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Petrographic Characterization of Basaltic Rocks from the Breueh Volcanic Formation, Breueh Island, Indonesia

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Abstract

The Breueh Volcanic Formation on Breueh Island, Aceh Besar District, is part of the outer arc volcanic zone related to subduction between the Indo-Australian and Eurasian plates. In addition, the volcanic rocks exposed on Breueh Island provide important geological information for understanding the volcanic history, tectonic processes, and magmatic evolution in the outer arc region of Aceh. This study aims to determine the rock classification using optical petrography, and to evaluate its possible relationship to the regional tectonic setting. Petrographic analysis was performed on three basaltic rock samples collected from outcrops in the east-southeast area of the formation. Thin sections were examined under a polarizing microscope at Geological Engineering Laboratory Syiah Kuala University, and modal mineral percentages were quantified using the point-counting method with JMicroVision software. The analyzed rocks display massive to amygdaloidal textures, with amygdales filled by zeolite and celadonite. Petrographic observations show that the rocks are dominated by plagioclase (40.17–43%), pyroxene (3.58–20.17%), and opaque minerals (1–2.92%) as major constituents, with minor alkali feldspar (<6.5%), minor quartz (<2.33%), and olivine (~0.5%). Based on the IUGS/Streckeisen classification, all samples are classified as basalt. The occurrence of zeolite and celadonite indicates low-temperature hydrothermal alteration. The dominance of mafic minerals is consistent with basaltic magma typical of subduction-related volcanic settings. Overall, the petrographic characteristics suggest that the basaltic rocks are consistent with magma generated in a subduction-related outer arc volcanic environment.



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Introduction

The Breueh Volcanic Formation (Tlvb), mapped by Bennet, includes amygdaloidal basalt as one of its principal lithologies [1]. The presence of basaltic rock with amygdaloidal structure in this formation still lacks further study, especially detailed petrographic studies to

determine the mineral composition, as well as the origin of the basaltic rock within the regional tectonic system [2] [3]. The Breueh Volcanic Formation (Tlvb) itself is part of the outer-arc islands, which is the result of the subduction of two plates, the Indo-Australian Plate and the Eurasian Plate [4]. The Breueh Volcanic Formation on Breueh Island, Aceh Besar District, was selected as the study area because it represents part of the outer arc volcanic zone associated with subduction between the Indo-Australian and Eurasian plates and preserves amygdaloidal basalt exposures that remain insufficiently investigated. Previous studies in the region have mainly focused on regional geological mapping and tectonic evolution, while detailed petrographic and mineralogical investigations of the basaltic rocks are still very limited. In particular, information regarding mineral composition, textural characteristics, and the petrogenetic implications of the amygdaloidal basalt has not been comprehensively documented. In addition, the relatively remote island setting and limited accessibility have contributed to the scarcity of detailed volcanological and geochemical studies in this area. Therefore, this research is important to provide new insights into the characteristics and origin of the basaltic rocks within the Breueh Volcanic Formation. Therefore, this research was conducted to understand the geological history based on the tectonic evolution from the petrographic analysis of basaltic rocks taken from the research area with the Breueh Volcanic Formation (Tlvb)[1].

Geographically, Breueh Island lies west of Sumatra and physiographically belongs to the Outer Arc Islands zone as described by Van Bemmelen. The formation comprises amygdaloidal basalt, pyroclastic deposits, chert, locally developed volcanic units, and dyke complexes of inferred Early Oligocene age. Structural discontinuities, including faults and fractures, cut the formation and may have facilitated hydrothermal fluid circulation responsible for secondary mineral infilling [1]. A few faults and fractures cut across these rock units, indicating post-formation tectonic activity also potentially serving as pathways for hydrothermal fluid circulation.

Basalt is a dark-colored extrusive igneous rock characterized by fine grains composed of plagioclase, pyroxene, and magnetite, with or without olivine, and containing no more than SiO_2 . Most basalts contain phenocrysts of olivine, plagioclase, and pyroxene [5]. Basalt commonly is divided into three types based on its magma type: alkaline basalt, calc-alkaline basalt, and tholeiite [3] [5]. Alkaline basalts are generally found on oceanic islands and on the continental crust in areas of crustal uplift and rifting [3]. Calc-alkaline basalts are generally formed on the continental side of subduction zones [6]. This study aims to (1) quantify modal mineral composition of basaltic rocks using optical petrography and point-counting analysis, (2) document textural characteristics and amygdale-fill mineral assemblages, and (3) classify the rocks using the IUGS/Streckeisen scheme while evaluating alteration features that may inform magma genesis.

Method

The sampling technique in this study was conducted through systematic geological field observations combined with the selection of representative sampling sites. Sampling locations were determined based on lithological distribution, outcrop availability, and the presence of amygdaloidal basalt within the Breueh Volcanic Formation. This approach was

intended to ensure that the collected samples adequately represent the petrographic characteristics of the study area. Rock samples for petrographic testing were taken from three outcrops of basaltic rock in the research area, found with different textures, so that it represents petrographic analysis of basaltic rock in the Breueh Volcanic Formation. The rock samples taken were fresh basaltic rocks that had not affected by oxidation, to achieve more accurate petrographic analysis results [7].

The rock samples for petrographic analysis were first cut and polished according to thin section preparation procedures until the sample was approximately $\sim 30 \mu\text{m}$, allowing the rock sample to be analyzed using a polarizing microscope [7]. Observation under the polarizing microscope aimed to observe the optical properties of the constituent minerals, such as birefringence, interference color, extinction angle, and twinning under XPL (Cross-Polarized Light) observation, as well as relief, pleochroism, crystal shape, and cleavage under PPL (Plane-Polarized Light) observation [8].

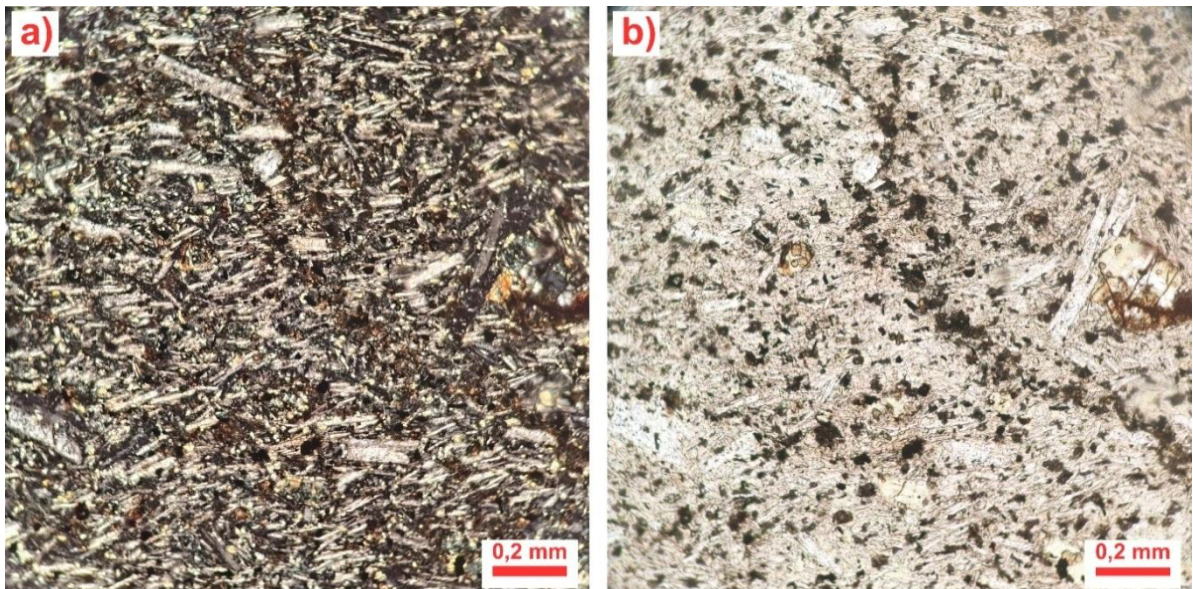


Figure 1. The Result Thin Section Observation under a Polarizing Microscope (Sample Pb 01): (a) Cross-Polarized Light (XPL), (b) Plane-Polarized Light (PPL)

Following petrographic observation of the mineral optical properties under the microscope, point counting of the percentage of each identified mineral was performed under the polarizing microscope to determine the rock name based on the percentage of minerals present and to relate the basaltic rock formation process of the Breueh Volcanic Formation to the tectonic evolution in the research area [9]. Point counting was performed for a total of 1200 points using JMicroVision software.

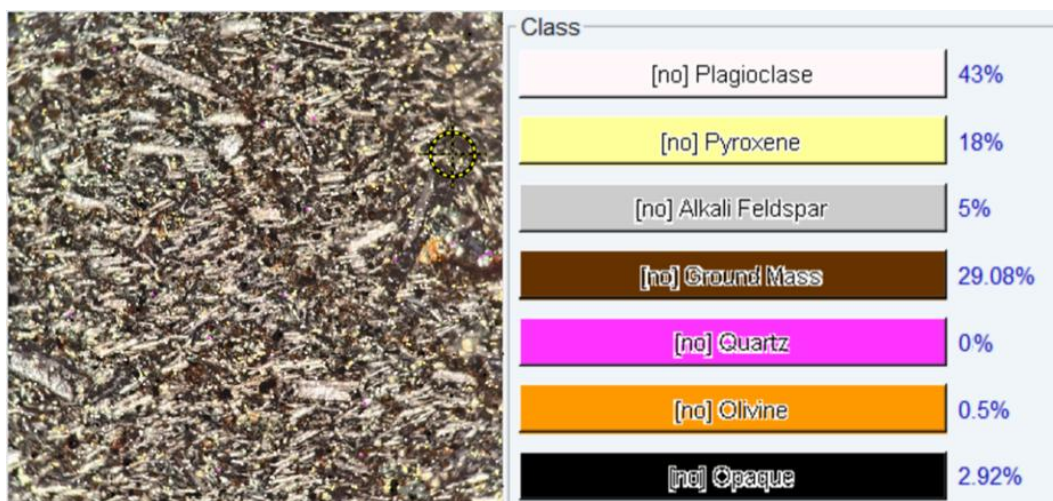


Figure 2. Point Counting Using JMicroVision Software to Determine the Percentage of Each Mineral in Basalt Petrographic Sample Pb 01 from the Breueh Volcanic Formation

The naming of each rock sample that had analyzed by petrographic observation and point counting was performed based on the IUGS (1973) and Streckeisen (1978) extrusive igneous rock classification diagrams. The IUGS (1973) and Streckeisen (1978) classifications diagrams can determine the naming of extrusive and intrusive igneous rocks if the required mineral percentages are present, namely QAPF minerals (Quartz, Alkali Feldspar, Plagioclase, and Foid/Feldspathoid). Based on the samples obtained in the research area, which are extrusive igneous rocks, the IUGS (1973) and Streckeisen (1978) classifications will be used, specifically for the naming of extrusive igneous rocks [10].

Result and Discussion

The Breueh Volcanic Formation (Tlvb) represents a Tertiary volcanic unit regionally grouped within the Tertiary Sediments and Volcanics. It is dated to the Oligocene–Early Miocene and forms part of the older volcanic assemblages in the regional lithostratigraphic framework [11]. The formation is characterized by porphyritic and amygdaloidal structures, with fractures commonly infilled by secondary minerals. The occurrence of zeolite, calcite, and chlorite reflects hydrothermal alteration associated with the evolution of these volcanic rocks [12]. Structural and chronological evidence indicates that volcanic activity on Breueh Island was linked to the tectonic development of the Sunda Arc during the Tertiary [13].

Based on observations in the research area, namely the Breueh Volcanic Formation, with a total of 8 outcrop observation points assumed to be basaltic rock in the east-southeast area of Breueh Island, basaltic rock with two types of rock structure was found: massive basalt and basalt with an amygdaloidal structure. The location of the outcrops is presented in Table 1 and Figure 3. The discovery of basaltic rock with an amygdaloidal structure is also macroscopically divided into two types: one type has secondary minerals filling the rock pores, which is a characteristic feature of amygdaloidal igneous rocks, macroscopically appearing pale white, suspected to be Zeolite minerals at STA Pb 04, Pb 05, and Pb 06. This differs from the amygdaloidal basaltic rock at STA Pb 07 and Pb 08, where the secondary minerals filling the rock pores macroscopically appear dark green, suspected to be

Celadonite minerals. Both secondary minerals mentioned, Zeolite and Celadonite, are minerals resulting from low-temperature alteration processes.

Table 1. Sampling Point Coordinates

Outcrop Code	Coordinates		Lithology	Location
	X	Y		
Pb 01	95,08759	5,691142	basalt	Lapeng, Pulau Breueh
Pb 02	95,09915	5,696162	basalt	Lapeng, Pulau Breueh
Pb 03	95,10717	5,692306	basalt	Lampuyang, Pulau Breueh
Pb 04	95,13361	5,678351	amygdaloidal basalt	Lampuyang, Pulau Breueh
Pb 05	95,12742	5,689705	amygdaloidal basalt	Lampuyang, Pulau Breueh
Pb 06	95,11346	5,687713	amygdaloidal basalt	Lapeng, Pulau Breueh
Pb 07	95,10392	5,679284	amygdaloidal basalt	Paloh, Pulau Breueh
Pb 08	95,11019	5,670657	amygdaloidal basalt	Paloh, Pulau Breueh

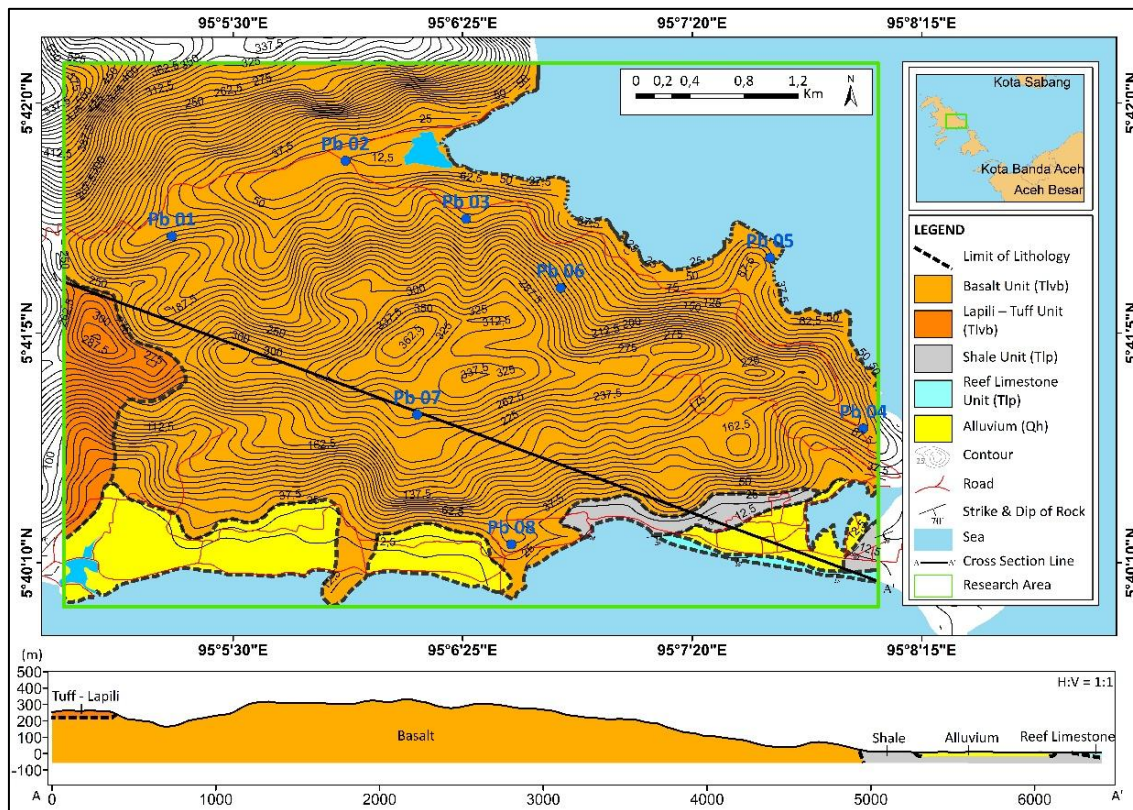


Figure 3. Location of 10 Basalt Outcrop Points on the Geological Map

Massive basaltic rock was found at station Pb 01, Pb 02, and Pb 03. The rock description includes a massive structure, fresh color of grayish-black, weathered color of brownish-black, aphanitic holocrystalline texture, inequigranular fabric, and subhedral crystal (Figure 4).



Figure 4. Documentation of the Sample Pb 01, Pb 02, and Pb 03 Basalt Outcrop of the Breueh Volcanic Formation

Amygdaloidal basaltic rock with zeolite filling minerals was found at station Pb 04, Pb 05, and Pb 06. The rock description includes an amygdaloidal structure, fresh color of grayish-black, weathered color of brownish-black, aphanitic holocrystalline texture, inequigranular fabric, and subhedral crystal shape; the HCl liquid test on the secondary mineral filling of this rock did not react (Figure 5).



Figure 5. Documentation of the Sample Pb 04, Pb 05, and Pb 06 Zeolite Amygdaloidal Basalt Outcrop of the Breueh Volcanic Formation

Amygdaloidal basaltic rock with celadonite filling minerals was found at station Pb 07 and Pb 08. The rock description includes an amygdaloidal structure, fresh color of grayish-black, weathered color of brownish-black, aphanitic holocrystalline texture, inequigranular fabric, and subhedral crystal shape [14]. The HCl liquid test on the secondary mineral filling of this rock reacted, suggesting the possible presence of carbonate mineral (calcite or dolomite) content as well [15].



Figure 6. Documentation of the Sample Pb 07 and Pb 08 Celadonite Amygdaloidal Basalt Outcrop of the Breueh Volcanic Formation

Petrographic Analysis

The samples used for petrographic analysis are the same amount as the macroscopic description, where the rock samples used are divided into 3 types of basaltic rock: the first is one massive basalt sample, and the other two are amygdaloidal basalts with a difference in the secondary mineral filling the amygdaloid pores, one having pores filled by Zeolite minerals and the other by Celadonite minerals (confirmed petrographically) [16].

a. Basalt Pb 01

The petrographic sample of basalt Pb 01 has a massive structure and was petrographically analyzed to represent other massive basaltic rock outcrops. The petrographic analysis of this sample Pb 01 under a polarizing microscope with 10x magnification shows a mineral composition of plagioclase, groundmass, pyroxene, alkali feldspar, opaque as an accessory mineral, and olivine.

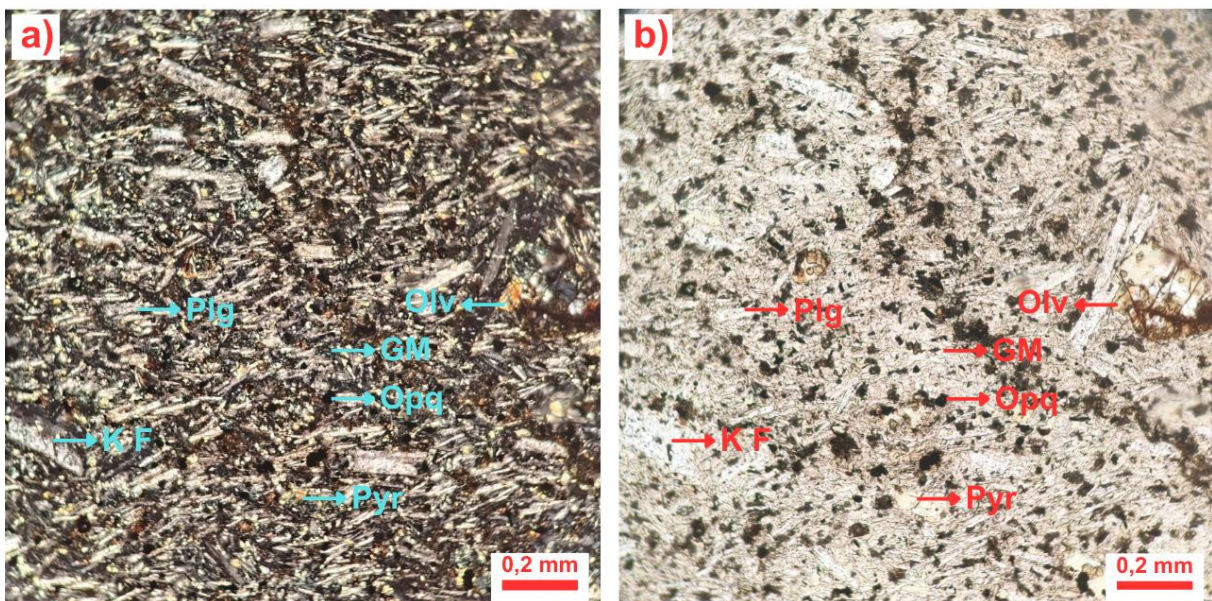


Figure 7. Petrographic Analysis of Basalt Rock from Sample Pb 01

The composition is arranged with the following percentages. Plagioclase (43%), interference color from gray to white Order I, with Carlsbad-Albite twinning, and euhedral - subhedral crystal shape. Groundmass (29,08%), consisting of plagioclase, and pyroxene. Pyroxene (18%), bright yellow interference color Order II, and anhedral - subhedral crystal shape. Alkali Feldspar (5%), interference color from gray to white Order I, with Carlsbad twinning, and euhedral - subhedral crystal shape. Opaque (2,92%) black in color with high relief. Olivine (0,5%), bright orange interference color Order III, no twinning, and subhedral crystal shape.

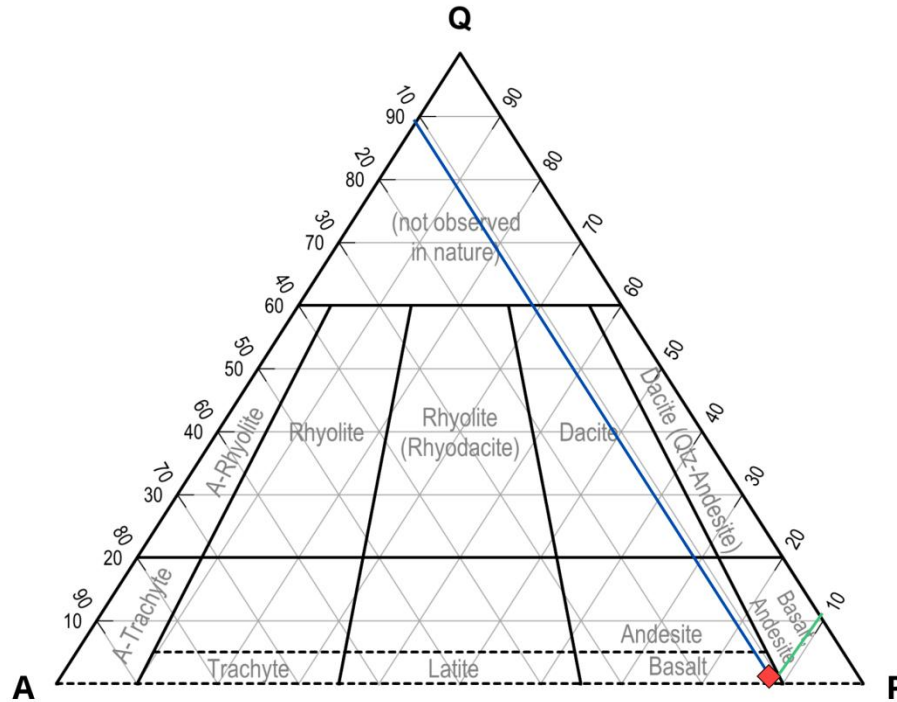


Figure 8. Rock Naming from Petrography Sample Pb 01 Using the IUGS Diagram

After calculating the percentage of quartz, alkali feldspar, and plagioclase based on the IUGS (1973) and Streckeisen (1978) classifications [10] for the basalt thin section sample Pb 01 results in a plot point in the basalt column.

b. Amygdaloidal Basalt Pb 06

The petrographic sample of basalt Pb 06 has an amygdaloidal structure with secondary mineral infill consisting of low-temperature alteration minerals, namely zeolite, and was petrographically analyzed to represent other zeolite amygdaloidal basaltic rock outcrops [16]. The petrographic analysis of this sample Pb 06 under a polarizing microscope with 4x magnification (Figure 9 in the source) shows a mineral composition of plagioclase, groundmass, alkali feldspar, pyroxene, and opaque as an accessory mineral, while the secondary minerals filling the amygdaloidal rock pores consist of zeolite.

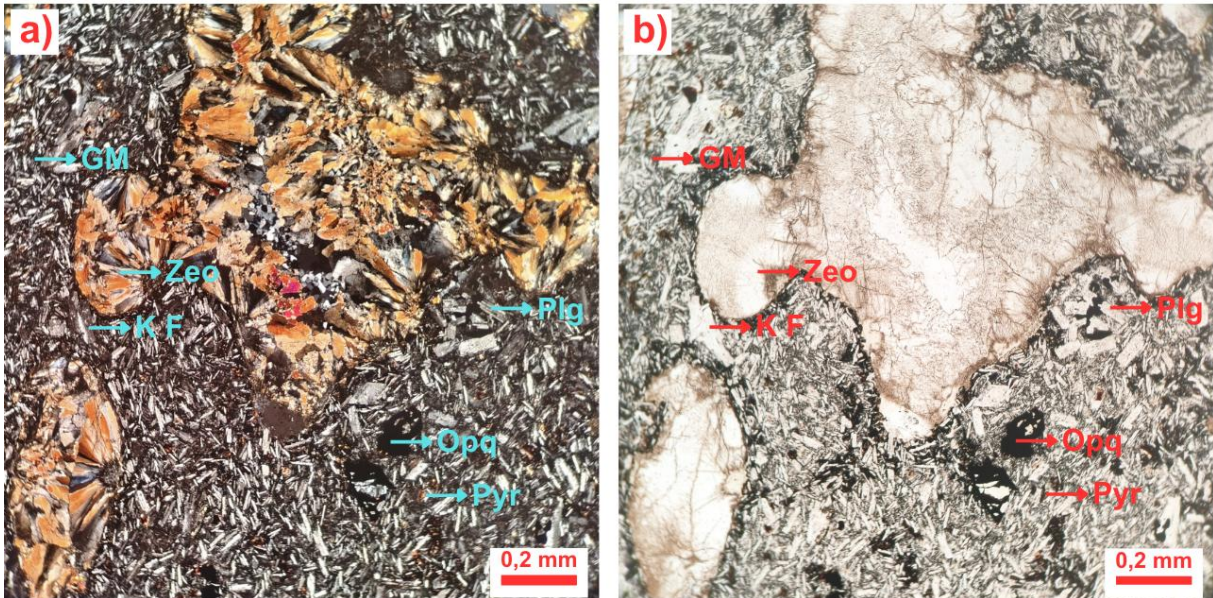


Figure 9. Petrographic Analysis of Zeolite-Bearing Amygdaloidal Basalt Rock from Sample Pb 06

The composition is arranged with the following percentages. Plagioclase (39,58%), interference color from gray to white Order I, with Carlsbad-Albite twinning, and euhedral - subhedral crystal shape. Groundmass (12,42%), consisting of plagioclase, quartz, and pyroxene. Alkali Feldspar (5,17%), interference color from gray to white Order I, with Carlsbad twinning, and euhedral - subhedral crystal shape. Pyroxene (3,58%), bright yellow interference color Order II, and anhedral - subhedral crystal shape. Opaque (1%) black in color with high relief. Zeolite (35,75%), low-temperature alteration product of plagioclase and pyroxene minerals.

Sample Pb 06 is dominated by plagioclase and zeolite, indicating that the original rock is a mafic igneous rock that has undergone low-temperature hydrothermal alteration. Plagioclase remains abundant with euhedral-subhedral crystal forms, while the high proportion of zeolite (35.75%) reflects significant alteration of the primary minerals (plagioclase and pyroxene). The presence of residual pyroxene, minor primary quartz, and opaque minerals supports the characteristics of a volcanic rock. Overall, the rock represents an altered basalt with a high degree of zeolitization.

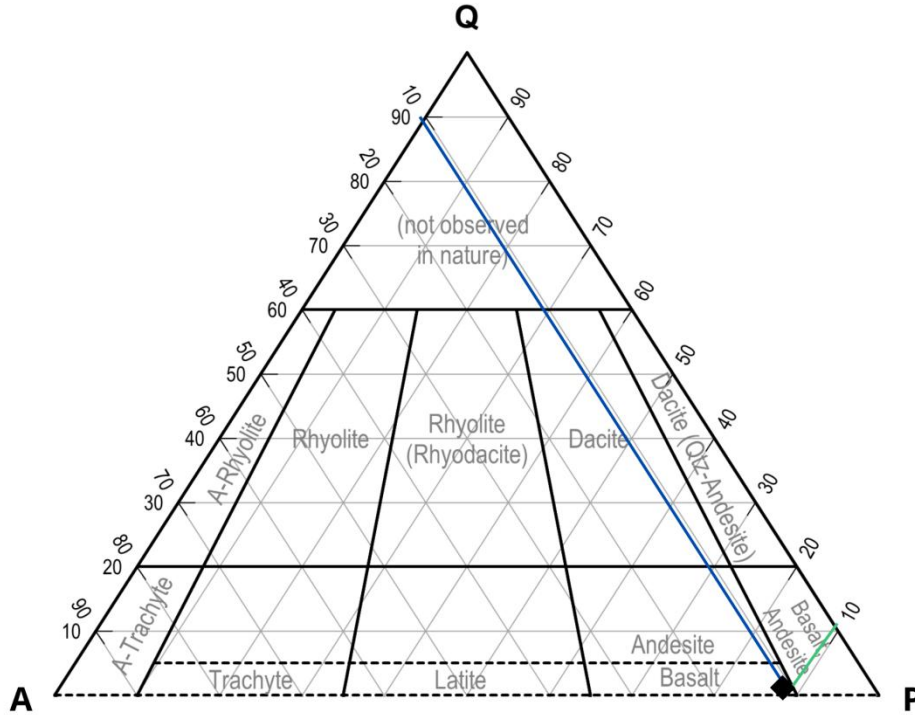


Figure 10. Rock Naming from Petrography Sample Pb 06 Using the IUGS Diagram

After calculating the percentage of alkali feldspar, and plagioclase based on the IUGS (1973) and Streckeisen (1978) classifications [10] for the basalt thin section sample Pb 06 results in a plot point in the basalt column (Figure 10).

c. Amygdaloidal Basalt Pb 07

The petrographic sample of basalt Pb 07 has an amygdaloidal structure with secondary mineral infill consisting of low-temperature alteration minerals, namely celadonite, and was petrographically analyzed to represent other celadonite amygdaloidal basaltic rock outcrops [17]. The petrographic analysis of this sample Pb 07 under a polarizing microscope with 4x magnification (Figure 11 in the source) shows a mineral composition of plagioclase, pyroxene, groundmass, alkali feldspar, quartz, and opaque as an accessory mineral, while the secondary minerals filling the amygdaloidal rock pores consist of celadonite, calcite, and dolomite.

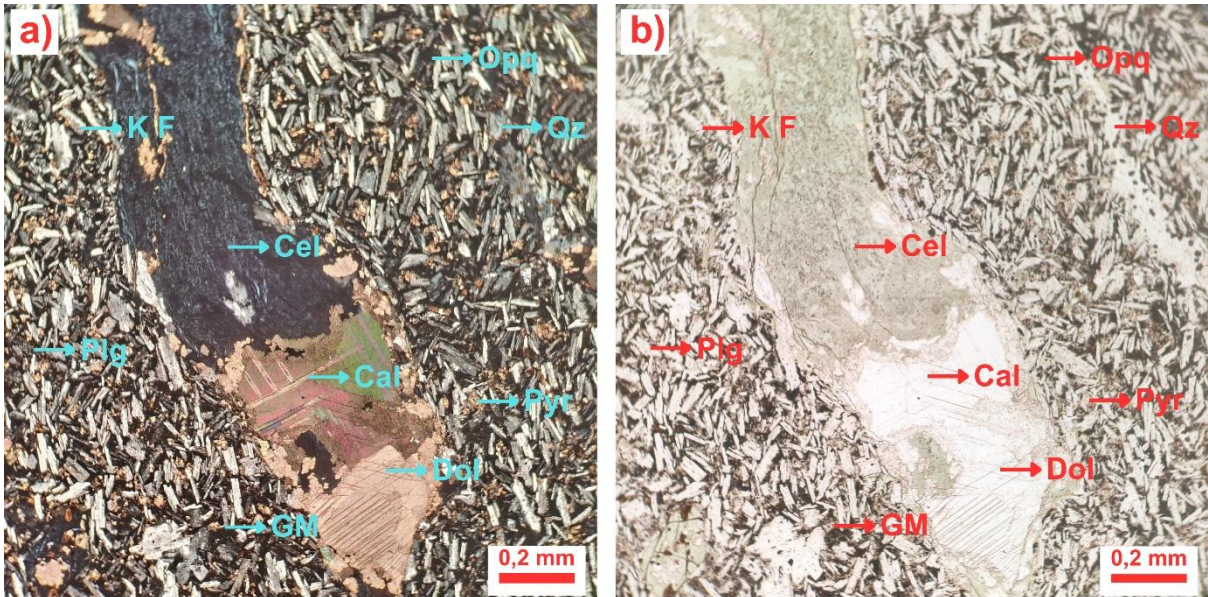


Figure 11. Petrographic Analysis of Celadonite-Bearing Amygdaloidal Basalt Rock From Sample Pb 07

The composition is arranged with the following percentages. Plagioclase (40,17%), interference color from gray to white Order I, with Carlsbad-Albite twinning, and euhedral - subhedral crystal shape. Pyroxene (20,17%), bright yellow interference color Order II, and anhedral - subhedral crystal shape. Groundmass (11,33%), consisting of plagioclase, quartz, and pyroxene. Alkali Feldspar (6,17%), interference color from gray to white Order I, with Carlsbad twinning, and euhedral - subhedral crystal shape. Quartz (<2,33%), interference color from gray to white Order I, no twinning, low relief, and anhedral crystal shape. Opaque (1,25%) black in color with high relief. Celadonite (11,92%), low-temperature alteration product of olivine and pyroxene minerals. Calcite (5,33%), bright and high-order striped interference color, polysynthetic twinning, and anhedral crystal shape. Dolomite (1,33%), white and high-order interference color, lamellae twinning, and anhedral crystal shape.

The basalt is dominantly composed of plagioclase and pyroxene indicating a mafic igneous composition [18]. The euhedral to subhedral plagioclase and anhedral to subhedral pyroxene suggest rapid to moderate cooling, typical of volcanic environments [19]. The presence of a groundmass consisting of plagioclase, quartz, and pyroxene confirms the extrusive nature of the rock [20]. Minor primary minerals such as alkali feldspar, quartz, and opaque minerals occur in small amounts and represent accessory phases. The occurrence of celadonite as a low-temperature alteration product, together with secondary carbonate minerals (calcite and dolomite) [21], indicates that the basalt has undergone post-magmatic alteration, likely related to hydrothermal processes or weathering [22]. Overall, this basalt represents a mafic volcanic rock that experienced significant secondary alteration after emplacement.

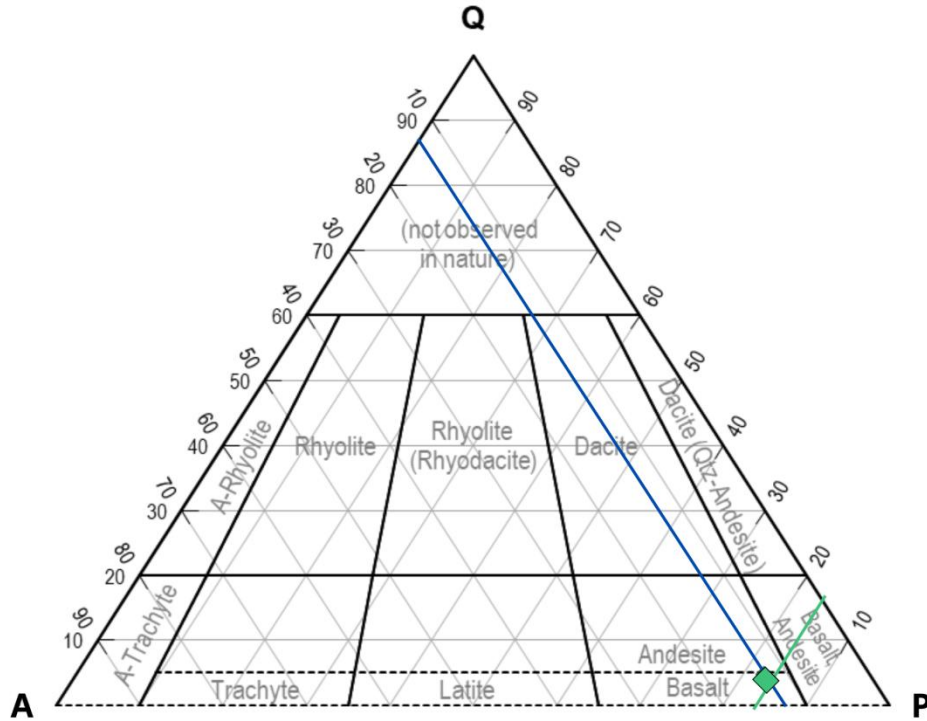


Figure 12. Rock Naming from Petrography Sample Pb 07 Using the IUGS Diagram

Based on observations of rock samples, the percentage of quartz is > 0%, which automatically means that Foid/Feldspathoid minerals are not present, as the two cannot exist together. After calculating the percentage of quartz, alkali feldspar, and plagioclase based on the IUGS (1973) and Streckeisen (1978) classifications [10] for the basalt thin section sample Pb 07 results in a plot point in the basalt column.

The percentage of mafic minerals is more dominant, pyroxene (3.58 – 20.17%) and a small amount of olivine (0.5%) found in Pb 01, although some mafic minerals have been altered into secondary minerals filling pores in Pb 06 as zeolite (35.75%) and in Pb 07 as celadonite (11.92%). Meanwhile, the percentage of felsic minerals found is not dominant, namely quartz less than 2.33% and alkali feldspar (5 – 6.17%) among the three petrographic samples. The dominant mineral composition of plagioclase and pyroxene with a little olivine, supported by the presence of non-dominant felsic minerals like quartz and alkali feldspar, typically characterizes rocks formed from calc-alkaline magma [23]. This is consistent with the condition of the Breueh Volcanic Formation on Breueh Island, which is part of the outer arc islands, explained as islands formed by the subduction process [24].

Another process that can be explained is the presence of secondary minerals found in the petrographic analysis, namely zeolite in station Pb 06 and celadonite in station Pb 07, which are inferred to be formed by low-temperature hydrothermal alteration processes that occurred after the end of volcanic activity. Amygdaloidal basaltic rocks with celadonite and carbonate fillings reflect a multi-stage, low-temperature hydrothermal alteration process [25]. The mineral assemblage and sequence provide valuable insights into the post-eruptive history, fluid evolution, and reservoir characteristics of volcanic rocks.

Conclusion

The basaltic rocks of the Breueh Volcanic Formation are composed of the main minerals plagioclase and pyroxene, with opaque accessory minerals, and minor minerals alkali feldspar, quartz, and olivine. Some mafic minerals have been altered into zeolite and celadonite, indicating the presence of weak hydrothermal alteration processes post-rock formation. The basaltic rocks of the Breueh Volcanic Formation were found to have massive and amygdaloidal structures. The amygdaloidal basalt rocks divided into 2 different textures, one having pores filled by Zeolite minerals and the other by Celadonite minerals. Based on the IUGS (1973) and Streckeisen (1978) classifications, all samples petrographically analyzed (Pb 01, Pb 06, and Pb 07) are classified as basalt rock. The proportion of dominant mafic minerals with the presence of fewer felsic minerals is characteristic of rocks originating from the calc-alkaline magma series. Tectonically, the basalt rock of the Breueh Volcanic Formation can be linked to an outer arc zone as a result of the subduction activity of the Indo-Australian Plate beneath the Eurasian Plate, which resulted in calc-alkaline magmatism. The predominance of mafic minerals with limited felsic components is consistent with basaltic magma typical of subduction-related environments. However, petrographic data alone do not allow definitive assignment to a specific magma series. Consequently, any calc-alkaline affinity and outer-arc tectonomagmatic interpretation should be regarded as preliminary pending supporting geochemical evidence.

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