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Distribution and Mineralogical Characteristics of Raya Volcanic Rocks, West Kalimantan

Persebaran dan Karakter Mineralogi Batuan Vulkanik Raya, Kalimantan Barat

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ABSTRACT

There are several volcanic rocks in a radius of 150 km from where the Nuclear Power Plant (NPP) site project in West Kalimantan. The Mesozoic volcanic rocks have not been characterized for volcanic hazard evaluation purposes due to their old age. However, the distribution of Raya Volcanic Rocks that covers the site area and the wider area up to 150 kilometers from the site makes this rock group quite important to be characterized to find out how its activities in the past. This paper's objective is to comprehend the distribution and characteristics of Raya Volcanic Rocks for NPP site volcanic hazard evaluation purposes. Fieldwork and lineament analyses were conducted to map and interpret the distribution of Raya Volcanic Rocks while mineralogical analysis using petrography and micro XRF were conducted to characterize the Raya Volcanic Rocks. The distribution of Raya Volcanic Rocks that relatively show NNW–SSE orientation is probably controlled by the NNW–SSE fault system. The analyses resulted that Raya Volcanic Rocks erupted as lava flows derived from mafic magma as a product of mantle partial melting that underwent crystal fractionation, injection of hotter/more Ca-rich magma, and magma mixing on an open-system magmatic process.

Keywords: Raya Volcanic Rocks, distribution, petrography, micro XRF, magmatic process

ABSTRAK

Terdapat beberapa batuan vulkanik dalam radius 150 km dari lokasi proyek tapak Pembangkit Listrik Tenaga Nuklir (PLTN) di Kalimantan Barat. Batuan vulkanik Mesozoikum belum dikarakterisasi untuk tujuan evaluasi bahaya vulkanik karena umurnya yang relatif tua. Namun, sebaran Batuan Vulkanis Raya yang meliputi area tapak dan wilayah yang lebih luas hingga 150 kilometer dari tapak menjadikan gugusan batuan ini cukup penting untuk dikarakterisasi untuk mengetahui bagaimana aktivitasnya di masa lalu. Penelitian ini bertujuan memahami sebaran dan karakteristik Batuan Vulkanik Raya untuk evaluasi bahaya gunung api di lokasi PLTN. Observasi lapangan dan analisis kelurusan dilakukan untuk memetakan dan menginterpretasi sebaran Batuan Vulkanik Raya, sedangkan analisis mineralogi menggunakan petrografi dan XRF mikro dilakukan untuk mengkarakterisasi Batuan Vulkanik Raya. Sebaran Batuan Vulkanik Raya yang relatif menunjukkan orientasi NNW–SSE kemungkinan dikendalikan oleh sistem sesar berarah NNW–SSE. Berdasarkan analisis yang telah dilakukan, Batuan Vulkanik Raya meletus sebagai aliran lava yang berasal dari magma mafik sebagai produk pencairan parsial mantel yang kemudian mengalami fraksionasi kristal, injeksi magma yang lebih panas/kaya Ca, serta pencampuran magma pada proses magmatik sistem terbuka.

Kata kunci: *Batuan Vulkanik Raya, persebaran, petrografi, XRF mikro, proses magmatik*

INTRODUCTION

The nuclear power plant (NPP) project in West Kalimantan which was initiated in 2019 leads to several site evaluations. Volcanic hazard is one evaluation aspect that is required. The purpose is to ensure the safety of the nuclear power plant site from volcanic hazards that could disturb the power plant installation and operation.

Initial volcanic products data collection requires all volcanic activity in the vicinity of the NPP site that occurred less than 10 million years ago and those that occurred more than 10 million years ago. The earlier regional-scale geological map of West Kalimantan [1]–[5] denoted several volcanic rocks from Late Triassic to Pliocene in the 150 kilometers radius from the site. The Triassic rocks of Serian and Sekadau Volcanics are limitedly distributed compared to the later volcanic rocks. The Cretaceous rocks of Raya Volcanic Rocks are widely distributed from the site to almost 150 kilometers away radius. The Eocene rocks of Serantak Volcanics and Bawang Dacite lie approximately 70 kilometers from the site, while the Pliocene rocks of Niut Volcanics are widely distributed 100–50 kilometers from the site.

The Niut Vocanics that erupted less than 10 million years ago is the main evaluation target based on the IAEA volcanic hazard safety guide [6]. A recent study showed that the volcanic products of Semadum Volcano of Niut Volcanics are low in viscosity so that its volcanic activity is interpreted as locally effusive [7]. Due to its far-away location, it was thought that the volcanic activity of Niut Volcanics does not give any impact on the NPP site.

The older volcanic rocks have not been characterized for volcanic hazard evaluation purposes. Their older age doesn't make them occur as mandatory evaluation targets. However, the distribution of Raya Volcanic Rocks that covers the site area and the wider area up to 150 kilometers from the site makes this rock group quite important to be characterized to find out how its activities in the past. A recent study of Raya Volcanic Rocks [8] gives the characteristic of the rock group to conclude the tectonic setting of the rock formation. The sampling of the recent study was wide covering the southern part of Raya Volcanic Rocks and other intrusive rocks equivalent in age, but the samples were relatively far from the NPP site.

This paper's objective is to comprehend the distribution and characteristics of Raya Volcanic Rocks for NPP site volcanic hazard evaluation purposes. The samples for the characterization are concentrated near the site and distributed in other locations covering 150 kilometers radius from the site. Therefore, the conclusions of this research can be judged to be more detailed compared to the previous researches that discuss Raya Volcanic Rocks because it is more focused on how volcanic activity in the past was, especially near the NPP site. The area of this research is depicted in Figure 1.

Figure 1. The research area of the study.

REGIONAL GEOLOGY

The physiography of Northwest Kalimantan is noted as part of Kuching Zone that extends to the Lupar Zone in the north and the Schwaner Mountains in the south. Regionally, the area consists of Mesozoic metamorphic and intrusive rocks overlain by Mesozoic and Cenozoic sedimentary rocks and volcanic products which also intruded by Cenozoic intrusive rocks [1]–[5]. The simplified geological map of Northwest Kalimantan is depicted in Figure 2.

The Mesozoic metamorphic and intrusive rocks are ophiolite Seminis Formation in the north, a small part of Pinoh Metamorphic in the south, and granitoid–metamorphic rocks of Embuoi Complex in the east. These rocks were overlain by the Jurassic sedimentary rocks of Sungaibetung Formation and Bradung Formation. The Triassic volcanic rocks are Serian and Sekadau Volcanics, alongside its temporally-coincide sedimentary rocks of Bengkayang Group, Kayan Sandstone, Banan Formation, and Tutoop Sandstone. In Cretaceous Raya Volcanic Rocks and Setinjam Gabbro were formed, alongside the intrusion of Mensibau Granodiorite and the sedimentation of Pendawan Formation. Raya Volcanic Rocks consist of volcanic arc setting rock association such as basalt-andesite-dacite-rhyolite. They were originated from recycled sediment-modified wedge mantle [8]. Meanwhile, Mensibau Granodiorite that often-called Singkawang Batholite is a high-K calc-alkaline I-type granitoid derived from the juvenile mafic crust. These two rock groups were interpreted to be the products of westward subduction of the paleo-Pacific plate in the Early Cretaceous, considering the 90º anti-clockwise rotation of Kalimantan since Cretaceous [8]–[11]. The magmatic activity producing these rock groups is named the first magmatic period of NW Kalimantan [12].

The two other magmatic periods in NW Kalimantan happened in Cenozoic at Eocene–Miocene and Pliocene [12]. The Eocene volcanism produced Serantak Volcanics and Bawang Dacite that formed circular features in the north of Bengkayang capital city. The magmatism continued in the Late Oligocene–Early Miocene with the emerging of Sintang Intrusion. It coincided with the fluvial sedimentation of Hamisan Formation and Landak Sandstone in the Late Oligocene. In Pliocene, the Niut Volcanic erupted with calc-alkaline affinity [7,12]. The product of this volcanism was andesite-basaltic lava with vesicular-scorian texture, massive andesite lava, andesite-fragmented pyroclastic breccia, tuff, and lapilli breccia, and lava dome [7]. The succession was then overlain by Recent sediment.

The structure of NW Kalimantan is mostly dominated by the presence of Mensibau Granodiorite along with Raya Volcanic Rocks. Faults and lineaments in the plutonic and volcanic rocks of the area trend mainly N-NW. The N-NE trending conjugate fractures are also present [2]. The Raya Volcanic Rocks appear to be an extensive remnant of the large eroded volcanic cover of Mensibau Granodiorite. In the northern part of NW Kalimantan faults and lineament are largely follow W-NW in the west and E-NE in the east [4]. There is no clear structural significance on Niut Volcanics eruption but the NW trend of the eruption may be indicating a relationship with the prominent NW-trending faults and lineaments.

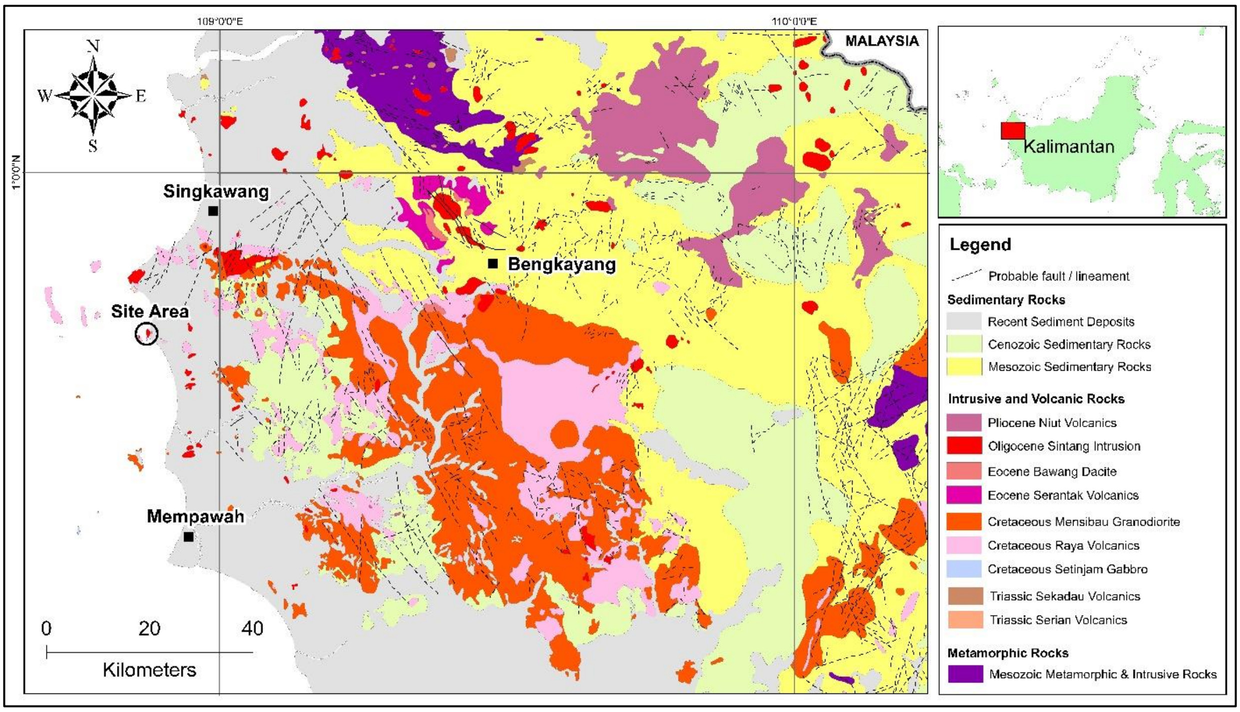

Figure 2. Simplified geological map of Northwest Kalimantan (modified from [1–5])

METHODS

There were three methods used for this study. They were field observation and sampling, lineament mapping, and mineralogy analyses. The field observation was conducted in Raya Volcanic Rocks outcrops near the NPP site and extended to a broader region around NW Kalimantan. The rock sampling was carried out on fresh rock with a minimum sample size of an adult human fist.

The lineament mapping was carried out using visual interpretation (manual tracing) to identify the lineament of the geologic and topographic features. The data set that was used was DEMNAS data with a spatial resolution of 0.27 arcsecond.

Mineralogy analyses were conducted using petrography and Advanced Mineral Identification and Characteristics (AMICS) from micro XRF scanning. The petrography analysis and micro-textures identification were identified in Petrography Laboratory, PRTBGN, using a polarization microscope. There were 14 samples for petrography analysis. micro XRF analysis was conducted using Bruker M4 Tornado Plus in a vacuum state at 500kV 600 µA. Scanning was performed in area mode with an X-ray spot size of 20 µm and an acquisition time of 12 ms/pixel, with a pixel size range from 25-50 µm. The instrument then collects the X-ray spectrum for each pixel. The spectrum intensity for each pixel represents element content from the scanned area. The outputs of this analysis were the map of elemental distribution and elemental composition of the scanned area. The data was then evaluated using Advanced Mineral Identification and Characteristics (AMICS) software provided by Bruker Nano Analytics. This software database consists of more than 2,000 minerals to provide rapid and easy automated identification and quantification of minerals present in the sample. Mineral identification is carried out by comparing the spectrum in the pixel with the mineral spectrum from the database. The result is a mineral distribution map with modal mineralogy from the scanned

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area. There were 16 samples for micro XRF analysis.

RESULTS AND DISCUSSION

Raya Volcanic Rocks Distribution

The result of field observation and sampling location for petrography and micro XRF analysis is displayed in Figure 3. The distribution of Raya Volcanic was wide, from Lemukutan Archipelago in NW until Sungai Temila in SE. The distribution was sparse in most of the area except in Banyuke Hulu and Menyuke.

The lithology of Raya Volcanic found in the observation points was andesite and basalt. In general, the appearance of andesite in this formation shows a dark gray to light gray, with inequigranular–subhedral porphyritic texture and massive structure. The phenocrysts were 2 to 5 mm in size, composed of plagioclase, pyroxene, hornblende, and a small amount of orthoclase mineral in several locations.

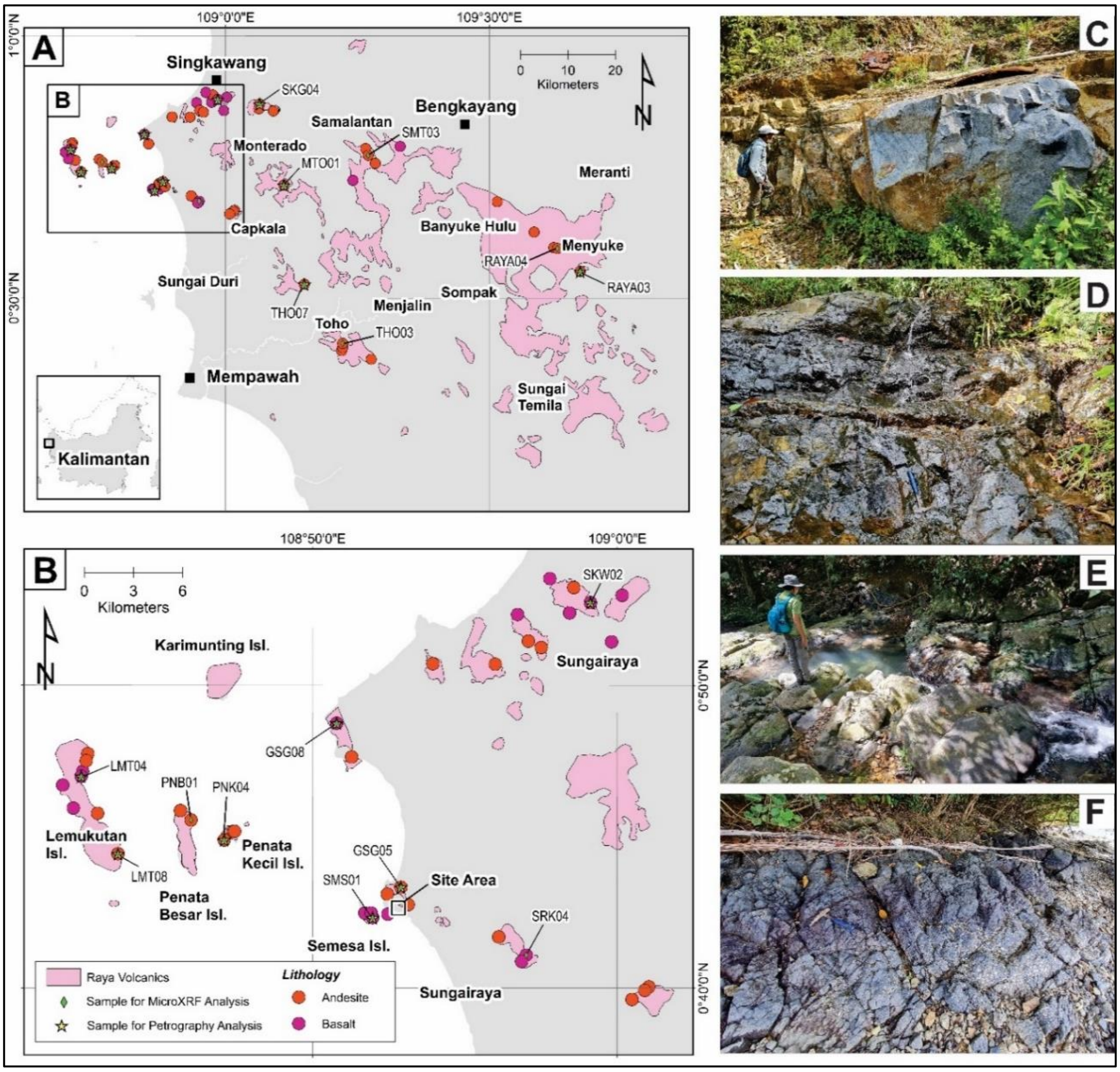

Figure 3. (A) Field observation result and sampling location, (B) Inset on near-site area, (C) andesite outcrops near Toho, (D) Basalt outcrop near Samalantan, (E) Andesite outcrop near Singkawang, and (F) Basalt outcrop on Semesa Island.

The basalts were dark gray to black, with aphanitic to porphyro–aphanitic texture and massive structure. They were composed of 1 to 3 mm plagioclase, pyroxene, olivine, and hornblende phenocryst, and aphanitic mafic mineral groundmass. The andesites were evenly distributed in all parts of Raya Volcanic Rocks, while the basalts were mainly found in the northern and western locations.

Lineament Analysis

The results of lineament mapping in Raya Volcanic and its surrounding shows that lineament highlight two major geological structures related to the geological process. The rose diagram of lineaments is presented in Figure 4. It shows two dominant orientations of the lineaments, oriented NNW–SSE and WNW–ESE.

Interpretation of older and younger faults is based on the morphological displacement effected by the lineaments. The displacement shows that the NNW–SSE orientation is cut by the WNW–ESE orientation indicating the former orientation is the older fault The WNW–ESE orientation is interpreted as the strike direction of sedimentary rocks or minor younger faults in West Kalimantan. The distribution of Raya Volcanic Rocks that relatively show NNW–SSE orientation is probably controlled by the NNW–SSE fault system.

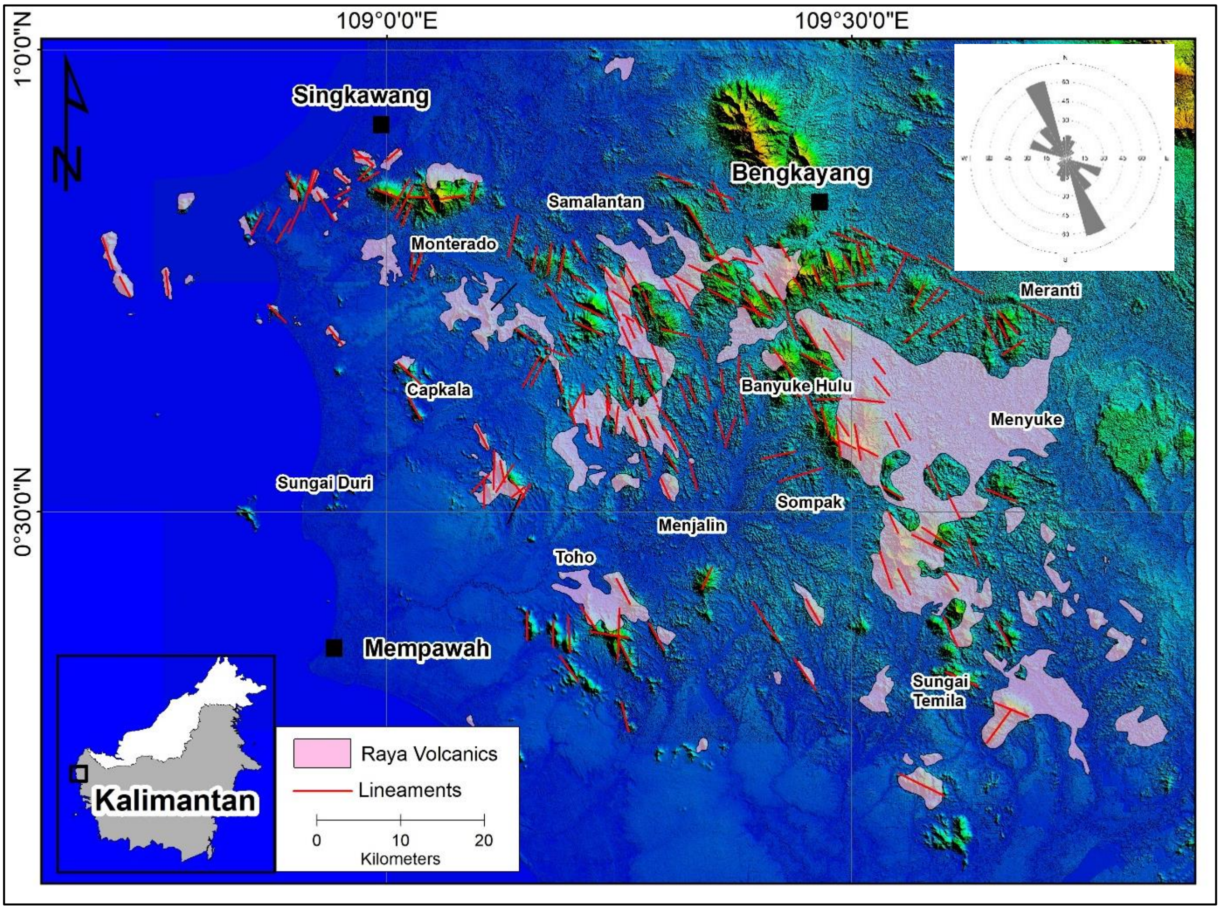

Figure 4. Manually digitized lineaments in Raya Volcanic Rocks and its surrounding using DEMNAS data and rose diagram of digitized lineaments using DEMNAS data.

Mineralogical Analysis

Based on the mineralogical analysis, lavas from Raya Volcanic were andesite to basalt in composition, shows dark hypocrystalline porphyritic rocks and altered in some places. The effects of mild alteration on the rock's samples are not considered in detail in this research.

Samples were characterized by a moderate abundance of phenocryst (up to 60% of the rock mass) dominated by plagioclase (30–45%), alkali feldspar (10–20%), pyroxene (10–15%), hornblende (3–5%), olivine (1–3%), quartz (1–5%), and opaque minerals (Fe-Ti oxides) (2–5%) phenocryst in some glassy-microlithic groundmass. Intergranular, latite, poikilitic, trachytic, and glomerocryst textures are commonly found in thin sections. Some mineral analysis described as follows:

1. Olivine

Olivine was found in three samples as greenish and rounded phenocryst. Most of them were corroded and shows embayment textures. Based on micro XRF quantification, the type of olivine is fayalite with FeO number above 40 wt% as displayed in Figure 5.

2. Plagioclase

Plagioclase was the most dominant phenocryst in the Raya Volcanic lava sample. The plagioclase phenocrysts are subhedral to anhedral, prismatic, colorless, mostly altered to sericite. Based on micro XRF analysis, the type of plagioclase is labradorite to oligoclase. There are some inclusions in the body of plagioclase that contain opaque minerals and pyroxene. Many plagioclase crystals, especially the large size crystal, developed diverse and multiple micro-textural domains.

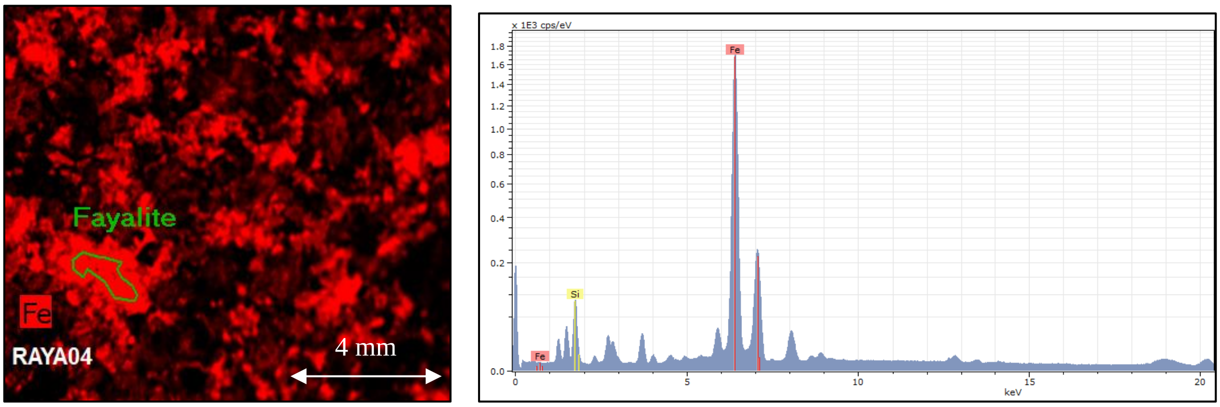

Figure 5. Fe-distribution map of RAYA04 and micro XRF Spectrum of fayalite phenocryst (green area).

Micro textures of plagioclase that were observed in the samples are sieve (coarse sieve, fine sieve), cumulocryst, glomerocryst, zoning, synneusis, and resorption surface (rounded corner zone). Most of the plagioclase is normally zoned but some show reversed and more complex zoning in the same samples. Representative plagioclase micro textures are presented in Figure 6.

3. Alkali Feldspar

Alkali feldspar was identified as colorless and subhedral to euhedral crystal in a thin section. The alkali feldspar common formed glomerocryst with plagioclase and pyroxene as can be seen in Figure 7A. Most of them were altered to sericite.

4. Pyroxene

Pyroxene was found in all samples as a phenocryst. The pyroxenes are anhedral to subhedral and mostly altered or undergo opacitization. They are displayed in Figure 7B-7E. Based on micro XRF analysis, the pyroxene found in the samples was dominated by orthopyroxene. The pyroxene phenocryst exhibits normal and oscillatory zoning with the zoning pattern of pyroxene phenocryst as depicted by the micro XRF section in Figure 7F.

5. Hornblende

Hornblende is identified as a greenish-brown crystal in subhedral–anhedral forms. Its shows a reaction relict. Most of them were replaced and rimmed by opaque minerals. Pyroxene is found as the inclusion of hornblende together with opaque minerals. Micro XRF data shows that the hornblende belongs to calcic amphibole. Hornblende from SKG4 shows complex chemical zoning (fluctuation pattern from core to rim), indicating magma mixing process in the magma chamber as depicted in Figure 8.

6. Opaque Minerals (Fe-Ti oxides)

Opaque minerals as Fe-Ti oxides are present in all samples. Mostly it was found as inclusions in other phenocrysts and abundant in the groundmass. The Fe-Ti oxides are mostly ilmenite and magnetite. The micro XRF Spectrum of manganoan ilmenite and ilmenite are shown in Figure 9 and Figure 10.

7. Quartz

Samples identified from Raya Volcanic show the occurrence of embayment quartz as xenocryst. It is 0.2–1.5 mm in size and embayed in the rounded form. The photomicrograph of embayment quartz is depicted in Figure 11.

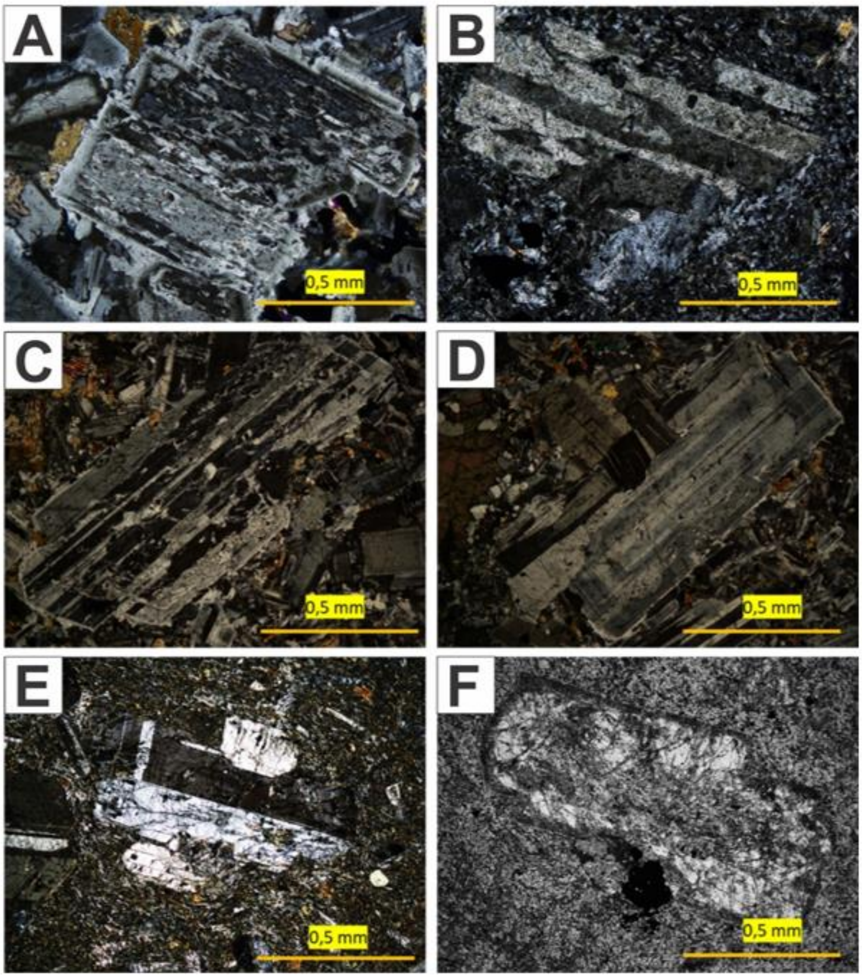

Figure 6. Photomicrographs from Raya Volcanic samples showing disequilibrium textural features of plagioclase. (A) Coarse sieve with rounded zone corner, (B) spongy cellular sieve, (C) seritization, rounded zone corner, (D) zoning, (E) synneusis phenocryst in trachytic microlith groundmass, (F) fine sieve in the crystal rim.

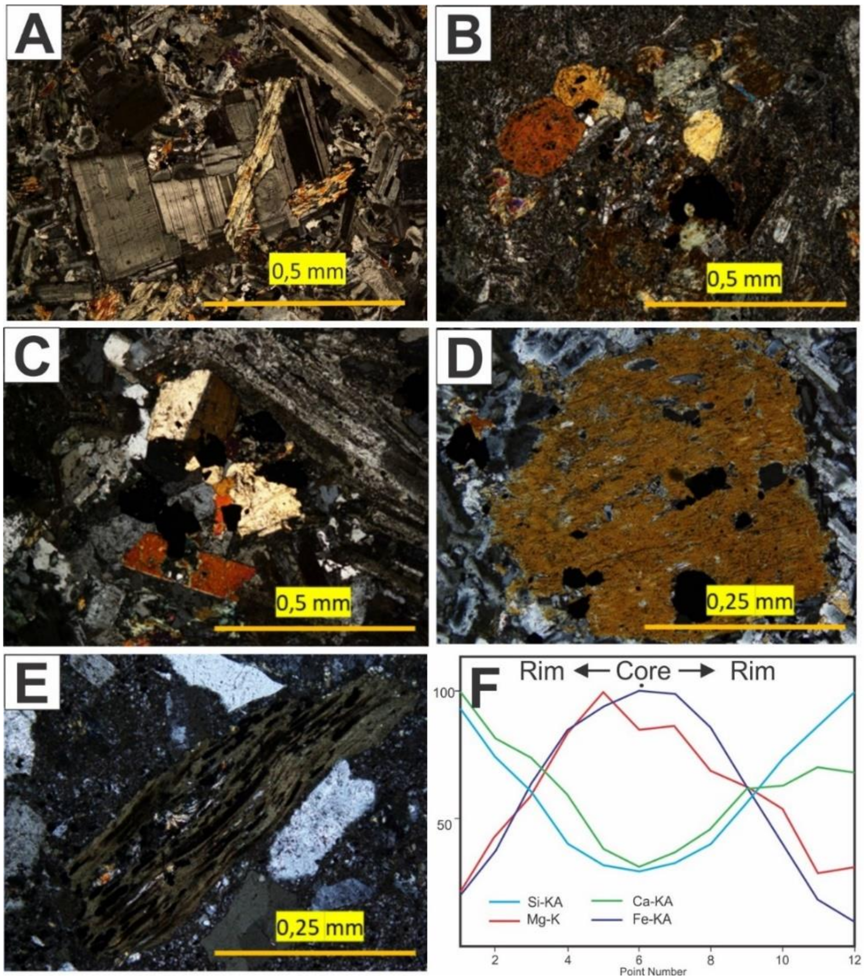

Figure 7. Photomicrograph of alkali feldspar and pyroxene in Raya Volcanic samples. (A) Alkali Feldspar, (B) twin pyroxene, (C) glomerocryst-pyroxene and plagioclase, (D) opaque inclusion in pyroxene, (E) opacitization in pyroxene, and (F) normal zoning pattern of pyroxene phenocryst.

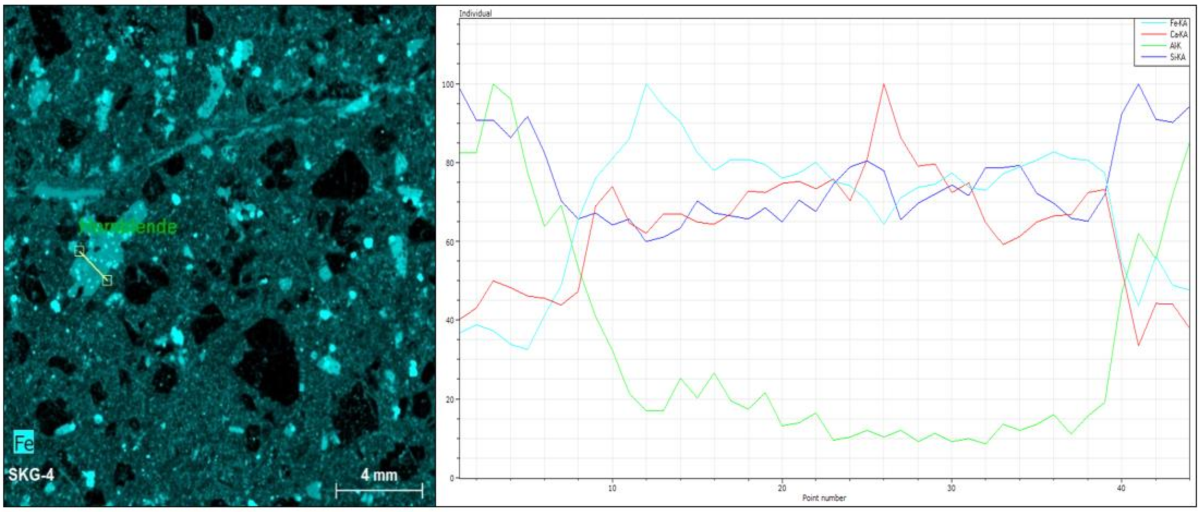

Figure 8. Fe distribution of SKG4 and complex chemical zoning pattern in hornblende (yellow line).

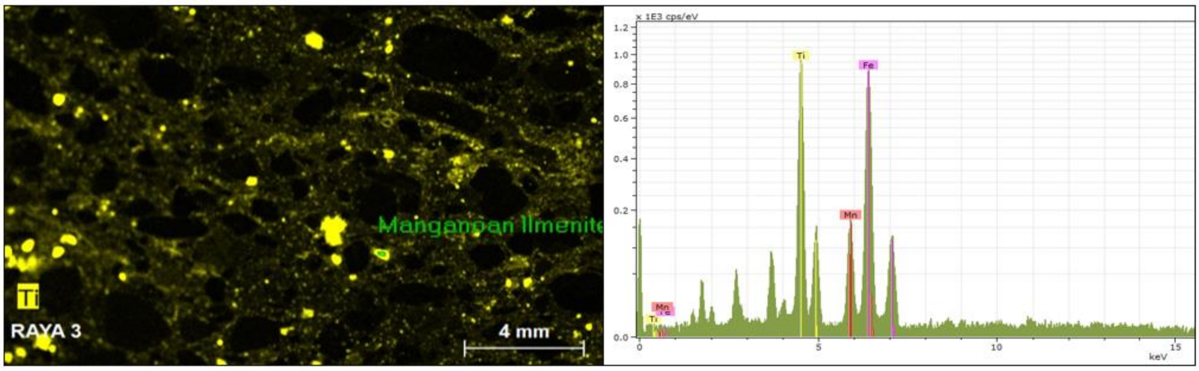

Figure 9. Ti distribution of RAYA3 and micro XRF spectrum of manganoan ilmenite (green point).

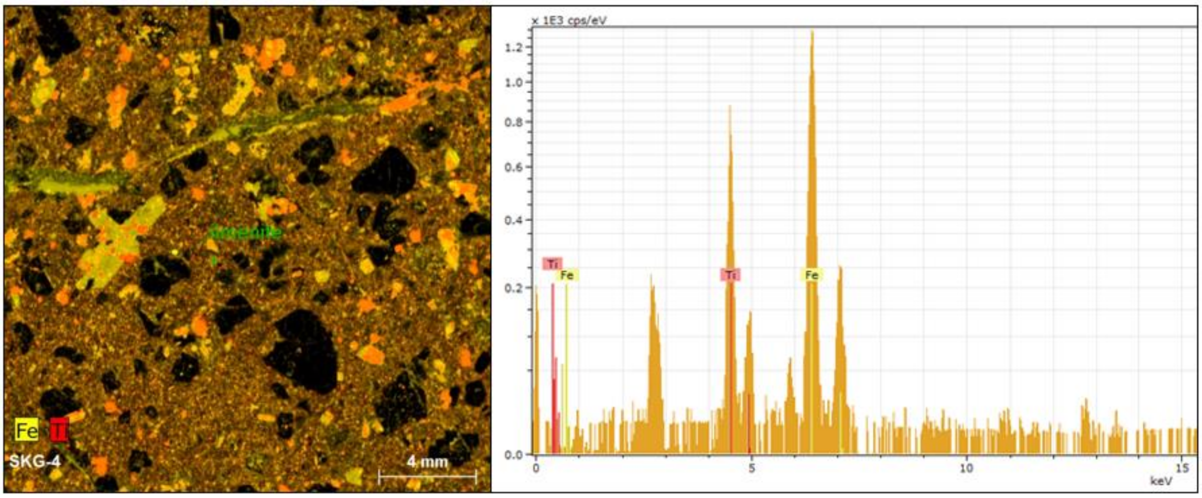

Figure 10. Fe-Ti distribution map of SKG-4 and micro XRF spectrum of ilmenite (green point).

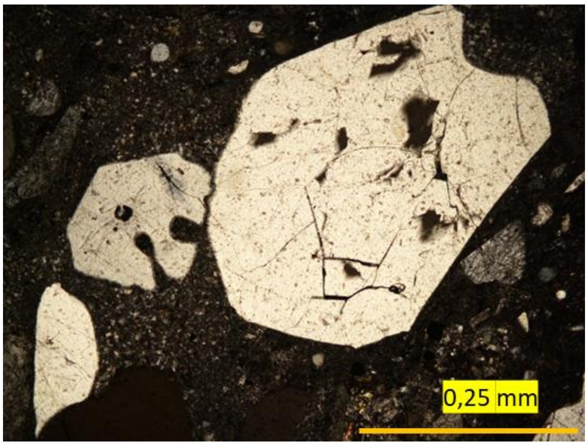

Figure 11. Quartz xenocryst showing embayment texture.

Crystal fractionation and magma mixing happened in the magma chamber during magma ascent beneath Raya. Crystal fractionation is indicated by the variation of crystal present in the rock samples starting from olivine to hornblende and labradorite to oligoclase. Magma mixing was interpreted based on scanline mineral chemistry analysis of hornblende and plagioclase that shows increasing Ca content in the middle crystal followed by decreasing Ca content to the rim [13]. This interpretation is supported by the occurrence of plagioclase micro textures in identified samples.

Plagioclase zoning is commonly found in the thin section of Raya Volcanic samples. Zoning in the crystal's body shows that each layer indicated its characteristic of crystal melts equilibrium [14]. The equilibrium of crystal melts can be different for each layer/zone in plagioclase. Detailed analysis of the chemical pattern in zoning could help the interpretation of magmatism in the magma chamber [13]. Hornblende crystal also shows chemical zoning based on micro XRF scanline analysis. Its fluctuating chemical zoning from core to rim indicated the raising of temperature during the crystallization process followed by slow cooling at the end of crystallization [15]. It may relate to some Ca-rich magma injection in a deep magma chamber [16],[17]. Unlike plagioclase and hornblende (Figure 7D), zoning identified in pyroxene under micro XRF scanline common shows as normal zoning.

Fine sieve textures in plagioclase can be formed during the decompression process or reaction with hotter Ca-rich melt [18],[19]. It shows that the new injection magma has a higher Ca-content, with a higher temperature. The dissolution and crystal fractionation process then followed the injection process. The dissolution process occurred due to the ascend of H_2O-undersaturated magma at a fast rate that caused the $P(H_2O)$ of the system to increase when re-injection happened. It can reduce the stability of plagioclase crystals [20]. The dissolution process made the void a trap for the entrained melt and later formed as sieve textures.

The size of coarse sieve morphology that decreases towards the outer margin implies the variation of the dissolution process that occurred in the magma chamber. The variation may be due to the variation rate of H_2O content or ascent dissolved in magma [20]-[22]. While the interconnected and large size sieve textures indicated an intense and prolonged dissolution.

Glomerocryst texture is also related to the dissolution process [19]. Dissolution could create a boundary layer melt around the grains, when it is followed by a cooling process then the crystals will bind together the similar phenocryst nearby. This texture can be followed by further growth as single grain by developing a common growth zone with a fine sieve or clear plagioclase along the outer rim as seen in the studied samples.

During magma ascent, assimilation also occurred in the magma chamber. Rounded-embayment quartz in andesite could indicate the partial melting process [23]. The partial melting process could produce gasses that flow through the compositional boundary layer. It makes the instability in magma reservoir and the embayment texture formed [24].

The opacitization textures were identified in hornblende and pyroxene. Opacitization of hornblende and pyroxene in andesite could indicate the intensive oxidation process during magma cooling [15],[25]. The intensive oxidation process can be related to the slow cooling process. The interpretation of the slow cooling process during the formation of Raya Lavas is supported by the occurrence of Fe-Ti oxides as inclusion in some phenocryst.

During the syn-eruptive stage, decompression, and oxidation process occurred in the shallow magma chambers. Plagioclase microlith in the Raya Lavas samples implies that the lava has undergone effective cooling near the surface or increased the liquidus temperature, degassing, and vesiculation induced by magma syn-eruption due to decompression. When the erupting magma decompressed, the gas-rich vesicles try to escape and provide the broken crystal [19].

To sum up, petrographic features of Raya Volcanic Rocks samples reflect a complex magmatic process of the open magmatic system [26]. The scenario of the magmatic process could be conceived as follows: it began with mafic magma as a product of partial melting of the mantle, crystal fractionation starts here, magma cooling slowly in the deep/bottom of the magma chamber, and there is the separation of olivine and melts. The density of melts was decreased, and magma move upward. During magma ascent, there was magma-rocks interaction and provide assimilation process. Besides that, there is also an injection of hotter/more Ca-rich magma that produces disequilibrium textures in the crystal. This process is followed by magma mixing. The magma mixing process continued throughout the generation of Raya Volcanic products. When magma reach the shallow magma chamber, intensive cooling and decompression occurred and magma erupted as lava flowed.

Raya volcanic lava flows are distributed along the faults indicated by the present lineament. Vents or eruption centers formation was affected by a fault in the surface. In this case, vent distribution is not associated with a single central conduit [27] but is related to fault that creates space for magma to move laterally or fissure-like system.

CONCLUSION

The distribution of Raya Volcanic Rocks that relatively show NNW–SSE orientation is controlled by the NNW–SSE fault system. Vent distribution of Raya Volcanic is controlled by a fault that formed a fissure-like system and its distribution is not associated with a single central conduit. Based on the field observation and mineralogical analysis, Raya Volcanic Rocks erupted as lava flows derived from mafic magma as a product of mantle partial melting that underwent crystal fractionation, assimilation, injection of hotter/more Ca-rich magma, and magma mixing that produces basaltic-andesitic magma on an open magmatic system.

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AUTHOR CONTRIBUTIONS

The first six authors were the main contributors while the other three were the member contributors. WAD: manuscript draft, visualization, methodology, mineralogy analysis, data interpretation. FP: manuscript draft, methodology, mineralogy analysis. N: Team leader, methodology, supervising, editing, and review. IGS: Methodology, fieldwork, sampling collection, supervising, editing and review. TBA: Fieldwork, sampling collection, database, lineament analysis, manuscript drafting. RCC: Fieldwork, sampling collection, GIS, database, manuscript drafting, figures visualization. ENSA: sample preparation. EA: sample preparation, petrography analysis. VDS: sample preparation, micro XRF, and AMICS analysis. All author has read and approved the final manuscript.

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