

Volcanic Rock Characteristics of Arjuno–Anjasmoro Volcanoes in Tulungrejo Geothermal Prospect Area, East Java

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Abstract

Tulungrejo is situated between the Arjuno and Anjasmoro volcanoes, a region with geothermal potential. The area exhibits hot-water manifestations and contains volcanic and pyroclastic rocks within its geological framework. This study aims to identify the petrographic characteristics of the region's volcanic rocks to provide insights into their crystallization and magmatic evolution and to support assessment of the geothermal system. The research involved geological mapping, the study of hot water manifestations, representative rock sampling based on lithological variations, and petrographic analysis. The results indicate that the volcanic rocks consist of basaltic andesite, andesite, pyroxene andesite, and hornblende andesite. These rocks exhibit porphyritic, pilotaxitic, and trachytic textures, with primary constituent minerals comprising plagioclase, pyroxene, hornblende, and opaque minerals. Plagioclase is the dominant mineral, with compositions ranging from andesine to labradorite. The variety of volcanic rocks present indicates a non-linear differentiation trend. The abundance of phenocrysts is characteristic of an island-arc setting. Evidence of magmatic activity and hot springs suggests that the region holds promising geothermal energy potential. Therefore, this study is expected to be followed by further exploration aimed at developing the area into a new geothermal field to increase East Java's electricity supply potential.

Keywords *Geothermal, Volcanic Rock, Magmatism, Island Arc*

INTRODUCTION

Arjuno and Anjasmoro volcanoes are part of the Sunda magmatic arc, formed from the subduction of the Indo-Australian plate beneath the Eurasian plate (Pratiwi et al., 2021; Muttaqy et al., 2022). This tectonic setting has generated a series of volcanic structures and volcanic rocks showing diverse petrographic and petrological characteristics. These differences reflect variations in the magmatism that controlled volcanic rock formation.

These characteristics are investigated through petrographic and petrological analyses. Petrographic analysis is conducted using a polarizing microscope (Chacón et al., 2025; Keller et al., 2024), where petrology integrates these mineralogical and textural observations to classify igneous rocks and to interpret crystallization processes and magmatic evolution (Toro et al., 2025). Furthermore, distinct textural features, such as opaque rims on mafic minerals, reflect changes in

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magma during crystallization.

Although the Arjuno and Anjasmoro volcanoes developed in a tectonic framework, their volcanic histories vary significantly (Suaidi et al., 2023). As a result, petrographic and petrological characteristics are expected to vary. However, petrological studies between these two volcanoes remain surprisingly sparse. This study examines the volcanic rocks of Mount Arjuno and Mount Anjasmoro. Its primary objective is to improve understanding of magma crystallization and evolution through mineralogical and textural data, while also providing a crucial reference for future petrological studies of these mountains in the context of geothermal manifestations.

The study's key novelty lies in its integrated approach—combining geological survey data, surface manifestations, and petrographic analysis from both the Anjasmoro and Arjuno volcanoes—to elucidate non-linear magma differentiation across two adjacent Quaternary volcanic edifices: the older Anjasmoro and the still-active Arjuno. This distinguishes the research from previous studies (such as Harijoko et al. (2017)) that offered only partial explanations and did not consider the two adjacent volcanoes in tandem. Furthermore, this study addresses the presence of hot water manifestations located between the two volcanoes.

LITERATURE REVIEW

Located in East Java, Indonesia, the study area spans much of the Arjuno and Anjasmoro volcanic complexes within the Sunda magmatic arc (Pratiwi et al., 2021; Muttaqy et al., 2022). Volcanism in East Java is associated with the Sunda Arc, which is generated by the subduction of the Indo-Australian Plate beneath the Eurasian Plate (Deegan et al., 2021). Anjasmoro complex represents an older Quaternary volcanic structure that has undergone advanced erosion, whereas the Arjuno complex is an active composite volcano representing younger Quaternary volcanism.

Arjuno volcano is an active Quaternary volcanic system dominated by lava flows, volcanic breccia, and tuff, with compositions ranging from basaltic-andesite to andesite. The presence of geothermal manifestations such as Cangar and Padusan hot springs with near-neutral pH and temperatures ranging from 39.5- 46.5 °C (Zulaikah et al., 2023), and fumaroles on the summit of Arjuno volcano and the occurrence of magmatic hot springs indicate an ongoing magmatic system within the Arjuno-Welirang volcanic complex (Sidik & Harmoko, 2022). Based on crustal architecture, eruptive products in the region are dominated by a calc-alkaline volcanic series ranging from basalt to basaltic andesite to andesite (Bennett et al., 2025).

Microscopic evaluation of standard thin section provides critical insights into pre- and syn-eruptive magmatic evolution (Chacón et al., 2025). Key textural features commonly observed in arc volcanic rocks include porphyritic texture, characterized by phenocrysts embedded in a microcrystalline or glassy groundmass, reflecting two distinct stages of magma cooling (Toro et al., 2025). Rock classification based on quantitative modal mineral proportions (QAPF) adheres to the International Union of Geological Sciences (IUGS) standards (Aragão et al., 2020). Petrographic interpretation of the Arjuno and Anjasmoro complexes is essential for reconstructing magmatic differentiation trends, chamber dynamics, and their broader implications for geothermal system potential in East Java (Toro et al., 2025; Zulaikah et al., 2023).

Differences in age and eruptive history between Arjuno and Anjasmoro volcanoes are believed to have affected the petrographic and petrological characteristics of their volcanic products. These differences provide details on mineral assemblages, textures, and crystallization patterns to understand how these two magmatic systems evolved over time.

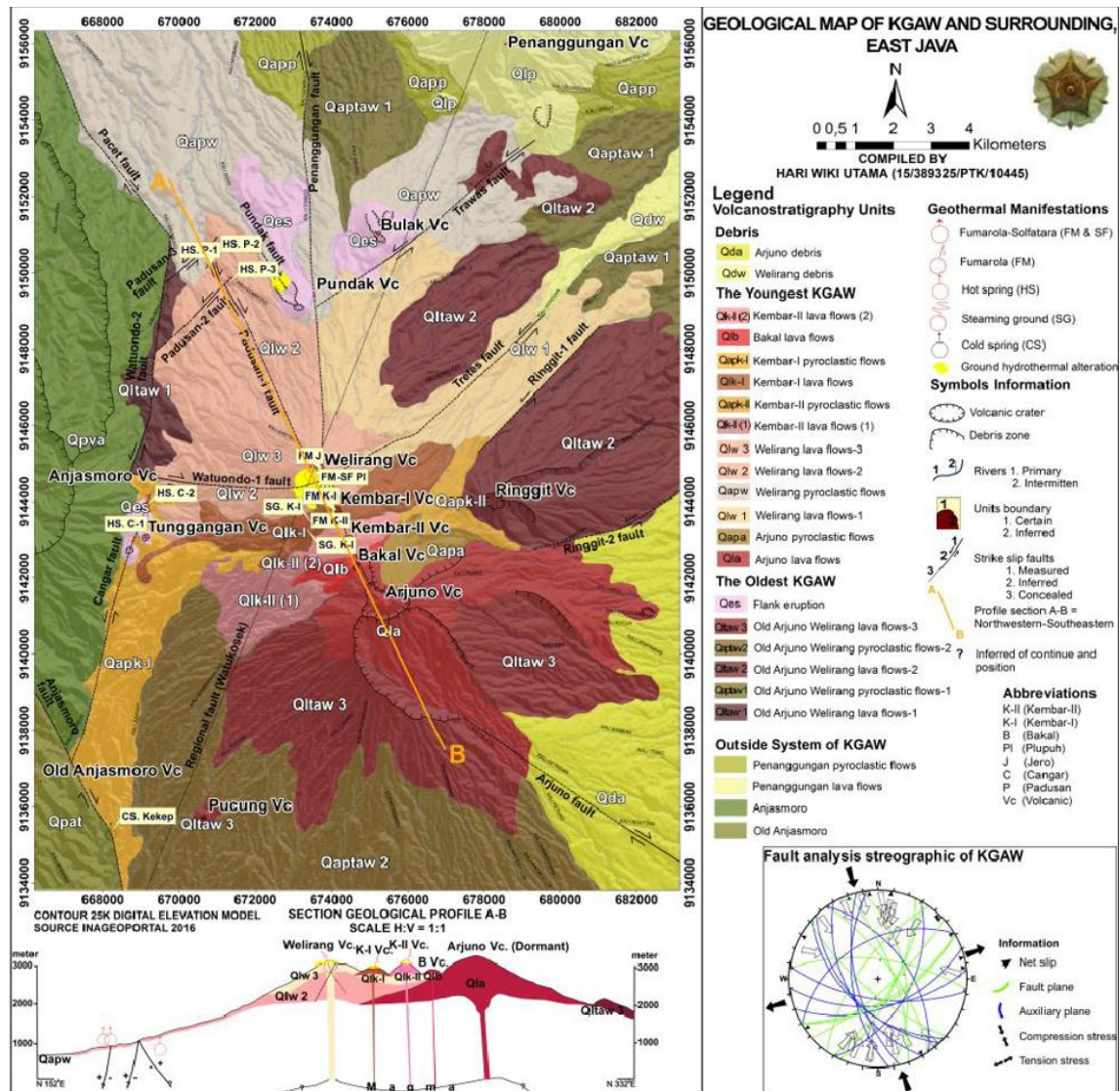


Figure 1. Geological map of the Arjuno–Welirang Volcanic Complex (AWVC) and surrounding areas (Harijoko et al., 2017).

RESEARCH METHOD

The study area covers the Arjuno–Welirang volcanic complex and the Anjasmoro Mountains, with a rectangular extent defined by the diagonal coordinates 9143579.29 m S, 667479.26 m E and 9151822.35 m S, 673036.96 m E in the UTM coordinate system. DEMNAS data supported the interpretation of volcanic morphology, geomorphological unit boundaries, and the preliminary distribution of lithological units. These interpretations were subsequently verified through field observations. Rock samples were collected from locations within the study area, and their sampling coordinates are presented in Table 1.

Table 1. Rock samples and geothermal manifestation coordinates

No Sample	Coordinates		Unit
	X	Y	
Arjuno			
Lpa7	9,149,787	672,327	Arjuno andesite lava

No Sample	Coordinates		Unit
LpCs 2	9,148,607	669,769	Fragment of Arjuno pyroclastic flow breccia 2
LpCs 1	9,149,808	670,103	Fragment of Arjuno pyroclastic flow breccia 2
Lp6	9,144,805	668,694	Arjuno hornblende andesite lava
Lps1	9,151,540	669,442	Fragment of Arjuno pyroclastic flow breccia 1
Cangar 1	9,143,902	669,125	Hot Spring
Cangar 2	9,143,998	669,233	Hot Spring
Anjasmoro			
Padusan 1	9,150,227	670,864	Hot spring
Lpcp4	9,147,632	668,280	Anjasmoro basalt lava
Lpcp3	9,148,522	668,801	Anjasmoro basalt lava
Lp5	9,145,093	668,850	Anjasmoro pyroxene andesite lava
Lp4	9,145,344	668,411	Anjasmoro pyroxene andesite lava

The area was divided into six representative units based on stratigraphic relationships and lithological characteristics observed in the field, including relative stratigraphic position, lithological composition, macroscopic features, and spatial distribution. These units represent the main lithological and stratigraphic variations rather than individual local variations. Nine representative hand specimens were then selected using stratified purposive sampling to characterize the main lithologies within the six units. Sampling focused on fresh and relatively unweathered outcrops, considering lithological characteristics, stratigraphic position, and accessibility. Although the nine samples represent the principal lithological characteristics of the study area, suitable exposures were limited in some locations, restricting sample availability.

For petrographic analysis, samples were cut into approximately 1 mm thick slices, mounted on glass slides using epoxy resin or Canada balsam, and ground to a standard thickness of approximately 30 μm (Chacón et al., 2025). Petrographic observations were conducted under plane-polarized light (PPL) and cross-polarized light (XPL). Minerals were identified based on diagnostic optical properties, including pleochroism, cleavage, extinction, interference colors, relief, and crystal morphology. Modal mineral proportions were determined by point counting, while grain size, crystal morphology, textural relationships, groundmass characteristics, and mineral zoning were documented. Lithologies were classified from normalized modal mineral proportions using the IUGS QAPF classification scheme of Streckeisen.

FINDINGS AND DISCUSSION

Field observation and microscopic description of rock samples indicate that the area around Arjuno and Anjasmoro volcanoes is dominated by dark gray to blackish-gray volcanic rocks. These rocks generally exhibit a porphyritic and trachytic texture, characterized by phenocrysts measuring 1- 5 mm within an aphanitic groundmass. The identified lithologies include massive basalt-andesite lava flows and volcanic breccias with angular to subangular fragments ranging from pebbles to boulders. The geological map of the study area shows the distribution of these volcanic units (Figure 2).

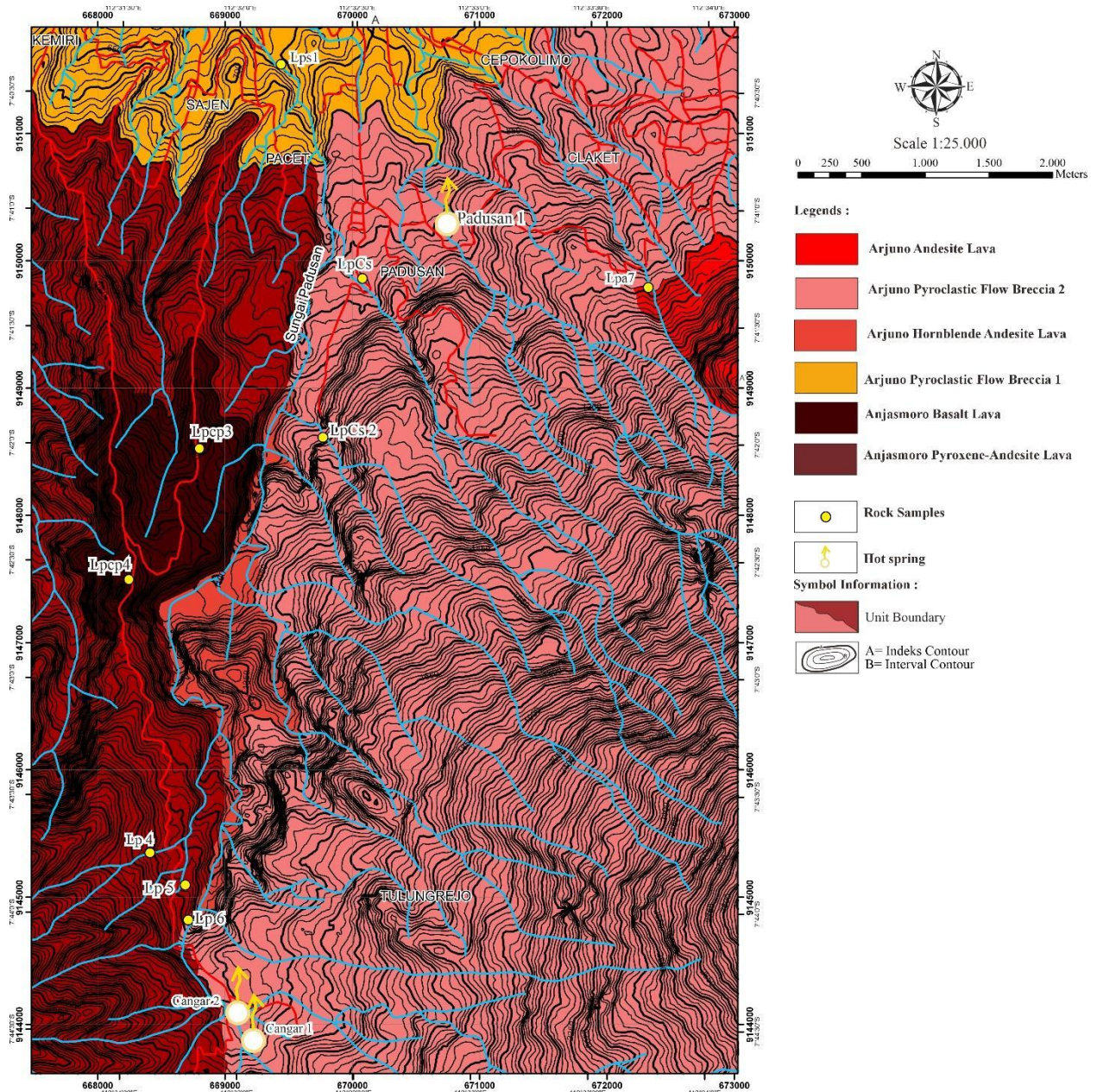


Figure 2. Geological map of the Tulungrejo area

Geological Characteristics

Geological mapping results show that the study area is divided into two main groups based on the volcanic complexes that formed them: the group associated with Arjuno volcano and the group associated with Anjasmoro volcano. This division reflects the contrasting lithological characteristics of the two complexes, as shown on the geological map of the study area (Figure 2).

Petrographic analysis from the four sampling locations reveals porphyritic, trachytic, pilotaxitic, intersertal, and intergranular textures, dominated by plagioclase phenocrysts and mafic minerals in varying proportions. Based on the [Streckeisen \(1979\)](#) classification, which relies on the abundance of minerals observed under thin section rather than whole-rock data.

Geothermal Manifestations

Three geothermal manifestations (Figure 2) were identified in the study area: Cangar 1,

Cangar 2, and Padusan 1 hot springs, all of which emerge through fracture zones in the andesite host rock. Cangar 1 recorded a surface temperature of 43°C, a pH close to neutral at 7.4, and a total dissolved solids (TDS) value of 711 ppm. In contrast, Cangar 2 is cooler and slightly more acidic, with a temperature of 31°C, a pH of 6, and a TDS of 462 ppm. Padusan Spring has the highest temperature and mineral content, reaching 53°C with a neutral pH of 7 and a TDS of 820 ppm.

Stratigraphy of Tulungrejo

The study area's stratigraphy consists of rock units organized from oldest to youngest: the Anjasmoro Volcanic Group (oldest) and the Arjuno Volcanic Group (youngest). The Anjasmoro Group comprises Anjasmoro pyroxene andesite lava and Anjasmoro basaltic lava. Meanwhile, the Arjuno Volcanic Group includes Arjuno pyroclastic flow breccia 1, Arjuno hornblende-andesite lava, Arjuno pyroclastic flow breccia 2, and Arjuno andesite lava. Descriptions of each rock group are presented below:

Anjasmoro pyroxene andesite lava

This outcrop consists of volcanic rock originating from Anjasmoro (Figure 3). It consists of fresh pyroxene andesite lava (Lp4, Lp5) ranging from dark gray to black, showing no signs of alteration and exhibiting a massive structure.



Figure 3. Outcrop of Anjasmoro pyroxene andesite lava (Lp4) (Figures A and B).

Anjasmoro basalt lava

These basalt lavas (Lpcp3, Lpcp4) are generally fresh, dark gray to black, unaltered, and exhibit a massive structure (Figure 4). Morphologically, this unit forms a parasitic cone on the slope of the main Anjasmoro volcano, as shown by the conical landform and radial lava distribution pattern interpreted from the spatial analysis.



Figure 4. Outcrop of Anjasmoro basalt lava (Lpcp4) (Figure A and B).

Arjuno pyroclastic flow breccia 1

This pyroclastic flow breccia (Lps1) is a product of volcanic activity from Arjuno volcano (Figure 5). The rock is brown and exhibits a massive structure; while it shows signs of weathering, it displays no evidence of hydrothermal alteration. Advanced weathering is indicated by spheroidal weathering, resulting in concentric exfoliation on the rock surface.



Figure 5. Outcrop of Arjuno pyroclastic flow breccia 1 (Lps1) (Figure A and B).

Arjuno hornblende andesite lava

The hornblende andesite lava (Lp6) outcrop is a volcanic product of Arjuno volcano (Figure 6). The rock is generally fresh, light gray, shows no signs of alteration, and exhibits a massive structure. Morphologically, this unit forms a parasitic cone on the slope of the main Arjuno volcano, shown by the conical landform and radial distribution pattern of lava interpreted from spatial analysis.



Figure 6. Outcrop of Arjuno hornblende andesite lava (Lp6) (Figures A and B).

Arjuno pyroclastic flow breccia 2

Pyroclastic flow breccia 2 (LpCs 1; LpCs 2) outcrop exhibits a fresh, matrix-supported deposit interpreted as a product of Arjuno volcano. Light gray to whitish gray in color with minimal weathering, the breccia consists of block-sized pyroxene andesite fragments ranging in shape from angular to subangular (Figure 7). These fragments are embedded within a whitish, lapilli-sized matrix. The well-preserved, blocky fragments with a low degree of rounding indicate that the material was transported a short distance before deposition. This indicates deposition in proximal volcanic facies.

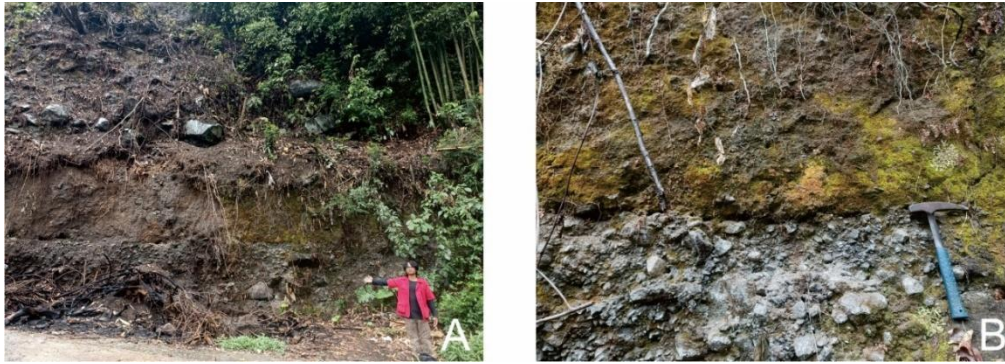


Figure 7. Outcrop of Arjuno pyroclastic flow breccia 2 (LpCs2) (Figure A and B).

Matrix-supported deposits with an abundance of block fragments are a characteristic feature of pyroclastic density current (PDC) deposits. These deposits formed from high-temperature pyroclastic density currents generated when a viscous lava dome collapsed under its own weight during eruption ([Shimizu, 2022](#)).

Arjuno andesite lava

The andesite lava (Lpa7) outcrop is a volcanic product of Arjuno volcano (Figure 8). The rock is moderately weathered, light gray, shows no signs of alteration, and exhibits a massive structure. Morphologically, this unit forms a parasitic cone on the slope of the main Arjuno volcano, shown by the conical landform and radial distribution pattern of lava interpreted from spatial analysis.



Figure 8. Outcrop of andesite lava (Lpa7) (Figure A and B).

Petrography

Twenty rock samples were collected, described, and grouped by volcanic origin: Arjuno and Anjasmoro. Next, nine samples (six lavas and three fragments) were selected for thin section petrographic analysis using a polarizing microscope to determine mineral associations and textures. The petrographic analysis results revealed rock types consisting of andesite (Lp7), hornblende andesite (Lp6 and Lps1), pyroxene andesite (Lpcs1, Lpcs2, Lp5, Lp4), and basalt (Lpcp3, Lpcp4). Nine samples were then selected for thin-section petrographic analysis under a polarizing microscope to determine mineral associations and textures (Table 2).

Table 2. Petrographic Results from Research Area

No Sample	Phn	Plg	Px	Hb	Bio	Opq	Texture	Name	Unit
Arjuno									
Lpa7	◆	◇	○			○	Trachytic, pilotaxitic, intergranular	Andesite	Arjuno andesite lava
LpCs 2	◆	◇	○		○	○	Porphyritic	Pyroxene Andesite	Fragment of Arjuno pyroclastic flow breccia 2
LpCs 1	◆	◇	○		○	○	Porphyritic	Pyroxene Andesite	Fragment of Arjuno pyroclastic flow breccia 2
Lp6	◆	◇	○	Δ	○	○	Porphyritic, intergranular	Hornblende andesite	Arjuno hornblende andesite lava
Lps1	◆	◇	○	□	○	○	Porphyritic, intergranular	Hornblende andesite	Fragment of Arjuno pyroclastic flow breccia 1
Anjasmoro									
Lpcp4	◆	◇	○			○	Trachytic, pilotaxitic, intersertal	Basalt	Anjasmoro basalt lava
Lpcp3	◆	◇	○			○	Porphyritic, intersertal	Basalt	Anjasmoro basalt lava
Lp5	◆	◇	○		○	○	Porphyritic, intergranular	Pyroxene andesite	Anjasmoro pyroxene andesite lava
Lp4	◆	◇	□		○	○	Porphyritic, intergranular	Pyroxene andesite	Anjasmoro pyroxene andesite lava

Annotation :

◆ 75%; Δ >20%; □ 10-20%; ○ <10%

Phn: Phenocryst; Plg: Plagioclase; Px: Pyroxene; Hb: Hornblende; Bio: Biotite; Opq: Opaque Mineral.

◇ Phenocryst and groundmass

Andesite

The andesite sample is found in Arjuno volcano, a lava from Lpa7 belonging to the Arjuno andesite lava unit (Figure 9). Under the polarizing microscope, the samples display a trachytic, pilotaxitic, intergranular texture, indicated by the alignment of plagioclase microlites, reflecting magma flow during crystallization.

The rocks are predominantly composed of plagioclase (75%), accompanied by a small amount of pyroxene and opaque minerals (<10%) as phenocrysts. Plagioclase phenocrysts such as andesine and labradorite commonly display albite and Carlsbad twinning.

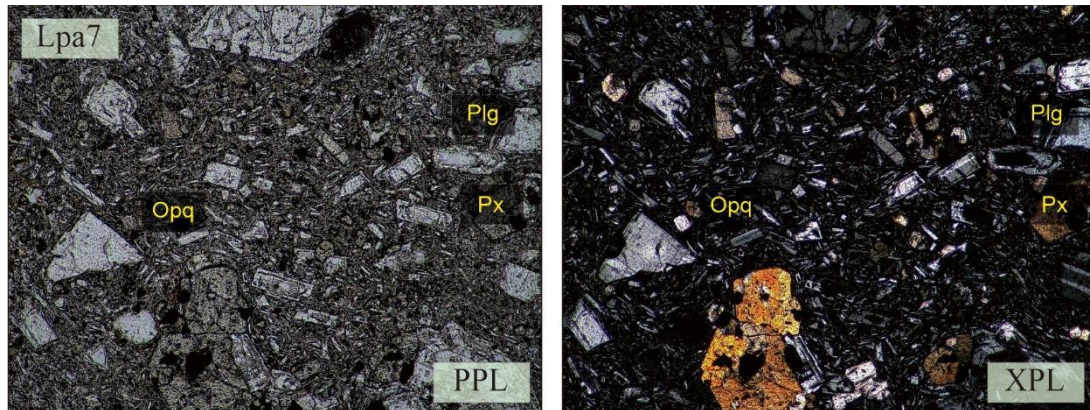


Figure 9. Petrographic image of andesite showing intergranular texture with the presence of plagioclase, pyroxene, and opaque minerals; Plg: plagioclase; Px: pyroxene; Opq: opaque mineral;

Pyroxene andesite

Andesite pyroxene rocks (Figure 10) are found on both Anjasmoro and Arjuno volcanoes. Pyroxene andesite in Anjasmoro is represented by lava from Lp5 and Lp4, which is part of the Anjasmoro pyroxene andesite lava unit. Arjuno volcano is represented by LpCs 1 and LpCs 2, fragments of the Arjuno pyroclastic flow breccia 2 unit. A porphyritic and intergranular texture was observed in the pyroxene andesite samples, with phenocrysts embedded within a fine-grained groundmass. The rock is composed predominantly of plagioclase (75%), accompanied by pyroxene (10-20%) and minor opaque minerals (<10%). Plagioclase and pyroxene occur mainly as subhedral phenocrysts.

Hornblende andesite

This rock occurs at Arjuno volcano and is represented by Lps1, a fragment of Arjuno pyroclastic flow breccia 1 unit, and lava from Lp6, from the Arjuno hornblende andesite lava unit. This rock (Figure 11) is dominated by plagioclase (75%) along with an abundance of hornblende (>20%), and a minor amount of pyroxene, biotite, and opaque minerals (<10%). Plagioclase occurs as subhedral to anhedral crystals that commonly exhibit albite and Carlsbad twinning. Hornblende exhibits opaque rims, indicating an increase in Fe-oxides.

Basalt

This sample occurs only in the Anjasmoro volcano and is represented by lava from Lpcp3 and Lpcp4, belonging to the Anjasmoro basalt lava unit. This sample exhibits a trachytic, pilotaxitic, and intersertal texture dominated by subhedral to euhedral labradorite-type plagioclase (75%), accompanied by a small amount of pyroxene and opaque minerals (<10%) (Figure 12).

Magmatic Characteristics

All nine thin sections are predominantly comprised of plagioclase phenocrysts (>75%) as subhedral to euhedral crystals with albite and Carlsbad twinning. Mafic minerals such as pyroxene, hornblende, biotite, and opaque minerals, whereas olivine was not found across all nine thin sections. Samples exhibit porphyritic, trachytic, and intergranular textures, with a few samples showing pilotaxitic and intersertal textures showing subparallel alignment of the groundmass microlites.

Plagioclase abundance classifies the rocks as basalt, andesite, pyroxene andesite, and hornblende andesite. The plagioclase-pyroxene-hornblende-opaque mineral assemblage,

particularly hornblende phenocrysts, reflects the crystallization of hydrous, water-rich intermediate magmas typical of island arc subduction zones and composite volcanoes (Zhao et al., 2021; Yudiantoro et al., 2022; Keller et al., 2024; Santos et al., 2026), confirming the subduction arc affinity of the Anjasmoro and Arjuno volcanic products.

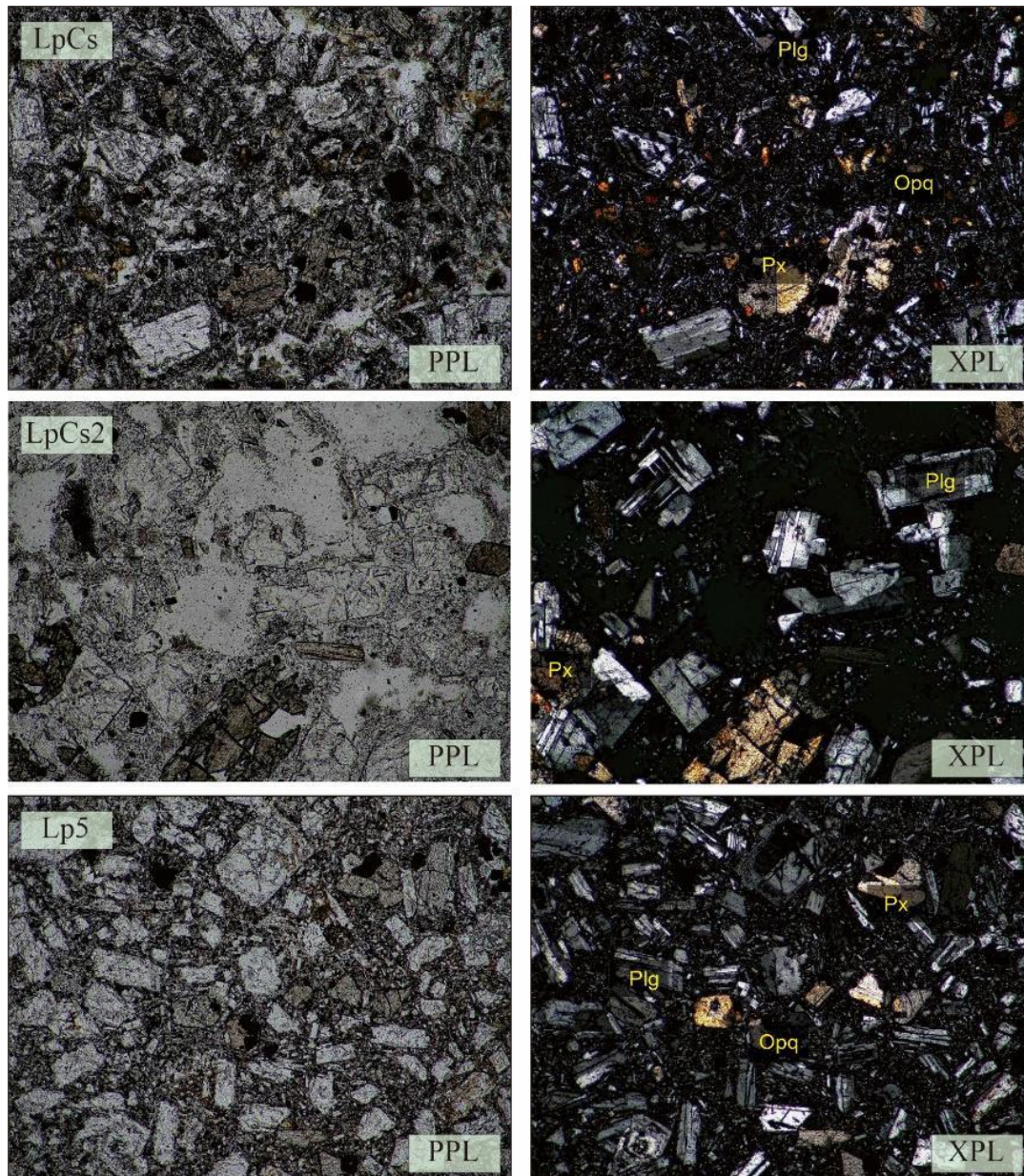


Figure 10. Petrographic image of pyroxene andesite showing intergranular texture with the presence of plagioclase, pyroxene, and opaque minerals. Plg: plagioclase; Px: pyroxene; Opq: opaque mineral

Magmatic Differentiation

Evidence of compositional differentiation within the Anjasmoro system is observed in the differences between two lava units. Pyroxene andesite lava constitutes the main volcanic edifice, whereas the basaltic lava (Lpcp4) is identified via remote sensing as a parasitic cone consisting of basalt with a pilotaxitic to intersertal groundmass texture (Figure 12). The occurrence of less evolved magmas in parasitic cones compared with the main volcanic edifice may reflect a complex

magmatic plumbing system involving multiple magma reservoirs and variable degrees of fractional crystallization (Molendijk et al., 2024).

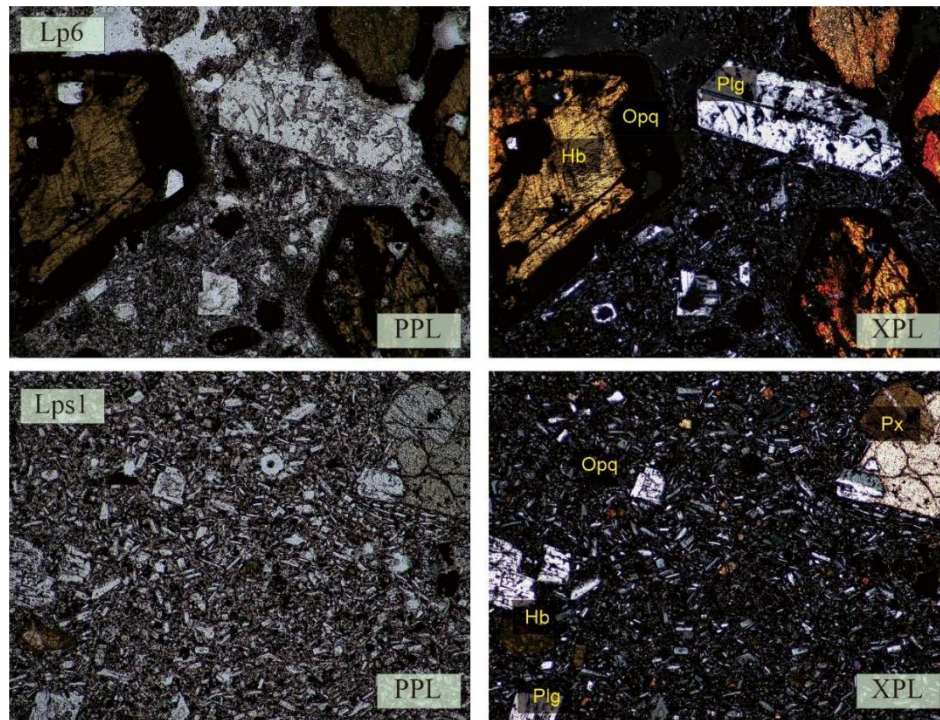


Figure 11. Petrography of hornblende andesite showing intergranular texture and exhibiting the presence of plagioclase, pyroxene, hornblende, and opaque minerals. The hornblende crystal exhibits an opaque rim.

Plg: plagioclase; Hb: hornblende; Px: pyroxene; Bio: Biotite; Opq: opaque mineral

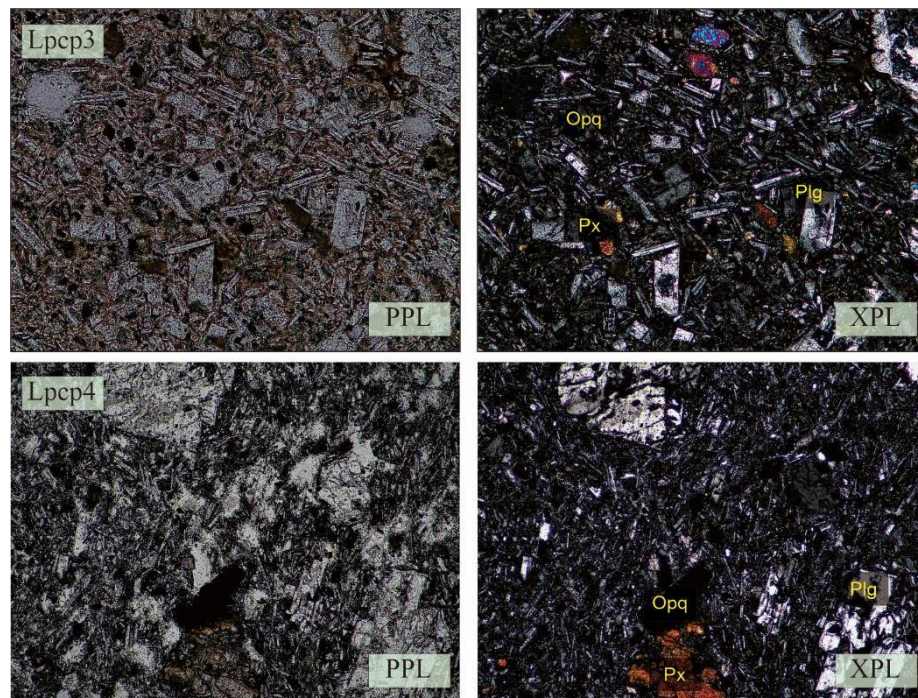


Figure 12. Petrography of basalt showing intersertal texture with the presence of plagioclase, pyroxene, and opaque minerals. Plg: plagioclase; Opq; Opaque mineral; Px: Pyroxene

Hornblende abundance in hornblende andesite ranges from <10% to >20%, reflecting magma hydration state and P-T conditions, whereas pyroxene-dominated (>10%) samples indicate drier, destabilizing decompression conditions (Keller et al., 2024). The intermediate-mafic-intermediate stratigraphic sequence demonstrates a non-linear evolutionary history, likely driven by open-system dynamics featuring repeated primitive magma recharge and fractional crystallization (Keller et al., 2024).

The results indicate that the magmatic systems of the older Anjasmoro volcano and the younger Arjuno volcano have undergone non-linear differentiation. This is evidenced by petrographic observations showing a compositional shift in Anjasmoro from hornblende andesite and pyroxene andesite to andesite, whereas Arjuno exhibits a transition from pyroxene andesite to basalt. This is further indicated by hornblende rims being replaced by opaque minerals. Fracture structures are shown to directly control the emergence of hydrothermal fluids from the geothermal systems at the Cangar 1, Cangar 2, and Padusan 1 sites; these systems are characterized by temperatures ranging from 30°C to 53°C, mineralization levels (TDS) of 462–820 ppm, and andesitic-basaltic magmatism serving as the heat source.

CONCLUSIONS

The volcanic rocks in the study area—comprising basalt, andesite, pyroxene andesite, and hornblende andesite—are characterized by plagioclase dominance, indicating formation within a volcanic arc associated with an island-arc subduction zone. Meanwhile, the presence of hornblende suggests that the magma was water-rich (hydrous) during crystallization.

The sequence of magmatic activity—progressing from intermediate to mafic compositions and then back to intermediate (from oldest to youngest)—reveals a non-linear differentiation trend. This suggests episodic recharging of the magma reservoir by less differentiated magma. These patterns imply that the Anjasmoro volcanic system likely possesses a heterogeneous magma plumbing system.

The presence of hot spring manifestations and magmatism indicates that the region holds promising geothermal energy potential. Consequently, this research is expected to provide supplementary data for further geothermal exploration in East Java, aiming to secure additional electrical energy supplies.

LIMITATIONS & FURTHER RESEARCH

A limitation of this study is its reliance on qualitative/semi-quantitative optical petrography and surface physicochemical parameters, lacking supporting data from whole-rock geochemistry (major/trace elements), radiometric dating, and fluid isotopes ($\delta^{18}\text{O}$ and δD). Consequently, future research should include whole-rock geochemical analysis, mineral geothermobarometry, fluid isotope hydrogeochemical analysis, and subsurface geophysical modeling (magnetotellurics) to reconstruct magma chamber conditions and map reservoir geometry and geothermal flow paths in 3D.

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