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The Petrology and Volcano-Stratigraphy of The Muria-Peninsula High-K Volcanic Rocks, Central Java, Indonesia

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Abstract

The Muria-Peninsula is a Quaternary volcano located in the northern Sunda arc. Its activity was controlled under high potassic and very high potassic magma series resulting in leucite-rich trachyte and pyroxene-rich basaltic-andesite. It is a strato-type volcano that is composed of lava, breccia, and tuff layers, and some dikes have some volcanic craters and maars varying in age and composition. The study area is covering the volcanoes of Muria, Genuk, and Patiayam. This paper aims to describe the petrology, mineralogy, and volcano-stratigraphy of the different volcanic materials. The data and materials were sourced from the primary and secondary data. The methods are field mapping, stratigraphy measurements, collecting samples, thin section analyses, and major element geochemistry using X-Ray fluorescence (XRF). The results describe two groups of volcanic rocks consisting of pyroxene-rich andesitic-basaltic volcanic materials and leucite-rich trachytic volcanic materials. Augite presents in the andesitic basalt together with small grains of olivine and a few anorthite and foid minerals. Aegirine (Na-Pyroxene) is present in the leucite-rich trachyte that is often associated with biotite and hornblende. Na-Ca Plagioclase such as labradorite-andesine is often present in the basaltic-trachy-andesite that is usually rarely leucite. The major elements show high-K volcanic rocks with % K_2O is 4-5.9% and very high-K volcanic rocks (with % K_2O is between 6-8.24%) and low-K volcanic rocks that contain % K_2O is 2-3,9%. There are two groups of high-K to very high-K volcanic materials consisting of silicic-rich volcanic materials (~57-64% of SiO_2) and low-silicic volcanic materials (~46-50%). The TAS diagram identifies tephrite, phonolite, and trachyte. Stratigraphic data identifies calcareous sediments of the Bulu Formation as the basement rocks of the Muria trachyandesite. Beds of pumice-rich volcanic breccia of the Ujungwatu Formation are the basement rocks of the basanite-tephrite of the Genuk Volcano, and the tuff of the Ujungwatu is also exposed consisting of the basanite-tephritic-phonolite of the Patiayam Volcano. The leucite-like feldspars are very common in the andesite lava and dikes that compose the crater of Muria. Most of the Muria volcanic materials are rarely in leucite, while some maars contain pumice-rich pyroclastic flows and basaltic lava. The results of the major elemental analysis of the Muria materials indicate that the rock tends to be of medium to high K affinity (~2% K2O). The Genuk and older Muria are consisting of leucite-rich tephrite-phonolite. It was two periods of magmatic series developed in the Muria-Peninsula that was resulting in the high-K to very high-K magmatism and the medium K Kalk-alkaline magmatism.

Keywords: petrology, mineralogy, stratigraphy, high-K volcanic rocks, very high-K volcanic rocks, characteristics.

1. Introduction

Muria-Peninsula is located in the northern Java Island, Central Java, Indonesia. It is part of the Sunda Volcanic Arc, which is associated with the subduction zone of the Indian Plate beneath the Eurasian Plate (Handley et al., 2014, Handley, 2006, and Setijadji et al., 2006) from the Java Trench trending east-west, approximately 400 km south of the Muria and ~175 km to the main volcanic arc. As reported by the previous studies, the Muria has been deduced as a long-dormant volcano; it is over 10k years and has not shown any activity yet (McBirney et al., 2003, Bronto and Mulyaningsih, 2007, Latengke et al., 2019, and Wibowo et al., 2011). The previous study recorded three types of rock associations in it including the high silica-oversaturated or saturated potassic series, the weakly silica-saturated alkaline-potassic series, and the strongly silica-oversaturated ultrapotassic series (Leterrier et al., 1990). Those imply the mineral association that some of them have foid minerals and some others rare in foid minerals (Wibowo et al., 2022, Marin et al., 2019, Nicholls and Whitford, 1983, Mulyaningsih et al., 2008, and Mulyaningsih and Sanyoto, 2012). As a long-dormant volcano, Muria still has a probability of future eruptions for the next 100 years, although the probability value is very low $5x10^{-4}$ – $4x10^{-4}$ (McBirney et al., 2003). For this reason, there is a need for an in-depth study of everything related to its activities and its materials.

According to Pacey et al. (2013), central Sunda Arc Volcanism probably originated from 3 sources, subducting the Indo-Australian Plate that induces stress in the arc lithosphere, the downward flexure of the arc lithosphere triggered by the mantle flows, or by the loaded arc. All of them should consist of different magmatic series and different magmatic products. As discussed by Latengke et al. (2019), Muria has two types of magma, the ultrapotassic series and the Kalk-alkaline ultrapotassic series (shoshonitic series), while the central volcanic arc is represented by basaltic and basaltic andesitic medium K and high K Kalk-alkaline series (Gertisser and Keller, 2003). As Quaternary volcanism of post-collisional potassic and ultrapotassic series, The Golcuk Volcano (Isparta, Turkey) consists of an asthenospheric source than a lithospheric source that originates from lamprophyre and tephrite (Platevoet et al., 2014). The recorded data shows ultrapotassic foid-rich volcanic materials of the Muria-Peninsula (Marin et al., 2019), which differ from the plagioclase and clinopyroxene-rich volcanic materials that resulted from the central arc of Sunda, such as the volcanoes of Merapi, Merbabu, Sumbing, and Sindoro in the Central Java (Kirchenbaur et al., 2022, Mulyaningsih and Shaban, 2020, Gertisser and Keller, 2003, and Edwards, 1990). As proposed by Leterrier et al. (1990) Muria has two types of volcanic materials, i.e the HK-series Muria and the K-series Muria.

Tephrite is characterized by low silica and high total K_2O+Na_2O (7-9%), phonolite is characterized by higher silica and very high total K_2O+Na_2O (>8%), and trachyte is characterized by higher silica and total K_2O+Na_2O (6-11%), while the Kalk-alkaline volcanic materials are characterized by lower total K_2O+Na_2O (<5%) with high silica (Le Bas et al., 1992, Le Maitre et al., 2005, Bas et al., 1986). The hypothesis were tephrite and phonolite are grouped into the high and very high K shoshonitic magmatism originated from the deeper mantle, while the Kalk-alkaline magma series that producing basalt, andesite, and dacite mostly result from magmatic arc volcanism of subduction zone.

As a result of strato-type volcanism, intersecting of coherent and volcaniclastic materials associated with dikes, sills, and normal to oblique faults are common in developing the volcano-type as a symmetric cone. The body was developed as the result of volcanic activities that vary in compositions and affinities. As a result of the Sunda arc volcanism, Muria-Peninsula has Kalk-alkaline magma series. A deeper magmatic source has influenced the volcanism and developed varying volcanic type materials from the Kalk-alkaline to the tephritic-phonolitic materials. A long period of volcanism will be described that probably built more than a crater during the volcanism and building more than a crown even one brigade of volcanoes.

2. Tectonic Setting

The Muria-Peninsula was a result of the Sunda Arc volcanism; it was developed by the subduction zone of the Indian-Australian oceanic plate below the Eurasian continental plate; it formed Lasem Fault passes Muria trending southwest-northeast (Fig. 2; Kertapati, 2006). The stratigraphy of the Muria Peninsula consists of the volcanic rocks of the limestone of the Bulu Formation, the very fragmented volcanic rocks of the Ujungwatu Formation, and the high-K and very high-K volcanic rocks of the Muria Formation. The calcareous sediments of the Bulu Formation are exposed only on the northern side of the study area. It consists of crystalline limestone, fossiliferous claystone, massive reef, calcarenite, and calcilutite. The Ujungwatu Formation consists of layers of crystal tuff, trachyte-rich volcanic breccia, and greenish-yellowish chlorite-rich claystone; it is composing the Genuk Volcano, the Tritip, and the Patiayam Volcano. Suwarti & Wikarno (1992 in (Astjario and Kusnida, 2016)) grouped three volcanic formations regarding the stratigraphy of the volcanic rocks, namely (1) the Genuk Volcanic Rocks consist of lava, tuff, and breccia; (2) the Muria Tuff consists of tuff, lahars, and sandy tuff; and (3) Muria Lava consists of basalt-andesite, tephrite, syenite, leucitite, and trachyte (Fig. 1).

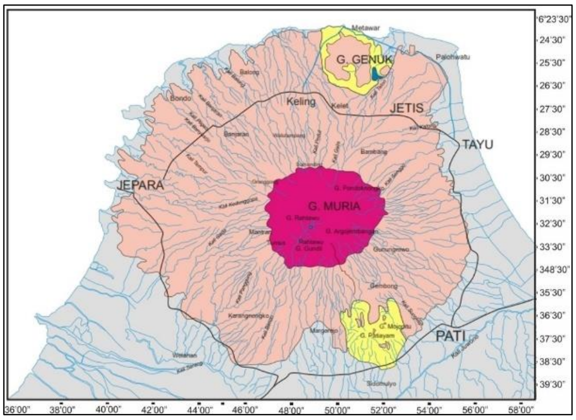

Fig 1. Regional geology of Muria Peninsula according to Suwarti and Wikarno (1992) and Kadar & Sudijono (1993). Blue: Bulu Formation, yellow: Ujungwatu formation, pink: Quaternary Volcanic rocks, red: lava, grey: alluvium

By the incidental communication, Kartapati (2006) informed varying epicenters of the tectonic earthquake were occurred in the Muria-Peninsula region, which was triggering many fault systems, namely the Rawapening Fault trending northwest-southeast along the south of the volcano, Semarang Fault trending north-south separating Semarang-Jepara-Kudus, Lasem Fault trending southwest-northeast that probably triggering the activity of the Patiayam volcano in the southern Muria (illustrating in Fig. 2).

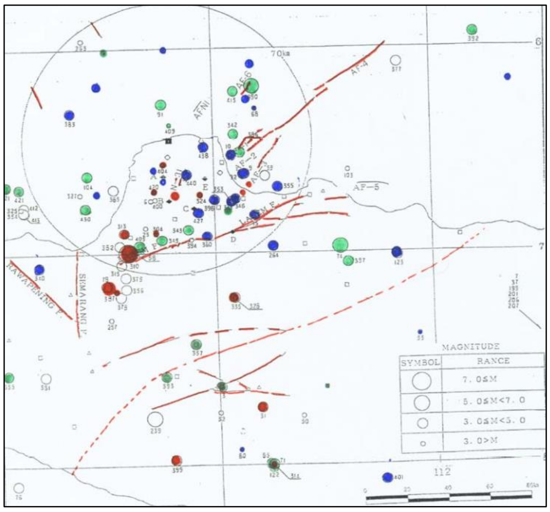

Fig 2. Map of the distribution of earthquakes and faults in the Muria-Peninsula (contributed by Kartapati, 2006)

Maars are recorded in the surroundings of Muria. There are three identified maars i.e the Gembong Maar, the Bambang Maar, and the Gunungrowo Maar; and the interpreted older maars (Bronto and Mulyaningsih, 2007). White and Ross (2011) described maars as a diatreme-volcano that is formed by an explosive eruption that cut deeply into the country rocks. Muria-Peninsula Maars are normally formed with circular, semi-circular, and within the ring-geomorphologies consist of volcanic-clastic materials varying in thickness and composition that are not too different from the host volcano (Muria) (Bronto and Mulyaningsih, 2007).

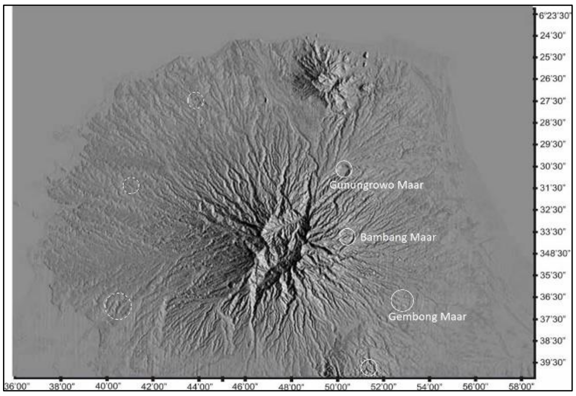

Fig. 3. Map of the distribution of the identified maar volcano on the Muria Peninsula (Gunungrowo, Bambang, and Gembong; (Bronto and Mulyaningsih, 2007)) and the interpreted maars with a dashed line symbol

3. Results

As described above (Fig. 3), the Muria Peninsula Volcanic complex consists of three volcanic sources, i.e the Genuk Volcano in the north, the Patiayam Volcano in the south, and the Muria Volcano in the central. The Genuk Volcano has located about 30km to the north, the body consists of Old Genuk and Young Genuk; while Patiayam Volcano has located about 26km to the south of Muria Volcano. The Genuk Volcano has two craters, namely the Old Genuk with tephrite-basanite materials and the Young Genuk with basaltic volcanic materials (Bronto and Mulyaningsih, 2007). The Patiayam Volcano has a peak as the crater that is dominated by pumice-rich volcanic rocks (Mulyaningsih et al., 2008), and looked like the oldest with more eroded geomorphologies. The lower flanks of both Genuk and Patiayam are covered by the epiclastic sediments of Muria's lahars/fluvio-vulcanic. Three identified maars and some interpreted maars are recorded around the Muria Volcano. The identified maars are Bambang, Gembong, and Gunungrowo (Bronto and Mulyaningsih, 2007); and have circular valleys consisting of clastic and coherent volcanic materials (Fig. 4).

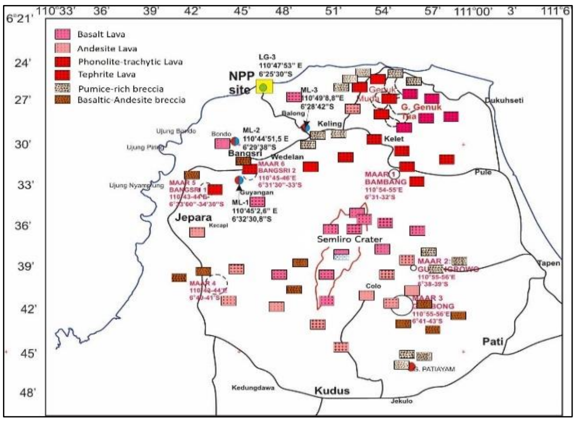

Fig. 4. Map of the volcanic rock distribution; it illustrates basalt, andesite, tephrite, trachyte, and the pyroclastic breccia, epiclastic breccia, and lapilli with pumice fragments.

Based on the stratigraphic measure section in the Muria Peninsula, from the north to the south (Fig. 5) are crystalline and un-structureless limestone of the Bulu Formation is exposed locally in many places; pumice-rich tuff and breccia with pebble and boulder basalt lithic fragments within a leucite-rich matrix of the Ujungwatu Formation are exposed at Goa Tritip and Gunung Ragas; lava with columnar joints, very thin sheeting joints, and entablature structures of identified trachyte, tephrite, phonolite, and leucite-rich basalt exposed at the Old Genuk; pyroxene-rich basalt that is exposed at the Young Genuk; and basaltic-andesite, trachy-andesite, and basalt compose the Muria Volcano.

The tephrite of the Old Genuk is vesicular-amygdaloidal, porphyritic, and composed of feldspars, pyroxene, amphibole, and biotite. Oriented foid-like minerals often build a trachytic texture even to the dike (Fig. 6). But the thin section observed tephrite is dominated by aegirine and leucite under trachytic texture and vesicular structure (Fig. 9.E). The phonolite is light grey color, sheeted-layered structures, trachytic, and composed of biotite, hornblende, and leucite. It is composed of 56-64% of silica, less alumina (~17%), very low iron and CaO (1-3%), very high K_20 (5-7%), and less TiO_2 (Table 1). The TAS diagram describes phonolite and trachyte (Fig. 11). The high potassium versus silica of the Herker diagram represents the presence of the leucite and the aegirine (that was recorded by the thin section observation) than biotite/hornblende. The low % of the iron and CaO versus silica represents the absence of the orthopyroxene (hypersthene) such as the exposed basalt/basanite of the Young Genuk.

The Muria Volcano has three craters according to Usman and Lugra (2016) plus the southern smallest crater described by McBirney et al. (2003), so there are four craters. The craters are located in the northernmost peak, southwestern peak, southern peak, and the boundary between craters I, II, and III within the elevations of 1550-1600 asl. The basalt lava dome is exposed near Crater I; it is dark grey, columnar, porphyritic, and composed of clinopyroxene, a few hypersthenes, and very fine crystal of labradorite (very rare), and glass, not dated, yet. The trachyte lava dome is exposed at the crater II within an elevation of 1300-1400 asl. It is light grey, sheeted and columnar jointed, trachytic, and consists of hypersthene, leucite, andesine (plagioclase), and groundmass. McBirney et al. (2003) had dated the trachy-andesite exposed at Silamuk, a parasitic cone on the elevation of 1200 asl below the lava dome, is 0,69±0.3 Ma. A sequence of volcanic rocks that compose the crater IV are deeply weathered, but columnar lava and a dome are exposed below the crater at the elevation of ~1300 asl. It is a grey, sheeted structure, porphyritic, and is composed of labradorite-andesine, clinopyroxene, and an aphanitic groundmass. According to McBirney et al. (2003), an outcrop near the summit that was probably erupted from the crater IV is having a K/Ar age of 0.5±0.2 Ma. Tephrite and basanite are widely exposed in the northeastern medial facies of Muria Volcano (Tengger and Tirto), Bambang Maar, and Gembong Maar (Fig. 7-9). It is dark grey, mostly sheeting and columnar jointed. the Bambang Maar has about 12km to the northeast, and Tengger-Tirto has about 5km to the north, and the Gembong Maar has about 13km to the southeast of the summit of Muria. The field data recorded vesicular structure, trachytic and porphyritic textures, and composed of foid, pyroxene, hornblende, and biotite as the phenocryst in the aphanitic groundmass. These volcanic rocks are often associated with pumice-rich volcanic breccia and leucite-rich tuff. The volcanic breccia is light to yellowish-grey, very thick layering (@ 60-200cm), medium sorted, and composed of foid as the matrix. The thickness is more than 200m exposed on the surface. The volcano-stratigraphy measured at Bambang Maar, Gembong Maar, and the medial facies of Tirto-Tengger identifies tephritic-basanite lava and breccia covering the basement of the limestone Bulu Formation. The Basanite lava is partially produced by the eruptions of Bambang Maar, northwestern Muria. Basanite lava and breccia (pyroclastic flow deposits), and tuff are widely exposed around the Gembong Maar. A thin section photograph (Fig. 10) shows vesicular with porphyritic texture, subhedral-euhedral, with aegirine and leucite as the phenocryst and glass as the groundmass. The major elements in the tephrite and the basanite are explained by low silica (46-49%) and high sodium+potassium (7-10%; Table 1). The Harker Diagram (Fig. 12) shows high-K properties that should be represented by the presence of leucite. The total sodium versus silica represents the presence of the aegirine. The hornblende and biotite that were recorded during the field mapping are identified as aegirine in thin sections (Fig. 10). Those deposits are covered by the Young Muria lahars and fluvio-vulcanic deposits (sandy to boulder fragments). A thick layer of basanite blocky lava is composing the valley of the maar. Above it is a basaltic-andesite volcanic sequence of the Young Muria volcano (Fig. 5). The oxy-hornblende (Fig. 10. D) of the Gembong maar deposits that were recorded as the mafic mineral in megascopic observation is nearly looked at as hypersthene in depleted plagioclase of the basaltic rocks. According to McBirney et al. (2003) the younger tuff that covers the Pleistocene paleosol above the Bambang maar lava has an Ar/Ar dating age of 0.53±0.01 MA, while the leucite-rich basalt (basanite) lava exposed at Gembong maar gave a K/Ar age of 0.59±0.03 MA. It is looked that during the activities of the Muria volcano, there were also maar activities. The volcanism was possibly influencing the opening circular cracks around it that formed a concentric pattern.

The Patiayam volcanic rocks are dominated by tuff and pumice-rich breccia (Mulyaningsih et al., 2008). The tuff is described as a sandstone of the Ujungwatu Formation by Suwarti & Wikarno (1992) and Kadar & Sudijono (1993). A layer of basalt lava and breccia are exposed at Krajan-Gebog (Patiayam) as the basis of the pumice-rich tuff. Locally, there is kaolinite clay with basalt bomb fragments above a paleosol as the product weathering of the basalt breccia. Basalt lava with massive-vesicular structure, porphyritic, and consists of pyroxene, hornblende, and biotite is exposed at Pojok River-Krajan. Fig. 8 illustrates some outcrops of the Patiayam volcanic rocks and the Gembong maar hydro-volcanic materials. Unfortunately, these volcanic rocks have not been analyzed for the major elements, the thin sections, and the date. It is interpreted there were two periods of volcanism, erupted basaltic volcanic sequence and explosively ejected very fragmented volcanic materials within a long time gap that formed a paleosol layer.

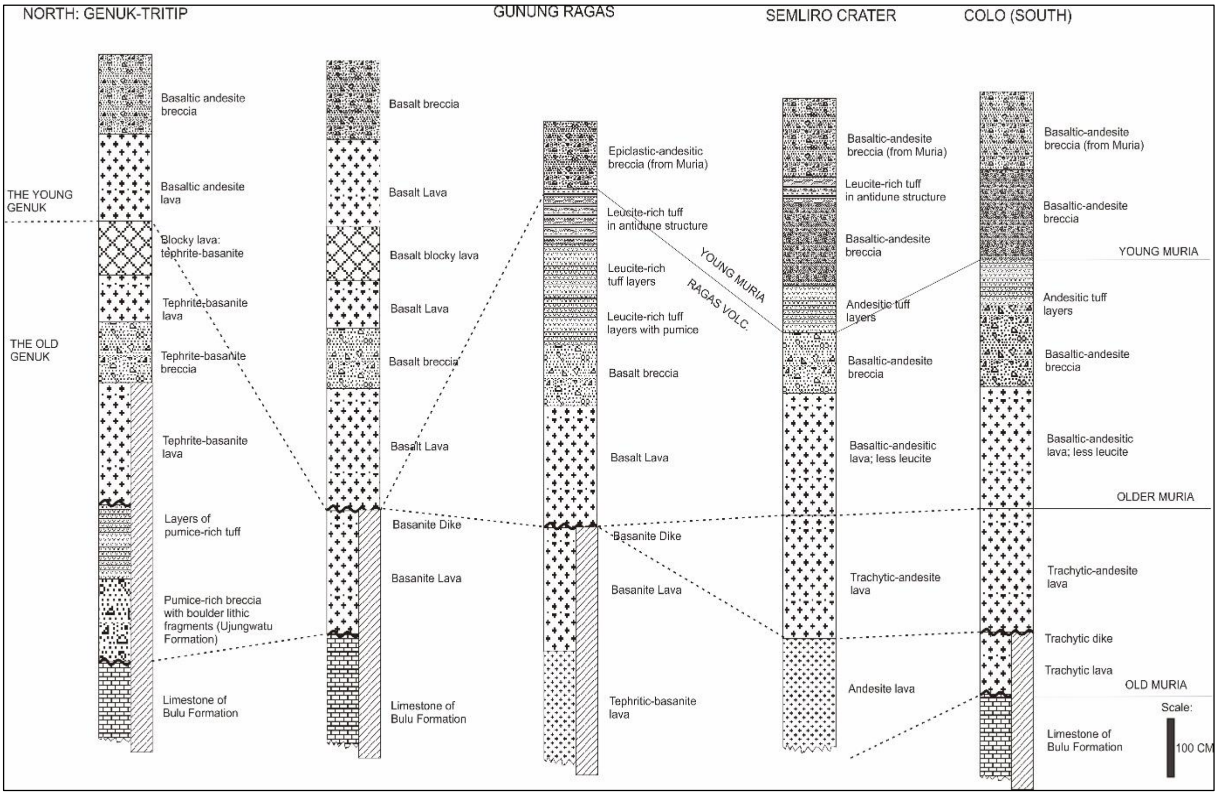

Fig. 5. Lithostratigraphic correlation of the northern Genuk (N) till southern Muria (S) outcrops

Fig. 6. The outcrops of the Old Genuk Volcanic Rocks and the Old Muria Volcanic Rocks

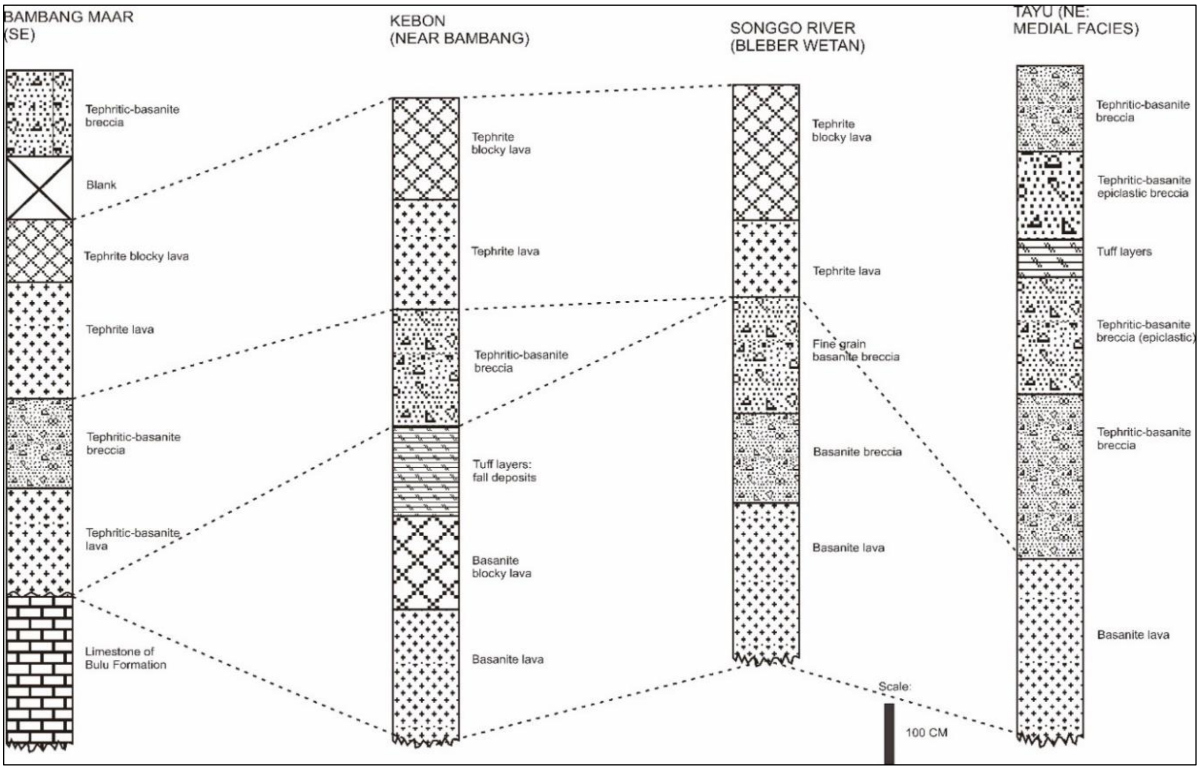

Fig. 7. Lithostratigraphic correlation of the northeastern Muria at Bambang Maar till Tayu and its surrounding areas

Fig. 8. The volcanic-clastic deposits that consist of basalt breccia, pumice-rich tuff, and kaolinite clay of Patiayam Volcano and the volcaniclastic deposits product of Gembong Maar

Fig. 9. The varying Muria Volcanic Rocks consist of trachyte-phonolite, basanite, and the leucite-rich volcaniclastic

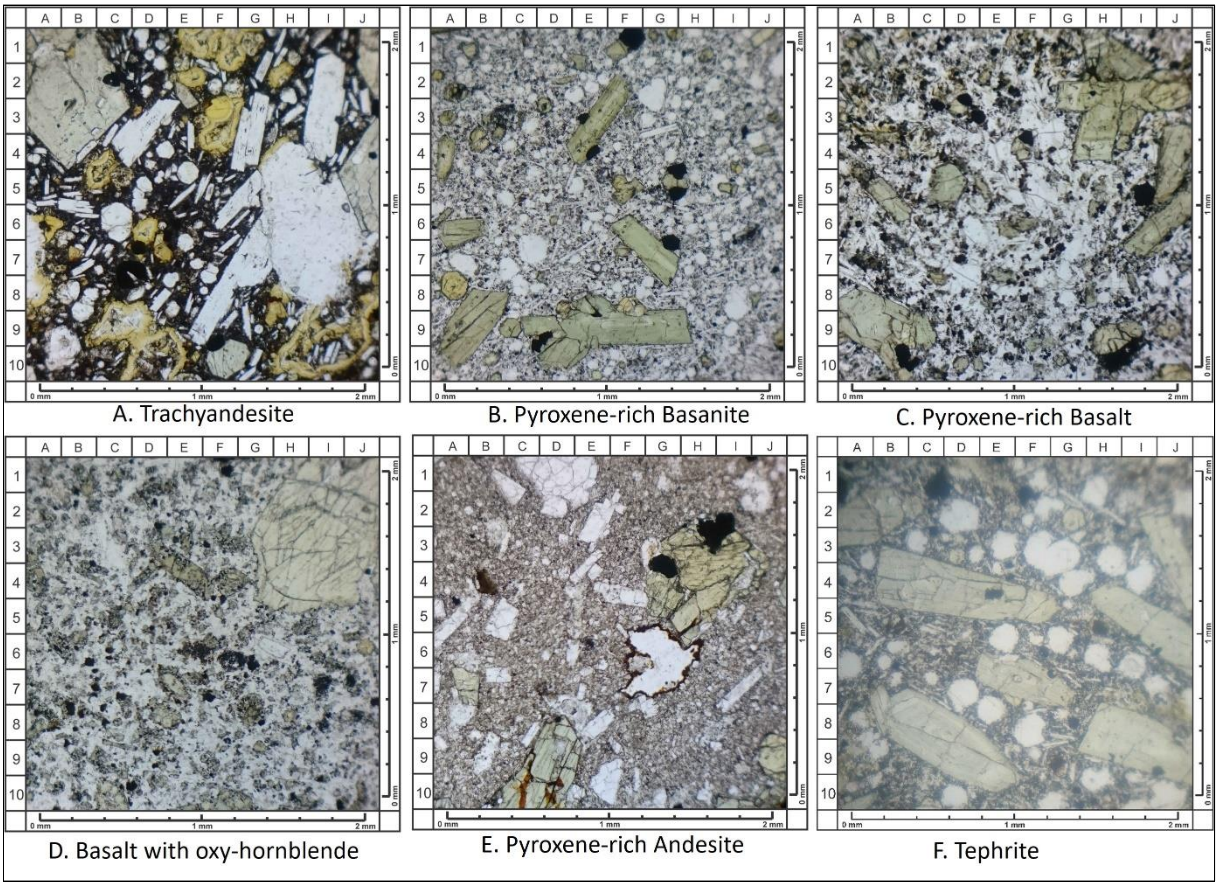

Fig. 10. The thin section photomicrographs of the varying volcanic rocks exposed at the Muria-Peninsula Volcano (trachy-andesite, andesite, basalt, basanite, and tephrite)

Table 1. The major elements of the volcanic rocks exposed in the Muria Peninsula consist of tephrite, phonolite, trachyte, basanite, basalt, and andesite

Sample Code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	TiO_2	P_2O_5	MnO	LOI	Total
MR/01.G	47,5556	16,2705	10,5491	11,8772	1,602	4,729	3,155	0,714	0,82	0,196	2,106	99,5744
MR/02.G	48,93	18,4294	8,429	7,956	1,43	6,427	3,592	0,553	0,478	0,188	2,745	99,1574
MR/04.G	53,797	17,971	7,916	7,159	1,784	2,558	4,249	0,547	0,539	0,150	2,617	99,2872
MR/05.G.1	53,421	21,202	4,196	3,927	0,397	8,24	5,656	0,377	0,115	0,17	3,23	100,931
MR/05.G.2	49,8108	18,4112	9,5613	9,2443	2,022	4,745	3,882	0,642	0,569	0,189	0,493	99,5696
MR/05.G.3	56,418	17,174	5,718	5,581	0,802	4,7891	3,177	0,456	0,288	0,149	5,085	99,6371
MR/05.G.4	50,0303	17,0847	9,176	10,32	2,656	4,049	2,631	0,63	0,436	0,17	2,019	99,202
MR/05.G.5	46,472	16,368	9,467	8,375	1,765	4,729	3,15	0,594	0,705	0,186	7,382	99,193
MR/06.G	52,713	15,377	7,868	7,253	2,88	4,764	4,169	0,567	0,608	0,129	3,168	99,496
MR/08.G	49,675	17,6999	8,783	8,285	2,11	2,517	4,325	0,547	0,542	0,224	4,835	99,5429
MR/09.G.1	51,455	17,776	7,36	7,883	1,49	3,903	3,268	0,509	0,414	0,175	5,735	99,968
MR/09.G.2	50,8907	17,364	7,236	7,77	1,461	3,9388	3,208	0,501	0,408	0,174	6,31	99,2615
MR/09.G.3	50,839	19,114	7,456	6,538	1,27	5,106	3,23	0,489	0,351	0,226	4,506	99,125
MR/11.G.1	58,59	20,002	2,479	2,271	0,225	5,768	6,905	0,266	0,042	0,201	2,547	99,296
MR/12.G.1	64,2785	18,854	1,935	0,717	TT	6,386	5,897	0,271	0,02	0,157	0,938	99,4535
MR/15.G	51,4195	17,068	9,345	9,0126	2,3513	3,3246	3,5087	0,587	0,56	0,17	2,093	99,4397
MR/19.G	51,2205	17,8595	7,286	7,4	0,996	5,939	2,391	0,469	0,347	0,231	5,236	99,375
MR/20.G	46,5077	16,2632	11,7142	12,6332	1,528	4,395	3,123	0,762	0,926	0,2	1,293	99,3453
MR/21.G	51,3457	18,0666	9,263	8,052	1,994	3,982	3,755	0,594	0,51	0,19	1,873	99,6253
MR/22.G	53,682	18,0024	7,0769	7,4129	2,053	4,242	4,353	0,498	0,41	0,171	1,249	99,1502
MR/23.G	46,8918	12,6314	9,6195	14,1126	8,8968	2,17	2,59	0,65	0,873	0,174	0,758	99,3671
MR/24.G	49,1388	18,0268	7,522	8,248	1,707	3,207	4,1856	0,51	0,493	0,187	6,012	99,2372
MR/27.G	51,194	18,91	8,155	7,5512	1,425	5,022	4,762	0,55	0,479	0,194	1,236	99,4782
MR/28.G.1	51,42	18,358	8,359	7,441	1,59	4,712	4,759	0,54	0,591	0,189	1,612	99,571
MR/28.G.2	49,6501	16,8079	9,8352	10,708	2,0918	5,354	3,5132	0,667	0,643	0,175	0,469	99,9142
MR/29.G	48,6774	14,9572	10,26	13,2919	3,183	3,6157	3,2018	0,758	0,698	0,166	0,999	99,808
MR/30.G	51,4124	17,4757	10,1164	8,5955	3,37	3,0865	2,8937	0,691	0,459	0,173	1,612	99,8852

Andesite (basaltic andesite) is mostly exposed in the northwestern-western Muria; it is characterized by dark grey, porphyritic, and consisting of oxy-hornblende (pseudo-hornblende) and labradorite-andesine as the phenocryst. Some of them are brecciated forming autoclastic breccia that is exposed in the south of the Muria Volcano, i.e Rahtawu. Those volcanic rocks are covering the foid-rich volcanic rocks (older rock units). So, the sequence is found in the form of lava, dikes, and breccia as the product of the Young

Muria (Fig. 5 and Fig.9.B-C). The field data recorded it is grey, columnar jointed and sheeted, vesicular, porphyro-aphanitic, and composed of feldspar, hornblende, clinopyroxene, and biotite as the phenocrysts, but it's not recognized by the thin section that composed of aegirine, Ca-Na plagioclase (andesine-labradorite), and glass, which is depleted leucite. (Fig. 10.B). It has ~50-52% of SiO_2, 7-9% of CaO, 1-2% of MgO, and 7-7,5% of total Na_2O+K_2O (Table 1). According to the TAS Diagram (Fig. 11, (Cox, 2013)), it is trachy-andesite. The Harker Diagram (Fig. 12) shows positive trends for the K_2O, Na_2O, and Al_2O and negative trends for the CaO, MgO, Fe_2O, MnO, TiO_2, and P_2O_5. In basaltic-andesite shows, the high Na_2O represents the presence of aegirine, while the plot SiO_2 versus CaO represents the presence of labradorite and andesine. The difference between the Young Muria andesitic volcanic rocks and the Young Genuk basaltic volcanic rocks based on the thin section is the presence of leucite within the Genuk Volcanic Rocks. The higher percent volume of the CaO within the Young Muria Volcanic Rocks represents the sequencing of the materials. It associates with non-foid minerals more than the Young Genuk that still contain little more foid.

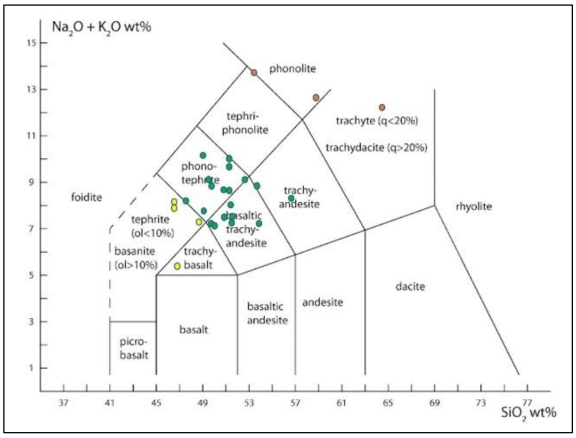

Fig. 11. The TAS Diagram for the Muria Peninsula Vulcanic Rocks (after (Cox, 2013))

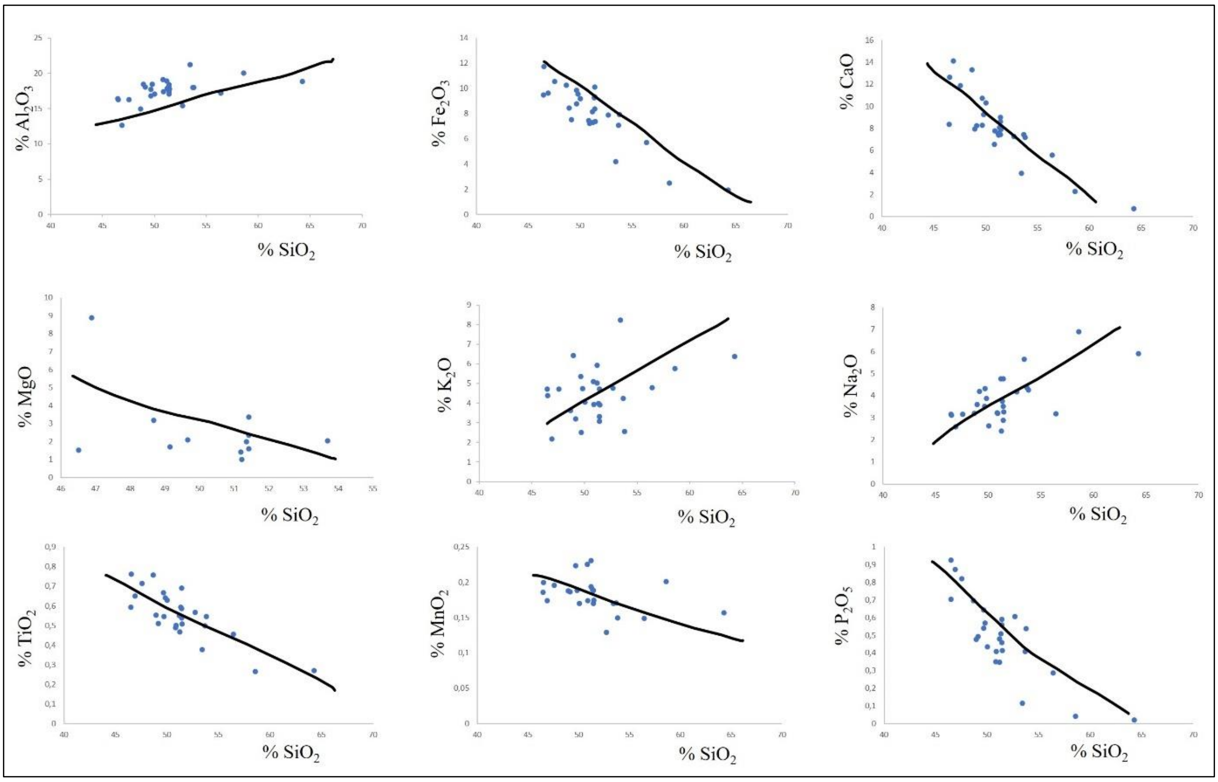

Fig. 12. The Harker Diagram of the varying Muria Peninsula Volcanic Rocks exposed in the study area

The volcano-stratigraphic data (Fig. 5 and 7) noted polygenetic eruptions over a long period resulting in alternating effusive and explosive eruptions, followed by epiclastic lahars and fluvio-volcanic. The eruptions of maars were hydrovolcanic, explosively, and effusively developed circular features with rings, which consist of the ejecta and sub-vertical volcanic-clastic deposits (Fig. 7) of the Gembong, Bambang, Gunungrowo, Bangsri, Mlonggo, Bondo, and Ngelakmulyo. According to White and Ross (2011), maar-diatreme eruptions are mostly episodic. The roots are growing as far as the conduit places so that their magma source and the resulting volcanic deposits tend to be similar to the main volcano. According to McBirney et al. (2003) the Gunungrowo-maar deposits have a K/Ar age of 10,335±430 years BP, the Bambang maar has 0.53 Ma and the Gembong maar has 0.59 Ma (Table 2) indicates that the maars formations were not during the same period. If those were episodic, so there have probabilities of the maar eruptions. According to Basuki et al. (2011) the activity of the Muria Volcano depends on the significant changes in the tectonic cycles. But on the other hand based on the diagram of the ratio Zr/Nb Vs. 87Sr/86Sr (Bowin et al., 1980 op cit Basuki et al., 2011), the scenario of the magma source is influenced by the combination of Mid Oceanic Ridge Benioff (MORB) and the differentiation pattern of the Australian plate sediments. Based on the plot Nb/Y vs. Rb/Y, it is interpreted that the high-K series of Muria has enriched within the plate, while the plot of Ta/Yb vs. Th/Yb shows the influence of the mixing of subduction zone enrichment and plate enrichment (Fig. 13). So that there is still any probability of the capability magmatism below the Muria Peninsula as long as the Java trench's subduction is still active.

Petrologically, there are three types of volcanic rocks; the very high-K alkaline series, the high-K alkaline series, and the high-K Kalk-alkaline series (Fig. 11). In the thin section identified leucite-rich volcanic rocks (Fig.10.A-B,F), leucite-plagioclase-rich volcanic rocks (Fig. 10.E), and the free-leucite volcanic rocks (Fig. 10.C-D). Stratigraphically (Fig 5 and 7; Table 2), the oldest volcanic rocks are found in the Old Genuk, the Old Muria, and Patiayam deposited potassic alkali basalt and trachy-andesite age 1.1-1.2 Ma; consist of lava, dike, and volcaniclastic deposits. So that it was constructive phase volcanism that erupted as effusively. There were no volcanic activities during 1-0.76 Ma. The activities are recorded erupting very high-K volcanic rocks that consisted of tephrite, and phonolite during 0.69-0,5 Ma interfingering between the Young Genuk, Young Muria, and Patiayam. Maars eruptions were also recorded in many phases in explosive, effusive, and hydrovolcanic mechanisms. Paleosol layers are also recorded as an indication of the lag time of deposition from the previous activity to the next activity. Zaim and Delaune (1990) identified any signs of life during the rest period in Patiayam. This indicates that the resting period of the volcano was quite long so that various animals and humans could thrive in this area.

The high-K andesitic to basaltic volcanic rocks in 0.5 Ma and the maars eruptions during 0.53-0.59 Ma, deposited the less leucite basalt and andesite. The next period was leucite tephrite and tephrite-phonolite which were deposited during 0.32-0.34 Ma. The last eruption was by maar Gunungrowo that deposited tuff and breccia of the 10335 years BP. For a while, it can be interpreted those indicating the differences in magmatism sequences that occurred in successive periods of volcanic activity, alternately by the influence of the mixing of the MORB and the resulted Kalk-alkaline magma during the occurring partial melting. In each period, it was the influence of the MORB declined in line with the increasing influence of the supply of magma resulting from the partial melting, which was triggered by the approach of the partial melting zone to the magma chamber and/or magma reservoir that supplied magma to the Muria Peninsula. Those were repeated by the next period of volcanism.

Table 2. The collecting age of the volcanic rocks exposed within the Muria-Peninsula according to McBirney et al. (2003) and Leterrier et al. (1990).

Outcrops	Rock type	Phenocryst / Groundmass	Age (Ma)
Gunung Rowo Maar	**Paleosols** below base surge deposits and accretionary lapilli		0.010335±430
The eastern side of Muria, in Crater-IV	Trachyandesite lava	Augite, andesine-labradorite, and leucite	0.32±0.07
Peak Crater Lava Dome IV	Trachyandesite lava	Augite, andesine-labradorite, and leucite	0.34±0.02
Alas Krasak (parasitic cone)	Leucite tephrite lavas with columnar joint	Leucite and augite (phenocryst) sit in glasses as the groundmass	0.34±0.02 0.32±0.07
Crater IV: Joglo Lava Dome	Andesitic lavas: porphyritic	Augite and andesine in an aphanitic groundmass	0.5±0.2
Bambang Maar	Tuff and volcanic breccias	Leucite, labradorite, and hypersthene	0.53±0.01
Gembong Maar	Basalt	Leucite, labradorite, and hypersthene	0.59±0.03
Patiayam (Bellon, et al., 1987)	Leucite basanite, leucite tephrite, phonolite	Leucite and orthopyroxene	0.6-0.4
Bondo village	Pyroxene-andesite	Leucite, andesine-labradorite, and orthopyroxene	0.637±0.03
Sutarengga Lava Dome (Crater II)	Trachyandesites	Leucite, andesine-labradorite, and orthopyroxene	0.67±0.034
Silamuk that correlates with Crater II	Trachyandesites	Leucite, andesine-labradorite, and orthopyroxene	0.69±0.03
Argojembangan	A cinder cone		
Rahtawu Lava Dome (Crater III)	Tephrite	Augite, biotite, and plagioclase	0.69±0.03
inside Crater-V of Genuk	Diabasic basanite	Leucite, olivines, plagioclase, and aegirine-augite	0.69±0.03
Pligen River	Trachyte	Augite and plagioclase	0.75±0.2
Kedung Dowo Dam-Banjaran River	Leucite basanite and autoclastic pyroxene andesitic lava	Laucite, aegirine, oxy-hornblende, and plagioclase	
Muria II (Maury et al., 1987)	Potassic trachy-basalt and trachyandesite	Leucite, andesine-labradorite, and orthopyroxene	0.75-0.2
Patiayam (Bellon, et al., 1987)	Volcaniclastic breccia intruded by shoshonite dike	Leucite, andesine-labradorite, and orthopyroxene	1.0-0.5
Muria I (Maury et al., 1987)	Potassic alkali basalt	Augite, plagioclase, leucite	1.1-0.6
Genuk (Bellon, et al., 1987)	Leucite basanite and tephrite	Leucite, olivines, plagioclase, and aegirine-augite	1.2-0.5

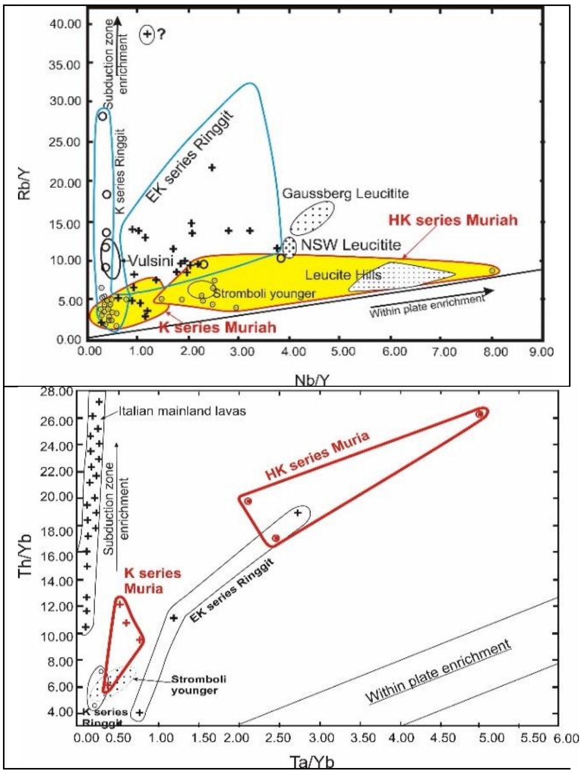

Fig. 13. The diagram plot of Nb/Yb versus Rb/Yb (above) and the Ta/Yb versus Th/Yb (below) of the high-K series and K-series of the Muria Peninsula volcanic rocks compared with the K-series of Ringgit, Stromboli Volcano, and the Italian Mainland lava

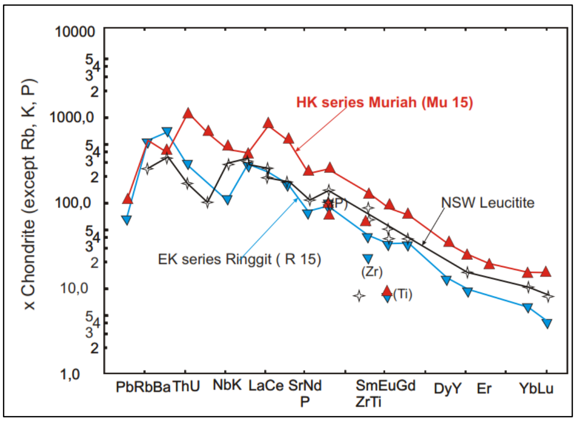

Fig 14. Chondrite normalized REE diagram for the HK-series Muria compared with EK-series Ringgit (Edwards et al., 1994, Cembrano and Lara, 2009) and New South Wales (NSW) leucite (Birch, 1976) (after Sun and McDonough, 1989)

The chondrite normalized diagram for the Muria volcanic rocks compared with the EK-series (Fig 14) and the K series (Fig 15) from Ringgit (Edwards, 1990) and (Edwards et al., 1994) and the NSW leucite (Birch, 1976) has indicated depleted mantle source (MORB) for both the HK-series (Fig 14) and the K series (Fig 15). The higher LREE than HREE is defined as the increase of the incompatible elements and decreasing the compatible elements for both the HK and K series. (Chien, 1984) described the maximum concentrations of the continental crust are not less than 50 to 100 times compared with the value of the primitive mantle with the most incompatible elements of Cs, Rb, Ba, and Th; compared with the oceanic crust is less than 10 times that reached by the medium incompatible elements of Na, Ti, Zr, Hf, Y, and other light, moderately, and heavy incompatible elements. The same REE pattern is found in the Muria HK-series, the Ringgit EK-series (Edwards, 1990) and (Edwards et al., 1994), and the NSW leucite (Birch, 1976) have LREE enrichment compared with the HREE and the MREE. It can be interpreted that the volcanic rocks of the Muria Peninsula tended to relate to the subduction zone than to the back-arc basin volcanism (rift zone). It's indicated by the LILE enrichment partially are Th, K, La, Ce, Ba, and Rb; and depleted in MREE and HFSE including Sm, Eu, Zr, Ti, Gd, Dy, Yb, and Lu.

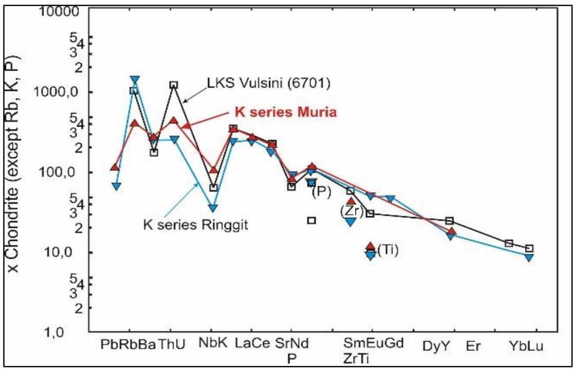

Fig 15. Chondrite normalized REE diagram for the K-series Muria compared with K-series Ringgit (Edwards, 1990, Edwards et al., 1994 and Cembrano and Lara, 2009)) and LKS Vulsini (Birch, 1976) (after Sun and McDonough, 1989)

4. Discussion

Tectonically, Muria Peninsula Volcanic Range is part of the Late Tertiary to Quaternary Sunda Arc volcanism, but based on the petrological study, it is different than the southern range. As concluded by Soeria-Atmadja et al. (1994), Basuki et al. (2011), and Latengke et al., (2019) that is not related to the middle zone of the Java Quaternary Volcanic Arc. In line with them, Usman (2012) and Usman and Lugra (2016) described it as the back-arc basin volcanism. Back arc basin volcanism is used to resulting basaltic materials with pillow structures, floods basalt, and other tholeiitic volcanic materials which are developed within a rift zone volcanism (Maccaferri et al., 2014, Pollard et al., 1983, and Walker, 1999).

The volcano-stratigraphic data (Fig. 5 and 7) lead to conclude polygenetic eruptions that consist of alternating effusively and explosively eruptions. Repeating lahars, fluvio-volcanic, and transitional sedimentations were performed in the lower land until the beach. The maars activities were also in many periods (Fig. 7) and many places (Gembong, Bambang, Gunungrowo, Bangsri, Mlonggo, Bondo, and Ngelakmulyo (Bronto and Mulyaningsih, 2007)). As episodic activities, maars around the Muria, Genuk, and Patiayam have probabilities of eruptions. The Muria Peninsula is a group of strato-type volcanoes. Each volcano has symmetrical cone geomorphology with more than 2 craters, consisting of layers of lava, volcanic breccia, dikes, and other kinds of shallow intrusions. For the Genuk and Muria volcanoes are surrounded by maars. So that the Muria Peninsula is not like back-arc volcanism even to be back-arc basin volcanism.

As recorded in the stratigraphic (Fig 5 and 7), petrologic (Fig 10), and chemical composition (Table 1, Fig 11-15); there were repeating properties of the high-K of Kalk-alkaline and the high-K and very high-K alkaline, that also illustrated in the Harker Diagram. It might all of the volcanoes around the Muria Peninsula had the same magma source and magma type which originated from the subduction zone. The mineral composition (Table 2) is in line with the spider diagram (Fig 14-15) and the petrography, which mostly contains clinopyroxene (augite and aegirine), plagioclase (in repeating andesine and labradorite), and foid minerals, indicate that it was influenced due to the fractional crystallization within the magma chamber.

Paleosol layers are also recorded as an indication of the lag time of deposition from the previous activity to the next activity. Zaim and Delaune (1990) identified any signs of life during the rest period in Patiayam. This indicates that the resting period of the volcano was quite long so that various animals and humans could thrive in this area. Genuk, Muria, and Patiayam volcanoes have the same range of time in their activity. All three are indicated to cross each other. Same magma sources in different magma chambers are possible to show interfingering activities within the same mechanism, eruption results, and periodization.

Conclusion

The Muria Peninsula is a range of composite/strato-type volcanoes, known within 1.2 Ma-10 Ka, consisting of Genuk, Muria, Patiayam, and episodic maars. As composite volcanoes, those consist of constructive and destructive phases of activities, periodically. During their activities, three types of volcanic series that consist of very high-K alkaline, high-K alkaline, and the high-K Kalk-alkaline series were alternately took place, by efusive, explosive, and maar hydrovolcanic eruptions. Those were in the same tectonic setting of subduction zone of Sunda Arc that influenced by the same magma sources in the same time range, but in different magma chambers. Magmatic differentiation and fractional chrystalization influenced the activities and the volcanic series products. The Muria Peninsula has probability to re-active when magma is supplied from the subduction zone. The probability value requires further statistical study.

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