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Long-Term Volcanic Evolution Surrounding Dieng Geothermal Area, Indonesia

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ABSTRACT

The Dieng Volcanic Complex (DVC), in the Central part of Java Island, is characterized by a collapse structure containing 17 post intra-caldera eruptive centers. This volcanic complex shows long-term volcanic activity of about 3 M.y. and is possibly record the long-term magma evolution at a single volcanic complex. The volcanic edifices in DVC can be grouped into three stages, namely pre-caldera (~3 Ma), post-caldera I (~2 to 1 Ma) and post-caldera II (< 1 Ma). Major element rock compositions suggest that the DVC magma cyclically evolved from basaltic to dacitic composition. Both pre-caldera and post-caldera I have a wide range of composition from basalt to dacite, in contrast the post-caldera II ranges from andesite to dacite. Phenocryst assemblage of all the stage show similar composition including plagioclase, clinopyroxene, orthopyroxene, olivine and magnetite. The post-caldera II lava also contain biotite phenocrysts and are richer in groundmass glass. The increase of silica content is followed by increasing potassium content ($K_{57.5}$) so that we can distinguish medium-K and high-K magmatism in early and late stage of each group in pre- and post-caldera.

Harker diagrams indicate that magma in DVC is differentiating from the same magma source. Chondrite normalized incompatible element plots show similar patterns among for all edifices, and are typical of the island arc compositions, with enrichment of LILE and LREE compared to HSFE and HREE. Ta/Nb and Zr/Nb ratios of the lava from all stages are similar and range from 0.04 to 0.1 and 16 to 37, respectively, indicating that the mantle composition beneath DVC is still the same and resembles the ratio of Indian MORB. Ce/Pb and Th/Yb ratios indicate the contribution of continental material either as crustal contamination during the passage of magma to surface or sediment influx during partial melting. There are no significant geochemical differences among magmas at DVC.

1. INTRODUCTION

Volcanic rock compositions depend on many factors including the contribution of slab-derived fluid, sediment influx, and heterogeneity of mantle wedge. Furthermore, the ascending magmas undergo differentiation processes involving magma mixing, fractional crystallization and crustal assimilation during its passage to the surface (e.g. Edwart, 1982; Davidson et al., 1987; Hildreth and Moorbarth, 1988; Tepley et al., 2000).

Most of the discussions on magma composition are emphasized in the along and across arc variation. The Sunda arc is considered an ideal example of geochemical composition variation of magma across an arc. Whitford (1975) documented the increase of K_2O content towards the back-arc for the Quaternary lavas of the Sunda arc, whereas the shift from medium-K to high-K composition in the single volcano has been documented at Merapi by Gertisser and Keller (2003). Edwards et al. (1993) indicate homogenous slab contribution along Sunda arc, but Turner & Foden (2001) identified heterogeneity in this component.

The Dieng Volcanic Complex (DVC) is situated on the backarc-side the Quaternary Sunda volcanic arc. The arc has been active since the Tertiary as a result of subduction of the northward moving oceanic crust of the Indo-Australia plate beneath Eurasia plate (Carlile and Mitchel, 1994). Setijadji et al. (2006) classified the DVC as a backarc-side volcano as a part of double volcanic chain consists of Sumbing-Sindoro-Dieng volcanoes. Volcanic activities in DVC are characterized by caldera structure with several volcanic edifices within the caldera. Radiometric age dating using the K-Ar method has indicated that the oldest rocks erupted from the DVC are about 3.6 Ma, while the youngest are 0.07 Ma (Boedihardi et al., 1991). Therefore, the main objective of this study is to understand volcanic evolution within the DVC over this time. In this study we analyzed the chemical and mineral composition of the rocks collected from edifices within DVC.

2. TECTONIC FRAMEWORK

Java Island is situated in the central part of Sunda volcanic arc that has formed due to subduction of northward moving oceanic crust Indo-Australia beneath Eurasia plate extended from Andaman Island to the east through Sumatra, Java, Bali until Flores Island (Hamilton, 1978). The thickness of Eurasia plate beneath Sumatra to Java is about 20 to 30 km (Ben-Avraham and Emery, 1973; Curray et al., 1977; Whitford, 1975) and is around 18 km close to Bali. The subducting plate is an oceanic plate with the age from ~80 Ma to ~130 Ma range from Sumatra to Java (Plank and Langmuir, 1998; Widiyantoro and van der Hilst, 1996). The subduction rate of the Indo-Australian plate beneath Eurasia is 6 to 7 cm/year (DeMets et al., 1990; Tregoning et al., 1994, Simandjuntak and Barber, 1996).

There have been two different configurations of this subduction system. During the Cretaceous subduction extended from Sumatra to Central Java to East Kalimantan, and since Early Tertiary to Recent times, the subduction has extended to the east of Java continuing to Banda arc (e.g., Katili, 1975; Hamilton, 1979; Carlile and Mitchell, 1994; Metchalfe, 1996). Therefore, some researchers believe that the overriding plate in western Java includes continental crust of Sundaland while the crust from eastern Java onwards is transitional to oceanic crust (Miyazaki et al., 1998; Carlile and Mitchell, 1994; Simandjuntak and Barber, 1996). Hamilton (1978) suggested that the boundary of continental crust beneath Java is around Kebumen where mélange rock is exposed in this area to the northeast until east Kalimantan (Fig. 1).

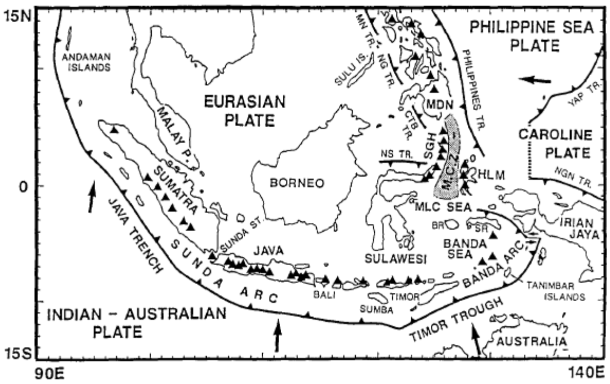

Figure 1: Map of Recent tectonic setting of Indonesia. Sunda arc forms due to northward moving Indo-Australian plate subducting beneath Eurasian plate. Java Island that elongates east-west is parallel to the trench. Map is from Puspito et al. (1992).

3. OVERVIEW OF DIENG VOLCANIC COMPLEX

The DVC is situated on a broad plateau of about 2000 m elevation consisting of several volcanic edifices constructed within a caldera structure with dimensions of about 14 x 6 km^2 (Fig. 2). The caldera structure is most evident where cuts the western flank of Prahu volcano. It is underlain by Tertiary marls, limestones, tuffaceous sandstones and volcanics (Sukhyar, 1994 cited in Van Bergen, 2000). The various edifices of the DVC can be grouped into pre-caldera (~3 Ma), post-caldera I (~2 – 1 Ma) and post-caldera II, or latest stage (<1 Ma), based on their relationship to the caldera structure and their distribution and radiometric ages (Fig. 3). The radiometric age data were determined by K-Ar dating method.

1. The pre-caldera stage consists of Prahu, Rogojembangan and Telerejo the peak of the magma evolution is the explosive eruption of Prahu forming caldera structure.

2. The second period stage or Post-caldera I stage is composed of Nagasari (2.99 Ma), Bisma (2.53 Ma), Sidede, Bucu, and Jimat.

3. The last period or Post-caldera II inludes Pagerkandang (0.46 Ma), Pangonan Merdada (0.37 Ma), Butak, Kendil (0.19 Ma), Pakuwaja (0.09 Ma), Prambanan, Seroja (0.07 Ma), and Sikunir.

4. SAMPLES AND ANALYTICAL TECHNIQUES

In order to understand the evolution of magma composition in the DVC, samples were collected from each volcanic edifice, emphasizing lavas from the summit areas. Since the area includes an active geothermal field, care was taken in selecting samples that were not hydrothermally altered.

In total we collected and analyzed of about 177 rock samples. The sample locations are depicted in Figure 4. The samples generally had a low range of loss on ignition (LOI) between 0.02 and 1.44%. Le Bas et al. (1986) suggested the condition of suitable samples for geochemical analysis having LOI values less than 2%. This indicates that the rocks are fresh and suitable for chemical analysis.

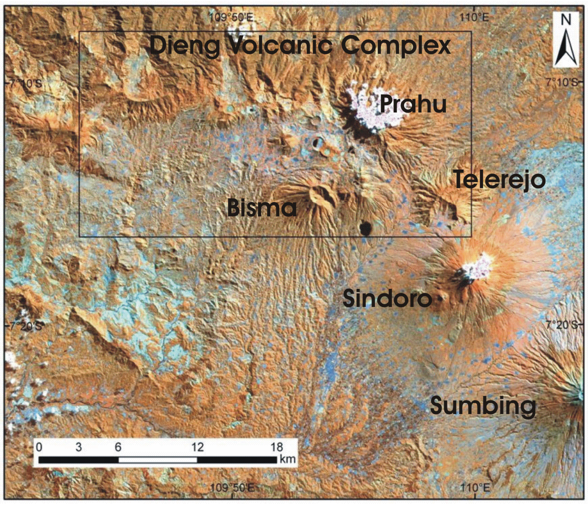

Figure 2: Satellite image of Dieng Volcanic Complex and its vicinity. It shows that DVC is situated in the northern tip of northwesterly trending volcanic chain of Sumbing – Sindoro – Dieng. The trench is located in the south. DVC consists of Prahu volcano that has a caldera collapse structure and several volcanic edifices within the caldera structure.

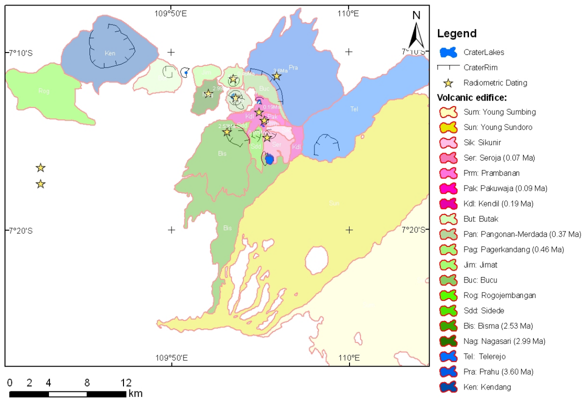

Figure 3: The succession of the volcanic edifices within the Dieng Volcanic Complex. The succession is constructed based on the caldera structure, morphology of volcanics and radiometric data. The radiometric data are from Boedihardi et al. (1991).

Major and trace elements compositions of rocks were analyzed using X-ray fluoresence spectrometer (XRF) using Rigaku RIX 2100 at the Department of Earth Resources Engineering of Kyushu University, whereas Rare Earth Element (REE) compositions were analyzed in a commercial laboratory (ACME). Thin section petrography was carried out at the Department of Geological Engineering, Gadjah Mada University, Indonesia.

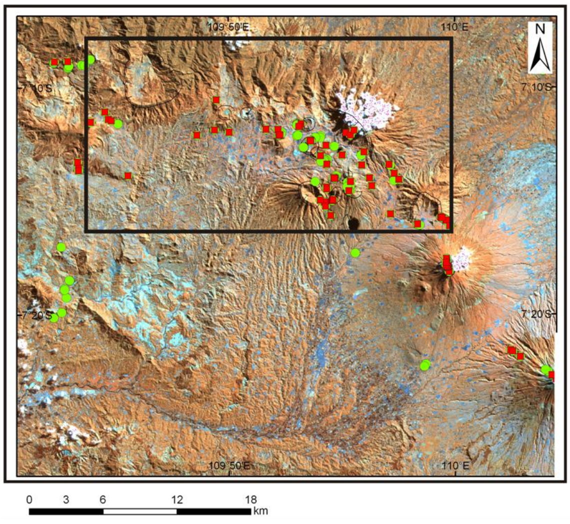

Figure 4: This figure shows the location of samples (red circle) and location of field observation (green circle).

5. THIN SECTION ANALYSIS

Thin section analysis revealed that the composition of lavas in the DVC ranges from basaltic to dacitic. Rock textures were mainly porphyritic with phenocrysts up to 3 mm in size that consisted mainly of plagioclase, olivine, clinopyroxene and orthopyroxene, and rare hornblende. Biotite phenocrysts occurred only in dacitic rocks from Kendil, Seroja and Pakuwaja that are included in the last stage or post caldera II. So far no quartz phenocrysts were found in the rocks from DVC.

Plagioclase in most samples is commonly labradorite in composition, showing compositional zoning and sieve texture. Clinopyroxene in the rocks also shows compositional zoning. Some olivine grains contain iddingsite and have reaction rim at the margin of the grain. The occurrence of iddingsite indicates that the rocks were formed at or near surface (Edwards, 1938).

6. GEOCHEMISTRY

6.1. Major Elements

SiO_2 is commonly used as index of differentiation of evolved magma. Major elements indicate that magmas in the DVC are calc alkaline, having a wide range of SiO_2 from 48 to 65 wt%, typical of subduction zone magmas. The plot of Total Alkali versus Silica (TAS) of Le Bas et al. (1986) is shown in Figure 5, and confirms that the DVC magma compositions range from basaltic to dacitic. The range of SiO_2 of the magma from Pre-caldera stage is similar with that of second stage (Post-caldera I) ranging from 48 to 65%. In contrast, the range of last stage (Post-caldera II) ranges from 52 to 65%. This demonstrates the composition of first and second stages range from basaltic to dacitic, while the third stage ranges from andesitic to dacitic. Overall, magmatism shows a cyclic pattern of differentiation from basaltic to dacitic composition over the past 3 million years.

The Alkali, FeO*, MgO (AFM) diagram of Irvine and Baragar (1971) is shown in Figure 6. It confirms that the composition of rocks in the DVS is calc alkaline and differentiated to higher alkali content and decreasing MgO content. K_2O versus SiO_2 diagram exhibits repetition from medium-K to high-K in each period. K_2O versus SiO_2 of Peccerillo and Taylor (1976) are presented in Figure 7. In general, there is an increase of $K_{57.5}$ value of Pre- and post caldera magma from 1.85, 2.08 and 2.10 respectively. Ni (<14 ppm), Cr (<30 ppm) and MgO (< 6%) concentrations are low in DVC magma.

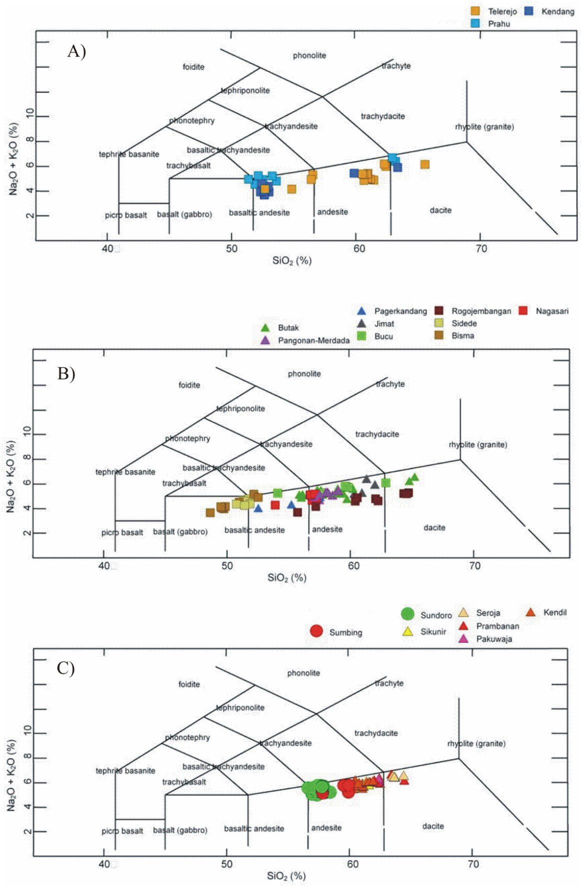

Figure 5: Total Alkali Silica diagram of Le Bas et al. (1986). A) Pre caldera magma of DVC shows wide range from basaltic to dacitic. B) Post-caldera I magma shows wide range of composition from basaltic to dacitic similar to stage 1 or pre-caldera. C) The last stage or post caldera II magma shows narrower is composition from andesitic to dacitic.

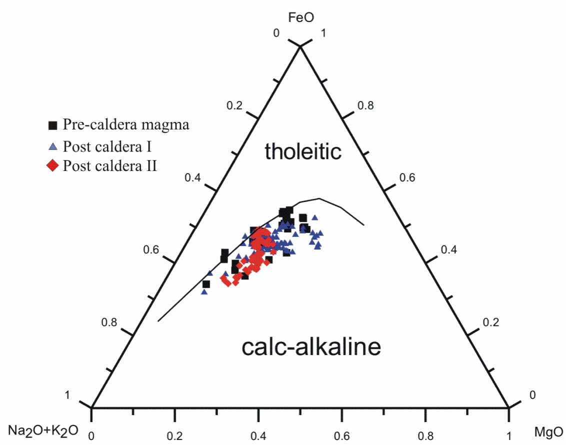

Figure 6: AFM plot of Irvine and Baragar (1971).

6.2 Trace Elements

The result of REE analysis is portrayed in Figure 8. The figure shows that the trace element concentration of DVC magma is enriched in LILE and depleted in HSFE, with a minor negative Eu anomaly that becomes slightly more pronounced in the most evolved rocks. There is no distinctive feature of trace elements concentration among magma in DVC.

7. DISCUSSION

The compositions of parental magmas derived from mantle undergo modification due to differentiation processes such as magma mixing, fractional crystallization and crustal assimilation during ascent. Moreover magma compositions are governed by the proportion of possible source materials during magma formation.

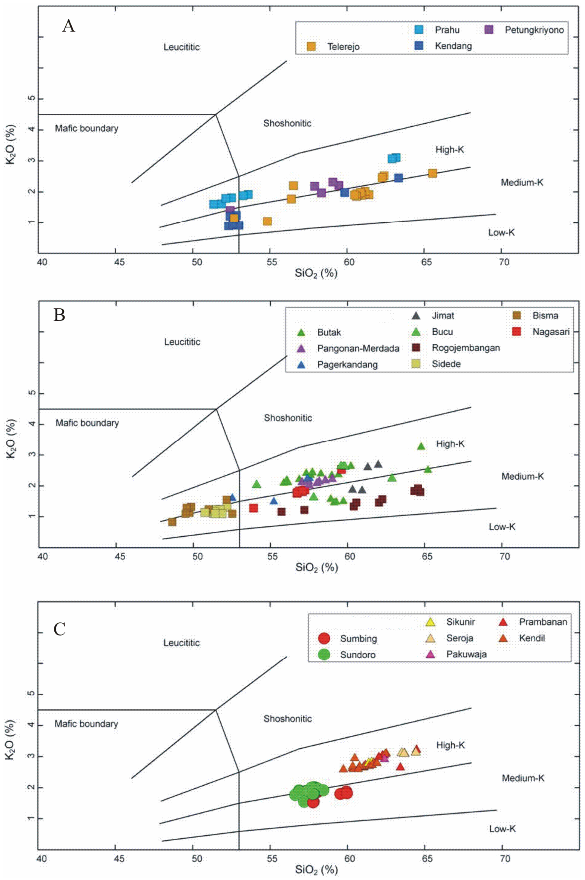

Figure 7: Alkalinity of magma represented by diagram K_2O vs. SiO_2. Peccerillo and Taylor (1976). A and B) Pre-caldera and Post caldera I magmas show alkalinity in the range from medium-K to high-K. C) Post caldera II magma is only high-K.

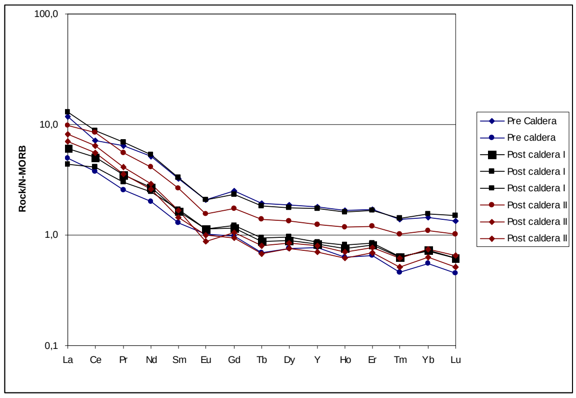

Figure 8: Spider diagram of trace elements from DVC.

Subduction zone magmas are formed in the upper mantle and modified as they ascend through the crust. The primary magma in subduction zone can be deduced based on the chemical composition such as Ni, MgO and Cr. Magmas in DVC have low concentrations of Ni, MgO and Cr, indicating that no primary or primitive magmas were sampled in the DVC. It appears that the magmas that reached the surface were differentiated, resulting in a wide range of composition from basaltic to dacitic.

Magma differentiation in DVC is indicated by distinctive phenocryst assemblages, wide ranges of SiO_2 concentration, and increasing alkalinity. The long-term volcanic activity in DVC indicates that in the single volcanic complex, magma composition may cycle from low to high SiO_2 concentration as a function of time.

The mineral assemblage of the last stage magmatism in the DVC is different with that of previous ones. One distinctive feature of the last stage magma is the occurrence of biotite phenocrysts. The alkalinity of DVC magma increases when the magma differentiates. Moreover, when we compare the alkalinity of each stage using criteria of $K_{57.5}$ values we can see that the alkalinity of magma is also increasing from medium-K to high-K. Such phenomena were also observed at Merapi (Gertisser and Keller, 2003). However, the major elements concentration is not a distinctive criterion to know the cause of alkalinity increment. The differentiation processes in DVC are fractional crystallization and possibly magma mixing. The fractional crystallization is indicated by the similar spectrum of major elements, while the magma mixing is indicated by the coexisting of compositional zoning and sieve texture in plagioclase in DVC magma.

Magma in DVC is enriched in LILE and depleted in HFSE typical of subduction zone magma. Ratio of LILE/HSFE is useful for interpretation of mantle composition and any contamination of sediment material during subduction. Ta/Nb and Zr/Nb ratios of the lava from all stages are similar range from 0.04 to 0.1 and 16.75 to 24.39, (Table 1) respectively; it is similar with those of Ijen Volcanic Complex (IVJ), indicating that the mantle composition beneath DVC is still the same and resemble the ratio of Indian MORB. Ce/Pb and Th/Yb ratios indicate the contribution of continental material, either as crustal contamination during the passage of magma to surface, or sediment influx during partial melting in the mantle.

Table 1. Ratio of trace elements of DVC compared to other selected magma and source component compositions. Data sources: I-MORB: Chauvel and Blichert-Toft (2001); N-MORB: Sun and McDonough (1989); bulk Java sediment: Plank and Langmuir (1998), Ijen Volcanic Complex (IVC): Handley et al. (2007).

Ratio	I-MORB	N-MORB	Bulk Java sediment	IVC	DVC
Ta/Nb	0.07	0.06	0.08	0.07–0.13	0.04 – 0.1
Zr/Nb	26	32	13	14–23,	16.75 – 24.39
Ce/Pb	15	25	3	3–7	0.36 – 4.57
Th/Yb	0.17	0.04	3	1–4	1.56 – 7.84

CONCLUSIONS

Magma in DVC underwent differentiation to have wide range of chemical composition especially SiO_2 and K_2O concentration. The differentiation is due primarily to fractional crystallization and magma mixing.

Trace elements compositions indicate that magmatism in DVC may have crustal or sediment contributions. The crustal composition during magmatism is the same.

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