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Magma Evolution of Ngebel Volcano, Ponorogo, East Java, Indonesia

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Abstract - The magma evolution of Ngebel Volcano, both temporally and spatially, is represented by the characteristics of its lava. Ngebel Volcano, located in East Java, is a Quaternary andesitic stratovolcano. This volcano is part of the Wilis Volcanic Complex. The volcanism stage of Ngebel Volcanic Complex can be divided into the Jeding with andesitic basalt (SiO_2 49 - 59%), pyroxene andesite Kemlandingan (SiO_2 49 - 59%), Manyutan with hornblende andesite (SiO_2 49 - 59%), and Ngebel with dacite (SiO_2: 49 - 59%). The variation of major elements combined with petrographic features such as plagioclase, pyroxene, hornblende, quartz, and opaque minerals from basaltic andesite to dacite is interesting. The minerals show that the magma differentiation process of Ngebel Volcanic Complex is the results of fractional crystallization of magma. The purpose of this study is to determine the evolution of magma from volcanic rocks of which stratigraphic positions have been determined. The analytical methodology used is petrographic and geochemical analysis. Detailed temporal evolution shows that magma from the Ngebel Volcanic Complex underwent a differentiation process that changed the magma composition from mafic to more felsic.

Keywords: volcano, lava, magma, evolution, Ngebel, Ponorogo

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Introduction

Background

Ngebel Volcano is part of the Wilis Volcanic Complex of the Sunda Arc. The volcanoes in Sunda arc from the west to the east of Java grow with a distinctive volcanism style. Several geothermal fields are located within the Early Quaternary caldera, overgrown by Pleistocene volcanic structures (Setijadji, 2010). This volcanoes were resulted from the subduction process between the Eurasian and Australian Plates (Hariyono and Liliasari, 2018) on the southern side of Indonesia. This subduction is still ongoing today. The subduction has started since the Oligocene-Miocene to the present at a rate of 6 to 7 cm per year (Lallemand, 2016). Along the arc, many volcanoes are active and have erupted to date. Ngebel Volcano is a type B (Volcanological Survey Indonesia, 2021). The Ngebel stratovolcano consists of four volcanic centres from old to young age including Jeding Volcano, Kemlandingan Volcano, Manyutan Volcano, and Ngebel Volcano. Some of the eruptions of Ngebel Volcano produce pyroclastic rocks and lava. Changes in the composition of magma will affect the type of volcanic eruption. The more felsic the magma, the more explosive eruptions are likely to occur. This is like what happened in Ijen Volcano, which is composed of basaltic andesite to dacite (Hinsberg *et al*., 2017; Berlo *et al*., 2020). The study of magma composition is significant for volcanic monitoring to predict future volcanic hazards.

Several studies have been carried out on several volcanoes concluding that changes in the volcanic magma complex can be caused by fractional crystallization, such as in the Gorely Volcano in the southern of Kamchatka Peninsula, forming several composite volcanic centres. The fractional crystallization process leads to changes in magma composition from several volcanic composite centres (Gavrilenko *et al*., 2016). Therefore, to understand it further, in this study, mineralogical and petrochemical studies of the volcanic rocks of the Ngebel Volcano Complex were conducted. This research was conducted to determine the evolution of magma from volcanic rocks whose stratigraphic position has been determined.

Geology of the Ngebel Volcano

The Ngebel Volcano Complex (NVC) is located about 900 m above sea level. Physiographically, it is located in the Solo Zone, according to Bemmelen (1949). The Solo Zone is occupied with Quaternary volcanic mountains (Bemmelen, 1949; Hartono, 1994), which stretch from west to east. This zone is the result of plate subduction between India-Australia and the Eurasian continental plate (Asikin, 1974; Hamilton, 1979) occuring from the Eocene era to the present. This impact resulted in the Quaternary volcanic range where the studied site is located. The volcanic range shows a similar calc-alkaline affinity with Late Eocene-Pliocene volcanic mountains in the south (Soeria-Atmadja *et al*., 1994). In addition, the pattern of volcanic alignment follows the pattern of Java geological structure, which is west-east oriented (Pulunggono and Martodjojo, 1994). According to Smyth *et al*. (2008), the cycle of magmatic arc activity in East Java (Figure 1) started from the Middle Eocene (42 Ma) and ended in the Early Miocene (20 Ma). Meanwhile, the eruption of Mount Wilis occurred during the Lower Pleistocene which formed the Pucangan Formation in the East Java Basin (Bemmelen, 1949).

In Wilis Volcano Complex (WVC), the peaks are found in almost all advantages and can be exploited along the ridges of Mount Liman, Mount Doro, and Mount Argotawang. These had developed from the WVC crater wall and are called the Argokalangan Crater (Verbeek and Fenema, 1896 *in* Hartono 1994). Other morphological forms that are similar and form slopes can be used from Mount Jogopodo through Mount Cemorokandang, Mount Lombok, Mount Malang, Mount Limas, to Gajahmungkur. The valley opens to the north and can be interpreted as a crater. While the NVC is located on the Wilis Volcano Complex side with around 900 m high volcanoes surrounding the lake.

NVC is located in the western part of the Wilis Volcano Complex. Based on lithological variations, NVC is divided into four groups of eruption centres, namely: Klotok, Pawonsewu, Ngebel, and Argokalangan (Hartono, 1994).

Analytical Method

A morphological analysis of the Ngebel volcano was carried out to understand the morphostratigraphy of the volcanic unit. Topographic maps with a scale of 1:45,000 were used to create a Digital Elevation Model (DEM). The stratigraphic unit will be interpreted based on

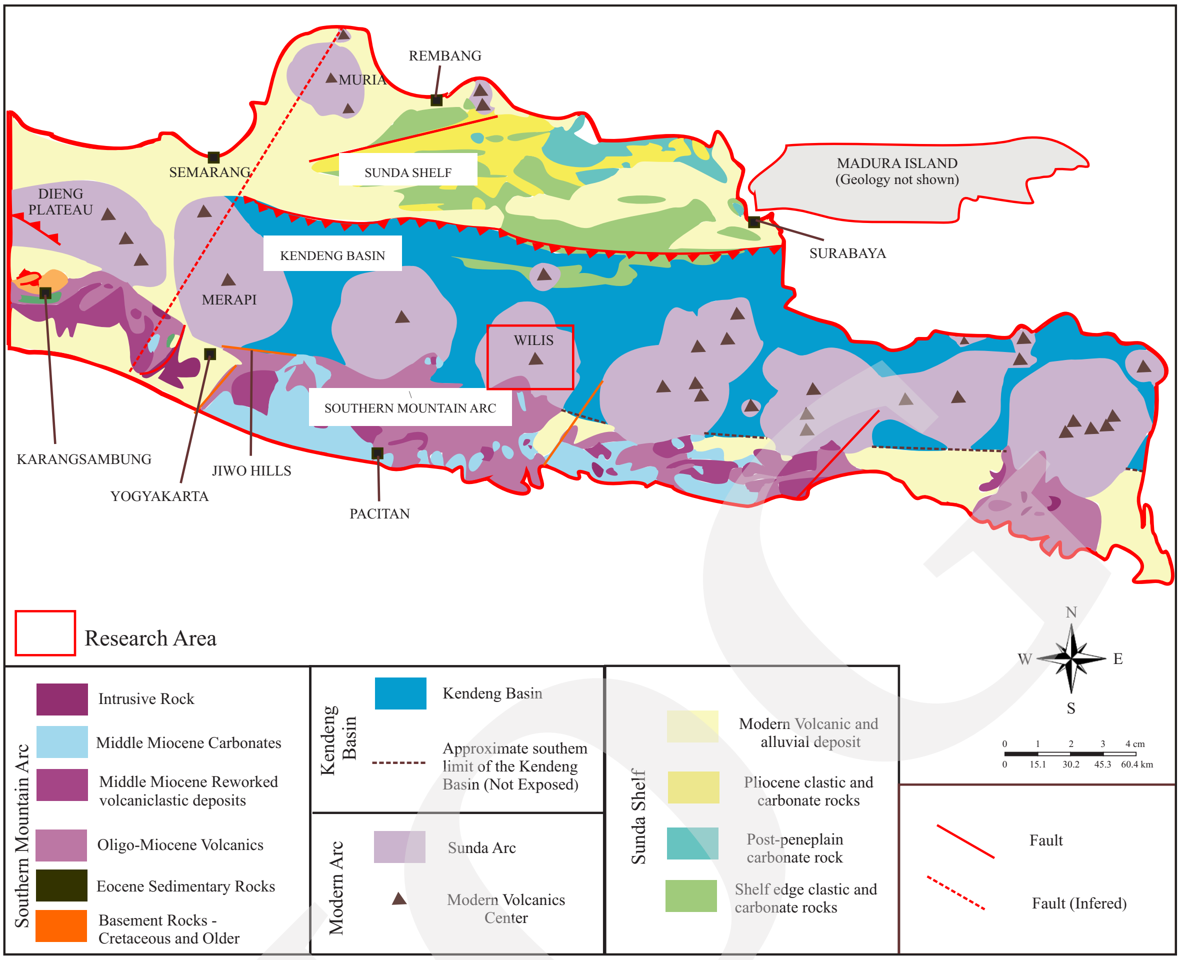


Figure 1. Simplified geological map of East Java, showing the main geological province and stratigraphic units (Smyth *et al.*, 2008).

the DEM map. After the studio works, field data and rock samples were collected from the field and cross-checked for pre-field analysis. For this study, several lava samples from eruption centres were taken representing the Basaltic Andesite of Jeding Volcano, Pyroxene Andesite Kemlandingan Volcano, Hornblende Andesite Manyutan Volcano, and Dacite Ngebel Volcano outcropping around the volcanic complex.

Four lava samples were prepared for petrographic analysis carried out at the Geological Engineering Department of UPN "Veteran" Yogyakarta. Petrographic analysis was carried out on volcanic rock samples, which had previously been sliced 0.03 mm thick, then observed under a polarizing microscope. The analysis was performed to determine the structure, texture, and composition of rocks to study the relationship between minerals in rocks and their genesis. The samples represent groups of volcanic rocks in the studied area. For the naming classification of volcanic rocks, the Williams *et al.* (1982) classification was used

The geochemical analysis was carried out using the X-Ray Fluorescents (XRF) method to determine the major oxides, namely SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5. Then the concentration of these elements was processed using Igpet software. Petrochemical data of these rocks was used to determine the chemical characteristics of the volcanic rocks in the studied area. Seven rock samples that represent the igneous rock groups in the researched area were used for XRF analysis. The analysis was carried out at the Bandung Institute of Technology.

Results

Stratigraphy of NVC was determined using morphological analysis. The stratigraphic sequence from oldest to youngest eruption centres is Jeding Volcano and Kemlandingan Volcano. Manyutan Volcano and Ngebel Volcano are each divided into sixteen rock units, as shown in Figure 2. The relative age of each unit was determined using the law of superposition (Yudiantoro *et al*., 2021).

Petrographic Analysis

The four selective samples of lava representing volcanic rock in the studied area were analyzed. These samples generally showed pilotaxitic, glomeroporphyritic, and intergranular textures. These samples generally showed pilotaxitic, glomeroporphyritic, and intergranular textures. The phenocrysts in lava are related to lava viscosity. Lava that is more viscous tends to form dome with a slower cooling rate compared to lava flows. Crystallization of crystal formation becomes more intensive and produce more phenocrysts. According to Hasibuan *et al.* (2020), all lavas have porphyritic texture, similar phonocryst size, and groundmass characteristics, but vary in phenocryst assemblages. The types of igneous rocks found in the studied area, are Jeding basaltic andesite, Kemlandingan pyroxene andesite, Manyutan hornblende andesite, and Ngebel dacite (Figure 3). The type of volcanic rock is detemined using William *et al.* (1982) classification.

Basaltic Andesite (Jeding Volcano)

Jeding Volcanics consist of basaltic andesite lava, porphyritic and intergranular with pilotaxitic texture. According to Mulyaningsih *et al.* (2020) pyroxene-rich basalt is called basaltic andesite. Phenocryst (52 - 54%) of 0.2 - 1.2 mm - sized comprises plagioclase, pyroxene, and opaque

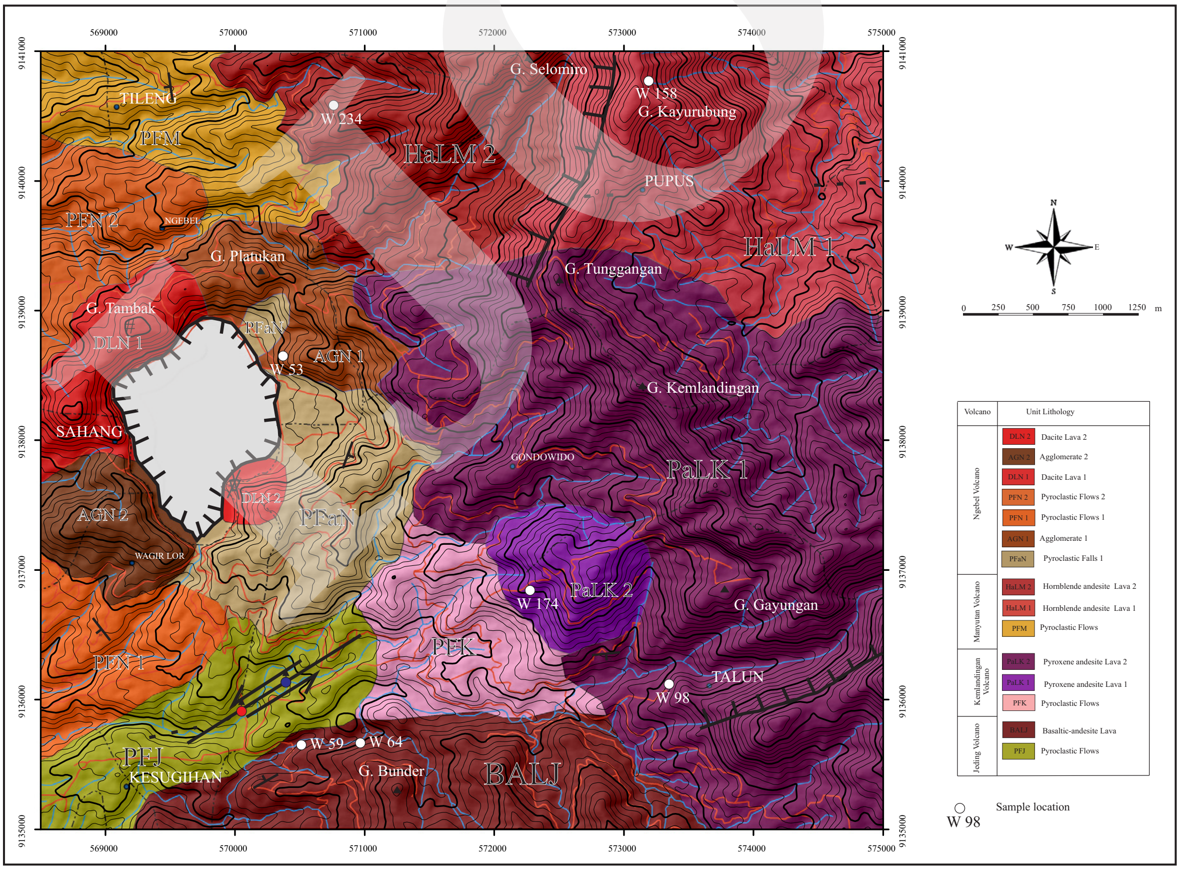
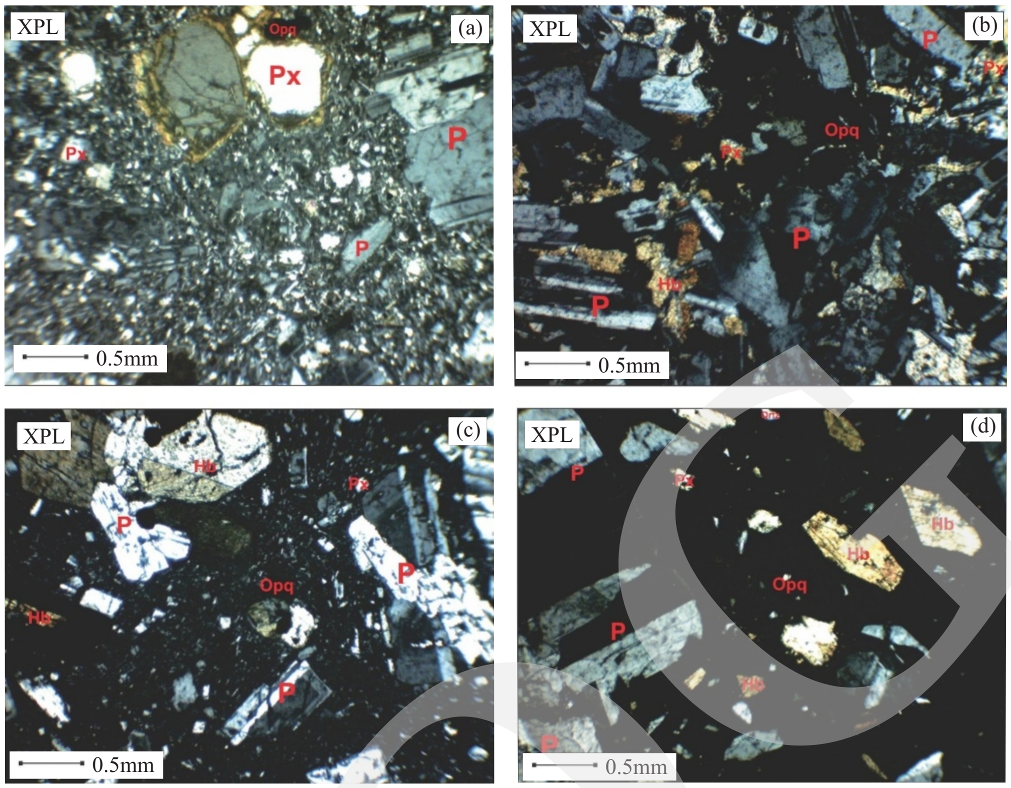


Figure 2. Geological map and sample location of Ngebel Volcano. Volcanostratigraphically, NVC is divided into four volcanoes, from older to younger is Jeding, Kemlandingan, Manyutan, and Ngebel Volcanoes (Yudiantoro *et al*., 2021).



Mineral abbrevariation: Px: Pyroxene; P: Plagioclase; Hb: Hornblende; Opq: Opaque

Figure 3. Photomicrograph of NVC lavas. Each unit has a different mineralogy and petrographic texture a.) Jeding basaltic andesite, b). Kemlandingan pyroxene andesite, c). Manyutan hornblende andesite; and d). Dacite Ngebel.

minerals. Pyroxene has a reasonably large amount of 8 - 11%. Plagioclase has the highest content, in the range of 38 - 42% with the type of labradorite (An64).

Pyroxene Andesite (Kemlandingan Volcano)

The Kemlandingan lava consists of pyroxene andesite with a glomeroporphyritic and intergranular texture. Phenocryst (66 - 77%) of 0.2 - 1.2 mm in size consists of plagioclase, pyroxene, hornblende, and opaque minerals. Plagioclase has the highest content, reaching 38 - 42% Andesine (An46).

Hornblende Andesite (Manyutan Volcano)

Manyutan Volcanics consist of hornblende andesitic lava, with a glomeroporphyritic and intergranular texture. Phenocryst (69 - 72%) having size of 0.2 - 1.2 mm is composed of plagioclase, pyroxene, and opaque minerals. Hornblende has a significant amount, reaching 11 - 14% of the mafic mineral composition. In addition, quartz is present up to 1 - 3%. Plagioclase of andesine (An46) has the highest a mount, up to 38 - 42%.

Dacite (Ngebel Volcano)

Ngebel lava consisting of hornblende dacite type has a glomeroporphyritic and intergranular texture. The lava consists of 64 - 70% phenocrysts of 0.2 - 1.2 mm in size of plagioclase, pyroxene, hornblende, quartz, and opaque minerals. Hornblende has an amount that reaches 13 - 14%. While plagioclase of andesine type has the highest content, reaching 38 - 43%.

Geochemistry

Seven lava samples from each unit were analyzed using the XRF method to obtain geochemical data, as shown in Table 1. This data is used to determine rock classification and magma affinity.

Geochemical data from the lava of the studied area was plotted on the Total Alkali-Silica (TAS) diagram (Le Bas *et al*., 1989) for rock classification. The plotting results show that the composition of NVC lava varies from basaltic andesite to dacite (Figure 4). The rock has a silica content of 52.3 - 64 wt %.

Meanwhile, to determine the series and affinity of magma, the variation diagram of K_2O vs SiO_2 from Peccerillo Taylor (1976) was used as shown in Figure 5. The samples from the area show the calc-alkaline medium-K series.

Tabel 1. Chemical Analysis Data of Major Oxides of Volcanic Igneous Rocks in the Studied Area

No. Sample	W64	W59	W174	W98	W234	W158	W53
Unit Lithology	**Jeding**		**Kemlandingan**		**Manyutan**		**Ngebel**
Name	**Basaltic Andesite**		**Pyroxene Andesite**		**Hornblende Andesite**		**Dacite**
Elemen (wt%)							
SiO_2	52.30	54.90	56.40	56.90	58.40	59.4	64.00
TiO_2	0.62	0.54	0.66	0.61	0.55	0.56	0.42
Al_2O_3	23.3	21.2	20.90	20.00	19.50	18.50	18.70
Fe_2O_3	7.78	7.34	7.15	6.95	6.53	5.23	4.03
MnO	0.16	0.19	0.18	0.16	0.17	0.16	0.11
MgO	1.68	1.69	1.71	1.83	1.40	1.70	0.98
CaO	9.87	9.77	8.3	8.70	8.77	7.94	6.71
Na_2O	2.68	2.64	2.69	2.54	2.50	2.88	3.10
K_2O	1.16	1.1	1.22	1.45	1.45	1.76	1.43
P_2O_5	0,21	0.27	0.25	0.17	0.23	0.22	0.18
norm							
Q	72.51	72.51	70.11	70.11	70.11	67.23	53.97
Or	12.91	15.02	19.41	20.40	22.30	26.96	29.82
Ab	6.26	6.26	6.26	6.32	6.25	6.38	6.17
An	17.92	17.92	17.92	18.09	17.90	18.27	26.51
lc	47.28	47.28	42.02	42.02	41.98	37.48	31.09
di	2.40	0.28	1.15	1.16	0.09	0.97	1.12
wo	10.95	10.95	10.95	9.29	9.19	7.59	3.02
il	2.30	2.30	2.30	2.32	2.30	2.35	2.27

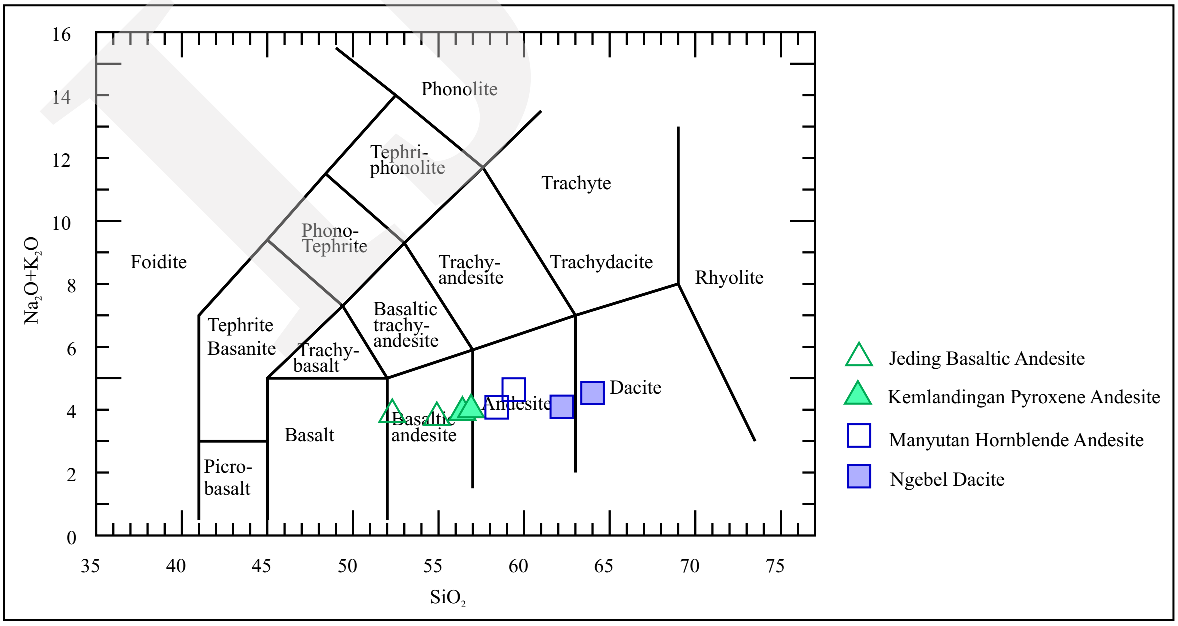


Figure 4. Alkali-Silica (TAS) diagram (Le Bas *et al*., 1989) plot shows rocks type of NVC.

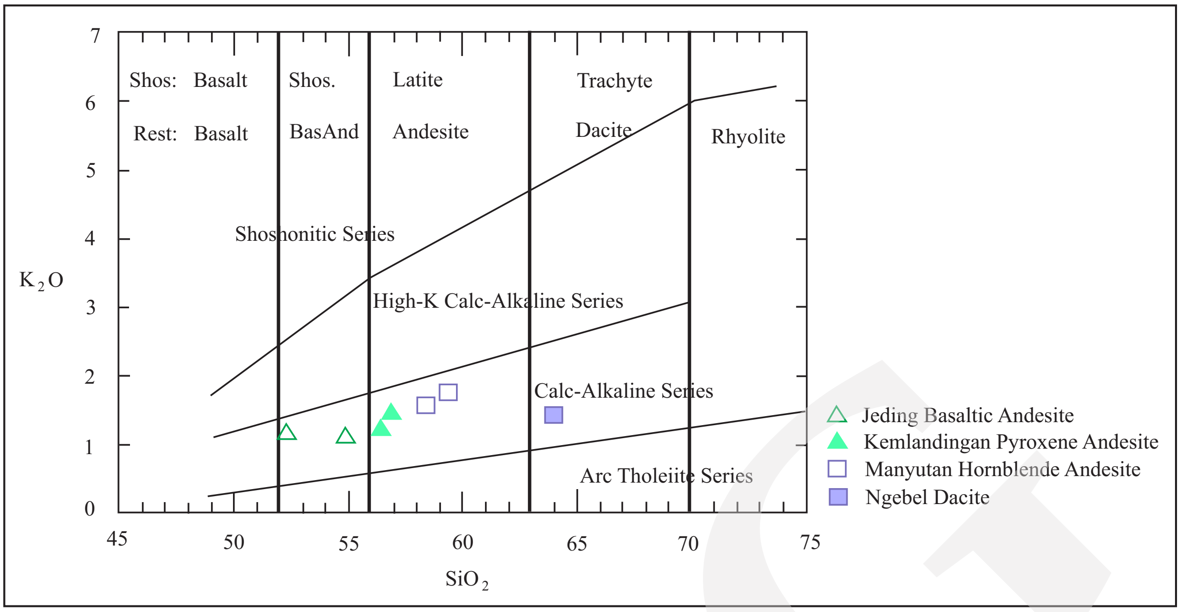


Figure 5. K_2O *vs*. SiO_2 diagram (Peccerillo and Taylor, 1976) plot shows a trend of calc-alkaline series of medium K affinity.

Based on petrographic and geochemical analysis of volcanic rocks in the studied area, the types of volcanic rocks present from the stratigraphic sequence from oldest to youngest are Jeding basaltic andesite lava, Kemlandingan pyroxene andesite, and Manyutan hornblende andesite to Ngebel dacite. The volcanic rocks of NVC are evidence of a fractional crystallization process. The Harker diagram shows that the values of Al_2O_3, Fe_2O_3 (Figure 6a); CaO, MgO (Figure 6b); TiO_2, P_2O_5, and MnO (Figure 6c) from the volcanic rock set decreased with the increase in SiO_2 content,

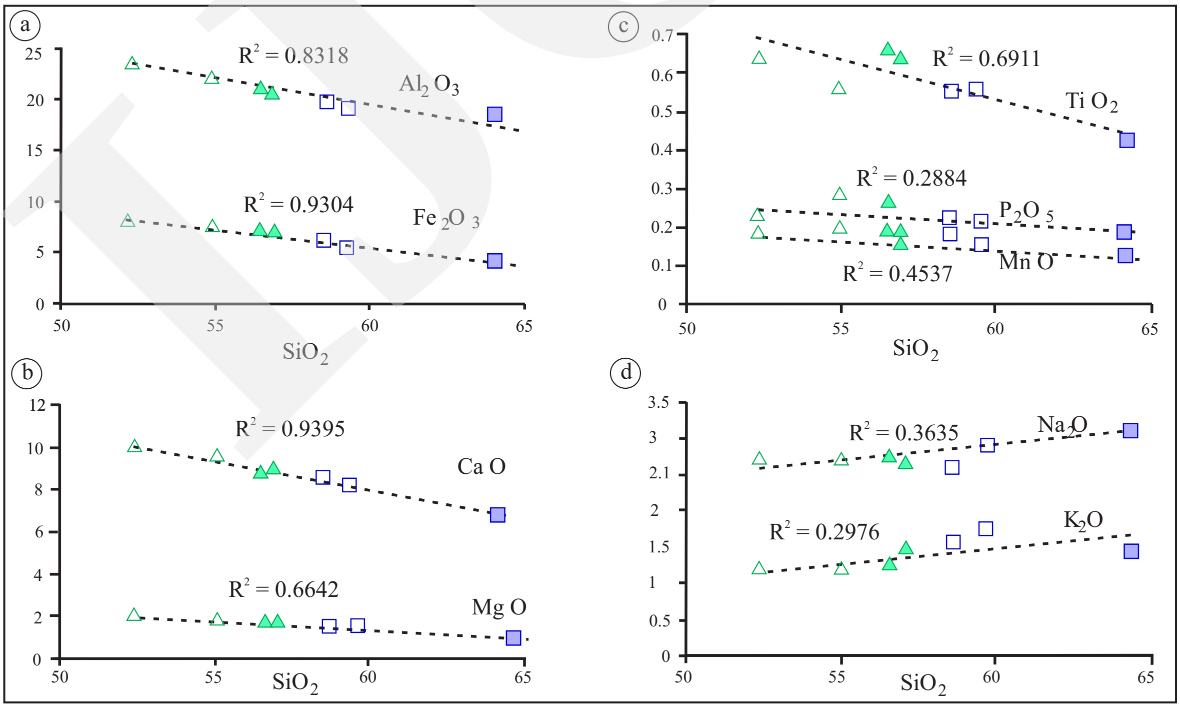


Figure 6. Harker diagram of NVC lava. Diagrams show the linear lines of differentiation of NVC magma indicated by SiO_2 element to other oxide elements.

whereas the elements of K_2O and Na_2O increase ith the increasing SiO_2 (Figure 6d).

During the fractional crystallization process, the major chemical elements of these volcanic rocks formed mafic minerals such as pyroxene and hornblende, and also quartz. The mafic composition will decrease during the fractional crystallization process as the SiO_2 content increases. In addition, there was an increase in nonmafic minerals such as plagioclase, quartz, and bedrock to form dacitic rocks. The content of CaO, Al_2O_3, and an increase in SiO_2 followed by an increase in the value of Na_2O to form plagioclase from basaltic andesite to dacite.

The cause of changes in magma composition during cooling process is due to crystal freezing starting from the molten magma. With the presence of phenocrysts during magma cooling, the chemical composition of magma will change. This occurs due to the process of fractional crystallization in the magma body. The process is similar to what occurs in the volcanic rocks of the studied area. Magma crystallization started from Jeding basaltic andesite, Kemlandingan pyroxene andesite, Manyutan hornblende andesite, and Ngebel dacite.

Discussion

Four types of lavas were found in the researched area, including basaltic andesite, pyroxene andesite, hornblende andesite, and dacite. According to Hartono *et al.* (2008) and Harahap (2011), a group of volcanic rocks which includes basaltic andesite, pyroxene andesite, hornblende andesite, and dacite can be formed from magma of continental origin in the subduction area. The four rock types represent each volcano, namely Jeding, Kemlandingan, Manyutan, and Ngebel Volcanoes. The plagioclase, pyroxene, opaque minerals, and volcanic glass were found in Jeding, Kemlandingan, and Manyutan lavas. However hornblende was only found in Manyutan and Ngebel lavas. Rock geochemical data shows that NVC generally has a varied silica content along with the gradual formation period from basaltic andesite, andesitic to dacitic (SiO2 52.3 - 64%). It has a magma affinity in the form of Calc-Alkaline Medium-K. The characteristic of high K calc-alkaline series indicates that plagioclase (andesine) and pyroxene (dominantly diopside and hypersthene) are present in the phenocryst phase (Rachmat *et al*., 2016). The K_2O - SiO_2 variation diagram shows the presence of assemblages of volcanic rocks with calc-alkaline affinity low to medium calc-alkaline with K_2O content between 0.10 -1.54% (Hartono *et al*., 2008). The data plots on the Harker diagram provide some evidence of the magma source of the Ngebel Volcano.

Subduction in southern Java produces primitive magma as a source of NVC. Magma undergoes a process of differentiation and becomes more felsic than primary magma. The fractional crystalization process occurs intensively in NVC magma. The process of fractional crystallization can be shown from the presence of mineralogy and chemistry of minerals with rock compositions in harmony with the decrease in temperature during the magma solidification process. Changes in the main composition of the magma lead to a reduction in plagioclase-olivine-augite from basalt or a reduction in plagioclase-pyroxene low Ca-clinoproxene-magnetite from more different magmas (Julian *et al*., 1995). This is evidenced by the composition of the lava, which is basaltic to dacite composition. Based on the temporal changes in the composition of SiO_2, MgO, CaO, Al_2O_3 , Fe_2O_3 , and TiO_2 in each unit, the Ngebel Volcano has gone through a fractional crystalization process. Likewise, Sutawidjaja *et al.* (2015) explained that geochemical and petrological evidences can show that magma is cogenetic, and can relate to each other through crystal fractionation.

The evolution of this volcano is based on the approach of geological data and petrochemical analysis of rocks, so in general, the evolution of magma from the NVC undergoes four phases of magma evolution from the oldest to the youngest, namely the Jeding phase, Kemlandingan phase, Manyutan phase, and Ngebel phase. The magma evolution, as has been done on Mount Salak by

Godang *et al.* (2021), occurred from basaltic trachyandesite to trachyte composition. Also Harijoko *et al.* (2022) explained that evolution of magmatism in the Lasem and Senjong Volcanic Complex occured in calc-alkaline series from basaltic trachyandesite to trachyte composition.

Volcanic evolution in the NVC is characterized by changes in the increasing SiO_2 content and the stratigraphic position of the volcanic rock collection of rock units in the studied area from old to young age (Figure 7).

Jeding Phase

In this phase, volcanic activity in the studied area started from the site of Jeding Volcano, which is in the Early Pleistocene age (Hartono *et al.*, 1992). This Jeding Volcano activity based on petrographic and geochemical analysis is a volcano with andesitic basalt composition. The minerals that make up the rock consist of plagioclase, pyroxene, and opaque minerals. The results of the geochemical analysis show that the SiO_2 concentration is 52.30 - 54.90%.

Kemlandingan Phase

Volcanic activity from the centre of the Kemlandingan eruption in this phase is on the east side of the studied area. The activity of this eruption centre based on petrographic and geochemical analyses shows the magma crystallization fractionation process from the freezing process of the Jeding phase. The Kemlandingan phase is characterized by pyroxene andesite lava with a mineral content of plagioclase, pyroxene, and opaque minerals. The SiO_2 concentration of this pyroxene andesite is 56.40 - 56.90%.

Manyutan Phase

In this phase, the volcanic activity of the Manyutan eruption centre is on the north side of the studied area. This volcanic activity is characterized by the presence of hornblende andesite with accompanying minerals such as plagioclase, hornblende, pyroxene, and opaque minerals. The rock is intermediate in composition with SiO_2 content of 58.40 - 59.40%.

Ngebel Phase

The Ngebel phase is the last volcanic activity phase in the studied volcanic complex area. This phase is marked by the presence of several rock units around Lake Ngebel. Based on petrographic and geochemical analyses, the activity product of the Ngebel eruption centre is composed of dacite lava with the constituent mineralogy of

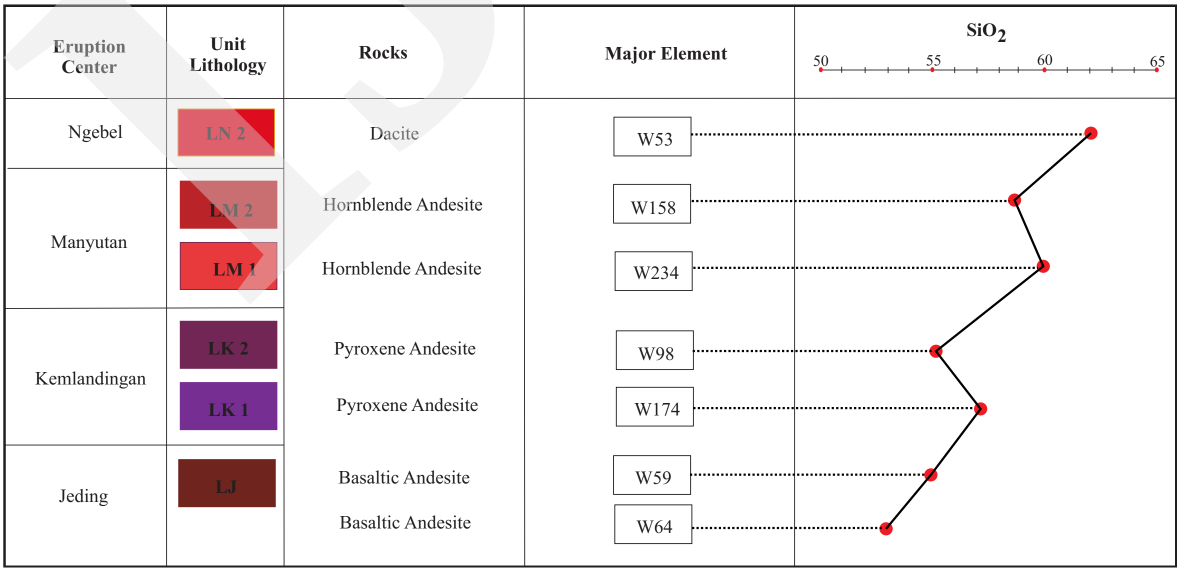


Figure 7. Evolution of magmatism of the NVC.

plagioclase, pyroxene, hornblende, quartz, and opaque minerals. While the SiO_2 content is 62.20 - 64.00% which is included in the type of intermediate magma composition.

Conclusion

The evolution of the NVC can be studied from the fractional crystallization process of magma. This process can be observed from the linear pattern of the distribution of the major oxides on the Harker diagram. This linear pattern started from the oldest to the youngest volcanic rocks, namely Jeding basaltic andesitic, Kemlandingan pyroxene andesite, Manyutan hornblende andesite to Ngebel dacite.

The values of MgO, CaO, Al_2O_3, Fe_2O_3, and TiO_2 decrease along with the increase in SiO_2 content. It is also known that the main elements are mafic minerals such as pyroxene and hornblende. In addition, there is a decrease in CaO levels as SiO_2 levels increase, followed by an increase in Na_2O levels. These two main elements are carried by plagioclase minerals which undergo substitution between Ca and Na compositions when the SiO_2 level increases with decreasing temperature, as depicted in the Bowen series. Changes in the main chemical elements of the volcanic rock followed by an increase in the element SiO_2 occurred during the fractional crystallization process. The affinity magma of NVC is calc-alkaline medium-K associated with the tectonic environment in island arcs.

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References

Asikin, 1974. *Geological Evolution of Central Java and Its Surrounding Areas in terms of New World Tectonic Theory. Doctoral Dissertation, ITB*, Unpublished.

Bemmelen, R.W. Van, 1949. *The Geology of Indonesia.* Vol. 1A, General Geology of Indonesia and Adjacent Archipelagos (Amsterdam: The Hague).

Berlo, K., Hinsberg, V. van, Purwanto, S., Heri, B., and Hendra, G., 2020. Using the composition of fluid seepage from the magmatic-hydrothermal system of Kawah Ijen Volcano, Indonesia, as a monitoring tool. *Journal of Volcanology and Geothermal Research*, 399, p. 106899. DOI: 10.1016/j.jvolgeores.2020.106899.

Gavrilenko, M., Ozerov, A., Kyle, P.R., Carr, M.J., Nikulin, A., Vidito, C., and Danyushevsky, L., 2016. Abrupt transition from fractional crystallization to magma mixing at Gorely Volcano (Kamchatka) after caldera collapse. *Bulletin of Volcanology,* 78 (47). p.46-47. DOI: 10.1007/s00445-016-1038-z, https://www.researchgate.net/publication/303831112_Abrupt_transition_from_fractional_crystallization_to_magma_mixing_at_Gorely_volcano_Kamchatka_after_caldera_collapse.

Godang, S., Priadi, B., Fadlin, Van Leeuwen, T., and Idrus, A., 2021. Geochemistry Study of Cross-castic Magma Alkalinity Evolution. *Indonesian Journal on Geoscience*, 8 (2), p.177-196. DOI: 10.17014/ijog.8.2.177-196

Hamilton, 1979. *Tectonics of the Indonesian Region* (Washington: US Geological Survey).

Harahap, B.H., 2011. Magma Genesis in Kabanjahe Region Continental Margin Arc of Sumatra. *Jurnal Geologi Indonesia*, 6 (2), p.105-127. DOI: 10.17014/ijog.6.2.105-127

Harijoko, A., Wibowo, H.E., Moktikanana, M.L.A., and Abdillah, M.Y., 2022. Magma

Evolution of Lasem and Senjong Volcanic Complex: High-K Magmatism in Sunda Arc, Indonesia. *Indonesian Journal on Geoscience*, 9 (1), p.131-145. DOI: 10.17014/ijog.9.1.131-145

Hariyono, E. and Liliasari, S., 2017. The *Characteristics of Volcanic Eruption in Indonesia*. DOI: 10.5772/intechopen.71449, www.intechopen.com/chapters/57502.

Hartono, U., Baharuddin, and Brata, K., 1992. *Geological Map of Sheet Madiun, East Java Scale 1:100000.*

Hartono, U., 1994. *The Petrology and Geochemistry of The Wilis and Lawu Volcanoes, East Java, Indonesia*. *Dissertation.* University of Tasmania, p.19-31, 37.

Hartono, G., Sudrajat,A., dan Syafri, I., 2008. Gumuk gunung api purba bawah laut di Tawangsari - Jomboran, Sukoharjo - Wonogiri, Jawa Tengah. *Jurnal Geologi Indonesia*, 3 (1), p.37-48. DOI: 10.17014/ijog.3.1.37-48

Hartono, U., Syafri, I., and Ardiansyah, R., 2008. The origin of Cihara granodiorite from South Banten. *Jurnal Geologi Indonesia*, 3 (2), p.107-116. DOI: 10.17014/ijog.3.2.107-116

Hasibuan, R.F., Ohba, T., Abdurrachman, M., and Hoshide, T., 2020 Temporal Variations of Petrological Characteristics of Tangkil and Rajabasa Volcanic Rocks, Indonesia. *Indonesian Journal on Geoscience*, 7 (2), p.135-159. DOI: 10.17014/ijog.7.2.135-159

Hinsberg, V. Van, Vigouroux, N., Palmer, S., Berlo, K., Mauri, G., Williams-Jones, A., Mckenzie, J., Williams-Jones, G., and Fischer, T., 2017. Element flux to the environment of the passively degassing crater lake-hosting Kawah Ijen Volcano, Indonesia, and implications for estimates of the global volcanic flux'. *Geological Society Special Publication*, 437(1), p.9-34. DOI: 10.1144/SP437.2.

Julian, A.P, Baker, P.E., Harvey, P.K., and Luff, I.W., 1995. Geochemical Evidence for Subduction Fluxes, Mantle Melting and Fractional Crystallization Beneath the South Sandwich Island Arc. *Journal of Petrology,* 36 (4), p.1073-1109 DOI: 10.1093/petrology/ 36.4.1073.

Lallemand, S., 2016. Philippine Sea Plate inception, evolution, and consumption with special emphasis on the early stages of Izu-Bonin-Mariana subduction. *Progress in Earth and Planetary Science*, 3 (15), p.2-27. DOI: 10.1186/s40645-016-0085-6, https://progearthplanetsci.springeropen.com/track/pdf/10.1186/s40645-016-0085-6.pdf.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1989. A Chemical Classification of Volcanic Rock Based on the Total Alkali - Silica Diagram. *Journal of Petrology*, 27 (3), p.745-750. DOI: 10.1093/petrology/27.3.745.

Mulyaningsih, S. and Shaban, G., 2020. Geochemistry of Basaltic Merbabu Volcanic Rocks, Central Java, Indonesia. *Indonesian Journal on Geoscience*, 7 (2), p.161-178. DOI: 10.17014/ijog.7.2.161-178

Peccerillo, A. and Taylor S.R., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu Area, Northern Turkey. *Contribution to Mineralogy and Petrology,* 58, p.63-81. DOI: 10.1007/bf00384745

Pulunggono and Martodjojo, S., 1994. Paleogene-Neogeneous Tectonic Changes are The Most Important Tectonic Events in Java. *Proceedings, Geology and Geotectonics of Java Island from Late Mesozoic to Quaternary*, p.1-14.

Rachmat, H., Rosana, M.F., Wirakusumah, A.D., and Jabbar, G.A., 2016. Petrogenesis of Rinjani Post-1257-Caldera-Forming-Eruption Lava Flows. *Indonesian Journal on Geoscience*, 3 (2), p.107-126. DOI: 10.17014/ijog.3.2.107-126

Setijadji, L.D., 2010. Segmented Volcanic Arc and its Association with Geothermal Fields in Java Island, Indonesia. *Proceedings of World Geothermal Congress 2010 Bali*, Indonesia, p.1-12.

Smyth, H.R., Hall, R., and Nichols, G.J., 2008. Cenozoic volcanic arc history of East Java, Indonesia: The stratigraphic record of eruptions on an active continental margin. *In:* Draut, AE, Clift, P.D., and Scholl, D.W. (eds.), Formation and Applications of the Sedimentary Record in Arc Collision Zones. *Geological Society of America Special Paper,* 436, p.199-222, DOI: 10.1130/2008.2436(10).

Soeria-Atmadja, R., Maury, R.C., Bellon, H., Pringgoprawiro, H., Polve, M., and Priadi, B., 1994. Tertiary Magmatic Belts in Java. *Journal of Southeast Asia and Petrology,* 9, p.13-27. DOI: 10.1016/0743-9547(94)90062-0

Sutawidjaja, I.S., Rosana, M.F., and Watanabe, K., 2015. Magma Chamber Model of Batur Caldera, Bali, Indonesia: Compositional Variation of Two Facies, Large-Volume Dacitic Ignimbrites. *Indonesian Journal on Geoscience*, 2 (2), p.111-124. DOI: 10.17014/ijog.2.2.111-124

Volcanological Survey Indonesia, 2021. *Tipe Gunung api di Indonesia (A, B, dan C),* Magma Indonesia, https://magma.esdm.go.id/v1/edukasi/tipe-gunung-api-di-indonesia-a-b-dan-c. DOI: 10.17014/ijog.vol1no4.20065

Williams, H., Turner, F.J., and Gilbert, C.M., 1982. *Petrography: An Introduction to the Study of Rocks in Thin Sections* , 2nd ed. W.H. Freeman, San Francisco, CA, 626pp.

Yudiantoro, D.F., Ratnaningsih, D.R., Pratiknyo, P., Mahreni, Sayudi, D.S., Paramitahaty, I., Hamdalah, H., Abdurrahman, M., Takashima, I., Ismunandar, W., Muhammad, R., and Sampurno, D.G., 2021. Hydrothermal Fluids-Rock Interactions in the Geothermal Area of the Ngebel Volcano Complex Ponorogo, East Java, Indonesia, 1 (1), p.267-280.DOI: 10.31098/cset.v1i1.378