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The First Occurrence of Mafic Alkaline Rock (Lamproite) in The Mamuju District, West Sulawesi, Indonesia: Implications for The REE and Critical Elements Enrichment

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Abstract - Mafic alkaline igneous rocks, along with their weathering products, are a significant source of Rare Earth Elements (REEs) and critical elements. One of the mafic alkaline rock-related REE and critical element sources is lamproite. Various methods were utilized in this study, including optical microscopy, X-ray diffraction (XRD), and scanning electron microscopy with Energy Dispersive Spectroscopy (SEM-EDS), as well as whole-rock geochemical analyses using X-ray fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry/Optical Emission Spectroscopy (ICP-MS/OES). Based on mineralogical observations, it has been confirmed that the dykes from West Sulawesi are orendite-type lamproite rocks. Sanidine, phlogopite, diopside, and aegirine are the main minerals found in these rocks, including apatite and oxide minerals as accessory minerals. The dykes' whole-rock geochemistry indicates an ultrapotassic nature with a K_2O/Na_2O ratio > 3. Lamproite dykes display an increase in the large ion lithophile elements (LILEs) and a decrease in Ti, Sr, and P, with minimal Eu anomalies. They also show an increase in the light rare earth elements (LREEs), ranging from 901 to 1558 ppm, and a significantly higher content of Zr (968-3083 ppm), Th (152-408 ppm), and U (30-37 ppm). The dykes are related to an orogenic lamproite that formed during post-collisional tectonic continental extension. It contained a significant amount of REE-Zr-Th-bearing minerals, such as apatite (La-Ce-Nd), zirconosilicate (Zr-Ce), and Ba-perovskite (Zr-Th-Ce-Tb). The enrichment of light rare earth elements (LREEs), thorium (Th), and zirconium (Zr) in these dykes can be attributed to both primary and secondary enrichment processes, such as metasomatism and hydrothermal alteration. This phenomenon is evidenced by mineral replacement textures or pseudomorphs, as well as a skeletal texture resulting from rapid cooling in a hydrothermal fluid environment. Therefore, understanding the formation of mafic alkaline rocks, especially lamproite, and their role in enriching REEs and critical elements is a crucial future scientific goal.

Keywords: Lamproite, metasomatism, hydrothermal alteration, REE-critical element enrichment, West Sulawesi

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Introduction

Mafic alkaline rocks are a group of mafic-ultramafic igneous rocks with high alkali content (Na_2O and K_2O). The alkali category consists of various rock types with a broad spectrum ranging from the brightest to darkest and from ultramafic to mafic rocks. The distribution of alkaline mafic rocks, especially lamproite rocks, which are rare and account for less than 1% of exposed igneous rocks on Earth's surface. All mafic alkaline rocks can be considered part of either the sodic or potassic series. Generally, potassic rocks are defined as those containing a higher weight percentage of K_2O than Na_2O, while sodic rocks have ($Na_2O > K_2O$). The potassic series is further divided into potassic and ultrapotassic. Rocks are considered potassic when they have a K_2O/Na_2O ratio of 1-3, including common rocks such as granite, trachyte, latite, leucite tephrites, and leucite basanite. They are classified as 'ultrapotassic' when $K_2O/Na_2O > 3$ (Foley et al., 1987). According to Foley et al. (1987), ultrapotassic rocks have $K_2O > 3$ wt.%, $K_2O/Na_2O > 2$, and $MgO > 3$ wt.%. Ultrapotassic rocks, commonly referred to as 'highly potassic', are generally used to describe rocks with high K_2O content (>3 wt.%), $K_2O/Na_2O > 2$ ratio, $MgO > 3$ wt.%, and high concentrations of Ni and Cr. Based on major geochemical element content, there are three groups of ultrapotassic rocks (Foley et al., 1987): Group I (Lamproite), characterized by very low Na_2O, CaO, and Al_2O_3 content; high K_2O and TiO_2 content, with a K_2O/Na_2O ratio > 5 and SiO_2 range of 45–55 wt.% (Foley et al., 1987). Lamproite is commonly found in various forms of igneous rocks, mostly in dikes and flows, and can also take the form of diatremes, often associated with petrogenesis aspects with kimberlites, lamprophyres, and alkali basalts. Lamproite generally lacks plagioclase, nepheline, or melilite minerals (Mitchell and Bergman, 1991). Group II (Kamafugites), characterized by high TiO_2 content (almost similar to Group I) but richer in CaO and Na_2O. Additionally, they have SiO_2 and Al_2O_3 content, with $SiO_2 < 45$ wt.%. Mineralogically, kamafugite is identified by olivine phenocrysts in the groundmass consisting of phlogopite, clinopyroxene, leucite, melilite, perovskite, and kalsilite, reflecting very low SiO_2 content. Group III (Orogenic Ultrapotassic Rocks), characterized by low TiO_2 content, high Al_2O_3 and CaO content, and rocks with $SiO_2 < 42$ wt.% (Foley et al., 1987). They also have a characteristic K_2O/Al_2O_3 ratio of < 0.5 (Müller, 1993). Examples of these rock products are found in the Roman region, Italy, with $Al_2O_3 > 12$ wt.% (Boari, 2009).

A significant source of Rare Earth Elements (REEs) and other critical elements is associated with mafic alkaline rocks, including their weathering products. There are several REE deposits in the world that are associated with mafic alkaline rocks like kimberlite (carbonatite), such as Bayan Obo, China; Araxá, Brazil; Karonge, Burundi; Mountain Pass, USA; Nolans Bore, Australia; and Steenkampskraal, South Africa (Weng et al., 2014). Another REE deposit that is related to alkaline complexes and alkaline pegmatites (e.g., Khibina and Lovozero, Russia; Norra Kärr, Sweden; Bokan, USA; Thor Lake, Canada; Kipawa Lake, Canada; Kola Peninsula, Russia) (Weng et al., 2014). Therefore, gaining a deeper understanding of the petrogenesis of mafic alkaline rocks, especially lamproite, in relation to the enrichment of REEs and other critical elements is an essential future scientific objective.

Rare earth elements (REE) have played an important role in global economics. Modern technology has relied heavily on REE. Many products rely on them, including superconductors, high-strength magnets, mobile phones, flat-screen TVs, lasers, and energy-efficient lighting. Furthermore, REE is essential in "green technologies" such as hybrid automobiles, wind turbines, and next-generation rechargeable batteries (Balaram, 2019). The prices of individual REEs have significantly increased along with the demand for REEs in recent years, causing an exploration to escalate and enhancing REE's reputation (Dostal, 2017). Most of the REE used in global markets comes from a few deposits, such as Bayan Obo, South China, which have deposits with grades over 500 ppm of rare earth oxide (Yang et al., 2013). There are 15 rare earth elements (REE/REEs) classified as light REE (LREE; La-Sm) and heavy REE (HREE; Eu–Lu+Y). Rare earths are substitutional elements formed in minerals related to rock-forming minerals along the magmatic evolution and/or in mantle metasomatism. Rare earth element (REE) mineralization can be classified based on the geological process that took place in the formation of rare earth elements and its mineralogy type in each deposit (Weng et al., 2014) (Table 1), including igneous rock process, hydrothermal and sedimentary processes or commonly grouped into regolith (ion-adsorption clay), basinal, metamorphic and magmatic types (Hoatson et al., 2011). Both felsic and mafic alkaline igneous rocks host various rare metals, industrial rocks, and mineral deposits. These rocks' commodities of particular economic importance are rare earth elements (REE) (Weng et al., 2014**;** Dostal, 2017). This paper describes the potential of REE-Zr-Th enrichment associated with mafic alkaline rocks in West Sulawesi, Indonesia, based on petrography and whole-rock geochemistry. Thus, primary ores, such as alkaline rocks, will supply the world REE demand in the future.

The preliminary study of rare earth elements in Mamuju, West Sulawesi, based on spotted regional ground geology and geochemistry data around West Sulawesi was conducted by SRK Consulting (PT. LTJ Global Jaya, 2014, unpublished *report*). This reconnaissance indicated the occurrences of several rare earth element (REE) ion-adsorption clay deposits and Th prospects in the Semboro area, Mamuju district, West Sulawesi. Several areas of Adang are composed mainly of alkaline volcanic rocks up to intermediates, which have high

Table 1. The summary of whole rock geochemistry results of five sample mafic alkaline dykes from the Mamuju district

Element	**SiO_2 (wt. %)**	**TiO_2**	**Al_2O_3**	**Fe_2O_3**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K2O**	**P_2O_5**	**Cr_2O_3**
Min	49.5	1.45	10.7	9.83	0.14	2.90	3.43	1.40	7.86	0.55	0.04
Max	52.4	2.34	14.3	14.52	0.34	6.19	5.01	2.38	8.37	1.10	0.04
Average	51.5	1.78	12.0	11.97	0.20	4.05	4.13	1.87	8.12	0.79	0.04
Element	P (ppm)	Ti	Cr	Cu	Ni	S	Sc	V	Zn	Ag	As
Min	2410	8800	8.00	173	16.0	80.0	9.00	275	138	0.30	5.00
Max	4820	13600	122	217	93.0	1460	22.0	388	234	1.30	44.0
Average	3431	10587	49.3	200	40.8	604	16.2	319	168	0.80	15.4
Element	Ba	Bi	CD	Co	Cs	Ge	In	Mo	Pb	Rb	Re
Min	2190	0.51	0.68	23.0	10.9	0.70	0.09	0.20	148	124	0.00
Max	9380	2.56	1.40	34.0	142	1.80	0.12	2.90	460	470	0.00
Average	5314	1.33	0.96	29.2	55.4	1.14	0.10	0.98	248	284	0.00
Element	Sb	Se	Sr	Te	Tl	Be	Ga	Hf	Li	Nb	Sn
Min	0.60	1.00	369	0.00	1.46	21.0	19.0	26.9	38.0	68.0	16.0
Max	1.20	1.00	1440	0.00	3.53	39.0	30.0	72.2	48.6	238.0	48.0
Average	0.86	1.00	943	0.00	2.76	28.7	23.6	44.8	44.3	135.6	27.2
Element	Ta	**Th**	**U**	W	**Zr**	La	Ce	Pr	Nd	Sm	Eu
Min	3.90	**152**	**30.9**	4.00	**968**	194	413	45.2	164	29.4	5.10
Max	16.20	**408**	**136.5**	10.00	**3083**	388	760	80.1	282	49.3	9.30
Average	8.58	**243**	**60.9**	7.53	**1756**	258	520	57.5	203	35.3	6.56
Element	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	**Y**	**LREE**	HREE
Min	19.6	2.70	12.5	2.10	5.30	0.70	4.20	0.60	**59.7**	**846**	114
Max	35.0	4.90	25.8	4.00	11.10	1.40	8.20	1.20	**124.8**	**1559**	226
Average	24.7	3.32	16.7	2.72	7.00	0.92	5.54	0.78	**78.8**	**1074**	147

levels of radioactivity (Sukadana et al., 2015). Due to the fact that radioactive minerals have never been found in Indonesian basaltic-andesitic rocks, it becomes extremely interesting to research their formation. The latest research was conducted by Godang et al. (2016), which stated that the rare earth elements (REE) ion-adsorption clay prospect is related to mafic alkaline volcanic rocks formed by the tectonic setting of within-plate continental extension as mantle magma which experienced high metasomatism enriched in REE and other critical elements such as Zr (zircon), Th (thorium) and Nb (niobium). This study explores a possibility of primary REE-Zr-Th mineralization in West Sulawesi, Indonesia, by investigating REE and other critical mineral contents of mafic alkaline rocks (lamproite).

Regional geology

The research is located in Simboro Sub-District, Mamuju District, West Sulawesi Province. This location can be reached with regular transportation from Mamuju City in around 45 minutes (Figure 1). Numerous geological researchers, both from governmental institutions/universities and private companies, have done research in this area and also surrounding areas related to the petrogenetic and tectonic setting of this area, including the mineral resources potential (e.g., Hall, 1996; Elburg et al., 2003; Satiyana, 2011; White et al., 2017; Liu et al., 2020). In the formation of Sulawesi, drifted parts of southeastern Sundaland collided with drifted microcontinents of the Australian Plate (Elburg et al., 2003; Satyana, 2011). Four mega-tectonic provinces formed on Sulawesi and adjacent islands during the Oligocene-early Pliocene (Hall, 1996; Elburg et al., 2003). Tectonic processes of Sulawesi spanned the middle Eocene to the early Pliocene, including the separation of western Sulawesi from eastern Borneo by the opening of the Makassar Straits and subduction, accretion, and collision of eastern Sulawesi areas and the Buton-Tukang Besi and Banggai-Sula Islands (Satyana, 2011; White et al., 2017; Liu et al., 2020). There is no doubt that tectonic events in the Neogene period contributed significantly to the current configuration of Sulawesi. The episode is called the Sulawesi Orogeny. Eastern Sulawesi collided with Buton-Tukang Besi and Banggai-Sula microcontinents, triggering the orogeny (Elburg et al., 2003; Satiyana, 2011; White et al., 2017; Liu et al., 2020). The geological framework of the region shows a complex pattern of rotation blocks and strike-slip faulting corresponding with the subduction in Sulawesi's Northern Trough (Silver et al., 1983a; b). There are no clear volcanic activities which are related to subduction, except in the northern arm of Sulawesi. There is evidence

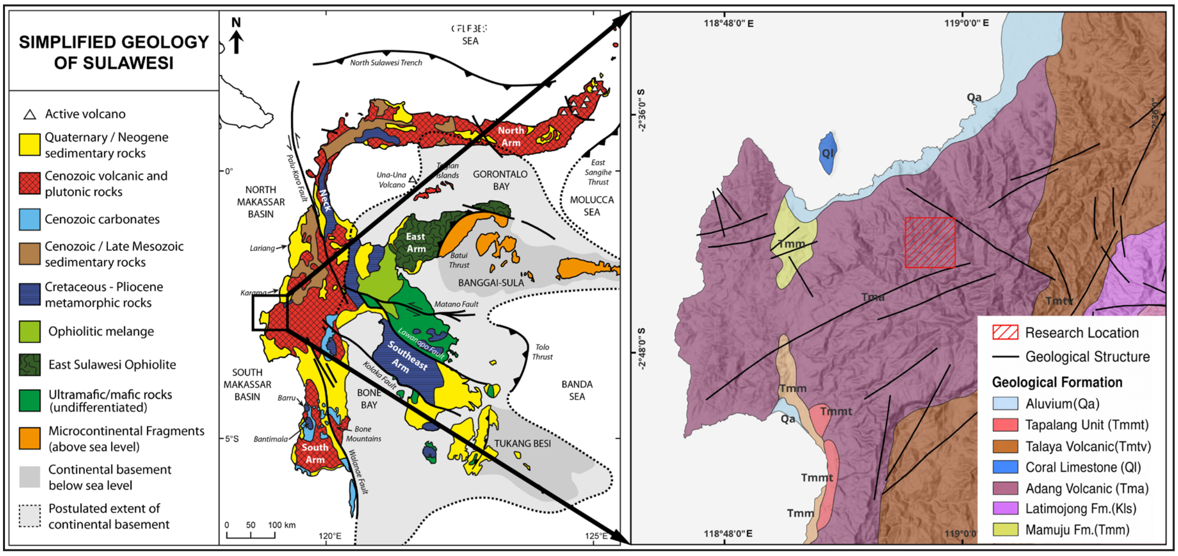


Figure 1. Structural geology of Sulawesi (modified from White et al., 2017) and regional geological map of West Sulawesi (Ratman and Atmaniwata, 1993).

for the occurrence of an oceanic arc in the northern part of the Makassar Strait, on the basis of gravity modelling by Cloke et al. (1999) and seismic profiling (Baillie et al., 1999). West Sulawesi experienced active subduction along the east Sunda land margin with calc-alkaline volcanic activities until the early Miocene (Priadi et al., 1994). In the Late Oligocene until the Early Miocene in Sulawesi, a large collision happened (Milsom, 2000; White et al., 2017), and there is evidence for this collision between a microcontinental block and a subduction zone (Hamilton, 1979; Elburg et al., 2003). The indented part on the west of Makassar Strait is interpreted as a manifestation of an orogenic event that took place in the Early Miocene and the formation of Makassar Strait by tectonic rifting (Satiyana, 2011). The eastern margin formed a basin which is a product of past tectonic events. The geology of the study area regionally refers to the Mamuju Geological Sheet Map, Sulawesi Island (Ratman and Atmaniwata, 1993). During the Cretaceous, a complex granitoid rock was unconformably underlain by undifferentiated volcanic rocks aged Middle Miocene. During the Pliocene, volcanic rocks were unconformably underlain by reef limestone and sedimentary carbonate clastic rocks (Figure 1). The youngest units are coastal mangroves and consolidated sediments and alluvial plains along the active drainage system (Ratman and Atmaniwata, 1993). Makassar Strait Thrust-Mamuju Segment (MSTM) as a channel for hydrothermal fluids in controlling the enrichment of REE mineralization in Mamuju (Ciputra et al., 2025).

METHODS AND MATERIALS

Methods

Petrographic observation includes X-ray diffraction (XRD), Scanning Electron Microscope with Energy Disperse Spectroscopy (SEM-EDS), and whole-rock geochemistry analysis, which were used to accomplish the goals of this study. Petrography analysis of mafic alkaline intrusions was done by microscope polarisation (Nikon ECLIPSE LV100N POL) to determine the name of the rock, textures, rock-forming mineral, and alteration of mineral assemblages. X-ray diffraction was performed using a RIGAKU MultiFlex machine. This analysis was also used to identify rock-forming minerals, alteration phases, and potential REE-bearing minerals. Scanning electron microscopy with Energy Disperse Spectroscopy (SEM-EDS) analysis was used for qualitative mineral identification for polished thin section and polished section samples. This study used this method to clarify the mineral assemblage, including rock-forming minerals, alteration, and ore minerals of mafic alkaline intrusions. An Oxford Instrument JEOL JSM-6610 SEM-EDS machine was used for this analysis. The laboratory analysis was conducted at the economic geology laboratory at Akita University, Japan. The whole-rock geochemistry of five samples of mafic dyke was conducted by ICP-MS and ICP-OES methods at the Intertek Utama Services' laboratory in Jakarta. Analytical method codes selected were 4A/OE, 4A/MS, and 4A/MS 11, allowing for the analysis of all major, trace, and REE elements. QA/QC of whole-rock geochemistry analysis followed the standard operational procedure of the Intertek Utama Services laboratory, which is internationally certified and accredited. The whole-rock geochemistry analysis aims to understand the distribution of the elements related to mafic, including major, trace, and rare earth elements. The analytical results of whole-rock geochemistry are listed in Table 1. In this study, we also used whole-rock geochemistry data of mafic alkaline rocks of the Dharwar Craton complex (source: *https://georoc.eu/*) as a comparison.

RESULT AND ANALYSIS

Field outcrop relationship

The mafic alkaline dykes are situated in Boteng village near the Mamuju district, which is around 15 km east of Mamuju city. Both the rocks are well exposed and intrude the Baropa tuff of the Adang volcanic complex, with strike direction relatively north-south. The average length is about 2-15 m with a varying width of 0.3-2 m. The mafic alkaline rock has a greenish-gray colour and is slightly coarse-grained. The rock also displays slight alteration effects, which make it appear unconsolidated, a feature that is prominently visible on the surface. These characteristics imply that they were possibly subjected to autometasomatism processes and not hydrothermal alteration because there is no significant hydrothermal effect found on that body of alkaline mafic rock (Figure 2).

Mineralographic observation

All of the thin sections of the mafic alkaline dyke represent a holocrystalline, porphyritic, sanidine and phlogopite-rich igneous rock and are brown-coloured due to weathering of their groundmass (Figures 3a, 3b, and **3c**). It consists of abundant sanidine, phlogopite and diopside as phenocrysts and in the groundmass and subordinate amounts of aegirine. Sanidine and pyroxene are idiomorphic to hypidiomorphic granular (euhedral to subhedral), whereas phlogopite is hypidiomorphic to allotriomorphic granular (subhedral to anhedral). Generally, the dyke consists of sanidine (~55%), phlogopite (~18%), aegirine (~17%), diopside (~8%), apatite (~1%) and opaque mineral/iron oxides (1%) (Figure 3a; 3b; 3c).

Sanidine phenocrysts are up to 1 mm and locally form a glomeroporphyritic texture. Small inclusions of anhedral light brown phlogopite flakes, green actinolite needles, or apatite (less common) are locally present in sanidine phenocrysts (Figure 3a; 3b; 3c). Smaller sanidine is commonly present in the groundmass together with fine phlogopite flakes (Figures 3b, 3c), abundant needles of aegirine, less abundant pyroxene prisms and (*weathered*) opaque minerals (Figures 3a, 3b). Phlogopite is light brown in colour and shows

Figure 2. Representative outcrops of mafic alkaline dyke from the Mamuju district (research area) (a, b) and hand specimen samples which show the phlogopite mineral as a phenocryst (c, d).

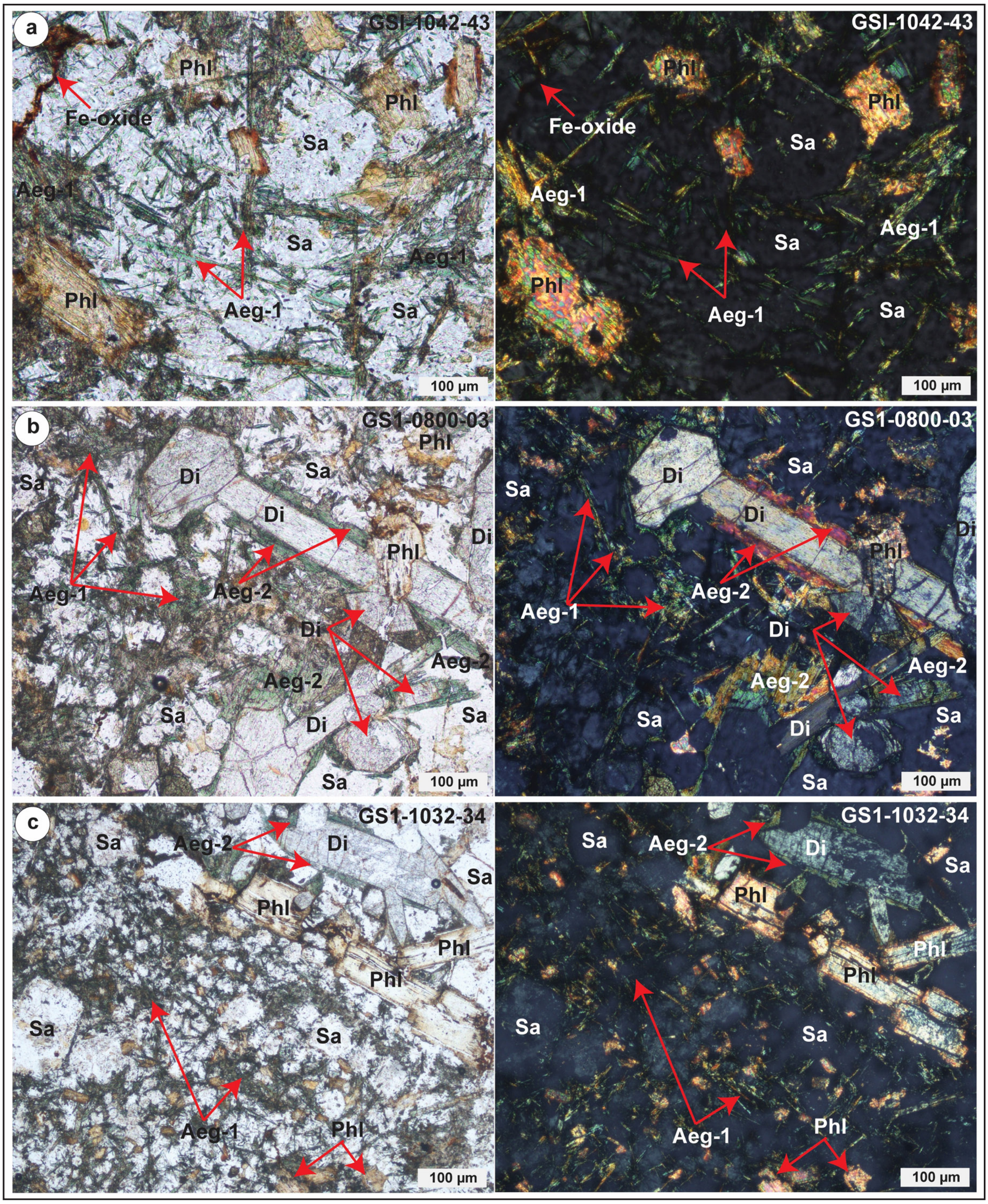


Figure 3. Representative microphotograph of mafic alkaline dyke from Mamuju district (research area): a. sample GSI 1042-43, b. sample GSI 0800-03, and c. sample GSI 1032-3 4. *Note: left=parallel nicol, right=crossed nicol.*

weak pleochroism, suggesting low Ti contents. Composition zonation is marked by changes in colour, from light brown (inner part) to dark brown colour (outer part-crystal margin) (Figures 3a, 3b, 3c), probably indicating a Ti-content increase due to the metasomatism process. It resembles titaniferous mica's characteristics (Mitchell and Bergman, 1991). Alterations to form reddish dark brown oxides are commonly present along cleavages (Figures 3a, 3b, and 3c). Diopside is present as a euhedral phenocryst (up to 1 mm, but not common) and more common as fine prisms in the groundmass (Figures 3b, 3c). It is characterized by a colourless to pale greenish colour (less common) and commonly shows a deep green colour along margins, probably due to a compositional change to aegirine (Figure 3b). A cumulophyric texture of diopside with sanidine, phlogopite and apatite is noted. Deep green aegirine is abundant in groundmass, as fine needles often form fibrous or fan shapes and partially replace the diopside mineral (Figures 3a, 3b, and **3c**). On the other hand, the mineral aegirine also shows an interstitial relationship with sanidine, phlogopite, and diopside (Figure 3b). It shows moderate pleochroic and small-angle extinction. Apatite is rarely present as phenocrysts but more commonly as fine euhedral crystals in groundmass, and in some cases, it can also be found in inclusions within diopside and phlogopite. (Figure 3b). Opaque minerals/iron oxides are present as fine grains in the groundmass and locally present as inclusions in phlogopite. They have been altered/weathered to form reddish-dark brown patches or stains (Figures 3a, 3b, and 3c). Furthermore, the porphyritic texture of the sample combined with abundant sanidine and phlogopite as the main constituents is similar to the textures and mineralogy of sanidine phlogopite lamproite. This sample shows similarities in texture and mineralogy to sample GSI-0800-03 (Figure 3b); however, clinopyroxene is less abundant, whereas phlogopite is more abundant in this sample. Moreover, the presence of abundant deep green aegirine needles in the groundmass and along diopside crystal margins also distinguishes it from sample GSI-1032-34 (Figure 3c).

The XRD analysis result of mafic alkaline rocks shows a consistency in compositions with petrographic observation, where the samples are dominantly displaying a peak of sanidine, phlogopite, diopside and aegirine minerals (Figure 4). Furthermore, the SEM-EDS analysis results also confirm the presence of rock-forming minerals as characteristics of these rocks, such as sanidine, phlogopite and diopside as phenocrysts and the abundance of aegirine as a groundmass (Figure 5**)**, and moreover, they are still showing up consistently in compositions with the XRD analysis and petrographic observation results. In addition, the SEM-EDS analysis also displays a significant

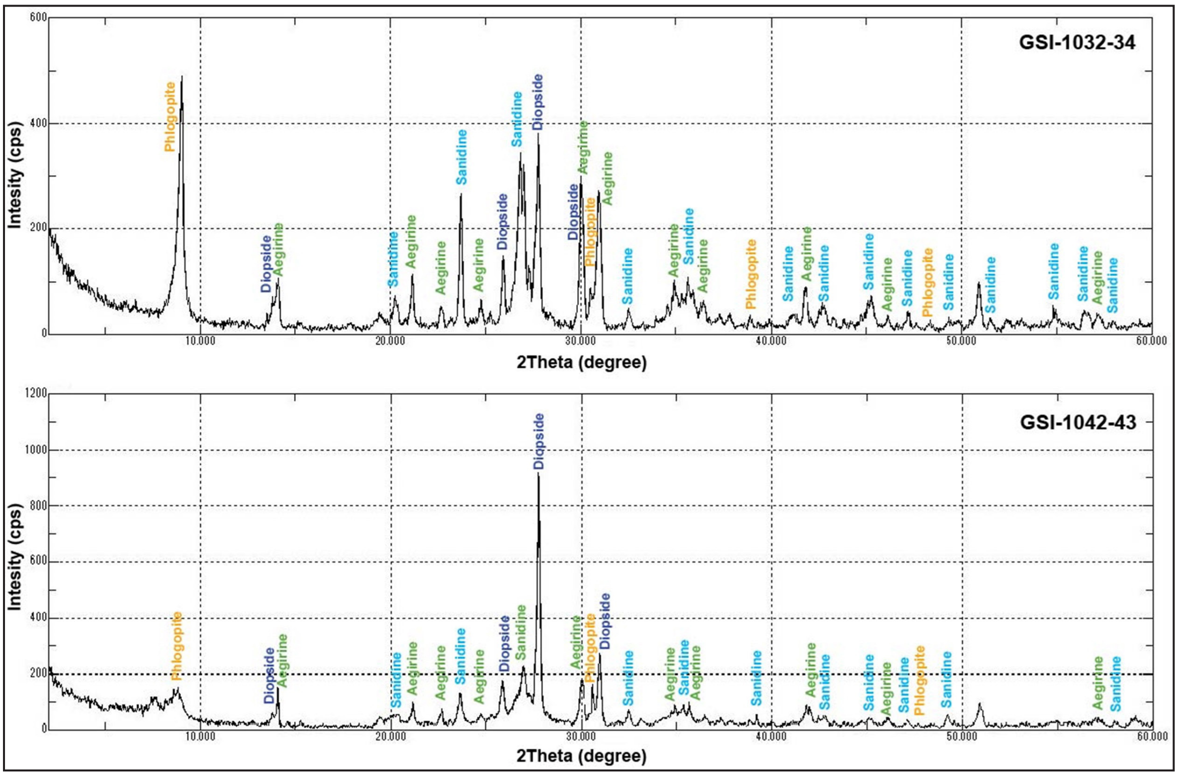


Figure 4. Representative X-ray diffraction results of a mafic alkaline dyke from the Mamuju district (research area).

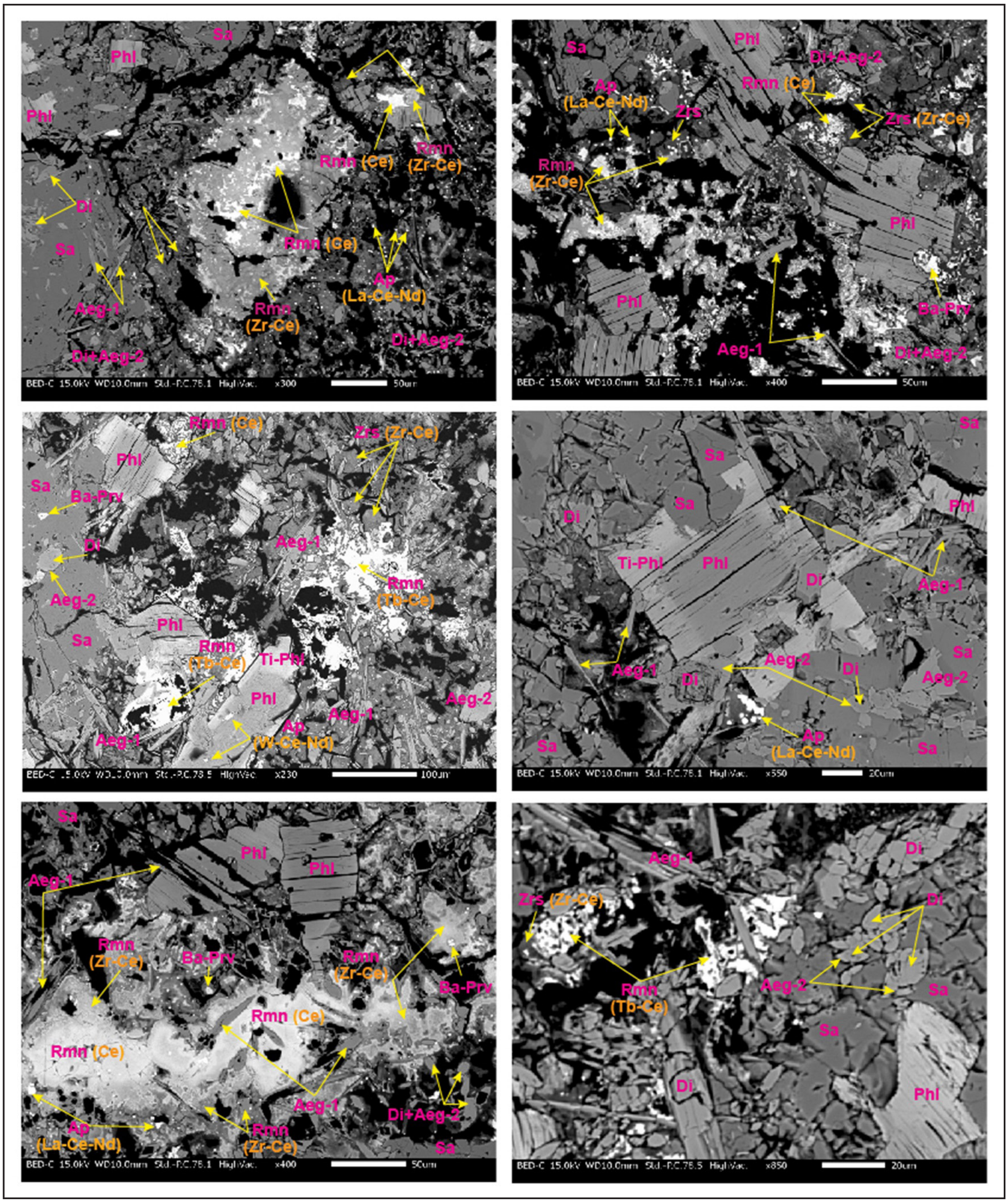


Figure 5. BSE images of mafic alkaline dykes from the Mamuju district (research area), which show rock-forming minerals, include REE-Zr-Th-bearing minerals. Abbreviations: *Diopside (Di), Sanidine (Sa), Phlogopite (Phl), Aegirine (Aeg), Apatite (Ap), Zirconosilicate (Zrs), Ba-Prv (Barium-perovskite) and Romanechite (Rmn).*

amount of the REE-Zr-Th-bearing minerals, including apatite (La-Ce-Nd), zirconosilicate (Zr-Ce), Ba-perovskite, and romanechite-like (Ba-Mn oxide with trace REE) (Figure 5). In general, the REE-bearing minerals within the mafic alkaline dykes from the Mamuju district are present with various crystal sizes, ranging from 3 µm to 200 µm, and mostly display a white colour with irregular shapes (Figure 5). The REE ore mineralisation is commonly found and occurs during the late stages of magma evolution, a process known as metasomatism (Dostal, 2017).

A secondary deuteric/metasomatism process occurs in the late magmatism stage, as indicated by replacement texture or pseudomorphic texture (Putnis & Austrheim, 2010).

Whole-rock geochemistry (major-trace elements)

The whole-rock geochemistry results of five samples of mafic alkaline dykes are presented in Table 1. The mafic alkaline dykes show a short range of SiO_2 contents, ranging from 49.5 to 52.4 wt.% TiO_2 (1.45 - 2.34 wt.%), CaO (3.43 - 5.01 wt.%), K_2O (7.86 - 8.37 wt.%), Na_2O (1.40 - 2.38 wt.%) and P_2O_5 (0.55 - 1.10 wt.%). However, the mafic alkaline dykes show a wide range of MgO (2.90 – 6.19 wt.%), Fe_2O_3 (9.8 - 14.5 wt.%) and Al_2O_3 (10.7 - 14.3 wt.%) (Table 1). Furthermore, the mafic alkaline dykes are also displaying very high content of large-ion lithophile elements (LILEs), e.g., Cs (10.9 - 142 ppm), Rb (124 - 470 ppm), and Ba (2190 – 9380), and HFSE, e.g., Zr (968 - 3083 ppm), Hf (26.9 - 72.2 ppm), Th (152 - 408 ppm), and U (30.9 - 136.5 ppm), and also show high total REE (TREY = 971 - 1784 ppm). The average content of light rare earth elements (LREEs) of 1074 ppm is higher than that of heavy rare earth elements (HREEs), which is around 147 ppm (Table 1**)**. Therefore, it can be assumed that the mafic alkaline dykes are enriched in LREE, including other critical elements such as Y, Zr, and Th. The REE within the mafic alkaline dykes from the Mamuju district have experienced quite significant enrichment compared to the initial REE in the crust, where the average REE concentration is estimated to range from 130 to 240 µg/g in the Earth's crust (Zepf, 2013).

DISCUSSION

Petrographical classification of the dykes

Based on petrography results, the classification of mafic alkaline dykes from the Mamuju district using the modern nomenclature of lamproite rock approaches (Mitchell, 2020; Krmícek and Chalapathi, 2022); as in the table below, the mafic alkaline rock can be classified as ***'orendite' or,*** in modern name, can be categorised into ***'sanidine-phlogopite-diopside lamproite rocks',*** which is related to *anorogenic* lamproite (Table 2). Furthermore, the presence of lamproite rocks in the Mamuju district (research area) is a new discovery in Indonesia. Primarily, lamproite rocks from the Mamuju district are composed of sanidine, phlogopite, diopside, and aegirine from both primary and secondary processes (Figure 3; 5). It's also containing accessory minerals such as apatite. The presence of the secondary aegirine mineral is probably as a result of the autometasomatic process. Where dissolution-

Table 2. Modern nomenclature of lamproite rocks (Mitchell, 2020; Krmícek and Chalapathi, 2022)

Genetic	Historic	Modern
Anorogenic lamproite	Wyomingite	Diopside-leucite-phlogopite lamproite
	Orendite	Diopside-sanidine-phlogopite lamproite (this study)
	Madupite	Diopside madupitic lamproite
	Cedricite	Diopside-leucite lamproite
	Mamilite	Leucite-richterite lamproite
	Wolgidite	Diopside-leucite-richterite madupitic lamproite
	Fitzroyite	Leucite-phlogopite lamproite
Orogenic lamproite	Verite	Hyalo-olivine-diopside-phlogopite lamproite
	Juinillite	Olivine-diopside-richterite madupitic lamproite
	Fortunite	Hyalo-enstatite-phlogopite lamproite
	Cancalite	Enstatite-sanidine-phlogopite lamproite
	Raabsite	Phlogopite-richterite olivine microcline lamproite
	Thuresite	Richterite diopside microcline lamproite
	Kharlsteinite	Richterite microcline lamproite

transport-precipitation can effectively achieve mineral re-equilibration, which is driven by small differences in free energy between parent and product phases (Putnis & Austrheim, 2010). Metasomatism allows an element to be added or removed from a rock. As Nakamura and Watson (2001) demonstrated, this condition can occur when a reduction in free interfacial energy induces recrystallisation. During this process, one mineral is replaced by another with a different chemical composition (Nakamura and Watson, 2001). Specifically, aegirine metasomatism occurs when sodium- and iron-rich fluids influx into environments that cause the original rock's chemical composition to change. A simplified representation of this substitution is as follows: $CaMgSi_2O_6$ (Diopside) + Na-Fe-Si-OH (metasomatic fluid) → $NaFe_3$ + Si_2O_6 (Aegirine) + Ca-Mg-OH (residual fluid). Furthermore, two types of aegirine minerals are found in alkaline mafic dyke samples from the Mamuju district, including aegirine-1 and aegirine-2. The aegirine-1 has a needle-shaped texture and is the result of full recrystallisation and tends to be the result of the early magmatic process, while the aegirine-2 has a partial and full replacement or pseudomorph texture, interpreted as a product of metasomatism processes (Figure 3; 5).

The presence of primary minerals in the mafic alkaline dykes of the Mamuju district indicates the occurrence of rock-forming minerals not commonly found in other mafic rocks, which have no quartz or plagioclase (Figures 3 and 4). Consequently, based on Mitchell & Bergman (1991), the composition more closely resembles that of the exotic rock of lamproite. The abundance of minerals such as sanidine, phlogopite, and diopside in those samples (Figures 3 and 4) led to the nomenclature approach of classifying these rocks as lamproite. Typically, it contains phenocrysts such as phlogopite (Niggli, 1923). Generally, lamproite is a product of post-orogenic magmatism in regions that have experienced continental plate collisions with a fossilised Benioff Zone beneath them (Foley, 1987), or it may result from continental plate extension/rifting (Mitchell & Bergman, 1991). Previously, lamproite had existing names, but they needed to be more informative, localised, or region-specific. Unlike common rock types, lamproite rocks cannot be identified solely through petrographic analysis due to their complex mineralogy with fine-grained texture, especially orogenic lamproite (Mitchell, 1995). Moreover, identifying orogenic lamproite can be challenging, as it is situated in tectonic settings linked to leucite, shoshonite, and various potassic rocks like kamafugite, tephrite, and leucite phonolite (Mitchell, 2020). These rocks are formed in connection with the intricate subduction process presently taking place (Mitchell, 2020). Therefore, Mitchell (2020) and Krmícek and Chalapathi (2022) modified the nomenclature using a descriptive mineralogy scheme to make it easier to differentiate from the results of petrographic analysis using mineralogical criteria.

Geochemical characteristics and petrogenesis of dyke

The mafic alkaline dykes show SiO_2 contents are relatively lower than the Dharwa Craton lamproite field (Chalapathi Rao et al., 2010) (Table 1). Their TiO_2, CaO, and MgO contents are also distinctly lower than those from the Dharwa lamproite field. These rocks show slightly higher Fe_2O_3 than the Dharwa lamproite field. There is overlapping and relatively high potassium (K_2O) content in mafic alkaline dykes from the Mamuju district compared to lamproite fields from the Dharwa Craton (Table 1), likely because of phlogopite and sanidine (Table 1) (Chalapathi Rao et al., 2010). Mafic alkaline dyke samples from the Mamuju district have a lower Na_2O content (**Table 1**) than Dharwa Craton lamproite fields due to the modal Na-clinopyroxene proportion (Chalapathi Rao et al., 2010). However, $K_2O/Na_2O > 3$ in all mafic alkaline dyke samples from the Mamuju district indicates their ultrapotassic nature. The mafic alkaline dyke samples from the Mamuju district have a ratio of (Na$_2$O + K$_{2O)/Al_2O_3 < 1}$ and are *not peralkaline rocks*. They resemble the lamproites from the Dharwa Craton lamproite field (Chalapathi Rao et al., 2010). The Al_2O_3 contents of the mafic alkaline dyke samples from the Mamuju district are higher than those of the Dharwa craton lamproite fields; this reflects the difference in modal mineralogy of aluminous phases (Chalapathi Rao et al., 2010) (Table 1**)**.

In general, the geochemical characteristics of trace elements of mafic alkaline dyke samples from the Mamuju district have relative similarity in trend with the Dharwa Craton lamproite fields (Figure 6). Both mafic alkaline dyke samples from the Mamuju district and Dharwa craton lamproite fields show depletion in Nb and Ti (Figure 6). However, in some cases, it shows that the mafic alkaline dyke samples from the Mamuju district tend to be more enriched in several elements of LILE, LREE and high field strength elements (HFSE) such as Pb, Th, U, Zr and Hf (Figure 6). It is caused by the crust contamination, which is indicated by the positive spike of the Pb element and the negative spike of Nb and Ti (Mitchell, 2020; Krmícek and Chalapathi, 2022). Furthermore, the elevation of Th, U, Zr, and HREE is likely influenced by the secondary upgrading of these components through strong metasomatic processes.

The geochemistry plot results on the diagram of TiO_2 *vs*. Al_2O_3 (Muller and Groves, 1993; Figure 7) show both mafic alkaline dyke samples

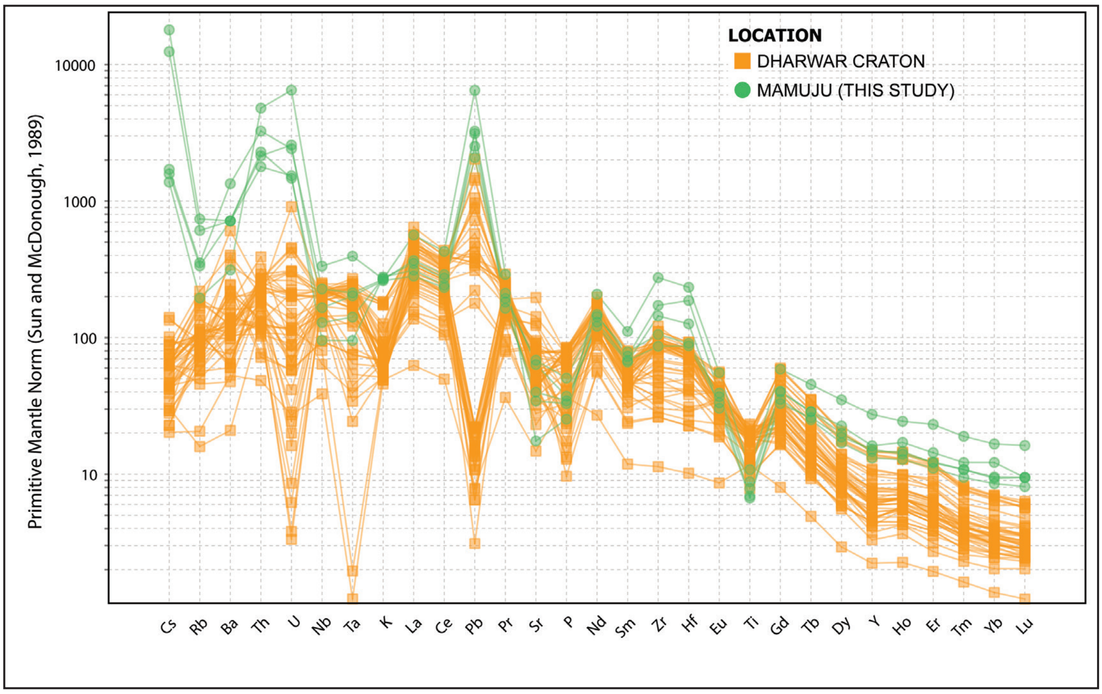


Figure 6. Mafic alkaline rocks trace element normalised to primitive mantle (n = 5) (Sun and McDonough, 1989)

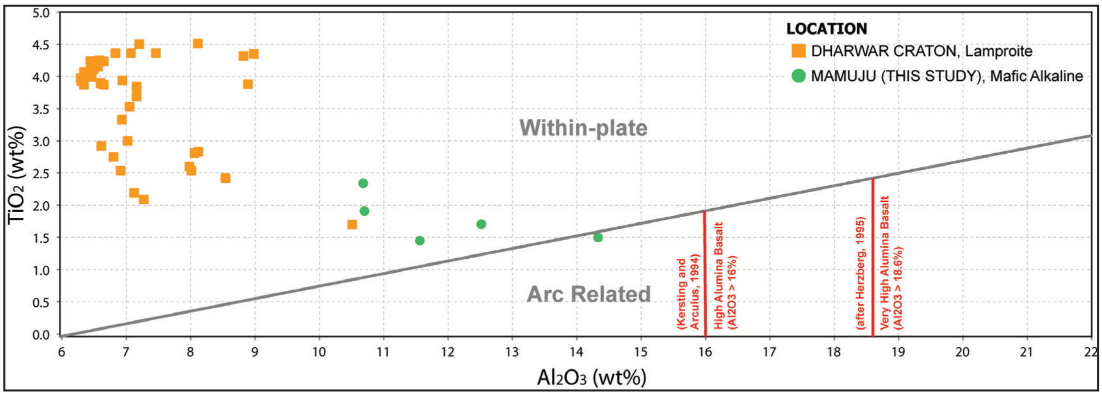


Figure 7. Geotectonic diagram for within-plate vs arc-related (Muller and Groves, 1993).

(Mamuju district, Western Sulawesi) and lamproites (Dharwar craton, India) formed from within-plate magmatism (anorogenic).

The geochemistry plot results on the ternary diagram Ternary classification of Lamprophyres–Lamproites–Kimberlites (after Bergman, 1987) [Ternary Plots: (Al_2O_3)-(MgO)-(K_2O) (in wt.%)] with an expanded field for lamproites according to Krmícek et al. (2020a) (Figure 8a) show that the mafic alkaline dykes (Mamuju district, Western Sulawesi) fall into *lamproites*, while the samples from the Dharwar craton, India, fall into *lamprophyres to lamproites*, respectively. The determination of the magmatic alkalinity series uses a comparison approach to the ratio of K_2O to Na_2O with the variable of CaO-K_2O-Na_2O (in wt.%) (Godang et al., 2021; modified from binary K_2O *vs*. Na_2O (Turner et al., 1996)), which shows that the plot results fall on the *ultra-potassic field* with the ratio of $K_2O/Na_2O > 2$ (Figure 8b).

In the Sulawesi region of Indonesia, regional tectonics refers to the combined influence of surrounding plates on the region. A main influence is the movement of transform faults in the east-southeast and northeast, pushing the small continent to the west and northwest. On the other hand, from the west, it is associated with the expansion of the Eurasian continent, which led to the opening of the Makassar Strait, while from the northeast, it is associated with the movement of the Pacific plate westward. In contrast, from the north, it is related to the rotation of the Sulawesi Sea (Zakaria & Sidarto, 2015). The tectonic activity started during the Mesozoic period, when Australia's northwestern shelf expanded, causing several microcontinents to be formed, which were then pushed toward Sulawesi by a strike-slip fault mechanism. Meanwhile, current activities include compression and lifting phases throughout Sulawesi (Zakaria & Sidarto, 2015). West Sulawesi is characterized by Cenozoic magmatism whose petrogenesis, sources, and tectonic settings have been sufficiently studied by geological, petrologic, geochemical, and isotopic methods (Elburg et al., 2003; Sukadana et al., 2015; Maulana et al., 2016; Jaya et al., 2017). Volcanic rocks from the Late Cenozoic era possess a unique trait of being predominantly potassic to ultrapotassic in composition. These rocks can be divided into two categories: shoshonitic to ultrapotassic (HK) and high-K calc-alkaline (CAK). It has been determined that these rocks were formed in a post-subduction (extensional) tectonic environment (Elburg et al., 2003). In contrast, Sukadana et al., 2015, consider the formation of potassic-ultrapotassic rock in the Adang volcanic complexes associated with the subduction system, which is the active continental margin (ACM). According to the tectonic discrimination diagram for volcanic rocks, this research shows results that align with those of previous researchers (e.g., Hall, 1996; Elburg et al.,

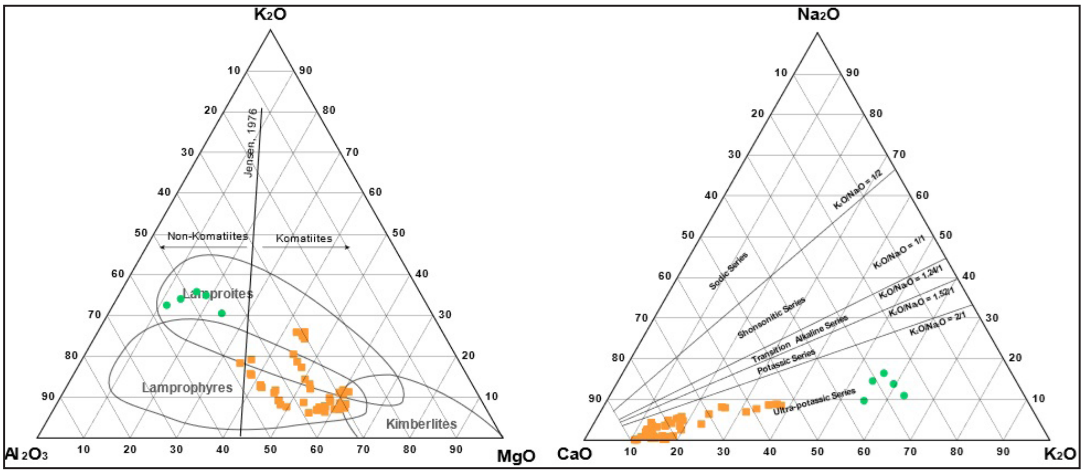


Figure 8. Ternary classification of Lamprophyres–Lamproites–Kimberlites (after Bergman, 1987) [Ternary Plots: (Al_2O_3)-(MgO)-K_2O) (in wt.%)] with an expanded field for lamproites according to Krmícek et al. (2020a) (a). Ternary magmatic alkalinity classification CaO-K_2O-Na_2O (in wt.%) (Godang *et al.*, 2021; modified from binary K_2O *vs*. Na_2O after Turner et al., 1996) (b).

2003; Liu et al., 2020). The tectonic discrimination diagram for volcanic rocks (Saputro et al., 2022; modified after Sun et al., 2006) shows that mafic alkaline dykes (Mamuju district, Western Sulawesi) is formed in a tectonic setting of *within-plate continental extension* (Figure 9). On the other hand, the lamproites from the Dharwar craton (India) as comparator data show that the lamproites from the Dharwar craton (India) are associated with *continental rifting tectonics*, where the magma originates from interactions between plumes and non-plumes (Figure 9). It shows a different tectonic origin with mafic alkaline dykes (Mamuju district, Western Sulawesi) and lamproites from the Dharwar craton (India). However, both mafic alkaline dykes (Mamuju district, Western Sulawesi) and lamproites from the Dharwar craton (India) can be categorised as *anorogenic lamproite*. It shows consistency with the previous result from Chalapathi Rao et al. (2010).

The petrogenesis of mafic alkaline rocks from the Mamuju district (research area) began in the Miocene, when in the Early Miocene, the collision of the Banggai-Sula microcontinent with West Sulawesi occurred (Hall, 1996). Collision causes thickening of the crust, subduction stops, and slab detachment (Liu et al., 2020). Crustal contamination from previous subduction causes enrichment of REE and incompatible elements such as K, Rb, Th, and Ba so that it will produce high-K calc-alkali magma for a long time (Liu et al., 2020). In the Middle Miocene, magma that previously formed in the continental arc tectonic setting began to evolve into a potassic-ultrapotassic alkaline magma, which was caused by the delamination process (Liu et al., 2020). The negative buoyancy of the lower continental crust and mantle lithosphere is responsible for the occurrence of delamination. This complex geological phenomenon has significant implications for geology (Meissner & Mooney, 1998). This condition is generated by unstable mechanical equilibrium due to the differences in density, where a greater density of the mantle lithosphere underlies the low density of the crustal lithosphere (Bird, 1979). Furthermore, the temperature, composition, and phase changes may be causing the difference in densities (Kay & Mahlburg, 1993). The lower crust can break off from the upper crust and sink into the mantle due to a density inversion in areas with high mantle temperatures. According to Rollinson (2009), the phenomenon can only be observed in specific geological settings. This process can impact the region's geological and tec-

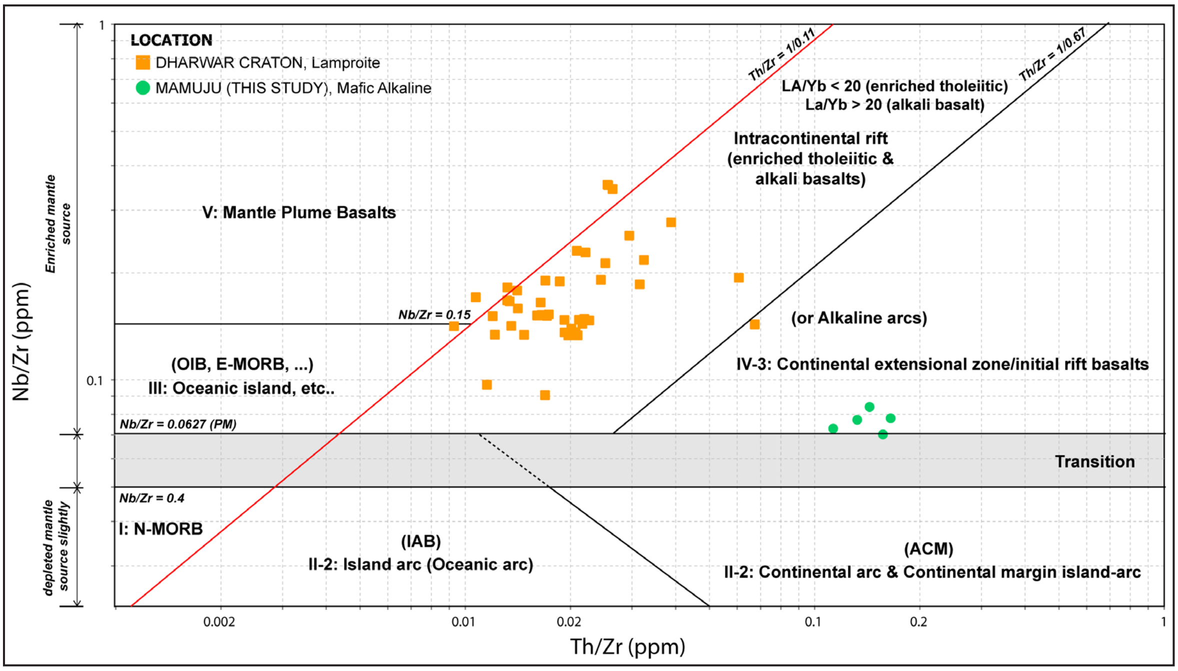


Figure 9. Tectonic discrimination diagram for volcanic rocks (Saputro *et al*., 2022; modified after Sun *et al*., 2006).

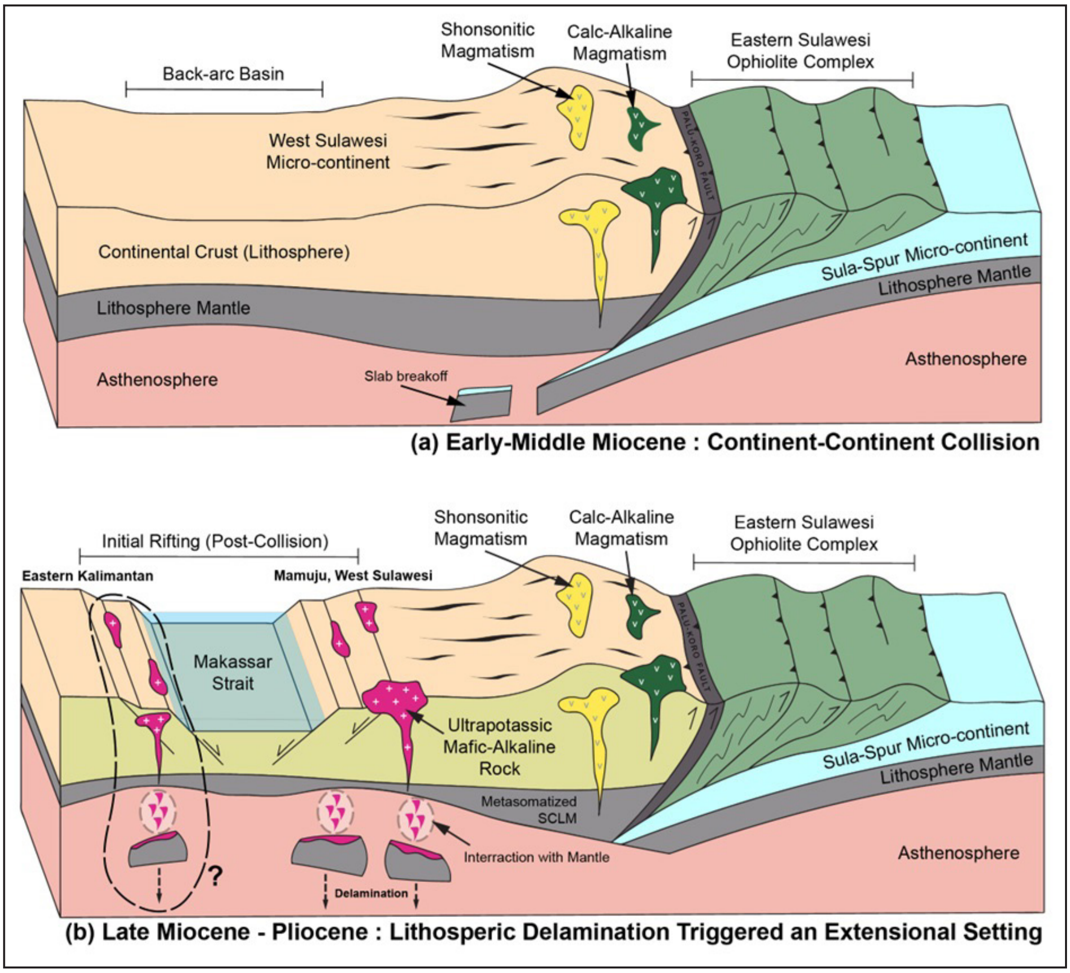
tonic activities (Rollinson, 2009). These include areas with volcanic-rifted margins, continental areas undergoing extension, and arc environments (Rollinson, 2009). It is important to note that this phenomenon is limited to these particular settings and may not be observed in other geological environments. The asthenosphere's upward movement leads to separating the lower crust and the lithospheric mantle (Rollinson, 2009). Therefore, it facilitates the intrusion of the underlying asthenosphere through slumping, cracking, or plume erosion (Bird, 1979). These mechanisms provide a pathway for the asthenosphere to rise until it encounters the base of the lower crust. At this point, it initiates the lower crust and lithospheric mantle peeling away. Bird (1979) proposed this process as a means of explaining the intrusion of the asthenosphere. In this case, the Adang volcano complex, in particular research areas, suggests that this remarkable type of magma is formed due to the interaction between the metasomatised subcontinental lithospheric mantle and the asthenosphere. This magma is known for introducing a new type of magma related to ultrapotassic mafic alkaline rocks, such as lamproite and other shosonitic-ultrapotassic volcanic rocks. Increased Ti and Nb contents, more enriched concentrations of REE and incompatible elements, and higher Zr and Hf indicate that this process is related to the (post-collision) extension or *within-plate tectonic system* **(**Figure 9**).** The proposed cartoon of the tectonic system, which shows the condition of the delamination process and the formation of the ultrapotassic mafic alkaline rocks in Mamuju district, west Sulawesi (modified from Liu et al., 2020), can be seen in Figure 10. Furthermore, there is a possibility of finding the potential for ultra-potassic mafic alkaline rocks on the eastern part of Kalimantan Island, considering that the Makassar Strait to the eastern part of Kalimantan continues the tectonic pattern of initial rifting due to delamination as in West Sulawesi.

The Enrichment of REE-Zr-Th

Through thorough SEM-EDS observations, it has been definitively concluded that two minerals are unequivocally associated with enriching rare earth elements (REEs) and critical elements (Th, Zr), including diopside and zirconosilicate (Figure 5). These minerals are the main initial source of the REE and critical elements (Th, Zr) before secondary upgrading/enrichment occurs by the metasomatism process to form new REE-bearing minerals such as apatite, Ba-perovskite, and romanechite (Figure 5**).** Apatite is a phosphate mineral that is often found in intrusive igneous rocks associated with alkaline rocks as an important alternative source of REE (Kurniawan and Saepuloh, 2025). The existence of zirconosilicate and diopside as the main initial source of REE in alkaline mafic igneous rocks has been widely discussed by previous researchers (e.g., Bernard et al., 2020; Van Orman et al., 1998, 2001; Koga et al. , 1999). The REE transport is strongly affected by diffusion properties of diopside (Van Orman et al., 2001). In the production and transportation of melts (e.g., Van Orman et al., 1998), diffusion may influence the distribution of REEs and another critical element during solid-state phase transformations (e.g., Koga et al., 1999), as well as during phenocrysts growing from magmas.

Based on the SEM-EDS observations, it is interpreted that similar processes involve the enrichment of the REE and critical element (Th-Zr) within mafic alkaline dykes from the Mamuju district. The presence of the REE and critical element (Th-Zr)-bearing minerals is very closely related to the evolution of the diopside to the formation of secondary aegirine minerals (aegirine type-2) (Figure 5). In the magmatic stage, the presence of REE and critical elements (Th-Zr) is moderate to low and mostly embedded with diopside minerals. During the metasomatism stage, the diopside is partially replaced by aegirine type-2 (Figure 5). It allows for the relative enrichment of the REE and critical element (Th-Zr) in the *residual fluid*, forming new minerals as REE and critical element (Th-Zr) hosts, such as apatite, Ba-perovskite and romanechite.

The abundance of inclusions and patches of apatite (Figure 5) in this rock is attributed to the metasomatism association, even though apatite can be a primary mineral in the formation of igneous rocks (Bachmann et al., 2013). On the



(a) Early-Middle Miocene : Continent-Continent Collision

(b) Late Miocene - Pliocene : Lithosperic Delamination Triggered an Extensional Setting

Figure 10. The proposed cartoon of the tectonic system of the Mamuju district (research area), which shows the delamination process and the formation of the ultrapotassic mafic alkaline rocks of the Adang volcano complex (modified from Liu et al., 2020).

other hand, zirconosilicate minerals also undergo a similar process to diopside. It is proven by the existence of replacement by new REE and critical element (Th-Zr)-bearing minerals such as apatite, Ba-perovskite and romanechite within these minerals (Figure 5). Furthermore, the late stages of the hydrothermal process extend the upgrading of the enrichment of the REE and critical element (Th-Zr). It has generally been considered highly mobile of the trace elements REE, Th, and Zr, as well as U, Nb, Hf, Pb and Y, during the hydrothermal stage/hydrothermal systems (Rubin et al. 1993). It is assumed that the residual fluid carries more content of REE and critical elements (Th-Zr) due to the dissolution of the diopside in the hydrothermal environment to form a more abundant amount of the REE and critical elements (Th-Zr)-bearing minerals. It is confirmed by the presence of the skeletal texture of the diopside remnant (Figure 5).

The rearrangement and reforming of minerals containing rare earth elements and critical elements are frequently associated with the reinitialisation of trace elements and isotopic systems (Geisler et al., 2007; Martin et al., 2008). It clarifies the reason for the increased prevalence of metasomatic and hydrothermal REE-critical element-bearing during this phase. Therefore, the abundance of REE and critical element (Th-Zr) content depend on the initial conditions of the host rock composition. In this case, the more abundant the diopside and zirconosilicate, the higher the intensity of REE and critical element (Th-Zr). The proposed flow diagram illustration of the formation of REE-bearing minerals within mafic alkaline dykes from the Mamuju district is shown in Figure 11.

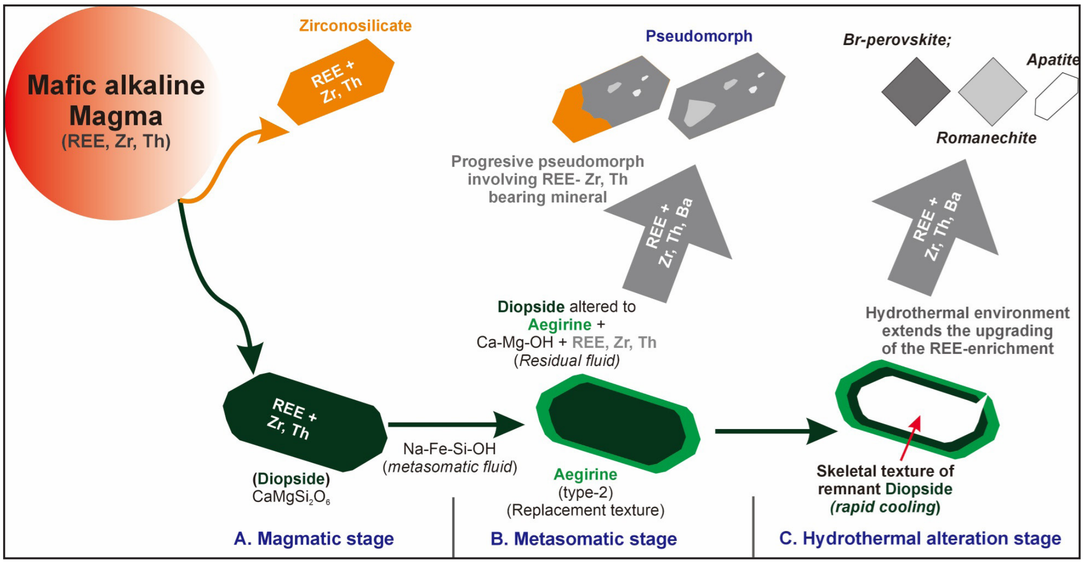


Figure 11. The proposed illustration diagram of the formation of REE-bearing minerals within mafic alkaline dykes from the Mamuju district.

CONCLUSIONS

The mafic alkaline dykes from the Mamuju district can be classified as orendite lamproite rocks or, in the modern classification, can be classified as diopside-sanidine-phlogopite lamproite in modern nomenclature. The whole rock geochemistry of these dykes exhibits a K_2O/Na_2O ratio > 3, indicating an ultrapotassic nature. Moreover, a ratio of $(Na_2O + K_2O)/Al_2O_3 < 1$ indicates that the dykes are not peralkaline rocks. The large ion lithophile elements (LILEs) are enriched in these dykes, with simultaneous depletions of Ti, Sr, and P, along with negligible Eu anomalies. Notably, these dykes exhibit enrichment in light rare earth elements (LREEs) within the range of 901–1558 ppm, as well as elevated Zr (968–3083 ppm), Th (152–408 ppm), U (30–37 ppm), Nd (164–282 ppm), and Pb (148–460 ppm). The mafic alkaline dykes from the Mamuju district are related to anorogenic lamproite, which formed in a tectonic continental extension. These dykes contain a significant amount of the REE-Zr-Th-bearing minerals, including apatite (La-Ce-Nd), zirconosilicate (Zr-Ce), Ba-perovskite, and romanechite (Zr-Th-Ce-Tb). Furthermore, the enrichment of LREEs, Th, and Zr of this dyke can be attributed to both primary (fractional crystallisation) and secondary enrichment through deuteric (autometasomatic) and hydrothermal alteration processes, as indicated by the replacement or pseudomorph and skeletal texture due to rapid cooling within a hydrothermal fluid environment. The parent magmas likely originate from a metasomatised subcontinental lithospheric mantle (SCLM) source. The discovery of an excellent source of rare earth elements (REE) and critical elements in alkaline mafic rock in Indonesia is a relatively new and exciting development. Thus, we suggested that future exploration must target these rock types. Ground and airborne geophysical exploration methods are “standard” exploration tools for the REE deposits hosted in mafic alkaline rocks. The enrichment of the deposits in U and Th and their radioactivity make radiometric surveys very effective exploration methods. In addition, magnetic and gravity surveys are also used to locate mafic alkaline rock complexes and their deposits. We also suggest that the Government of Indonesia and relevant private companies developing the REE industry and REE and critical element industry-related mafic alkaline complex extend the exploration area to the eastern part of Kalimantan Island because there are possibilities and opportunities for finding the REE-critical element potential within ultra-potassic mafic alkaline rocks on the eastern part of Kalimantan Island, considering that the Makassar Strait to the eastern part of Kalimantan continues the tectonic pattern of initial rifting due to delamination as in West Sulawesi.

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