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Geology and Petrogenesis of Igneous Rocks from Batur Paleovolcano, Gunungkidul, Yogyakarta: Evidence from their Textures, Mineralogy, and Major Elements Geochemistry

Fahmi Hakim*, Yanuardi Satrio Nugroho, Cendi Diar Permata Dana, and Anastasia Dewi Titisari

Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia

ABSTRACT. Batur paleovolcano is located in Wediombo Beach area, Gunungkidul Regency, Yogyakarta and is being part of Wuni Formation. Several volcanic products including lava flow, autoclastic breccia and volcanic breccia can be found associated with diorite intrusions. This research is aimed to characterize geological, mineralogical and geochemical variations of igneous rocks from Batur paleovolcano to understand its petrogenesis. Detailed geological mapping with scale of 1:12,500 is conducted to identify geological aspects and delineate igneous rocks distributions. Igneous rocks and selected wall rocks samples were prepared for laboratory analysis including 8 samples for petrography and 5 samples for ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometry) analysis. Several geochemical data from previous study are also added to investigate the geochemical variations. Geological condition of the research area consists of four rock units including colluvial deposit, limestone, andesite lava and diorite intrusion. Geological structures found are normal fault and shear joint where the main stress direction is north–south. Petrography analysis showed that igneous rocks in this research area consist of diorite intrusion and andesite lava with phorphyritic texture. Plagioclase become the most abundant minerals found both as phenocryst phase and groundmass. Hornblende only occur as phenocryst phase in minor amounts as accesory mineral. Major elements geochemistry analysis showed the rocks are characterized by intermediate silica with low alkali content. They are can be categorized as calc-alkaline series. However, some samples are fall into tholeiitic series. Major elements variation and textural study also indicate the magma is experienced differentiation process by fractional crystallization mechanism. This study suggests that igneous rocks from Batur paleovolcano is formed by two phases of formation. Earlier phase is the formation of andesite lava in island arc tholeiitic tectonic setting then at the later phase is formation of diorite intrusion in the calc-alkaline basalts tectonic setting.

Keywords: Igneous rocks · Batur paleovolcano · Petrogenesis · Calc-alkaline basalt · Major elements · Yogyakarta.

1 INTRODUCTION

Batur volcanic complex is located in southernmost of Gunungkidul area next to Hindia Ocean. Administratively, it is located in Wediombo Beach area, Girisubo district and is interpreted as paleovolcano (Hartono and Bronto, 2007). It is characterized by an isolated hill composed by several intrusion, lava and volcanic breccia facies and is surrounded by Wonosari Formation limestone. Petrogenetic study had been carried out by Hartono and Bronto (2007) by volcanostratigraphy and major elements geochemistry approach. However,

*Corresponding author: F. HAKIM, Department of Geological Engineering, Universitas Gadjah Mada. Jl. Grafika 2 Yogyakarta, Indonesia. E-mail: fahmihakim@ugm.ac.id

only 3 samples are used for that analysis. This research will provide more sufficient samples both from intrusion and lava in order to understand the geological framework and petrogenesis of Batur paleovolcano in more detailed scale and systematic based on its geochemical signatures.

2 Regional Geology

Physiographically, this studied area is part of southern mountains complex especially Gunung Sewu sub-zone. Southern mountains are an ancient magmatic arc (Oligo-Miocene) composed by series of volcanic and flysch-like deposits (Toha, 1994). Several formations can be found adjacent to this studied area including Mandalika, Semilir, Wuni and Wonosari Formation. Those formations mostly composed by volcaniclastic-mix siliciclastic facies resulted by Oligo-Miocene volcanism except the Wonosari formation which is dominated by carbonate facies. Volcaniclastic facies is resulted by Oligo-Miocene volcanism. Surono *et al.* (1992) mentioned that Batur paleovolcano is part of Wuni formation which is composed by several lithologies including agglomerate, tuffaceous sandstone siltstone and limestone. The location of study area related to regional geology map can be seen in Figure 1.

Sjarifudin and Hamidi (1992) in Blitar quadrangle geological map indicate that Wuni formation is composed by andesitic breccia, lahar, and basalt with tuffaceous sandstone intercalation. Wuni formation is interfingered with Wonosari formation. Structural analysis by Hartono and Bronto (2007) using SRTM image indicates 3 main lineament patterns dominated by N–S and NW–SE direction and minor W–E direction.

3 Methodology

Detailed geological mapping using 1:12,500 scale topographic map is conducted to understand the geological framework of this studied area. Detailed petrographic analysis using point counting method of 8 representative samples was carried out at Optical Geology Laboratory, Department of Geological Engineering, Universitas Gadjah Mada. Five samples consist of 2 lavas and 3 intrusive rocks were selected for geochemical analysis using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) in ALS Minerals Laboratory, Vancouver, Canada. Several additional major elements geochemistry data from previous study by Hendrawan (2017) are added to compare the major elements variation of igneous rock in studied area.

4 Results

4.1 Local geology

Batur paloevolcano was formed in 13.22 Ma and can be categorized as Paleogene (Eocene-Middle Miocene) magmatic belt (Setijadji and Watanabe, 2009). This section will be focused in lithological and structural framework of the studied area.

Four lithological unit can be found in this studied area including colluvial deposit, limestone, diorite intrusion and andesite lava (Figure 2). Colluvial deposit mostly composed by soil mixed with several rock fragments that fall down and deposited near surrounded area. Andesite lava and limestone fragments are commonly found within this colluvial. Limestone is underlain unconformably and characterized by several dissolution features as the result of karstification process. Foraminera's fossil and shell fragments are commonly found as well as the carbonate minerals. This limestone can be classified as wackestone and packstone. Diorite intrusion unit covers an area about 0.75 km^2. It can be easily distinguished by its medium to coarse grained holocrystalline (porphyritic) texture and relatively in fresh condition (Figure 3E–H). It forms an isolated hill surrounded by andesite lava (Figure 4D). Collumnar joint is the most common features in this intrusion. Andesite lava covers an area about 1.75 km^2 and can be found either in fresh or weathered condition (Figure 3A–D). Autoclastic breccia is the most common features found in this unit.

Both joint and fault can be identified in this studied area. As mentioned before, columnar joints are commonly found in intrusive unit (Figure 4B) while shear joints mostly found in lava unit (Figure 4C). Based on shear joint direction, it can be inferred that it was formed by NNW–SSE stress. Striated fault plane with direction N115°E/55° and N128°E/43° can be identified at the contact between intrusion and lava unit (Figure 4A). Based on stereographic

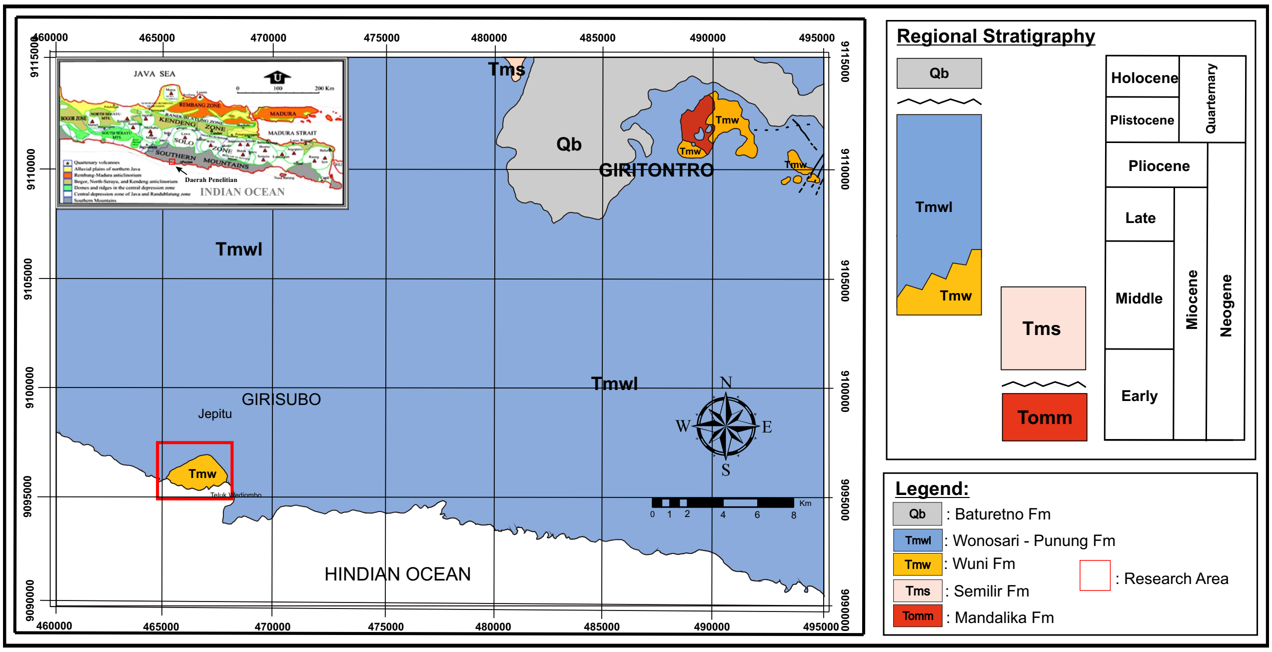

Figure 1: Regional geology of Batur Paleovolcano as the part of southern mountains and located in the southernmost of Central Java adjacent to the Hindia Ocean (modified after Surono *et al.*, 1992; physiographic index from Bemmelen, 1949)

analysis, it can be inferred that those faults are resulted by E–W extensional stress. This extensional stress is triggered by the main N–S compressional stress and possibly formed during uplifting process of southern mountains.

4.2 Petrographic characteristics

Petrographic observation shows that several minerals can be identified including plagioclase, hornblende, quartz, volcanic glass and others opaque and accessory minerals. Various texture also can be identified both in lava and intrusion samples. Mineralogical assemblage of igneous rocks both lava and intrusion from Batur Paleovolcano based on point counting analysis resumed in Table 1.

Intrusive rock is dominated by diorite. Crystal size ranges in diorite intrusion from <0.01–0.6 mm dominated by subhedral plagioclase. It is mostly holocrystalline and porphyritic texture. Oscillatory zoning and carlsbad twinning are commonly found within plagioclase crystals. Spherulite texture is also found in diorite intrusion (Figure 5A–B). Hornblende and opaque minerals also can be identified as phenocryst phase while the groundmass is dominated by plagioclase (Figure 5C–D). Clays and calcite are rarely found as secondary minerals resulted by weathering process. Oligoclase and andesine are the most common plagioclase found in this intrusion. Xenolith fragments also can be found which has the same mineral assemblage as diorite but coarser in texture and crystal size (Figure 5E–F).

Andesite lava is characterized by brownish grey colored and hypocrystalline. Crystal size ranges from <0.01-0.8 mm dominated by plagioclase both as phenocryst phase and groundmass. Hornblende and opaque minerals are also common in this andesite lava. Oscillatory zoning also commonly found within plagioclase crystal. It can be easily distinguished by trachytic texture resulted by lava flow process (Figure 5G–H). Clay minerals and chlorite are commonly found as secondary minerals replacing either plagioclase, mafic minerals or volcanic glass.

Mostly of andesite lava in the form of autoclastic breccia. Matrix part of autoclastic breccia showing the andesitic composition (Figure 5I–J). This autoclastic breccia is characterized by its fragment has similar composition with its matrix (Figure 5K–L).

4.3 Major elements signatures

Generally, the igneous rocks from Batur paleovolcano fall into intermediate composition based on total alkali silica (TAS) classification

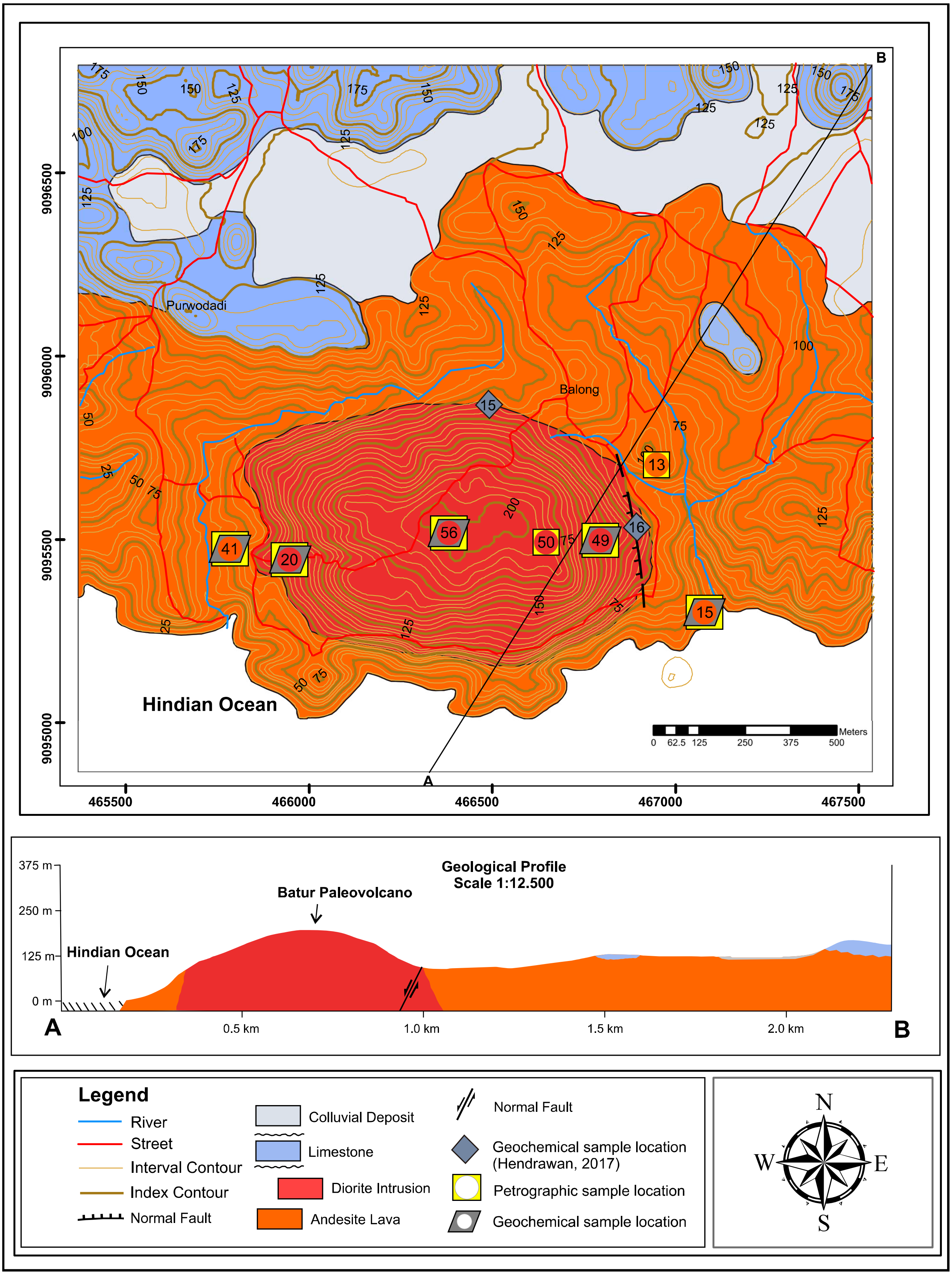

Figure 2: Geological map of Batur paleovolcano and surrounded area showing the stratigraphical relationship between each rocks facies.

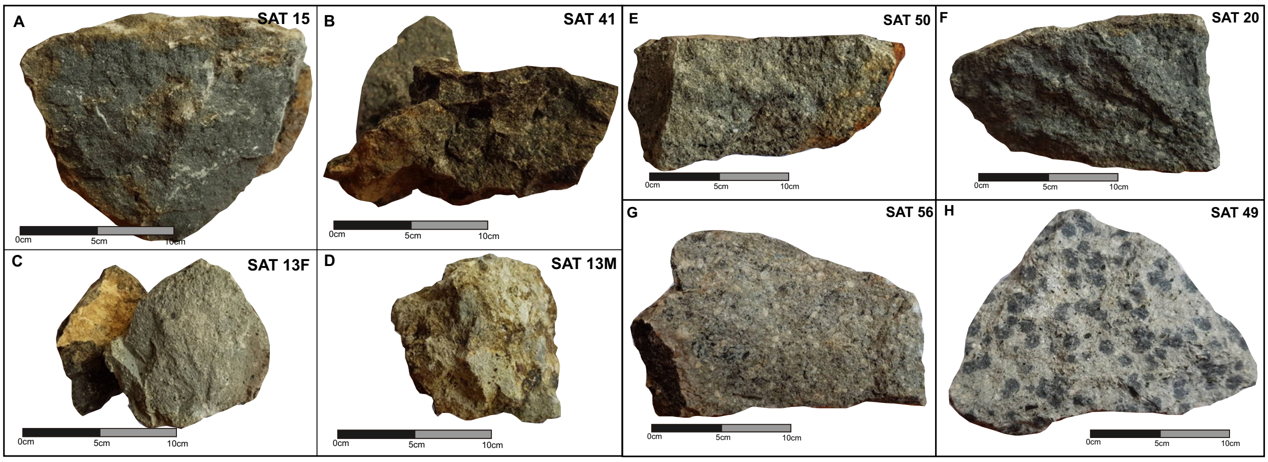

Figure 3: Andesite lava samples (A–D) showing various weathering intensity while the diorite intrusion samples (E–H) typically fresh and has porphyritic texture.

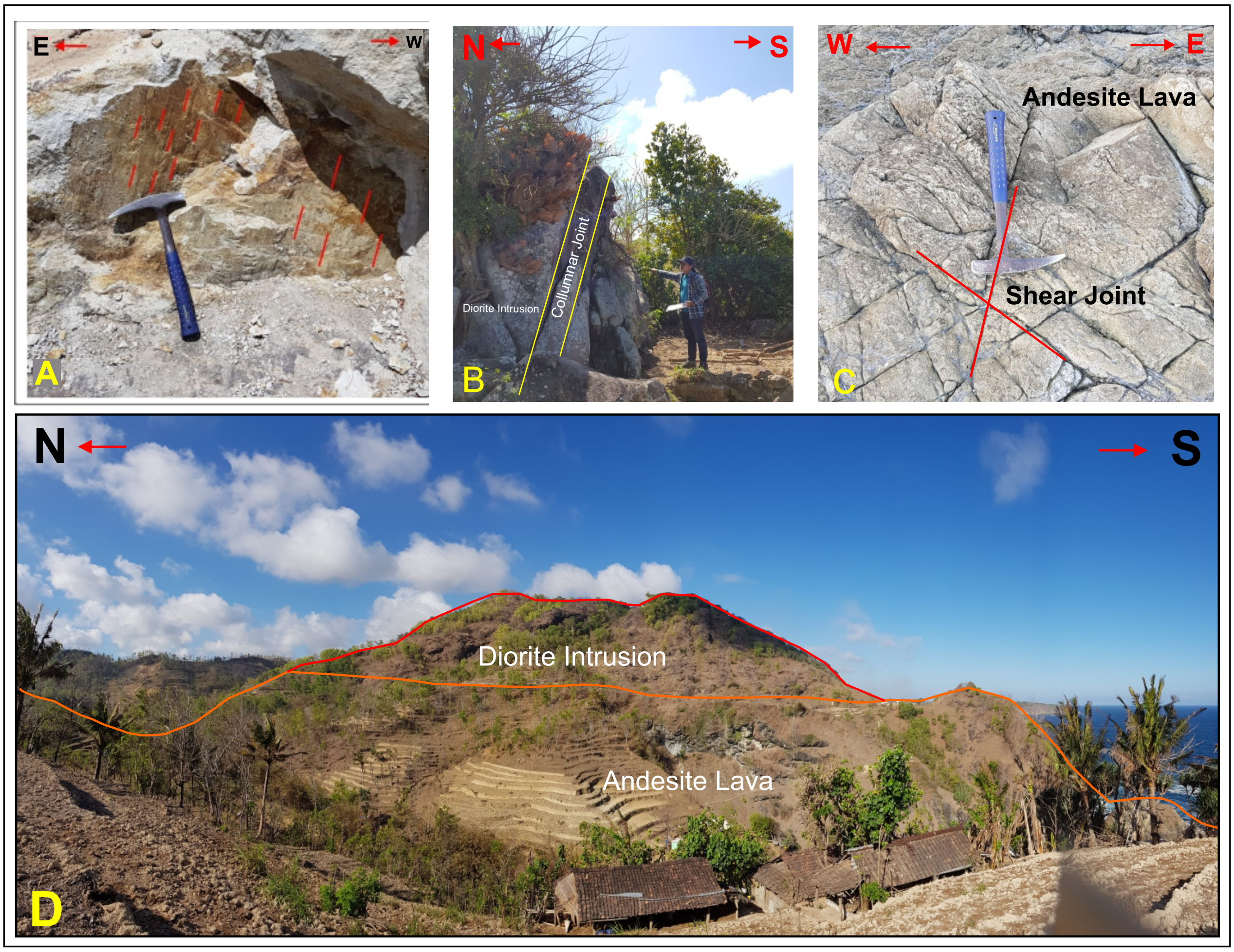

Figure 4: Geological condition of research area. (A) Normal fault plane with its striations. (B) Diorite intrusion with collumnar joints. (C) Most of shear joints are found in andesite lava. (D) Landscape of diorite intrusion as isolated hill surrounded by andesite lava.

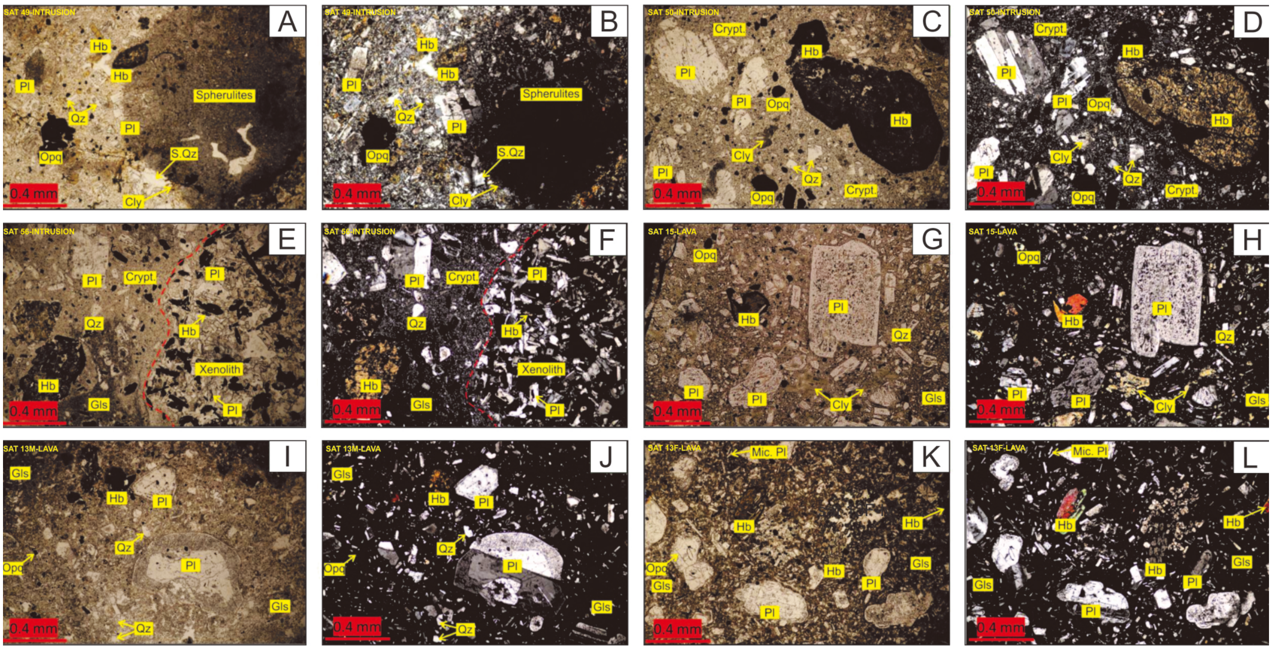

Figure 5: (A–B) Spherulite texture within diorite intrusion. (C–D) Hornblende and plagioclase as phenocryst phase in diorite intrusion. (E–F) Xenolith fragment within diorite intrusion. (G–H) Trachytic texture as typical characteristic of andesite lava. (I–J) Matrix part of autoclastic breccia showing the andesitic composition. (K–L) Fragment part of autoclastic breccia has similar composition with the matrix. Abbreviations: Pl = plagioclase, Hb = hornblende, Xen = xenolith, Opq = opaque, Qz = quartz, Gls = volcanic glass, Cal = calcite, Cly = clay minerals, Crypt = plagioclase (groundmass), Hem = hematite, Chl = chlorite.

(after Cox *et al.*, 1979). The lava samples can be classified as andesite while the intrusions are diorite (Figure 6). Silica content ranges from 59–63.16% while total alkali (Na_2O+K_2O) ranges from 3.59–4.51%. Previous studies also indicate the consistent result (Hendrawan, 2017; Hartono & Bronto, 2007). However, one sample from Idrus *et al.* (2014) has higher silica content and fall into dacite field.

Harker variation diagram which can be seen in Figure 7 is used to understand the differentiation process by combining the samples from this study and Hendarawan's (2017). Some major elements show a distinctive trend while the rest mostly have scattered result due to limited data. Na_2O and K_2O typically show positive trend as the result of normal feldspar crystallization process. Negative trends are shown by TiO2, MgO, CaO and P_2O_5, which indicate the fractional crystallization of mafic minerals. While MnO and Al_2O_3 mostly scattered due to higher LOI result from Hendrawan's sample. Al_2O_3 value is mostly high as represented by the abundance of plagioclase. Results on major elements geochemistry of the igneous rocks from Batur Paleovolcano compared with Hendrawan (2017) can be seen in Table 2.

Three different affinities diagram is used to characterize the magma series. Based on AFM ternary diagram (after Kuno, 1968) all the samples fall in calc-alkaline series field (Figure 8A). The SiO_2 vs K_2O binary diagram (Peccerillo and Taylor, 1976) show that most the samples can be classified as tholeiitic series but only one sample (AH-18) that fall into calc-alkaline series (Figure 8B). Tectonic setting classification based on TiO_2–$MnO\times10$–$P_2O_5\times10$ (Mullen,1983) shows that the igneous rocks were formed in the transition of calc-alkaline basalts and island arc tholeiitic setting (Figure 8C). Whereas FeO_{total}/MgO vs SiO_2 binary plot (after Miyashiro, 1974) show that most samples fall into calc-alkaline series except 2 andesite lava (SAT41 and AH43) which fall into tholeiitic series (Figure 8D).

5 DISCUSSION

This section will mainly discuss about the magmatic evolution process and petrogenesis of the Batur paleovolcano. Interpretation will

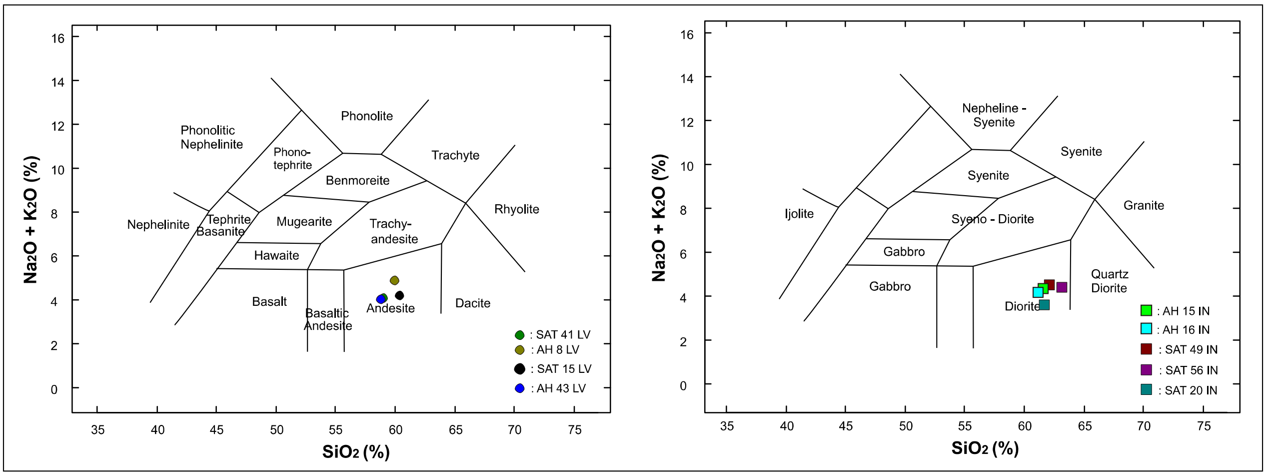

Figure 6: General igneous rocks classification based on total alkali-silica content showing that all the igneous rocks have intermediate composition where the lava can be classified as andesite (A) and the intrusion can be classified as diorite (B) (after Cox *et al.*, 1979)

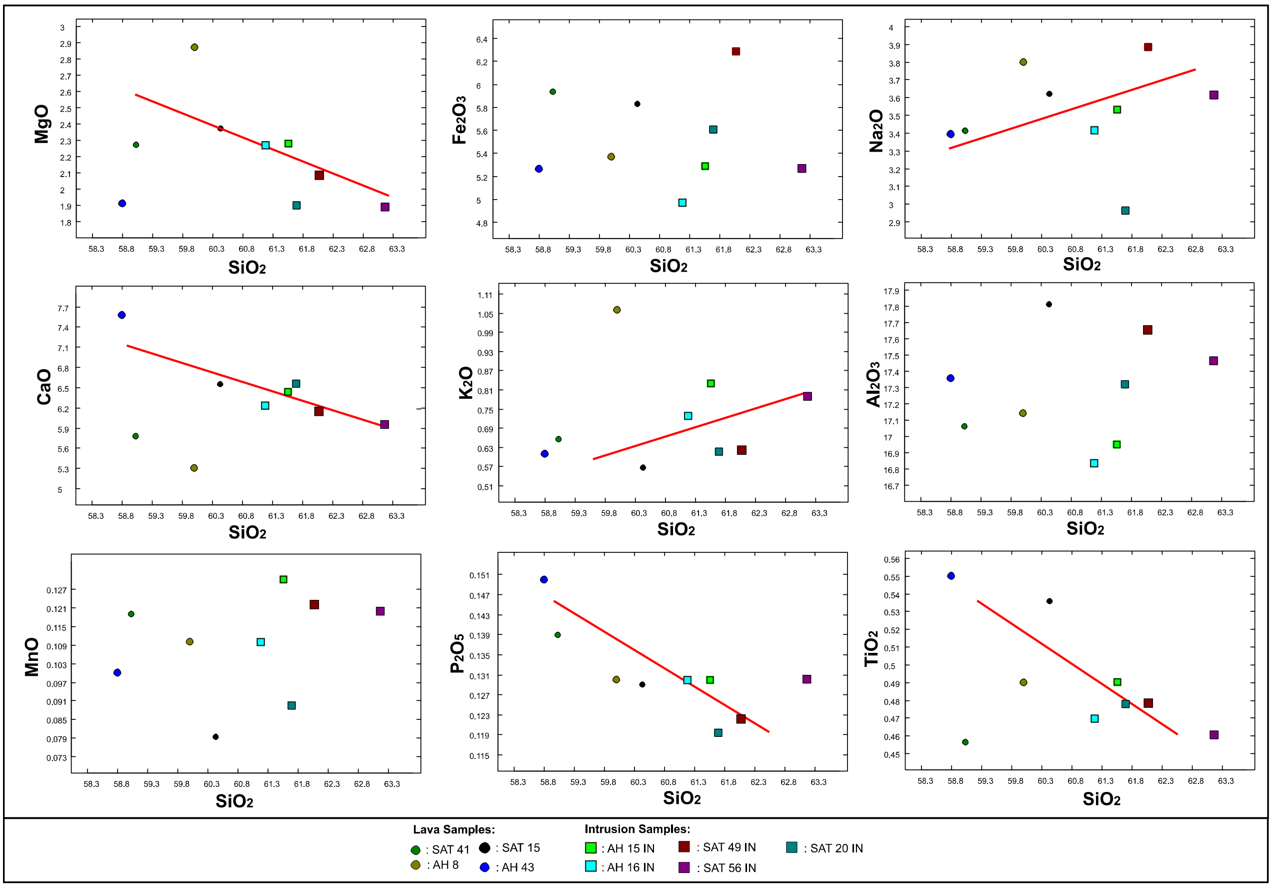

Figure 7: Harker variation diagrams showing the magma differentiation process as indicated by positive trends of SiO_2 vs Na_2O–K_2O and negative trends of SiO_2 vs MgO–CaO–P_2O_5–TiO_2.

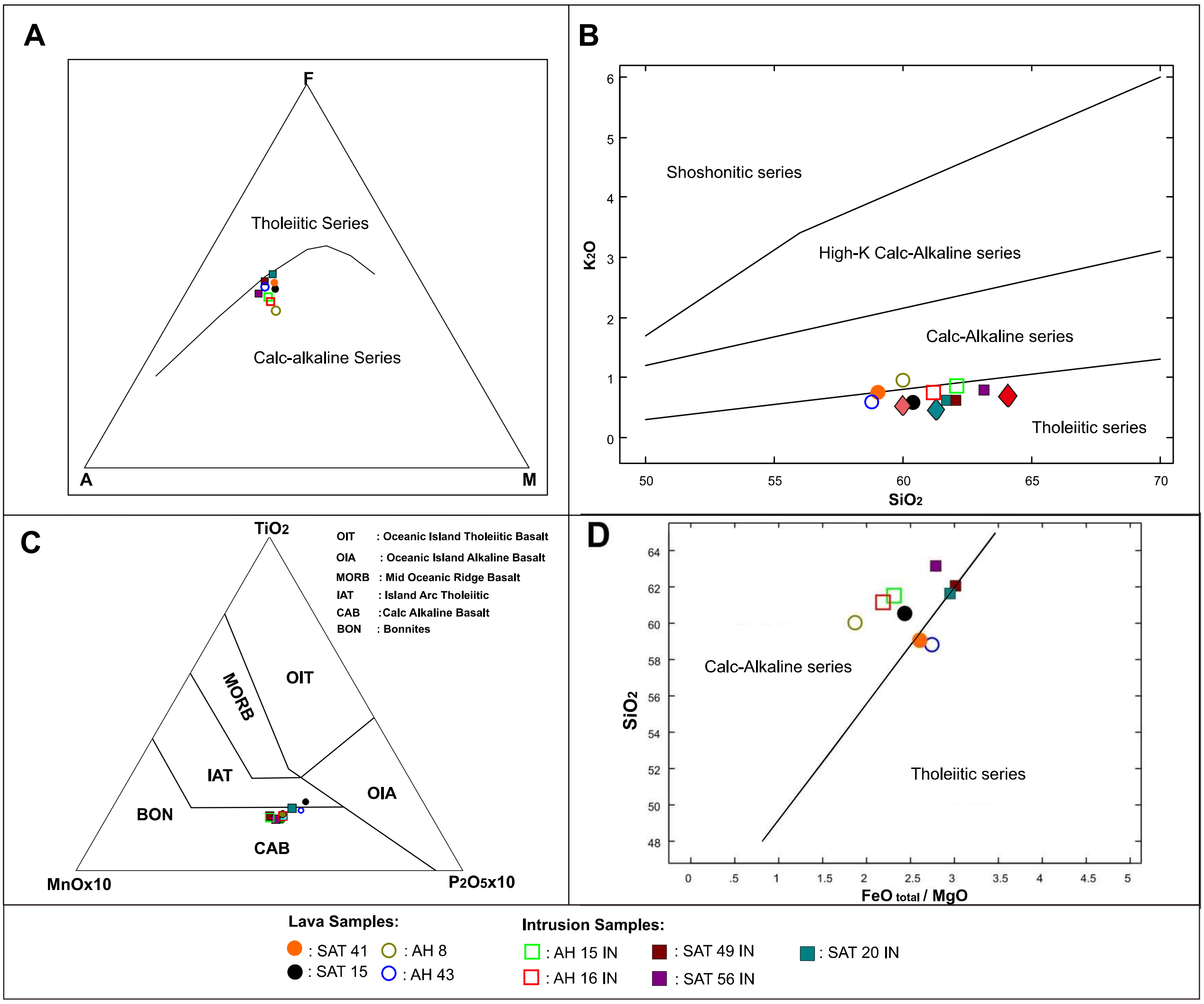

Figure 8: (A) The AFM ternary diagram (after Kuno, 1968) shows that all samples fall into calc-alkaline series. (B) K_2O vs SiO_2 binary diagram shows that most samples are falling into tholeiitic series (after Peccerillo and Taylor, 1976). (C) Tectonic setting classification based on TiO_2-$MnO \times 10$-$P_2O_5 \times 10$ (after Mullen, 1983) shows that the igneous rocks were formed in the transition of Calc-Alkaline Basalts (CAB) and Island Arc Tholeiitic (IAT) setting. (D) FeO_{total}/MgO vs SiO_2 binary plot (after Miyashiro, 1974) show that most samples fall into calc-alkaline series.

be made based on mineralogical, texture and major element geochemistry from this study and compared to previous result from another nearby paleovolcanic center in southern mountains.

Petrographic analysis shows that both intrusion and lava have porphyritic texture which indicates two phase of crystallization process. First phase is formed in the deeper location while the second phase is resulted by rapid cooling during volcanism activity when magma is rising up. Magma differentiation also indicated by the presence of oscillatory zoning texture. This zoning texture is formed due to pressure and temperature change during magma raising and volatile release during magmatic eruption which causes plagioclase compositional differentiation (Fenner, 1926 in Johannsen, 1939). Spherulitic texture as shown in sample SAT-49IN (Figure 5A–B) indicates a devitrification process in high temperature condition (McPhie *et al.* 1993).

Based on ternary diagram of Mullen (1983) using TiO_2, $MnO\times10$, $P_2O_5\times10$ data indicate that all the igneous rock from Batur paleovolcano is formed in calc-alkaline basalts tectonic setting as consistent as the AFM ternary plot result (Figure 8C). Calc-alkaline is typical magma resulted from subduction zone (Wilson, 1989). Simmilar result also shown by binary plot of FeO_{total}/MgO vs SiO_2 binary plot (after Miyashiro, 1974). However, different result is shown by binary plot of K_2O vs SiO_2 which is tholeiitic. Tholeiitic series is typical of magma resulted from initial stage of island arc formation. If we compare those results, it can be interpreted that lava samples can be categorized as tholeiitic series which mean it formed durng the initial stage of Batur paleovolcano formation while the intrusion can be categorized as calc-alkaline series which formed during the later stage as the result of magma differentiation process from the same magma source.

Differentiation process is dominated by fractional crystallization as indicated by harker variation diagram and the presence of oscillatory zoning texture. Assimilation process also occur as indicated by the presence of xenolith within intrusion body. However, this xenolith has the same dioritic composition which has no implication to the main magma composition. If

Table 1: Mineralogical assemblage of igneous rocks from Batur Paleovolcano based on point counting analysis.

Sample ID		Phenocryst (%)					Groundmass (%)										Total (%)
		Pl	Hb	Xen	Opq	Qz	Pl	Hb	Opq	Qz	Gls	Cal	Cly	Crypt	Hem	Chl	
INTRUSION	SAT 20	32	8	-	2	-	-	-	-	-	-	3	5	50	-	-	100
	SAT 50	29	12	-	2	5	-	-	-	-	-	-	4	48	-		100
	SAT 49	21	8	-	1	13	-	-	-	2	-	-	6	49	-	-	100
	SAT 56	24	8	2	4	10	-	-	-	-	5	-	-	40	-	-	100
LAVA	SAT13F	27	8	-	3	7	16	-	-	-	35	-	-	-	-	4	100
	SAT13M	28	7	-	2	8	12	-	5	-	36	-	-	-	2	-	100
	SAT 15	20	8	-	3	-	-	-	-	-	61	-	3	-	-	5	100
	SAT 41	35	10	-	6	4	-	-	-	-	37	-	-	5	-	3	100

Abbreviations: Pl = plagioclase, Hb = hornblende, Xen = xenolith, Opq = opaque, Qz = quartz, Gls = volcanic glass, Cal = calcite, Cly = clay minerals, Crypt = plagioclase (groundmass), Hem = hematite, Chl = chlorite.

Table 2: Major elements geochemistry of the igneous rocks from Batur Paleovolcano.

Sample	Diorite Intrusion					Andesite Lava			
	This Study			Hendrawan (2017)		This Study		Hendrawan (2017)	
	SAT 20	SAT 49	SAT 56	AH 15	AH 16	SAT 15	SAT 41	AH 8	AH 43
Major Elements									
SiO_2	61.69	62.07	63.16	61.56	61.18	60.43	59.03	60.00	58.80
Al_2O_3	17.32	17.56	17.47	16.95	16.83	17.81	17.06	17.14	17.35
Fe_2O_3	5.60	6.29	5.26	5.29	4.97	5.82	5.93	5.37	5.26
CaO	6.56	6.15	5.96	6.44	6.24	6.55	5.77	5.30	7.57
MgO	1.90	2.09	1.89	2.28	2.27	2.37	2.27	2.87	1.91
Na_2O	2.97	3.89	3.61	3.53	3.42	3.62	3.41	3.80	3.39
K_2O	0.62	0.62	0.79	0.83	0.73	0.57	0.65	1.06	0.61
Cr_2O_3	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01
TiO_2	0.48	0.48	0.46	0.49	0.47	0.54	0.46	0.49	0.55
MnO	0.09	0.12	0.12	0.13	0.11	0.08	0.12	0.11	0.10
P_2O_5	0.12	0.12	0.13	0.01	0.13	0.13	0.14	0.13	0.15
SrO	0.04	0.04	0.05	0.07	0.06	0.04	0.04	0.04	0.04
BaO	0.02	0.02	0.04	0.02	0.02	0.01	0.02	0.01	0.01
LOI	2.46	0.46	1.06	2.39	3.56	2.05	5.28	3.67	4.25

we compare to Pliocene volcanic rocks characteristics from Dana (2017) which represent the second cycle of volcanism, it can be shown that samples from this study has more felsic composition. However, samples from this study also have more felsic compositions in compared to the volcanic rocks from Old Andesite Formation (Ismail, 2016) but same composition with samples from Setijadji (2006). Based on those comparations, it can be interpreted that igneous rocks from Batur paleovolcano can be categorized as the part of later stage of Bemmelen's (1949) first cycle volcanism.

6 CONCLUSION

Batur paleovolcano is characterized by both calc-alkaline and tholeiitic series of igneous rocks which formed in Calc-Alkaline Basalts (CAB) and Island Arc Tholeiitic (IAT) tectonic setting. Igneous rocks consist of andesite lava which was formed at the initial stage (tholeiitic) and diorite intrusion which was formed during the later stage (calc-alkaline) as the result of magma differentiation process by fractional crystallization mechanism.

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