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RESEARCH ARTICLE

Basaltic Lava Characteristic in Goa Pandan Area, Sukadana, East Lampung: Inferences from Stratigraphy and Petrography Analysis

Happy Christin Natalia [1]*, Andreas Maruli Pakpahan[1], Hissy Ijitiha Sari[1], Bilal Al Farishi[1], Angga Jati Widiyatama[1], Risky Martin Antosia[2], Nono Agus Santoso[2]

[1] *Engineering Geology, Institut Teknologi Sumatera, Jl. Terusah Ryacudu, Way Huwi,, Kabupaten Lampung Selatan, Lampung 35365, Indonesia.*
[2] *Engineering Geophysic, Institut Teknologi Sumatera, Jl. Terusah Ryacudu, Way Huwi,Kabupaten Lampung Selatan, Lampung 35365, Indonesia.*

* Corresponding author: happy.natalia@gl.itera.ac.id
Tel.:+62-877-275-333-67
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Abstract

The presence of extensive basalt formations in East Lampung has its own attractions in the field of geology, particularly the presence of Goa Pandan as a lava cave and tourist attraction in East Lampung. The presence of basalt lava in the southern part of the South Sumatra Basin has drawn attention to the presence of this lava, but detailed research on the characteristics of the lava and its formation process is still very rare. This study aims to determine the eruption period of the basalt lava and magma evolution process based on the correlation between lava stratigraphy and petrography analysis. Field observations show a lava sequence that forms Goa Pandan. Each lava sequence is characterized by autobreccia and vesicular structures on the surface. In addition, the presence of columnar joints, sheeting joints, massive lava, and other additional structures indicate the characteristics of low-viscosity basalt lava. The presence of mineral structures and abundance under the microscope clearly shows the magma formation process when basalt lava flowed on the surface. Resorption-overgrowth of plagioclase and pyroxene minerals indicates an open system when basalt lava flowed on the surface. In addition, the presence of zoning and patching in plagioclase minerals indicates that magma variability is influenced by temperature. The documentation of this lava stratigraphy can serve as a basis for further understanding of magma characteristics and formation processes. There is still much geological work that can be done in the research area to get a detailed picture of the evolution process of magma and the presence of basalt lava in this area.

Keywords: *Goa Pandan, sequence lava, stratigraphy, Sukadana, lava characteristics.*

1. Introduction

Quaternary magma activity in Indonesia is closely related to the subduction process that has been started since the Mesozoic era (Gasparon, 2005). This tectonic activity results in a range of volcanoes that span from the west coast of Sumatra to the southern part of Java Island, turn aside in the eastern part of Banda Sea, and continue to the northern part of Sulawesi. The volcanic range is well known as the *Ring of Fire* and it consists of 127 active volcanoes (Center for Volcanology and Geological Hazard Mitigation, 2015). The Quaternary volcanoes in Sumatra generally have a stratovolcano morphology type which is characterized by basaltic to rhyolitic magma types, although basaltic and diorite are occasionally found (Bellon et al., 2004; Gasparon, 2005). However, an interesting phenomenon found in Girimulyo Village, East Lampung, was the widespread basalt plain without the stratovolcano feature. This basalt rock is known as the Quaternary Basalt Sukadana (Qbs) (Mangga et al., 1993, 1994). The Basalt Sukadana covers an area of about 1,000 km^2 in East Lampung Regency, with a lava thickness of 2-3 m (Figure 1).

The presence of basalt in East Lampung was first recorded in the geological investigation conducted by van Bemmelen in 1949 (Gasparon, 2005). This raises an interesting question regarding the origin and formation process of the volcanic rock due to its different lava characteristics compared to the lava in Sumatra and Java. In Girimulyo Village, the basalt lava forms a relatively long lava cave with an average height of 1.5-2 m and is known as Goa Pandan. The presence of a lava cave attracts researchers to study the stratigraphy of basalt lava in Goa Pandan because of its different composition and formation process compared to other caves in Indonesia, which are usually formed by the dissolution of limestone. Gasparon (1993) refers to this basalt plain as the Sukadana Plateau, which has a similar character to the basalt plain in areas such as Hawaii, Australia, Korea, Kenya, India, the United States, etc (Greene et al., 2004; Kim et al., 2020; NPS, 2022; Ray et al., 2011; Reidel, 2003; Verma & Khosla, 2019).

Since 2019, the Lampung Province government has submitted the establishment of the Krakatau-Way Kambas geopark area, and one of the proposed geosite locations is Goa Pandan (Natalia et al., 2021). Goa Pandan was a popular tourist destination visited by both local and national tourists due to its cave exploration attractions. However, this activity stopped when the pandemic occurred in 2020. Therefore, the local government hopes for efforts to develop the scientific and tourist values of Goa Pandan to be part of the geosite. The scientific value of a geosite can be determined based on the location that represents the geological framework, key research locations, scientific understanding, geological conditions, geological diversity, and geosite distribution in a region (Badan Geologi, 2017; Natalia et al., 2021).

To provide a feasibility assessment in Goa Pandan's area, volcanostratigraphy research has been carried out to give detailed information about the volcanic eruption and magma characteristics. In addition, volcanostratigraphy data can be used as a piece of primary information to create a volcanic hazard map. According to Martodjojo and Djuhaeni (1996), a correlation of stratigraphy at several observation points is needed to determine the relationship of stratigraphy formation in the study area. Providing supplement information for geosite assessment, the aims of this research are to determine the eruption period of the basalt lava and magma evolution process based on the correlation between lava's stratigraphy and petrography analysis.

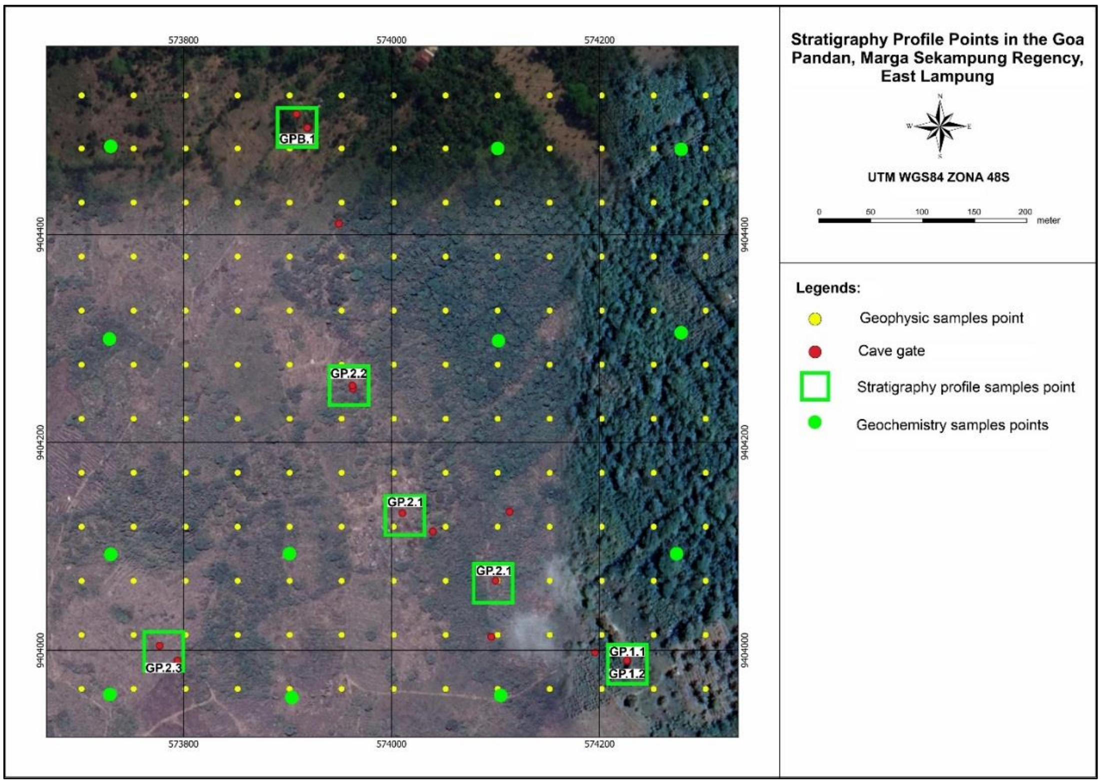

Fig 1. Location points for observation of stratigraphic profile and petrographic data collection in the Goa Pandan area.

2. Regional Geology

Sumatra is located along the boundary of the Eurasian and Indo-Australian plates, which has been undergoing subduction since the Mesozoic era with a rate of 6-7 cm/year (Gasparon, 2005; Hall, 2009; Metcalfe, 2017). This subduction has resulted in a chain of volcanoes along the western edge of Sumatra and in the southern part of the island (Hall, 2009). According to Gasparon (Gasparon, 1993, 2005), volcanic activity in southern Sumatra is more intense compared to the northern part. In southern Sumatra, the occurrence of volcanoes is believed to be from the Semangko Fault and the pull-apart basin in the Sunda Shelf. The existence of these two structures makes southern Sumatra an extensional regime, which results in large silicic pyroclastic and subordinate andesitic and basaltic eruptions (Barber & Crow, 2005a; Gasparon, 2005). The pull-apart basin also has an N35°E strike-slip direction that extends through Panaitan, Gunung Anak Krakatau, Pulau Sebesi and Sebeku, Gunung Rajabasa, and Sukadana (Gasparon, 2005; Susilohadi et al., 2009).

Gasparon (2005)wrote that the basalt lava that appears in Sukadana is the result of effusive eruptions during the post-orogenic stage related to tensional stress along NW-SE fissures in the Pleistocene (Barber, Crow, & Milsom, 2005; Barber & Crow, 2005b; Susilohadi et al., 2009). Some previous researchers have said that the basalt in Sukadana is an intra-plate and back-arc basin magmatic rock and has intermediate characteristics between Mid Ocean Ridge Basalt (MORB) and Oceanic Island Basalt (OIB) (Gasparon, 1993; Zulkarnain, 2011). Despite having the same characteristics as the andesite volcanic arc, such as other volcanoes in Sumatra. Based on isotopic and chemical analyses conducted by Gasparon (1993), the basalt lava was produced from several shallow mantle melting events.

According to a study by Mangga et al., (1994) and Gasparon (1993), the age of the basalt in the study area is 1.5 to 0.01 Ma (Pleistocene). In the Tanjung Karang map description, Mangga et al. (1994) state that the basalt is composed of about 5% phenocryst olivine, and the groundmass shows a phyric or vitro-phyric texture. For the local community, the vesicular basalt is known as "batu keriting." In a study on the potential site in Lampung Timur, Sukadana Basalt is a rock that composes the Pugung Raharjo historical site (Natalia et al., 2021).

Basalt plateau creates low-relief hills and spread along 1.000 km. The previous research said that the basalt lava in the study area came from rifting of the back-arc basin in South Sumatra that create the South Sumatra Basin (Barber, Crow, & De Smet, 2005; Bellon et al., 2004; Gasparon, 1993; Soeria-Atmadja & Noeradi, 2005; Susilohadi et al., 2009). Cruden & Weigen (2018) said that strike-slip faulting can be the main factor that creates fissures for lava migrates to the surface.

The presence of a lava cave in Girimulyo Village, East Lampung, has different formation processes than other caves in Indonesia. Based on Cox et al. (1979) and Cruden & Weinberg (2018), a lava cave can build when molten lava on the surface cools down but the interior lava is still in a hot liquidus phase. This molten lava will migrate through the interior lava and make a tube inside the igneous rock. Lava cave features like this are common in the Hawaii area with effusive processes along weak bands extending across the surface (Cruden & Weinberg, 2018). This unique lava plateau is also present in Deccan Trap, India (Ray et al., 2011). Some researcher did their study in this area and said that the basalt lava in Deccan Trap is a product of a plume mantle that arose to the surface through the cracks (Cruden & Weinberg, 2018; Ray et al., 2011). Besides the uncommon lava feature in Girimulyo Village, the lava stratigraphy profile depicts interesting information about the eruption period in the study area. Based on McPhie et al. (1993), an effusive eruption will be characterized by one lava sequence which consists of autobreccia, columnar joint, sheeting joint, and massive lava.

3. Methods

This research used 2 main methods in geology, there are observation fields and petrography analysis. Detailed information about the step by step during the study and methods used can be seen in Figure 2.

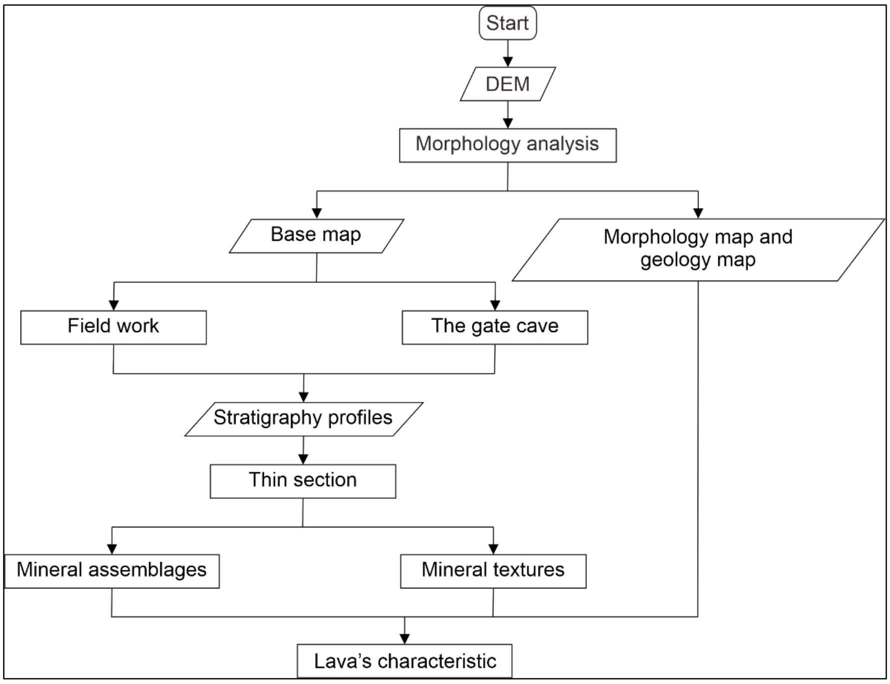

Fig 2. Flowchart describe the step-by-step in this research and show the methods used in this study.

3.1 Field observation

The eight outcrops of the effusive product were observed and a stratigraphic profile was created at the easily accessible cave entrances (Figure 1). Based on the lava sequence model by McPhie et al. (1993), each sequence was differentiated by the presence of auto-breccia or vesicle structures within each lava sequence, which shows a different time of formation (Figure 4). The different lithological characteristics were categorized based on visual inspection of the primary lava structures, mineral assemblages, and textures of the volcanic products, following non-genetic and non-stratigraphic schemes used by McPhie et al. (1993). The association of single or multiple-eruption units is referred to as an eruption episode.

The distribution of lava is heavily influenced by the topography of the volcanic area and fissure distribution. Lava fields are the main geologic feature in Eastern Lampung with shield-like formations. Eight key stratigraphy profiles were used to connect different volcanic products and create a representative stratigraphic section (Figure 2). The observation points are presented in UTM (Universal Transverse Mercator) coordinates, using the WGS (World Geodetic System) Datum 1984 for the southern hemisphere (Figure 8).

3.1. Petrography Analysis

Seven lava samples were analyzed petrographically to identify their name, mineral assemblages, texture, and structure (Figure 2). The analysis was performed at the Petrology Laboratory of the Geological Engineering Department at the Institut Teknologi Sumatra with a polarizing microscope. The rock classification of the petrographic samples was determined by evaluating the presence of primary minerals in the rock samples using and IUGS (Le Bas & Streckeisen, 1991) classifications. The rock structure was also studied to gain insight into the evolution of magma during the eruption of lava to the surface (Cox et al., 1979; Jerram et al., 2018; Nakamura & Shimakita, 1998) (Figure 6).

4. Results

The results of the geological mapping in Girimulyo Village, East Lampung showed that the study area has a shield shape and consists of ten units of volcanic rocks (Figure 7). This was determined based on the radial distribution of lava from the highest point, which is considered the center of the eruption. The lava in the area was found to have two sets of sequences, based on its characteristics. The analysis revealed that each sequence contains five main components, such as auto-breccia, vesicles, joints, massive lava, and accessory lava, the profile of which can be seen in Figure 4. The description of each sequence is based on the stratigraphic order, detailing the lava characteristics, mineral compositions, and the lithofacies classifications assigned to them.

4.1. Geomorphology

Based on the morphology map in DEM (Figure 3) and field observation, the research area has some dome morphology. It can be divided into three morphology units: High Plan Volcano, Plateau Volcanic, and Volcanic Dome. The report from the geological students in Girimulyo Village shows that the research area consists of ten volcanic unit lithologies and the lithology unit in the study area comes from Mount Duren eruption (Figure 7). The rock distribution is determined by the radial pattern from the high elevation that assumes as the central lava eruption.

The result of stratigraphic correlation gives information that the lava in the research area exhibits a complete lava sequence as described by McPhie et al. (1993) (Figure 8). The main texture and structure of the rocks show five primary characteristics of lava, namely autobreccia, vesicular, joints, massive lava, and accessory lava, which can be seen in Figure

3. The description of the lava sequence is based on the stratigraphic arrangement, texture, and structure of the rocks, also mineral composition (Figure 6).

4.2. Lava Sequence

The lava sequence (Sl) represents a single period of lava eruption observed in this study (Figure 8). The lava sequence is characterized by five main lava structures and textures with indistinct contacts and gradual yet distinct changes, which can be observed in each cave. One of the primary locations that exhibit complete lava structures and textures is Goa Pandan (GP1.1). Autobreccia is the first structure found on the surface of the aa lava in the research area, displaying fragments of lava ranging from small fragments to large blocks (1-5 cm). The presence of autobreccia indicates that the lava surface cooled faster than its interior, causing the surface to contract and break as the hot lava flows beneath the Earth’s crust (McPhie et al., 1993). Meanwhile, on the cave ceiling, sheeting joints are found, which characterize the lava flow on the surface.

At several observation points at cave entrances, such as Goa Kubah (GP2.1) and Goa Pandan (GP1.2), columnar joint structures were found. These structures have a height of 20-30 cm and exhibit a hexagonal shape with a surface diameter of 10-12 cm (Figure 9). Loockwood & Hazlett (2010) stated that these columnar joints are formed due to surface cooling of the lava resulting from contraction and vertical conduction of heat. As a result, the horizontal planes of the columnar joints always indicate the direction of perpendicular cooling to the lava flow.

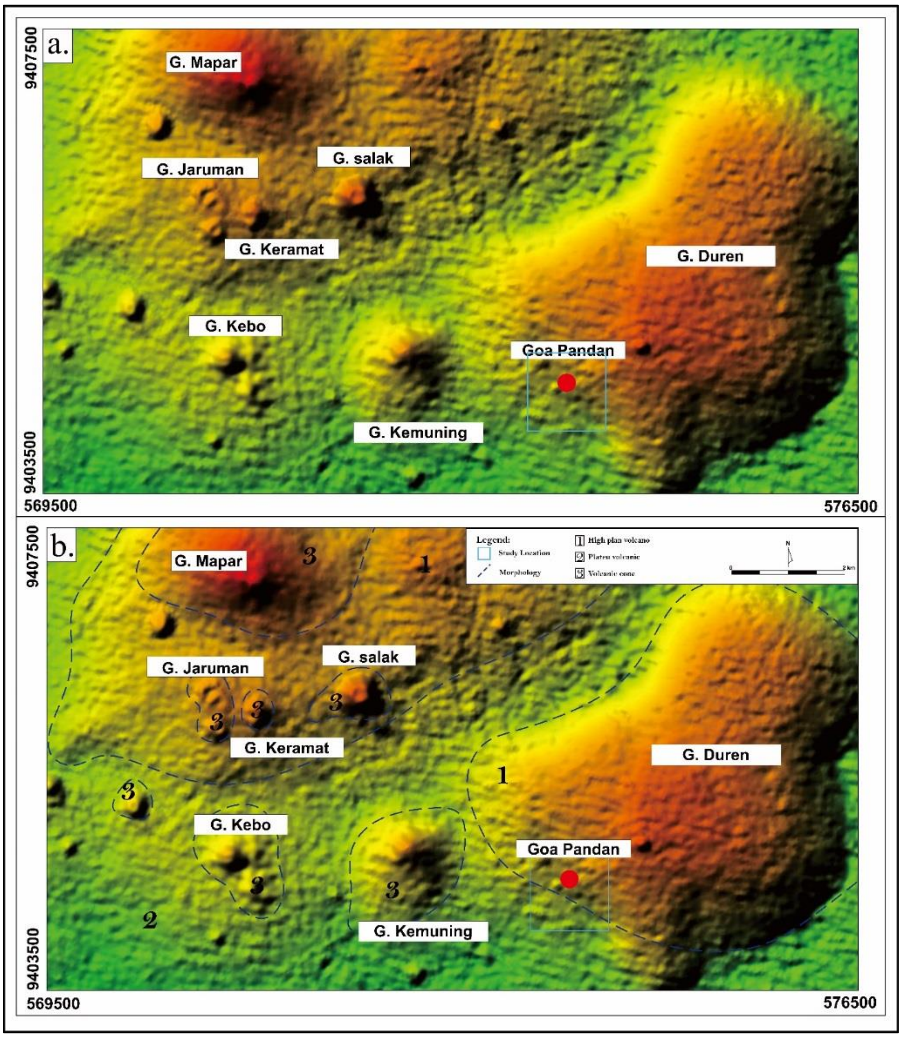

Fig 3. The presence of Sukadana basalt in the research area is marked by a blue box. The research area has several high-elevation points that are believed to be the centers of basalt lava eruptions (a). Topographic analysis shows that the research area has 3 main morphologies: volcanic highlands, volcanic plains, and volcanic cones (b). The stratigraphy and distribution of basalt rocks in the Sukadana area can be seen in point c. There are 10 volcanic units that originated from two main eruption points, namely Mount Mapar and Mount Duren.

In addition to columnar joints, some cave entrances display layers of lava known as sheeting joints. The presence of sheeting joints at cave entrances is typically associated with autobreccia and vesicularity with lava layers thickness ranging from 5-10 cm (Figure 4). Sheeting joints are also found on the lower parts of cave walls (Figure 4). According to the model developed by McPhie et al. (1993), the presence of layered cracks on the top and bottom of a lava sequence indicates the formation process of lava when it was formed at the surface.

At the bottom of the sheeting joint, massive lava with a porphyritic-aphanitic rock texture was found. Generally, the thickness of the massive lava in Goa Pandan reaches 110 m, but at certain locations, vesicular structures were found alternating with the massive lava (Figure 4, 8). The lava structures still indicate that the interior of a lava body experienced a longer duration of cooling, allowing some mineral crystals to form phenocrysts.

Vesicular structures are the dominant features that appear throughout the rock stratigraphy in every observed lava outcrop in the study area, exhibiting various shapes and sizes. The distribution, texture, and size of these vesicles are influenced by the duration of magma cooling and the rate of gas released from the lava as it cooled on the surface (Figure 5), as stated by McPhie et al. (1993).

In general, throughout the study area, there are two main forms of vesicular structures, namely pipe vesicles and spongy vesicles. Pipe vesicles can be found on the surface of the lava, along with autobreccia. Furthermore, their distribution and size decrease with increasing depth into the caves (Figure 5), such as Goa Pandan and Goa Pilar (GP.1.1, GP.2.1, and GPB.1) (Figure 8). According to McPhie et al. (1993), the presence of pipe-vesicles indicates a rapid gas release before the lava cools on the surface.

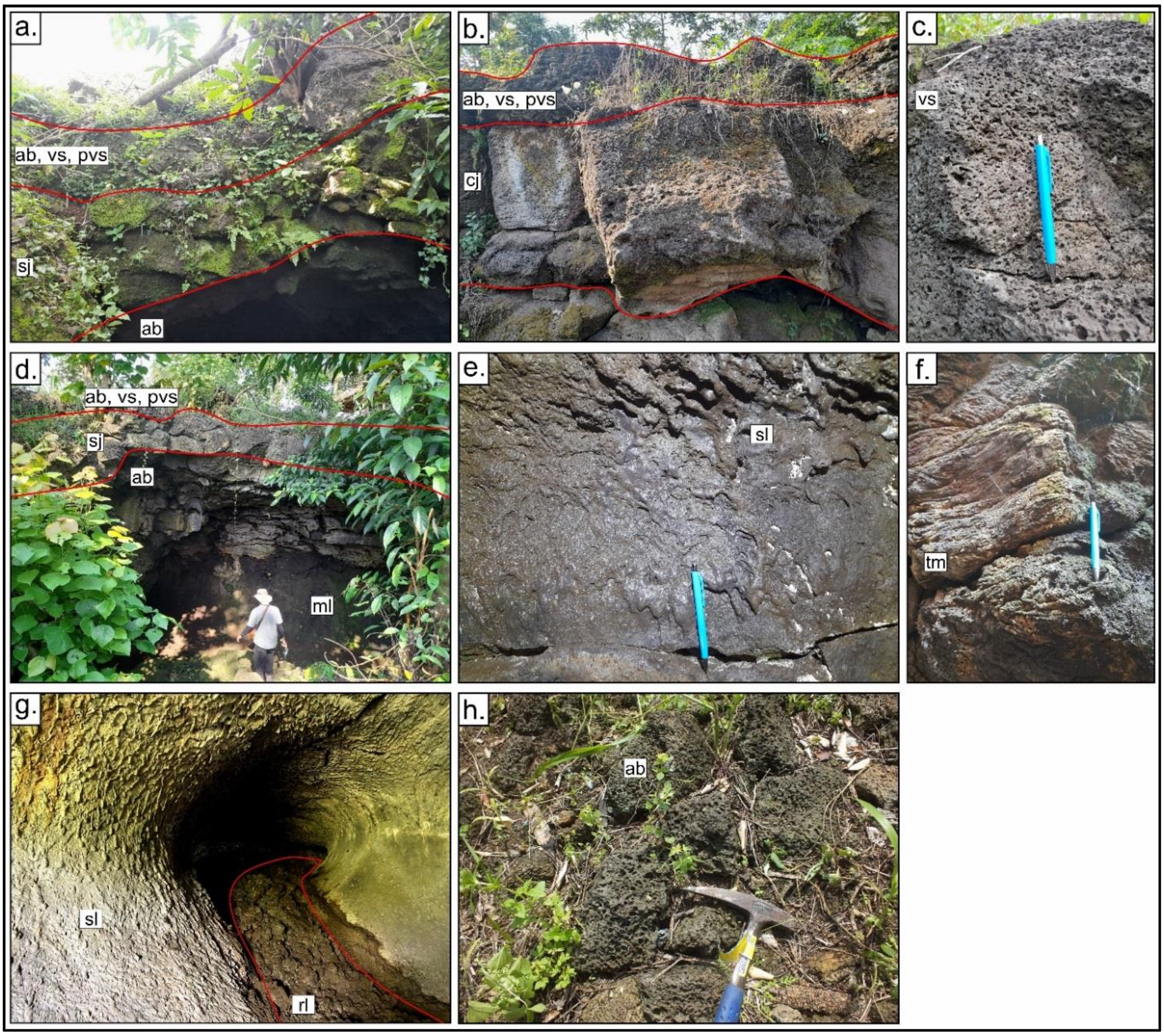

Fig 4. Exposure of lava in cave mouths. The entrance of Goa Pandan shows the appearance of vesicular lava on the surface and lava layers in the subsequent layer (a and b). In addition, a crust texture was found on the roof of Goa Pandan (d). The appearance of lava at GP 1.2 shows a layer of lava with a vesicular texture on the surface, but the next layer shows a columnar joint with a height of 40-50 cm (b). The vesicles found on the surface of the lava show a spongy and pipe shape with a vesicular diameter of 5-7 cm. Other lava textures found in the research area include lava stalactites (e) and mounds found on the cave wall (f).

Additionally, the research area also features abundant spongy vesicles in every observed lava outcrop (Figures 6 and 5). The spongy vesicles have a circular or spherical shape and can be found in various profiles, including Goa Kelelawar (GP.2.3). Similar to pipe vesicles, the presence and size of sponge vesicles decrease with increasing depth. This information is quantitatively summarized in Figue 6, which shows the ratio of vesicular presence to the total rock.

Additionally, tumuli and lava stalagmites are found in several outcrops (Figure 5). Tumuli can be seen at the entrance of the cave at GP.1.2 and are characterized by pockets of residual lava hanging on the walls of the cave's mouth. It is created as a result of the upper layer of lava expanding due to hot lava flowing beneath it (as described by Walker in McPhie et al., 1993). Lava stalagmite, on the other hand, is found in Goa Kubah (GP 2.1 and GP 2.2) and is characterized by streams of cooled lava hanging from the ceiling of the cave and attaching to its walls (Figure 4). The presence of stalactite lava indicates the rapid lowest temperature of lava in the wall (Loockwood & Hazlett, 2010).

As the final stage of lava cooling, Goa Kubah (GP 2.1 and GP 2.2) exhibits the presence of aa lava, with a higher intensity of lava fragments compared to autobreccia on the cave surface (Figure 4). This eruption point is identified by the rising lava floor that almost reaches the cave walls. The presence of aa lava at the end of a lava sequence indicates a change in viscosity, with the lava becoming increasingly viscous during a particular eruptive period.

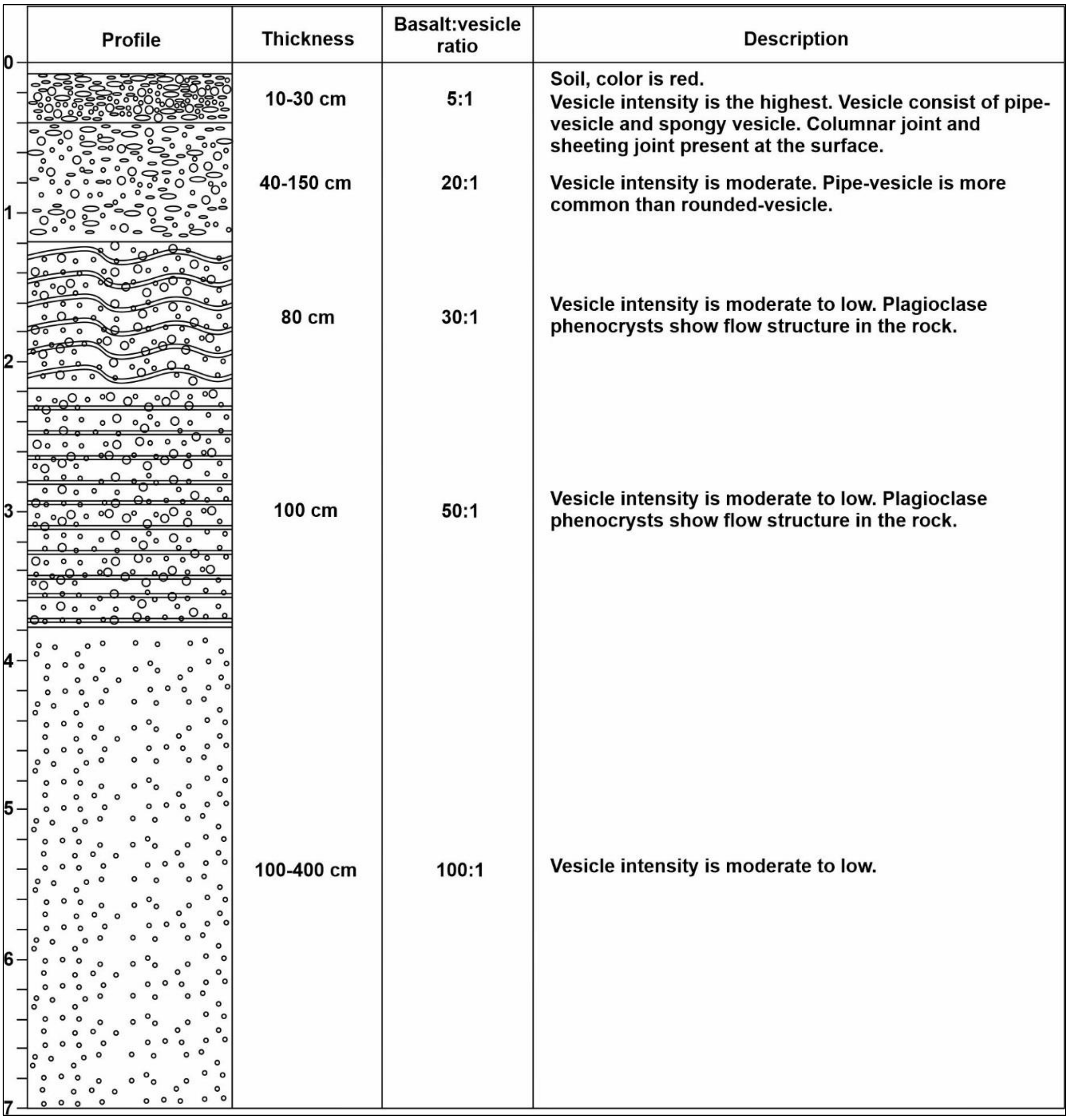

Fig 5. Characteristic abundance and vesicular form profile found in the research area. On the surface, pipe and spongy vesicular forms were found, with a 5-7 cm diameter and dominant abundance within the rock. As the depth increases, the abundance of vesicles decreases.

4.3. Petrographic Analysis

Generally, rock samples show a porphyritic texture with phenocrystic abundance from 40 to 50%. Phenocrysts have grain sizes from 0,05 to 1,25 mm. Plagioclase and olivine become dominant phenocrysts in each rock sample. Phenocrystic minerals are present as individual crystals or glomeroporphyritic aggregates. The aggregates consist of a combination of plagioclase, clinopyroxene, orthopyroxene, and olivine. Commonly present aggregates are plagioclase, clinopyroxene, and olivine (Figure 7).

The groundmass consists of micro-sized plagioclase and pyroxene with a little volcanic glass. The rock structure that characterizes the flow in each sample is the presence of intersertal and intergranular between plagioclase phenocrystic minerals. In addition, an intersertal between plagioclase minerals and olivine is also found (Figure 7).

Plagioclase is the dominant mineral that is present as phenocrysts and groundmass in each rock sample. Corrosion or sieve texture is commonly found in plagioclase. In addition, plagioclase is also found to be present together with olivine and pyroxene in a glomeroporphyritic texture. The type of plagioclase found in basalt samples ranges from anorthite to labradorite (An_{82-56}) indicating the type of plagioclase from labradorite to andesine. Olivine is a mafic mineral that is the main phenocryst in each rock sample with mineral sizes of 0.25-1.5 mm, even in some samples olivine is found as groundmass together with plagioclase (Figure 7).

In some rock samples, the presence of olivine that has been rimmed by iron oxide (Fe-Ti) or pyroxene minerals is seen, giving a brownish appearance on the mineral boundary. Clinopyroxene is present as a phenocryst with a greater proportion and larger size than orthopyroxene (Figure 6).

Pyroxene present as a phenocryst has a lower abundance compared to olivine. However, pyroxene is abundant as groundmass and also rims olivine. Some pyroxene minerals have a sieve appearance characterized by corrosion formation in the center of the crystal. Some pyroxene mineral observations show polysynthetic twins (Figure 7). In some thin-section samples, orthopyroxene is more abundant than clinopyroxene (Figure 6).

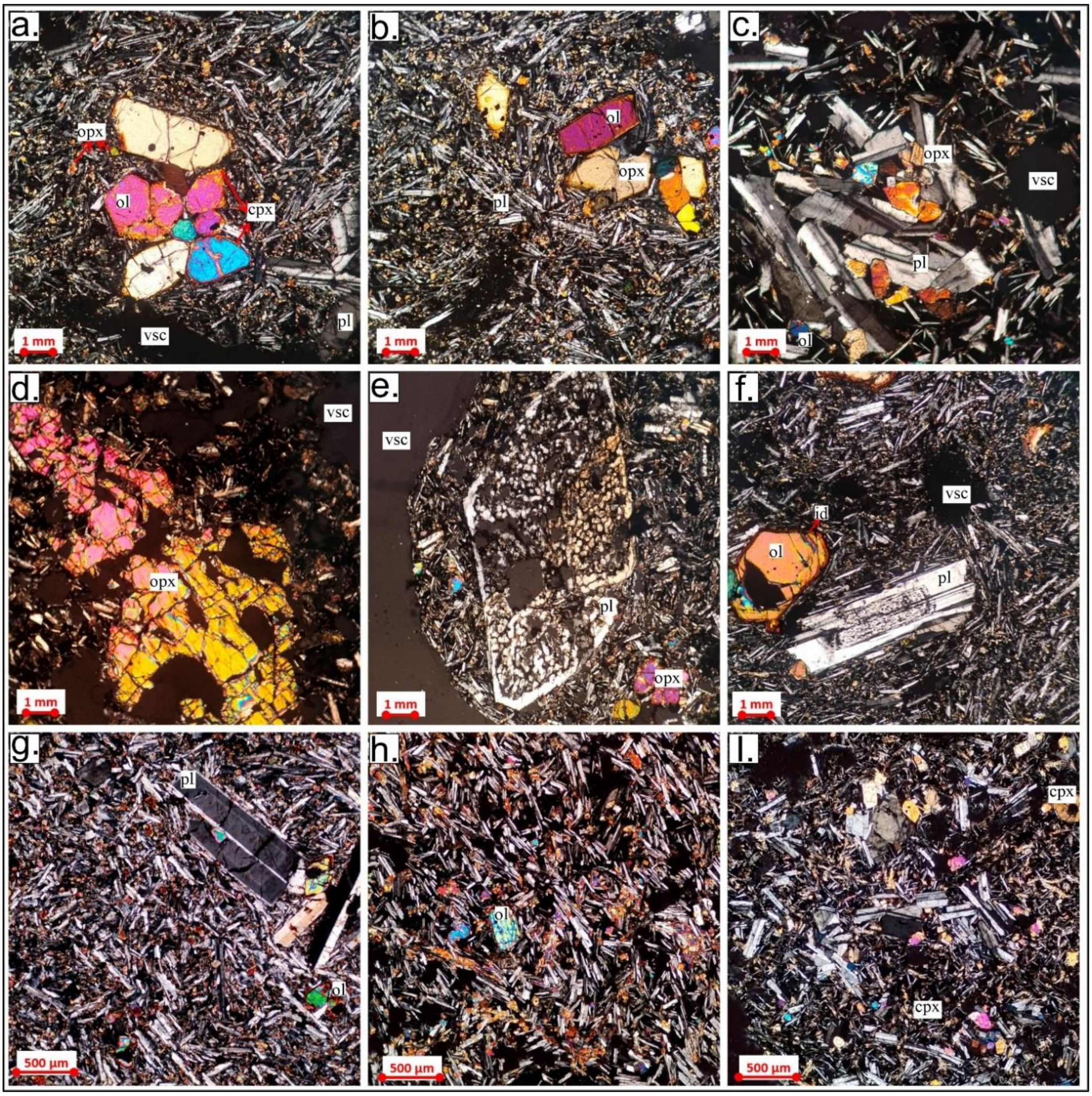

Fig 6. Texture and structure within basalt rock. Glomeroporphyritic texture is formed between minerals olivine (a), pyroxene+olivine+plagioclase (b), and orthopyroxene+plagioclase+olivine (c). Intersertal texture can be observed in the presence of plagioclase minerals (b and i). Orthopyroxene-overgrowth texture (d) and plagioclase (e and f). The form of plagioclase absorption leaves behind plagioclase shells, and the plagioclase's edge is filled with andesine-type plagioclase (e). The base of basalt is characterized by plagioclase, olivine, and pyroxene minerals that show a trachytic texture (g-i).

5. Discussion

Field observations indicate that the basaltic lava in the research area is a flood lava field, generated during a single eruption period from Gunung Duren (at 1.01 Ma) (Gasparon, 2005). Another piece of evidence indicating that the basaltic lava in Sukadana originates from the same eruption period is the consistent relationship between the entrances of the caves based on geoelectric data conducted by Antosia et al. (2023).

Morphological analysis and stratigraphic correlation indicate that the lava in the Sukadana region is a large volume of flood lava. Research conducted by Walker (1993 in Sigurdsson, 2000) states that floodplain basalt can occur in rifting crustal or fissures, allowing hotspot material to rise to the earth's surface. This basalt lava can create new and extensive landforms. Additionally, some eruption sources can be characterized by the presence of cinder, spatter, and agglutinate (Sigurdsson, 2000).

The flood basalt in the research area is characterized by the presence of a complete lava sequence, which is marked by vesicular texture, columnar joints, sheeting joints, tumuli, and autobreccia (Figure 8). Even though drilling by residents has revealed multiple lava layers beneath the surface, a comprehensive lava profile can generally be observed in Goa Pandan. Furthermore, at certain points, basaltic lava demonstrates increased viscosity due to cooling, gas loss, and rapid crystallization over time (Cas & Wright, 1987). This is evident in the presence of aa lava over pahoehoe lava in Goa Kelelawar (GP2.3).

Low-viscosity basaltic lava allows for the lava flow to extend far from the eruption source. The initial formation of pahoehoe lava indicates a high concentration of gas within the lava flow, characterized by numerous pipe and spherical-shaped vesicular textures on the lava surface. Changes in vesicular shapes within the lava layers indicate variations in cooling rates during the lava flow. Additionally, the presence of columnar joints in certain cave entrances suggests that lava cooling occurred relatively slowly, leading to surface tension in the lava and the formation of sigmoidal patterns on the lava surface.

Furthermore, the lava creates empty spaces in the interior, with a height of 2 m. These empty spaces are known as lava tubes, indicating different stages of lava cooling. The basalt lava surface, with its low viscosity and direct contact with the atmosphere, cools first. Meanwhile, the inner part of the lava remains molten and continues to flow, leaving behind lava cavities. In this case, large-sized lava tubes are referred to as lava caves (NPS, 2022; Peterson & Swanson, 1974 in Cas & Wright, 1987). The same process also occurs in the formation of tumuli. The cooling lava surface then becomes like a lava pocket when the hot liquid lava leaves its original shape.

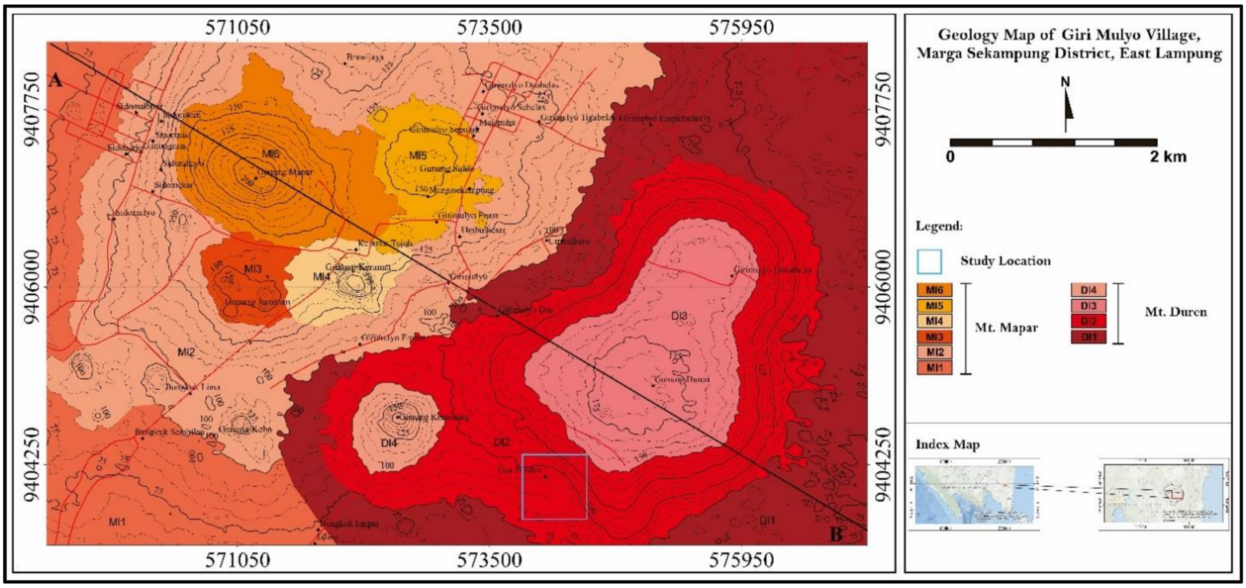

Fig 7. Geological map in the research area shows the flood plain basalt and some eruption center. There are 10 lithology units in the Sukadana Basalt. The basalt in the research came from Gunung Duren eruption.

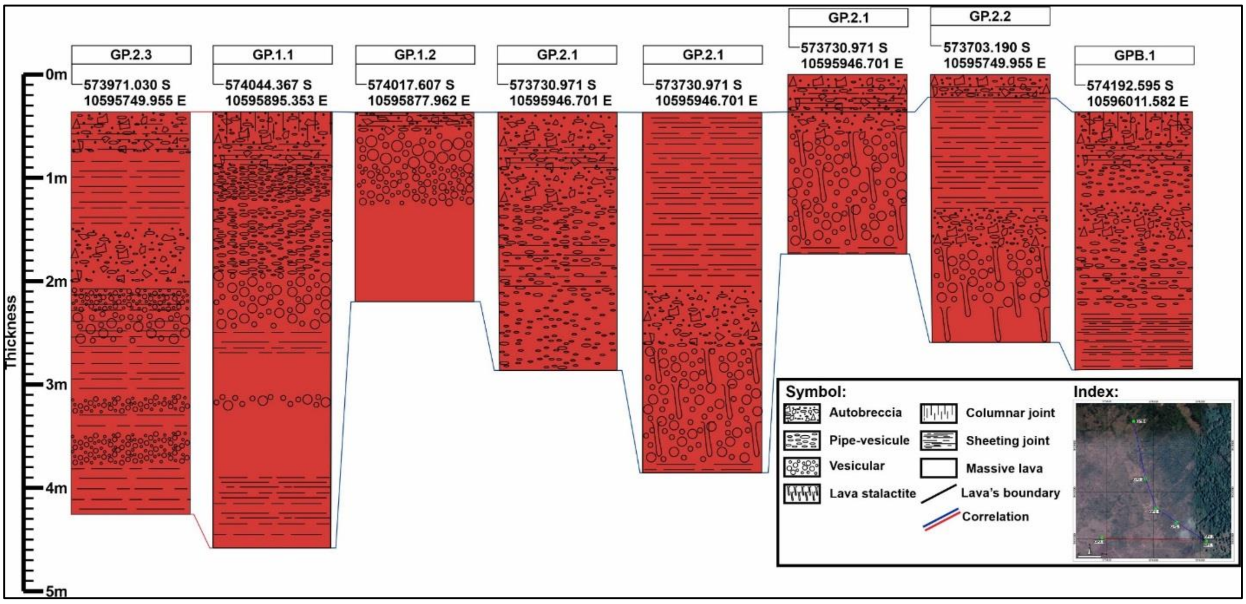

Fig 8. Lava stratigraphy correlation from eight point in the study area. Generally, all of profile show the common lava flow in the surface, such as vesicle texture and autobreccia. However, some profile show detail subaerial lava sequence. The lava cave is generated by one lava basalt eruption.

Petrographic analysis of the basalt rock reveals that the magmatic processes in this area exhibit an open system. This evidence is observed in the form of corroded textures in plagioclase, which can appear irregular and overlapping or display cellular or vermicular appearances with melt inclusions (Nakamura & Shimakita, 1998). These textures result from changes in magmatic conditions experienced during crystal growth, such as heating, melt hydration, or decompression. Once the magma enters the reservoir, it continues to differentiate through cooling, convection, decompression, and replenishment with fresh magma. Partial dissolution of the crystal exterior is indicated by excessive growth of Ca-rich plagioclase on the crystal surfaces. These textures align with the findings of Nakamura & Shimakita (1998), who believed that these textures arise from dissolution-recrystallization processes. Irregular or vermicular cores and euhedral clear edges are formed under different conditions and stages, through heating, hydration, or decompression.

The texture of resorption-overgrowth in pyroxene crystals also indicates open system processes. Anhedral and rounded cores in pyroxene suggest that they underwent resorption. Resorbed cores are only found in reversely zoned clinopyroxene. Iron-rich cores are characterized by embayed morphology and uneven interfaces with the mantle, indicating the absorption of iron-rich pyroxene (Svetov et al., 2020). Dissolution surfaces within pyroxene are formed in response to external factors such as an increase in temperature above the liquidus, compositional changes (including oxygen fugacity), or decompression. Some pyroxene minerals undergoing resorption show the presence of iron oxide mantle minerals and orthopyroxene. The mantle indicates normal zoning with polygonal growth zones, indicating a gradually evolving melt composition during cooling. The coexistence of clinopyroxene coated by orthopyroxene, as well as normal and inverted zoning of clinopyroxene in the same sample, reflects a wide variation. This texture can be explained by heating and a change in melt composition, in which the clinopyroxene was first resorbed and then overgrown by orthopyroxene (Incel et al., 2022).

Changes in temperature, water content, or chemical composition of ambient magma can lead to evolving core resorption and excessive growth of less developed mantles in plagioclase and pyroxene. The presence of multiple layers of excessive dissolution-growth textures in plagioclase indicates repeated changes in magmatic conditions, while the lack of such layers in other minerals suggests a faster rate of chemical diffusion (Cox et al., 1979; Nishimura et al., 1986). Olivine originates from the mafic end member. The repeated heating and cooling of mafic magma reservoirs is a result of repeated injections or recharge of high-temperature mafic magma.

The presence of mafic minerals and rock textures in each petrographic sample indicates that magmatic activity in the research area is closely related to the presence of northwest-southeast fault orientation during the Late Pleistocene (Susilohadi et al., 2009). The presence of these structures allows for partial melting od the crust to migrate into reservoirs and become magma in magma pockets.

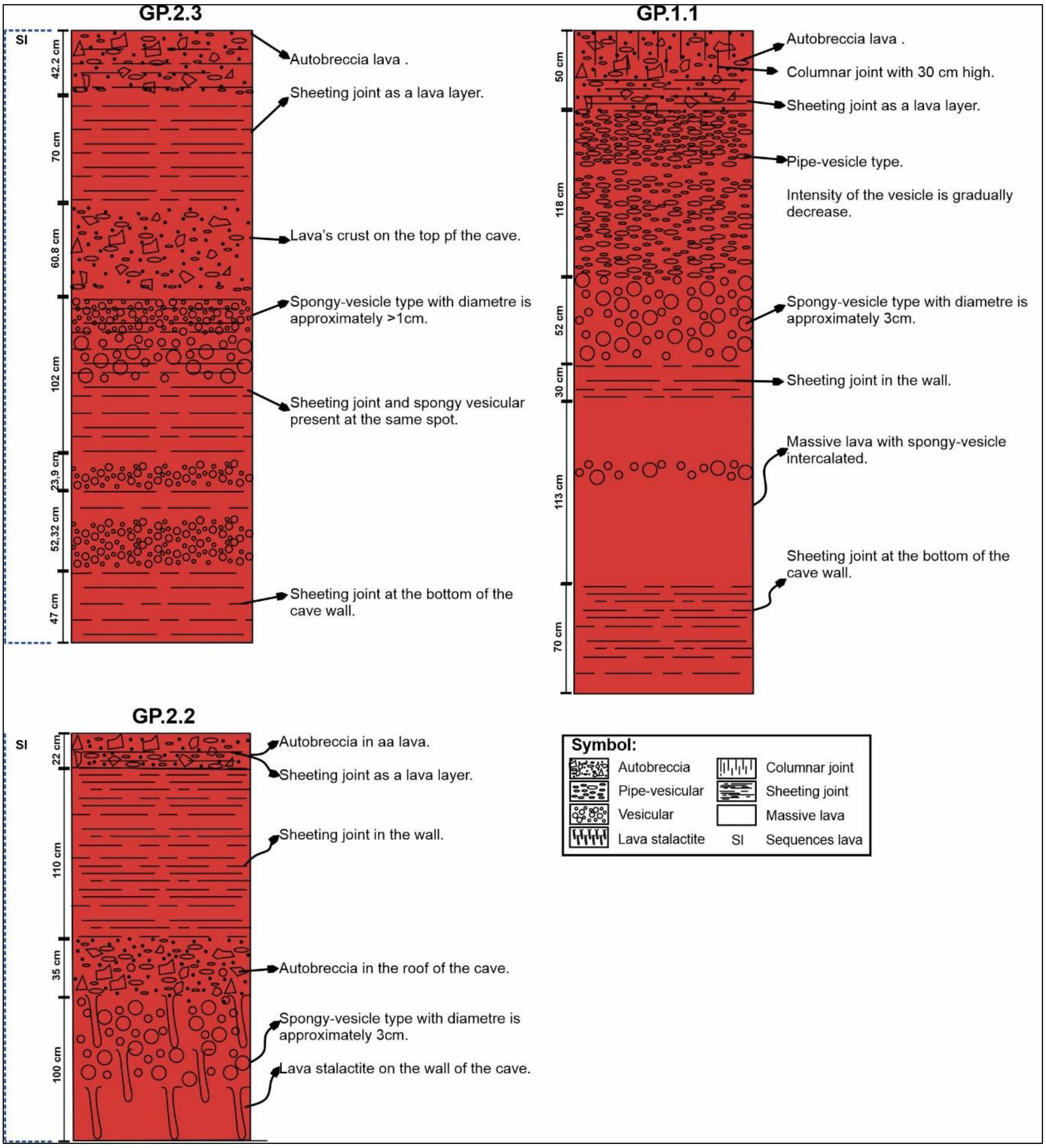

Fig 9. Detailed composite stratigraphy with complete structure in Goa Pandan area.

6. Conclusion

Based on the field research and petrography results, the following conclusions can be drawn:

1. Stratigraphic correlation at each cave entrance indicates a complete sequence of lava, which is the main characteristic of a single period of the surface lava flow.
2. The open system magmatism in the research area indicates the activity of structures that developed concurrently with the formation of magma within the magma chamber.

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References

Antosia, R. M., Akbar, H. H., Santoso, N. A., Putri, I. A., Farishi, B. A., & Natalia, H. C. (2023). Underground-caves connectedness preview using the geoelectrical profiling method as an effort to revive natural tourism in "Gua Pandan," East Lampung Regency. *IOP Conference Series: Earth and Environmental Science*, *1173*(1), 012072. https://doi.org/10.1088/1755-1315/1173/1/012072

Badan Geologi. (2017). Petunjuk Teknis Asesmen Sumber Warisan Geologi. In *Pusat Survei Geologi*. Pusat Survei Geologi.

Barber, A. J., & Crow, M. J. (2005a). Pre-Tertiary Stratigraphy. In A. J. Barber, M. J. Crow, & J. S. Milsom (Eds.), *Sumatra: Geology, Resources, and Tectonic Evolution* (Vol. 31, pp. 24–53). The Geological Society. http://mem.lyellcollection.org/

Barber, A. J., & Crow, M. J. (2005b). Structure and structural history. In A.J. Barber, M.J. Crow, & J.S. Milsom (Eds.), *Sumatra: Geology, Resources, and Tectonic Evolution* (pp. 175–233). The Geological Society. http://mem.lyellcollection.org/

Barber, A. J., Crow, M. J., & De Smet, M. E. M. (2005). Tectonic Evolution. In A.J. Barber, M.J. Crow, & J.S. Milsom (Eds.), *Sumatra: Geology, Resources, and Tectonic Evolution* (pp. 234–258). The Geological Society. http://mem.lyellcollection.org/

Barber, A. J., Crow, M. J., & Milsom, J. S. (2005). Tectonic Evolution. In *Sumatra: Geology, Resources and Tectonic Evolution* (Vol. 31, pp. 234–259). www.geolsoc.org.uk.

Bellon, H., Maury, R. C., Soeria-atmadja, R., Cotten, J., & Polvé, M. (2004). long magmatic activity in Sumatra (Indonesia), from Paleocene to Present. In *Bull. Soc. géol. Fr* (Issue 1).

Cas, R. A. F. (Ray A. F.), & Wright, J. V. (John V.). (1987). *Volcanic successions, modern and ancient : a geological approach to processes, products, and successions*. Allen & Unwin.

Center for Volcanology and Geological Hazard Mitigation. (2015). *MAGMA Indonesia*. Geological Agency. https://magma.vsi.esdm.go.id/

Cox, K. G., Bell, J. D., & Pankhurst, R. J. (1979). *THE INTERPRETATION OF IGNEOUS ROCKS*. Chapman & Hall. https://telegram.me/Geologybooks

Cruden, A. R., & Weinberg, R. F. (2018). Mechanisms of Magma Transport and Storage in the Lower and Middle Crust—Magma Segregation, Ascent and Emplacement. *Volcanic and Igneous Plumbing Systems: Understanding Magma Transport, Storage, and Evolution in the Earth's Crust*, 13–53. https://doi.org/10.1016/B978-0-12-809749-6.00002-9

Gasparon, M. (1993). *Origin and evolution of mafic volcanics of Sumatra (Indonesia): their mantle sources, and the roles of subducted oceanic sediments and crustal contamination. STATEMENT*.

Gasparon, M. (2005). Quaternary volcanicity. In A.J. Barber, M.J. Crow, & J.S. Milsom (Eds.), *Sumatra: Geology, Resources and Tectonic Evolution* (pp. 120–130). The Geological Society. http://mem.lyellcollection.org/

Greene, A. R., Scoates, J., & Weis, D. (2004). Flood basalts of the Wrangellia Terrane, southwest Yukon: Implications for the formation of oceanic plateaus, continental crust and Ni-Cu-PGE mineralization characterization of RM View project. *Yukon Exploration and Geology*, 109–120. https://www.researchgate.net/publication/254854292

Hall, R. (2009). The Eurasian SE Asian margin as a modern example of an accretionary orogen. *Geological Society Special Publication*, *318*, 351–372. https://doi.org/10.1144/SP318.13

Incel, S., Milke, R., & Wunder, B. (2022). Orthopyroxene rim growth during reaction of (Co, Ni, Mn, Zn)-doped forsterite and quartz: Experimental constraints on element distribution and grain boundary diffusion. *Mineralogy and Petrology*, *116*(2), 137–149. https://doi.org/10.1007/s00710-022-00773-3

Jerram, D. A., Dobson, K. J., Morgan, D. J., & Pankhurst, M. J. (2018). The petrogenesis of magmatic systems: Using igneous textures to understand magmatic processes. In *Volcanic and Igneous Plumbing Systems: Understanding Magma Transport, Storage, and Evolution in the Earth's Crust* (pp. 191–229). Elsevier. https://doi.org/10.1016/B978-0-12-809749-6.00008-X

Kim, J., Lin, S.-Y., & Oh, J.-W. (2020). Quaternary Lava Tubes Distribution in Jeju Island and Their Potential Deformation Risks. *Natural Hazards and Earth System Sciences*. https://doi.org/10.5194/nhess-2020-321

Le Bas, M. J., & Streckeisen, A. L. (1991). The IUGS systematics of igneous rocks. *Journal of the Geological Society*, *148*(5), 825–833. https://doi.org/10.1144/gsjgs.148.5.0825

Loockwood, J. P., & Hazlett, R. W. (2010). *Volcanoes Global Perspectives*. Wiley-Blackwell.

Mangga, S. A., Amiruddin, Suwarti, T., Gafoer, S., Tobing, S., Sidarto, & Andra, A. (1994). *Geologi Lembar Tanjungkarang, Sumatera*.

Mangga, S. A., Amirudin, Suwarti, T., Gafoer, S., & Sidarto. (1993). *PETA GEOLOGI LEMBAR TANJUNG KARANG, SUMATERA*.

McPhie, J., Doyle, M., & Allen, R. (1993). *Volcanic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks*. University of Tasmania.

Metcalfe, I. (2017). Tectonic evolution of Sundaland. *Bulletin of the Geological Society of Malaysia*, *63*, 27–60. https://doi.org/10.7186/bgsm63201702

Nakamura, M., & Shimakita, S. (1998). Dissolution origin and syn-entrapment compositional change of melt inclusion in plagioclase. *Earth and Planetary Science Letters*, *161*(1–4), 119–133. https://doi.org/10.1016/S0012-821X(98)00144-7

Natalia, H. C., Harbowo, D. G., & Ikhram, R. (2021). Potensi Geodiversity di Sekitar Kawasan Anak Krakatau-Way Kambas, Provinsi Lampung, Sebagai Kandidat Geopark Indonesia. *Journal of Science and Applicative Technology*, *5*(1), 47–57. https://journal.itera.ac.id/index.php/jsat/article/view/318

Nishimura, S., Nishida, J., Yokoyama, T., & Hehuwat, F. (1986). Neo-tectonics of the Strait of Sunda, Indonesia. *Journal of Southeast Asian Earth Sciences*, *1*(2), 81–91. https://doi.org/10.1016/0743-9547(86)90023-1

NPS. (2022). *Lava Caves/Tubes - Caves and Karst (U.S. National Park Service)*. https://www.nps.gov/subjects/caves/lava-caves-or-tubes.htm

Ray, J., Sen, G., & Ghosh, B. (2011). Topics in igneous petrology. In *Topics in Igneous Petrology*. Springer Netherlands. https://doi.org/10.1007/978-90-481-9600-5

Reidel, S. P. (2003). *Geologic mapping of the Columbia Basin View project*. https://www.researchgate.net/publication/320625543

Sigurdsson, H. (2000). *Encyclopedia of Volcanoes*. Academic Press.

Soeria-Atmadja, R., & Noeradi, D. (2005). Distribution of early tertiary volcanic rocks in south Sumatra and west Java. *Island Arc*, *14*(4), 679–686. https://doi.org/10.1111/j.1440-1738.2005.00476.x

Susilohadi, S., Gaedicke, C., & Djajadihardja, Y. (2009). Structures and sedimentary deposition in the Sunda Strait, Indonesia. *Tectonophysics*, *467*(1–4), 55–71. https://doi.org/10.1016/J.TECTO.2008.12.015

Svetov, S. A., Chazhengina, S. Y., & Stepanova, A. V. (2020). Geochemistry and texture of clinopyroxene phenocrysts from paleoproterozoic picrobasalts, karelian craton, fennoscandian shield: Records of magma mixing processes. *Minerals*, *10*(5). https://doi.org/10.3390/min10050434

Verma, O., & Khosla, A. (2019). Developments in the stratigraphy of the Deccan Volcanic Province, peninsular India. *Comptes Rendus - Geoscience*, *351*(7), 461–476. https://doi.org/10.1016/j.crte.2019.10.002

Zulkarnain, I. (2011). Geochemical Evidence of Island-Arc Origin for Sumatra Island; A New Perspective based on Volcanic Rocks in Lampung Province, Indonesia. *Jurnal Geologi Indonesia*, *6*(Desember), 213–225.