Preliminary study of the origin of mafic mineral megacrysts in volcanic rocks in the southwestern part of Kulon Progo Mountains, Indonesia

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Abstract. The Bagelen district in the southwestern part of Kulon Progo Mountains has a unique aspect in the form of the occurrence of mafic mineral megacrysts in volcanic rocks. This research is conducted to determine the type, the distribution, and the origin of those megacrysts, which are abundant in pyroclastic rocks. Detailed geological mapping on an area of 4 x 4 km with a scale of 1: 25,000 and petrographic analysis were done to explain the geological aspects that led to the presence of mafic mineral megacrysts in the study area. Petrographic analysis shows that the types of mafic mineral megacryst are hornblende, clinopyroxene, and plagioclase. Their features under the microscope observation are oscillatory zoning, half oscillatory zoning, sieve, and breakdown texture. These minerals are found as single crystal fragments and also as clinopyroxene and hornblende cumulate fragments in pyroclastic breccia. Based on mineralogical composition and texture, these mafic mineral megacrysts were formed by fractional crystallization process in the form of crystal settling mechanism. These minerals were initially accumulated in the bottom of magma chamber, then carried upward by rapid magma rising in association with explosive eruption event of Mount Ijo. These minerals were then transported on the surface through the mechanism of pyroclastic flow and were deposited in the valley to form an alluvial fan morphology in the southwestern part of Kulon Progo Dome.

Keywords: megacrysts, hornblende, cumulate, pyroclastic flow, Kulon Progo

1. Introduction
Kulon Progo Mountains, which are located in the west of the city of Yogyakarta are mainly composed of Eocene to Pliocene rocks. Many of these rocks are volcanic rocks of Oligocene to Miocene age, which presents many interesting aspects to study. One of the interesting locations to study in Kulon Progo Mountains is located in the Bagelen District, Purworejo Regency, Central Java, which is specifically located in the southwestern part of Kulon Progo Mountains (Figure 1). This location has a unique aspect because some of giant mafic minerals are found in volcanic rocks which have been interpreted before as hornblende. Hornblende and other mafic minerals like pyroxene and olivine are certainly very common in igneous and volcanic rocks in the Kulon Progo area. However, mafic minerals with large crystal size (>1 cm) which considered as megacryst are quite rare. Occurrence and abundance of the megacrysts in the study area are very intriguing to study, especially their origin.

Megacryst is a large crystal (1 to 7 cm long xenocryst and phenocryst) with at least one crystal face [1] usually euhedral crystal set in fine grained groundmass or matrix. This term does not have genetic
implications like phenocryst [2]. Megacryst also refers to monomineralic aggregates which have an uncertain relationship with the host rock [3].

Megacryst minerals in the study area are found as fragments in pyroclastic rocks. It is very difficult to determine whether the mineral is hornblende or pyroxene by hand specimen observation. Previous studies related to the mineralogy in the region are limited in terms of the origin of igneous rock [4] [5] [6] [7] and no research has yet discussed the presence of these megacrysts. These igneous rocks in Semono Area, Bagelen District are pyroxene andesite, hornblende andesite, and dacite [6]. Other studies suggest that the rock is composed of pyroxene basaltic andesite and hornblende basaltic andesite as lava flows and shallow intrusions [4] [5] [7]. This study shows the results of the analysis of megacryst minerals in pyroclastic rocks along with their mineral types to their origins from a textural and mineralogical perspective.

Figure 1. Regional geological map of the southwestern part of Kulon Progo Mountains from [9] and the location of studied area (red box).

2. Regional Geology
Kulon Progo Mountains is a part of the South Serayu Mountains Zone which is composed of Eocene to Miocene volcanic rocks and known as Kulon Progo Dome or "oblong dome" because of the unique morphological expression of an elongated dome [8]. The regional stratigraphy of Kulon Progo Dome is composed of four formations, from the old to the young in succession is Nanggulan Formation, Old Andesite Formation, Jonggrangan Formation, Sentolo Formation, and Alluvial Deposit [9].

The Old Andesite Formation [8] or Kebo Butak Formation [9] refers to all volcanic rocks in the Kulon Progo Mountains. Volcanism during the Tertiary period resulted in the formation of a volcanic complex in the Kulon Progo Mountains. Volcanic activity in Kulon Progo began with the formation of the Gajah Volcano formation during the Oligocene [10]. Then in the Middle Miocene, the southern side was intruded by the Ijo Volcano. Furthermore, Menoreh volcano emerges at Late Miocene in the northern part of Kulon Progo Mountains. The Oligocene - Miocene volcanism are controlled by the North - South compression stress and produced a sinistral fault with the north-northeast direction [11].

3. Research Methods
The detailed geological mapping covered an area of 4 x 4 km with scale of 1:25,000, consist of lithology, stratigraphy, geomorphology, and geological structures has been conducted to identify the
geological conditions, distribution of rock types, and the distribution of megacryst minerals. This research uses a smart mapping method and fresh samples collected only from locations that represent all lithological types in this study area.

Textural characterization of the rocks and minerals was conducted by megascopic and petrographic analysis. A total of fifteen (15) sections from twelve (12) rocks and one crystal sample were analysed with a polarization microscope. The petrographic observations were undertaken at the Get-In Cicero Laboratory of the Geological Engineering Department, Universitas Gadjah Mada. Topography map and Digital Elevation Model (DEM) also used to analyze morphological features including geological landscape and the distribution of intrusion bodies.

4. Result
4.1 Geology of the Study Area
The geomorphological unit in the study area is divided into pyroclastic flow ridge unit, intrusion hill unit in the north, and alluvial plain unit in the west. The pyroclastic flow ridge unit is characterized by ridges separated by several valleys that have an appearance of an alluvial fan and have a northeast-southwest trending morphological alignment. The intrusion hill unit has a rough morphological appearance and is formed from the erosion process of the tertiary intrusion body in Mount Ijo. The alluvial plain unit is a flat morphology that can be easily distinguished from other units because of its smooth appearance.

The research area consists of three types of lithological units, which are sorted from oldest to youngest, namely pyroclastic breccia units, andesite intrusions, and alluvial deposits. In several locations, can be found pyroclastic breccia were intruded by andesite (Figure 2A). Pyroclastic breccia in this study area is the main object of research which is composed of various volcanic fragments (Figure 2B, 3C) and found a lot of megacrysts as well as cumulate rocks (Figure 3E). Fragments are composed of hornblende, plagioclase, pyroxene, lithic tuff (Figure 3A), lapilli tuff (Figure 3B, 3F), and andesite (Figure 3D).

*Figure 2. Pyroclastic breccia outcrop contact with andesite intrusion (A). Pyroclastic breccia composed of various volcanic fragments (B).*
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Figure 3. Rock samples from the study area which are most of them consist of mafic megacrysts. Lithic tuff (A), Lapilli tuff (B), Tuff breccia (C), Andesite (D), Contact of pyroxene cumulate with lapilli tuff (E), Lapilli tuff with hornblende megacryst fragments (F).

The geological map of the study area can be seen in Figure 4. The geological structure found in the form of an uncertain sinistral strike slip fault is thought to be trending northeast southwest through the andesite intrusion unit and the breccia pyroclastic unit.

4.2 Lithological Characteristics
The various types of pyroclastic breccia unit are lapilli tuff, tuff, and pyroclastic breccia. Lapilli tuff has a blackish gray color, massive structure, matrix supported, and strongly consolidated. It is composed of hornblende, pyroxene, and plagioclase minerals that appear as fragments, while the matrix is composed of plagioclase and volcanic ash. In some parts (Figure 5B), hornblende fragments are found with flow structure.

Megascopically, pyroclastic breccias are composed of fragments (1 - 30 mm) and a matrix (<1 mm) with angular roundness, poor sorting, matrix supported, and massive structures. Fragments are composed of hornblende, plagioclase, pyroxene, lapilli tuff, lithic tuff and andesite. Hornblende and pyroxene present as individual crystal fragments and as cumulates (Figure 5A; 5D). In some locations, pyroxene appears as a large crystal with cumulate structure and commonly in contact with lapilli tuff (Figure 5C). Both of them are fragments in pyroclastic breccia (Figure 5D).

The andesite intrusion unit is composed of pyroxene andesite, hornblende andesite, and basaltic andesite. Pyroxene andesite and hornblende andesite, both have porphyrophanitic textures, but they are distinguished based on the type of phenocryst. Whereas basaltic andesite has an aphanitic texture.

This research is focused on pyroclastic breccia units which consist of mafic megacryst fragments. The pyroclastic breccia occupies an area around 7 km² with fresh to slightly weathered rock conditions. Characteristics of mafic mineral megacrysts (hornblende and pyroxene) are discovered in the lapilli tuff and pyroclastic breccia in the southwestern part of Mount Ijo, Kulon Progo Mountains.
Figure 4. Geological map and geological profile of the study area.
Figure 5. Hornblende cumulate as fragment in pyroclastic breccia (A), hornblende with flow structure (B), contact of pyroxene cumulate with lapilli tuff (C), pyroxene megacrysts as fragment in pyroclastic breccia (D).

4.3 Petrographic Characteristic
4.3.1. Types of Mafic Minerals.
Based on petrographic observations, lapilli tuff is composed of fragments in the form of hornblende, plagioclase, clinopyroxene, and opaque minerals while the matrix is composed of plagioclase minerals, volcanic glass, and mafic microliths. Typical mineral assemblages in the tuff consist of plagioclase, hornblende, clinopyroxene, volcanic glass, and opaque minerals. Opaque minerals are more common in this lithology (Figure 6a).

Pyroclastic breccia is composed of fragments in the form of hornblende, plagioclase, clinopyroxene, opaque minerals and andesite rocks as lithic. The matrix is composed of lithic volcanic, volcanic glass, plagioclase, and mafic microliths. Plagioclase with subhedral crystals is present both as fragment and matrix.

According to the optical properties, the clinopyroxene cumulate fragments (Figure 6b) are characterized by medium grain size (1 - 10 mm) and subhedral prismatic shaped. This clinopyroxene cumulate fragments are rarely composed of olivine and plagioclase crystals.
4.3.2 Textural Characteristics

Hornblende minerals in lapilli tuff found in the form of oxy-hornblende which some of them have plagioclase and opaque mineral inclusions (Figure 6c). Oxy-hornblende fragments are the most common mafic minerals in this lithology. The oxy-hornblende has green-dark brown color, high relief with rim margin that is composed of oxide minerals. The form of oxy-hornblende crystals is mostly prismatic subhedral with high relief and green to brown pleochroism. Other samples show remnant of pyroxene and plagioclase inside hornblende crystals. In general, the condition of the hornblende shows different breakdown textures which represent as internal breakdown patches and rim margin (Figure 6c; 6d).

Pyroxenes in lapilli tuff are characterized by internal breakdown patches and iron oxide rim texture (Figure 6a). The pyroxene found in this study area have second order blue reference color, 0.5 mm in size, and inclined extinction angle which is typical of clinopyroxene.

Some of plagioclase show the patchy-zoned texture with patchy-spongy cellular core type (Figure 7a) [12] and also show sieve texture (Figure 7b). It is composed of oscillatory zoned rims with a core of irregular-shaped bright and dark patches. Fewer plagioclase crystals are anhedral and surrounded by pyroxene in cumulate rock fragments (Figure 7d).

Most of the plagioclase crystals show oscillatory zoning texture (Figure 7c). Half oscillatory zoning is also found in some plagioclase (Figure 6d). Those crystals show albite twinning while some of them was altered into clay minerals. Most of plagioclase shows various breakdown textures.
Figure 7. Plagioclase (Pl) shows the patchy-zoned texture with patchy-spongy cellular core type in plane polarized (a), sieve textured plagioclase in cross polarized (b), oscillatory zoning in plagioclase in cross polarized (c), anhedral plagioclase (Pl) surrounded by clinopyroxene (Cpx) with opaque minerals inclusion in cross polarized (d).

5. Discussion

5.1 Geological Control of the Distribution of Mafic Mineral Megacrysts

Field observations show that most of the pyroclastic rocks in the study area has large mafic minerals as fragments. Based on the distribution map of megacryst minerals and Digital Elevation Model (DEM) analysis, these minerals were carried by pyroclastic flows that passed through the valleys and were deposited in an alluvial fan (Figure 4) in the southwest distal part of an ancient volcano (Mount Ijo). The distribution of these minerals is mostly exposed at the distal area of the volcano as a result of an explosive eruption that produces pyroclastic flows towards the southwest of the volcano. These minerals were deposited in the valley to form an alluvial fan morphology in the southwestern part of Kulon Progo Dome.

The same orientation of mafic minerals i.e hornblende with the direction of the slopes of alluvial fan could indicates pyroclastic flow deposition mechanism. Other supporting data, such as rock texture which are poor sorting and matrix supported, can bolster this interpretation. The mafic minerals were carried away by a pyroclastic flow during the explosive eruption of Mount Ijo so that it was mixed with glass material and fine-grained plagioclase minerals. The products of the eruption were in the form of lapilli tuff and pyroclastic breccia.
5.2. Interpretation of Their Origin
The oscillatory zoning texture of plagioclase showing the magma differentiation process. Oscillatory zoning can be explained as a crystal's response to fluctuating external conditions. This texture is a reflection of composition changes of the magma by external causes [13]. This texture can be formed due to several things, as stated in [14]: a. movement of crystals in the magma and crystal may settle due to differentiation whether by gravitation; b. Movement of the magma as a whole into a region with different conditions of temperature and pressure; c. additional magma into the crystallizing liquid; d. loss of volatile constituent due to rapid crystallization. Meanwhile, based on [15] oscillatory zoning textures are due to kinetics of crystallization. The oscillatory zoning, breakdown and sieve texture in plagioclase minerals exhibit evidence of mineral-melt disequilibrium [16].

Furthermore, Patchy zoning of plagioclase is formed due to open-system processes or due to diffusional chemical re-equilibration of a crystal zoning [17]. Disequilibrium condition initiates a spongy-like dissolution of the plagioclase crystal and crystallization can occur with composition reflecting changes in conditions [17]. Pyroxene megacrysts contain opaque and plagioclase inclusions (Figure 7d) that may indicate magma mixing or disequilibrium crystallization during the volcanic evolution [16].

The oxy-hornblende found in pyroclastic rocks is a product of green hornblende alteration [18] and is possibly associated with hot gases at the late magmatic stage [19]. The breakdown texture in hornblende indicates the time spent by the crystal outside its field of stability [20] although this depends on the ambient conditions [21].

During the eruption period, crystal settling of mafic minerals (pyroxene, hornblende, as well as plagioclase) was occurring in the magma chamber (Figure 8). The pyroxene that found in the field was in the form of cumulate while hornblende was found as individual crystals, although in some locations, hornblende cumulates were also found. The mafic minerals occur in the surface as fragments in the pyroclastic breccia.

The difference in texture between hornblende and pyroxene indicates a magma differentiation through fractional crystallization process. Pyroxene which formed earlier than hornblende, was concentrated at the bottom part of magma chamber. When the pyroxene began to crystallize, plagioclase also began to crystallize. Pyroxene and plagioclase will settle at the bottom of the magma chamber due to density (gravity settling). This process causes the formation of a pyroxene layer at the bottom of the magma chamber. After that, hornblende started to crystallize. The zoning texture in the plagioclase becomes supporting data that there is a change in composition due to the differentiation process and the presence of crystal settling [14].

For some reason, an explosive eruption occurred when the formation of hornblende was taking place so that the mafic minerals that had been formed were carried to the surface. Changes in crystallization conditions are characterized by the presence of a patchy-spongy texture [17].

When an explosive eruption occurs, the rate of magma cooling becomes faster, so that fine-sized plagioclase crystals (<1 mm) and volcanic glass are formed. This explosive eruption resulted in a product in the form of pyroclastic breccia with mafic mineral megacrysts as fragments, and plagioclase with volcanic glass as matrix. These minerals are carried by pyroclastic flows so that the mafic minerals condition is in the form of destruction. Most of the pyroxenes found as fragments have a cumulate texture, while most of hornblende are found as individual crystals. This indicates that the pyroxene has undergone crystallized or solidified before being carried out of the magma chamber.
Figure 8. Petrogenetic model to illustrate the occurrence of mafic mineral megacryst fragments in pyroclastic breccia in the study area.

6. Conclusion
Mafic mineral megacrysts found in the study area consists of hornblende, pyroxene, and plagioclase. They are found as fragments in pyroclastic breccias. Most of the pyroxene that found in the field was in the form of cumulate while hornblende often found as individual crystals, although in some locations, hornblende cumulates were also found. Based on mineralogical composition and texture, mafic mineral megacrysts in the study area are interpreted to have formed as a result of fractional crystallization process through a crystal settling mechanism in the magma chamber. These minerals were carried out to the surface along with the rapid rise of magma and were transported as pyroclastic flows in an explosive eruption event of Mount Ijo. These pyroclastic flows passed through the valleys and were deposited in an alluvial fan morphology in the southwestern part of Kulon Progo Dome.

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