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Tertiary Magmatism in Northwestern Kalimantan: Probability of Volcanic Hazard to The Nuclear Power Plant Site Candidate at Gosong Beach, Bengkayang Regency

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Abstract - Gosong Beach in Bengkayang, West Kalimantan, is selected as a potential Nuclear Power Plant (NPP) site candidate. Volcanic and intrusive rocks are found in the radius of 150 km from it. Based on IAEA (International Atomic Energy Agency) standard, the main assessment target is volcanic rock that is younger than 10 Ma. However, there are Tertiary volcanic and intrusive rocks next to and cover a wide area around the NPP site that show volcanic activities over the Tertiary period. Therefore, it is necessary to investigate this group of rocks to understand its characteristics. This study aims to characterize the geochemistry and petrology of the Tertiary volcanic and intrusive rocks found in northwestern Kalimantan. The fieldwork was conducted to observe and to take Serantak volcanic rocks, Bawang dacite, Niut volcanics, and Sintang intrusion samples. The XRF and micro-XRF analyses were conducted to characterize the geochemical aspect, while petrography and AMICS analyses were conducted to characterize the mineralogical aspect. The result shows that Serantak volcanic rocks, Bawang dacite, Niut volcanics, and Sintang intrusion are derived from tholeiitic to calc-alkaline as a product of mantel partial melting in the subduction zone which go through fractional crystallization. The volcanic activity was initiated by the rise of primitive parental magma from partial melting in the shallow-depth subducted crust as indicated by the garnet-free HREE pattern, the enrichment of LILE and LREE, and the depleted HREE. The Tertiary magmatism in northwestern Kalimantan was found in a small activity with a small impact on the NPP candidate site at Gosong Beach, Bangkayang.

Keywords: Tertiary, volcanic-intrusive rocks, Sintang intrusive, Niut volcanic, Bawang and Serantak volcanics

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Introduction

Background

Gosong Beach in Bengkayang, West Kalimantan, is selected as a potential NPP site (Figure 1). Based on a previous study, this area suits the criteria for an NPP site. It has relatively stable soil and rocks with low seismicity, far from active geological structure, proper land use and terrain, and is near a road network (Alhakim *et al.,* 2019; Susianti and Sunarko, 2019; Hasanah and Reinhart, 2019; Salsabila *et al.,* 2021). However, further site evaluation assessments still need to be done to ensure the safety of the facility and the activity of the nuclear installation. One aspect that needs to be evaluated is hazard due to volcanic activity (IAEA, 2019).

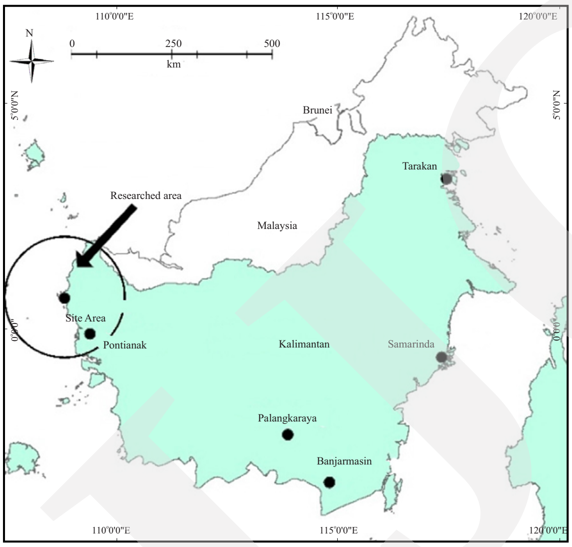

Figure 1. Location of the researched area.

Volcanic hazard is a phenomenon related to volcanism that could impact the site suitability or the design of a nuclear power plant (IAEA, 2016). The initial stage for volcanic hazard assessment for nuclear installation is to define the investigation area surrounding the candidate of the NPP site that covers all potential sources of volcanic hazard and data collection of volcanic activity within a defined region, especially during the past 10 Ma.

Indonesia is famous for its chain of active volcanoes as part of the Pacific Ring of Fire. As a region far from it, Kalimantan is usually left out of any volcanic hazard study. However, several volcanic rocks from the Late Triassic to Pliocene were identified in the 150 km radius of the site on the regional-scale geological map of West Kalimantan (Pieter and Sanyoto, 1989; Rusmana *et al*., 1993; Supriatna *et al*., 1993; Suwarna *et al.,* 1993). The Late Triassic Serian, and Jambu volcanics are identified near the border with Sarawak, Malaysia, whilst Sekadau volcanics are identified in the Sambas area. The Cretaceous Raya volcanics are widely distributed and which can be found around the vicinity of NPP site candidate to nearly 150 km from the study site. Serantak volcanics and Bawang dacite of Eocene age are located approximately 70 km from the site. The Pliocene Niut volcanics are around 100-150 km from the site. Furthermore, the Sintang intrusives of Early Oligocene to Early Miocene, although not a volcanic rock, are located at a short distance from the potential NPP site.

The quality of basic geologic research, the history of volcanic processes, and the investigators familiarity with a wide range of eruptive activities all contribute to the success of volcanic hazard assessments in the NPP site (McBirney *et al.,* 2003). Moreover, due to their close connections, volcanic hazard assessment could be the input for seismic assessment. Based on the IAEA safety guide, the main assessment target is Niut volcanics which were active during the past 10 Ma. A recent study of volcanic products from Semadum Volcano, part of Niut volcanics, concludes that the activity of Semadum Volcano does not have any impact on the potential NPP site, because the products of Semadum Volcano have low viscosity and has a VEI score of less than 2 (Hussein *et al*., 2020).

Based on the IAEA safety guide, volcanic events older than 10 Ma are not an obligatory object for volcanic hazard assessment. However, there are Tertiary volcanic and intrusive rocks next to and covering a wide area around the NPP site in West Kalimantan that show volcanic activities over the Tertiary period. Most volcanic terrains have seismicity, which can cause mass movement on the volcano slopes even without new magmatism (McBirney *et al.,* 2003). Thus, it is vital to understand its characteristics and to assess the magmatism process related to intrusion and volcanic rocks found near the Gosong Beach. However, most of the rocks are older than 10 Ma.

The objective of this study is to characterize the geochemistry and petrology of Tertiary volcanic and intrusive rocks found in Bengkayang Regency, West Kalimantan. The result from this study thus can be used to evaluate whether there is any potential hazard to NPP site from these Tertiary magmatism activities.

Regional Geology

Multiple accretions of crust form Kalimantan to Sundaland from the Mesozoic onwards (Breitfeld *et al.*, 2017). The northwestern Kalimantan area is grouped into the Kuching Zone. Generally, the northwestern part of Kalimantan composed of underlying Mesozoic metamorphic and intrusive rocks are overlain by Mesozoic and Cenozoic sedimentary and volcanic rocks which are also intruded by various kinds of Cenozoic intrusive rocks (Pieter and Sanyoto, 1989; Pieter and Supriatna, 1990; Rusmana *et al.*, 1993; Supriatna *et al.*, 1993; Suwarna *et al.*, 1993). A previous research has revealed the simplified geological map of the area (Draniswari *et al.*, 2021) as illustrated in Figure 2. This paper focuses on the Cenozoic magmatic period of northwestern Kalimantan that formed three magmatic products. The first is Eocene volcanism producing Serantak volcanic rocks and Bawang dacite. The Sintang intrusion then emerged from the Late Oligocene - Early Miocene magmatism. The last is Pliocene volcanism that erupted the Niut volcanic rocks.

Serantak volcanic rocks and Bawang dacite are identified by circular features in the north of Bengkayang capital city. These rock groups lay unconformably on Mesozoic sedimentary rocks of the Bengkayang Group and Raya volcanic rocks. Serantak volcanic rocks consist of dacitic lapilli, crystal and lithic tuff, tuffaceous breccia, and rhyodacite. Bawang dacite comprises dacite with phenocrysts of plagioclase, quartz, and minor biotite. It was thought to be the late-stage of magmatic activity accompanying the Serantak volcanic rock formation. A single K-Ar age of Bawang dacite reveals the formation at 51.3 Ma or Early Eocene (Suwarna *et al.*, 1993).

Sintang intrusion consisting of diorite, quartz diorite, granodiorite, tonalite, and quartz gabbro were widely distributed in northwestern Kalimantan. The studied area intruded the central part of Serantak-Bawang Complex, the northeastern part near the border of Indonesia

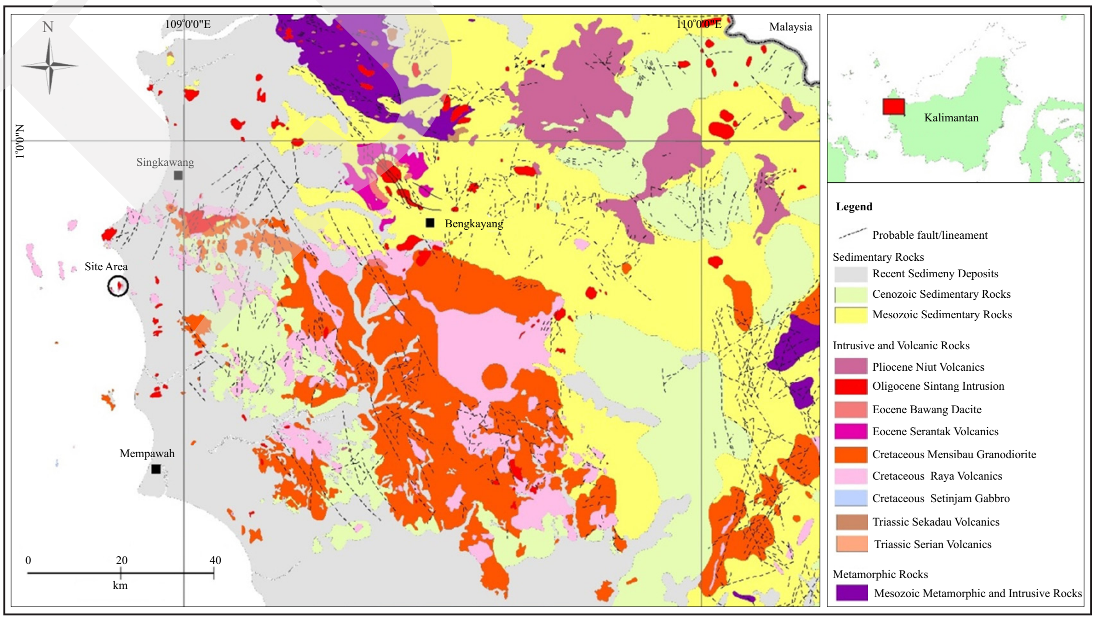

Figure 2. Simplified geological map of the researched location (Draniswari *et al.*, 2021).

and Malaysia, and on the coast of Singkawang and Bengkayang including the NPP site. It was noted as postsubduction magmatism in the Oligocene - Early Miocene (Suwarna *et al*., 1993).

Niut volcanic rocks are widely distributed in the northeastern part of the studied area. The morphology reflects several cones and circular features. This rock group comprises porphyritic basalt and minor basaltic andesite (Suwarna *et al*., 1993). A recent study (Hussein *et al*., 2020) described the lithology of a cone named Semadum Volcano of Niut volcanic rocks. Vesicular-scoria texture of andesite-basaltic lava, massive andesite lava, pyroclastic breccia with andesite fragment, tuff, lapilli breccia, and lava dome were found on the Semadum Volcano (see Figure 3). Vesicular-scoria of andesitic-basaltic lava with texture is distributed widely on the low plain of the Semadum Volcano. Meanwhile, the other lithologies construct a cone morphology. The study of Semadum Volcano also revealed the calc-alkaline affinity of the rock group.

Research Methods

Three methods were conducted in this study, those are field investigation, petrological analysis, and geochemical analysis.

The fieldwork was conducted in three areas. The first was conducted at Singkawang area to observe and to take samples of Sintang intrusion

Figure 3. Products of Semadum Volcano as Niut volcanics: (a) Lava dome, (b) Massive andesitic lava, (c) Andesitic-basaltic lava, (d) Tuff, (e) Andesitic fragmented pyroclastic breccia, (f) Tuff and lapilli.

near the site. The second area is the Serantak-Bawang Volcanic Complex near the capital of Bengkayang Regency to observe and to take samples of Serantak volcanic rocks, Bawang dacite, and Sintang intrusion. The last area is Niut Volcanic Complex near Sanggau Ledo to observe and to take samples of Niut volcanic rocks.

Petrographic analysis was conducted at the Mineralogical Laboratory at the Centre for Nuclear Materials and Radioactive Waste Technology-BRIN using an Olympus BX-51 microscope. Eight samples from Bawang dacite (3), Serantak Volcanics (2), and Sintang intrusive (3) were analyzed. Niut Volcano petrographic results will refer to the data from Hussein *et al*. (2020).

Nineteen samples of Tertiary volcanic and intrusive rocks from Bawang dacite Serantak Volcanics (6), Niut Volcanics (8), and Sintang intrusive (5) around the proposed NPP site at northwestern Kalimantan were analyzed for their major and trace elements content. The concentration of major elements and trace elements were determined at the P.T. Indo Mineral Research-Laboratory. Major elements were determined using X-ray fluorescence on a Bruker XRF S8 Tiger spectrometer and OREAS 482. OREAS 543 was also used as the standards. The trace ele- ments were determined using ICP-MS on a 7900 ICP-MS spectrometer. OREAS 74b and OREAS 460 were used as the standards. Loss on Ignition (LoI) value for XRF analysis was obtained by using LECO TGA701. These tools can determine

the weight loss or LoI from various materials.

Further analysis to get mineralogical data was carried out using Micro-XRF and AMICS (Advanced Mineral Identification and Characteristics). Micro-XRF analysis was conducted using Bruker M4 Tornado Plus (Flude *et al*., 2017). Bruker M4 Tornado Plus operates at 500kV and 600μA set in the area mode with 20 μm spot size, 12 ms/pixel acquisition time, and pixel size ranging from 30-40 μm. The result is an elemental distribution map, which then was evaluated using AMICS Software provided by Bruker Nano Analytics to identify the mineral composition of the scanned area (Barker *et al*., 2020). The identification of mineralogy was car- ried out by comparing the spectrum from each pixel with the spectrum of minerals from the AMICS database.

Result And Discussion

Field Observation

Three areas of field observation are shown in Figure 4. Outcrops of Serantak volcanic rocks have the lithology of andesite, tuff, and pyroclastic breccias. Andesite is bright grey, massive, inequigranular porphyritic, phenocryst size 1−3 mm in the form of plagioclase and pyroxene. Lithological characteristics of tuff in this formation are white to dark grey showing layers intercalated with lapilli, composed of ash tuff and lithic tuff. An outcrop of layers of tuff is displayed in Figure 5a. The pyroclastic breccia is reddish brown, intercalated with brown tuff. The size of the fragments in the pyroclastic breccia ranges from 0.5 to 3 cm, composed of tuff and andesite lithic, also plagioclase minerals.

Meanwhile, Bawang dacite outcrops comprises of lithology in the form of bright grey dacite, showing an autoclastic breccia structure, porphyritic, hypo-crystalline, subhedral inequigranular texture. The phenocrysts are 3-5 mm in the form of plagioclase and quartz. The outcrop of Bawang dacite is depicted in Figure 5b.

Niut volcanic rocks were divided into the products of Semadum Volcano and Niut Volcano. The central eruption and lithologic type differentiate those two classifications. The Semadum Volcano products have been described in the previous work (Hussein *et al*., 2020), while the Niut Volcano itself is composed of dacitic lava with massive structure and porphyritic texture. The outcrop of dacite of Niut volcanics is depicted in Figure 5c. The dacite shows a light grey colour and massive structure, the phenocryst consisted of quartz and feldspar with 1 3 mm size, subhedral inequigranular texture. Those lithologies are

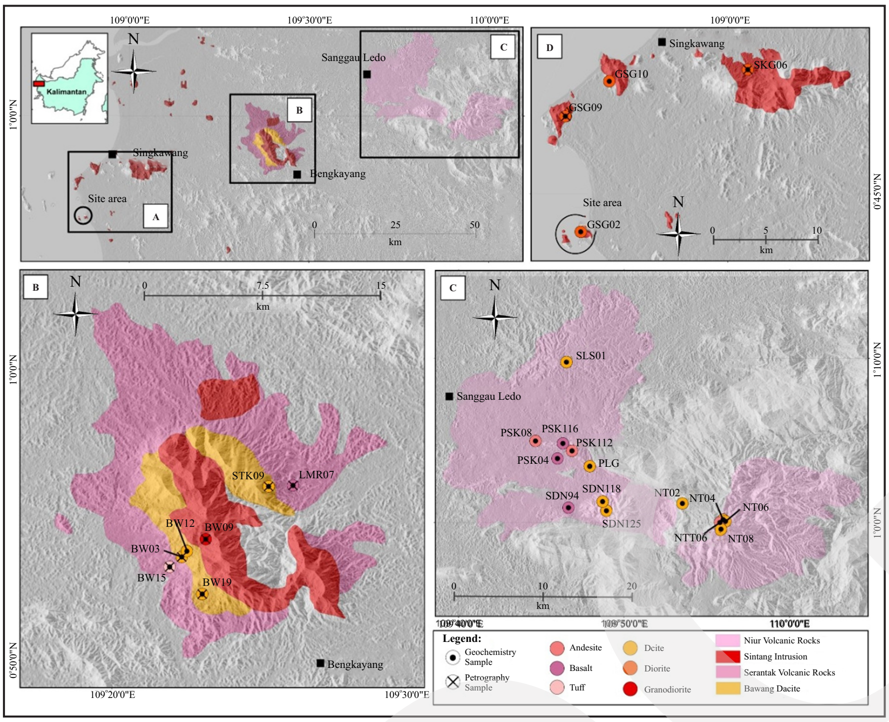

Figure 4. Field observation result and sampling locations.

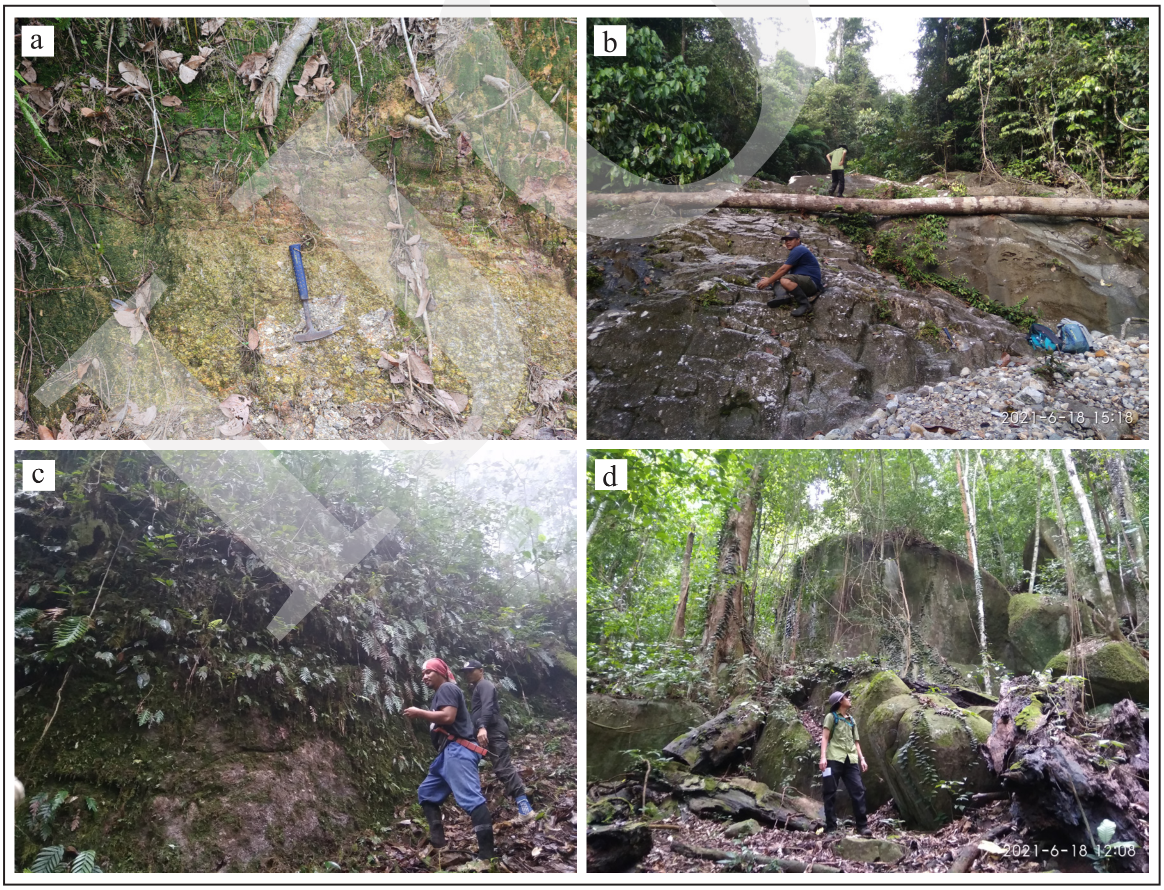

Figure 5. Outcrops observed in the studied area: (a) layers of tuff and lapilli of Serantak volcanics, (b) dacite outcrop of Bawang dacite, (c) dacite lava outcrop of Niut volcanics, (d) granodiorite of Sintang intrusion.

distributed around the peak of Niut Volcano and its east flank.

The outcrops observed as part of Sintang intrusion were quite diverse including diorite, granodiorite, and microdiorite. The granodiorite shows a white colour, massive structure, phaneritic, crystal size 2–5 mm, subhedral equigranularity. The crystals composed of quartz, plagioclase, biotite, and a little hornblende. Andesite intraclast is also present at several observation locations. The diorite shows a grey colour, massive structure, phaneritic, crystal size 2−3 mm, subhedral equigranular. The crystals are composed of plagioclase, hornblende, biotite, and a little quartz. The microdiorite has a similar appearance and composition to diorite, but has a finer crystal size. An outcrop of granodiorite is depicted in Figure 5d.

Petrography

Sintang Intrusive

Three samples that represent different lithologies collected from Sintang intrusive were petrographically analyzed. They consisted of diorite, granodiorite, and quartz granodiorite. Petrographically, they show a holocrystalline phaneritic texture with euhedral to anhedral crystal. Intergranular, poikilitic, and hypidiomorphyc texture were also observed. The samples also show some mild alterations in some places.

The samples comprises of plagioclase, alkali feldspar, quartz, pyroxene, and hornblende with a minor amount of biotite, muscovite, olivine, and opaque minerals. Secondary minerals such as epidote and chlorite are also found in the samples. From micro-XRF analysis (see Figure 6), opaque mineral is found as ilmenite, titanite, and pyrite.

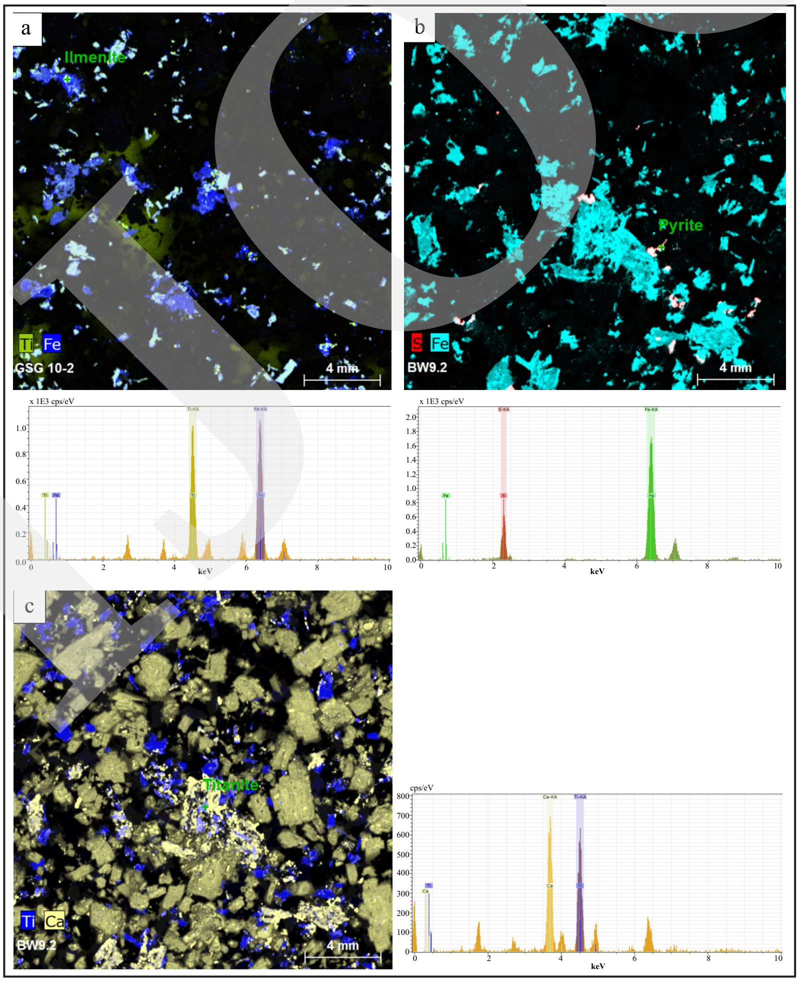

Figure 6. Element distribution and spectrum of opaque mineral. (a) Fe-Ti distribution and ilmenite spectrum, (b) Fe-S distribution and pyrite spectrum, (c) Ca-Ti distribution and titanite spectrum.

Plagioclase is the dominant mineral found in these samples. It shows euhedral to anhedral prismatic crystal. The plagioclase crystal often shows polysynthetic twinning (albite and calsbad twinning). Some of the plagioclase also shows microtextures such as resorption surface (rounded corner), the inclusion of opaque minerals, and zoning. Zoning in plagioclase is normal, indicated by a decrease in Ca content from the core to the rim in the zoned plagioclase (see Figure 7) and oscillatory zoning. Based on micro-XRF analysis, the plagioclase type in these samples are albite to andesine. Photomicrographs of plagioclase micro-texture are shown in Figure 8.

Bawang and Serantak Volcanics

Bawang and Serantak volcanics consist of lava, pyroclastic breccia, and tuff. Five samples of lava and one sample of tuff collected from this rock unit were petrographically analyzed. The result of petrography observation shows lavas have various compositions from andesite to rhyolite (see Figure 9).

In general, lavas have porphyritic with hypocrystalline to holocrystalline texture, and show mild alteration in some places. The rhyolite is made up of plagioclase, quartz, alkali feldspar, opaque mineral, and hornblende phenocryst embedded in volcanic glass and microcrystalline felsic groundmass. Zeolite, biotite, muscovite, chlorite, and epidote are found as a secondary mineral. The vein of chlorite, epidote, and quartz also occur in this sample.

The andesite consist plagioclase, hornblende, pyroxene crystal, and opaque minerals, with zeolite found as secondary minerals. Some

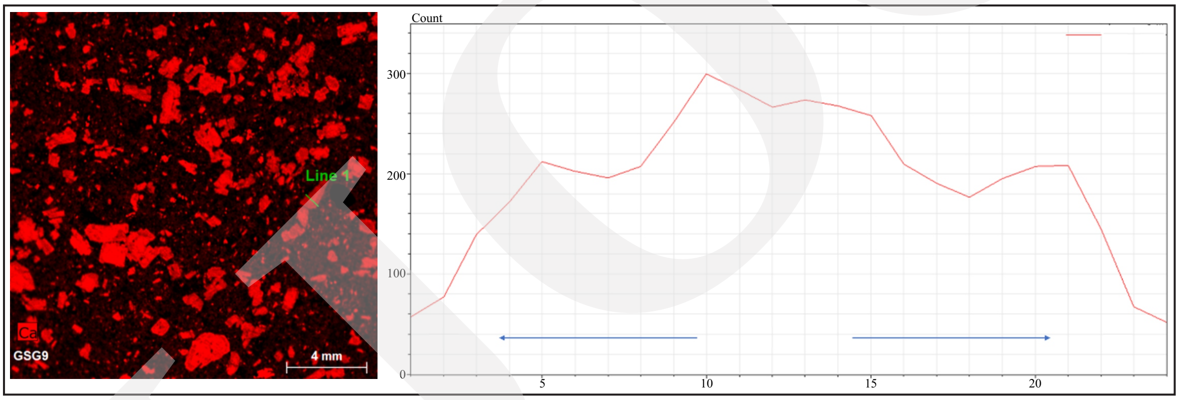

Figure 7. Ca distribution and normal zoning pattern of plagioclase.

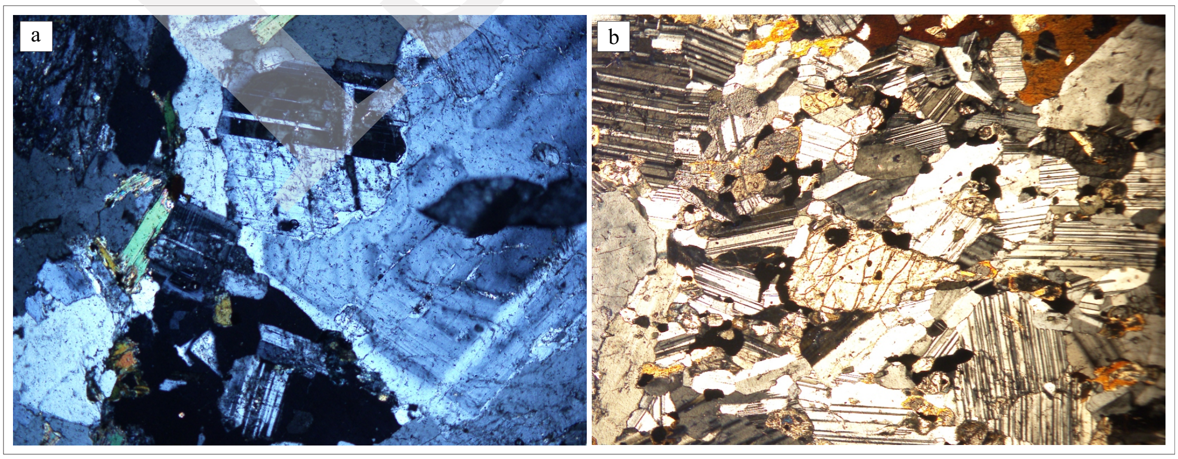

Figure 8. Photomicrographs of plagioclase microtexture from Sintang intrusive. (a) Zoning and resorption surface, (b) Polysynthetic twinning. Field of view 4 mm.

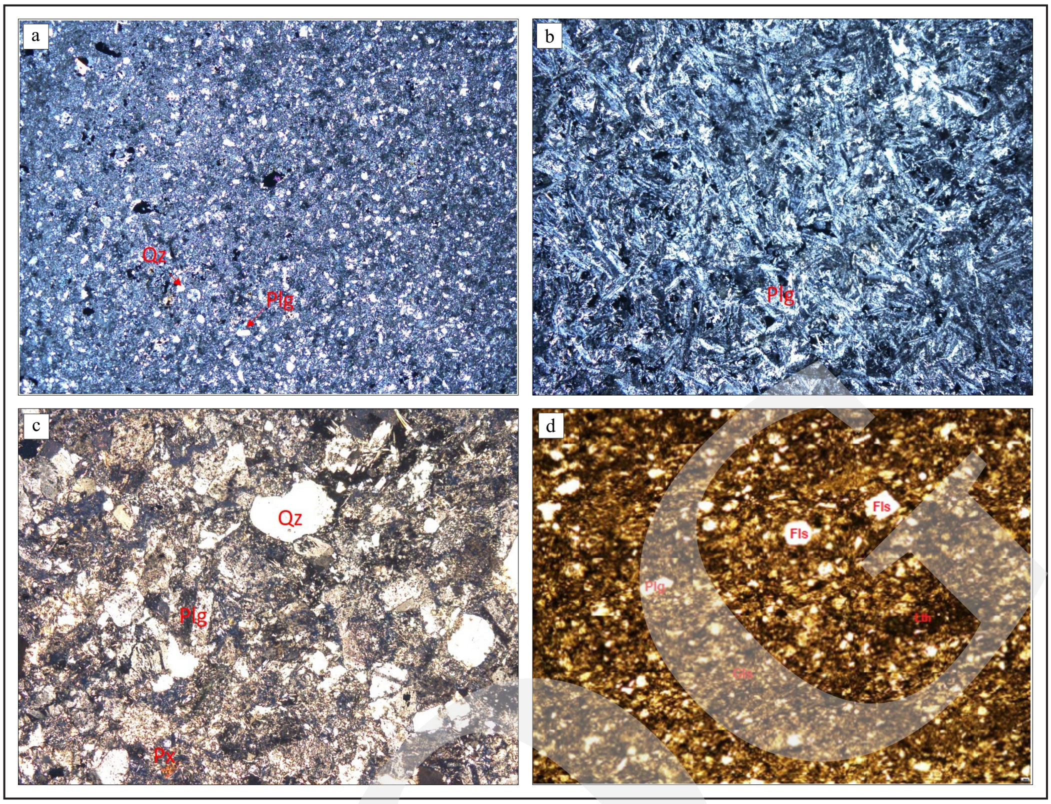

Figure 9. Photomicrographs of rocks from Bawang and Sintang volcanics (a) Rhyolite, (b) Andesite, (c) Dacite, (d) Crystal tuff. Field of view 4 mm.

of the plagioclase crystal shows a swallow-tail texture.

The dacite comprises plagioclase, quartz, alkali feldspar, hornblende, pyroxene, and opaque mineral phenocrysts embedded in plagioclase microlite groundmass. The zeolite, chlorite, and epidote are recognized as secondary minerals.

Based on micro-XRF analysis, the opaque mineral is found as titanite and pyrite (see Figure 10).

The tuff is composed dominantly of crystal fragments consisting of plagioclase, alkali feldspar, quartz, opaque minerals, and pyroxene. Lithic and glass fragments were observed in less than 20 %.

Porphyritic texture indicates the rock form in the magma that has cooled and solidified in two stages. Bigger crystals (phenocrysts) grow earlier during slow, subsurface cooling magma, then rapid solidification of the melt formed finer crystal or volcanic glass (groundmass) during eruption (McPhie *et al.*, 1993). Swallow-tail texture found in plagioclase in dacite is a skeletal texture that implicates it generated during syn-eruptive fast decompression of degassed magma (Viccaro *et al.*, 2010). The presence of plagioclase microlites in andesite as groundmass implies that there is a rapid crystallization due to degassing or undercooling during the emplacement of the lava (Lai *et al.*, 2016).

<u>Niut Volcanics</u>

Niut volcanics consist of lava and pyroclastic rocks, such as tuff and pyroclastic breccia.

Based on the petrography analysis (Hussein *et al.*, 2020) the pyroclastic rock is composed of juvenile and cognate lithic. The present juvenile fragments include juvenile tachylyte (dark volcanic glass), juvenile pyrogenic crystal (plagioclase and mafic minerals), and juvenile sideromelane (Pele's hair). The present cognate lithic includes lithic andesite and lithic tuff.

Based on the petrography analysis (Hussein *et al.*, 2020) the lava has various compositions from basaltic to dacitic. The andesite-basalt scoria

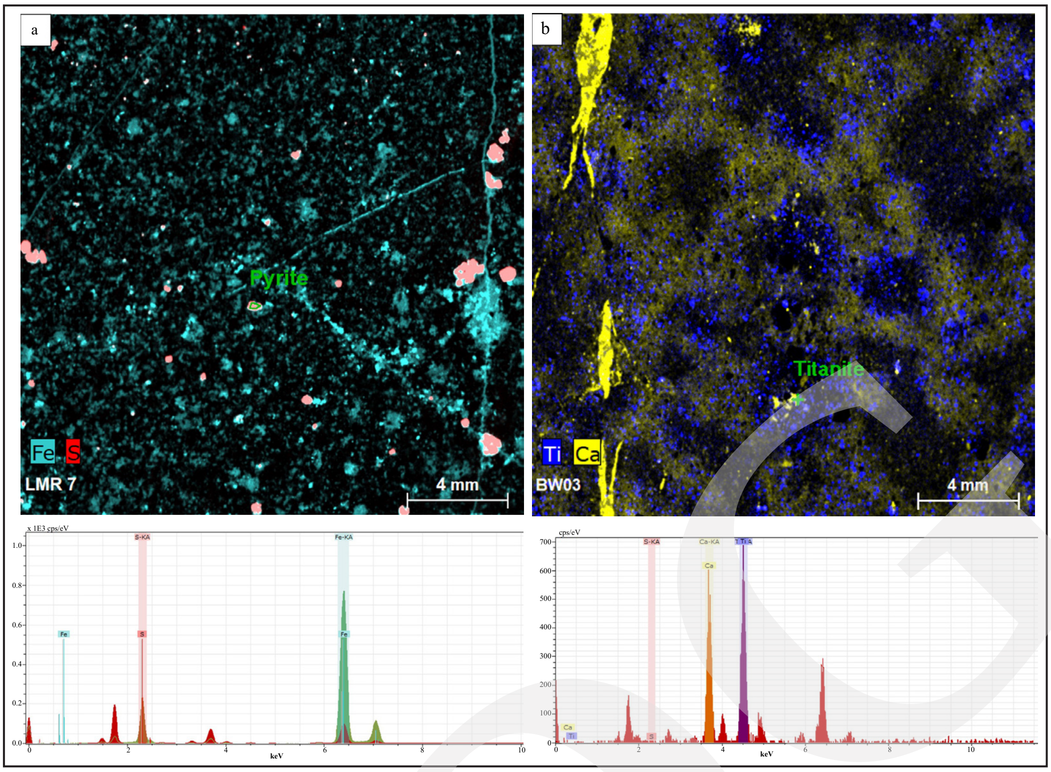

Figure 10. Element distribution and spectrum of opaque mineral: (a) Fe-S distribution and pyrite spectrum, (b) Ca-Ti distribution and titanite spectrum.

has a glomero-phorphyritic texture, composed of plagio-clase andesine, pyroxene, and olivine phenocryst embedded in a plagioclase microlite groundmass (Figure 11a). The massive andesite has a trachytic texture, composed of plagioclase andesine and hornblende with opacitic rim texture embedded in a volcanic glass groundmass. The lava dome andesite (Figure 11b) has a porphyritic texture, composed of plagioclase andesine with zoning and sieve macrotexture and hornblende with rim opacitic texture embedded in plagioclase microlite and volcanic glass groundmass.

Geochemistry

Six samples from Bawang and Serantak volcanics, twelve samples from Niut volcanics, and five

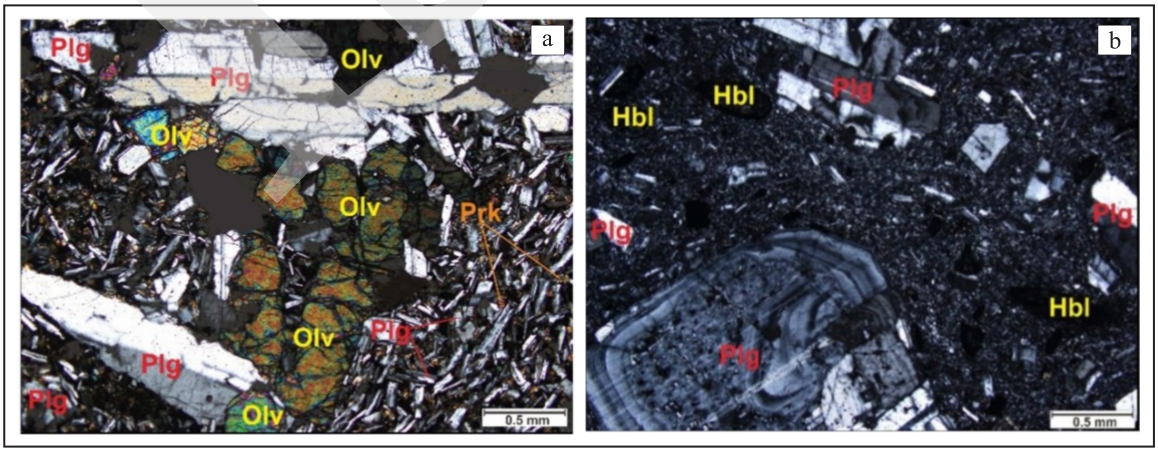

Figure 11. Photomicrograph of rock from Niut volcanics; (a). Andesite-basalt scoria, (b) Lava dome andesite (Hussein *et al*., 2020).

samples from Sintang intrusive were analyzed for major, trace, and rare earth elements. The chemical data are given in Tables 1 and 2.

<u>Major Elements</u>

Analysis of major element geochemistry on Bawang and Serantak volcanics shows that the rock samples are rhyolite dominantly with some basaltic to dacitic rocks (Figure 11a) containing SiO_2 from 53.87 to 81.52 wt. %. On the other hand, Niut volcanics have two types of lithol- ogy, those are basaltic to dacitic rocks (Figure 12a) with SiO_2 content varying from 52.66 to

70.42 wt. %. The dacitic rocks are reflected on the peaks of Niut and Semadum Volcanoes, while the basaltic rocks are distributed in the lower morphology. Several basaltic rocks of Niut volcanics have relatively high MgO content of more than 6 wt. % and TiO_2 of up to 1.80 wt. %. Sintang intrusive has a dioritic to granitic composition with the exception of one gabbro from SKG 6 (Figure 12b). SiO_2 content varies from 45.72 to 73.44 wt. %. All rocks contain low LoI, except two samples (NTT06 and SDN 94). Most of them were fresh to slightly weathered rocks with LoI values of less than 2 % (Gupta and Rao, 2001), and still appropriate for further analysis.

AFM and Silica vs Potassium diagram show magmatic affinity from these samples consisting of tholeiitic and calc-alkaline series (Figure 13). The tholeiitic series mostly consists of basaltic to dacitic rocks. Conversely, the calc-alkaline series is composed of dacitic to rhyolitic rocks. Figure 14 shows a Harker variation diagram for three rock groups. This diagram can portray the general differentiation trends of magma (Winter, 2014).

From the REE-Chondrite normalized spider diagram, all samples show small enrichment in LREE concentration (Figure 15), with Eu anomalies occurring in Serantak volcanics.Meanwhile, Niut volcanics and Sintang intru- sive do not show Eu anomalies. The HREE side from these curves in Figure 15 is relatively flat, suggesting a garnet-free source, which reflects the shallow depth of magma generation (Winter, 2014). In the MORB, normalized spider diagram (Figure 16) LILE (Sr, K, Rb, and Ba) and more mobile HFSE (Ce) are enriched, whereas HFSE decreases(except from tholeiitic rock that shows low K content). This pattern of high LILE/HFSE is recognized as a sign of most subduction zone magma (Winter, 2014).

Table 1. Major Element Geochemical Data in Bawang and Serantak Volcanics, Niut Volcanics, and Sintang Intrusive (in wt. %)

Group	Sample	Megascopic	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	MnO	Na_2O	K_2O	TiO_2	LOI	Total Oxide
Bawang and Serantak Volcanics	BW 12	Dacite	81.52	2.30	9.60	2.21	1.22	0.05	1.12	1.22	0.18	0.59	100.03
	BW 19	Dacite	58.23	7.69	18.83	8.00	3.83	0.11	1.30	0.14	0.39	1.42	99.96
	BW 3	Dacite	76.93	2.34	12.45	3.52	0.54	0.08	1.19	2.39	0.20	0.32	99.96
	BW 9	Dacite	79.51	2.73	10.52	2.35	1.32	0.06	1.41	1.61	0.22	0.31	100.03
	LMR 7	Basalt	72.37	4.27	12.83	4.92	1.62	0.03	1.27	1.68	0.38	0.57	99.94
	STK 9	Dacite	53.87	11.27	18.89	6.27	6.79	0.17	1.40	0.10	0.92	0.47	100.16
Niut Volcanics	NT 06	Dacite	70.42	2.69	17.45	2.99	0.49	0.04	2.06	2.20	0.46	1.02	99.83
	NT 08	Dacite	69.36	2.78	17.21	3.34	1.07	0.04	2.70	2.14	0.46	0.82	99.93
	NTT 06	Dacite	61.79	4.16	21.15	1.13	1.40	0.06	0.90	1.14	0.53	7.52	99.79
	PSK 4	Basalt	53.17	12.76	16.07	7.81	6.61	0.15	1.43	0.51	1.38	0.35	100.24
	PSK 8	Basalt	54.04	11.80	16.14	7.83	6.96	0.13	1.50	0.57	1.25	<0.01	100.21
	SDN 118	Dacite	68.60	3.29	17.94	3.24	1.10	0.03	1.81	2.05	0.47	1.39	99.93
	SDN 125	Dacite	68.29	2.95	16.72	3.66	0.76	0.04	3.83	2.23	0.47	0.94	99.89
	SDN 94	Basalt	56.67	10.30	18.26	4.46	3.99	0.09	1.13	0.95	1.12	3.12	100.10
	PLG	Basalt	53.10	12.24	16.07	8.00	7.18	0.15	1.48	0.60	1.27	<0.01	100.09
	SLS 1	Basalt	51.89	12.93	15.94	8.55	6.71	0.16	1.55	0.62	1.49	<0.01	99.84
	NT 02	Andesite	62.27	7.28	18.08	5.04	4.40	0.09	0.79	0.89	1.13	<0.01	99.98
	PSK 116	Basalt	52.66	12.08	15.70	8.25	6.26	0.14	1.49	0.89	1.80	0.43	99.70
Sintang Intrusive		Granite	60.32	6.68	16.60	6.18	4.52	0.11	1.81	1.69	0.76	1.03	99.69
		Diorite	71.10	3.77	15.91	3.20	1.06	0.08	2.07	1.91	0.38	0.47	99.96
		Diorite	45.72	12.92	22.48	11.38	5.21	0.16	0.55	0.06	1.26	0.11	99.83
		Granodiorite	66.86	3.64	16.86	4.60	2.02	0.06	1.84	2.41	0.47	0.98	99.74
		Granite	73.43	2.47	14.37	2.53	1.16	0.06	2.01	3.27	0.25	0.44	100.01

Table 2. Trace Element Geochemical Data in Bawang and Serantak Volcanics, Niut Volcanics, and Sintang Intrusive (in ppm)

Group	Sample	Lithology	Rb	Sr	Y	Zr	Nb	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Ta	Th	U
	BW 12	Dacite	29.09	100.01	25.56	22.15	3.38	199.87	46.78	97.47	11.29	40.74	8.16	0.96	3.84	0.58	3.97	0.84	2.12	0.27	1.62	0.23	0.69	3.08	0.92
	BW 19	Dacite	5.58	165.46	39.32	79.18	7.07	125.30	96.13	225.06	23.10	79.11	14.56	0.83	7.27	0.91	6.10	1.26	3.51	0.46	3.02	0.42	2.51	7.99	3.40
Serantak Volcanics	BW 3	Dacite	31.98	96.31	50.91	19.51	2.45	234.22	8.36	19.44	2.60	12.34	4.05	1.18	2.13	0.55	5.91	1.54	4.57	0.61	3.85	0.46	0.17	2.08	0.47
	BW 9	Dacite	30.80	126.41	21.57	27.05	3.19	293.11	86.49	193.03	20.50	70.47	13.19	1.04	6.30	0.75	4.24	0.76	1.83	0.23	1.38	0.22	0.58	3.72	1.75
	LMR 7	Basalt	39.67	216.86	34.33	38.63	4.51	416.07	48.08	107.27	11.89	42.88	8.25	1.25	4.12	0.61	4.79	1.08	3.01	0.40	2.49	0.32	0.72	4.13	1.39
	STK 9	Dacite	4.24	902.32	30.68	26.35	4.65	55.81	109.64	241.42	24.38	83.49	15.00	0.91	6.93	0.87	5.37	1.04	2.63	0.32	1.95	0.27	1.59	3.68	2.66
	NT 06	Dacite	52.47	466.43	29.58	79.98	11.49	415.73	73.21	72.66	14.04	47.78	6.94	2.33	3.29	0.49	3.71	0.81	2.31	0.31	2.03	0.29	0.83	7.69	1.25
	NT 08	Dacite	51.57	489.16	20.73	96.25	9.83	419.79	48.49	61.65	9.67	31.71	4.97	1.79	2.47	0.35	2.62	0.58	1.65	0.22	1.47	0.20	0.76	7.64	1.69
	NTT 06	Dacite	8.83	100.71	23.50	301.36	16.88	687.67	33.66	66.25	8.17	26.17	5.13	2.16	2.61	0.41	3.40	0.79	2.46	0.36	2.59	0.37	1.12	11.77	0.91
	PSK 4	Basalt	10.43	201.18	28.24	106.65	8.47	104.58	9.38	18.53	2.60	11.84	3.56	1.32	1.75	0.40	3.77	0.88	2.54	0.33	2.21	0.30	0.51	1.88	0.47
	PSK 8	Basalt	13.11	218.64	27.70	104.78	7.95	101.20	8.12	17.11	2.21	10.19	3.14	1.26	1.59	0.36	3.52	0.84	2.43	0.32	2.10	0.29	0.48	1.61	0.38
Niut Volcanics	SDN 118	Dacite	67.37	385.31	14.71	61.99	9.41	449.61	30.83	54.94	5.70	19.45	3.44	1.46	1.96	0.27	2.03	0.45	1.31	0.18	1.21	0.17	0.69	8.09	1.21
	SDN 125	Dacite	65.85	411.56	34.18	65.41	8.67	438.12	42.51	58.09	9.50	33.45	5.94	1.91	2.84	0.47	3.86	0.90	2.63	0.34	2.27	0.32	0.70	8.41	1.11
	SDN 94	Basalt	24.26	225.39	54.70	186.18	10.36	322.32	41.69	58.43	9.03	35.57	7.57	2.78	3.98	0.76	6.73	1.56	4.42	0.57	3.70	0.53	0.69	4.88	1.17
	PLG	Basalt	16.90	216.44	25.62	96.11	8.22	106.55	8.79	18.93	2.37	10.47	2.92	1.25	1.50	0.35	3.14	0.74	2.10	0.29	1.88	0.27	0.52	1.79	0.42
	SLS 1	Basalt	13.44	383.70	30.08	123.83	12.01	141.57	21.86	48.10	6.25	24.11	5.06	1.75	2.53	0.48	3.90	0.89	2.46	0.34	2.19	0.31	0.73	2.21	0.53
	NT 02	Andesite	45.18	244.19	30.14	141.43	9.28	196.74	16.29	31.13	3.66	14.91	3.70	1.49	1.97	0.41	3.50	0.82	2.30	0.31	2.04	0.30	0.66	3.80	0.91
	GSG 2	Granite	31.84	503.97	28.58	15.74	5.85	497.01	20.70	45.00	5.69	23.63	5.17	1.67	2.35	0.42	3.59	0.84	2.47	0.33	2.19	0.30	0.37	2.92	0.69
Sintang Intrusive	GSG 9	Diorite	49.01	476.07	14.40	44.26	7.80	823.48	37.52	64.58	7.76	24.77	4.52	1.80	2.28	0.31	2.14	0.45	1.23	0.15	0.91	0.11	0.70	2.46	0.95
	SKG 6	Diorite	1.49	>1000	13.99	12.02	1.77	65.46	35.12	74.62	8.79	29.59	5.79	0.98	2.72	0.36	2.47	0.51	1.30	0.15	0.95	0.13	0.69	1.58	0.62
	BW 9.2	Granodiorite	83.07	558.65	17.12	12.87	13.62	683.76	34.22	61.97	7.20	23.35	4.35	1.81	2.27	0.31	2.33	0.51	1.47	0.19	1.28	0.17	1.04	15.29	4.41

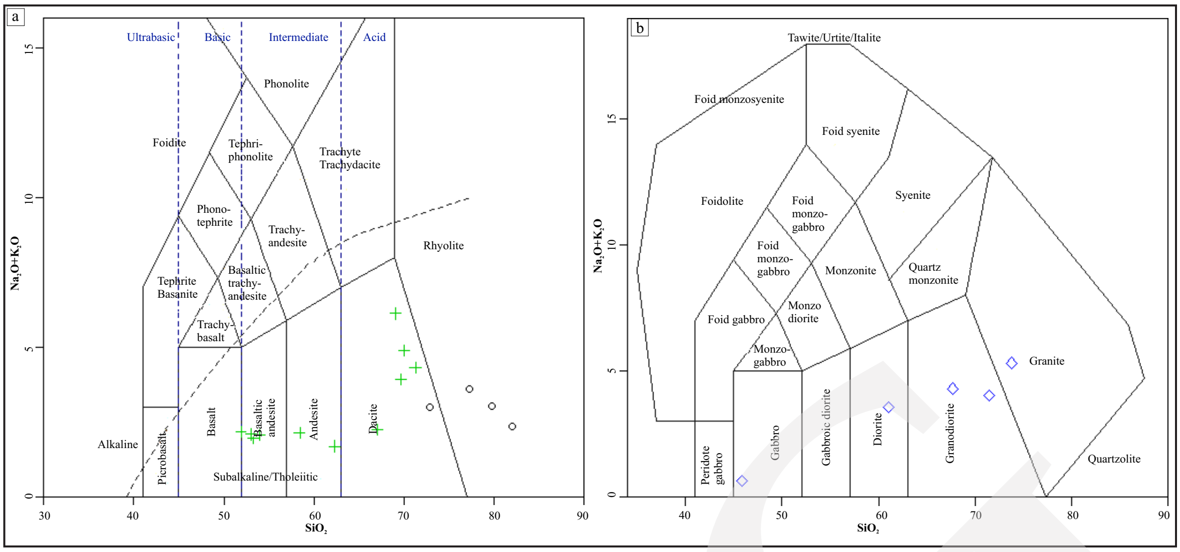

Figure 12. Rock type classifications: a) Based on the graph from Le Bas *et al*. (1986) in Bawang and Serantak volcanics and Niut volcanics, b) Based on Middlemost (1994) for Sintang intrusive.

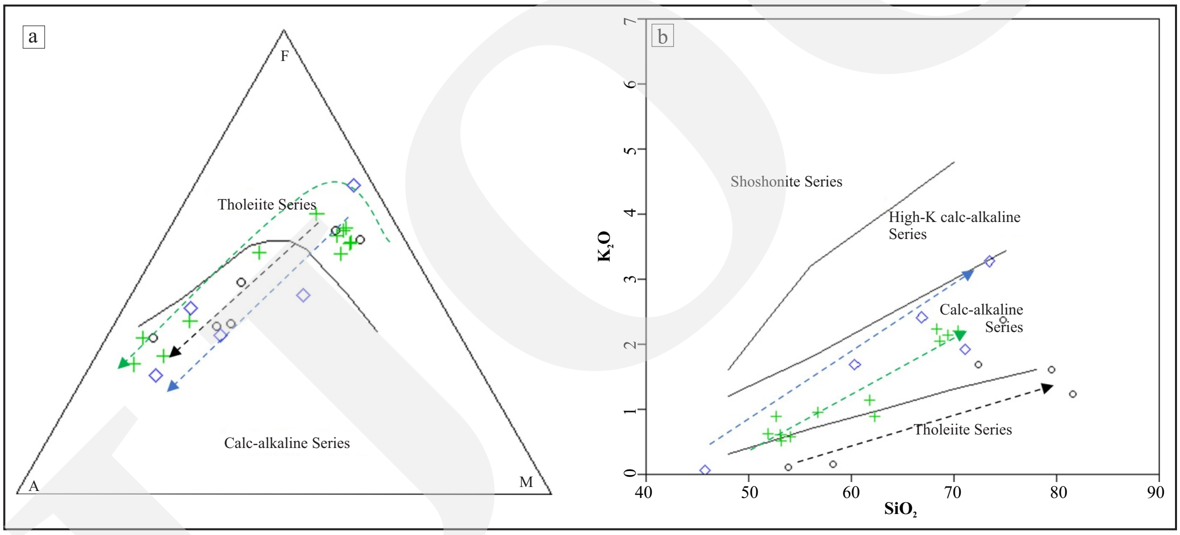

Figure 13. Magmatic series discrimination in the researched area. a). AFM diagram after Irvine and Baragar (1971), b). silica versus potassium diagram after Peccerillo and Taylor (1976). The dashed line with the arrow shows magma differentiation.

The geochemical characteristics are consistent with rocks formed by magma in the sub-duction zone. Most samples are calc-alkaline series, essentially restricted to sub-duction zone mag- matism (Winter, 2014). The enrichment of LILE and LREE and the depletion of HREE also shows the characteristics of volcanic rock generated in a subduction area (Zheng, 2019). The data of volca- nic rock association and petrology also indicated a subduction zone. The volcanic rock showing alternating layers of lavas and pyroclastic, are characteristics of stratovolcanoes that are typi- cally found in subduction zones (Scarth, 1994). The andesitic lava which is generally more pyr rhic than basaltic, dacitic, and rhyolitic lava, is typical of volcanic arcs (Winter, 2014).

From the AFM diagram, all three groups show a significant alkali enrichment as they evolve from tholeiitic to calc-alkaline series and the Niut group shows minor Fe enrichment in the early stages of differentiation.

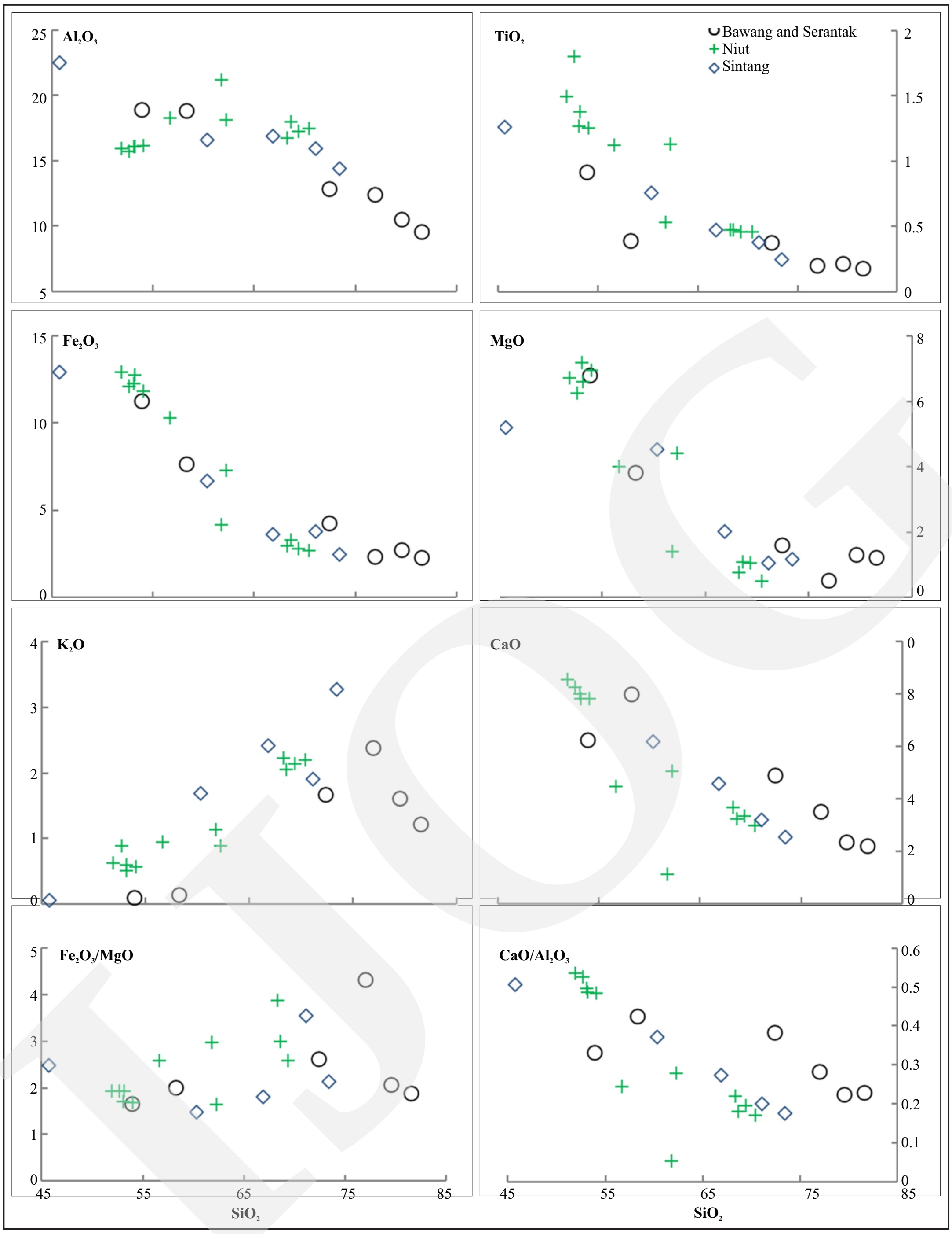

Figure 14. Harker variation diagram for three groups of rocks in the studied areas.

Fractional crystallization indication can be seen from the Harker diagram in Figure 14. The decrease of Al_2O_3 and CaO with increasing SiO_2 implies a fractional crystallization of plagioclase. Small negative Eu anomaly (Figure 15) can also be related to the removal of plagioclase from melts (Winter, 2014). Fractional crystallization of mafic minerals, such as pyroxene and olivine are indi- cated with the decrease of MgO and Fe_2O_3 with SiO_2 increase. Fractionation of plagioclase should result in CaO/Al_2O_3 increase, but it de- creases with increasing SiO_2. It is suggested that clinopyroxene also forms and removes calcium from melt. The decrease of TiO_2 is probably

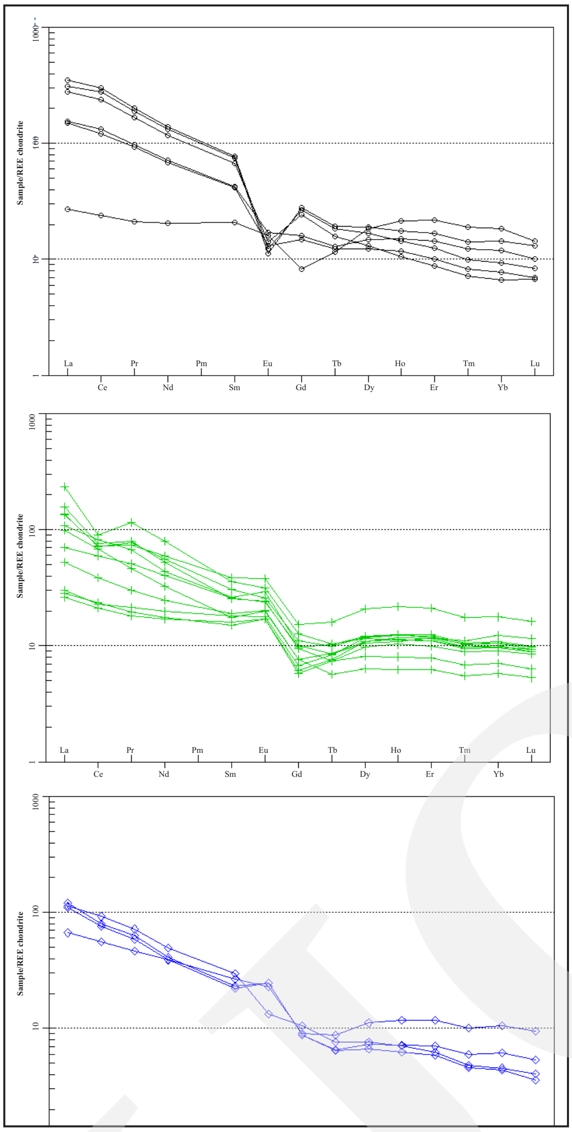

Figure 15. REE chondrite normalization for each formation based on the graph from Boynton (1984): a). Serantak volcanics, b). Niut volcanics, c). Sintang intrusive.

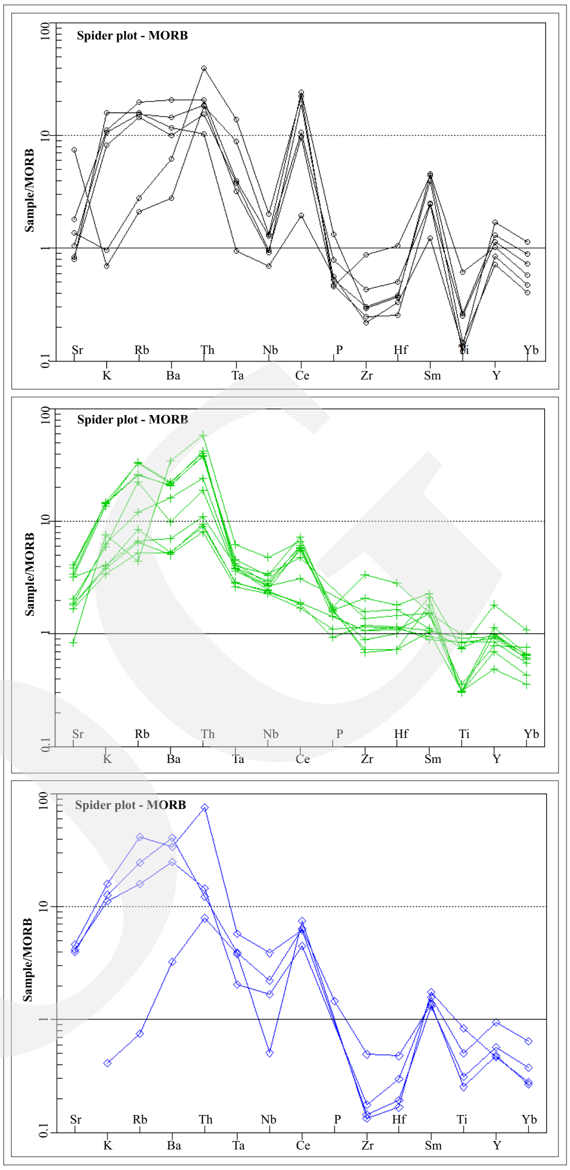

Figure 16. MORB normalization for each formation based on the graph from Pearce (1983): a). Serantak volcanics, b). Niut volcanics, c). Sintang intrusive.

caused by the fraction- ation of Fe-Ti oxides such as ilmenite and titanite.

The geotectonic setting of the samples shows that Serantak volcanics and Sintang intrusive were formed in orogenic domains (compressive, island arc, and active margins). On the other hand, the Niut volcanics were formed either in orogenic or post-orogenic domains (Figure 17).

Tertiary Magmatism in Bengkayang Area

Tertiary magmatism in Bengkayang produces volcanic edifices and intrusive rocks within the researched area. The Tertiary magmatism starts from Eocene-Late Oligocene. In these periods, magmatism in Bengkayang area produced Bawang dacite and Serantak volcanics that were formed at 51.3 Ma (Suwarna *et al.*, 1993). The Bawang and Serantak volcanism created andesitic to rhyolitic rocks in the form of lava, pyroclastic breccia, and tuff.

Geochemical signatures of these edifices show calc-alkaline magma affinity with enrichment of LILE-LREE and depletion of HREE. Its geochemical characteristics resemble the subduction zone magmatism. The subduction magmatism

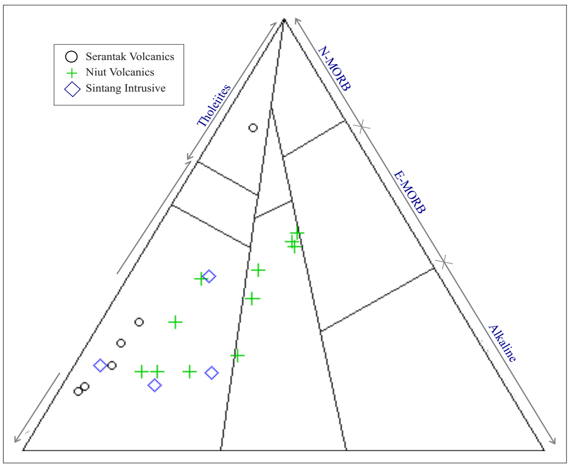

Figure 17. Geotectonic discriminant diagram for each formation studied based on the graph from Cabanis and Lecolle (1989).

in the Eocene-Late Oligocene was related to the subduction process between Sundaland and Luconia Block in Rajang Trench (Soeria-Atmadja *et al.*, 1999). This subduction also created several magmatism processes in Kalimantan Island including Nyaan, Kelian, Mandai, and Piyabung (Soeria-Atmadja *et al.*, 1999).

Sintang intrusion represented the Late Oligocene - Early Miocene magmatism in the Bengkayang area. This magmatism formed phaneritic igneous rocks including gabbro, diorite, granodiorite, and granite. The geochemical properties of these rocks show calc-alkaline magma affinity with a high LILE/HSFE ratio that reflects the subduction zone magmatism (Zheng, 2019).

Sintang intrusion in the Bengkayang area was grouped as the northern Sintang Suite that was formed in 16.4 - 17.9 Ma (Williams and Harahap, 1987; Breitfeld *et al.*, 2019). Previous studies stated that the magma source responsible for the forming of Sintang intrusion might be derived from a remnant of Eocene subduction slab (Soeria-Atmadja *et al.*, 1999; Hartono, 2006), post-subduction settings (Williams and Harahap, 1987; Zaw *et al.*, 2011), or crustal re-melting (Breitfeld *et al.*, 2019). This study shows that the magmatism of Sintang intrusion was derived from orogenic domains (Figure 16). Probably, this process was related to the collision of Luconia Blocks to Kalimantan in the Middle Miocene (Soeria-Atmadja *et al.*, 1999; Zaw *et al.*, 2011).

The Niut Volcano which formed in 4.4 - 4.9 Ma (Bladon *et al.*, 1989; Harahap, 1994; Breitfeld, 2021) produces basaltic-dacitic rocks in the form of lava, pyroclastic breccia, lapilli, and tuff. Geochemically, Niut volcanics show calk-alkaline magma affinity that resembles the subduction zone magmatism. Several samples of Niut lava show low SiO_2 < 54 wt. %, high MgO content of more than 6 wt. %, and relatively high TiO_2 up to 1.80 wt. %. Those characteristics were comparable to primitive magma characteristics or ocean-floor basalt (Harahap, 1987; Wilson, 1989). The studies show that Niut Volcano magmatism was formed in intra-plate domains. Therefore, the magmatism process that formed Niut volcanic did not come from the subduction process, but is likely correlated to post-orogenic intra-plate magmatism (Harahap, 1987).

NPP Site Assessment Related to Volcanic Hazard

The volcanic hazard assessment was undertaken to describe the volcanism characteristic of an area of approximately 150 km from the proposed site near Gosong Beach. Within the screening distance, based on the volcanic and intrusion products found in the researched area, there are at least three possible types of events, *i.e.* pyroclastic flow, lava flow, and intrusion.

Three scientific approaches suggest the minimum impact of volcanic hazard in the NPP site:
1). The record of volcanism was examined to determine whether any of the volcanic centres have recent activity. The assessment reveals that there is no record of a recent volcanic vent and eruption in northwestern Kalimantan.
2). The examination of any manifestation of the current magmatic activity shows no hydrothermal or manifestation related to an active magmatism was found in this area.
3). The assessment of the magmatism process shows geology and geochemical approaches revealing that the Tertiary volcanic and intrusive rocks of northwestern Kalimantan represent com-

positional diversity from basalt to dacite with a minor process related to new magma injection. The presence of alkali enrichment confirms the differentiation from tholeiitic to calc-alkaline series. However, no further evidence of magmatism activity and magma differentiation have been found recently. Thus, even though there are volcanism products near the site, it can be concluded that the volcanic activities in northwestern Kalimantan were not capable or just had small impacts on the NPP site as a consequence of a secondary process on the igneous and pyroclastic rocks related to weathering.

Conclusions

Tertiary volcanic and intrusive rocks of northwestern Kalimantan represent the compositional diversity from basalt to dacite. The presence of alkali enrichment confirms the differentiation from tholeiitic to calc-alkaline series. The Eocene Bawang dacite and Serantak volcanic activity was initiated by the rise of primitive parental magma from partial melting in a shallow-depth subducted crust as indicated by garnet-free HREE pattern, enrichment of LILE and LREE, and depleted HREE. Then, the magmatism changed into post-subduction orogenic domain forming Sintang intrusion. Pliocene Niut volcanic activity was probably controlled by post-orogenic intra-plate magmatism. The activity of Tertiary magmatism in northwestern Kalimantan is concluded not to be capable or just had a small impact on NPP candidate site as a consequence of a secondary process on the igneous and pyroclastic rocks related to weathering.

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