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Untangling differentiation in arc lavas: constraints from unusual minor and trace element variations at Salak Volcano, Indonesia

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1   **Abstract**

2   Volcanic rocks from Salak Volcano in West Java display intriguing minor and trace

3   element geochemical variations with silica. TiO_2 and P_2O_5 contents, Y, HFSE and REE

4   concentrations are abnormally rich in the central vent group (CVG) lavas (e.g. Y = 32-69

5   ppm; Yb, 3-6.5 ppm) and display striking positive correlations with SiO_2. This contrasts with

6   rocks erupted at side vents (SVG) on the eastern and western flanks of Salak and with rock

7   suites of most other Javan volcanoes where these elements remain relatively constant with

8   increasing SiO_2. Modelling of major and trace element data indicate that low pressure

9   fractional crystallisation exerts strong control on the composition of CVG lavas. HFSE and

10   HREE data are inconsistent with magma mixing, and can be explained by incompatible

11   behaviour during fractionation of plagioclase, clinopyroxene and Fe-Ti oxide $\pm$ orthopyroxene

12   and olivine. The observed variations in K/Rb and Ba/Th ratios and correlation of $^{87}Sr/^{86}Sr$

13   with indices of differentiation necessitate assimilation of a low K/Rb, low Ba/Th, Sr-rich

14   contaminant with $^{87}Sr/^{86}Sr$ of ~ 0.7048 during fractional crystallisation. For the eastern flank

15   SVG, deep fractionation of a phase in which HFSE and HREE are compatible (e.g.

16   amphibole) is implicated. By extension, this is also suggested to occur beneath the majority of

17   Javan volcanoes. Radiogenic isotope ratios (Sr-Hf-Nd) of Salak lavas are similar to other

18   Javan lavas. SVG rocks erupted from the eastern flank vent have significantly more primitive

19   Hf-Nd isotope ratios than other Salak volcanic rocks and may represent the least

20   contaminated (by arc crust or subduction input) Salak lavas.

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22   *Key words*: crustal contamination; fractional crystallisation; geochemistry; HFSE;

23   petrogenesis; Sunda arc

24

1. Introduction

Understanding how geochemical signatures are imparted to arc rocks is problematic. Element compositions in arc lavas are dependent not only on the composition of the primary magma from which they originated, but also on the multitude of differentiation processes primary magma may suffer en route to the Earth's surface. Therefore elucidating composition-modifying processes in arc lavas is a prerequisite before the nature, composition and components of the source can be determined. Among the variety of processes capable of masking element concentrations of primary magmas, fractional crystallisation, crustal contamination and magma mixing (e.g. Ewart, 1982; Davidson et al., 1987; Hildreth and Moorbath, 1988; Tepley et al., 2000) are commonly identified in arc lavas.

Separate differentiation trends occur in lavas from within the single volcanic centre at Salak Volcano in West Java, and so this volcano provides a great opportunity to study the impact of shallow level processes on the composition of arc lavas. The steeply-sloped, positive correlations of HFSE (high field strength elements) and HREE (heavy rare earth elements) with indices of differentiation displayed by rocks erupted from the central vent at Salak are highly unusual compared to most other Sunda arc volcanic rock suites. This paper constrains the relative importance of various differentiation processes at Salak, in order to explain the abnormal HFSE-HREE differentiation trends displayed by the central vent eruptive products and their genetic relationship to flank vent volcanic rocks. This information is essential before the characteristics of the source can be investigated and it will aid in elucidating the nature of crust in West Java, of which relatively little is known. We suggest that fractionation of an (unseen) HFSE-HREE bearing phase plays an important role in the chemical evolution of most Javan island arc magmas.

2. Tectonic setting

1 Gunung Salak, 2211m, is a prominent stratovolcano located in the Quaternary volcanic

2 front of the Sunda arc in West Java. The Sunda arc stretches from the Andaman Islands north

3 of Sumatra to Flores in the Banda Sea and has developed as a result of the 6-7cm^{-1} northward

4 migration and consequent subduction of the Indo-Australian Plate beneath the Eurasian Plate

5 (Le Pichon, 1968; DeMets et al., 1990; Tregoning et al., 1994). The tectonic features of the

6 area have been described in detail by Hamilton (1979). Beneath Java (and Salak) the crust is

7 ~20 km thick and has a 'quasi-continental' seismic velocity structure, intermediate between

8 continental and oceanic (Ben-Avraham and Emery, 1973, Curray et al., 1977; Jarrard, 1986).

9 Further east, seismic data indicate that the crust is ~18 km thick near Bali and 5-10 km

10 beneath Flores (Curray et al., 1977). The south-eastern boundary of Sundaland (SE Asian

11 continental part of the Sunda block/Eurasian plate with pre-Tertiary basement) is suggested

12 by Hamilton (1979) to be located in West Java. However, due to limited knowledge of the

13 precise structure and composition of the Javan crust, the exact location and nature of this

14 boundary remain unknown.

15

16 **3. Geology of Salak and sampling details**

17 Salak forms the north-eastern part of the Salak-Perbakti-Gagak volcanic massif (Fig. 1),

18 which consists of Upper Pleistocene to Recent stratovolcanoes, parasitic vents and

19 phreatomagmatic craters. The Perbakti-Gagak range to the south-west is strongly eroded.

20 Both areas in the north-east and south-west are sites of extensive hydrothermal activity.

21 Intermittent volcanism occurred at Salak between ~0.2 to 1.2 my ago (Stimac, 2003). In

22 historic time, volcanic activity at Salak has been limited to a number of phreatic explosions

23 occurring at side vents on the flanks of the volcano. The summit area of Salak is characterised

24 by two large breached craters, one open to the northeast and another to the southwest (Fig. 1),

25 which are associated with volcanic sector collapse events. The westernmost crater was the

1   source of a large debris-avalanche deposit which extends over 10 km from the summit.

2   Satellitic cones are mainly found on the south-west flank of Salak and on the northern

3   foothills on the eastern side of the volcano. A late-stage dome built on the western crater rim

4   is a result of the most recent activity.

5   The volcanic products of Salak can be divided into two main groups based on eruption

6   location: those erupted from the central vent (CVG) and those erupted from flank or side

7   vents (SVG). The CVG, consisting of multiple lava flows and pyroclastic units, dominates the

8   volcanic deposits at Salak and therefore the majority of samples in this study were collected

9   from this group (filled circles, Fig. 1). SVG samples S102 and S103 were taken from lava

10   flows erupted from a side vent on the eastern slope of Salak. S107A and S107B SVG samples

11   are from the western flank. Sampling of SVG products for geochemical analysis on the

12   western flank was of limited success due to extensive alteration of lava caused by

13   hydrothermal activity. Sample S112 is from a lava flow (SL3) thought to originate from the

14   main vent (CVG) (Zaennudin et al., 1993). However, this sample is geochemically similar to

15   the SVG samples in major and trace element composition. This unit extends down the western

16   flank of Salak, therefore it is possible that S112 may have been erupted from one of the

17   western side vents. As a result of uncertainty in the provenance of this sample it is

18   distinguished from the other samples in all diagrams. Two pumice samples collected on the

19   western slope of Salak (S100 and S101) are from extensive airfall deposits related to pre-

20   Salak activity (Zaennudin, et al., 1993). These deposits are overlain by thinner airfall deposits

21   from Salak. Limited dating has been carried out on Salak-Perbakti-Gagak volcanic products

22   (Stimac, 2003). Reliance on geological maps and relative stratigraphy in this study limits a

23   detailed temporal evaluation of Salak lavas and therefore this is not carried out here.

24

25   **4. Analytical techniques**

1   Mineral analyses were performed on carbon-coated polished slides of selected Salak

2   volcanic rocks using a Cameca SX 100 at the University of Manchester NERC facility. The

3   accelerating voltage was 15kV and beam current was 2nA. Detection limits (wt%) for Al, Mg,

4   K, Ca, Ti are 0.01 or lower, Na, Si, Cr, Ni are around 0.03, while Fe is slightly higher around

5   0.08. Element precision is dependant on the mineral being analysed, but was typically less

6   than 1% for Ca, Ti, Si, Al and Mg, between 1-2% for Fe, 2.7% for Ni and around 4% for Na,

7   K, Mn and Cr.

8   Major element contents of Salak whole-rock samples were determined on fused glass discs

9   produced by the Fusion method (spectroflux 105) using the Automated Philips PW2404 X-ray

10   fluorescence spectrometer at the University of Edinburgh. In-house rock standards were used

11   to calibrate the machine and monitor accuracy and precision during analysis.

12   Trace element concentrations of Salak rock powders were determined on the PerkinElmer

13   ELAN 6000 quadrupole ICP-MS at Durham University following the analytical procedure

14   and instrument operating conditions described by Ottley et al. (2003). Multiple analyses of

15   procedural blanks (3 per batch), in-house standards and international reference materials: W2,

16   BHVO-1, AGV1, BE-N and BIR1 during each session e.g. at the start, mid-way, and at the

17   end of a run, allowed any drift in the instrument calibration to be detected. Reproducibility

18   (internal and external) of standard values on the ELAN were less than 5% relative standard

19   deviation.

20   Preparation of whole rock powders for Sr, Nd and Hf isotope analysis was undertaken in

21   the Arthur Holmes Isotope Geology Laboratory (AHIGL) at Durham University. The sample

22   dissolution procedure and chemical separation of Hf and Nd from rock samples is based on

23   that presented by Dowall et al. (2003). The separation procedure for Sr follows that detailed

24   by Charlier et al. (2006) except Sr was collect from the column in 300 μL MQ (rather than

25   0.05M HNO_3) followed by addition of 15 μL 10M HNO_3 to the collected Sr fraction. Sr, Nd

1 and Hf isotope ratios were determined on the AHIGL ThermoElectron Neptune Multi-

2 collector Plasma Mass Spectrometer (MC-ICP-MS). Details of instrument operating

3 conditions are presented in Nowell et al. (2003) and Dowall et al. (2003). Instrumental mass

4 bias was corrected for using a $^{88}Sr/^{86}Sr$ ratio of 8.375209 (the reciprocal of the $^{86}Sr/^{88}Sr$ ratio

5 of 0.1194), $^{146}Nd/^{145}Nd$ ratio of 2.079143 (equivalent to the more commonly used $^{146}Nd/^{144}Nd$

6 ratio of 0.7219) and $^{179}Hf/^{177}Hf$ ratio of 0.7325 plus an exponential law. Data quality was

7 monitored over several analytical sessions by regular analysis of standard reference materials

8 during each run. The reproducibility of the $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios for the

9 respective standard solutions in each of the individual analytical sessions are better than 21

10 ppm in all cases. Sr-Nd-Hf isotope data presented are plotted relative to NBS 987, J&M and

11 JMC 475 standard values of 0.71024 (Thirlwall, 1991), 0.511110 (Royse et al., 1998) and

12 0.282160 (Nowell, et al., 1998) respectively. Blank samples processed (at least 2 per sample

13 batch) were analysed by ICP-MS on the PerkinElmer ELAN 6000 quadrupole at Durham

14 University. Total analytical blanks for Sr, Nd and Hf were below 1.2 ng for Sr (typically <

15 300 pg), 219 pg for Nd and 73 pg for Hf. These values are insignificant considering the

16 quantity of Sr, Nd and Hf processed from the volcanic rocks (12-65 µg, 2-7 µg and 0.5-1.2 µg

17 respectively).

18   Oxygen isotope analyses of mineral separates (~10mg per sample) were determined by

19 laser-fluorination at Royal Holloway, University of London; using an analytical procedure

20 following that of Macpherson et al. (2000). In-house standard values of SC olivine 2 and

21 GMG II during the period of study were within 0.01‰ of accepted values: +5.24‰ ± 0.04

22 (1σ, n = 6) and +5.69‰ ± 0.08 (1σ, n = 15), respectively. Oxygen yields were slightly low,

23 but consistent over the individual sessions: 93% for plagioclase (n = 7) and between 92-94%

24 (n = 20) for clinopyroxene. Replicate analyses of plagioclase and clinopyroxene throughout

1   the study were within 0.09‰ and 0.04‰ respectively. Oxygen results are reported as per

2   mille deviations relative to the standard mean ocean water (V-SMOW) standard.

3

4   **5. Petrology and mineral chemistry**

5   Modal analyses of Salak lavas and representative mineral compositions are given in Tables

6   1 and 2-5, respectively. Andesites are the most common rock type sampled at Salak. The

7   andesites of the SVG are generally more phenocryst rich than those of the CVG with total

8   phenocryst abundances ranging between ~50-60 % and 20-46 % (modal volume), respectively

9   (Table 1). Both andesite groups contain a typically observed island-arc mineral assemblage of

10 plagioclase, clinopyroxene, orthopyroxene and Fe-Ti oxide. Basaltic-andesites of the CVG

11 contain olivine phenocrysts, which commonly occur with both clinopyroxene and

12 orthopyroxene (indicating magmatic disequilibrium in the latter case). The olivine

13 phenocrysts (Fo$_{54-66}$, Table 2) are generally small and subhedral, some showing slight

14 alteration to iddingsite at crystal edges. The SVG rhyolite and Pre-Salak pumice samples are

15 dominated by glassy groundmass and phenocrysts of plagioclase with minor pyroxene. Small

16 amounts of amphibole and quartz ± biotite are also present (Table 1).

17 Orthopyroxene phenocrysts in the basaltic-andesites of the CVG are mostly subhedral-

18 euhedral and infrequently contain smaller inclusions of early-formed olivine (S104). In some

19 basaltic-andesites (S104, S105 and S108) the orthopyroxene phenocrysts are surrounded by a

20 thin rim, or jacket of clinopyroxene. This disequilibrium feature appears to be relatively

21 common in arc lavas and has been observed in the volcanic products of several Javan

22 volcanoes: Ijen (Sitorus, 1990), Slamet (Vukadinovic and Sutawidjaja, 1995), Lamongan

23 (Carn and Pyle, 2001) and Gede (Handley, 2006). Mineralogically, clinopyroxene and

24 orthopyroxene in the basaltic andesites of the CVG lack evidence for compositional

25 disequilibrium, displaying normal zoning of phenocrysts from Mg-rich cores towards more

1   Fe-rich rims. Orthopyroxene and clinopyroxene compositions available for the andesites show

2   slightly more variation in the SVG than the CVG (Figs. 2a & b). The limited pyroxene

3   analyses available for the SL3 lava show restricted compositional variation (Fig. 2c).

4   Plagioclase is the most abundant phenocryst phase in all CVG and SVG rocks. Plagioclase

5   phenocrysts exhibit a wide range in composition in the basaltic-andesites of the CVG (Figs.

6   3a & b; Table 4), with plagioclase rims displaying the largest variation in anorthite content

7   (An_{58-91}). Phenocryst interiors are more restricted in composition and have fairly high An

8   contents (above 80). The An contents of several plagioclase rims are higher than those in

9   respective groundmass plagioclase ($< An_{55}$) indicating that not all phenocrysts were in

10   equilibrium with the host liquid. Disequilibrium textures of plagioclase phenocrysts

11   (oscillatory zoning, sieve textures and infrequent resorbed cores) are observed in all CVG

12   basaltic-andesite samples. CVG and SVG andesites display similar compositional ranges in

13   plagioclase (Table 4). In the CVG (Fig. 3c) plagioclase phenocryst and groundmass

14   compositions are extremely homogeneous (An_{48-59}) with the exception of one core analysis

15   (An_{72}). The SVG plagioclases display a slightly wider compositional range and often the core

16   sections possess lower anorthite contents than respective mid and rim sections (Fig. 3e). Sieve

17   textures and oscillatory zoning are common in plagioclase phenocrysts of both groups of

18   andesites. The SL3 andesite displays a fairly restricted range in plagioclase composition

19   (An_{54-68}) similar to the andesite analysed from the CVG (Fig. 3d). Some SL3 plagioclase

20   phenocrysts show reverse zoning from less An-rich cores to more An-rich rims.

21   Fe-Ti oxide (titanomagnetite) occurs as a phenocryst phase in all rocks and is often

22   associated with the other mafic phases, commonly occurring as inclusions within pyroxene, or

23   forming a glomerocrystic texture with pyroxene. Titanomagnetite is slightly more Ti-rich in

24   the CVG andesite compared to the SVG andesite (Table 5).

1   Cognate xenoliths are observed in SVG samples from the eastern flank unit, PD1 (S102

2   and S103), displaying sharp contacts with the surrounding lava. The xenoliths are composed

3   of heavily sieve-textured and oscillatory-zoned plagioclase phenocrysts, clinopyroxene,

4   orthopyroxene and Fe-Ti oxide phenocrysts (titanomagnetite and ilmenite; in close

5   association with ferromagnesian minerals) set in a medium-grained groundmass. The

6   groundmass is dominated by euhedral plagioclase laths, elongate acicular pyroxene, small

7   oxide crystals and minor devitrified glass. Clinopyroxene occasionally forms thick jackets

8   around orthopyroxene phenocrysts. Fig. 2b shows there is some overlap in clinopyroxene and

9   orthopyroxene compositions between the xenolith (black crosses) and the host rock (open

10   squares). However, orthopyroxene phenocrysts in the xenolith also contain significantly more

11   En-rich compositions. Plagioclase compositions in the xenolith (Fig. 3f) are scattered, but

12   generally more An-rich than those in the host lava (Fig. 3e).

13

14   **6. Geochemistry**

15   *6.1. Major and trace element variations*

16   Major and trace element data are reported in Table 6. Salak lavas are relatively evolved,

17   with MgO contents less than 4 wt %. Salak volcanic rocks display negative correlations on

18   diagrams of Al_2O_3, Fe_2O_3, MgO and CaO against SiO_2, and positive correlations between

19   SiO_2 and both K_2O and Na_2O (Fig. 4), although Na_2O contents in the SVG are relatively

20   constant with increasing SiO_2. TiO_2 and P_2O_5 variation is split into two markedly different

21   trends. Lavas erupted from the CVG generally show an increase in TiO_2 and P_2O_5 contents

22   with increasing SiO_2, whereas SVG lavas possess lower TiO_2 and P_2O_5 contents and plot

23   within the field of other Javan volcanic rocks (Figs. 4g and h). TiO_2 and P_2O_5 contents

24   measured in the more evolved CVG rocks (~60% SiO_2) are unusually high (up to 1.18 and

25   0.48 wt%, respectively) when compared to the majority of values reported for other Javan

1   lavas (Fig. 4g) and from volcanic rocks of other island arc systems at comparable silica

2   content e.g. Kermadec (Gamble et al., 1993; Ewart et al., 1994; Turner et al., 1997), Lesser

3   Antilles (Thirlwall et al., 1996; Zellmer et al., 2003) and Mariana (Woodhead, 1989; Elliot et

4   al., 1997). Increasing TiO_2 content with increasing silica (Fig. 4g) is not normally observed in

5   arc andesites, most probably due to the early fractionation of magnetite (Gill, 1981; Pearce,

6   1982).

7   The high field strength elements (HFSE) and the rare earth elements (REE), particularly

8   the heavy REE, also show abnormally high concentrations in the more evolved CVG samples

9   (Y = 32-69 ppm; Yb, 3-6.5 ppm) and display strikingly positively-sloped, linear trends on

10   SiO_2 variation diagrams (Figs. 5a and b). This contrasts again with the SVG rocks and the

11   majority of other volcanic rock suites of Java, where concentrations remain relatively constant

12   with increasing SiO_2 (Figs. 5a and b). High concentrations of TiO_2, P_2O_5, Y and systematic

13   increases of these elements with SiO_2 are so far only evident at one other volcano in Java,

14   namely Tengger Caldera in East Java (Figs. 4g and h and 5a). This unusual feature was not

15   noted in the study of Tengger Caldera by van Gerven and Pichler (1995). Extensive

16   comparisons of trace element variations between Tengger Caldera and Salak are however

17   restricted due to the limited geochemical data available for the former volcanic system. In

18   contrast to the separate HSFE and REE variation trends displayed by the CVG and SVG,

19   variations in large ion lithophile elements (LILE) are similar, displaying positive correlations

20   with SiO_2 (Figs. 5e and f). Sr generally decreases as SiO_2 increases within each group (Fig.

21   5g). The SVG rocks containing around 60 wt% SiO_2 are slightly displaced below the main

22   Salak trend in the majority of these diagrams with the exception of Sr, where they sit at

23   slightly elevated values.

24   Chondrite normalised REE patterns of selected Salak lavas are displayed in Fig. 6. Salak

25   volcanic rocks are enriched in the light REE compared to mid-ocean ridge basalts (Normal-

1   MORB and Indian Ocean-MORB). With the exception of the high silica rhyolite, the heavier

2   REE show concentrations more similar to those in MORB than the light REE. The higher

3   silica CVG andesite is located parallel to, but at higher REE concentrations than the less

4   evolved CVG rock. The enrichment of the REE in the evolved CVG sample is made clear

5   when compared to a SVG rock of comparable silica content (unfilled squares). Strong

6   depletions are observed in the middle to heavy REE concentrations of the high SiO_2 (west

7   flank) SVG rocks, compared to less evolved Salak rocks.

8

9   *6.2. Radiogenic isotopes*

10   Sr, Nd and Hf isotope data are presented in Table 6 and shown in Figs. 7 and 8. $^{87}Sr/^{86}Sr$

11   and $^{143}Nd/^{144}Nd$ isotope ratios of Salak volcanic rocks define a negative array, lying within

12   the field of previously published Java data. Salak exhibits a relatively wide range in $^{87}Sr/^{86}Sr$

13   ratios, 0.704262 to 0.705051, although the majority of the lavas are more tightly constrained

14   within the range 0.704569-0.705051. The two SVG samples, S102 and S103, erupted on the

15   eastern flank of Salak are displaced from the rest of the Salak lavas, possessing significantly

16   lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios (Fig. 7 inset). In Hf-Nd isotope space (Fig. 8),

17   Salak volcanic rocks also lie within the field defined by Java, possessing lower $^{143}Nd/^{144}Nd$

18   and $^{176}Hf/^{177}Hf$ isotope ratios than MORB, and higher ratios than Indian Ocean sediments.

19   The eastern-flank SVG samples, S102 and S103, possess significantly more primitive

20     $^{176}Hf/^{177}Hf$ isotope ratios compared to the other Salak lavas (Fig. 8 inset).

21

22   *6.3. Stable isotope data*

23   Oxygen isotope data from mineral separates are presented in Table 7. The restricted

24   clinopyroxene and plagioclase analyses of Salak lavas have low $\delta^{18}O$ values ranging from

25   +5.18 to +5.44‰ (n = 3) and +5.96 to +6.07‰ (n = 4), respectively. The former values are

similar to mantle clinopyroxene δ^{18}O values reported by Mattey et al. (1994) and Ionov et al.

(1994): +5.57 ± 0.32‰ and similar to or slightly lower than those reported from other

volcanoes in Java (Galunggung, Harmon and Gerbe, 1992; Gede Volcanic Complex,

Handley, 2006; Ijen Volcanic Complex, Handley et al., 2007). Plagioclase δ^{18}O values of

Salak are generally higher than those of Galunggung (+5.6 to +6.0‰, Harmon and Gerbe,

1992), but lower than those analysed in Merapi volcanics (+6.5 to +7.00‰, Gertisser and

Keller, 2003a). Differences in δ^{18}O values between coexisting plagioclase and clinopyroxene

($\Delta_{plag-cpx}$) are between 0.63 to 0.79‰ and suggest most of the mineral pairs record oxygen

isotopic equilibrium at typical magmatic temperatures for andesite liquids. The limited

number of analyses from Salak prohibits intra-group comparisons of δ^{18}O data, however, the

lowest δ^{18}O clinopyroxene value is measured in the sample with the most primitive radiogenic

isotope ratios (SVG, S103).

7. Discussion

Minor and trace element variations at Salak are intriguing, and raise two important

questions: 1) Why do the CVG display atypical differentiation trends and unusually high

concentrations in minor and trace elements, in particular for the HREE, Y, TiO$_2$ and P$_2$O$_5$

compared to other Javan volcanoes? 2) Why are there strikingly different differentiation

trends in lavas from a single volcanic centre?

Assuming that variations in the silica content of volcanic rocks are generated as a result of

differentiation of magma (Gill, 1981; Davidson et al., 2005), systematic increases of Y, Yb,

TiO$_2$ and P$_2$O$_5$ with SiO$_2$ within the CVG (Figs. 5a & b and Figs. 4g & h, respectively) are

compelling evidence for geochemical variation being imparted during differentiation in the

crust e.g. through magma mixing, fractional crystallisation and/or combined assimilation and

fractional crystallisation.

1

7.1. Differentiation in the Central Vent Group

7.1.1. Magma Mixing

Magma mixing is identified as an important composition-modifying process within the

evolution of many arc magmas (e.g. Conrad et al., 1983; Tepley et al., 2000) including some

Sunda arc magmas (Slamet, Reubi et al., 2002; Merapi, Gertisser and Keller, 2003b; Batur,

Reubi and Nicholls, 2004). Linear correlations displayed by the CVG rocks on bivariate

element-silica diagrams (Figs. 4 and 5) suggest that chemical variation within this group may

be explained by the interaction and mixing of chemically distinct magmas. Phenocryst

textures and mineral disequilibria in CVG lavas (section 5) indicate that open system

processes may have occurred at one or several points in the magmatic evolution of the CVG.

A purely geochemical approach to evaluate mixing processes utilises element ratios

(Langmuir et al., 1978; Vogel, 1982; Flood et al., 1989). Magma mixing should produce

hyperbolic arrays in plots of a trace element ratio versus a concentration. Figs. 9a and b show

that the CVG data largely define a curved array on some element-ratio diagrams. K/Rb and

Ba/Th ratios were chosen as these ratios correlate with SiO_2 and display a wide range in the

CVG. The former ratio is also a potentially useful monitor of crust-magma interaction

(Davidson, 1987, Hildreth & Moorbath, 1988), providing that the melt and crust have

distinctive values for the ratio. K/Rb and Ba/Th ratios are plotted against Rb (which

represents the degree of magmatic differentiation) and Yb (to check whether the model can

account for the highly unusual variations in concentrations observed for this element). The

results of bulk-mixing calculations between one of the least evolved CVG samples (S106B)

and several end members are shown in Figs. 9a and b. If element variation in the CVG is a

result of simple mixing, the other end member must be more evolved (higher SiO_2) in

composition. Granite xenoliths found within a deposit of cream tuff in the Perbakti-Gagak

1   area adjacent to Salak provide evidence for the presence of evolved, granitic material (Stimac,

2   2003) in West Java. No data are available from this granite for use in modelling, therefore the

3   more evolved end member magmas in mixing calculations are represented by a rhyolite from

4   Salak (S107A) and by arc-related granites from some of the southern-most plutonics in

5   Sumatra (i.e. close to West Java): monzodiorite (75413) and granodiorite (75415) (Gasparon,

6   1993). Mixing with a more basic end member (tholeiitic lava) from Guntur in West Java

7   (Edwards, 1990) is also shown for comparison. The end member compositions used in mixing

8   calculations are given in Table 8.

9   Fig. 9a shows that mixing in K/Rb-Rb space between S106B and a granitic sample with a

10   high K/Rb ratio (MM D) is unable to generate a mixing curve to fit the CVG data. Similar

11   unsatisfactory mixing trends would result from mixing with bulk upper-crustal material,

12   which also has relatively high K/Rb (~250; Taylor, 1977). Mixing between S106B and

13   granodiorite (MM B) or Javan tholeiite (MM C) also fail to fit the data, generating curves that

14   have a large decrease and increase (respectively) in K/Rb ratio, with only a small change in

15   Rb. The mixing curve produced using the Salak rhyolite (MM A) as the evolved end member,

16   produces the best fit to the CVG data. Fig. 9b, Ba/Th-Yb, shows mixing curves generated

17   between the same end members in Fig. 9a. Mixing in all cases is inadequate in explaining the

18   Salak CVG data due to the low Yb content of the end members chosen. Low Yb contents of

19   basic and evolved Javan lavas and evolved Sumatran plutonics, suggests that Yb contents of

20   the CVG cannot be explained by simple mixing.

21

22   *7.1.2. Fractional crystallisation*

23   Fractional crystallisation was modelled by least squares analysis of Salak major element

24   data using the XLFRAC programme (Stormer and Nicholls, 1978; Table 9). The results

25   suggest that the most evolved CVG lava can be produced by fractionation of the least evolved

1   CVG lava by 61% crystallisation ($\Sigma r^2 = 0.13$; model 1). Smaller values of Σr^2 are obtained in

2   models to less differentiated final lavas (models 2 & 3), regardless of whether orthopyroxene

3   or olivine is included in the mineral assemblage (compare models 3 & 4). This suggests that

4   major and minor element variation within the CVG can be explained by fractional

5   crystallisation of plagioclase, clinopyroxene, Fe-Ti oxide +/- olivine and orthopyroxene (e.g.

6   Figs. 4g and h). But, can fractional crystallisation explain the unusual trace element variation

7   trends not seen in the majority of Javan lavas using the same mineral assemblage?

8   Y and the REE often behave as incompatible elements in primitive arc tholeiites, however

9   they usually remain constant or decrease in concentration with increasing magmatic

10   fractionation in the calc-alkaline series, where they can be accommodated within amphibole,

11   apatite and zircon (Pearce, 1982). This is exemplified by the Java data in Figs. 4g and h, and

12   amphibole fractionation curves in Figs. 5a and b. To examine whether fractional

13   crystallisation can produce the large increases in Y, Yb and Ti of the CVG (over a relatively

14   narrow range in silica) and test the conclusions of least squares analysis, simple calculations

15   were made using the Rayleigh fractionation equation: $C_l = C_o\ F^{(D-1)}$ where C_l is the

16   concentration of an element in the liquid, C_o is the concentration of an element in the original

17   liquid, F is the fraction of liquid remaining and D is the bulk distribution coefficient. The

18   degree of fractionation (F) and the phase proportions used are those suggested by major

19   element modelling (Table 9, model 1). The distribution coefficients used are given in Table

20   10. Calculated Ti, Y and Yb compositions expected in the daughter rocks (Table 10, Figs. 4g,

21   5a and b) show that incompatible behaviour of HFSE and HREE during fractional

22   crystallisation can account for the high concentrations of these elements in Salak rocks. In all

23   three models in Table 10 the concentrations predicted in the daughter rocks are higher than

24   those actually measured. This contrasts with the results of mixing (Fig. 9b) between a basic

25   CVG rock and the tholeiitic and more evolved volcanic and plutonic samples, which were

1   unsuccessful in accounting for high Yb concentrations. Fractional crystallisation curves (FC)

2   are shown on K/Rb-Rb and Ba/Th-Yb diagrams (Figs. 9a and b) for removal of the same

3   mineral assemblage used above. It should be noted that an identical FC curve is produced if

4   the modal mineral assemblage of S106B (Table 1) is used instead. The Salak CVG data

5   diverge from the calculated FC curve towards lower K/Rb and Ba/Th, thus suggesting that

6   pure closed-system fractional crystallisation cannot explain all of the geochemical variation

7   observed in the CVG lavas.

8

9   *7.1.3. Assimilation and Fractional Crystallisation (AFC)*

10   AFC processes are recognised in the evolution of magma in arc settings (Davidson et al.,

11   1987; Hildreth and Moorbath, 1988; Davidson and Harmon, 1989) and have been suggested

12   for the Sunda arc (Gasparon et al., 1994). Little is known about the nature and composition of

13   the crust in West Java. Seismic velocities suggest that the crust in West Java is thicker than

14   that at the eastern end of Java (Ben-Avraham and Emery, 1973; Curray et al., 1977;

15   Kieckhefer et al., 1980) and in West Java the arc may be built on continental material, i.e.

16   Sundaland pre-Tertiary basement (Hamilton, 1979). Large granite blocks found in a tuff

17   deposit in the vicinity of Salak (Perbakti-Gagak area, Fig. 1) display partially melted margins

18   with adhering rhyolitic lava (Stimac, 2003). It is unknown when this granite was emplaced in

19   the crust, but it suggests that interaction and possible contamination of magma by evolved

20   plutonic rocks may occur at Salak. AFC curves are shown on Figs. 9a and b for contamination

21   of the most basic Salak magma, by evolved volcanic (AFC A) and plutonic (AFC B) rocks,

22   possessing low K/Rb and Ba/Th ratios. These curves fit the array of Salak data well, even

23   though the contaminants possess low Yb concentrations (cf. mixing) Assimilation of upper

24   and bulk crust (e.g. Taylor, 1977; Sumatran granitoid 75413) would generate concave-down

25   AFC curves, inconsistent with the CVG data. It was suggested by Hamilton (1979) that the

1 crust in West Java is not truly silicic in character and may consist of older volcanic-arc rocks

2 and ophiolite slivers. However, AFC models involving basic arc rocks (e.g. Fig. 9 AFC C)

3 and a range of basic and ophiolite compositions (see below) are also inconsistent with the

4 CVG array.

5 In summary, major and trace element modelling suggests that the unusual increases in

6 HFSE and HREE with increasing SiO_2 are created due to incompatible behaviour of these

7 elements during fractional crystallisation. Systematic variations in some trace element ratios

8 (K/Rb and Ba/Th) and disequilibrium textures observed in the rocks indicate that assimilation

9 of a contaminant with low K/Rb and Ba/Th ratios occurs during fractional crystallisation in

10 the crust.

11

12 *7.1.4. Isotopic constraints*

13 Continental-type crustal rocks commonly have elevated $^{87}Sr/^{86}Sr$ isotope ratios compared

14 to Quaternary volcanic rocks and mantle-derived magmas. Assimilation of crust during

15 crystal fractionation (DePaolo, 1981) in arc magmas may therefore cause modification to the

16 isotope ratios in resultant lavas. Consequently, a plot of Sr isotope ratio against an index of

17 differentiation, e.g. SiO_2, can be used to detect AFC processes, in cases where the crust being

18 assimilated is isotopically distinct. Even though the number of samples with isotope data is

19 relatively limited and the variation in $^{87}Sr/^{86}Sr$ of the CVG is small, the more evolved CVG

20 samples display generally higher $^{87}Sr/^{86}Sr$ ratios (Fig. 10), and the data patterns observed in

21 this plot are identical (though the inverse) to those of Ba/Th with SiO_2 (see inset to Fig. 10).

22 This suggests that Ba/Th, for which there is more data compared to $^{87}Sr/^{86}Sr$, might serve as a

23 proxy for isotopic composition. The roughly hyperbolic trend observed in Fig. 10 and

24 variation in $^{87}Sr/^{86}Sr$ isotope ratio with SiO_2 in the CVG further support control by

25 differentiation, and more specifically by AFC processes.

1   The five CVG data points define a concave-down hyperbola on Ba/Th versus $^{87}Sr/^{86}Sr$ (Fig.

2   11). The AFC curves displayed here are for the same AFC end members used in trace element

3   modelling (see Fig. 9 caption for details). Neither model on Fig. 11 using evolved volcanic

4   nor plutonic rocks produces hyperbolic curves to fit the CVG data. AFC curves for these

5   models largely follow the same vertical trend shown by fractionation crystallisation (FC)

6   alone (arrow, Fig. 11), and altering the rate ratio of mass assimilated to mass crystallised (r)

7   has little effect on the shape of the curve. The basic contaminant (see captions to Figs. 9 and

8   10 for details) produces an AFC curve (C) with a much better fit to the CVG data, but

9   suggests a large amount of contamination is required compared to crystallisation ($r = 0.8$).

10   Such high AFC r-values are not unreasonable and have been proposed for differentiation of

11   basalts at Jebel Marra volcano in Sudan (Davidson and Wilson, 1989) and by Bourdon et al.

12   (1998) for the Grande Comore volcanics.

13   A contaminant with a significantly higher Sr content than that of the parental rock would

14   be able to generate a hyperbola curving in the required direction from the parental

15   composition of S106B and not necessitate such a high r-value. Fig. 10 also indicates this as

16   assimilation of a contaminant with low Sr concentration would produce a concave-up curve

17   initially projecting in a horizontal direction away from the least evolved CVG sample, which

18   is inconsistent with the concave-down data array in Fig. 10. The apparent plateau in $^{87}Sr/^{86}Sr$

19   isotope ratio in SiO_2-rich CVG rocks suggests that the $^{87}Sr/^{86}Sr$ ratio of the contaminant is

20   asymptotic to the $^{87}Sr/^{86}Sr$ ratio of the more evolved CVG samples (i.e. ~0.7048). If the

21   distribution coefficient for Sr in plagioclase is greater than one, then a magma crystallising

22   this phase would become progressively more sensitive to Sr in the contaminant (which is

23   assumed to be fixed). The more AFC magma endures, the more isotopically sensitive to the

24   contaminant it would become, and therefore, for a given shift in silica the magma would

25   obtain a larger shift in $^{87}Sr/^{86}Sr$ isotope ratio if the contaminant had a higher $^{87}Sr/^{86}Sr$ ratio.

1   Consequently, it is argued that if the data are consistent with AFC, the contaminant has a high

2   Sr concentration and Sr-isotope ratio ~0.7048 (curved arrow, Fig. 10) contamination by a high

3     $^{87}Sr/^{86}Sr$ component would result in a data array with a steeper positive correlation on Fig. 10

4   (diagonal arrow). The moderate decrease in Sr concentration with increasing SiO_2 in the CVG

5   (despite the modelled involvement of large amounts of plagioclase fractionation) further

6   argues for a high-Sr assimilant. An AFC calculation using S106B as the parent magma and

7   the Sumatran granodiorite as the contaminant suggest that to produce a concave-down

8   hyperbola to fit the data in Fig. 11 an extremely unrealistic Sr concentration in the

9   contaminant of >7000 ppm is required. Evolved volcanic or plutonic contaminant end

10   members are unlikely to possess higher Sr concentrations than the basaltic andesite S106B

11   being contaminated as Sr content generally decreases with differentiation in arc-related

12   igneous rocks due to plagioclase fractionation. Incorporation of the assimilant as a partial melt

13   (0.1 - 10% melting), rather than bulk addition of this component, does not increase the Sr

14   concentration sufficiently enough to improve the fit of the models for Ba/Th versus Sr isotope

15   ratio and also leads to a more rapid decrease in Ba/Th ratio, creating an AFC trend further

16   away from the CVG array.

17   If Sr isotope variation in the CVG is controlled by AFC processes as suggested above, then

18   the contaminant is characterised by high Sr concentration, $^{87}Sr/^{86}Sr$ isotope ratio of around

19   0.7048 and low K/Rb and Ba/Th ratios (< ~110 and < ~45, respectively). Table 11 shows

20   trace element data and Sr-isotope ratios for a variety of rocks that may represent the West

21   Javan crust and could therefore be potential contaminants. However, none of the samples

22   listed possess all of the required criteria envisaged for the contaminant, therefore at present, a

23   suitable contaminant is unidentified.

24

7.2. Relationship of the SVG to the CVG

If increases in HFSE and HREE with increasing silica in CVG rocks can be explained by highly incompatible behaviour during differentiation, then relatively low and decreasing HFSE and HREE concentrations in the SVG lavas may indicate relatively more compatible behaviour of these elements during differentiation of SVG magmas. A distinct difference in the type or abundance of phases crystallising from the magma may therefore be expected. However, there is little difference between the mineralogies of the CVG and the eastern flank SVG volcanic rocks. In contrast, the western flank SVG samples have small amounts of amphibole (hornblende) in their modal mineralogies (Table 1). Strong depletions in HREE and the steep decrease from La-Sm shown by the western flank SVG samples, relative to those with lower silica content from the eastern flank (Fig. 6), suggests that very late-stage fractionation of hornblende ($\pm$ accessory phases) may account for the relatively low HREE and HFSE concentrations in these highly evolved samples (cf. deep, early-stage fractionation). The similarly shaped REE profiles and modal mineralogies of the CVG and SVG lavas with <70 wt % SiO_2 precludes a similar explanation for the differences observed in the geochemistry of these samples.

In addition to mineralogical differences, isotopic differences also occur between the western and eastern flank SVG lavas (Figs. 7 and 8 insets). The western vent SVG rocks are isotopically similar to the CVG group and may, therefore, be genetically related to each other, sharing a similar source and evolutionary history. The notably more primitive radiogenic isotope ratios of the eastern flank SVG lavas suggest that they may have evolved from an isotopically distinct source, or may represent the least contaminated (either by arc crust or a subduction component) Salak lava. In the latter case, they reveal the best estimate of least modified mantle wedge isotopic composition beneath Salak. The similar REE patterns of the lower SiO_2 SVG and lower SiO_2 CVG lavas (Fig. 6), suggests the magmatic source region of

1   the two groups probably contained a comparable mineralogy and underwent similar degrees

2   of melting.

3   Trace element ratios of HFSE and HREE (e.g. Zr/Nb, Y/Nb) are often used to investigate

4   the source characteristics of magmas (McCulloch and Gamble, 1991; Woodhead et al., 1993;

5   Reubi and Nichols, 2004). However, the limited number of samples from the SVG, combined

6   with the relatively differentiated nature of all Salak lavas and the uncertainty of HFSE/HREE

7   concentrations in less differentiated samples (due to unusual increases of these elements in the

8   CVG) hampers this approach at Salak

9   A schematic diagram showing the proposed evolution of magma beneath Salak is displayed

10   in Fig. 12. Petrographic and radiogenic isotope data suggest that the high SiO_2 SVG rocks

11   from the western flank vent may be related to the CVG lavas, evolving to lower HFSE and

12   REE concentrations due to prolonged residence in the crust and the late-stage fractionation of

13   hornblende (± accessory phases) prior to eruption (A). However, the lower SiO_2 (and

14   isotopically more primitive) eastern SVG lavas are proposed to have taken a separate

15   evolutionary pathway to the surface. Low concentrations of HFSE and HREE in these

16   samples may be the result of fractionation of a HFSE-REE-compatible phase at depth (B),

17   such as amphibole, which effectively inhibits the relative increase of these elements during

18   fractional crystallisation at shallower levels. A number of factors control amphibole

19   fractionation from magma (see Davidson et al. 2007 for a recent discussion), which include

20   the water content of the magma and also the pressure of crystallisation. Therefore, an apparent

21   lack of deep-seated amphibole crystallisation in the CVG may imply that the water content

22   was not as great in the parental magma, or CVG magmas were not stored at deeper levels in

23   the arc crust. Other arc studies that support a proposal of multiple independent conduits and

24   reservoirs in the crust beneath active volcanoes include those of Reubi and Nicholls (2004)

25   and Grove et al. (2005).

1   Within andesitic volcanic rock suites REE concentrations commonly increase with silica

2   (Gill, 1981). Therefore, due to the relatively constant within suite REE concentrations (black

3   crosses, Figs. 5b and h) and general lack of hornblende phenocrysts in Javan volcanic rocks,

4   we speculate that amphibole, or other HFSE-HREE bearing phase, may fractionate at depth

5   below most Javan volcanoes. Although amphibole-bearing xenoliths have not been found in

6   Salak lavas, gabbroic xenoliths with variable amphibole contents are observed in lavas

7   erupted at Sangeang Api volcano in the East Sunda arc (Turner et al., 2003) and gabbroic

8   mafic inclusions composed of plagioclase and amphibole are present in lavas at Merapi

9   volcano in Central Java (Camus et al., 2000).

10

11   **8. Conclusions**

12   Unusual HFSE and HREE variation trends (compared to most other volcanic rocks from

13   Java) displayed by the CVG lavas of Salak are produced during differentiation in the crust.

14   Differentiation processes have been modelled to show that: 1) CVG element variation is not

15   consistent with simple mixing due to the low HFSE and HREE concentrations found in

16   continental and oceanic crustal end members. 2) Evolution to high HFSE and HREE

17   concentrations in the CVG can be explained by incompatible behaviour of these elements

18   during fractional crystallisation. 3) Variation in some trace element ratios (K/Rb and Ba/Th)

19   of the CVG suggest assimilation of crust also occurs during fractional crystallisation of the

20   magma. AFC modelling and $\delta^{18}O$ data suggest that typical continental-type upper-crustal

21   contaminants are not likely to be involved in AFC processes at Salak (cf. the Andes and

22   Lesser Antilles, Davidson et al., 2005 and references therein). Geochemical constraints

23   suggest that the contaminant is largely similar in geochemical and isotopic composition to the

24   lavas themselves (e.g. volcanic and/or plutonic arc-related or ophiolitic rocks) and

1   characterised by $^{87}Sr/^{86}Sr$ ~ 0.7048, extremely high Sr concentration and relatively low K/Rb

2   and Ba/Th ratios.

3   Evolution to high HFSE and HREE concentrations in the CVG lavas suggests that magma

4   beneath the central part of the volcano has bypassed deep-level storage in the lower crust,

5   which is envisaged beneath the eastern flank vent. Volcanic rocks of the western flank SVG

6   display lower HFSE and HREE contents compared to the CVG, which may be explained by

7   relatively shallow, late-stage hornblende (± accessory phase) fractionation from a CVG-type

8   parent.

9   HFSE and HREE variations in Salak lavas have drawn attention to the fact that Javan lavas

10   do not show highly incompatible behaviour of these elements during differentiation. Y and

11   Yb concentrations in eruptives from the volcanic front on Java display near-horizontal trends

12   when plotted against silica. With little direct evidence of amphibole fractionation in these

13   lavas, it is speculated that fractionation of a HFSE-HREE-compatible phase may occur at

14   depth beneath the majority of volcanoes on Java. Tengger Caldera, in East Java also displays

15   abnormally steep, Y, P_2O_5 and TiO_2 differentiation trends (similar to the CVG at Salak),

16   suggesting deep-fractionation of a HFSE-HREE-compatible phase does not take place at this

17   volcano and further corroborates the idea that the cause is related to crustal-level processes,

18   rather than isolated source contributions at single volcanic centres in both East and West Java.

19   This interpretation would benefit greatly from further sampling and geochemical analysis of

20   Salak SVG deposits, to better constrain differentiation trends within this group and refine the

21   geochemical models.

22   Finally, the presence of a wide HFSE and HREE variation within a single volcanic centre,

23   such as that at Salak, emphasises the importance of detailed geochemical study of individual

24   volcanoes. Arc lavas are generally characterised by high LREE/HFSE ratios, attributed to

25   involvement of a subducted component. However, LREE/HFSE ratios in Salak lavas are

1 relatively low in the CVG, even though LREE concentrations are relatively high, due to high

2 HSFE concentrations and positive correlations of both LREE and HFSE with SiO_2 in the

3 CVG rocks.

4

15

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4

5 **Figure Captions**

6 Fig. 1. Topographic sketch map of the Salak-Perbakti-Gagak Complex, showing the

7 distribution of samples used in this study and corresponding data symbols used on subsequent

8 figures. CVG = Central Vent Group; SVG = Side Vent Group; SL3 = Salak lava 3 (Zaennudin

9 et al., 1993). Selected rivers are shown in black dash; solid lines with ticks represent

10 escarpments. Inset diagram shows the location of Salak (large black triangle) in West Java, in

11 relation to major centres of population (grey fill) and Quaternary volcanoes (small black

12 triangles).

13

14 Fig. 2. Analyses of pyroxene phenocrysts in Salak lavas. Dashed lines represent 10%

15 increments.

16

17 Fig. 3. Compositional variation of plagioclase phenocrysts in Salak volcanic rocks. Grey lines

18 represent 10% increments.

19

20 Fig. 4. Major element variation diagrams for Salak volcanic rocks. Tengger Caldera (open

21 circles) distinguished from the other Java volcanic data (small crosses) to highlight the

22 unusual geochemical properties of the rocks (data from van Gerven & Pichler, 1995). Java

23 data: B, Bayah Dome (Marcoux and Milesi, 1994; Alves et al., 1999); C, Cereme (Edwards,

24 1990); G, Gede Volcanic Complex (Handley, 2006); Ga, Galunggung (Gerbe et al., 1992; de

25 Hoog et al., 2001); Gu, Guntur (Edwards, 1990; de Hoog et al., 2001); I, Ijen Volcanic

1   Complex (Handley et al., 2007); M, Merapi (Gertisser and Keller, 2003a); S, Slamet

2   (Vukadinovic and Sutawidjaja, 1995; Reubi and Nicholls, 2002). Model fractionation curves

3   are shown for removal of the mineral assemblage suggested by least squares modelling from

4   S106B (model 1) in Table 9: 0.7 Plag, 0.1 Cpx, 0.13 Opx, 0.07 Fe-Ti oxide. Mineral data used

5   in modelling is given in Tables 3-5. Fractionation curves are labelled with the percentage of

6   melt remaining.

7

8   Fig. 5. Selected trace element variations with SiO_2 for Salak volcanic rocks. Java data sources

9   as in Fig. 4. SVG samples erupted from eastern flank (E. Flank) and western flank (W. Flank)

10 vents are indicated in b). Model fractionation curves (FC) are shown for 100% amphibole

11 fractionation (crosses) from Javan basalt (Ijen Volcanic Complex KI69, Handley et al., 2007)

12 using mineral partition coefficients from Bottazzi et al. (1999) and mineral composition from

13 Rapp and Watson at 8kbar, 1000ºC (1995), and for fractionation of the mineral assemblage

14 suggested by least squares modelling (horizontal ticks) see Fig. 4 for details. Curves are

15 labelled with the percentage of melt remaining.

16

17 Fig. 6. Chondrite normalised rare earth element diagram of Salak rocks. Normalising factors

18 and Normal (N)-MORB values from Sun and McDonough (1989). Indian (I)-MORB

19 (Chauvel and Blichert-Toft, 2001).

20

21 Fig. 7. Variation of $^{143}Nd/^{144}Nd$ with $^{87}Sr/^{86}Sr$ for Salak volcanic rocks. Data sources: I-

22 MORB: Rehkämper and Hofmann, 1997; Ito et al., 1987; Price et al., 1986; Chauvel and

23 Blichert-Toft, 2001; N-MORB: Ito et al., 1987; Chauvel and Blichert-Toft, 2001; Java: White

24 and Patchett, 1984; Whitford et al, 1981; Edwards, 1990; Gertisser and Keller, 2003a; Gerbe

25 et al, 1992; Handley et al., 2007; Handley, 2006; Indian ocean sediments: Ben Othman et al.,

1   1989; Gasparon and Varne, 1998. Inset: Nd and Sr isotope ratio diagram separated by group.

2   2σ external errors shown for each analysis. E. Flank = eastern flank vent samples S102 and

3   S103.

4

5   Fig. 8. ^{176}Hf/^{177}Hf - ^{143}Nd/^{144}Nd variation in Salak volcanic rocks. Data sources: I-MORB:

6   Salters, 1996; Nowell et al., 1998; Chauvel and Blichert-Toft, 2001; N-MORB: I-MORB refs.

7   and Salters and Hart, 1991; OIB: Salters and Hart, 1991; Salters and White, 1998; Nowell et

8   al., 1998; Patchett and Tatsumoto, 1980; Patchett, 1983; Stille et al., 1986; Java: White and

9   Patchett, 1983; Woodhead et al., 2001; Handley et al., 2007; Handley, 2006; Banda: White

10   and Patchett, 1984; Indian ocean sediments: Ben Othman et al., 1989; White et al., 1986;

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12   al., 1999. Inset: Hf-Nd isotope diagram of Salak volcanic rocks separated by group. 2σ

13   external errors shown for each analysis on the inset diagram. E. Flank = eastern flank vent

14   samples S102 and S103.

15

16   Fig. 9. a) K/Rb-Rb and b) Ba/Th-Y, showing fractional crystallisation (FC), combined

17   assimilation and fractional crystallisation (AFC A, B and C), and bulk mixing (MM A, B, C

18   and D) curves for models involving Salak basaltic andesite S106B and A: rhyolite (this

19   study), B & D: Seputih granite plutonics 75415 and 75413 respectively (southern Sumatra,

20   Gasparon, 1993) and C: Javan arc tholeiite from Guntur, GU1/T (Edwards, 1990). See Table

21   8 for end member compositions. Tick marks on FC and AFC curves indicate the percentage of

22   liquid remaining. Tick marks on mixing curves represent the percentage of A, B, C or D

23   mixed with the magma. FC and AFC calculations use the mineral proportions suggested by

24   least squares major element modelling of CVG rocks S106B to S110B (Table 9, model 1):

25   Plag = 0.7; Cpx = 0.1; Opx = 0.13; Oxide = 0.07. AFC curves calculated using DePaolo

1   (1981). The rate ratio (r) of mass assimilated to mass crystallised in AFC model: A = 0.5, B =

2   0.05, C = 0.8.

3

4   Fig. 10. Variation of $^{87}Sr/^{86}Sr$ isotope ratio versus SiO_2 for Salak volcanic rocks. Arrows
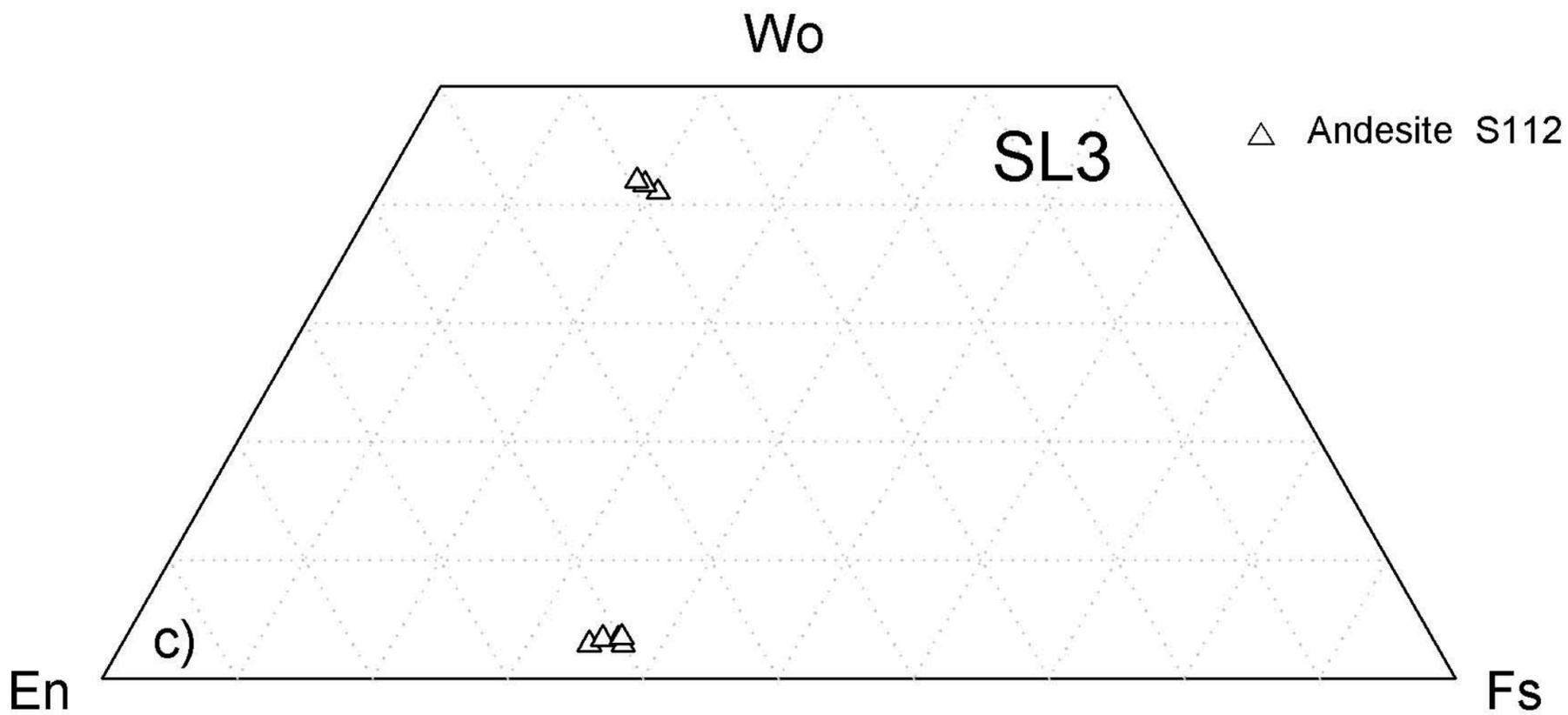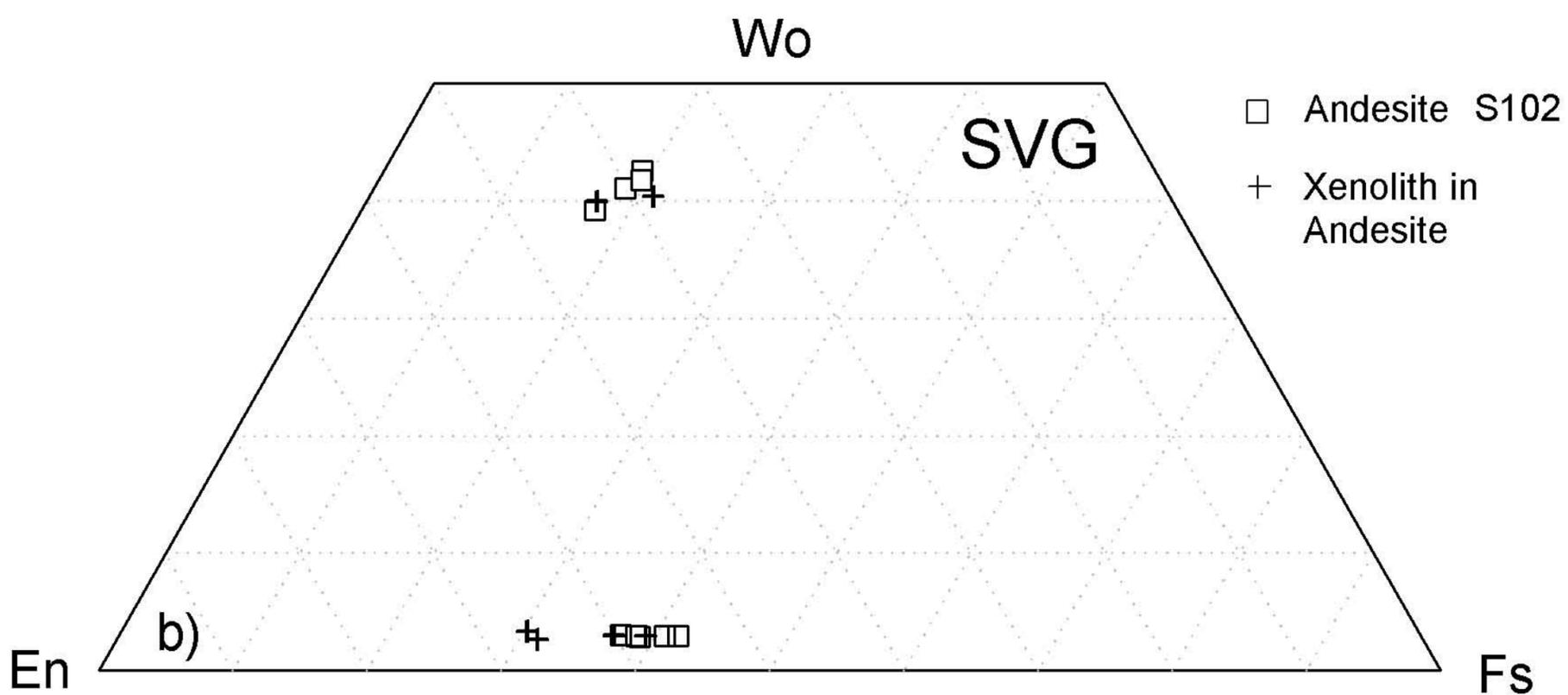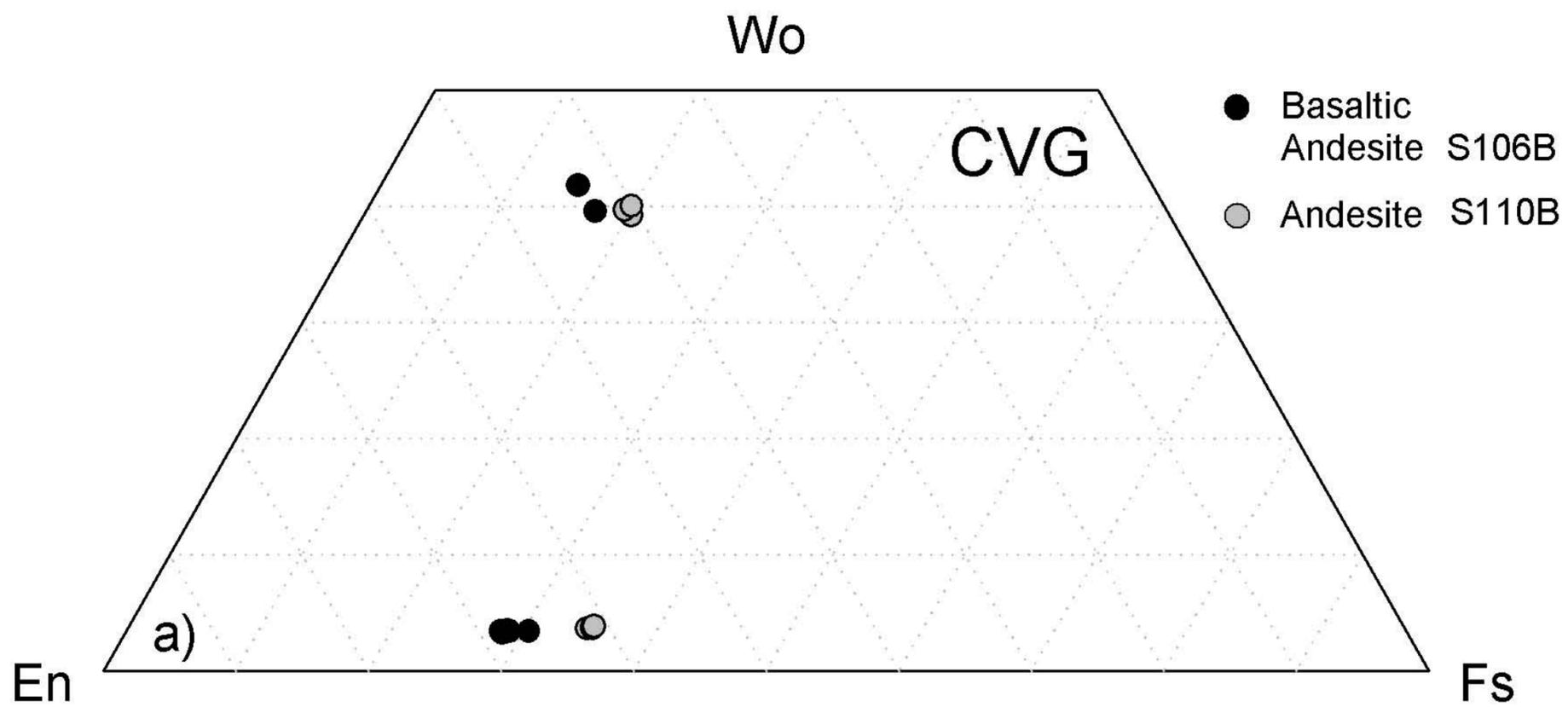
5   labelled SH, AFC and FC indicate the hypothesised data trends related to: heterogeneity in the

6   mantle source (SH), combined assimilation and fractional crystallisation (AFC) and fractional

7   crystallisation (FC). Inset shows Th/Ba versus SiO_2 for Salak rocks, highlighting the similar

8   differentiation patterns between Th/Ba and $^{87}Sr/^{86}Sr$ and suggesting the former, for which

9   there is more data, might serve as a proxy for isotopic composition.

10

11   Fig. 11. Ba/Th against $^{87}Sr/^{86}Sr$ for Salak volcanic rocks. FC and AFC curves are shown for

12   the same models (AFC A, B and C) in Fig. 9 (see caption for details). $^{87}Sr/^{86}Sr$ ratios used in

13   model AFC C is that of GU2/C (Edwards, 1990). Arrow labelled FC indicates differentiation

14   trend expected from fractional crystallisation alone. Tick marks on FC and AFC curves

15   indicate the percentage of liquid remaining.

16

17   Fig. 12. Schematic representation of magmatic evolution, showing the multiple magma

18   storage areas and pathways envisaged in petrogenesis at Salak. (A) and (B) relate to

19   discussion in the text: (A) indicates continued magmatic evolution from a CVG-type parent at

20   shallow depth, involving late-stage fractionation of hornblende in petrogenesis of the western

21   flank SVG rocks, (B) indicates hypothesised fractionation of a HFSE-HREE compatible

22   phase at depth in the evolution of SVG magma below the eastern flank vent.

a) CVG — Basaltic Andesite S106B (● Basaltic Andesite S106B), Andesite S110B (● Andesite S110B)

b) SVG — Andesite S102 (□ Andesite S102), Xenolith in Andesite (+)

c) SL3 — Andesite S112 (△ Andesite S112)

An

core
mid
rim
groundmass

100

90

80

70

% 60

50

40

30

20

10

0

a)   b)   c)   d)   e)   f)

Ab

→ Or

S106B   S111   S110B   S112   S102   S102XEN

basaltic andesite   andesite

CVG   SL3   SVG

WEST

EAST

CVG

SVG lavas
(higher SiO_2)

SVG lavas
(lower SiO_2)

(A)

Further fractional
crystallisation.
Magmas > 70 wt%
SiO_2 fractionate
amphibole

Fractionation of
plag, cpx, Fe-Ti oxide
+/- ol and opx

Arc crust

Combined assimilation of
arc crust and fractional
crystallisation of plag, cpx,
Fe-Ti oxide +/- ol and opx

(B)

Fractionation of a
HFSE-HREE-
compatible phase
at mid-lower
crustal depth

?

Isotopically
heterogeneous
source ?

Mantle source isotopically
similar to low SiO_2 SVG lavas ?

Table 1
Modal proportions of mineral phases in selected Salak volcanic rocks

	CVG								
	S104	S105	S106A	S106B	S108	S109	S110A	S110B	S111
Ol	2.1	4.2	3.3	3.2	-	1.9	-	-	9.1
Opx	1	0.8	7.2	5.9	2.3	3.2	4.2	3.2	-
Cpx	0.3	0.4	2.1	3.8	1.4	7.1	4.3	2.1	-
Plag	26.4	32.8	31.2	32.3	15.5	28.6	14.3	12.7	31.5
Ox	1.1	1.8	2	2	1.9	2	2.1	1.5	2.1
Hbl	-	-	-	-	-	-	-	-	-
Bio	-	-	-	-	-	-	-	-	-
Qtz	-	-	-	-	-	-	-	-	-
GM	69.1	60	54.2	52.8	78.9	57.2	75.1	80.5	57.3

	SVG				SL3	Pre-Salak
	S102	S103	S107B	S102XEN	S112	S101
Ol	-	-	-	-	-	-
Opx	6.2	10.8	-	2.7	7.4	1.5
Cpx	5.1	9	0.1	4.6	10.2	0.25
Plag	34.3	35.4	4.3	10.3	41.1	8.2
Ox	2.9	3.9	0.5	1.7	4	-
Hbl	-	-	0.25	-	-	0.25
Bio	-	-	0.25	-	-	-
Qtz	-	-	1.5	-	-	0.5
GM	51.5	40.9	93.1	80.7	37.3	89.3

Modal phase volume (%) established from point-counting between 200-300 points per sample. Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Plag, plagioclase; Ox, Fe-Ti oxide; Hbl, hornblende; Bio, biotite; Qtz, quartz; GM, groundmass; XEN, xenolith.

Table 2

Representative chemical analyses of olivines

Group	CVG			
Sample	S106B	S106B	S111	S111
Grain-Position	INC	P2-M	P2	P3
SiO_2	36.27	35.09	35.14	36.42
TiO_2	0.01	0.02	0.05	0.04
Cr_2O_3	0.00	0.00	0.00	0.01
MgO	32.79	27.32	25.64	29.66
CaO	0.17	0.19	0.22	0.18
MnO	0.58	0.82	0.82	0.71
FeO	29.60	36.65	38.66	33.94
NiO	0.01	0.01	0.04	0.03
Na_2O	0.01	0.01	0.00	0.00
Total	99.44	100.10	100.56	100.99
Si	0.99	0.99	0.99	1.00
Fe(ii)	0.67	0.86	0.91	0.78
Mn	0.01	0.02	0.02	0.02
Mg	1.33	1.14	1.08	1.21
Ca	0.00	0.01	0.01	0.01
Total	3.02	3.02	3.01	3.01
Fo	66.39	57.06	54.18	60.91
Fa	33.61	42.94	45.82	39.09

Grain: P#, phenocryst; INC, inclusion.

Position: M, mid point.

Fo, forsterite content; Fa, fayalite content.

Structural formula based on 4 oxygens.

Table 3

Representative mineral chemical analyses of pyroxenes

	Clinopyroxene					Orthopyroxene					
Group	CVG		SVG		SL3	CVG		SVG			SL3
Sample	S106B	S110B	S102	S102(XEN)	S112	S106B	S110B	S102	S102(XEN)	S102(XEN)	S112
Grain-Position	P1-R	P1	P1*R	P2	P1-M	P1-R	P1	P1-C	P1	P3	P2-C
SiO_2	49.92	50.64	51.24	52.78	50.99	52.71	51.93	51.68	51.88	53.37	52.25
TiO_2	0.68	0.70	0.37	0.49	0.26	0.32	0.40	0.21	0.19	0.22	0.23
Al_2O_3	3.42	2.21	1.47	1.83	1.07	2.09	1.20	1.00	1.23	0.65	0.88
Cr_2O_3	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.02	0.02	0.01
Fe_2O_3	4.23	3.65	3.70	0.79	3.97	1.73	1.81	2.67	2.18	1.37	2.26
FeO	6.79	9.05	7.36	9.63	7.85	16.50	20.13	21.43	20.81	17.88	20.91
MnO	0.35	0.47	0.50	0.48	0.51	0.48	0.68	1.02	0.92	0.63	0.70
MgO	15.10	14.33	15.54	15.15	13.70	24.80	21.97	21.00	21.54	24.24	21.76
CaO	19.28	19.26	19.48	19.64	21.13	1.63	1.83	1.46	1.49	1.69	1.67
Na_2O	0.33	0.31	0.23	0.27	0.29	0.01	0.03	0.04	0.03	0.03	0.03
K_2O	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
NiO	0.01	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Total	100.11	100.61	99.91	101.07	99.78	100.27	99.99	100.52	100.30	100.09	100.70
Si	1.88	1.91	1.93	1.95	1.94	1.93	1.95	1.95	1.95	1.97	1.95
Al	0.15	0.10	0.07	0.08	0.05	0.09	0.05	0.04	0.05	0.03	0.04
Fe(ii)	0.21	0.28	0.23	0.30	0.25	0.50	0.63	0.67	0.65	0.55	0.65
Fe(iii)	0.12	0.10	0.10	0.02	0.11	0.05	0.05	0.08	0.06	0.04	0.06
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mn	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.03	0.03	0.02	0.02
Mg	0.85	0.80	0.87	0.83	0.78	1.35	1.23	1.18	1.21	1.33	1.21
Ca	0.78	0.78	0.79	0.78	0.86	0.06	0.07	0.06	0.06	0.07	0.07
Na	0.02	0.02	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Total	4.04	4.03	4.03	4.01	4.03	4.01	4.01	4.02	4.02	4.01	4.02
Wo	39.54	39.21	39.15	39.94	42.75	3.22	3.68	2.92	2.99	3.33	3.31
En	43.10	40.59	43.45	42.89	38.58	68.25	61.33	58.48	60.10	66.41	60.18
Fs	17.36	20.20	17.40	17.17	18.67	28.53	35.00	38.60	36.91	30.26	36.51

Grain: P#, phenocryst; *mantling orthopyroxene. XEN = xenolith. Position: C, core; M, mid point; R, rim.
Wo, wollastonite content; En, enstatite content; Fs, ferrosilite content. Structral formula based on 6 oxygens.
Fe(iii) = 2X(1-T/S), where X = number of oxygens, T and S = correct and observed cation totals, respectively.

Table 4
Representative mineral chemical analyses of plagioclase

Group	CVG					SVG				SL3	
Sample	S106B	S106B	S110B	S111	S111	S102	S102	S102(XEN)	S102(XEN)	S112	S112
Grain-Position	P3-M	P4-R	P3-C	GM	P4-R	P2-C	P2-R	P2-C	P2-M	P3-C	P3-R
SiO_2	45.33	51.16	53.97	55.44	45.66	54.69	53.72	53.87	48.00	54.10	52.46
TiO_2	0.01	0.04	0.05	0.07	0.01	0.04	0.02	0.02	0.03	0.02	0.03
Al_2O_3	33.88	29.59	28.19	27.05	34.05	27.57	27.77	28.05	31.69	27.71	28.94
MgO	0.05	0.08	0.07	0.06	0.02	0.05	0.05	0.04	0.07	0.05	0.05
CaO	18.56	13.85	11.90	11.04	18.60	11.09	11.45	11.83	16.37	11.45	13.03
MnO	0.02	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02
FeO	0.60	0.66	0.59	1.22	0.62	0.41	0.57	0.48	0.51	0.45	0.54
Na_2O	1.16	3.80	4.97	5.50	1.08	5.42	5.26	4.94	2.41	5.27	4.42
K_2O	0.03	0.11	0.21	0.31	0.02	0.14	0.13	0.11	0.02	0.22	0.17
Total	99.63	99.29	99.96	100.69	100.05	99.41	98.95	99.34	99.09	99.27	99.64
Si	8.43	9.41	9.81	10.01	8.44	9.96	9.85	9.83	8.91	9.88	9.59
Al	7.42	6.42	6.04	5.76	7.42	5.92	6.00	6.03	6.93	5.97	6.24
Fe	0.09	0.10	0.09	0.18	0.10	0.06	0.09	0.07	0.08	0.07	0.08
Ca	3.70	2.73	2.32	2.14	3.68	2.16	2.25	2.31	3.25	2.24	2.55
Na	0.42	1.36	1.75	1.93	0.39	1.91	1.87	1.75	0.87	1.87	1.57
K	0.01	0.03	0.05	0.07	0.00	0.03	0.03	0.03	0.00	0.05	0.04
Mg	0.01	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.02	0.01	0.01
Total	20.07	20.06	20.07	20.10	20.04	20.05	20.10	20.04	20.06	20.09	20.09
An	89.72	66.38	56.30	51.69	90.45	52.64	54.20	56.59	78.92	53.87	61.39
Ab	10.13	32.98	42.51	46.61	9.46	46.60	45.06	42.77	20.98	44.89	37.68
Or	0.15	0.63	1.19	1.71	0.09	0.76	0.74	0.64	0.10	1.24	0.93

Grain: P#, phenocryst; GM, groundmass. Position: C, core; M, mid point; R, rim. Structural formula based on 32 oxygens.
XEN, xenolith within rock. An, anorthite content; Ab, albite content; Or, orthoclase content.

Table 5
Representative mineral chemical analyses of Fe-Ti oxides

Group	CVG									SVG				SL3				
Sample	S106B	S106B	S106B	S110B	S110B	S110B	S111	S111	S111	S102	S102	S102(XEN)	S102(XEN)	S112	S112	S112	S112	S112
Grain-Position	P1-C	P2-C	P3	INC	P1	P2	P1	P2	P3	P1	P2	P1	P2	P1	P2	P3	P4-C	P4-C
SiO_2	0.08	0.07	0.07	0.08	0.07	0.08	0.07	0.10	0.05	0.10	0.06	0.05	0.11	0.05	0.05	0.03	0.06	0.04
TiO_2	11.05	11.32	15.56	15.95	18.18	15.03	10.29	12.77	11.18	11.64	12.85	9.68	46.52	13.32	13.78	13.52	13.45	13.46
Al_2O_3	4.24	3.66	1.85	3.11	2.46	2.69	4.37	2.74	3.66	2.41	2.09	2.84	0.05	2.53	2.34	2.39	2.44	2.48
Cr_2O_3	0.03	0.05	0.07	0.01	0.04	0.03	0.16	0.24	0.14	0.02	0.01	0.06	0.00	0.03	0.02	0.04	0.02	0.03
Fe_2O_3	43.72	43.25	37.35	34.37	31.46	37.93	44.32	41.08	43.62	43.53	41.30	47.13	0.00	41.14	41.01	40.57	40.16	40.84
FeO	37.57	38.13	42.54	41.35	45.19	42.08	37.46	39.94	38.31	39.58	40.24	37.59	46.67	41.53	41.56	40.31	40.31	40.79
MnO	0.43	0.44	0.47	0.51	0.58	0.59	0.40	0.42	0.42	0.52	0.62	0.48	1.26	0.51	0.58	0.52	0.49	0.49
MgO	2.67	2.25	1.82	2.61	1.68	1.96	2.19	1.89	2.11	1.33	1.37	1.50	1.63	1.31	1.60	1.94	1.86	1.77
CaO	0.00	0.00	0.03	0.02	0.00	0.03	0.00	0.01	0.00	0.00	0.02	0.00	0.19	0.01	0.00	0.05	0.00	0.00
Total	99.79	99.15	99.75	98.00	99.66	100.42	99.26	99.19	99.48	99.12	98.55	99.32	96.42	100.42	100.93	99.37	98.79	99.90
Si	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.01	0.03	0.02	0.01	0.04	0.02	0.01	0.01	0.02	0.01
Ti	2.43	2.52	3.47	3.58	4.05	3.32	2.28	2.86	2.49	2.63	2.92	2.18	10.78	2.96	3.05	3.03	3.03	3.00
Al	1.46	1.28	0.65	1.09	0.86	0.93	1.52	0.96	1.27	0.85	0.74	1.00	0.02	0.88	0.81	0.84	0.86	0.87
Cr	0.01	0.01	0.02	0.00	0.01	0.01	0.04	0.06	0.03	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.01
Fe(iii)	9.62	9.63	8.35	7.71	7.00	8.38	9.84	9.20	9.70	9.83	9.38	10.61	0.00	9.16	9.07	9.08	9.04	9.10
Fe(ii)	9.19	9.44	10.56	10.31	11.18	10.33	9.24	9.94	9.46	9.93	10.16	9.40	12.03	10.27	10.21	10.03	10.09	10.11
Mn	0.11	0.11	0.12	0.13	0.14	0.15	0.10	0.11	0.10	0.13	0.16	0.12	0.33	0.13	0.14	0.13	0.12	0.12
Mg	1.16	0.99	0.81	1.16	0.74	0.86	0.96	0.84	0.93	0.59	0.62	0.67	0.75	0.58	0.70	0.86	0.83	0.78
Ca	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.06	0.00	0.00	0.01	0.00	0.00
Total	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
TiO_2	11.97	12.21	16.30	17.40	19.17	15.82	11.17	13.61	12.01	12.29	13.62	10.25	49.92	13.88	14.30	14.32	14.32	14.15
Fe_2O_3	47.35	46.66	39.14	37.50	33.17	39.90	48.14	43.80	46.85	45.94	43.75	49.93	0.00	42.86	42.56	42.98	42.76	42.95
FeO	40.69	41.13	44.57	45.11	47.65	44.28	40.69	42.58	41.14	41.77	42.63	39.82	50.08	43.26	43.14	42.70	42.92	42.90

Grain: P, phenocryst; GM, groundmass; GLOM, glomerocryst; INC, inclusion (mineral included within is stated in parentheses) XEN = xenolith.

Spot: C, core; M, mid point (number indicates relative position along transect from core to rim); R, rim. Structural formula based on 32 oxygens.

Table 6

Whole rock major element, trace element and isotopic compositions of Salak volcanic rocks

	CVG								
Sample	S104	S105	S106A	S106B	S108	S109	S110A	S110B	S111
SiO_2	54.90	54.09	54.01	53.77	57.50	56.58	59.97	60.57	53.66
Al_2O_3	19.43	20.16	18.71	18.78	17.49	17.60	15.83	15.94	19.61
Fe_2O_3	8.89	8.45	9.99	9.85	8.78	9.21	8.50	8.50	9.60
MgO	2.54	2.49	3.63	3.61	2.26	2.88	1.86	1.81	3.33
CaO	7.70	8.79	8.38	8.39	6.20	6.89	5.14	4.98	8.67
Na_2O	3.60	3.56	3.35	3.48	4.15	3.85	4.26	4.29	3.32
K_2O	1.03	0.93	0.83	0.84	1.56	1.34	2.07	2.11	0.80
TiO_2	1.04	0.97	1.02	1.01	1.15	1.18	1.16	1.17	0.98
MnO	0.17	0.17	0.19	0.19	0.21	0.20	0.19	0.16	0.18
P_2O_5	0.33	0.26	0.26	0.26	0.40	0.28	0.48	0.48	0.28
LOI	0.48	-0.13	-0.05	0.05	0.16	0.01	0.08	0.15	-0.08
Total	100.12	99.74	100.32	100.22	99.86	100.01	99.54	100.17	100.36
Sc	23	20	23	23	24	27	24	23	20
Ti	6851	6683	6671	6605	7618	7876	7750	7726	5568
V	160	143	178	177	99	161	75	74	164
Cr	2.2	1.1	2.4	4.3	0.4	0.5	0.3	0.9	7.7
Mn	1262	1239	1727	1743	1928	1835	1750	1193	1495
Co	19	18	22	22	14	17	13	10	21
Ni	4.7	1.5	4.3	4.2	0.8	1.1	1.1	0.9	8.1
Cu	52	26	38	36	38	35	54	41	18
Zn	72	58	70	74	87	73	81	76	70
Ga	20	19	19	19	19	19	19	19	19
Rb	33.8	27.8	23.7	23.8	52.3	44.4	68.8	74.1	22.4
Sr	374	451	422	422	354	358	292	291	395
Y	41	35	32	37	55	52	67	69	33
Zr	188	140	125	125	226	189	311	310	133
Nb	8.15	6.04	5.25	5.21	9.99	7.87	13.67	13.76	5.65
Cs	2.27	0.99	0.75	0.95	2.80	2.31	3.83	4.13	0.78
Ba	214	194	173	176	304	253	368	366	188
La	18.1	13.7	12.9	16.2	22.5	19.2	29.3	30.1	14.0
Ce	41.6	31.9	29.2	29.8	52.1	41.7	68.2	65.9	32.4
Pr	6.07	4.68	4.32	5.20	7.56	6.29	9.76	10.09	4.79
Nd	27.6	21.6	20.0	24.2	34.5	28.7	44.2	45.3	22.2
Sm	6.48	5.20	4.84	5.67	8.33	6.95	10.43	10.65	5.28
Eu	1.86	1.54	1.44	1.68	2.06	1.82	2.33	2.35	1.58
Gd	6.79	5.70	5.25	6.19	8.93	7.50	11.03	11.24	5.68
Tb	1.08	0.91	0.83	0.98	1.45	1.24	1.77	1.83	0.90
Dy	6.52	5.50	4.96	5.83	8.69	7.55	10.67	10.99	5.33
Ho	1.36	1.17	1.05	1.22	1.83	1.63	2.25	2.35	1.13
Er	3.77	3.24	2.90	3.36	5.06	4.56	6.27	6.42	3.09
Tm	0.60	0.51	0.46	0.51	0.79	0.71	0.97	1.02	0.48
Yb	3.84	3.28	2.94	3.29	5.08	4.57	6.31	6.54	3.07
Lu	0.64	0.54	0.49	0.55	0.85	0.77	1.07	1.08	0.52
Hf	4.58	3.58	3.23	3.19	5.82	4.87	7.94	7.93	3.41
Ta	0.47	0.34	0.30	0.31	0.60	0.47	0.81	0.87	0.33
Pb (total)	7.0	6.3	4.7	6.8	13.8	9.2	16.1	22.6	5.3
Th	3.49	2.87	2.44	2.43	5.94	4.66	7.88	7.90	2.51
U	0.81	0.64	0.56	0.56	1.32	1.02	1.72	1.74	0.58
$^{87}Sr/^{86}Sr_m$			0.704671±9	0.704639±9		0.704745±9	0.704778±10		0.704596±10
$^{143}Nd/^{144}Nd_m$			0.512735±7	0.512738±6		0.512741±6	0.512723±8		0.512746±9
$^{176}Hf/^{177}Hf_m$			0.283055±9	0.283040±6		0.283050±6	0.283041±6		0.283046±28

Major element contents in wt%; trace elements concentrations in ppm; $_m$ = measured; isotope ratios ± 2SE (2*standard internal error).

Table 7

Oxygen isotope data ($\delta^{18}O$) of mineral separates from Salak volcanic rocks

	clinopyroxene	plagioclase
S100		6.03
S103	5.18	5.97
S106A	5.37	
S111		5.96
S112	5.44	6.07

Table 8

End member compositions used in modelling calculations

	Sample	Type	Element Concentrations (ppm)				
			K	Rb	Ba	Th	Yb
	S106B	Salak basaltic andesite	3470	24	176	2.4	3.29
A	107A	Salak rhyolite	16545	158	582	20.1	2.24
B	75415	Sumatran granitoid	14652	237	12	34.9	1.35
C	GU1/T	Javan tholeiite	1374	3.4	97	0.8	2.94
D	75413	Sumatran granitoid	17101	68	937	5.9	1.86

Sumatran granitoid data from Gasparon (1993); Javan tholeiite
from Guntur (Edwards, 1990); Salak samples from this study

Table 9

Summary of least squares major element modelling calculations for CVG rocks

Model		1	2	3	4
Parent		S106B	S106B	S106B	S106B
Daughter		S110B	S108	S104	S104
SiO$_2$ range (%)		53.8-60.6	53.8-57.5	53.8-54.9	53.8-54.9
Σr^2		0.13	0.13	0.01	0.01
% of phase	Plag	43.4	32.9	10.6	8.2
removed	Cpx	6.0	5.7	4.3	4.5
relative	Ol	-	-	-	2.7
to initial	Opx	7.9	6.1	3.5	-
magma	Ox	3.9	3.0	1.6	0.8
%C		61	48	20	16

%C = percentage of crystallisation (sum of phases removed)
The mineral phases considered in modelling are limited to those observed as
phenocrysts in either the parent or daughter rocks.

Table 10
Click here to download Table: Table_10new.xls

Table 10
Results of trace element Rayleigh Fractionation modelling

Element	Yb	Ti	Y
normalised phase proportions			
Plag	70.97	70.97	70.97
Opx	12.84	12.84	12.84
Cpx	9.80	9.80	9.80
Fe-Ti Ox	6.40	6.40	6.40
Parent concentration (Co)	3.3	6605	37
Degree of fractionation (F)	0.39	0.39	0.39
D_{Plag}	0.052	0.052	0.076
D_{Opx}	0.283	0.423	0.028
D_{Cpx}	0.661	0.350	0.860
$D_{Fe\text{-}Ti\ Ox}$	0.218	9.500	0.322
D (bulk)	0.170	0.733	0.203
Calculated daughter comp. (Cl)	**7.2**	**8500**	**79**
Measured daughter comp. (Cl)	**6.5**	**7726**	**69**

Daughter (S110B) composition calculated by forward
modelling of parent S106B using $Cl = Co.F^{(D-1)}$.
Phase proportions and degree of fractionation values used
are those suggested by least squares modelling (Table 9,
Model 1). Distribution coefficients (D) are average values
for basaltic-dacitic systems from the GERM database
(http://earthref.org/GERM/index.html).

Table 11

Trace element and $^{87}Sr/^{86}Sr$ isotope compositions of potential crustal contaminants

	Sample no.	Rock Type	Sr (ppm)	$^{87}Sr/^{86}Sr$	K/Rb	Ba/Th
1	VM33-75	terrig.-bio. sediment	196	0.70925	106	16
2	VM33-79	terrigenous mud	160	0.70802	124	18
3	CS	calcareous-organogenic sediment	1258	~ 0.709	106	60
4	76100	S-Type granite	32	0.74036	185	0.2
5	ME99AL16	intrusive (51 wt % SiO_2)	609	0.706155	118	77
6	ME00AL42	intrusive (62 wt % SiO_2)	375	0.706600	126	53
7	H110x	intrusive (51 wt % SiO_2)	152	0.708561	139	292
8	J82x	intrusive (hbl spessarite)	173	0.705291	346	58
9	GU1/T	Javan tholeiitic lava	232	0.70393	404	127
10	TAF43/6	Tongan tholeiitic lava	118	0.70388	519	344
11	417D-418A	altered oceanic crust	118	0.704584	235	364
12	M22	basalt (ophiolitic)	143	-	416[a]	10
13	P-15	dolerite (ophiolitic)	171	-	4150	27
14	S-134	clinopyroxene gabbro (ophiolitic)	129	-	1245	70

Data sources: 1-4: Gasparon 1993; Gasparon et al., 1998; 5-8: Elburg et al., 2005; 9: (Guntur tholeiite) Edwards, 1990; 10: Turner et al., 1997; 11: (average 417D-418A n = 7) Staudigel et al., 1996; 12-14 (Sulawesi ophiolite) Kadarusman et al., 2004.

[a] Rb concentration below detection limit therefore Rb abundance used is of sample P-33 (0.5 ppm) from the same area.