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Petrogenesis of Andesite Rocks in Datae Area, Sidenreng Rappang Regency, South Sulawesi Province

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Abstract
The research area is in the Datae Area, Watangpulu District, Sidenreng Rappang Regency, South Sulawesi Province. This study aims to determine the distribution of volcanic rocks, determine the crystallization phase based on petrographic analysis, and determine the type, magma affinity and tectonic environment based on geochemical data. The method used in this study was field data collection and rock sampling for analysis through petrographic analysis and geochemical analysis using the X-Ray Fluorescence (XRF) method by analysing the main elements, trace elements and rare earth elements (REE). The results of the petrographic analysis show that the rocks found in the field are volcanic breccia and ignimbrite. Volcanic breccia showed coarse-grained texture composed of angular to rounded andesite fragments and pyroclastic material fused together in a matrix. Meanwhile, ignimbrite showed fine grained texture with lapilli to boulder-sized fragments, poor sorting, open-packed and non-layered structure. Based on the Total Alkali Silika (TAS) diagram, AFM diagram, and binary diagram, the results of the geochemical analysis showed that the rocks found in the study area were andesite and trachy-andesite, while the magma affinity area is high-K calc-alkaline and shoshonitic. High-K calc-alkaline magmas are associated with subduction zones and are characterized by elevated levels of potassium and aluminum, while shoshonitic magmas are typically found in intraplate or back-arc settings, characterized by their distinctive potassium, sodium, and barium-rich compositions. The results from ternary diagram and geochemical Spider plots proved that the magma tectonic environment is island arc—continental arc basalt, indicating that the rock was formed in a subduction area. This research supports previous research regarding the tectonics of the western arm of Sulawesi, which stated that this area was formed by subduction.

1. Introduction

South Sulawesi is a region that has several volcanoes. Even though many of these volcanoes are inactive, the traces of ancient volcanoes and the history of their appearance are still fascinating to be discussed. One of the exciting volcanoes is the Pare-pare Volcano, where the product of this volcano is widespread in the Barru and Pare-pare areas. Pare-pare volcanic products are included in the shoshonitic rock family formed after subduction [1] and it is characterized by pumice and ignimbrite [2]. It is explained that the West Sulawesi volcanic arc was formed by the subduction of the Pacific plate from east to west during the Oligocene-Miocene, which then developed into shoshonitic volcanoes [2].

Based on the literature studies that have been conducted, the area around Datae, Sidinreng Rappang Regency (see Figure 1) is composed of Pare-pare volcanic rocks consisting of Pare-pare volcanic breccias which have trachyte and andesite components, pumice, tuffaceous sandstones, conglomerates and tuffaceous breccias intruded by trachyte and andesite dykes [3]. Genetically, andesitic rock is one of the exciting rocks to discuss. Some references state that andesitic rocks are formed from differentiated basaltic magma, other references state that andesitic rocks originate from the melting process of part of the lower continental crust, and others refer that andesitic rocks form from partial peridotite melting from the upper casing under the influence of water [4], [5]. The petrogenesis of andesite rocks also varies in several cases in Indonesia which supports both theories [6] - [10]. These reference differences have encouraged the implementation of studies on the origin of andesitic rocks in the research area. The petrogenesis study discusses the origin or process of rock formation and this research is expected to provide outlook into the petrogenesis of andesite rocks in the Datae, Sidinreng Rappang Regency area to determine the rock formation conditions based on their physical and chemical properties.

2. Methodology

The study employed various methodologies to unravel the geological and petrological characteristics of the rocks, aiming to understand their formation processes. Field geological mapping was conducted to establish the lithological distribution and structural features. Petrographic analysis, including thin-section examination and mineral identification, provided crucial information about the rock textures, mineral assemblages, and alteration features [12], [13]. Additionally, X-ray fluorescence (XRF) analysis in 4 (four) samples based on each rock unit (two samples are taken from each unit) and their distribution in the research area was performed to determine the major, trace element, and rare earth elements (REE) compositions of the andesite samples. The samples were analyzed at Intertek laboratory, Jakarta. The obtained XRF data were plotted using diagrams that depict the concentrations of major elements (Total Alkali Silica (TAS) diagram, AFM diagram, and binary diagrams of major element) [11], [14]-[18]; trace elements, and REE (Zr-Y-Ti ternary diagram and geochemical Spider plots) [19]-[24]. These plots were essential in elucidating the petrogenesis of the igneous rocks, aiding in the interpretation of their formation mechanisms. The integration of each method (field geological mapping, petrographic analysis, and XRF analysis) provides valuable insights into the formation mechanisms of these andesite rocks, contributing to the broader understanding of their geological significance in the research area.

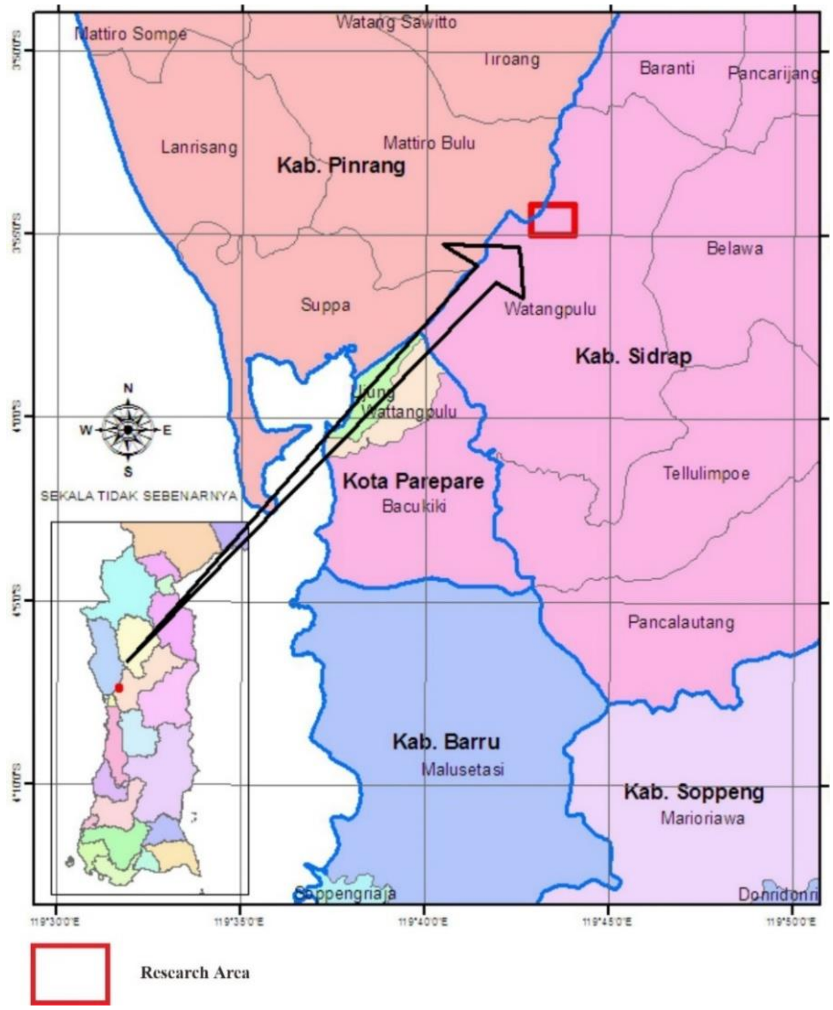


Figure 1. Location of research area

3. Results and discussions

This subchapter will discuss the geology of the research area, including the results of data collection in the field and the results of petrographic analysis; and also geochemistry and tectonic settings, which discusses the results of XRF analysis and plotting of geochemical data.

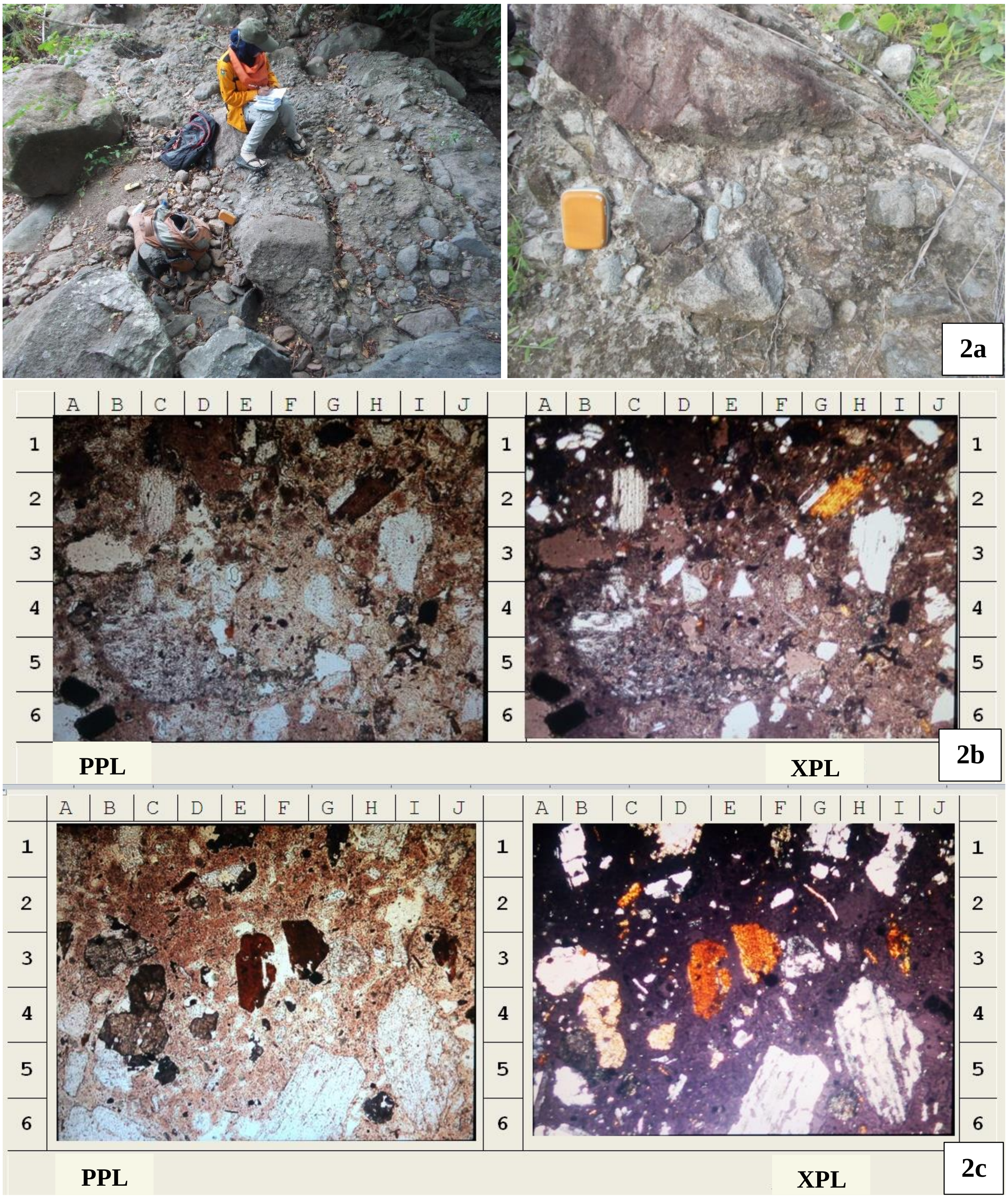


Figure 2. Appearance of volcanic breccia rock outcrops in research area **(2a)**. A thin sections photomicrography of breccia fragments (andesite) in sample SH05 which is composed of plagioclase (1B), pyroxene (3B), opaque minerals (4J), biotite (3E), hornblende (4D), groundmass glass (2B and 2I) **(2b).** A thin sections photomicrography of the SH05 matrix (crystal tuff) composed of plagioclase (1B), pyroxene (2G), opaque minerals (4I), biotite (1D), orthoclase (4E), rock fragments (5C) and volcanic glass (6A); PPL: plane polarization, XPL: cross-polarization **(2c)**.

3.1. Geology of research area

Based on the results of geological mapping, the stratigraphy in the research area is divided into two rock units from old to young (as shown in Figure 4, based on field and photomicrography appearance in Figure 2 and 3), including:

a. Volcanic breccia unit

Volcanic breccia units are exposed to the west to the north of the study area. The megascopic appearance of volcanic breccia shows brownish grey, clastic texture, and fragment sizes ranging from 8 mm to more than 50 cm (as shown in Figure 2a). The fragments found are andesite, poorly sorted, open-packed, layered structures. The results of the petrographic analysis on the SH05 sample, in volcanic breccia fragment, showed a blackish-grey interference colour, orange absorption colour, porphyritic texture, subhedral-anhedral, inequigranular, massive structure, mineral size 0.02 - 2.5 mm composed by: pyroxene (15%), plagioclase (30%), biotite (10%), hornblende (15%), opaque minerals (5%), with the groundmass of glass (15%), classified as andesite [12] (see Figure 2b). Samples from volcanic breccia matrix from the exact location showed orange absorption colour, blackish grey interference colour, coarse pyroclastic texture, 0.02 - 1.1 mm crystal size, subhedral-anhedral mineral form, poor sorting, material composition: plagioclase (20%), biotite (10%), pyroxene (10%), opaque minerals (10%), orthoclase (10%), volcanic glass (15%), and rock fragments (20%), classified as crystal tuff [12] (see Figure 2c). Based on similarities in physical characteristics and astronomical location which is relatively close to the research area, this volcanic breccia unit is compared to the Pare-Pare volcanic rocks (Tppv) of Pliocene age and formed in a terrestrial environment [3].

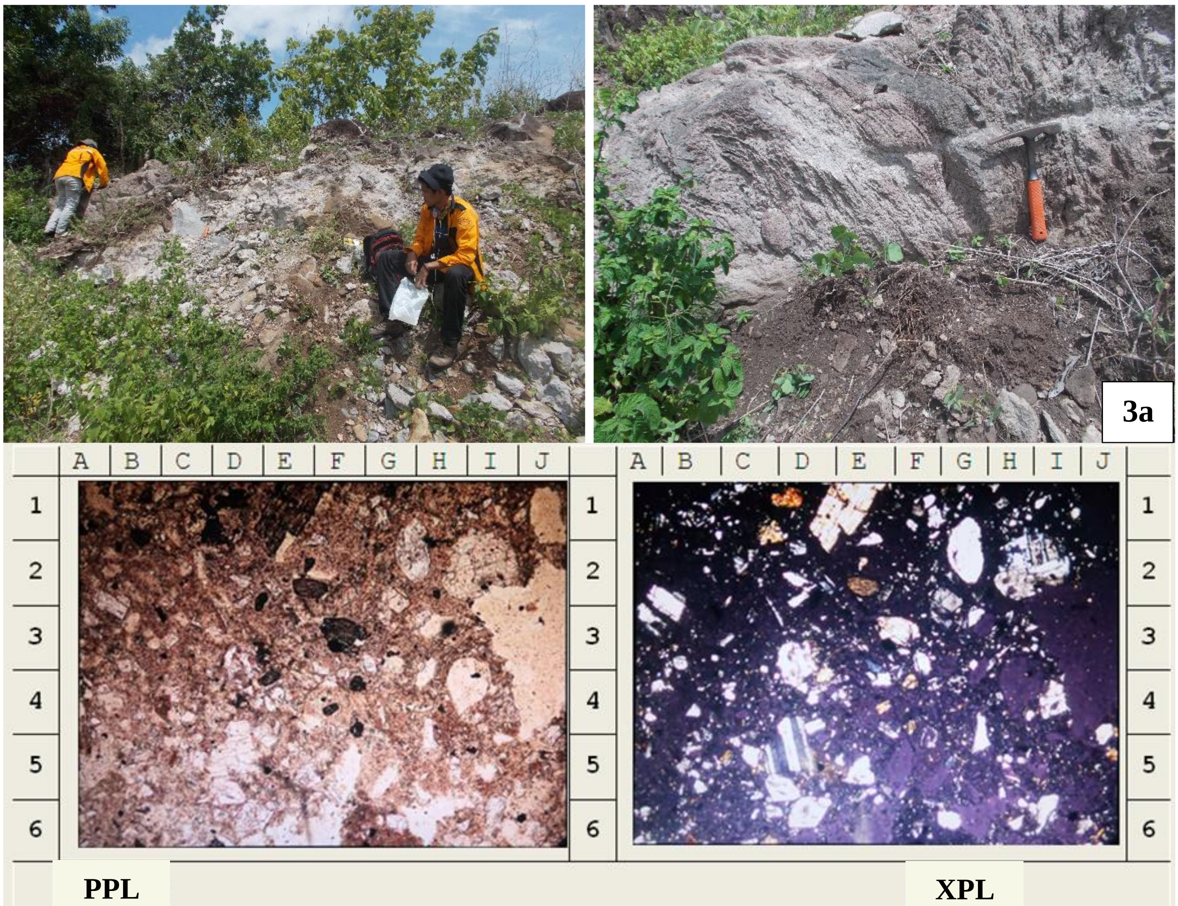


Figure 3a. Appearance of ignimbrite rocks in research area **(3a)**. A thin sections photomicrography of andesite in the Ignimbrite unit which is composed of orthoclase (4J), plagioclase (5C), pyroxene (1D), opaque minerals (6I) plagioclase and pyroxene crystallites (6A), and groundmass glass (6E); PPL: plane polarization, XPL: cross-polarization **(3b)**.

b. Ignimbrite unit

The ignimbrite unit is relatively exposed to the east of the study area. This unit consists of andesite ignimbrite, phonolite tephra and andesite. The megascopic appearance of the ignimbrite shows a fresh grey colour, weathered grey-black colour with angular to subangular andesite fragments, lapilli to boulder-sized fragments, poor sorting, open-packed and non-layered structure (as illustrated in Figure 3a).

Thin section of rock showing yellow-brown absorption colour, interference colour blackish-grey, porphyritic texture, unique zoning texture, size of the minerals making up the rock from 0.1 to 1.2 mm, subangular-angular mineral shape, closed-packing, good sortation, minerals composition consists of plagioclase, pyroxene, opaque minerals and plagioclase and pyroxene crystallites, with the groundmass of glass, and classified as andesite [12] (see Figure 3b).

3.2. Geochemistry and Tectonic Setting

The geochemical analysis carried out provided data in the form of major elements, trace elements and rare earth elements. The percentage of each of these elements can be seen in the table below.

Table 1. Result of geochemical analysis in the research area

Major elements (wt%)	**SH04**	**SH08**	**SH09**	**SH14**	**Trace elements (ppm)**	**SH04**	**SH08**	**SH09**	**SH14**
SiO_2	61.32	58.75	60.17	60.45	Cu	7	8	6	9
TiO_2	0,8	0.92	0.91	0.86	V	72	118	123	123
Al_2O_3	16.21	16.6	16.94	16.34	P	-	1740	1420	1460
Fe_2O_3	6.05	6.13	6.47	6.39	Cs	-	8	5.8	6
MnO	0.114	2.46	0.104	0.116	Ba	112	869	808	836
MgO	2.94	2.46	2.63	3.07	Cr	22	40	46	63
CaO	5.69	6.39	5.67	5.81	Ni	3	24	12	16
Na_2O	2.62	2.75	2.49	2.66	Co	4	15	12	16
K_2O	3.18	4.01	3.05	3.4	Sc	2	17	20	19
P_2O5	0.303	0.402	0.336	0.339	**REE (ppm)**				
LOI	0.8	1.5	1.1	0.5	La	17	54.2	46.7	53
Total	100.022	99.928	99.863	99.993	Ce		100	94.4	88.9
Trace elements (ppm)					Pr		12.2	10.4	11.7
Rb	-	151	109	123	Nd		45.8	38.9	44
Sr	215	550	490	490	Sm		8.8	7.9	8.8
Pb	3	31	25	25	Eu		1.9	1.7	1.8
Ta	<5	1.38	1.17	1.25	Gd		7.1	7.1	8.2
Hf	-	3.9	4.1	3.1	Tb		0.99	1.02	1.12
Nb	<1	19.2	15.5	16.6	Dy		5.5	5.9	6.4
Th	-	25.3	21	21.5	Ho		1	1.1	1.2
U	-	5.46	4.44	4.58	Er		2.8	3.1	3.3
Y	10	29.7	30.9	34	Tm		0.4	0.4	0.5
Zr	4	128	131	95.6	Yb		2.6	3	3.1
Zn	20	67	67	68	Lu		0.41	0.49	0.5

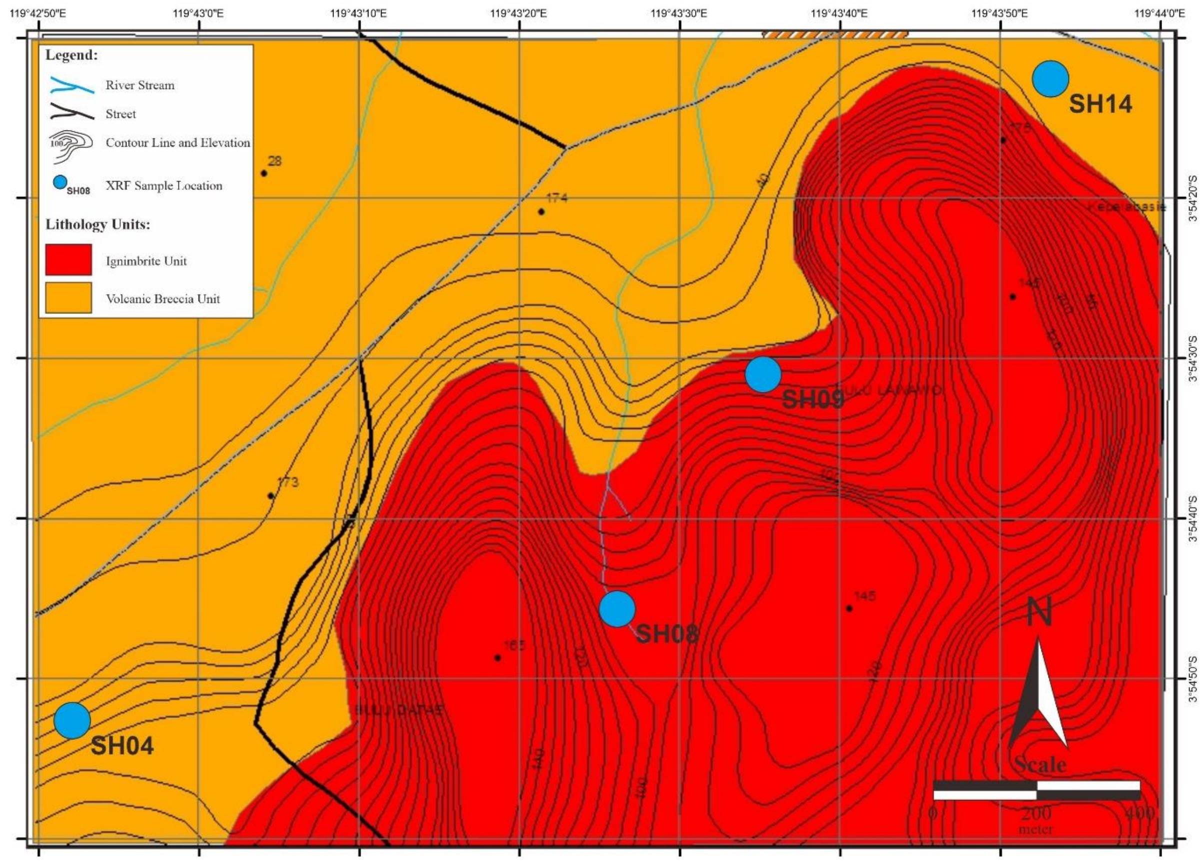


Figure 4. Geological maps in the research area, showed two rock units: volcanic breccia and ignimbrite unit and the geochemistry sampling location, the Stratigraphy of the research area, based on field and photomicrography appearance in Figures 2 and 3.

a. Major elements

The results of the major element geochemical analysis are shown in Table 1. The content of SiO_2 ranged from 58 – 61 wt%, Al_2O_3 16.21 – 16.94 wt%, MgO 2.46 – 3.07 wt%, Fe_2O_3 6.05 – 6.47 wt%, K_2O 3.18 – 4.01 wt%, TiO_2 0.82 – 0.92 wt%, and lost of ignitions (LOI) 0.5 – 1.5 wt%. From the analysis results, it can be seen that the content of Al_2O_3, Fe_2O_3, K_2O and CaO is quite high. The high content of these elements indicates the minerals characteristic of rocks that showed in petrographic analysis: plagioclase feldspar ((Ca, Na) $AlSi_3O_8$), pyroxene ((Mg, Fe) SiO_3), and K-feldspar ((Na, K) $AlSiO_4$).

The SiO_2 content of the rock samples ranged from 58 – 61 wt%, referring to the composition ratio of SiO_2 and $Na_2O + K_2O$ indicating that the rock types found in this area are andesite and trachy-andesite [13] (Figure 5a). Based on the AFM classification diagram (K_2O+Na_2O–total FeO–total MgO) showed that all rock samples are concentrated in the calc-alkaline series [14] (Figure 5b). This is also supported by an analysis that showed the percentage of K_2O with SiO_2, the magma series in this area can be classified into high calc-alkaline and shoshonitic series [15] (Figure 5c).

The variation of the oxides of the main elements with SiO_2 is shown in Figure 6. The results of the variation diagram of the major elements (TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, K_2O, Na_2O, and P_2O_5 against SiO_2) show that these elements show results that are negatively correlated to SiO_2 except for the MgO element which is positively correlate. This process is interpreted as a crystallization fractionation process in cogenetic magma, so the oxides Al, Fe, Ca, Mn, Na, P, and K will generally negatively correlate with SiO2. Mg oxides will have a positive correlation with SiO_2. Based on this diagram variation, the Pare-pare volcano's rock or lava originates from cogenetic magma. This positive correlation indicates the fractionation of the element Mg, which forms the mineral pyroxene (Mg, Fe) SiO_3. A negative correlation with SiO_2 indicates reduced plagioclase (Ca, Na) $AlSi_3O_8$ and feldspar minerals [16].

b. Trace elements

The results of the geochemical analysis for the trace elements shown in Table 1 are then plotted on the geochemical Spider plots that normalized to chondrite and MORB. The key difference between geochemical Spider plots normalized to chondrite and MORB samples lies in the choice of reference composition and the geological context. Chondrite-normalized plots are more general and can be used to study a wide range of geological settings, while MORB-normalized plots are specifically tailored to understanding the geochemistry of oceanic crust formation at mid-ocean ridges. The geochemical Spider plots showed an enrichment of LIL (Large Ion Lithopile) elements: Rb, Ba, K and Th and a reduction of HFS (High Field Strength) elements. This diagram also shows LIL enrichment with a steep proper slope (HFS). The enrichment of elements such as Ba, Rb, Th, and K and the impoverishment of Nb, Zr and Ti elements, as shown in Figure 7, are characteristics of calc-alkaline magmas. The negative Nb anomaly in the geochemical Spider plots indicates the presence of Nb-containing residues in the magma source during the partial melting process. This is evidenced by the Al_2O_3 content, which is less than 15%, melting the continental crust. The indentation of the Nb element in the geochemical Spider plots indicates the type of magma that erupted in the tectonic environment associated with subduction [17]. Based on the content of trace elements/HFSE (immobile) which is based on the ratio of Zr-Y-Ti elements, in this classification the tectonic environment of the igneous rocks in this area is included in the continental arc basalt zone [18] (see Figure 8).

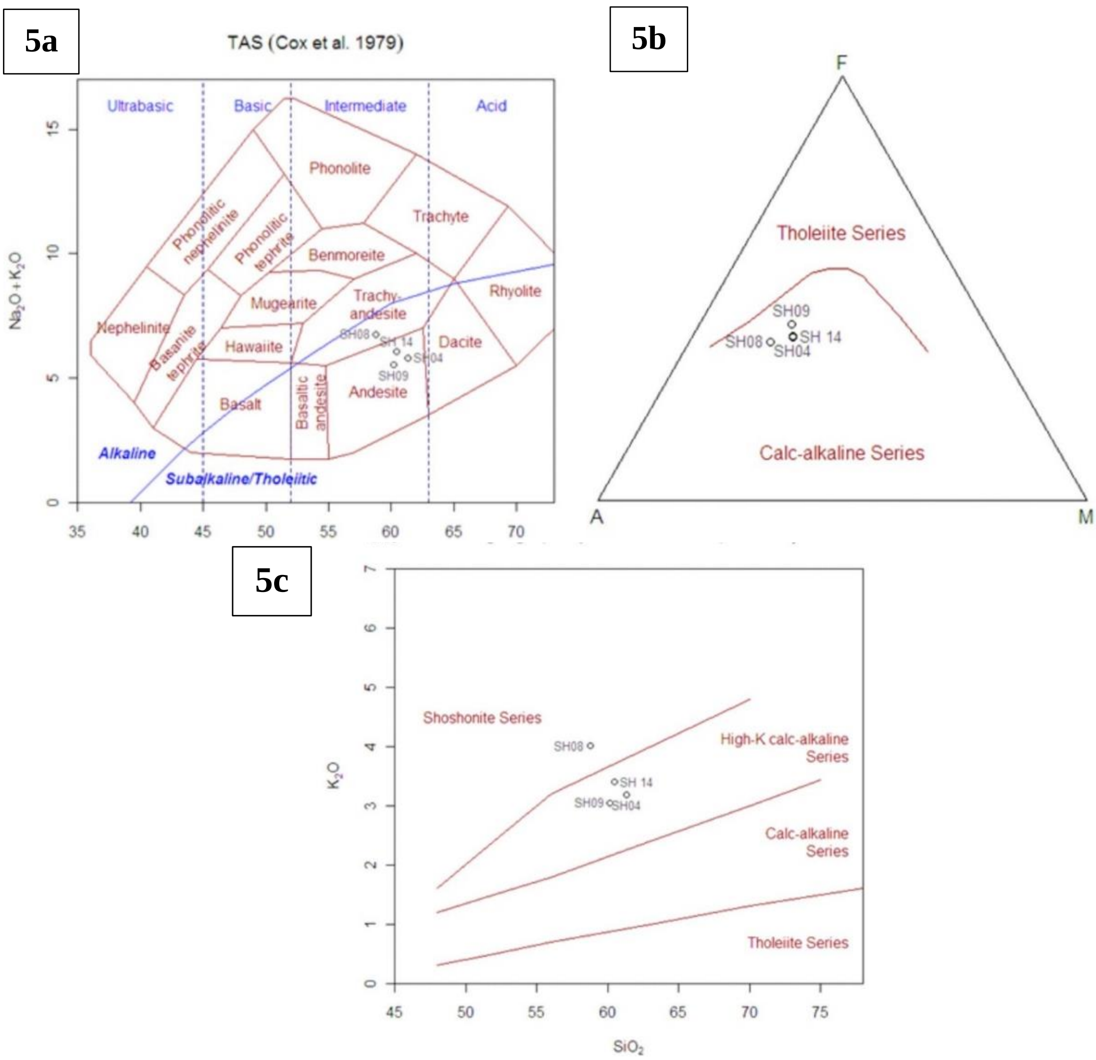


Figure 5a. Rock classification in research area based on total alkali silica (TAS) diagram [13]. **5b**. Samples plotting in the research area, based on AFM diagram (A=K2O+Na2O, F=FeO, M=MgO) [14], **5c.** Plotting of samples based on magma affinity classification through a comparison of K_2O and SiO_2 [15].

c. Rare earth elements (REE)

Rare earth elements (REE) determine the genesis of rock formation and reveal the petrological processes that occur. The elements are made into geochemical Spider plots (as illustrated in Figure 9) to get the REE pattern. This diagram is normalized to chondrites and values for rare elements for rock samples. The main difference between chondrite-normalized and primitive mantle-normalized REE plots depends on the specific geological questions being addressed. Chondrite-normalized plots are more general and can be used to study a wide range of geological materials and processes, while primitive mantle-normalized plots are tailored to understanding the mantle source characteristics of volcanic rocks. The classification shows an enrichment of light rare earth elements (LREE) and a decrease in heavy rare earth elements (HREE); this is a typical pattern in calc-alkaline series volcanic rocks [17]. The Geochemical Spider plots also shows a negative anomaly in the element Eu, indicating that the amphibole fractionation may control the magma differentiation. This negative anomaly in Eu is also a characteristic of the subduction zone environment [19]. The Geochemical Spider plots is also normalized to MORB, as seen in Figure 9. There is no difference between the two, both showing a negative anomaly in the element Eu.

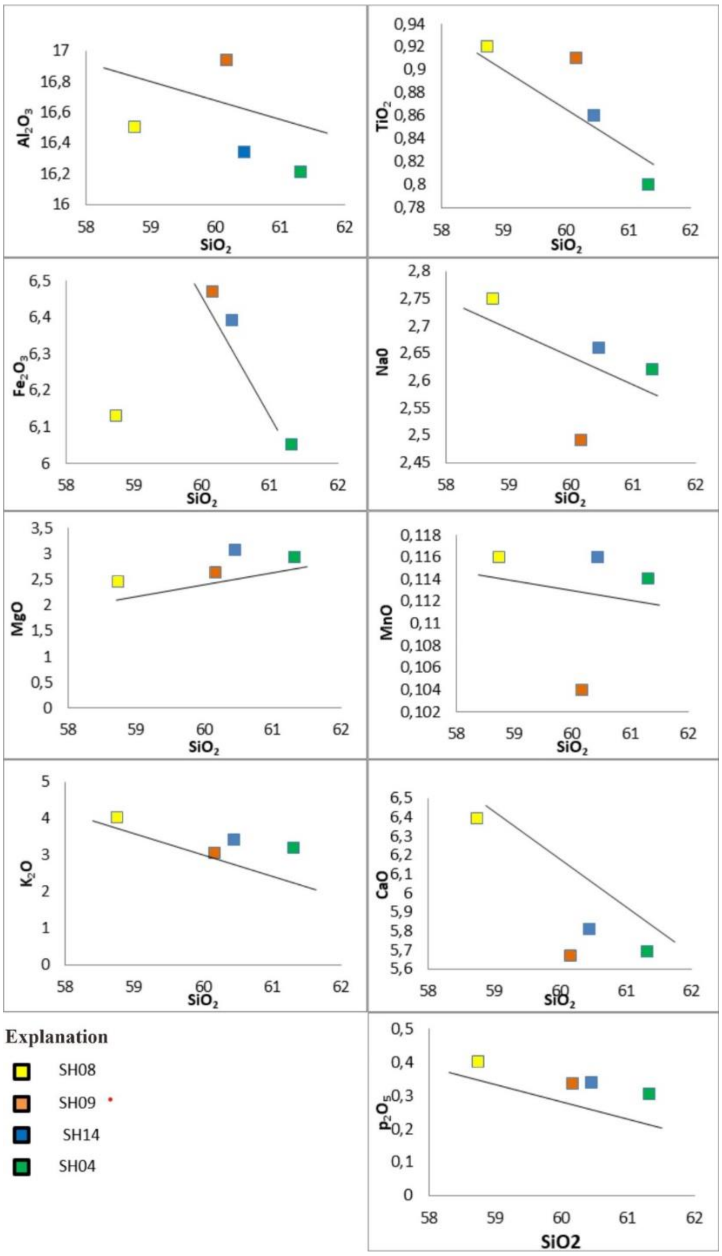
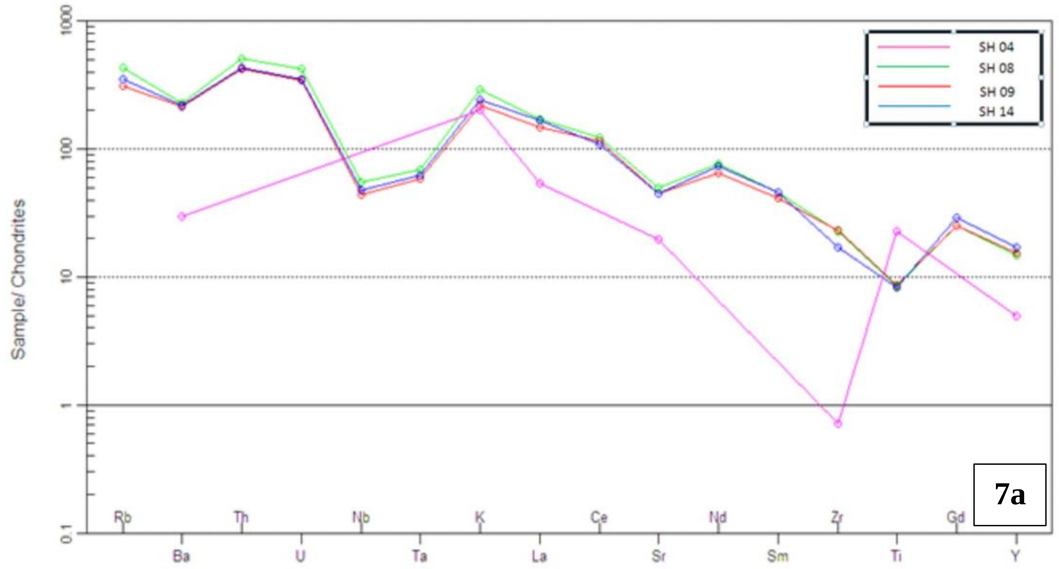


Figure 6. Diagram of variations of TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, K_2O, Na_2O, and P_2O_5 against SiO_2 in SH04, SH08, SH09 and SH14 samples [13].



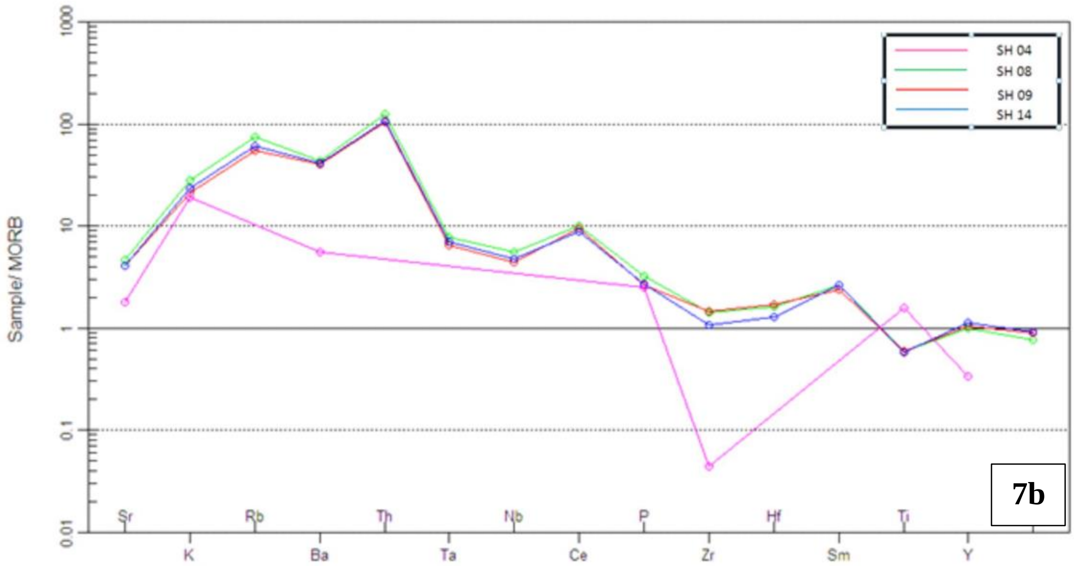


Figure 7a. Geochemical Spider plots of rock samples (SH04, SH08, SH09 and SH14), showed trace elements in the normalized to chondrite samples [20]. **7b.** Geochemical Spider plots of rock samples, showed trace elements in the normalized to MORB samples [21].

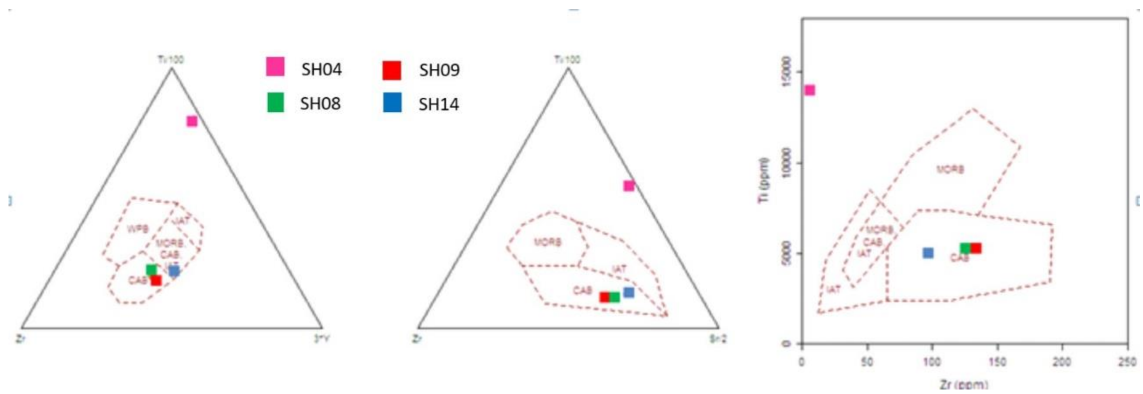


Figure 8. The determination of the tectonic environment, based on the Zr-Y-Ti content, showed that the samples in this area is included in the continental-arc basalt zone (CAB = continental-arc basalt, MORB = mid-oceanic ridge basalt. WPB = within plate basalt, IAT = island-arc tholeiite) [18]

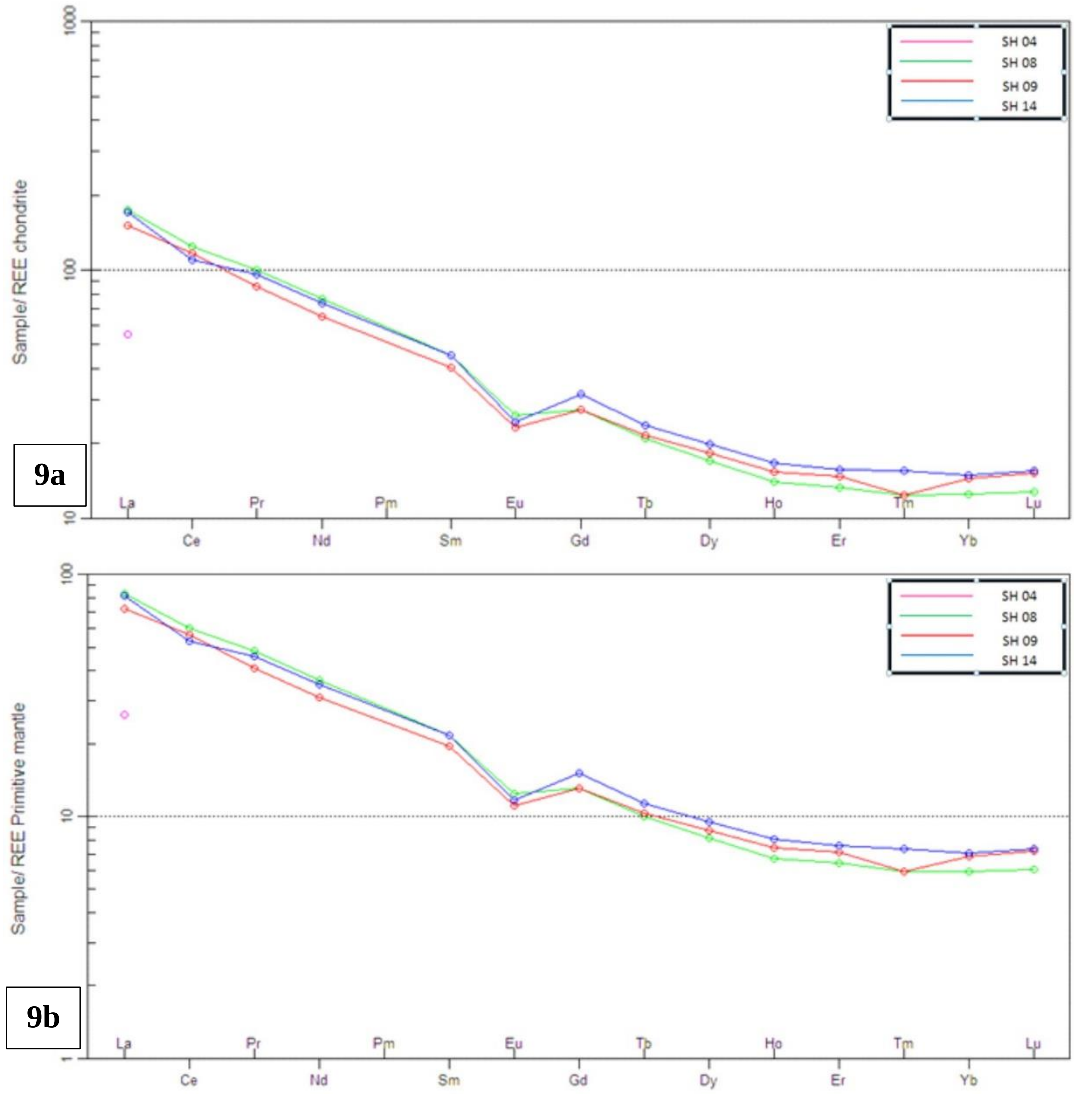


Figure 9a. Geochemical Spider plots of rock samples (SH04, SH08, SH09 and SH14), showed REE in the normalized to chondrite samples [22]. **9b.** Geochemical Spider plots of rock samples, showed REE in the normalized to primitive mantle samples [23].

4. Conclusion

Based on the results and discussions in the previous chapters, it can be concluded that volcanic rock units in the study area are divided into two types: volcanic breccias and ignimbrites. It has undergone a crystallization fractionation process in cogenetic magma. Based on the results of geochemical analysis, the type of magma that composes the research area is intermediate magma, the magma affinity of the study area is classified into high-K calc-alkaline and shoshonitic series. The geochemical analysis and geochemical Spider plots of trace elements indicate an enrichment of LIL elements (Rb, Ba, K, and Th) and a reduction of HFS elements, characteristic of calc-alkaline magmas. The trace element composition classifies the igneous rocks in this area as belonging to the continental arc basalt zone. Meanwhile, the geochemical Spider plots analysis of REE reveals an enrichment of LREE and a decrease in HREE, indicating a typical calc-alkaline series volcanic rock pattern associated with the subduction zone environment that supports the explanation of the tectonic setting of the western arm of Sulawesi from the previous research.

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