doi: 10.37905/jgeosrev.v8i2.36656 ejurnal.ung.ac.id/index.php/jgeosrev

Vol. 8, No. 2, July 2026: 175-185

Jambura Geoscience Review

p-ISSN 2623-0682 | e-ISSN 2656-0380

Department of Earth Science and Technology, Universitas Negeri Gorontalo

Magma Evolution and Petrogenesis of Volcanic Rocks at Kaba Volcano, Bengkulu

Muhammad Eval Juni Wijaya[1], Sakilla Gia Mentari[1], Chris John Sitinjak[1], Theo Sampit Mo Rizky Bantjin[1]

[1] Department of Geology Engineering, Institut Teknologi Sumatera, St. Terusan Ryacudu, Way Hui, Lampung Selatan, Lampung, 35365, Indonesia

ARTICLE INFO

Article history:
Received: 07 January 2026
Accepted: 27 June 2026
Published: 03 July 2026

Keywords:
Geochemistry; Kaba Volcano; Magma Evolution; Petrogenesis; Volcanic Rock

Corresponding author:
Muhammad Eval Juni Wijaya
Email:
muhammad.wijaya@gl.itera.ac.id

Read online:
Scan this QR code with your smart phone or mobile device to read online.

ABSTRACT

Mount Kaba is an active stratovolcano in the Bengkulu Province, Indonesia, characterized by explosive eruptions and multiple eruptive centers, reflecting a complex magmatic system. This study investigated the magma evolution and petrogenesis of volcanic rocks from the northern sector of Mount Kaba using integrated petrographic and whole-rock geochemical analyses. Fifteen representative lava and pyroclastic rock samples were analyzed for major elements using inductively coupled plasma–optical emission spectrometry (ICP-OES), while trace and rare earth elements (REE) were determined using inductively coupled plasma–mass spectrometry (ICP-MS). The analyzed rocks ranged from basalt to andesite, with SiO_2 contents between 44.41 and 63.41 wt%, and generally low loss-on-ignition values, indicating relatively fresh compositions. Petrographic observations revealed porphyritic, vesicular, subophytic, intersertal, zoning, sieve, and reaction rim textures, suggesting dynamic magma chamber processes and disequilibrium crystallization. Geochemical classification based on total alkali silica (TAS) and K_2O–SiO_2 diagrams indicates alkaline, calc-alkaline, and high-K calc-alkaline affinities, which can be grouped into two magma series: the Danau Mas Group and the Kaba Group. Major and trace element variation diagrams show decreasing MgO, Fe_2O_3, and CaO with increasing SiO_2, accompanied by enrichment of alkali and incompatible elements, indicating magma differentiation dominated by fractional crystallization. Primitive mantle- and chondrite-normalized patterns display enrichment of large ion lithophile elements (LILE) and light rare earth elements (LREE), together with depletion of high field strength elements (HFSE), suggesting derivation from a mantle source modified by subduction-related fluids. Overall, the results indicate that Mount Kaba magmatism evolved through mantle wedge melting, followed by crustal-level magma differentiation within a subduction-related volcanic arc system.

How to cite: Wijaya, MEJ. (2026). Magma Evolution and Petrogenesis of Volcanic Rocks at Kaba Volcano, Bengkulu. *Jambura Geoscience Review, 8*(2), 175-185. https://doi.org/10.37905/jgeosrev.v8i2.36656

1. INTRODUCTION

Mount Kaba is an active stratovolcano in the Bengkulu Province, Indonesia, located within the Bukit Barisan volcanic arc and associated with the Sunda subduction system (Wijaya & Setijadji, 2022). The volcano comprises a central edifice and several eruptive centers, including monogenetic features, indicating a complex volcanic system with diverse eruptive products (Westerveld, 1952; Kusumadinata et al., 1979; Sugianto et al., 2023). In subduction-related volcanic arcs, magma diversity commonly reflects interactions between slab-derived fluids, mantle wedge melting, fractional crystallization, magma mixing, and crustal processes (Cashman et al., 2017; Ducea et al., 2015). Therefore, petrographic and geochemical investigations are essential to constrain the evolution and petrogenesis of volcanic rocks in this setting (Winter, 2014).

Previous studies have shown that major, trace, and rare earth elements (REE) are effective indicators of magma source, tectonic setting, and differentiation processes (Rollinson, 1993; Jamali, 2017). In arc magmas, enrichment of large ion lithophile elements (LILE) and light rare earth elements (LREE), together with depletion of high field strength elements (HFSE), commonly indicates mantle source modification by slab-derived fluids (Harry & Green, 1999; McDonough & Sun, 1995; Münker et al., 2004; Magfira et al., 2026). Petrographic features, such as porphyritic textures, zoning, sieve textures, and reaction rims, may further indicate multi-stage cooling, magma recharge, and disequilibrium crystallization (Koyaguchi & Kaneko, 1999; Stewart & Pearce, 2004; Streck, 2008; Jerram et al., 2018).

Although Mount Kaba has been investigated from volcanological and geochemical perspectives, the processes controlling magma evolution remain insufficiently constrained. Existing studies have described the regional setting, volcanic products, and preliminary geochemical characteristics of the area (Wijaya & Setijadji, 2022; Marfian et al., 2023; Wijaya & Mentari, 2025; Wijaya et al., 2025). However, the relationship between petrographic textures, magma affinity, trace element variation, and petrogenetic processes has not been comprehensively evaluated. In particular, it remains unclear whether the observed compositional variability reflects fractional crystallization, magma mixing, source heterogeneity, or crustal-level differentiation.

This study aims to investigate the magma evolution and petrogenesis of volcanic rocks from Mount Kaba using integrated petrographic and whole-rock geochemical data. The analysis focuses on rock classification, magma affinity, major and trace element variation, rare earth element (REE) distribution, and magma source characteristics. The novelty of this study lies in distinguishing geochemical magma groups within the Mount Kaba volcanic system and linking them to petrogenetic processes and magma plumbing complexity. The scope of this study is limited to volcanic rocks collected from the northern sector of Mount Kaba, particularly around Sumber Urip Village, Selupu Rejang District, Bengkulu Province.

2. METHOD

2.1. Materials

This study used 15 representative volcanic rock samples collected from the northern sector of Mount Kaba, particularly around Sumber Urip Village, Selupu Rejang District, Rejang Lebong Regency, Bengkulu Province. The samples comprised lava, pyroclastic breccia, and tuff selected based on lithological variation, spatial distribution, and freshness. Petrographic analysis was conducted using standard thin sections, whereas whole-rock geochemical analysis was performed on powdered rock samples. Major elements were analyzed by ICP-OES, whereas trace elements and rare earth elements (REE) were determined by ICP-MS using ALS analytical package ME-MS81D at ALS Geochemistry Laboratory, Canada (Rollinson, 1993; Jochum et al., 2016).

2.2. Sample Preparation

Fresh rock samples (approximately 1–2 kg) were collected from outcrops after removing weathered surfaces. The samples were cleaned, labeled, dried, crushed, and pulverized to less than 75 μm to obtain homogeneous powders for geochemical analysis. Representative samples were also prepared as thin sections for petrographic observation. Approximately 2 g of powdered material from each sample was digested using a four-acid digestion method consisting of HF–HNO_3–$HClO_4$–HCl under controlled heating conditions to ensure complete dissolution of silicate minerals (Arslan & Lowers, 2024).

2.3. Experimental Set-up

Petrographic observations were conducted under plane-polarized light (PPL) and cross-polarized light (XPL) to identify mineral assemblages, textures, and disequilibrium features, such as zoning, sieve textures, and reaction rims (Streck, 2008; Jerram et al., 2018). Whole-rock geochemical analysis was conducted using ICP-OES for major elements and ICP-MS for trace elements and REE. Loss on ignition (LOI) was determined by heating approximately 1 g of powdered sample at 1000 °C for 1 h, and the percentage weight loss was calculated to evaluate volatile content and alteration intensity (Mathieu, 2018). The LOI value was calculated using Equation (1):

$$LOI\ (\%) = \frac{W_1 - W_2}{W_1} \times 100 \qquad (1)$$

where W_1 and W_2 are the initial and final sample weights, respectively, before and after ignition.

Geochemical data were normalized to 100 wt% on a volatile-free basis following igneous rock classification procedures (Le Maitre et al., 2005). Rock classification and magma affinity were evaluated using the total alkali-silica (TAS) diagram (Bas et al., 1986) and K_2O–SiO_2 diagram (Ewart, 1982). Magma evolution and source characteristics were interpreted using Harker variation diagrams (Harker, 1909), primitive mantle-normalized spider diagrams, and chondrite-normalized rare earth element (REE) diagrams (McDonough & Sun, 1995).

2.4. Parameters

The analyzed parameters include petrographic characteristics, major elements, trace elements, and REE compositions. Petrographic parameters included mineral assemblage, crystal habit, grain size, groundmass texture, vesicularity, and disequilibrium textures. Major elements included SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, MnO, P_2O_5, Cr_2O_3, SrO, and BaO. Trace elements included Ba, Rb, Cs, Hf, Nb, Ta, Th, U, Zr, and other selected elements, whereas REE included La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, and Lu. Elemental ratios, such as Nb/Yb, Ba/La, Sr/Y, La/Sm, Th/Yb, and La/Yb, were used to support the interpretation of magma source, differentiation, and crustal influence (Jamali, 2017).

2.5. Statistical Analysis

Geochemical data were processed using Microsoft Excel and visualized using the WinRock software (Janoušek et al., 2006). A descriptive statistical evaluation was applied to determine the compositional ranges, elemental trends, and geochemical clustering between the sample groups. Harker diagrams were used to assess magma differentiation trends, whereas normalized spider and rare earth element (REE) diagrams were used to evaluate enrichment and depletion patterns. Analytical quality was controlled using certified reference materials, blanks, and duplicate analyses following standard QA/QC procedures for geochemical datasets (Balaram & Satyanarayanan, 2022).

3. RESULTS AND DISCUSSION

3.1. Petrological and Mineralogical Characteristics of Rocks

Geochemical analysis of 15 representative volcanic rock samples from Mount Kaba indicated relatively low loss-on-ignition (LOI) values ranging from 0.11 to 2.36 wt%, suggesting that the samples are generally fresh and minimally affected by secondary alteration processes. Major element normalization to volatile-free compositions shows that the rocks range from basaltic to andesitic compositions, consistent with petrographic observations and field classifications. These compositional variations indicate the presence of magma evolution processes within the Mount Kaba volcanic system.

Petrographic observations reveal that the rocks are dominated by hypocrystalline textures with porphyritic and inequigranular grain distributions. The mineral assemblages mainly consist of plagioclase, pyroxene, olivine, volcanic glass, and minor hornblende. Samples STA01 and STA04 are classified as vesicular basalt with abundant volcanic glass and vesicle structures, whereas STA13, STA17, STA22, STA23, STA27, and STA29 are classified as andesite, characterized by subophytic, glomeroporphyritic, poikilitic, and intersertal textures. Variations in mineral assemblages are associated with increasing SiO_2 contents, where olivine abundance decreases and pyroxene becomes more dominant in evolved magma compositions.

The petrographic textures observed in the thin sections provide evidence for complex magma evolution processes. Porphyritic textures indicate two-stage cooling histories involving slow crystallization within magma chambers, followed by rapid cooling during magma ascent

(Koyaguchi & Kaneko, 1999). Zoning textures in plagioclase suggest changes in magma composition during crystallization, whereas sieve textures indicate disequilibrium conditions associated with magma recharge or magma mixing processes (Stewart & Pearce, 2004; Streck, 2008). Reaction rim textures further indicate chemical disequilibrium between early-formed minerals and surrounding melts. Collectively, these petrographic features support the interpretation that magmatism at Mount Kaba involved dynamic magma chamber processes rather than simple closed-system crystallization.

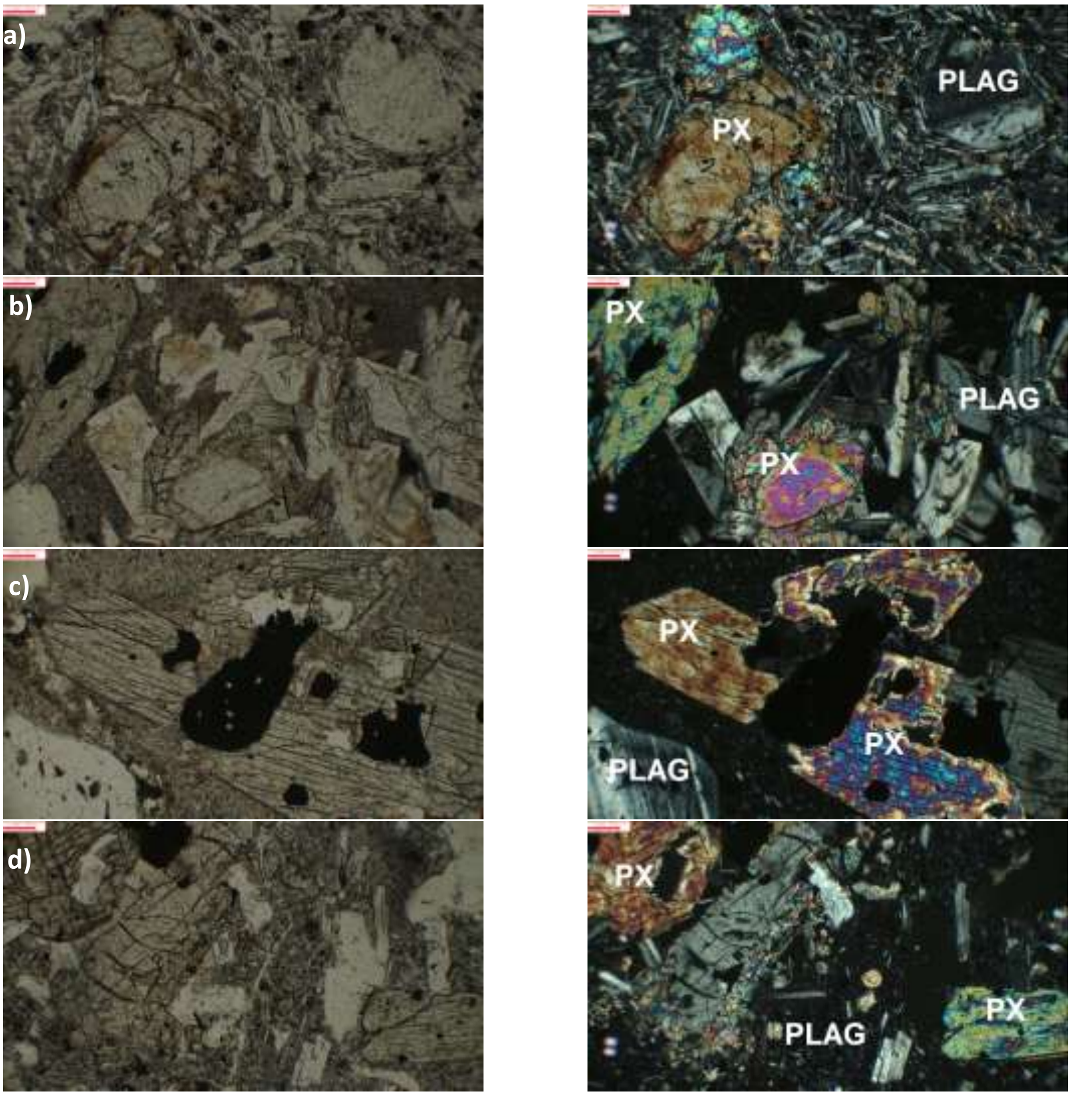

Figure 1. Textures Observed from Thin Sections : Sample STA 07, a) porphyritic & trachytic; b) Sample STA 13, subophytic & zoning; c) Sample STA 17, sieve; d) Sample STA 22, intersertal, reaction rim.

The observed petrographic features are comparable to the textures reported from other subduction-related volcanic systems, where magma differentiation, recharge, and crystallization disequilibrium commonly occur (Jerram et al., 2018; Parat et al., 2014). The coexistence of vesicular basalt and more evolved andesite suggests progressive magma differentiation from mafic to intermediate compositions. In addition, the occurrence of hornblende in higher-SiO_2 samples indicates increasing volatile content and hydrous magmatic conditions during magma evolution. These results support the interpretation that fractional crystallization played an important role in controlling magma evolution beneath Mount Kaba.

3.2. Geochemical Classification and Magma Affinity

The geochemical classification of volcanic rocks from Mount Kaba was evaluated using the total alkali silica (TAS) diagram and K_2O versus SiO_2 magma affinity diagram. Based on the TAS classification, the analyzed rocks range from basalt, basaltic-andesite, trachyandesite, basanite/tephrite, andesite, to dacite compositions with SiO_2 contents ranging from 44.41 to 63.41 wt%. STA04 and STA05 samples represented the most mafic compositions, whereas STA13, STA17, STA20, STA22, STA23, STA27, and STA29 samples represented more evolved andesitic to dacitic compositions.

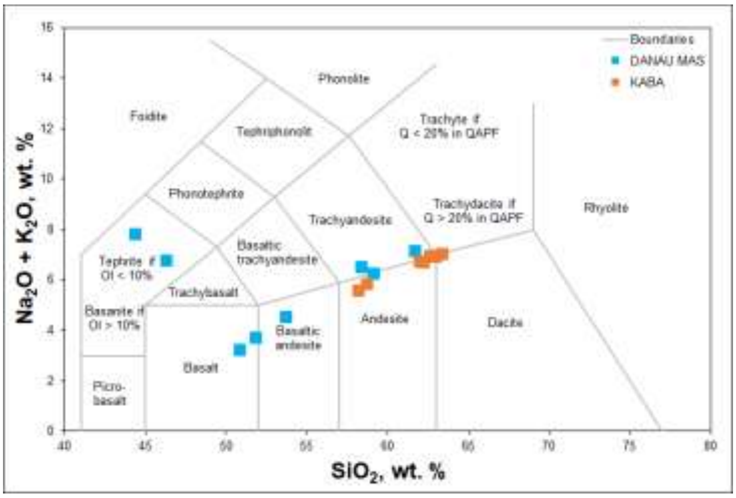

Figure 2. Geochemical plot of rocks in the study area on the TAS diagram according to based on sample group (Bas et al., 1986).

The K_2O versus SiO_2 diagram indicates that the volcanic rocks have alkaline, calc-alkaline, and high-K calc-alkaline magma affinities. Based on geochemical distribution patterns, the samples can be divided into two groups: the Danau Mas Group and the Kaba Group. The Kaba Group forms a relatively coherent high-K calc-alkaline cluster, whereas the Danau Mas Group exhibits wider compositional variability, ranging from calc-alkaline to alkaline affinities. This separation suggests the presence of multiple magma evolution trends within the Mount Kaba volcanic system.

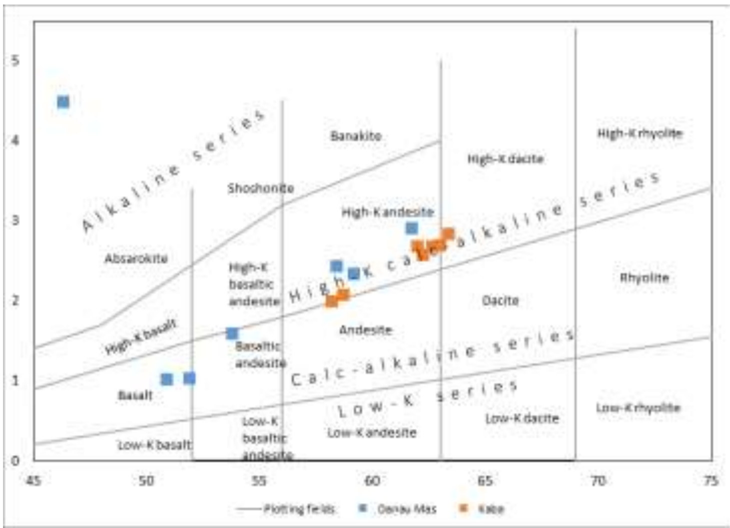

Figure 3. Distribution of magma types in the research area based on the K2O vs SiO2 rock geochemical diagram plot (Ewart, 1982).

The coexistence of different magma affinities within the same volcanic system may indicate variable magma sources, different degrees of partial melting, and separate differentiation pathways (Perugini & Poli, 2012). Similar magma diversity has been documented in other arc volcanic systems influenced by subduction-related magmatism and complex plumbing systems (Cashman et al., 2017). The relatively restricted compositional range of the Kaba Group suggests a more evolved and chemically coherent magma series, whereas the Danau Mas Group likely reflects a more heterogeneous magma system. These findings indicate that the magmatism of Mount Kaba was controlled by multiple interconnected magmatic processes operating beneath the volcano.

3.3. Major and Trace Element Variation

Major element variation diagrams plotted against SiO_2 display systematic geochemical trends associated with magma differentiation. Fe_2O_3, MgO, CaO, TiO_2, MnO, and Al_2O_3 generally decrease with increasing SiO_2, whereas Na_2O and K_2O exhibit positive trends. These patterns indicate progressive depletion of compatible elements and enrichment of alkali elements during magma evolution. However, several diagrams also display moderate scatter, suggesting that magma differentiation may not have occurred under completely closed-system conditions.

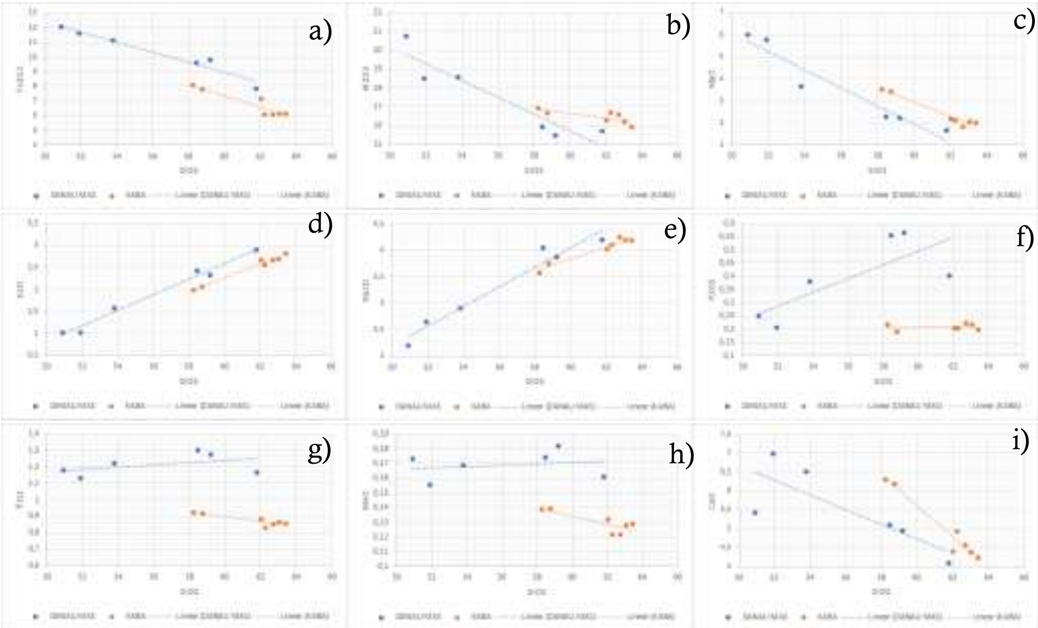

Figure 4. Harker diagrams showing major-element distributions by magma type: : a) Fe2O3, b) Al2O3, c) MgO, d) K2O, (e) Na2O, f) P2O5, g) TiO2, h) MnO, i) CaO

Trace element variation diagrams also show systematic relationships with increasing SiO_2. Large ion lithophile elements (LILE), such as Cs, K, and Rb, generally increase with magma evolution, whereas several high field strength elements (HFSE) display more variable trends. Elemental ratios, including Ba/La and Sr/Y, generally decrease with increasing SiO_2, whereas La/Sm and Th/Yb ratios increase in more evolved samples. In addition, the Nb/Yb diagram shows different trends between the Danau Mas and Kaba groups, suggesting differences in magma evolution history or source characteristics.

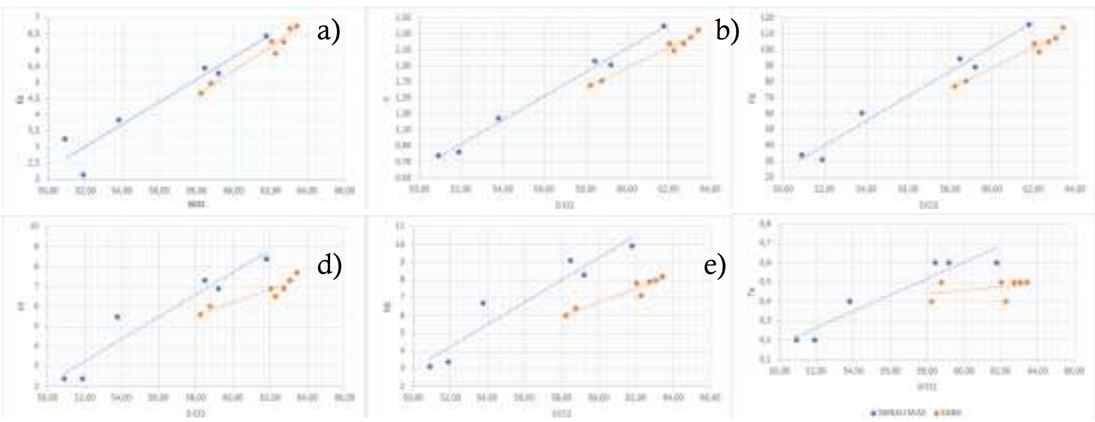

Figure 5. Harker diagrams showing trace-element distributions by magma type: a) Cs, b) K, c) Rb, d) Hf, e) Nb, and f) Ta.

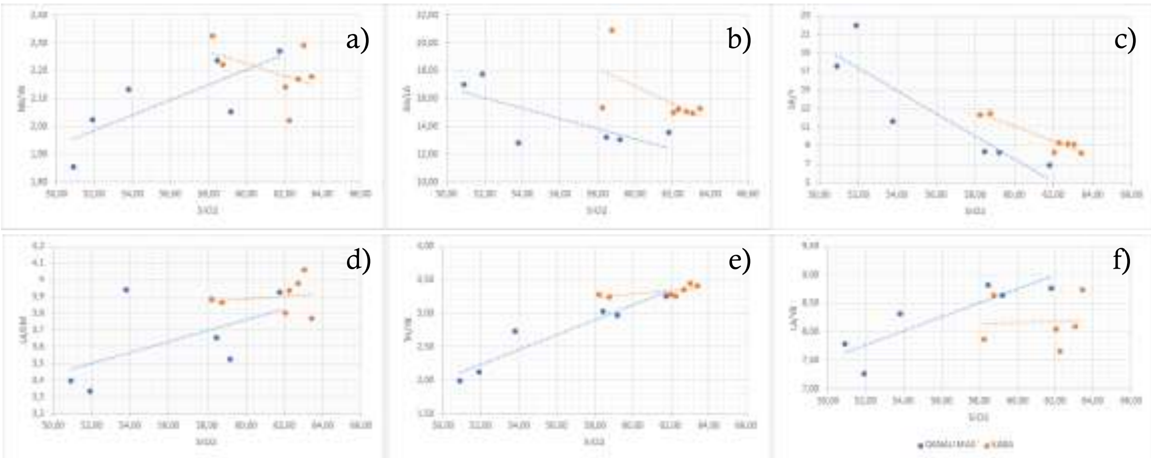

Figure 6. Plot diagram of SiO2 against, a) Nb/Yb, b) Ba/La, c) Sr/Y, d) La/Sm, e) Th/Yb, and f) La/Yb.

The observed geochemical trends are generally consistent with fractional crystallization processes involving the removal of olivine, pyroxene, and plagioclase from the melt (Kumar, 2014). The decrease in MgO, Fe_2O_3, and CaO with increasing SiO_2 reflects progressive crystallization of mafic minerals, whereas enrichment of incompatible elements in evolved rocks reflects residual melt enrichment during differentiation. Nevertheless, the scattered distributions observed in some diagrams may also indicate contributions from magma mixing, source heterogeneity, or assimilation–fractional crystallization (AFC) processes. Therefore, magma evolution beneath Mount Kaba was likely influenced by multiple magmatic processes rather than a single differentiation mechanism.

3.4. Trace Element and REE Characteristics

Primitive mantle-normalized spider diagrams show that the volcanic rocks of Mount Kaba are enriched in large ion lithophile elements (LILE) relative to high field strength elements (HFSE). The rocks display negative anomalies in Nb and Ta, together with enrichment in Rb, Ba, and Th. Such geochemical signatures are characteristic of subduction-related volcanic arcs, where slab-derived fluids enrich the mantle wedge in fluid-mobile elements (Harry & Green, 1999; Münker et al., 2004).

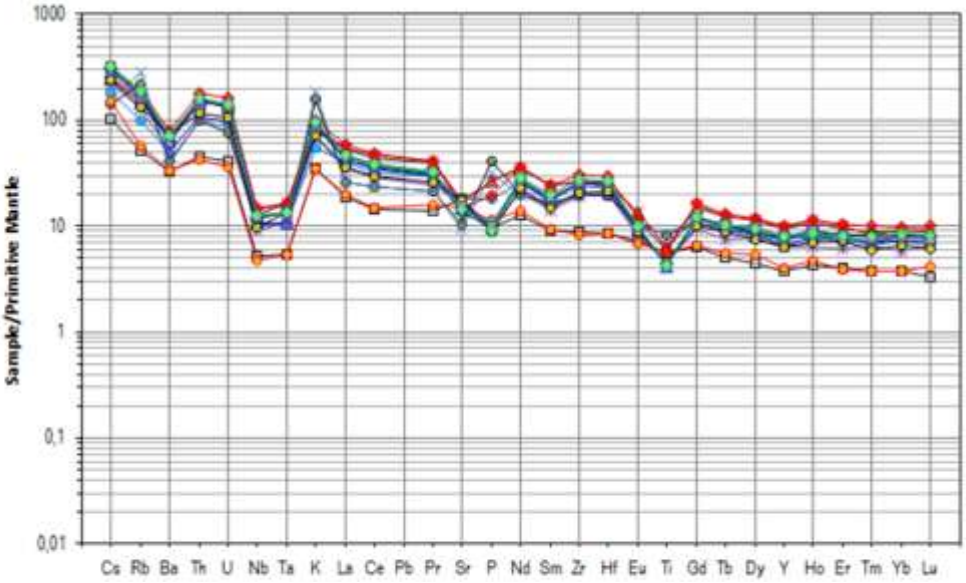

Figure 7. Spider diagram of trace elements in the study area normalized to the primitive mantle (McDonough & Sun, 1995)

Rare earth element (REE) patterns normalized to chondrites generally show enrichment of light rare earth elements (LREE) relative to heavy rare earth elements (HREE). More evolved rocks from the Kaba Group exhibit higher overall REE abundances than those from the Danau Mas Group, indicating progressive magma differentiation and enrichment of incompatible elements. Despite differences in abundance levels, both groups display relatively similar REE distribution patterns.

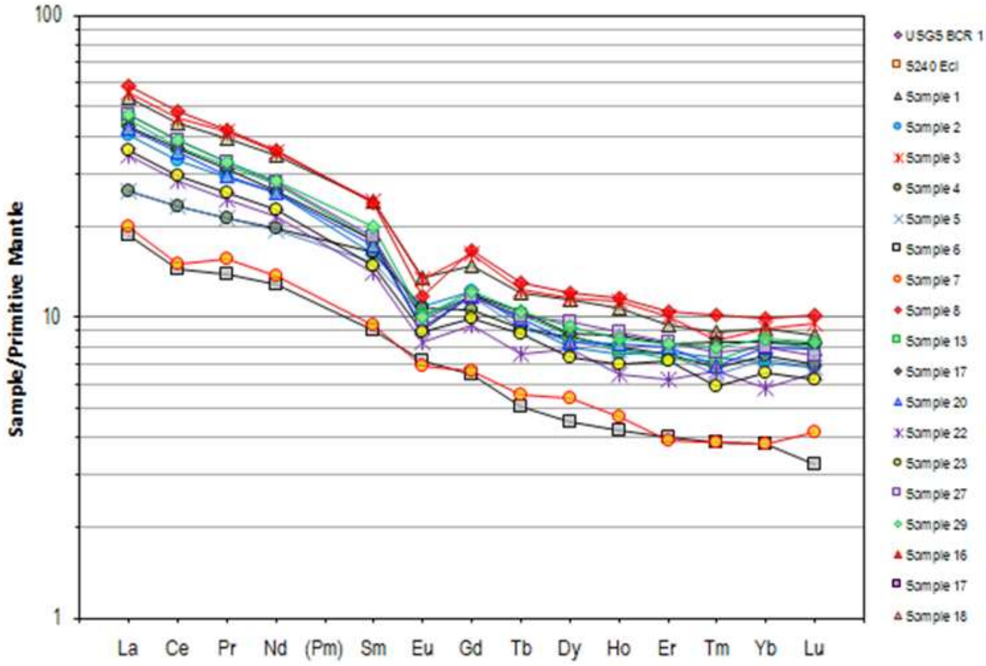

Figure 9. REE spider diagram of the research area normalized to chondrite based on sample number (McDonough & Sun, 1995).

The enrichment of LILE and LREE, together with depletion of HFSE, strongly supports the interpretation that Mount Kaba magmas originated from a mantle source modified by subduction-related fluids. Similar geochemical characteristics are commonly observed in volcanic rocks generated along convergent plate margins (Pin & Paquette, 1997; Kirchenbaur et al., 2022). However, the slightly different enrichment levels between the Danau Mas and Kaba groups may indicate varying degrees of magma differentiation or localized crustal-level magmatic processes. Coherent REE patterns suggest that both magma groups were generated within a broadly similar tectonic setting, although subsequent magma evolution processes likely produced their compositional differences.

3.5. Magma Evolution and Petrogenesis

Integrated petrographic and geochemical evidence indicates that magma evolution beneath Mount Kaba was primarily controlled by magma differentiation processes. The systematic decrease in MgO, Fe_2O_3, and CaO with increasing SiO_2, together with enrichment of incompatible trace elements and REE, is consistent with fractional crystallization involving the early removal of olivine, pyroxene, and plagioclase. Petrographic features, such as zoning, sieve textures, and reaction rims, further indicate that magma evolution occurred under dynamic and disequilibrium conditions.

The existence of two geochemically distinct magma groups suggests that the Mount Kaba volcanic system involves more than one magma evolution pathway. The Kaba Group is characterized by relatively evolved high-K calc-alkaline compositions and coherent geochemical trends, whereas the Danau Mas Group displays broader compositional variability, ranging from alkaline to calc-alkaline affinities. These differences may reflect varying magma storage conditions, differentiation histories or degrees of crustal interaction (Asaah et al., 2015; Bohrson & Spera, 2003).

Overall, the petrogenesis of Mount Kaba volcanic rocks is interpreted to involve mantle melting within a subduction-modified mantle wedge, followed by crustal-level magma differentiation. Fractional crystallization appears to be the dominant process controlling magma evolution, although contributions from magma mixing, source heterogeneity, and assimilation processes cannot be excluded. Therefore, the integrated petrographic and geochemical approach applied in this study provides important constraints on the complexity of magma plumbing and volcanic evolution beneath Mount Kaba.

4. CONCLUSIONS

The volcanic rocks of Mount Kaba in the northern sector of the study area are composed mainly of basalt to andesite, with minor more evolved compositions, and display alkaline, calc-alkaline, and high-K calc-alkaline affinities. Integrated petrographic and whole-rock geochemical data indicate that the volcanic products can be grouped into two magma series: the Danau Mas Group and the Kaba Group. The Kaba Group is characterized by relatively coherent high-K calc-alkaline compositions, whereas the Danau Mas Group shows broader compositional variability from alkaline to calc-alkaline affinities. Petrographic textures, including porphyritic textures, zoning, sieve textures, and reaction rims, indicate dynamic magma chamber processes involving multistage crystallization and disequilibrium conditions. Major and trace element variation diagrams show decreasing MgO, Fe_2O_3, CaO, and compatible elements with increasing SiO_2, accompanied by enrichment of alkali and incompatible elements, suggesting that fractional crystallization was a major process controlling magma evolution. Primitive mantle- and chondrite-normalized patterns show LILE and LREE enrichment together with HFSE depletion, indicating derivation from a mantle source modified by subduction-related fluids. Overall, the petrogenesis of Mount Kaba volcanic rocks reflects mantle wedge melting in a subduction setting, followed by crustal-level magma differentiation. However, whole-rock data alone cannot fully distinguish the relative roles of magma mixing, source heterogeneity, and assimilation processes. Future studies using mineral chemistry and isotopic data are therefore required to refine the magma evolution model.

5. REFERENCES

Arslan, Z., & Lowers, H. (2024). Trace Silicon Determination in Biological Samples by Inductively Coupled Plasma Mass Spectrometry (ICP-MS): Insight into the Volatility of Silicon Species in Hydrofluoric Acid Digests for Optimal Sample Preparation and Introduction to ICP-MS. *Minerals, 14*(3), 299. https://doi.org/10.3390/min14030299

Asaah, A. N., Yokoyama, T., Aka, F. T., Usui, T., Wirmvem, M. J., Tchamabe, B. C., Ohba, T., Tanyileke, G., & Hell, J. V. (2015). A comparative review of petrogenetic processes beneath the Cameroon Volcanic Line: Geochemical constraints. *Geoscience Frontiers, 6*(4), 557–570. https://doi.org/10.1016/j.gsf.2014.04.012

Balaram, V., & Satyanarayanan, M. (2022). Data Quality in Geochemical Elemental and Isotopic Analysis. *Minerals, 12*(8), 999. https://doi.org/10.3390/min12080999

Bohrson, W. A., & Spera, F. J. (2003). Energy-constrained open-system magmatic processes IV: Geochemical, thermal and mass consequences of energy-constrained recharge, assimilation and fractional crystallization (EC-RAFC). *Geochemistry, Geophysics, Geosystems, 4*, 8002. https://doi.org/10.1029/2002GC000316

Cashman, K. V., Sparks, R. S., & Blundy, J. D. (2017). Vertically extensive and unstable magmatic systems: A unified view of igneous processes. *Science (New York, N.Y.), 355*(6331), eaag3055. https://doi.org/10.1126/science.aag3055.

Ducea, M. N., Paterson, S. R., & DeCelles, P. G. (2015). High-volume magmatic events in subduction systems. *Elements, 11*(2), 99-104. https://doi.org/10.2113/gselements.11.2.99

Ewart, A. (1982). The Mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks; with special reference to the andesitic-basaltic compositional range. *Andesites: orogenic andesites and related rocks*, 26-87.

Harker, A. (1909). The natural history of igneous rocks. Methuen & Company.

Harry, D. L., & Green, N. L. (1999). Slab dehydration and basalt petrogenesis in subduction systems involving very young oceanic lithosphere. *Chemical Geology, 160*(4), 309-333. https://doi.org/10.1016/S0009-2541(99)00105-9.

Heryanto, R., & Suyoko, S. (2007). Karakteristik batubara di Cekungan Bengkulu. Indonesian *Journal on Geoscience, 2*(4), 247-259. https://dx.doi.org/10.17014/ijog.vol2no4.20075.

Jamali, H. (2017). The behavior of rare-earth elements, zirconium and hafnium during magma evolution and their application in determining mineralized magmatic suites in subduction zones: constraints from the Cenozoic belts of Iran. *Ore Geology Reviews*, 81, 270-279. https://doi.org/10.1016/j.oregeorev.2016.10.006

Jerram, D. A., Dobson, K. J., Morgan, D. J., & Pankhurst, M. P. (2018). The petrogenesis of magmatic systems: Using igneous textures to understand magmatic processes. In S. Burchardt (Ed.), Volcanic and igneous plumbing systems: *Understanding magma transport, storage, and evolution in the Earth's crust* (1st ed., pp. 191–229). Elsevier. https://doi.org/10.1016/B978-0-12-809749-6.00008-X

Jochum, K. P., Weis, U., Schwager, B., Stoll, B., Wilson, S. A., Haug, G. H., Andreae, M. O., & Enzweiler, J. (2016). Reference values following ISO guidelines for frequently requested rock reference materials. *Geostandards and Geoanalytical Research, 40*(3), 333–350. https://doi.org/10.1111/j.1751-908X.2015.00392.x

Kirchenbaur, M., Schuth, S., Barth, A.R. et al. Sub-arc mantle enrichment in the Sunda rear-arc inferred from HFSE systematics in high-K lavas from Java. *Contrib Mineral Petrol 177*, 8 (2022). https://doi.org/10.1007/s00410-021-01871-9

Koyaguchi, T., & Kaneko, K. (1999). A two-stage thermal evolution model of magmas in continental crust. Journal of Petrology, 40(2), 241–254. https://doi.org/10.1093/petroj/40.2.241

Kumar, S. (2014). Magmatic processes: Review of some concepts and models. In S. Kumar & R. Singh (Eds.), *Modelling of magmatic and allied processes* (pp. 1–22). Springer. https://doi.org/10.1007/978-3-319-06471-0_1

Kusumadinata, K., Hadian, R., Hamidi, S., & Reksowirogo, L. D. (1979). Data dasar gunungapi Indonesia. Direktorat Vulkanologi, Bandung, 820.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A. and Zanettin, B. (1986) A Chemical Classification of Volcanic Rocks Based on the Total Alkali-Silica Diagram. *Journal of Petrology*, 27, 745-750. https://doi.org/10.1093/petrology/27.3.745

Le Maitre, R. W., Streckeisen, A., Zanettin, B., Le Bas, M. J., Bonin, B., & Bateman, P. (Eds.). (2005). Igneous rocks: a classification and glossary of terms: recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks. Cambridge University Press.

Magfira, S. W., Asrafil, A., & Puspita, R. (2026). Geochemical characteristics of basalt in the Northern Taopa Area, Parigi Moutong Regency, Central Sulawesi. *Jambura Geoscience Review, 8*(1), 108–119. https://doi.org/10.37905/jgeosrev.v8i1.34364

Marfian, F., Permana, A. P., & Akase, N. (2023). Study of petrogenesis andesite rock in Bualemo Region, North Gorontalo Regency based on XRF geochemistry analysis. *Jambura Geoscience Review, 5*(1), 63–70. https://doi.org/10.34312/jgeosrev.v5i1.16941

Mathieu, L. (2018). Quantifying hydrothermal alteration: A review of methods. Geosciences, 8(7), 245.

McDonough, W. F., & Sun, S. S. (1995). The composition of the Earth. *Chemical Geology, 120*(3–4), 223–253. https://doi.org/10.1016/0009-2541(94)00140-4

Münker, C., Wörner, G., Yogodzinski, G., & Churikova, T. (2004). Behaviour of high field strength elements in subduction zones: Constraints from Kamchatka–Aleutian arc lavas. *Earth and Planetary Science Letters, 224*(3–4), 275–293. https://doi.org/10.1016/j.epsl.2004.05.030

Parat, F., Streck, M. J., Holtz, F., & Almeev, R. (2014). Experimental study into the petrogenesis of crystal-rich basaltic to andesitic magmas at Arenal volcano. *Contributions to Mineralogy and Petrology, 168*, 1040. https://doi.org/10.1007/s00410-014-1040-4

Perugini, D., & Poli, G. (2012). The mixing of magmas in plutonic and volcanic environments: Analogies and differences. *Lithos, 153*, 261–277. https://doi.org/10.1016/j.lithos.2012.02.002

Pin, C., & Paquette, J. L. (1997). A mantle-derived bimodal suite in the Hercynian Belt: Nd isotope and trace element evidence for a subduction-related rift origin of the Late Devonian Brévenne metavolcanics, Massif Central (France). *Contributions to Mineralogy and Petrology, 129*(2), 222–238. https://doi.org/10.1007/s004100050334

Rollinson, H. R. (1993). Using geochemical data: evaluation, presentation, interpretation. Routledge.

Stewart, M. L., & Pearce, T. H. (2004). Sieve-textured plagioclase in dacitic magma: Interference imaging results. *American Mineralogist, 89*(2–3), 348–351. https://doi.org/10.2138/am-2004-2-313

Streck, M. J. (2008). Mineral textures and zoning as evidence for open system processes. *Reviews in Mineralogy and Geochemistry, 69*(1), 595–622. https://doi.org/10.2138/rmg.2008.69.15

Sugianto, N., Nukman, M., & Suryanto, W. (2023). Characteristics of active volcanoes in Sumatra, Indonesia: From perspective seismicity, magma chemical composition and eruption history. *E3S Web of Conferences, 468*, 09002. https://doi.org/10.1051/e3sconf/202346809002

Westerveld, J. (1952). Quaternaky volcanism on Sumatra. *Geological Society of America Bulletin, 63*(6), 561–594. https://doi.org/10.1130/0016-7606(1952)63[561:QVOS]2.0.CO;2

Wijaya, M. E. J., & Mentari, S. G. (2025). Karakteristik geokimia batuan unsur jejak dan unsur tanah jarang Gunung Api Kaba untuk interpretasi tatanan tektonik berdasarkan analisis ICP-MS. *Jurnal Penelitian Inovatif, 5*(3). https://doi.org/10.54082/jupin.1674

Wijaya, M. E. J., & Setijadji, L. D. (2022). A preliminary volcanological study of North Eastern Kaba Volcano, Bengkulu Province, Indonesia. *IOP Conference Series: Earth and Environmental Science, 1071*(1), 012018. https://doi.org/10.1088/1755-1315/1071/1/012018

Wijaya, M. E. J., Mentari, S. G., Pratama, R. R., & Sitohang, V. R. (2025). Petrology and Geochemistry of Volcanic Rocks of Kaba Volcano, Bengkulu. *Journal of Earth and Marine Technology (JEMT), 6*(1), 23-38. https://doi.org/10.31284/j.jemt.2025.v6i1.8571

Winter, J. D. (2014). Principles of igneous and metamorphic petrology (Vol. 2). Harlow, UK: Pearson education.