Eksplorium
Volume 44 No. 1, May 2023: 13–24

p-ISSN 0854-1418
e-ISSN 2503-426X

Magmatic Evolution of Dago Volcano, West Java, Indonesia

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Article received: 29 April 2023, revised: 14 May 2023, accepted: 29 May 2023
DOI: 10.55981/eksplorium.2023.6873

ABSTRACT

Dago Volcano is a product of Miocene Sunda Arc volcanism located southeast of the capital city of Jakarta. The morphological change from flat lava flows to steeper lava morphology implies a process of magma evolution under Dago Volcano. This research provides an overview of the magma evolution that occurs on this volcano. The methods used include volcanostratigraphy analysis, petrographic analysis, mineral chemistry, and whole-rock geochemistry. The volcanostratigraphy of Dago Volcano is composed of two eruption centers and a flank eruption forming lava and cinder cone products. The mineralogical associations of Dago Volcano products include plagioclase, olivine, and clinopyroxene. The mineral textures of Dago edifices show zoning, sieve, and reaction rims textures. Geochemically, the Dago Volcano product has a magma affinity of med-K calc-alkaline with quite high levels of MgO, Ni, and Cr, approaching the characteristics of primitive magma. The magma evolution process of Dago Volcano includes fractional crystallization and magma mixing, which originates from the same magma source.

Keywords: Dago Volcano, magmatic evolution, primitive magma, volcanostratigraphy

INTRODUCTION

The Java volcanic arc results from the subduction of the Indo-Australian plate beneath the Eurasian plate [1],[2]. This volcanic arc extends 3,700 km from the western tip of Sumatra to Damar Island [2],[3] and has developed since the Mesozoic Age. The segment that stretches south of Java Island is called the Sunda Arc. The Sunda arc has been formed since the Late Cretaceous [4], proven by the obducted ophiolites series found in Ciletuh Bay [5],[6]. The Sunda Arc created various magmatism and volcanism products in West Java during the Tertiary to Quaternary.

Dago Volcano, located southwestward to Jakarta, is one of the Miocene volcanoes in West Java [7]. Dago Volcano was an Upper Miocene volcanic arc located north of Bayah Dome. The location of Dago Volcano was in line with Cianjur Andesite, dated 6.0 ± 0.7 Ma [8] (Figure 1). The morphology of Dago volcano is defined by flat basaltic lava flow overlying the sedimentary rock of the Genteng Formation (volcaniclastic sediment) with several eruption centers forming cinder cone product [9]. On the southeast side of Dago Volcano, steeper morphology was observed as the result of more evolved lava formed in the area. The change in morphology implies the evolution of magmatism below the Dago volcano. Thus, the study of the magmatic evolution of Dago volcano needs to be explored for future analysis.

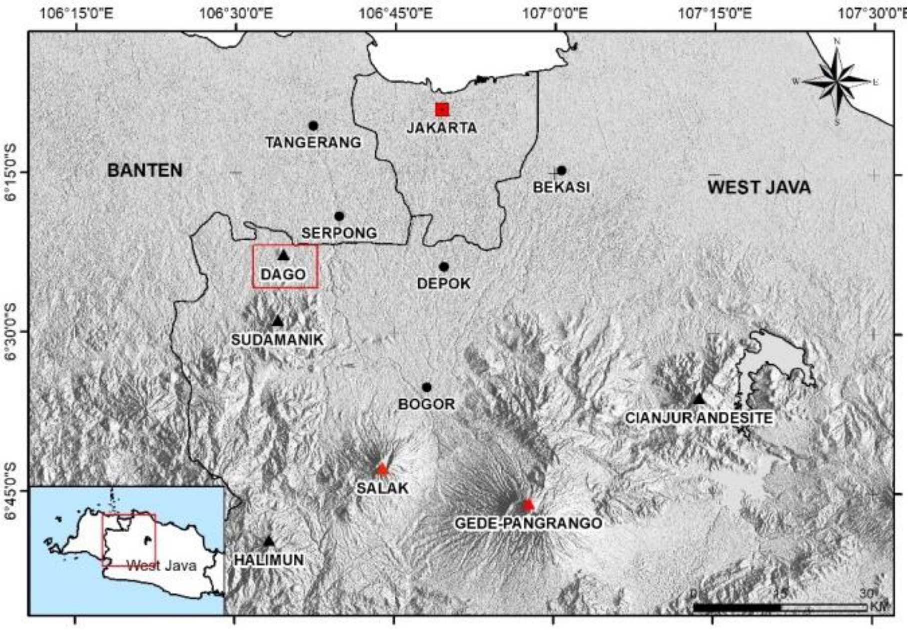

Figure 1. The location of Dago Volcano in West Java that in line with the Tertiary Cianjur Andesite.

This study shows petrographic and geochemical data from Dago volcano. The samples represent each lithology of Dago volcano, including lava and juvenile clast of cinder cone edifice. This study will explain the magma evolution below Dago volcano and the similarity to the primitive magma along the Java arc.

REGIONAL GEOLOGY

The physiography of the Serpong area was noted as part of the Bogor Zone adjacent to Quaternary Volcano in its southern part. The Bogor Zone is anticlinorium, which consists of folded Tertiary sediment and intrusion such as volcanic neck or stock [10]. Regionally, the area consists of Tertiary Sedimentary Rocks, Tertiary Dago Volcano Basaltic Rock, Quaternary Volcanic Rocks, and Quaternary Alluvial Fan (Figure 2). The Tertiary sedimentary rocks include the Rengganis Formation (sandstone, breccia, and claystone), the Bojongmanik Formation (alternating sandstone–claystone), the Genteng Formation (volcaniclastic sediment), and Serpong Formation (sandstone, conglomerate, claystone, and siltstone). The Basalt of Dago Volcano, the main object in this research, was mainly composed of fractured and weathered pyroxene basalt [7]. Dago Volcano was identified as a monogenetic volcanic system creating several volcanic products such as lava flows and cinder cones [9].

p-ISSN 0854-1418
e-ISSN 2503-426X

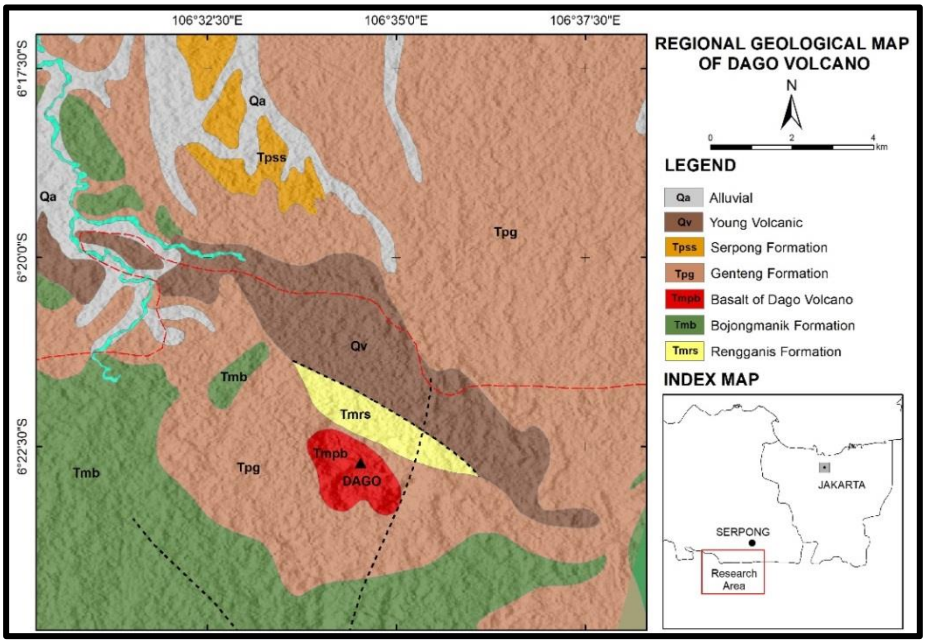

Figure 2. Regional Geological Map of Dago Volcano [7].

METHODOLOGY

The methods used in this research consist of volcanostratigraphy analysis, field observations, petrographic analysis, whole-rock, and mineral geochemistry analysis. Volcanostratigraphy analysis was conducted using the national digital elevation model (DEMNAS) with a spatial resolution of 0.27 arcseconds or about 8.1 meters. This method was carried out to delineate the distribution of each eruption product of Dago Volcano and to interpret its chronological process. The delineation of volcanic edifices was differentiated by its eruption center, lithology type, and eruption time [11]. The lateral distribution of the volcanic stratigraphy units is limited by the body of the volcano itself or the contact with the other units.

The field observation was conducted to confirm the volcanostratigraphy analysis, determine the lithology type and describe its characteristics, and collect rock samples from the outcrop. The petrographic analysis was conducted using a polarization microscope at the Petrographic Laboratory in Universitas Gadjah Mada, Indonesia. The petrographic analyses were carried out on four (4) lava samples (DG-1.2, DG-02, DG-03, DG-04) and one (1) juvenile clast sample (DG-01) of Dago volcanic products. The output of the petrographic analysis was micro-texture identification to indicate the volcanic process in Dago Volcano. The geochemical analysis was conducted using a SPECTRO XEPOS XRF Spectrometer at the National Research and Innovation Agency (BRIN) Laboratory, Indonesia. The samples were analyzed in the form of pellet-pressed samples.

Mineral chemistry analysis was conducted to identify the mineral composition and mineral type of Dago volcano edifices. The mineral chemistry analysis was conducted using Bruker M4 Tornado, micro-XRF equipment with a beam size of 20 microns. Mineral chemistry was analyzed on two samples of Dago Volcano products, DG-02 and DG-03. From that sample, olivine, pyroxene, and plagioclase phenocrysts were chosen and analyzed from its rim to its core.

RESULTS

Dago Volcano Eruption Products

Dago Volcano consists of two eruption centers, namely Kepuh and Dago eruption centers. Chronologically, the eruption products were composed of Kepuh Lava, Kepuh Cinder Cone, Dago Lava 1, Dago Lava 2, and Dago Cinder Cone. Due to the limited outcrops observed in the field, in this paper, the observed units that will be explained in detail are Kepuh Lava, Dago Lava 2, and Dago Cinder Cone.

Kepuh Lava was characterized by its smooth texture in DEM and distributed about 1 km west of its eruption center. The lithology of Kepuh Lava was basaltic trachyandesite, dark grey (Figure 3a), porphyroaphanitic, and massive textures. The phenocrysts were 1–3 mm, composed of plagioclase and pyroxene.

Dago Lava 2 was characterized by its dome-shaped morphology and distributed about 800 meters northeastward and southwestward from its eruption center. The lithology of Dago Lava 2 was trachyandesite, dark to light grey (Figure 3b), porphiroaphanitic, and massive texture. The phenocrysts were olivine and plagioclase with 1–2 mm in size.

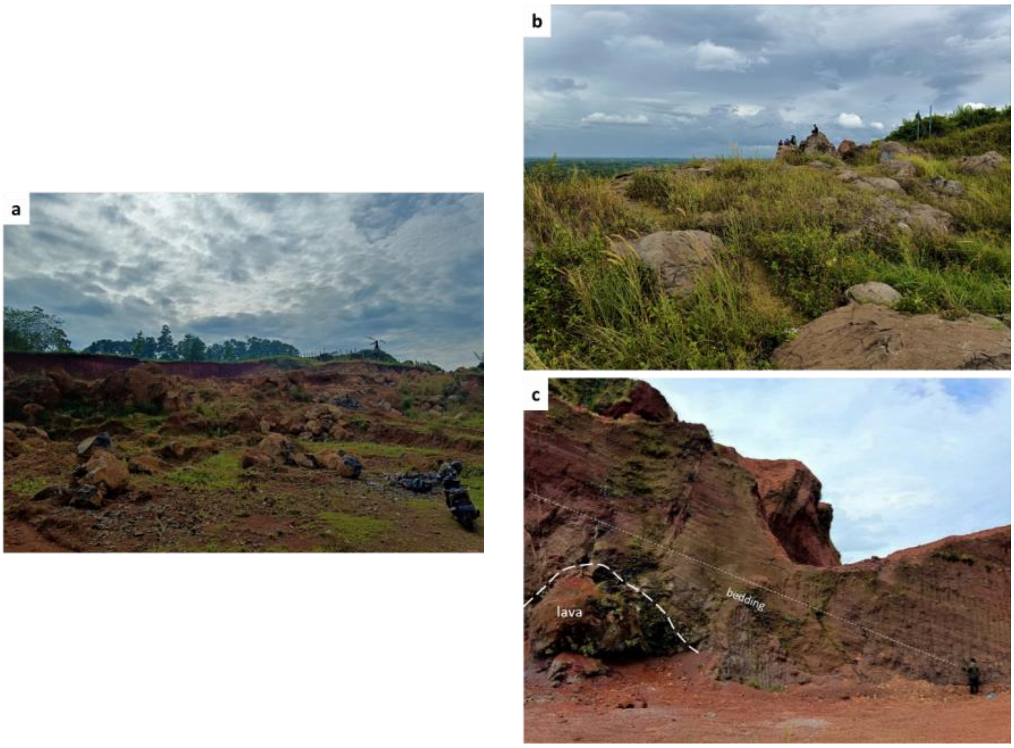

Figure 3. The outcrop in the research area shows a) Kepuh Lava, b) Dago Lava 2, and c) Dago Cinder Cone.

Dago Cinder Cone was identified by its cone-like morphology in DEM analysis. This eruption product is only distributed for about 300 meters radius on the flank of Dago Volcano body. Dago Cinder Cone is interpreted as a flank eruption at the end of Dago Volcano vulcanism period. The outcrop of Dago Cinder Cone shows scoria layers and lava breach (Figure 3c). Generally, the scoria layers show beds typically ~1 m to ~30 cm thick that dip outward from its center at angles of 20°–25°. The beds show grey to reddish color, clear reverse grading, good sorting, and clast supported. Most clasts were

p-ISSN 0854-1418
e-ISSN 2503-426X

vesicular and sub-angular to sub-rounded in shape. The grain-size characteristics of the scoria layers vary from tuff to 5 cm bomb. Lithic clasts were rarely observed in individual beds. In this cinder cone, a lava breach was observed on the southern side of the cone. The lava was light grey with a massive aphanitic texture. The lava is slightly vesicular in a narrow zone (up to 10 cm) along the contact with the scoria layer. The geological map of Dago volcano is shown in Figure 4.

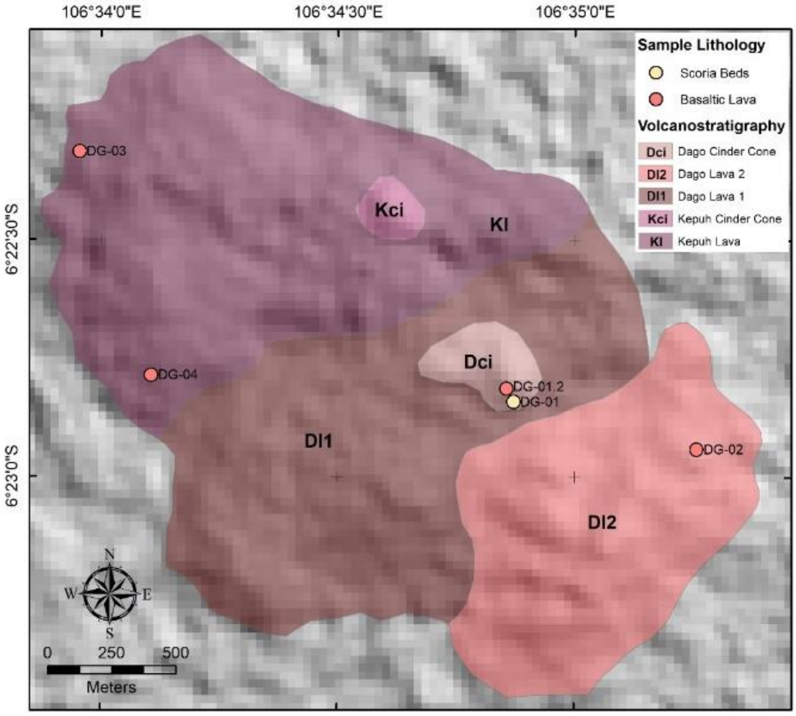

Figure 4. Volcanostratigraphy map of Dago Volcano.

Petrography

Kepuh lava, represented by samples DG-03 and DG-04 (Figure 5a), is basaltic andesite with crystal-rich groundmass. Plagioclase crystals show sub-parallel orientation, zoning, and sieve texture. Plagioclase in DG-03 shows an abundant sieve texture. Olivine is present as phenocrysts and minute crystals in the groundmass.

Clinopyroxene is present as phenocrysts and microlite crystals. The clinopyroxene crystal shows a reaction rim texture. Some glomerocrysts (~1 mm diameter) of clinopyroxene, olivine, and plagioclase were also present, and opaque minerals interpreted as Ti-magnetite were found as minute crystals in the groundmass.

Dago lava 2 (DG-02) typically contains phenocrysts of plagioclase, olivine, and less clinopyroxene in crystal-rich groundmass (Figure 5b). Olivine shows mild alteration to be iddingsite along the rims and cracks. Olivine crystals were found as clots (~1 mm diameter) with minute Ti-magnetite as an inclusion. Olivine crystal shows reaction rims texture with plagioclase. Ti-magnetite crystals were found in small numbers. Plagioclase shows sub-parallel orientation and abundant sieve texture. Some plagioclases show fine compositional zoning. Round-shaped vesicles were also present in the sample. Clinopyroxene was found as a phenocryst and microlite crystal in the groundmass.

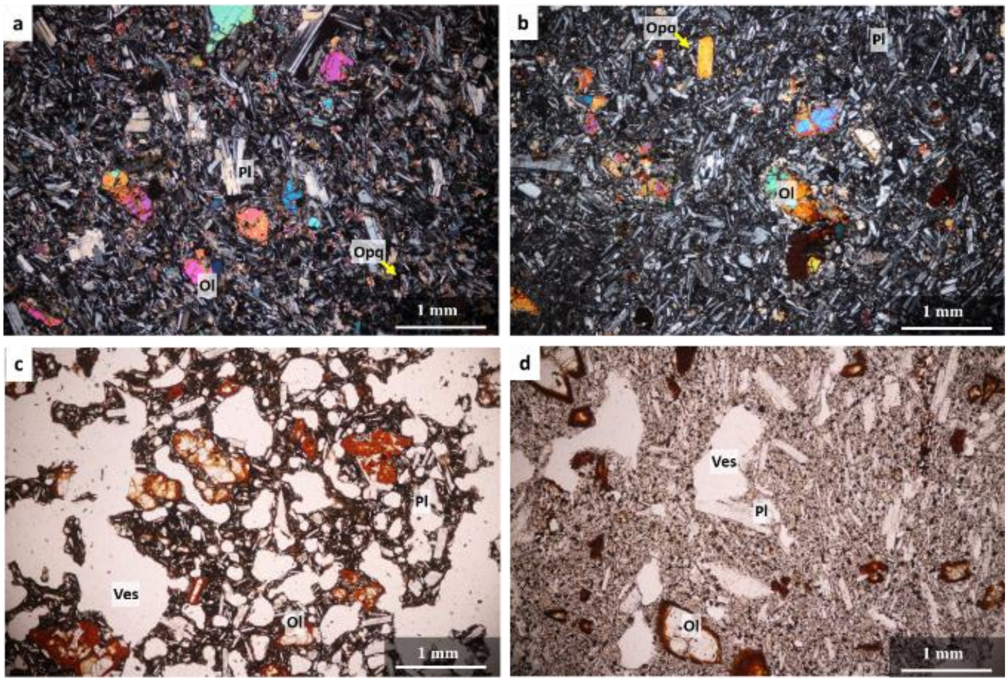

Figure 5. Thin section photograph of Dago volcano edifices typically shows plagioclase, olivine, and clinopyroxene association. a) Basaltic andesite of Kepuh Lava unit. b) Basaltic trachyandesite of Dago Lava 2. c) Scoria clast of Dago Cinder Cone. d) Lava breach of Dago Cinder Cone. (Ol: olivine, Pl: plagioclase, Cpx: clinopyroxene, Opq: Ti-magnetite, Ves: vesicles).

The scoria clast sample (DG-01) in Dago Cinder Cone shows a vitrophyric texture of glassy groundmass (Figure 5c). The phenocrysts consist of plagioclase and olivine, usually found in the form of glomerocrysts. Olivine shows intense alteration to iddingsite to almost all of its body. Subhedral to anhedral plagioclase shows clean textures. Irregular-shaped vesicles were dominant across the juvenile clast sample. The lava breach in the south of the cinder cones (DG-01.2) contains plagioclase and olivine as phenocrysts in crystal-rich groundmass (Figure 5d). Plagioclase phenocryst shows rare zoning and sieve texture, while the plagioclase microphenocryst shows sub-parallel orientation. Olivine phenocryst was up to 1.5 mm in size and displayed moderate alteration to iddingsite along its rims and cracks.

Mineralogy

Mineral chemistry was analyzed in sample DG-02 for the Dago Lava 2 unit and DG-03 for the Kepuh Lava unit. The forsterite (Fo#) content of olivine phenocryst from DG-02 on Dago volcano ranged from Fo_{71} to Fo_{85}. Generally, the olivine phenocryst shows normal zoning. The greater Fo# content was found in the core of the big phenocryst and going smaller to its rim. The core of smaller phenocrysts shows smaller Fo# content. Clinopyroxene phenocrysts in the olivine basalt of DG-03 are mostly subhedral-euhedral. The pyroxene types found in this sample are augite and pigeonite (Figure 6). The plagioclase of Dago volcano exhibits a wide range of anorthite content. The anorthite (An#) content in Dago Lava 2 is ranged from An_{24} to An_{71} (oligoclase–bytownite), while plagioclase phenocryst from Kepuh Lava shows narrower varieties from An_{35} to An_{62} (andesine–labradorite).

p-ISSN 0854-1418
e-ISSN 2503-426X

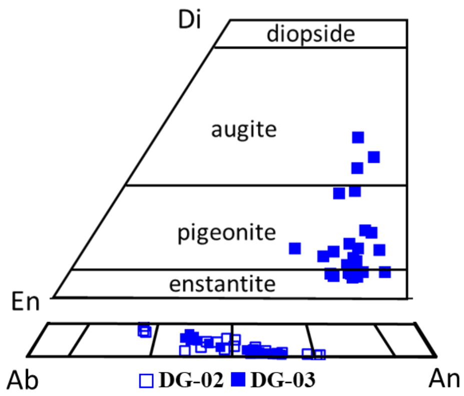

Figure 6. Mineral chemistry analysis on pyroxene and plagioclase phenocryst.

Dago Volcano Geochemistry

The rock type of Dago Volcano plotted in Figure 7 shows the range in basaltic andesite (DG-01), basaltic trachyandesite (DG-1.2, DG-03, DG-04), and trachyandesite (DG-02) according to Le Bas [12]. The range of SiO_2 was between 54.33–57.29% (Table 1). The Kepuh Lava unit was the most primitive magma found in Dago Volcano, and Dago Lava 2 was the most evolved in the area.

The Dago products were compared to Galunggung and Lamongan products as representative of primitive magma in West Java and East Java, respectively [12],[13]. The Dago products were plotted within the field of med-K calc-alkaline series within the same range as the Galunggung product but lower than the Lamongan product plotted in the med-K calc-alkaline series. The MgO of Dago volcano exhibits a narrow range from 4.77–6.94% with Mg# between 53.88–60.89. The bivariate plot of SiO_2 versus major oxide of Dago Volcano (Figure 8) shows almost all the bivariate plot of SiO_2 vs major oxide shows that Dago products were in the same trend as Galunggung product except for Na_2O and Al_2O_3. The Dago products show enrichment in Na_2O and depletion in Al_2O_3 more than the Galunggung and Lamongan products.

Table 1. Major oxide and trace elements concentration of Dago volcano rock samples.

Unit	**Kepuh Lava**		**Dago Lava 2**	**Dago Cinder Cone**	
Sample	DG03	DG04	DG02	DG1.2	DG01
Mg#	59.5	53.88	56.17	56.34	60.89
			(wt.%)		
SiO_2	54.68	54.33	57.29	54.57	54.85
TiO_2	0.65	0.87	0.74	0.85	0.82
Al_2O_3	14.31	14.54	14.06	14.31	14.26
FeO	6.88	7.41	6.63	7.67	7.95
MnO	0.19	0.18	0.17	0.19	0.18
MgO	5.67	4.86	4.77	5.56	6.94
CaO	8.81	9.33	8	9.13	8.64
Na_2O	5.9	6.26	5.91	5.95	4.85
K_2O	0.46	0.58	0.77	0.61	0.53
Cr_2O_3	0.08	0.12	0.06	0.13	0.09
P_2O_5	0.37	0.37	0.42	0.36	0.28
LOI	2	1.17	1.18	0.67	0.61
			(ppm)		
Sc	35	40	39	41	54
V	82	115	93	124	127
Cr	603	824	394	933	639
Co	30	32	27	31	35
Ni	132	154	103	153	166
Cu	21	47	24	21	29
Zn	61	64	69	66	72
Ga	12	9	13	11	13
Rb	6	14	26	13	16
Sr	503	487	552	496	481
Y	23	24	24	25	27
Zr	76	75	101	75	82
Ba	178	169	232	165	200
La	38	26	45	19	22
Ce	39	39	66	29	33
Pr	33	44	47	26	33
Nd	78	99	96	56	64
Sm	38	42	38	36	54
Hf	14	20	12	15	11
Pb	8	13	12	9	13
Th	6	7	11	7	7
U	3	3	4	3	3

The SiO_2 vs trace element variation diagram (Figure 9) shows that the Dago product shows a sharp decrease of compatible elements such as Ni and Cr towards higher SiO_2. The Dago products show a range value of Ni between 103–165 ppm and Cr between 393–933 ppm. Compared to Galunggung and Lamongan, Dago products display higher Ni and Cr concentrations in the same range of SiO_2. For trace elements such as Zr and Ba, Dago products display the same trend as Galunggung products.

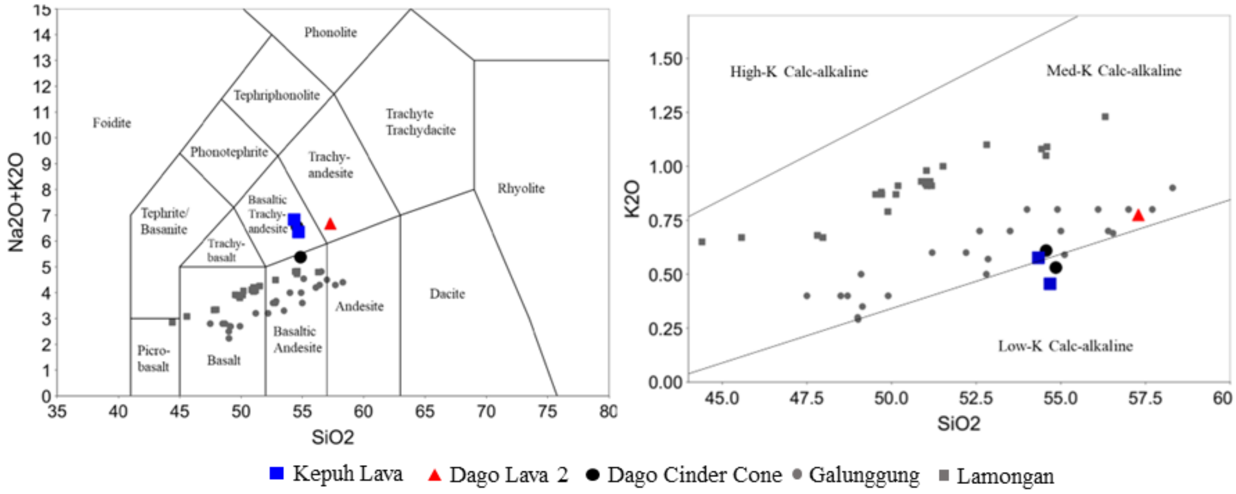

Figure 7. TAS classification [14] and andesite type diagram [15] for Dago, Galunggung, and Lamongan edifices.

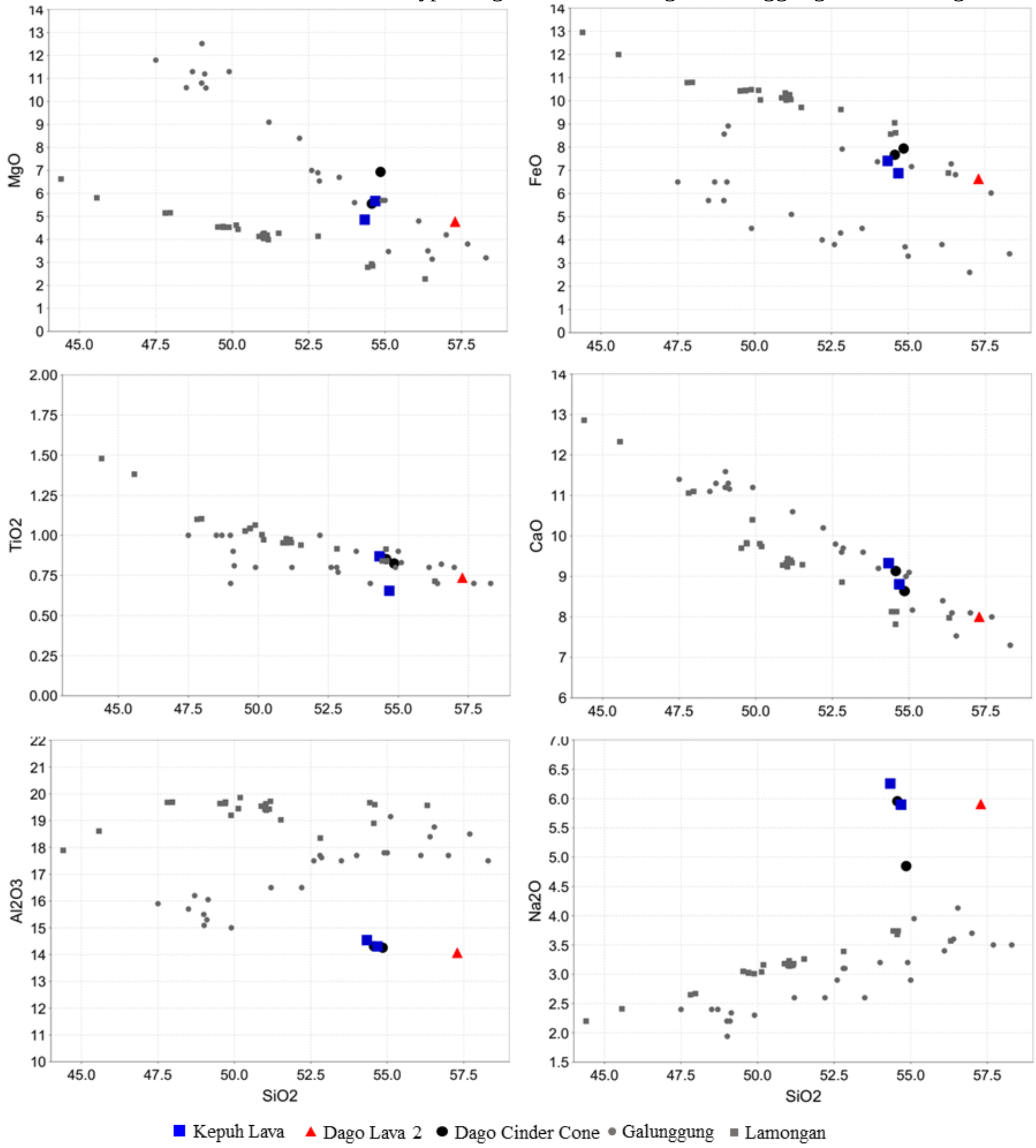

Figure 8. Harker diagram of SiO_2 vs major oxide for Dago Volcano eruption product. Eruption products from Galunggung and Lamongan as a comparison.

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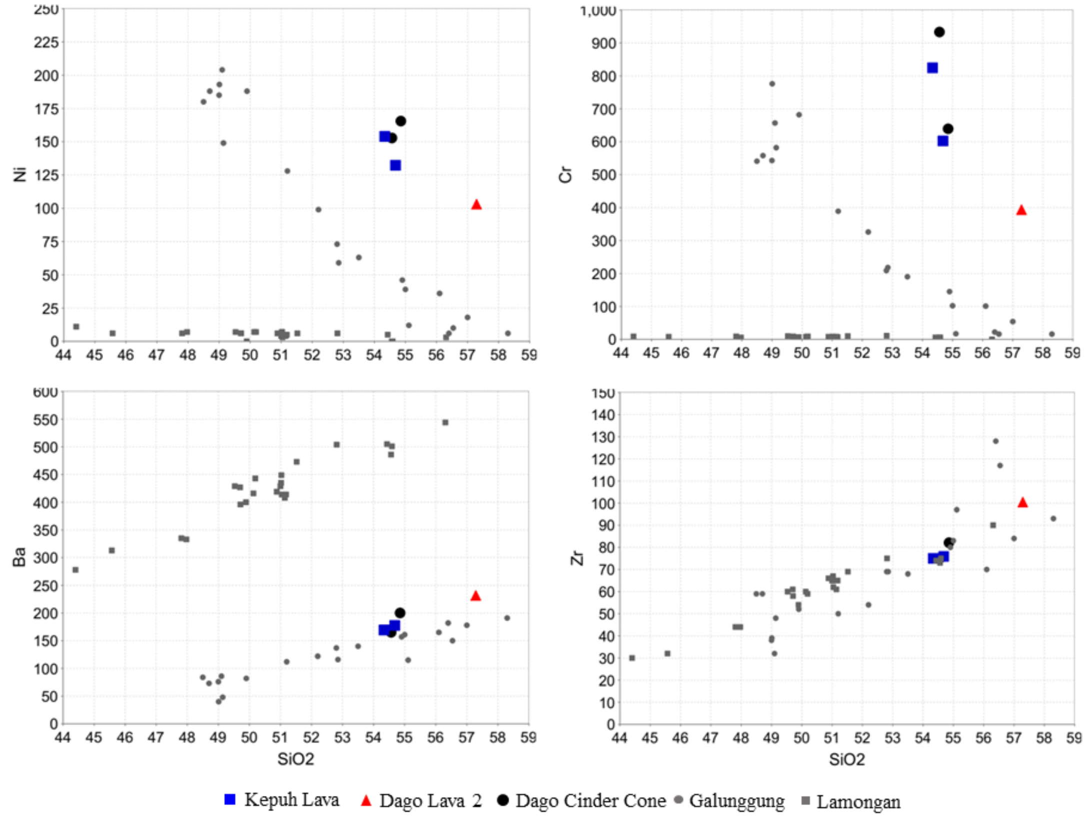

Figure 9. Harker diagram of SiO_2 versus trace element for Dago Volcano eruption product. Eruption products from Galunggung and Lamongan as a comparison.

DISCUSSION

Characteristics of Dago Magmas

The Total Alkali-Silica diagram [14] in Figure shows that Dago volcanic products are basaltic andesite, basaltic trachyandesite, and trachyandesite in composition. Dago magmas are all medium-K calc alkaline [15], showing low K_2O values ranging from 0.46–0.77%. The trend of K_2O value from Dago volcano products is within the trend of Galunggung products [12].

The mineralogy in these volcanic products is composed of olivine, clinopyroxene, and plagioclase. Mineral chemistry analysis showed that the olivine found in the Dago edifices had Fo_{71}–Fo_{85}. Pyroxene analysis shows that the eruption products of Dago Volcano have pyroxene types in the form of augite and pigeonite. The type of plagioclase found in the eruption products of this volcano is oligoclase to bytownite (An_{24}–An_{71}).

The magma characteristics of Dago Volcano were SiO_2 content ranging between 54.33–57.29 % and MgO content between 4.77–6.94% with Mg# values between 53.88–60.89. This magma also shows quite high levels of Ni and Cr, with 103–166 ppm and 394–933 ppm, respectively.

Referring to the expected value of primitive magma based on Tatsumi and Eggins [16] and Wilson [17], the magma characteristics of the Dago Volcano products have approached the primitive magma of Galunggung products (Table 2). In terms of Ni and Cr contents, Dago magma characteristics might be approaching the primitive magma characteristics. However, the SiO_2 and MgO contents are far from the expected value. Therefore Dago magma cannot be classified as primitive magma. The differentiation process experienced by the eruption products of Dago Volcano resulted in a decrease in MgO and an increase in SiO_2 contents. The high Ni and Cr content in Dago magma might be accommodated by the occurrence of olivine and clinopyroxene crystals.

Table 2. Comparison of expected primitive magma characteristics of the Dago Volcano edifices.

Parameter	Dago Volcano	Galunggung	Lamongan
Mg#	53.88–60.89	45.09–81.73	36.58–47.71
MgO	4.77–6.94%	3.14–12.52%	2.28–6.63%
Ni	103–166 ppm	6–204 ppm	3–11 ppm
Cr	394–933 ppm	16–776 ppm	5–11 ppm
SiO_2	54.33–57.29%	47.5–58.3%	44.4–56.31%

Magma Evolution Process

The magma evolution process includes various differentiation processes. There are fractional crystallization, magma mixing, and assimilation with host rocks. The occurrence of the magma differentiation process can be identified from petrographic observations, mineral chemical analysis, and geochemical analysis. Petrographic observations of plagioclase phenocrysts show a sieve texture, which indicates that the plagioclase mineral is undergoing partial dissolution due to plagioclase reactions due to magma mixing or re-injection by more mafic magmas [18].

Zoning textures in plagioclase phenocrysts are also shown in petrographic observation. Mineral chemistry analysis of the phenocrysts showed normal and reverse zoning textures. Normal zoning texture on plagioclase phenocrysts from sample DG-03 shows the decreasing value of An from the core to the rim of the crystal (Figure 10). Normal zoning indicates a fractional process of crystallization from the magma-cooling process. The reverse zoning texture is seen in the DG-02 sample, indicating an increase in An values from the core to the rim of the crystal (Figure 10). The reverse zoning indicates magma mixing with the more mafic one or re-injecting primitive magma into the magma chamber [18].

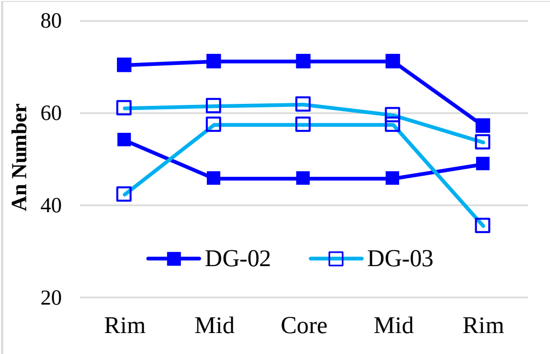

Figure 10. Plot of An# value to the position of the plagioclase phenocryst.

The histogram of plagioclase types based on mineral chemistry analysis shows the dominance of An values in rock samples (Figure 11). Dago volcano product shows a significant change in An value related to its SiO_2 content. Sample DG-03 with 54.68% SiO_2 shows a bimodal peak value of An number at An_{40} and An_{60}. The DG-02 sample, with 57.29% SiO_2, shows a wider range of An value from An_{25}–An_{75}. The bimodal peak and wide range of An value can indicate the magma mixing process in Dago volcano. The wide range of An value in DG-02 also supports the evidence of olivine occurrence in trachyandesite controlled by the magma mixing process. Petrographic observations also showed reaction-rim texture on pyroxene and olivine. The reaction rim texture on pyroxene was observed as microcrystalline growth of clinopyroxene on the edge of the clinopyroxene phenocrysts. The reaction-rim texture on olivine shows microcrystalline growth of plagioclases on olivine rims. The reaction rim texture on those crystals appears due to a disequilibrium of physicochemical conditions in the magma chamber, changing the rim of the crystals. This disequilibrium could happen due to magma mixing or re-injection of primitive magma [19].

 p-ISSN 0854-1418
e-ISSN 2503-426X

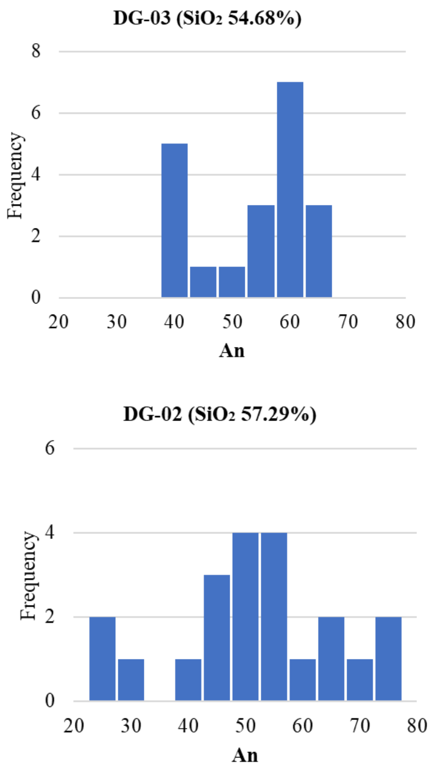

Figure 11. Histogram of An value on Dago volcano product showing bimodal peak and wide range distribution.

Dago magmas geochemistry reveals decreased FeO, MgO, TiO_2, CaO, and Ni with increased SiO_2. Those patterns could be affected by the fractional crystallization process due to the crystallization of mafic minerals that occurred earlier. Crystallization of mafic minerals causes increased levels of major oxides such as K_2O and Na_2O and incompatible elements such as Ba and Zr. The increased levels of major oxide and incompatible elements will be reflected in the Harker diagram, which shows a positive trend for those elements (Figure 8 and Figure 9).

Magmatic System

As mentioned, the magma that formed Dago Volcano edifices was characterized by low K_2O and high MgO magma with med-K calc-alkaline affinity. This magma forms mineral associations of plagioclase, olivine, and clinopyroxene. The first phase of the Dago Volcano eruption creates the flat body of Kepuh, forming Kepuh Lava (Kl) and Kepuh Cinder Cone (Kci) products. The eruption center then shifted southeastward to Dago eruption center. This eruption formed more evolved Dago Lava 1 (Dl1) and Dago Lava 2 (Dl2), creating steeper morphology in its eruption center. The flank eruption in Dago Volcano creates Dago Cinder Cone (Dci) products with more primitive characteristics. This flank eruption ends the volcanism of Dago Volcano. The schematics model of the magmatic system of Dago volcano is shown in Figure 12.

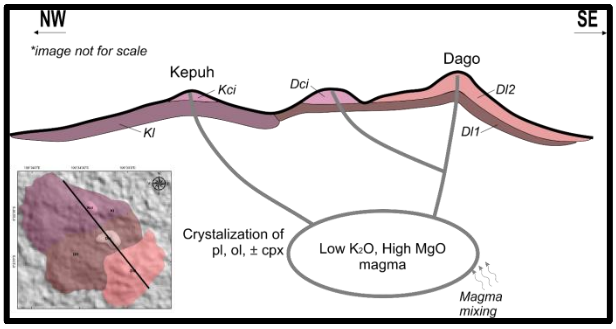

Figure 12. Schematic model of Dago Volcano magmatic system.

CONCLUSION

Dago Volcano is one of the Miocene volcanoes in West Java, Indonesia. The edifices formed by the volcano consisted of lava flows and cinder cones. The mineralogical compositions of Dago Volcano edifices were composed of plagioclase, olivine, and clinopyroxene. Geochemically, Dago magmas were basaltic andesite, basaltic trachyandesite, and trachyandesite with low K_2O content. The evolution of Dago magma was influenced by fractional crystallization and magma mixing, confirmed by the geochemical trend and mineral textures such as sieve, zoning, and reaction rim. Compared to Galunggung and Lamongan edifices, Dago products show relatively high Ni and Cr contents, approaching primitive magma characteristics. However, the MgO and SiO_2 contents were out of the criteria. Therefore Dago magma cannot be classified as primitive magma.

ACKNOWLEDGMENTS

The authors would like to thank the National Research and Innovation Agency (BRIN) for supporting funding and facilities to conduct this research. We also thank the anonymous reviewers for their thorough reviews and helpful suggestions.

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