plagioclase microlite observed in the analyzed lithic and pumice clasts of the 723 CE eruption

denser and less vesiculated magma, similar to Galeras volcano (Bain et al., 2019). However, the progressive transformation into swallowtail crystals in the later stage of the clast development suggest that the ascending magma may have experienced an increase in decompression, that may be possible due to the increment in ΔT after microlite started to crystallize. These conditions facilitated well-formed crystal growth under near-equilibrium settings (Shea and Hammer, 2013; Bernard and de Maisonnewe, 2020). This interpretation aligns with the lithic clasts being deposited from pyroclastic density currents (PDCs), where limited gas escape and slower crystallization occurred (e.g., Macorps et al., 2018).

In contrast, the microlite morphology that progressively transformed from skeletal into swallowtail and hopper-shaped observed in pumice clasts indicate rapid cooling and disequilibrium crystallization occurred continuously during magma ascend (e.g., Shea and Hammer, 2013; Bain et al., 2019). This process is typical in the explosive eruptive styles, where magma was highly vesiculated prior to the fragmentation (i.e., Rabaul volcano; Bernard and de Maisonnewe, 2020). Given the pumice clasts was formed in the fallout deposits, it is expected that the magma was subjected to intense decompression and rapid quenching in the air. The skeletal and hopper morphologies confirm the incomplete crystal growth during ascent, as the magma was unable to sustain the equilibrium conditions required for forming well-defined euhedral crystal shapes.

4.2 Ascent condition of 723 CE eruption inferred from microlite and groundmass compositions

The microlite morphology and groundmass composition provide critical insights into magma ascent conditions during the 723 CE eruption. In the early stage, when lithic-rich pyroclastic density

currents (PDCs) were produced, the predominance of euhedral-shaped microlites suggests a stable crystallization environment associated with slow magma ascent (Figure 7A). This indicates that, prior to the eruption, relatively slow decompression rates and prolonged cooling allowed microlite crystals to form in equant shapes (Shea and Hammer, 2013; Popa et al., 2021). The groundmass composition further supports this interpretation, showing more evolved compositions, reaching rhyolitic levels (Figure 5). Lithic clasts typically exhibit higher SiO_2 and K_2O values, suggesting that slow ascent enhanced the differentiation of the magma. This condition may reflect limited gas escape and crystallization under near-equilibrium conditions, allowing the magma to evolve further as it ascended at a controlled rate (e.g., Burkhard, 2005; Bain et al., 2019; Baumann et al., 2023). Additionally, the progressive transformation of microlites to swallowtail morphologies in lithic clasts indicates increasing pressure accumulation, as the rising magma began to form a plug or lava dome.

During the vulcanian eruption, pumice clasts was formed as the rapid decompression and cooling occurred to produced skeletal to hopper-shaped microlites (Shea and Hammer, 2013; Popa et al., 2021). These morphologies, along with their dacitic groundmass compositions, suggest that pumice-forming magma ascended more rapidly than the magma forming the plug or dome (Figure 7B). This rapid ascent led to magma fragmentation and the disruption of the previously developed plug or dome, driving the eruption to the surface (e.g., Macorps et al., 2018). The less evolved groundmass compositions of pumice clasts, compared to lithic clasts, highlight the inability of rapidly ascending magma to sustain equilibrium crystal growth. This resulted in skeletal microlite shapes and less evolved groundmass compositions.

4.3 Implication for hazard

The evolution of groundmass compositions and their respective microlites has important implications for the ongoing hazard assessment on the volcano with similar eruptive behavior, particularly surrounding area of Kelud, where similar eruption could occur in the future.

The predominance of euhedral microlites in lithic-rich pyroclastic density current (PDC) deposits reflects stable crystallization conditions associated with slow magma ascent (Bain et al., 2019; Bernard and de Maisonneuve, 2020). This suggests the formation of a dense plug or lava dome in the conduit, which can trap volcanic gases and lead to significant overpressure. If such conditions are followed by an explosive event, the lava plug or dome could heighten the potential for devastating eruptions with hazardous implications for communities nearby the volcano, as observed during the 2014 Kelud eruption and 2006

Tavurvur (e.g., Goode et al., 2019; Bernard and de Maisonneuve, 2020). Identifying this pre-eruptive phase through real-time monitoring of seismicity, gas emissions, and ground deformation is critical for anticipating dome collapse or explosive outbursts, which primarily threaten areas close to the vent due to their high density and velocity.

The transition from stable crystallization in lithic clasts to rapid decompression in pumice clasts highlights the complexity of vulcanian eruptions, which can shift between effusive and explosive phases (Sulpizio et al., 2016; Macorps et al., 2018; Baumann et al., 2023). This variability highlights the need to monitor not only eruption precursors but also real-time transitions during eruptive events. By linking microlite morphology and groundmass evolution to magma ascent conditions, this study provides a valuable framework for assessing hazards associated with similar volcanic systems.

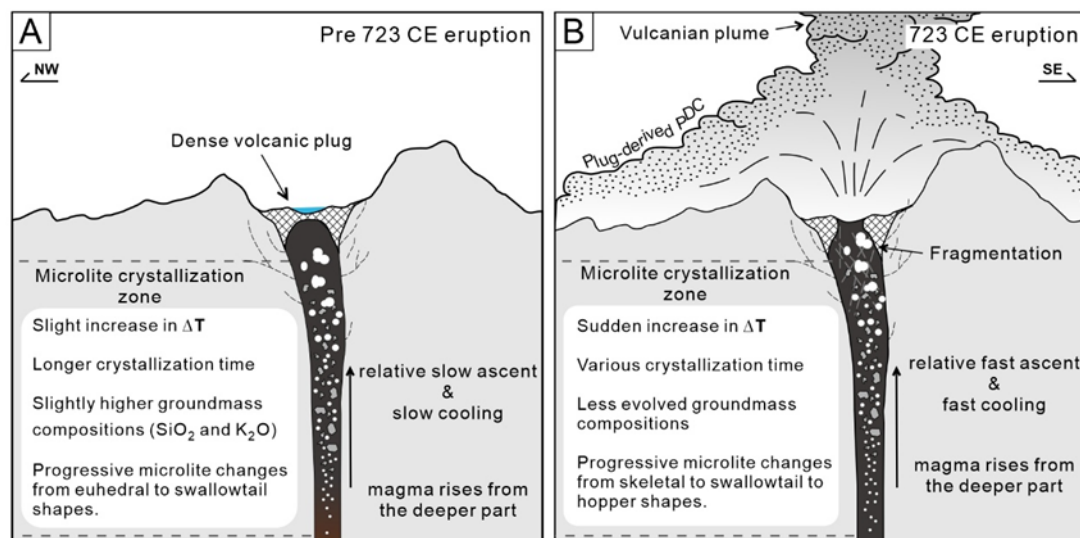


Figure 7 Conceptual model illustrating the ascent dynamics and crystallization conditions of magma during (A) Pre-eruptive stage and (B) Syn-eruptive stage of the 723 CE eruption.

5 Conclusion

The 723 CE Vulcanian eruption of Kelud Volcano demonstrates the critical role of magma ascent conditions in shaping eruption dynamics and associated hazards. Lithic-rich PDC deposits, formed during the early eruption phase, reflect slow ascent and stable crystallization within a dense plug or lava dome, as evidenced by euhedral microlite morphologies and rhyolitic groundmass compositions. Conversely, pumice fallout deposits represent rapid decompression and ascent during the explosive phase, producing skeletal microlites and less evolved dacitic compositions. These contrasting conditions underscore the transition from pre-

eruptive stability to syn-eruptive explosivity, driven by pressure accumulation and conduit dynamics.

The findings have significant implications for hazard assessment and risk mitigation. The identification of pre-eruptive phases, such as the formation of a lava dome or plug, provides early warning signs of potential explosive activity. Real-time monitoring of seismicity, gas emissions, and ground deformation is essential to detect such transitions and anticipate hazardous events. By linking microlite textures and groundmass compositions to ascent conditions, this study enhances our understanding of Vulcanian eruptions and offers a framework for assessing similar eruptions in other volcanic regions.

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