Stratigraphic Variations And Structural of Autobreccia: Implications Of Edaphic Potential in The Merapi-Ranti Volcanic Transition Zone, Geopark Ijen

Avanza Iqbal Ar Rafi[1], *Melati* Julia Rahma[2*], and *Firman* Sauqi Nur Sabila[3]

[1,2]Departemen Geografi, Fakultas Ilmu Sosial, Universitas Negeri Malang, Jalan Semarang No. 5, Malang, East Java
[3]Geology Geopark Ijen, Jalan Gajah Mada, Banyuwangi, East Java

Abstract. The transition zone between the Merapi Formation and the Ranti Formation in Kalibendo, Ijen Geopark, provides information in the form of rock outcrops that are used as parameters to understand and reconstruct geological phenomena in the past. The main problem in this study is the lack of clear stratigraphic information regarding the boundary between the two formations on geological maps and in previous studies. This study aims to reveal the stratigraphic sequence, identify autobreccia structures, and assess the edaphic implications in the Merapi–Ranti transition zone. This study uses a systematic method in the form of field observations and edaphic potential analysis as well as reconstructing geological phenomena and their potential for the surrounding environment. Based on rock outcrops at the research site, the stratigraphic sequence shows lava rocks from the Merapi Formation stacked on lava rocks from the Ranti Formation, indicating sequential formation. The discovery of autobreccia structures between the two formations is evidence of the interaction between molten lava from the Ranti Volcano and lava that had solidified from the Merapi Volcano. In addition, the diversity of rock and mineral structures is an indicator in reconstructing geological phenomena. Mineral diversity also correlates with edaphic potential, where soil resulting from the weathering of volcanic rocks is rich in minerals that can release nutrients, contributing to the formation of soil with high cation exchange capacity (CEC) that has long been utilized by the Osing ethnic for agriculture.

1 Introduction

Ijen Geopark is an area in Banyuwangi and Bondowoso that has geological, biological, and cultural diversity. This geopark features various natural landscapes such as volcanoes, rivers, lakes, karsts, and beaches, which were formed through long geological processes. Ancient volcanic activity left traces in the form of volcanic breccia, lava, and Pleistocene tuff [1]. The existence of volcanoes in this region is influenced by Indonesia's position at the meeting point of the Pacific, Eurasian, and Indo-Australian plates [2]. The collapse of the ancient Ijen Volcano around 50,000 years ago triggered the formation of new volcanoes, including

* Corresponding author: melatijuliarahma.fis@um.ac.id

Raung, Ijen, Merapi, Ranti, Pendil, and Suket [3]. This activity resulted in the formation of adjacent Quaternary volcanic rocks, creating a complex stratigraphy.

Although Ijen Geopark has been extensively studied from a general geological perspective, no specific studies have been conducted on the relationship between stratigraphy and autobreccia structures in the Merapi–Ranti transition zone. This research gap is an important basis for our study. The relevance of this research is further strengthened by the fact that Ijen Geopark is an area with geological diversity recognized by UNESCO. Detailed studies of stratigraphy and autobreccia not only enrich scientific information and support geological conservation, but also provide added value to edaphic utilization for local communities.

This diversity is inseparable from a long geological process, in which there were once major eruptions of ancient volcanoes that are evidenced by the presence of volcanic rocks such as volcanic breccia, lava, and tuff dating back to the Pleistocene era [1]. The presence of volcanoes in the Ijen Geopark area is the result of a geological process as Indonesia lies at the convergence of the the Pacific Plate, the Eurasian Plate, and the Indo-Australian Plate [2]. The geological phenomena that have been occurring since 50,000 years ago began when the ancient Ijen volcano collapsed, leading to a series of volcanic activities that formed new volcanoes, including Raung, Ijen, Merapi, Ranti, Pendil, and Suket [3]. The emergence of younger volcanoes led to the formation of various Quaternary volcanic rock formations were formed, which then formed the stratigraphy.

Stratigraphy refers to the study of the composition, relative age, distribution, and historical interpretation of rock layers. Stratigraphically, the Banyuwangi region and its surroundings are composed of various types of rocks dating from the Late Oligocene (28–23 million years ago) to the Early Miocene (23–16 million years ago), Middle Miocene rocks (11.6–16 million years ago), and Quaternary rocks (2.58 million years ago to present). The Oligo-Miocene rocks, dominated by volcanic rocks and lava, are the oldest exposed rocks. Additionally, shallow marine sedimentary rocks and volcanic clastic rocks were formed, including intrusive rocks such as granodiorite and andesite porphyry. These data are based on geological mapping by the Geological Research and Development Center (now the Geological Survey Center) from 1990 to 1993 [3].

The description of rocks based on their physical characteristics and composition is called lithology. Lithological studies are conducted to reconstruct past geological processes and their relationship with the surrounding environment. One of the lithological structures that can be found in the Ijen Geopark area is the autobreccia structure. Autobreccia is a type of rock that forms fragments on its own [4]. This structure is formed as a result of lava cooling, which causes the formation of angular rock fragments [5]. Its formation process is influenced by varying cooling times, resulting in the appearance of a arrangement of fragment components and matrix with the same composition [5]. The lithology and structure of autobreccia can serve as indicators for understanding lava eruption dynamics, volcanic deposition environments, and the volcanic activity history of a region.

Understanding magmatism and volcanoes requires exploration of the mineral diversity of a region. Minerals commonly found in igneous rocks, which are the product of volcanic activity, are pyroxene and plagioclase, formed in magma chambers under high temperatures and pressures. Pyroxene and plagioclase are generally found in oceanic crust undergoing subduction [6]. In addition to mineral diversity, the rock structure found at a site is necessary to understand the formation scheme of a region. The mineral diversity present in a region can contribute to edaphic potential, which is the capacity of soil to support vegetation growth through its physical, chemical, and biological characteristics.

Volcanic rocks contain minerals that can weather, releasing nutrients that are important for plants. Minerals such as feldspar, pyroxene, and olivine found in volcanic rocks will begin to weather over time, producing weathered minerals such as kaolin and clay that increase the

 https://doi.org/10.1051/e3sconf/202565209001

soil's capacity to retain water and nutrients, thereby enhancing soil fertility [7]. This mineral weathering process naturally increases soil fertility, but its speed and efficiency depend on the type of mineral and environmental conditions. Therefore, mineral-rich volcanic rocks that are easily weathered have great potential as a source of natural nutrients for the soil, supporting plant growth and soil ecosystem sustainability.

The 1993 Banyuwangi geological map, published by the Center for Geological Research and Development (now the Geological Survey Center), does not provide definitive information about the stratigraphy of the Merapi and Ranti formations. Both formations have the same code, Qv, which indicates volcanic rock. However, no studies have been conducted yet to explain the stratigraphic sequence or cross-section of these formations. The primary objective of this research is to reveal the stratigraphic sequence between the two formations to determine which formed first. Understanding the interaction between rock formations at the research site can indicate the diversity of rocks and minerals and their contribution to soil formation in a particular area. The geological features found at the research site can be systematically organized to reconstruct past geological phenomena.

2 Location and Methodology

2.1. Location

The research was conducted in the Kalibendo Waterfall area (8°09′37.854″ S; 114°16′18.196″ E) located within the Ijen Geopark, Banyuwangi Regency, East Java. This location is a relatively unspoiled natural tourist area, located at the foot of Mount Merapi and Mount Ranti, making it strategic for volcanic geological observation. The surrounding area consists of coffee plantations and agricultural land owned by the Osing tribe, the indigenous ethnic group of Banyuwangi. This area was chosen because it is located precisely at the transition zone between the Merapi Formation and the Ranti Formation, as shown on the Banyuwangi Geological Map **Fig.1**. The location's position on the contact line between the two volcanic rock units allows for direct observation of the differences in lithology, geological structure, and stratigraphic relationships between the two in the field.

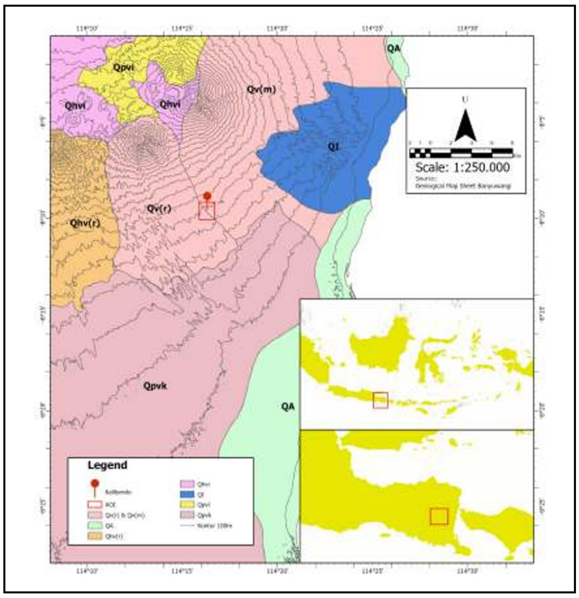

Fig. 1. Research Location Map

 https://doi.org/10.1051/e3sconf/202565209001

2.2. Data Analysis Techniques

This study used a systematic method [6], with the initial stage being the determination of the research location based on the Banyuwangi Geological Map. The location was then validated through field observations to identify the stratigraphic arrangement between the Merapi Formation and the Ranti Formation and determine the order of their formation [6]. Additionally, an analysis of rock characteristics was conducted based on igneous rock classification, by matching the physical and mineralogical characteristics of the rocks [5] .

Field data collection was carried out using various geological equipment. Geological hammers were used to collect rock samples, geological compasses to measure the orientation of structures, GPS to record location coordinates, and magnifying glasses to observe mineral details macroscopically. In addition, HCl solution was used to test for the presence of carbonate minerals, while cameras were used to document rock outcrops and geological structures. All of these activities were based on geological maps as the main reference for field mapping.

The field data obtained was then analyzed descriptively and comparatively, focusing on the differences in lithology, geological structure, and stratigraphic relationships between the two formations. Observations of rock outcrops around Kalibendo Waterfall were used as the main data to determine the stratigraphic sequence, rock structure, and mineral identification. All collected data were then compiled and analyzed to reconstruct the sequence of geological events in the transition zone between the Merapi Formation and the Ranti Formation. This interpretation was based on observations of characteristic geological structures such as autobreccia, xenoliths, sheeting joints, and vesicular structures found in outcrops at the research site.

3 Result and Discussion

3.1. Rock Outcrops and Stratigraphy

The rock outcrop around Kalibendo Waterfall, with a height of about 8 meters, reveals two rock units exposed vertically. The lower part of the outcrop is composed of rocks from the Merapi Formation, while the upper part is part of the Ranti Formation. The Merapi Formation is dominated by dark-colored andesitic-basaltic lava with a massive texture, while the Ranti Formation is composed of younger lava with volcanic breccia fragments and vesicular structures. These two formations are separated by an autobreccia structure formed by the interaction of young lava from the Ranti Volcano with lava that had solidified from the Merapi Volcano, so that the boundary between the two can be clearly identified.

Identification of the boundary between the two formations in **Fig.2** is based on the principle of superposition, whereby the lower layer tends to be older [8], and is reinforced by the presence of autobreccia formed by the interaction of young lava from Mount Ranti with lava that had already solidified from Mount Merapi. In addition to clear lithological differences, this outcrop also reveals other geological structures in the form of autobreccia and sheeting joints, which are important indicators in reconstructing the geological processes in the Merapi–Ranti transition zone.

 https://doi.org/10.1051/e3sconf/202565209001

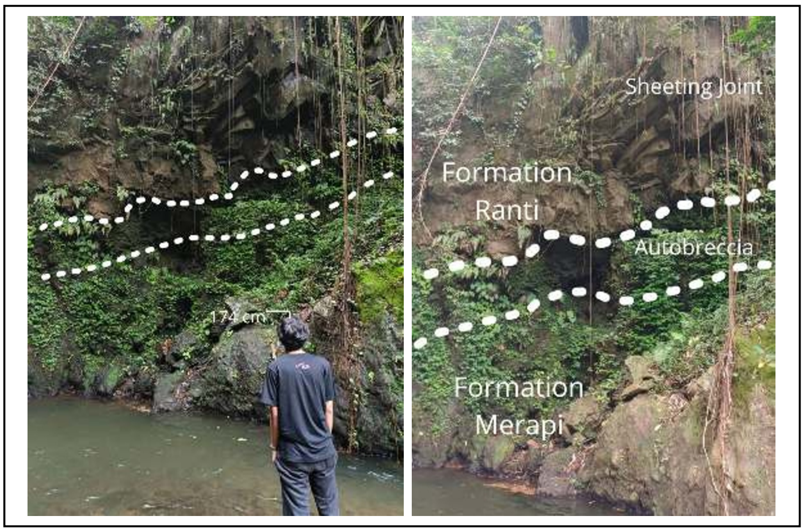

Fig. 2. Rock Formation Exposure

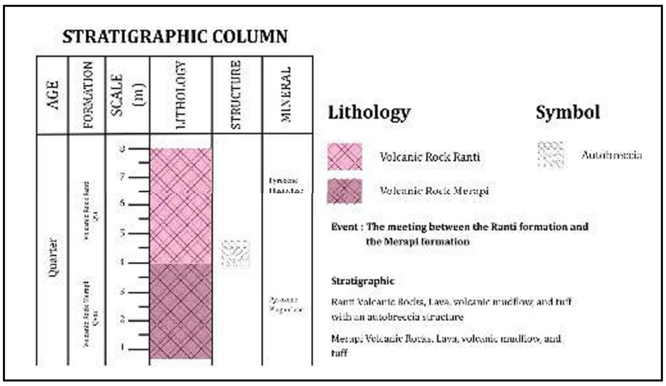

Fig. 3. Stratigraphic Column, Form Field observation

Stratigraphy in a region provides important clues about the geological phenomena that shaped the current landscape. In the Banyuwangi geological map sheet, cross sections show variations in rock composition around Banyuwangi, with each cross section cutting through a different formation. However, there are no sections that directly connect the Merapi Qv(m) Formation and the Ranti Qv(r) Formation, so the stratigraphic relationship between the two cannot be confirmed. Kalibendo, located between the two formations, shows rock outcrops that reveal the vertical stratigraphic sequence **Fig.2**. Based on the law of superposition, rock layers at the bottom in a normal position are generally older than the layers above them [8]. Thus, the stratigraphic sequence in Kalibendo consists of the Merapi Qv(m) Formation at the bottom and the Ranti Qv(r) Formation at the top **Fig.3**.

This formation structure forms the basis for assumptions regarding geological processes in the past, where the Merapi formation at the bottom, or older rock, was formed first, followed by the formation of the Ranti formation at the top, which is younger rock. The determination of these two formations is based on the surrounding geomorphology and the results of geological mapping conducted by the Geological Research and Development Center (now the Geological Survey Center). The exposed formations are of the same type, namely the Quaternary Volcanic Formation (Qv), but originate from two different volcanoes.

3.2. Rock Structure

The rock outcrops at Kalibendo not only reveal two rock formations but also show a rock structure in the form of an autobreccia **Fig.4a**. This structure was formed as a result of the interaction between hot lava and previously cooled rock. An autobreccia is a rock structure that is the product of volcanic activity [9]. The presence of this autobrexial structure indicates the formation process of these two formations, where the Merapi Formation formed first, followed by hot lava, which is a product of the Ranti volcano. The hot lava then interacted with the Merapi volcanic rock, resulting in the formation of an autobreccia structure consisting of rock fragments of similar size.

This finding reinforces the assumption of a sequence of geological events that indicate a gradual process between the two volcanic systems. Another structure found in the Kalibendo area is a xenolith structure, which is a fragment of older rock originating from an intrusion that was later trapped in a younger rock body [1]. These structures are commonly found in andesite rocks formed within the magma chamber **[8]**. In addition to autobreccia, other rock structures were also found and were quite diverse **Table 1**.

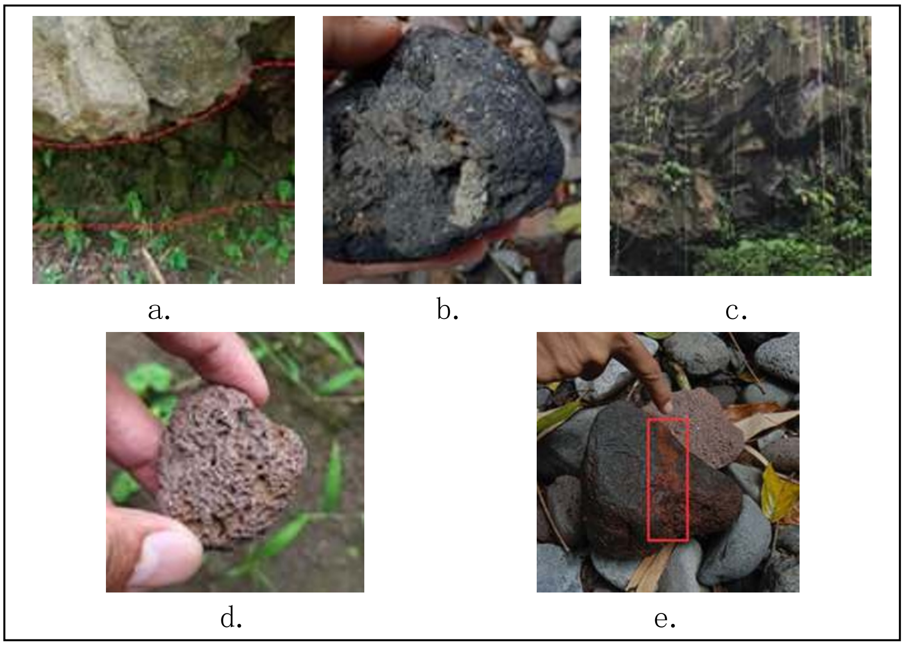

Fig. 4. Rock structure diversity a.) Autobrexial structure. b.) Xenolith structure. c.) Sheeting joint structure. d.) Vesicular structure. e.) Rock oxidation

Table 1. Rock structure diversity

No	Structure	Description
1	Autobreccia	This structure is not only found at one outcrop location, but also at several other outcrops in the study area. This indicates that the interaction process between hot lava and rocks that had already cooled down occurred repeatedly [9] and was evenly distributed across various points. This finding reinforces the assumption that the phenomenon of autobrecciation is an important part of the volcanic dynamics in this region.
2	Xenolith	Xenolith structures were found among rocks along the riverbed that had undergone erosion. The presence of older rock fragments trapped within younger rock masses indicates a process of young

https://doi.org/10.1051/e3sconf/202565209001

No	Structure	Description
		magma intrusion into previously formed rocks. This finding indicates that the geological processes at the site involved the intrusion of magma carrying older rock fragments, which were then trapped and solidified within the younger rock body [3].
3	Sheeting joint	This structure was found in the same outcrop as the autobreccia structure, indicating that the rock formation process occurred gradually through repeated lava flows. This structure was formed by the gradual cooling of flowing lava, which formed layers parallel to the surface. Over time, these layers were eroded by surface water flow, exposing the outcrop and revealing these structures in the field. This finding supports the interpretation that the Ranti Formation was formed through repeated volcanic processes with the contribution of lava deposition and gradual mechanical weathering [5].
4	Vesicular	Vesicular structures are found in many locations along the Kalibendo stream, characterized by the presence of holes or cavities on the surface of volcanic rocks formed by the release of volatile gases during the cooling and solidification of lava [10].
5	Rock oxidation	Oxidation in rock samples shows contrasting black and red colors, with the red color indicating zones that have cooled more quickly and undergone intense oxidation. These conditions are commonly found on the surface of autobreccia fragments or lava exposed to air, and are important indicators in the interpretation of the thermal and environmental conditions of lava solidification [13].

Data : Field observation

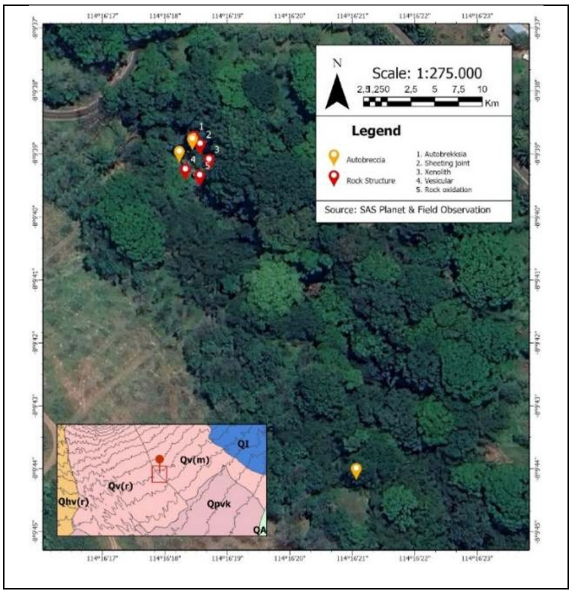

Fig. 5. Map of Rock Structure Sample Distribution

In rock findings in the area around the Kalibendo waterfall, there are xenolith structures in the form of old rock fragments that are thought to be volcanic products of Mount Merapi found trapped in young rocks from Mount Ranti **Fig 4b**. This finding indicates that during the formation of Mount Ranti, magma penetrated older rocks from Mount Merapi. This supports the interpretation that volcanic activity at Merapi occurred earlier than the development of the Ranti volcanic system.

The presence of these xenoliths does not stand alone, but is consistent with the findings of other rock structures located nearby at coordinates 8°09′37.854″ S and 114°16′18.196″ E. Based on the rock distribution map, this point is an important location for sample collection and also shows the distribution of autobreccia structures **Fig 5**. This distribution indicates that the interaction between young lava and old rocks occurred repeatedly in the Merapi–Ranti transition zone. Thus, both xenoliths and autobreccia provide strong evidence for reconstructing the complex volcanic dynamics in the Ijen Geopark area.

In addition to these two structures, field observations also revealed the presence of another rock structure in the form of sheeting joint **Fig 4c**. This structure develops parallel to the natural surface of the rock and is commonly found in massive or igneous rocks [5]. The presence of sheeting joints in Kalibendo usually forms on steep slopes and plays an important role as the main pathway for water movement, as seen in the Kalibendo Waterfall stream.
Sheeting joints formed gradually following topographic stress conditions, creating layers of rock [5]. These layers are traversed by water flow, causing the rocks to undergo weathering and deposition processes that expose these layers. Another structure found is a vesicular structure **Fig 4d**, which consists of porous rocks resulting from the release of trapped gas during cooling. The released gas is volatile gas contained in the magma and can be released during the magma's ascent to the surface [10]. This gas is more soluble in magma at high pressure and will undergo exsolution to form bubbles (vesiculation) when pressure decreases, affecting the behavior and properties of the magma during eruption [10].

There are rocks with different colors **Fig 4e**, the presence of these rocks indicates that there were different oxidation and cooling processes between parts of the rock. As explained by Morrison-Evans (2024), color variations such as dark gray to reddish or brownish represent different levels of oxidation in andesitic basaltic lava. These color changes reflect differences in temperature, exposure time to air, and oxygen diffusion during the cooling and weathering of the lava. The presence of these rocks allows us to make assumptions about the rock formation process. When lava flows and begins to solidify, the parts closer to the air or surface are more easily exposed to oxygen, resulting in more intense oxidation and a reddish-brown color, indicating a high content of oxidized iron. Meanwhile, the inner parts, which are less exposed to oxygen, remain dark gray, indicating minimal oxidation [13].

3.3. Geological Reconstruction

Based on the rock structures found at the research site, past geological reconstructions can be made by linking the relationships between structures and stratigraphic positions. After the formation of Mount Merapi, volcanic activity at Mount Ranti produced magma that broke through the Merapi rock layer, forming xenolith structures. Subsequently, lava flows from Ranti covered the cooled Merapi rocks, and the interaction between the hot lava and the cold rocks formed autobreccia structures.

In addition, lava flows also form layers that follow the contours of the local topography, which over time undergo weathering due to water flow. This process causes material deposition and produces sheeting joint structures in the form of fractures parallel to the rock surface. The discovery of vesicular structures in the outcrop also indicates an explosive eruption phase, in which high vesicularity affects the behavior of magma as it rises to the surface [10].

Although there are no written records of historical eruptions of Mount Merapi and Mount Ranti, stratigraphic observations and rock structures in Kalibendo show evidence of repeated volcanic activity during the Quaternary period. This is in line with the geological reconstruction of the Ijen region, which explains that the collapse of the ancient Ijen volcano triggered the formation of younger volcanoes, including Merapi and Ranti, which produced lava flows, breccias, and volcanic structures that can still be observed in the current outcrops [3,2]. Thus, field observations can be considered a historical representation of the volcanic activity of these two volcanoes.

3.4. Mineral Diversity

The long history of volcanic activity in the Merapi and Ranti volcanoes is rich in minerals resulting from magma crystallization. At the research site, particularly around Kalibendo Waterfall, macroscopic minerals such as plagioclase and pyroxene were found **Fig 6**. The presence of plagioclase, commonly found in continental rocks, as explained by [12], indicates that plagioclase is one of the main rock-forming minerals in the continental crust.

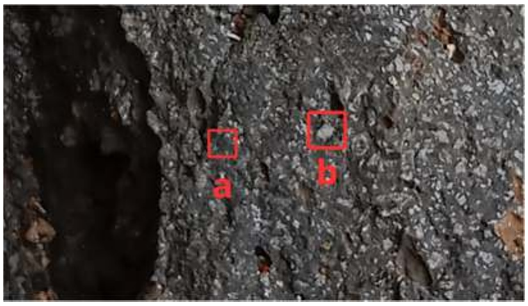

Figure 6. Macroscopic Minerals (a) Pyroxene, (b) Plagioclase

Pyroxene, which is commonly found in oceanic rocks is a common component found in basaltic rocks in marine environments [6]. These two minerals support the research assumption that magmatic activity in this area is related to the subduction zone, which is the meeting point between oceanic and continental plates. Although volcanic processes from volcanoes can produce various types of minerals, macroscopic observations in the field show the dominance of plagioclase and pyroxene as the main minerals present.

Tabel 2. Mineral Diversity

No.	Rock	Mineral
1	Andesite	Pyroxene Plagioclase Magnetite Amphibole Biotite Feldspar
2	Basalt	Pyroxene Plagioclase Olivine Magnetite
3	Scoria	Pyroxene Plagioclase Olivine Magnetite

Data : field observations & Toderaş et al. (2017) [13]

The abundance of minerals can also be seen from the rocks found at the research site. The results of the analysis and matching of rock and mineral characteristics show the diversity of minerals in each rock **Table 2**. Volcanic rocks such as andesite, basalt, and scoria match the results of previous research by Toderaş et al. (2017) [13], stating that the igneous rocks found at the research site are dominated by plagioclase, pyroxene, olivine, feldspar, and magnetite minerals. The minerals from these rocks will eventually undergo weathering and contribute to soil formation, becoming an important factor in soil fertility.

3.5. Edaphic Potential

Field studies show that the area around Kalibendo Waterfall, located in the volcanic transition zone between Mount Merapi and Mount Ranti, is dominated by land use in the form of coffee plantations and agricultural land. This land use pattern reflects high edaphic and environmental potential, influenced by local geological conditions, particularly the presence of mineral-rich volcanic rocks. These findings are consistent with another research, which states that volcanic lava rocks, such as those found in this area, generally contain primary minerals such as plagioclase and pyroxene [9]. When weathered, these minerals can release important nutrients such as K^+, Ca^{2+}, and Mg^{2+} into the soil.

The diversity of minerals in volcanic rocks in the Mount Merapi and Ranti volcanic areas is the result of active geological processes that produce primary minerals rich in nutrients. These minerals, such as plagioclase, pyroxene, feldspar, and olivine, play an important role in supporting soil fertility, but must first undergo weathering. Weathering is a series of chemical and physical processes that transform primary minerals into more stable forms that are easily absorbed by plants. These minerals fall into the category of primary minerals that are essential for plants when they undergo weathering and decomposition [17]. Once primary minerals have undergone weathering, they form simple charged compounds.

Environmental factors have a major influence on the intensity and direction of weathering. Parameters such as soil pH, temperature, humidity, redox conditions, and the presence of microorganisms will determine the rate of mineral decomposition and nutrient release. Humid and warm tropical conditions such as those found in the Kalibendo area of Ijen Geopark, tend to accelerate the weathering process and form soils that are richer in nutrients [17].

Previous studies have also shown that soil modification through the addition of volcanic materials such as basalt powder can increase macro and micro nutrient content. However, this effect can vary depending on the physicochemical properties of the rock, soil dynamics, and the complexity of the nutrient cycle [9]. Primary mineral weathering not only provides important nutrients such as K^+, Ca^{2+}, and Mg^{2+}, but also forms soil structures with high cation exchange capacity (CEC), which is very beneficial for plant growth. Soils developed from volcanic rocks tend to have high natural fertility due to the direct contribution of mineral weathering and intense biological activity [9].

3.6. Implications of Minerals on Edaphic Potential

The rocks found in the Kalibendo area are dominated by igneous rocks in the form of basalt and andesite, which are classified as basic rocks. These rocks are generally weathered, fine-grained, and produce clay with a predominance of 2:1 montmorillonite and high base saturation, making them relatively fertile [14]. Mineralogically, the rock contains primary minerals such as plagioclase, pyroxene, feldspar, and olivine, which play an important role as providers of nutrients such as K^+, Ca^{2+}, and Mg^{2+}. In addition, secondary minerals such as calcite, apatite, chlorite, and quartz were also found. According to Hanafiah (2014) in his book he mentions, secondary minerals play a role in determining the chemical and physical properties of soil and serve as indicators of the intensity of primary mineral weathering. The greater the proportion of secondary minerals, the more intense the weathering process and the more mature the soil genesis process. Hanafiah (2014) in his book he mentions, some non-silicate minerals, such as calcite, have relatively high nutrient content and function as sources of Ca and OH^-, so they are often used as liming agents for acidic soils. Basically, plants need macro nutrients such as N, P, K, Ca, and Mg, as well as other micro nutrients that generally come from parent rocks and their constituent minerals [15].

4 Conclusions

This study reveals the stratigraphic sequence between the Merapi Formation and the Ranti Formation in the Kalibendo transition zone, Ijen Geopark, Banyuwangi. This research was motivated by the lack of clear information regarding the stratigraphic cross-section of the two formations, both in regional geological maps and previous studies. Field observations show that the stratigraphic sequence at the research site consists of Merapi Formation lava at the bottom and Ranti Formation lava at the top. The presence of autobreccia structures in the contact zone is evidence of interaction between hot lava from the Ranti Volcano and solidified lava from the Merapi Volcano, reinforced by the discovery of other geological structures such as xenoliths, vesicular textures, and evidence of differential oxidation, which indicate a gradual and complex volcanic process. In addition, the diversity of primary minerals (plagioclase, pyroxene, olivine, feldspar, magnetite) and secondary minerals (calcite, chlorite, quartz) plays an important role in releasing nutrients such as K^+, Ca^{2+}, and Mg^{2+}, thereby supporting the formation of soil with high cation exchange capacity (CEC). These conditions have implications for the edaphic potential that has long been exploited by the Osing community, for example for coffee plantations and agriculture around Kalibendo. Thus, this study confirms that stratigraphy, autobreccia structure, and mineral diversity are not only important for geological reconstruction, but also have real implications for edaphic potential and land use. Further studies using petrographic and geochemical approaches can deepen our understanding of the relationship between rock mineralogy and edaphic potential in volcanic areas.

References

1. A. Prabowo, H. Samodra, Analisis batuan gunungapi di daerah Banyuwangi dan sekitarnya berdasarkan aspek geokimia. *Jurnal Geologi dan Sumberdaya Mineral* 21(4), 197–207 (2024). https://doi.org/10.33332/jgsm.geologi.v22.4.197-207
2. D. Bagus, V. Dosen, J. Tadris, I. P. Sosial, F. Tarbiyah, I. Keguruan, Ancaman erupsi Kawah Ijen terhadap masyarakat lereng Ijen (Kabupaten Bondowoso). (2020). http://www.vsi.esdm.go.id
3. H. Samodra, A. Prabowo, S. Permanadewi, J. Razak, S. Yalin, Bappeda Banyuwangi, Inventarisasi keragaman geologi dan identifikasi warisan geologi daerah Kabupaten Banyuwangi (Jawa Timur) (2019). https://doi.org/10.33332/jgsm.geologi.v22i4.658
4. J. P. Wiersma, E. M. Roberts, P. H. Dirks, Formation of mud clast breccias and the process of sedimentary autobrecciation in the hominin-bearing (Homo naledi) Rising Star Cave system, South Africa. *Sedimentology* 67(2), 897–919 (2020). https://doi.org/10.1111/sed.12666
5. J. Martí, G. Groppelli, A. Brum da Silveira, Volcanic stratigraphy: A review. *Journal of Volcanology and Geothermal Research* 357, 68–91 (2018). https://doi.org/10.1016/j.jvolgeores.2018.04.006
6. W. Ning, T. Kusky, L. Wang, B. Huang, Archean eclogite-facies oceanic crust indicates modern-style plate tectonics. *Proceedings of the National Academy of Sciences of the United States of America* 119, e2117529119 (2022). https://doi.org/10.1073/pnas.2117529119
7. A. L. Lewis, B. Sarkar, P. Wade, S. J. Kemp, M. E. Hodson, L. L. Taylor, K. L. Yeong, K. L. Davies, K. Nelson, M. I. Bird, I. B. Kantola, M. D. Masters, E. DeLucia, J. R. Leake, S. A. Banwart, D. J. Beerling, Effects of mineralogy, chemistry and physical properties

of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. *Applied Geochemistry* 132, 105023 (2021). https://doi.org/10.1016/j.apgeochem.2021.105023
8. R. Daniswara, Y. Firmansyah, R. M. Ganjar Gani, I. Syafri, Geologi daerah Desa Karangtengah dan sekitarnya, Babakan Madang, Bogor. (2020). https://doi.org/10.24198/pgj.v4i6.32199
9. X. Dupla, R. Claustre, E. Bonvin, I. Graf, R. C. Le Bayon, S. Grand, Let the dust settle: Impact of enhanced rock weathering on soil biological, physical, and geochemical fertility. *Science of the Total Environment* 954, 176297 (2024). https://doi.org/10.1016/j.scitotenv.2024.176297
10. K. V. Cashman, R. S. J. Sparks, How volcanoes work: A 25 year perspective. *Geological Society of America Bulletin* 125, 664–690 (2013). https://doi.org/10.1130/B30720.1
11. B. Morrison-Evans, E. Melekhova, J. Blundy, Experimental insight into basaltic andesite lava dome oxidation textures at La Soufrière, St Vincent. (2024). https://doi.org/10.1144/SP539-2022-298
12. M. Baïsset, L. Labrousse, A. Schubnel, J. Gasc, K. Béneut, M. Guillaumet, Rheology of hydrated plagioclase at lower crustal conditions: Cataclasis, creep and transformational plasticity. *Journal of Structural Geology* 178, 105010 (2024). https://doi.org/10.1016/j.jsg.2023.105010
13. M. Toderaş, R. I. Moraru, C. Danciu, G. Buia, L. I. Cioca, Model to assess the quality of magmatic rocks for reliable and sustainable constructions. *Sustainability* 9(10), 1925 (2017). https://doi.org/10.3390/su9101925
14. A. Andreas, A. Putra, Perbandingan karakteristik batuan beku erupsi Gunung Gamalama dan Gunung Talang. *Jurnal Fisika Unand* 7, 293–298 (2018). https://doi.org/10.25077/jfu.7.4.293-298.2018
15. I. Bali, A. Ahmad, C. Lopulisa, Identifikasi mineral pembawa hara untuk menilai potensi kesuburan tanah. *Jurnal Ecosolum* 7(2), 81–100 (2018). https://doi.org/10.20956/ecosolum.v7i2.5126