Characteristics of pyroclastic deposits and evolution of Maar Bethok Lamongan Volcano Tiris Probolinggo East Java Indonesia

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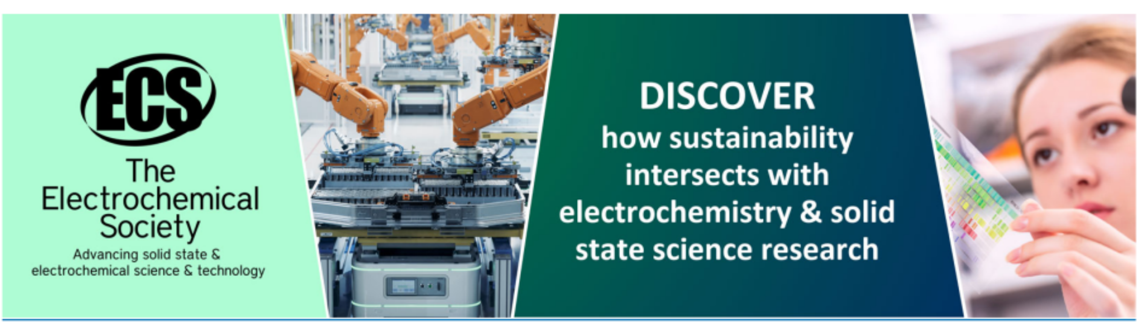

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Characteristics of pyroclastic deposits and evolution of Maar Bethok Lamongan Volcano Tiris Probolinggo East Java Indonesia

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Abstract. The Lamongan Volcano Complex has a very different character from the Bromo and Argopuro Volcano groups. Lamongan Volcano has 37 volcanic cones and 27 maars (ranu). This volcano is quarter-old and occupies part of East Java Province. Maar Bethok is composed of lava and intercalation between pyroclastic deposits from phreatomagmatic and magmatic falls that still need to be firmly consolidated. These pyroclastic deposits characterize a strombolian eruption with more lava dome or crater wall material ejected. The rocks that make up the Bethok maar include olivine-pyroxene basalt lava and pyroclastic fall deposits with fragments of olivine basalt and basalt composition. The evolution of the Bethok maar eruption started from magma with an alkaline composition and ended with a more acidic composition. The magmatism of Bethok maar has an island arc calc-alkaline affinity.

1. Introduction

Indonesia is located at the meeting point of three large plates: the Eurasian plate, the Indian-Australian plate, and the Pacific plate. As a result, Indonesia has a complex tectonic structure. Subduction between continental and oceanic plates results in the forming of volcanic pathways known as rings of fire. One of the volcanoes formed from subduction between plates on the island of Java is the Lamongan Volcano, which is located in Probolinggo, East Java, especially at Maar Bethok (coordinate UTM 49M 764019 mE, 9118818 mN) (Figure 1). This volcano is unique compared to volcanoes in the circle of fire because Lamongan Volcano has the characteristic of forming a dry maar or one filled with water and becoming a lake (water-filled maar). Lamongan Volcano has around 61 cinder cones and 29 maars [1]. The formation of maar volcanoes is related to the lithology of the bedrock, groundwater, and the influence of fracture structures. Ranu Bethok and several other small lakes around Lamongan Volcano are evidence that the maar shows water contact with magma and magmatic activity in its development.

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According to Schieferdecker [2], a maar is a basin generally filled with water, reaching 2 km in diameter and surrounded by sediment from the eruption. A maar volcano whose crater basin does not contain water is called a dry maar. Maar is a monogenic volcanic cone that cuts through bedrock below the groundwater level and forms a gently sloping cone composed of fine to coarse-grained volcanic material. Maar has a crater diameter between 100 – 3000 m and is often filled with water, thus forming lakes [3, 4]. Maar diatrema is a volcanic phenomenon that is much sought after and is profitable in mineral and geothermal exploration because it is clear evidence of the presence of a hydrothermal system that has the potential to produce mineral deposits and geothermal energy.

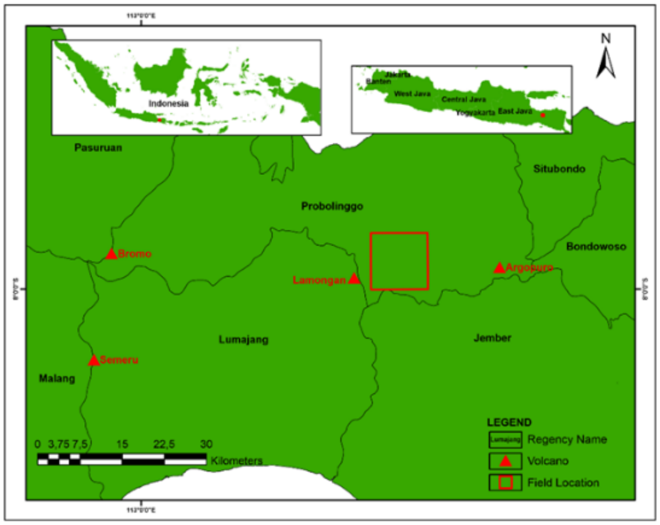

Figure 1. Location map of the research area.

Carn and Pyle [5] explained that Lamongan Volcano is a volcano that developed as a maar volcano or a volcano with negative topography. According to Lorenz [6], the formation of maar volcanoes is thought to be related to groundwater conditions, bedrock lithology, and the influence of fracture structures. Maar volcanic eruption activities include phreatic, phreatomagmatic, and magmatic eruptions [7]. Phreatic eruptions occur when hot jets of magma come into contact with groundwater in bedrock. Then, it becomes steam with increasingly higher pressure because of the cap rocks. Maar volcanic eruptions can occur if the pressure of the hot water vapor exceeds the pressure of the capping rock and the rocks above it. The eruption produced a phreatic eruption by scattering material of various sizes. The erupted material comes from bedrock (nonmagnetic material or hydroclastic deposits). These hydroclastics form maar lakes, an eccentric eruption with the eruption center being on the lower slopes of the main volcano [7].

Meanwhile, phreatomagmatic eruptions eject a small portion of magma components (magmatic material). The main ingredients resulting from magmatic eruptions come directly from the magma, forming pyroclastic deposits. If the gas pressure in the magma weakens, the magma comes out as melt (effusive eruptions). This effusive eruption can take the form of a lava flow, lava dome, or lava plug. Thus, the complete series of volcanic eruptions begins with a phreatic eruption, continues with a phreatomagmatic and magmatic eruption, and ends with an eruption of molten lava. This research aims to study the characterization of the pyroclastic deposits that make up the Bethok maar and the eruptive evolution of the Bethok maar eruption and magmatism in the Lamongan volcanic complex, especially in the Bethok maar area.

2. Data and Methodology

The analysis methods used are geological mapping and petrographic analysis. Geological mapping is mainly carried out in volcanic mapping. Meanwhile, field activities include observing outcrops, describing lithology, measuring outcrop profiles, measuring the position of rock layers, and taking rock samples. The rock outcrop data obtained was then plotted on a base map based on the observation location points using a GPS (Global Positioning System) tool. The field mapping results obtained seven rock samples, which will be subjected to petrographic analysis. Petrographic analysis was carried out in the Geological Engineering laboratory of UPN "Veteran" Yogyakarta.

This research also used the petrography method to analyze rocks with a polarizing microscope to determine mineral composition, rock texture, mineral optical properties, and other microscopic information. Thin sections of rock are the most effective object in describing rocks. A thin section is a piece of rock or material attached to a microscope slide using special media or a mounting agent (Epoxy glue or Canada balsam), then thinned until it reaches a thickness of ± 0.03 mm. A cover glass is attached to the surface at this thickness and then observed using a polarizing microscope with a transmission beam.

3. Results and Discussion

Bronto et al. [8] show that the eruption products of Lamongan Volcano can be divided into several products, namely the side eruptions of Young Lamongan (Lamongan Recent), the central eruption of Mount Tarub (Old Lamongan), phreatic eruptions, eccentric eruptions, and secondary deposits. While the eruption results from the central crater mostly consist of pyroclastic fall and lava, eccentric eruptions are composed of lava alone or pyroclastic and a combination of lava and pyroclastic. The result of side eruptions is usually in the form of lava flows. Secondary processes usually produce products in the form of lava and fluviatile deposits. The old lava of Lamongan Volcano usually contains phenocrysts in the form of plagioclase, clinopyroxene, olivine, and Ti-magnetite in basic volcanic glass crystals. The petrography of this lava is usually found to be uniform or without significant variations [5].

According to Sukhyar [9] explains that the rock units produced by the eruption of Lamongan Volcano are as follows:

- Old Lamongan lava consists of olivine basalt lava
- The old side eruptive lava consists of old olivine basalt
- Young Lamongan lava consists of olivine basalt lava
- Parang lava consists of pyroxene basalt lava
- The young side eruptive lava of Lamongan Volcano consists of olivine, microcrystalline, and pyroxene in a base mass of volcanic glass and basalt.
- The Pandan pyroclastic deposits consist of pyroclastics, lapilli sand scoria bombs
- Geni pyroclastic deposits consist of basaltic, scoria, and loose pyroclastic
- Young Lahar deposits consist of chunks of basalt lava, consisting of weak to strong amalgamated lava deposits, the base mass is the size of tuff silt sand
- The pyroclastic deposits of Lamongan are composed of pyroclastic materials consisting of basalt scoria and altered basaltic andesite that are loose until weakly combined

Lamongan volcano and its epigones cone are located in the basin area between the Java Island anticline, which forms an open fissure system trending west-southwest (WSW) and east-northeast (ENE) at a distance of 4 kilometers [10]. So, earthquakes often occur in the Lamongan Volcano area, which may be closely related to the structural pattern of development in the area. The geological structures found in the Lamongan Volcano area are normal and strong faults. Some lineaments are thought to be faults. Normal faults generally trend northwest-southeast and cut Pliocene-Holocene rocks. Joints develop in all rocks in irregular directions. From the results of the interpretation of the aerial portrait, it can be seen that several lineaments indicate northwest-southeast and north-south directions. From the results of Landsat image analysis in this area, there are graben, maar, and circular lineament structures [11]. Lamongan Volcano is surrounded by several very active parasitic cones or eccentric cones, and the distribution of these volcanic cones follows the pattern of Lamongan's geological structure. The structure is oriented west-east and south-north. These maars are characteristic of the Lamongan Volcano and are composed of basalt and andesite lava [9, 12].

Prakosa [13] explains that the lithology of Tiris and its surroundings is dominated by volcanic deposits resulting from the eruption of Lamongan Volcano with basaltic trachyte andesite and basalt lithology types, as well as deposits resulting from maar eruptions. Material deposits resulting from maar eruptions are divided into three types: pyroclastic fall deposits, pyroclastic flow deposits, and surge deposits. The mineralogical composition of the constituent rocks is dominated by andesine-type plagioclase, hypersthene orthopyroxene, and augite clinopyroxene as phenocrysts, and the groundmass is composed of plagioclase microliths, opaque minerals, and volcanic glass. The complex magma of Lamongan Volcano has undergone a differentiation process by crystallization fractionation. The type of maar-forming eruption in the research area is phreatomagmatic. The deposition mechanism in pyroclastic fall deposits is direct deposition through air by gravitational forces. The mechanism for the deposition of pyroclastic flow deposits (block and ash flow) is through currents with high particle concentrations. Meanwhile, the mechanism for depositing pyroclastic surge deposits is through currents with low particle concentrations.

3.1 Stratigraphy of Maar Bethok

3.1.1 Structure and texture

Morphologically, Ranu Bethok is surrounded by a rim consisting of interbedded pyroclastic falls and lava at the base of the rim. A rim is a circular morphological formation around the edge of a crater consisting of pyroclastic deposits and lava [14]. The rim encircles ranu or maar Lake with an area of around 500 m2. These pyroclastic deposits show a good layering structure. They are sometimes limited by paleosoil, which indicates that the old maar eruption was covered by deposits from the new maar eruption with a fairly long time lag, resulting in soil in the form of clay material that is slightly brownish. Some found traces of burnt grass due to pyroclastic deposits on it.

Fragments of pyroclastic deposits are basalt with a scoria structure and some form blocks or fragments. Blocky formations or sharp fragments indicate that the material comes from crater walls or lava domes and sometimes undergoes oxidation. These deposits are called phreatic deposits. These phreatic deposits are caused by magma heating the surrounding fluid and melting it to the surface [15]. Phreatic eruptions can produce maars, and most maars are produced by phreatomagmatic explosions. Phreatic eruptions are caused by eruptions with crater diameters ranging from several tens of meters to more than 1 km with an accumulation of angular rock fragments [16].

Meanwhile, fragments with a scoria structure indicate that the fragments originate from a magmatic eruption from within the diatreme, and deposits like this are called magmatic deposits. Magmatic eruptions occur when the fragmentation of the eruption is caused by the release and expansion of volatile substances [16]. Blocky fragments and scoria indicate that the eruption occurred due to a phreatomagmatic eruption. This phreatomagmatic eruption complies with Houghton et al. [15] to characterize eruptions where magma interacts directly with external water. To distinguish magmatic and phreatomagmatic deposits specifically by paying attention to lithic fragments. A deposit containing large amounts of lithic rock is called a phreatomagmatic layer, while magmatic deposits consist of several scorias, such as those produced by strombolian eruptions. So, the number of lithic fragments does not mean much [16].

According to Hasibuan et al. [17], the lava has a porphyritic texture with phenocryst sizes that are almost uniform within the groundmass and vary in size collection of phenocrysts. Seven selective samples of lava representing volcanic rocks in the study area were analyzed. These samples generally show porphyritic, aphanitic, hypocrystalline, glomeroporphyritic, and intersertal textures. These samples generally show porphyritic, glomeroporphyritic, and intersertal textures. The amount of phenocrysts in lava is related to viscosity. Thicker lava tends to form more phenocryst crystals.

3.1.2 Stratigraphy

Maar volcanoes are a type of volcano whose pyroclastic deposits usually contain a lot of lithic fragments that are deposited in maar ejecta rings or show tephra-ring growth [18]. Bethok maar pyroclastic deposits consist of interbedded magmatic deposits and phreatomagmatic deposits, which are underlain by basalt lava at the bottom (appendix). So the Bethok maar deposits can be divided into three deposit units, namely: olivine-pyroxene basalt lava, pyroclastic fall one deposit consists of interspersed magmatic and phreatomagmatic deposits, pyroclastics fall two consist of interspersed magmatic and phreatomagmatic deposits, while pyroclastics fall 3 are phreatomagmatic deposits which are part of the final eruption series from Bethok maar. The rock unit boundaries of each of these units are separated by paleosoil.

3.2.2.1 Lava basalt olivine-pyroxene

Lava basalt is an aphanitic (fine-grained) extrusive igneous rock that forms from the rapid cooling of low-viscosity lava rich in magnesium and iron (mafic lava) exposed at or very close to the surface [19]. The olivine-pyroxene basalt lava is gray, scoria in structure, and with texture from aphanitic, hypocrystalline with plagioclase phenocrysts, olivine, pyroxene, opaque minerals, and plagioclase microlites in volcanic glass as groundmass.

3.2.2.2 Pyroclastic fall 1 deposits

Pyroclastic fall 1 deposits consist of interbedded magmatic and phreatomagmatic deposits.The pyroclastic deposits of this fall are basalt lava at the bottom, while the upper part consists of interspersed magmatic and phreatomagmatic deposits.

This pyroclastic fall 1 deposit is covered by magmatic deposits as fall pyroclastic breccia of gravel-sized, angular, and scoria structure, as well as with graded bedding. The layer thickness is around 20-50 cm. The fragments consist of basaltic scoria. Phreatomagmatic deposits are composed of fallen pyroclastic breccia, slightly brownish in color and gravel in size, as well as angular fragments. The fragments consist of blocky and basalt scoria showing a graded bedding structure. Some fragments show oxidization and are about 0.5 m thick.

3.2.2.3 Pyroclastic fall 2 deposits.

The boundary between the pyroclastic fall 1 deposit and pyroclastic fall 2 deposit is limited by paleosoil. This paleosoil is soil or clay resulting from the topsoil on the surface so in this paleosoil you will find roots or grass growing on the surface of the soil before the next eruption covers it. This pyroclastic fall 2 deposit consists of interbedded magmatic and phreatomagmatic deposits.

Magmatic deposits are pebble-sized, angular, scoria, and graded bedded pyroclastic breccia. The fragments consist of basaltic scoria. Meanwhile, the phreatomagmatic deposits are pyroclastic fall breccia, the color is slightly brownish, the size is gravel and the shape of the fragments is at an angle. The fragments consist of blocky and scoria, together with the matrix forming a graded bedding sedimentary structure. The fragments consist of blocky basalt and scoria. Some fragments of this phreatomagmatic deposit show oxidization and are about 0.5 m thick.

3.2.2.4 Pyroclastic fall 3 deposits.

The boundary between pyroclastic fall 2 deposits and pyroclastic fall 3 deposits is limited by paleosoil. This pyroclastic fall 3 deposit is a phreatomagmatic deposit consisting of pyroclastic fall breccia. The color of this sediment is slightly brownish, slightly weathered, and has gravel-sized fragments with an angular shape. The fragments consist of blocky basalt and scoria basalt. The sedimentary structure is seen as a gradual arrangement or graded bedding. Some fragments show oxidation and the thickness of this rock unit is around 0.5 m.

3.3 Magmatism

3.3.1 Lava and fragment types

Petrographic observations to observe the structure, texture, and mineral composition of rocks. Such as observing the composition of plagioclase and the abundance of phenocrysts or basic mass in thin sections, to knowing the petrogenesis of rocks. The rock texture analyzed refers to the texture written in [20]. In the research area, rock textures observed include porphyritic, aphyric, and glomeroporphyritic. The rock fragments that make up the fallen pyroclastic deposits in the study area generally consist of pyroxene basalt. These rock types are taken to represent fragments of several layers of pyroclastic deposits. This is intended to determine the type of fragments, distribution of phenocrysts, and the nature of magmatism from the maar eruption period which is characterized by each layer of fallen pyroclastic deposits. The rock types that represent each of the pyroclastic deposits that make up the maar are as follows:

3.3.1.1 Basalt olivine-pyroxene

Olivine-pyroxene basalt is a lava (B-LP 32) located at the bottom of the Bethok maar pyroclastic deposits. Microscopically, this olivine-pyroxene basalt shows a scoria structure and has an intersertal, glomeroporphyritic, hypocrystalline texture. Phenocrysts (65%) measuring 0.2-1.2 mm consist of plagioclase minerals (45%), and plagioclase in groundmass is present as bytownite (An 72), Olivine is present at 15%, pyroxene/augite (2%), and opaque minerals (3%) (Table 1). Some olivine is converted into iddingsite. Phenocrysts are embedded in a groundmass of volcanic glass and plagioclase microliths. Some opaque minerals are present in inclusions of phenocrysts. Apart from that, this pyroxene basalt is also a fragment in almost every layer of the fallen pyroclastic deposits that make up the Bethok maar.

3.3.1.2 Basalt olivine

This olivine basalt is present in the form of fragments (B-LP 31-A3 and B-LP 31-A5) in pyroclastic fall unit 1. Microscopically, this olivine basalt shows a scoria structure and has an intersertal, glomeroporphyritic, hypocrystalline texture. Phenocrysts (45-55%) measuring 0.2-1.2 mm consist of plagioclase minerals (32-45%), olivine (8-12%), and opaque minerals (5%) (Table 1). Plagioclase in groundmass is present as labradorite (An 68). Phenocrysts are embedded in a groundmass of volcanic glass and plagioclase microliths. Some opaque minerals are present in inclusions of phenocrysts. Apart from that, pyroxene basalt is also a fragment in almost every layer of fallen pyroclastic deposits that make up the Bethok maar.

3.3.1.3 Basalt

Basalt is a fragment of pyroclastic fall 2 (B-LP 31-A6; B-LP 31-A1) and pyroclastic fall 3 (B-LP 31-B1 and B-LP 31-A4) which are located in the upper part of the Bethok maar pyroclastic deposits. Microscopically, basalt fragments generally have intersertal, pilotaxitic, aphyric, and hypocrystalline textures. Phenocrysts (25-45%) measuring 0.2-0.8 mm consist of plagioclase minerals (16-34%), olivine (1-3%) and opaque minerals (8%) (Table 1). A groundmass of volcanic glass and plagioclase microliths surround the phenocrysts. Plagioclase in the groundmass is present as labradorite (An 55).

Table 1. Table of the mineralogical presence of basalt fragments in the study area.

No.Sample	Texture	Mineralogy(%)				Phenocryst	Name	Unit
		plg	olv	px	Opq			
B-LP31-A4	Intersertal, afiric	16	1		8	25	Basalt	Pyroclastic fall 3
B-LP31-B1	Intersertal, afiric	20	2		8	30	Basalt	
B-LP31-A1	Intersertal, pilotaxitic	31	1		8	40	Basalt	
B-LP31-A6	Intersertal, pilotaxitic	34	3		8	45	Basalt	Pyroclastic fall 2

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B-LP31-A5	Intersertal	32	8		5	45	Basalt	Pyroclastic fall 1
B-LP31-A3	Intersertal	38	12		5	55	Basalt olivine	
B-LP32	Intersertal, glomerophorfiritic	45	15	2	3	65	Basalt olivine-pyroxene	Basalt olivine-pyroxene

Annotation: plg: plagioclase; olv: olivine; px: pyroxene; opq: opaque mineral

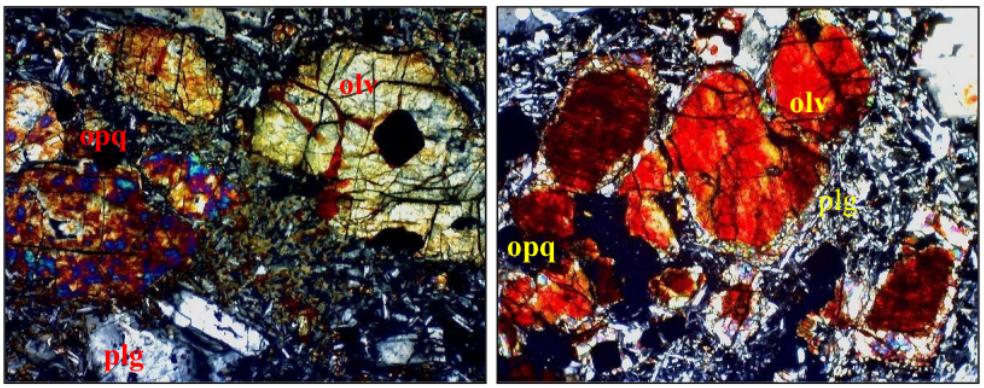

Figure 2. Showing photos of petrographic sections of olivine basalt rock (samples B-LP32 and B-LP31-A3) from pyroclastic deposit fall 1. The photo shows that the olivine (olv) has been transformed into iddingsite. Other accompanying minerals are plagioclase (plg) and mineral opaque (opq).

3.3.1.4 Magma evolution

From the stratigraphic sequence and mineralogical composition of the lava and fragments of pyroclastic deposits that fell from the Bethok maar, a sequence of the evolution of the Bethok maar eruption can be constructed. The evolutionary sequence of the Bethok Maar eruption starts from the formation of olivine-pyroxene basalt lava, then olivine basalt, and finally basalt.

Olivine-pyroxene basalt is lava from the effusive eruption of the Bethok maar and this lava is the oldest rock that makes up the Bethok maar. This lava shows the presence of 15% olivine and this mineral measuring around 1.2 mm, as well as the presence of augite (2%). The presence of these minerals indicates that the effusive eruption of this maar has an alkaline magma composition. Meanwhile, the next eruption was an explosive type with the presence of pyroclastic deposits from fall 1 to pyroclastic deposits from fall 3. These fall pyroclastic deposits show that the younger the explosive eruption from the Bethok maar, the more acidic it is. This is characterized by the lower presence of olivine in the fragments, namely around 1-12%. Apart from that, the size of olivine is getting finer, from around 0.8 mm to < 0.2 mm. Based on the presence of the mineral olivine and the size of the olivine, it can be interpreted that after the effusive eruption of olivine-pyroxene basalt, there was a change in the composition of the magma became more acidic, namely with the presence of olivine from basalt fragments as a constituent of pyroclastic fall 1 deposit to pyroclastic fall 3 deposits.

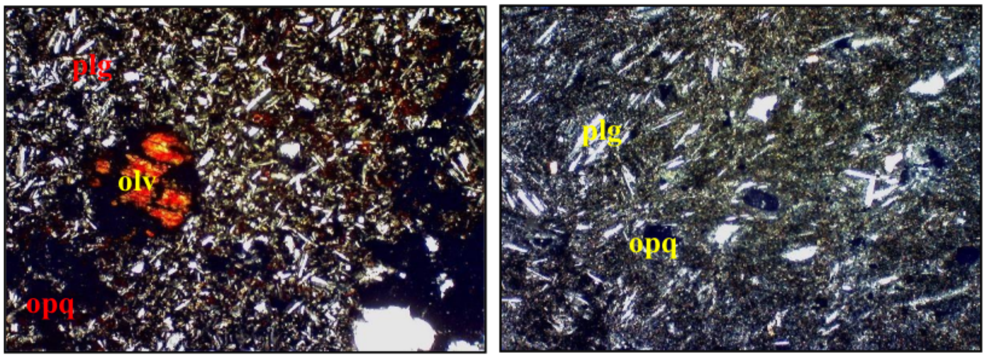

Figure 3. Show photos of petrographic incisions from basalt rocks (samples B-LP32-A6 and B-LP31 A5) from pyroclastic deposit fall 2. Sample B-LP32-A6 shows the presence of fine-sized olivine and has been converted into an iddingsite. Meanwhile, the B-LP31-A5 basalt sample shows a pilotaxitic texture. Other accompanying minerals are olivine (olv), plagioclase (plg), and mineral opaque (opq).

3.3.1.5 Magma affinity

Quaternary magmatic arc on the island of Java, as described by Soeria et al. [21] stretches from the west-east direction with a lime-base affinity. Likewise in East Java, a series of Quaternary volcanoes forms a straight line trending west-east. The results of petrographic observations of Lamongan Volcano samples show that the general composition of phenocrysts and groundmass forms a porphyritic texture with a high intensity of around 65-80% (Figures 2 and 3). Phenocrysts consist of the minerals plagioclase, olivine, pyroxene, and opaq.

According to Ewart [22] and Wilson [23], states that these characteristics are possessed by volcanic rocks that were tectonically formed on island arcs. Volcanic rocks in the study area have abundant phenocrysts of around 25-65%, consisting of plagioclase (16-45%), olivine (1-15%), pyroxene (2%), and opaque minerals around (5-8%). The presence of olivine, pyroxene, and opaque minerals indicates that the volcanic rocks in the research area are rich in iron. The abundance of these phenocryst minerals is characteristic of island arcs. So, based on these characteristics, the volcanic rocks in the study area are calc-alkaline, formed on island arcs [7, 23, 24]. So it can be concluded that the fragments from Bethok maar are volcanic rocks from Lamongan Volcano which were formed in an island arc environment with a calc-alkaline composition during the Quaternary period of the volcanic arc on the island of Java.

4. Conclusion

Maar Bethok is one of the maars resulting from the side eruption of the Lamongan Volcano Complex. This maar is on the eastern side of the volcano. In general, this volcano is a strato-type volcano with several parasitic cones growing at the foot of the mountain. The rocks that make up the Bethok maar consist of 3 lithological units, namely: olivine-pyroxene basalt lava, fallout pyroclastic deposits 1, fallout pyroclastic deposits 2, and fallout pyroclastic deposits 3. The olivine-pyroxene basalt lava unit is the oldest unit that makes up the Bethok maar and the unit is characterized by the presence of the minerals olivine and pyroxene. Meanwhile, each of the pyroclastic deposits in falls 1 to 3 consists of repeating magmatic deposits and phreatomagmatic deposits composed of basalt fragments. Significantly, basalt fragments from fallen pyroclastic deposits are characterized by the presence of olivine which decreases towards younger lithological units.

By arranging the stratigraphy from old to young of the rocks that make up the Bethok maar and the mineralogical content of the rocks that make up it, we can see the evolution of magma from the eruption period of the Bethok maar. The eruption of Bethok maar was initiated by magma with an alkaline composition which was characterized by the presence of olivine-pyroxene basalt and olivine basalt.

Then there was a change in the magma composition caused by the magma differentiation process so that at the end of the Bethok maar eruption period the magma showed a more acidic composition, which was indicated by the presence of basalt, where the amount of olivine contained in this basalt was decreasing and was no longer even found in the groundmass. However, based on the presence of these minerals, the Lamongan volcanic rocks have a calk-alkaline affinity which was formed in the island arc.

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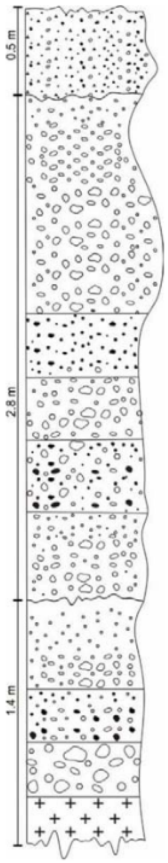

Appendix. Ranu Bethok stratigraphic profile

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