

Spatial Variations in the Geochemistry of Quaternary Lavas Across the Sunda Arc in Java and Bali

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Abstract. Since Mesozoic time, Java and Bali have formed part of an evolving system of island arcs comprising the Sunda arc of Indonesia. The present tectonic setting is relatively simple with subduction occurring at the Java Trench to the south. A north-dipping Benioff seismic zone delineates an underthrust lithospheric slab to depths of approximately 600 km beneath the Java Sea. Quaternary lavas of the 'normal island arc association' range from tholeiites to high-K calc-alkaline lavas over Benioff zone depths from 120–250 km, respectively. More abundant calc-alkaline lavas lie between these extremes. High-K alkaline lavas are found over Benioff zone depths in excess of 300 km.

Both within and between these groups of rocks there are consistent spatial variations in the observed geochemistry. For approximately 200 rocks, incompatible elements such as K, Rb, Cs, Sr, Ba, light REE, U and Th show an increase in abundance of almost an order of magnitude with increasing depth to the seismic zone. Abundances of compatible elements show little consistent variation and trace elements such as Ni, Co, Cr, and Sc are characteristically depleted except in some of the alkaline lavas. Major element abundances in rocks of the normal island arc association show little variation, except for K and P, which both increase in abundance across the arc and Al, which shows a relative decrease.

The major and trace element data are inconsistent with the derivation of the analyzed rocks by partial melting of the crustal component of the subducted lithosphere. On the other hand, low Ni abundances (~20 ppm) in the basalts suggest that most of the lavas are fractionated and few if any represent pri-

mary mantle-derived melts. The spatial variations in the geochemistry of erupted lavas across Java and Bali are best explained by a combination of two processes: melting of a geochemically zoned mantle source and smaller degrees of partial melting of that material at progressively greater depths. Primary tholeiitic magmas could be formed by 20–25% melting at depths of 30–40 km, primary high-K calc-alkaline magmas by 5–15% melting at 40–60 km depth, and primary alkaline magmas by 5% melting at depths of 80–90 km. The geochemical zoning in the mantle, which is also manifested by increasing $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in lavas across the arc, is interpreted to result from the addition of a small melt fraction derived from the crustal component of the subducted lithosphere.

Introduction

A zonal arrangement in the petrography and geochemistry of island arc volcanic rocks has been recognized for many years, particularly in the Sunda arc of Indonesia and in Japan (Sugimura, 1968). Van Bemmelen (1949) recognized an increase in the alkali contents in lavas across the Sunda arc from the 'trench' (i.e., Indian Ocean) side towards the hinterland (Java Sea) and Tomkiewit (1949) noted that the areas behind many island arcs in the Pacific are characterized by alkaline volcanics. Rittmann (1953, 1958) quantified the chemical variations in lavas across the Sunda arc using a number of indices based largely on the alkali contents of lavas. Kuno (1959), Katsui (1959), and Sugimura (1959), were the first to observe a correlation between the composition of lavas erupted in an island arc and the depth to underlying earthquake foci, and Hatherton and Dickinson (1969) showed that in many island arcs, the variation in

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the *K* content of erupted lavas correlates better with depth to the Benioff zone (*h*) than with distance from the trench.

Comprehensive recent surveys of the geochemical variations across island arc systems are those of Jakeš and White (1972) and Gill and Gorton (1973). They noted an increase in the abundance of K, Rb, Ba, Cs, P, Pb, Th, U and the light rare earth elements (REE) and increases in the ratios Th/U, Rb/Sr, and La/Yb, in lavas across island arcs with increasing *h*. They also noted a decrease in *Y* and heavy REE concentrations, maximum Fe contents and SiO₂ range and decreases in the ratios Na/K and K/Rb.

The most studied chemical variation across island arcs is that of potassium. Details of the relationship between the *K* content and K₂O/SiO₂ ratio in erupted lavas and *h* beneath Java and Bali have already been described by Hatherton and Dickinson (1969), Nin-kovich and Hays (1972), and Whitford and Nicholls (1976).

It is the purpose of this paper:

- (a) to outline briefly the tectonic and geologic setting of the western sector of the Sunda arc;
- (b) to examine the relationship between magmatism and tectonic environment;
- (c) to summarize the petrography and major and trace element geochemistry of the wide range of Recent lavas found in Java and Bali, and
- (d) to delineate the principal spatial variations in the geochemistry of the volcanic rocks and to examine the implications of these variations for petrogenetic models.

Tectonic and Geologic Setting

The Sunda arc represents part of the convergent collision zone between the Indian Plate to the south and the Asian or China Plate to the north. Le Pichon (1968) calculated convergence rates of 4.9 and 6 cm yr⁻¹ with a pole of rotation of 23.0° N 5.2° W. Compared with most island arcs, Java and Bali are characterized by a relatively simple tectonic setting, summarized by Hamilton (1973) (Fig. 1).

The evolution of the Indonesian Archipelago has apparently been dominated, since the late Palaeozoic, by an evolving system of island arcs (Katili, 1975; Hutchison, 1973). The fossil arcs are now represented by a series of linear volcano-plutonic igneous complexes with associated sedimentary deposits. The maximum age of these complexes decreases from Sumatra (late Palaeozoic) to the eastern end of the system in the Banda arc (late Tertiary). The present arc became a single entity in the mid-Tertiary (Audley-Charles, 1975) and the pre-mid Tertiary geological evolution of the sector of the arc west of Sumbawa was apparently distinct from that to the east. The pre-mid-Tertiary evolution of the eastern Sunda and Banda arcs seems related to that of the neighboring Australian continent while the western Sunda arc appears unrelated (McElhinny et al., 1974).

Tectonic environments along the Sunda arc reflect this evolutionary pattern. In Sumatra, the crust is relatively thick (~25 km,

Cummings and Schiller, 1971) and the presence of Palaeozoic granites and pelitic schists (Van Bemmelen, 1949; Katili, 1973) suggests a mature continental crust. The eastern Sunda and Banda arcs are young (Tertiary), immature features located on oceanic crust (Van Bemmelen, 1949; Ben Avraham and Emery, 1973; Curray et al., 1977; Purdy et al., 1977). The crust beneath Java and Bali, approximately 20 km thick, has a velocity structure intermediate between continental and oceanic, (Ben Avraham and Emery, 1973; Curray et al., 1977), and the oldest exposed rocks are thought to be Mesozoic (Van Bemmelen, 1949; Katili, 1973).

Seismicity studies of the Sunda arc show a regular spatial distribution of earthquake epicentres along the arc (Fitch, 1970, 1972; Fitch and Molnar, 1970). Shallow focus earthquakes (<70 km) occur along the entire length of the arc and are confined to a narrow zone, generally less than 200 km wide (Fitch, 1970, Fig. 3), located between the trench and the volcanic arc. Intermediate and deep focus earthquakes (>70 km) occur in a parallel zone farther from the trench.

West of the Sunda Strait, in Sumatra, there is a poorly defined Benioff zone dipping to the north-east, that has not been observed at depths greater than 250 km. East of the Strait, earthquakes at depths between 500–650 km are relatively common although there is a marked gap in seismic activity between about 300–500 km. The deep focus events define a Benioff zone dip of 60°, although it is less steep at depths of less than 100 km.

In Java and Bali, the oldest widely exposed rocks are lower Tertiary shallow marine sediments which were intruded and overlain by plutonic and related volcanic rocks in a zone only slightly south of the present-day volcanic arc. The igneous activity corresponds to Van Bemmelen's (1949) 'first cycle of volcanism' and gave rise to the 'Old Andesites' which are relatively common in the Southern Mountains of Java and in the Barisan Range of Sumatra, and it culminated in a period of uplift and intrusion in the mid-Miocene.

Van Bemmelen (1949) recognized a second cycle of volcanism of late Tertiary age marked by the appearance of more alkaline lavas such as those of the high-K calc-alkaline suite. This second cycle was located further north and north-east from the Miocene 'Old Andesites'. These rocks are found together with the Quaternary 'third cycle of volcanism'. The distinction between the products of these latter cycles is rarely clearcut.

Tectonic Environment and Magmatism

There are three principal volcanic associations represented in the Pleistocene and Recent lavas of the Sunda arc.

1. Normal Island Arc Association

This is the most abundant and widespread association and is found along the entire length of the arc. Rocks of this association range from those showing geochemical affinities with the island arc tholeiitic suite as defined by Jakeš and Gill (1970), which are found closest to the trench over Benioff zone depths of 100–150 km, through an apparently continuous spectrum of calc-alkaline to high-K calc-alkaline compositions more distant from the trench over Benioff zone depths of 150–250 km. This is the typical volcanic association of most island arcs and continental margins and in the Sunda arc probably accounts for more than 90% of erupted lavas.

2. High-K Alkaline Association

Rocks of this association are comparatively rare being found in only three or four Quaternary (probably early Pleistocene) vol-

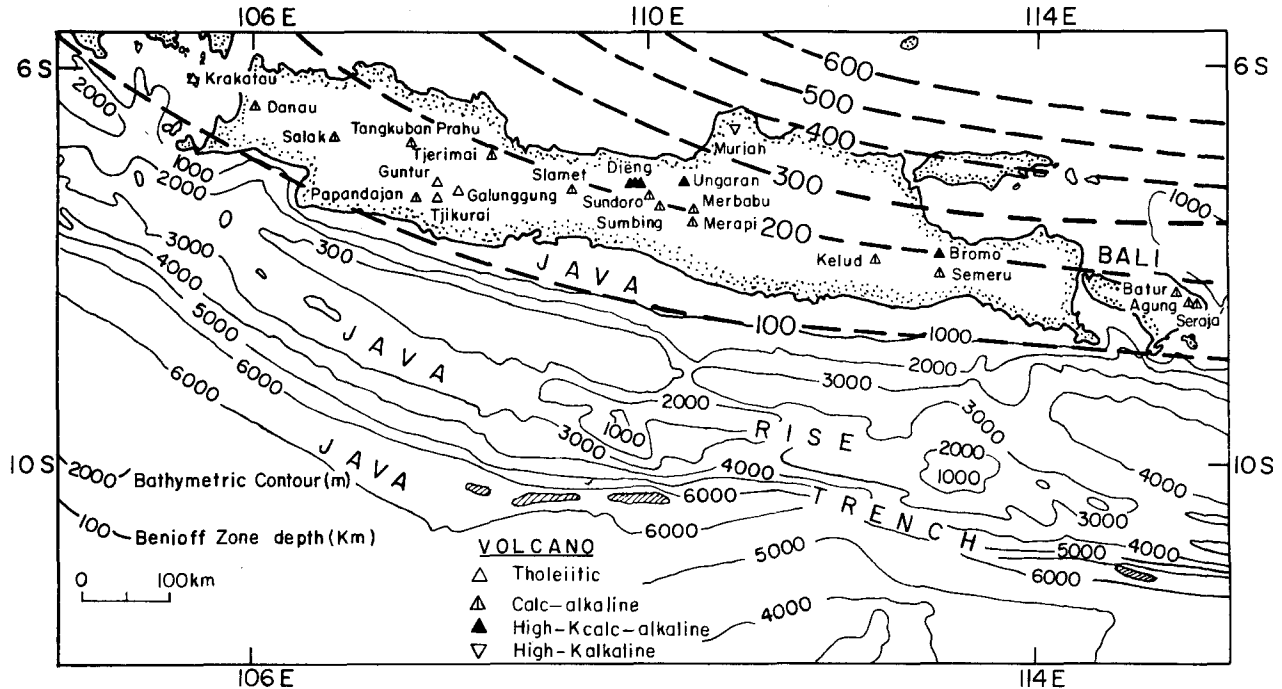


Fig. 1. Regional tectonic setting of Java and Bali. Bathymetry after Hamilton (1974a) and Benioff zone contours after Hamilton (1972). Volcanoes sampled as part of this study are denoted by triangles

canoes along the arc (Neumann van Padang, 1951). They generally occur over Benioff zone depths greater than about 300 km. This association appears to be petrographically and chemically distinct from the normal island arc association; the rocks generally being highly undersaturated, often very mafic and very alkaline (up to 13.5wt% alkalis).

3. Rhyolitic Association

This association is represented by the Quaternary rhyolitic tuffs and ignimbrites which are widespread in both Northern and Southern Sumatra (Westerveld, 1952). Their chemistry indicates an origin by partial melting of sialic crust (Whitford, 1975a). These rocks are found almost exclusively in Sumatra where the crust includes in major sialic component. The Benioff zone extends only to shallow depths and oblique convergence between the Indian-Australian and Asian plates is taken up by strike-slip movement along the Semangko Fault (Fitch, 1970; Katili, 1975).

Only the normal island arc association is represented in the Recent lavas from Java and Bali. Although included in the study of the spatial variations in the geochemistry, details of the geochemistry and petrology of the Pleistocene alkaline lavas will be presented separately (Nicholls and Whitford, in preparation). The location of volcanic centres, sampled as part of this study is shown in Fig. 1.

Petrography

1. Normal Island Arc Association

The dominant lavas of the normal island arc association are basaltic andesites, with a silica mode of around 55 wt.% (Nicholls and

Whitford, 1976). These rocks are strongly porphyritic with major phenocrysts of plagioclase (An_{90-60}), augite (average composition $Ca_{4.5}Mg_{4.0}Fe_{1.5}$), olivine (Fo_{80-60}) and Ti-magnetite (up to 60 mol.% ulvöspinel). Orthopyroxene phenocrysts (average composition $Ca_5Mg_{6.5}Fe_{3.0}$) occur in basaltic andesites of tholeiitic and calc-alkaline affinities, but they are progressively replaced in more potassic rocks by pargasitic amphibole, with up to 3 wt.% TiO_2 .

Andesites and dacites are common amongst calc-alkaline and high-K calc-alkaline lavas. Both types are very rich in strongly zoned plagioclase phenocrysts ($An_{80}-An_{40}$) and augite (average $Ca_{4.2}Mg_{4.0}Fe_{1.8}$). Phenocrysts of orthopyroxene (average $Ca_3Mg_{6.2}Fe_{3.5}$) are joined by pargasitic amphibole and phlogopitic biotite, with up to 6 wt.% TiO_2 , in lavas of high-K calc-alkaline affinities.

Groundmass assemblages in all rocks are dominated by plagioclase, pyroxenes (augite and hypersthene in tholeiitic and calc-alkaline rocks, augite alone in most high-K calc-alkaline rocks) and Ti-magnetite. Interstitial glass occurs in less potassic rocks, while interstitial alkali feldspar, and minor amphibole and biotite are present in rocks of the high-K calc-alkaline series.

2. High-K Alkaline Association

Many of these rocks are highly mafic, and the dominant phenocryst phases are olivine (Fo_{90-60}) and calcium-rich clinopyroxene (often strongly zoned diopsidic augite to aluminian augite). Phenocrysts of calcic plagioclase (An_{90-60}) and rare leucite occur in less mafic lavas, while pargasitic amphiboles with up to 2.8 wt.% K_2O , phlogopitic biotite, and rarely garnet (Ti-andradite) occur in more felsic types.

Groundmass assemblages are dominated by augite rich in Al_2O_3 , and Fe_2O_3 , plagioclase, alkali feldspar, leucite, nepheline and Ti-magnetite, but olivine is abundant in more mafic types. Sodalite and analcite are locally present.

Geochemistry

Classification of Analyzed Lavas

The normal island arc association has been arbitrarily subdivided into tholeiitic, calc-alkaline and high-K calc-alkaline series (see e.g. Jakeš and Gill, 1970; Jakeš and White, 1972; McKenzie and Chappell, 1972), groupings which reflect increasing contents of K and related incompatible elements within the apparently continuous spectrum of compositions present. The term 'shoshonite' as used by Smith (1972), which might be used to describe the high-K calc-alkaline lavas has been avoided because of confusion concerning its definition. Within each series a further arbitrary subdivision of rocks into basalt, basaltic andesite, andesite and dacite has been made on the basis of SiO₂ contents (Fig. 2). Parameters other than K₂O such as Rb, La, La/Yb, U or Th could equally well be applied.

Where lavas of an individual volcanic centre are geochemically coherent, they have been assigned to the series (tholeiitic, calc-alkaline, etc.) which best fits the group as a whole. Consequently, the boundaries of Fig. 2 have not been adhered to in all cases, and rocks of similar composition in different volcanic centres may have been assigned to different rock series. Where a wide variety of apparently unrelated lavas occurs within a single volcano (e.g. Krakatau, Guntur), more than one rock series has been distinguished.

In terms of the degree of depletion of incompatible elements the tholeiites described below are less primitive geochemically than those described by Jakeš and Gill (1970). However the term has been retained because of their similarities with the more primitive rocks and because they form one end of a compositional spectrum within the island arc association as it is represented in Java and Bali.

Because of the large volume of data available most of the following discussion is framed in terms of average compositions which are listed in Tables 1–3. Although this approach obscures the peculiarities of particular rocks or small groups of rocks, it provides a useful framework for more detailed studies (Whitford and Nicholls, in preparation). Individual analyses may be obtained from the authors.

Major Elements

The variation of abundances is shown in Fig. 3. Within each series the concentration of K and Na increase from basalt to dacite while Ti, Al, Fe, Mg, Ca, and P decrease. The differences between the series are best illustrated by K and less clearly by Si, Ca,

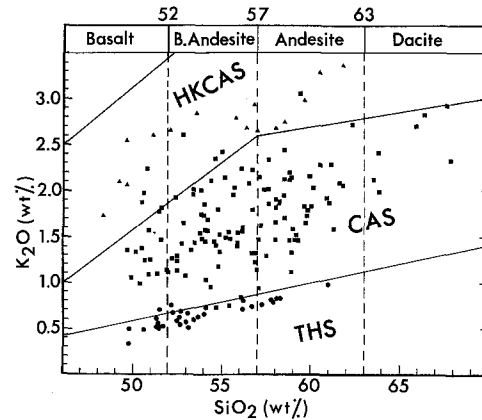


Fig. 2. Classification scheme for analyzed lavas of the normal island arc association from Java and Bali. Tholeiitic (THS), calc-alkaline (CAS) and high-K calc-alkaline series (HKCAS) respectively reflect increasing contents of K and related incompatible elements within an apparently continuous spectrum of compositions

and Al. Details of the variation of SiO₂ and the atomic ratio Mg/(Mg+Fe²⁺) for rocks of selected volcanoes have been described by Nicholls and Whitford (1976).

The lavas from Java and Bali show many similarities with lavas from other island arcs. They are characterized by high Al contents, low Mg, low atomic Mg/(Mg+Fe²⁺) and generally low Ti concentrations. In detail however, there are differences which may be significant. Most island arc lavas have TiO₂ concentrations of less than 1.2 wt.%. The average calc-alkaline basalt composition of Java and Bali has a slightly higher TiO₂ concentration of 1.27 wt.% which is a reflection of unusually high concentrations (up to 1.9 wt.%) in lavas from the volcano Slamet, Java (Fig. 1).

The variations of the average rock compositions in terms of Na+K, Fe, and Mg (AFM) is shown in Fig. 4. The tholeiites are the most Fe-rich but they do not exhibit a trend of Fe-enrichment with fractionation. The calc-alkaline and high-K calc-alkaline groups are almost indistinguishable. An interesting aspect of the major element geochemistry is the enrichment of Fe relative to similar lavas from other island arcs and continental margins. Taylor's (1969) average compositions of a number of andesites and related rocks are plotted in Fig. 4 and show that except for the low-K andesite, all are significantly less Fe-rich than the Indonesian rocks. There is a similar enrichment of Al in the Indonesian lavas.

Trace Elements

Trace element abundances in the Indonesian lavas closely match those found in rocks from other island

Table 1. Averaged major and trace element concentrations in Quaternary tholeiitic lavas from Java

	Tholeiitic Series								
	Basalt			Basaltic Andesite			Andesite		
		1 σ	n ^f		1 σ	n	1 σ	n	
SiO ₂ ^a	51.0	0.7	11	53.6	1.4	17	58.4	1.3	6
TiO ₂	0.96	0.05	11	0.85	0.1	17	0.71	0.07	6
Al ₂ O ₃	19.7	0.6	11	19.9	0.8	17	18.5	0.5	6
FeO* ^b	9.4	0.6	11	8.3	0.8	17	7.6	1.3	6
MnO	0.18	0.05	11	0.17	0.03	17	0.10	0.04	6
MgO	5.1	0.9	11	3.8	0.5	17	3.1	0.7	6
CaO	9.9	0.3	11	9.0	0.7	17	7.2	0.2	6
Na ₂ O	3.1	0.2	11	3.5	0.3	17	3.5	0.2	6
K ₂ O	0.51	0.09	11	0.64	0.08	17	0.83	0.08	6
P ₂ O ₅	0.16	0.03	11	0.20	0.04	17	0.16	0.02	6
Mg/(Mg + Fe ²⁺) ^c	0.53			0.49			0.46		
Cs ^d	0.5	0.1	3	0.9		1	1.2		2
Rb	11	2.9	11	15	3.8	17	26	3.9	6
Ba	120	26	4	160	42	8	200		2
Sr	310	30	11	290	30	17	300	16	6
Pb ^e	1.4		2				5.2		1
K/Rb	392			359			270		
K/Cs ($\times 10^{-3}$)	8.5			5.9			5.7		
K/Ba	34			33			34		
Rb/Sr	0.035			0.051			0.084		
Th	0.79	0.1	3	1.5		1	2.0		2
U	0.19	0.05	3	0.54		1	0.63		2
Zr	74	7.6	11	83	7.2	17	90	12	6
Hf	1.7	0.5	3	2.0		1	2.4		2
Sn	1.9	1.4	3	6.5		1	3.4		2
Nb	2.7	0.4	3	3.0		1	4.0		2
Th/U	4.2			2.8			3.2		
K/U ($\times 10^{-4}$)	2.2			0.98			1.1		
Zr/Hf	44			42			38		
Zr/Nb	27			28			22		
Cr	38	24	4	7.2	7	8	1.5		2
V	280	52	4	210	61	8	120		2
Sc	42	13	4	23	5	8	18		2
Ni	15	8	4	5.7	3.2	8	3.4		2
Co	30	3	4	20	4.8	8	13		2
Cu	66	18	4	61	38	8	30		2
V/Ni	19			37			35		
Cr/V	0.14			0.034			0.013		
Ni/Co	0.50			0.28			0.26		
La	5.2	1.2	4	7.4		1	9.5		2
Ce	14.6	2.7	4	16.2		1	23.0		2
Pr	2.0	0.5	4	2.4		1	2.9		2
Nd	9.2	1.7	4	11.2		1	13.0		2
Sm	2.4	0.4	4	2.6		1	2.8		2
Eu	0.86	0.16	4	0.93		1	1.0		2
Gd	2.7	0.5	4	3.0		1	2.9		2
Tb	0.48	0.1	4	0.51		1	0.54		2
Dy	3.0	0.5	4	3.3		1	3.5		2
Ho	0.69	0.1	4	0.74		1	0.80		2
Er	2.1	0.4	4	2.1		1	2.3		2
Yb	2.0	0.5	4	2.3		1	2.4		2
La/Yb	2.5			3.2			4.0		
Y	24	1.6	11	24	3.2	17	28	3.4	6

^a All major elements as wt.% of oxide calculated on a volatile-free basis

^b All Fe calculated as FeO

^c Atomic ratio calculated assuming

$Fe^{2+} = 0.85 \Sigma Fe^{2+*}$

^d All trace element data as ppm

^e Isotope dilution analyses

^f Number of analyses

Major element analyses were performed by X-ray fluorescence spectrometry and electron microprobe (Norrish and Hutton, 1969; Nicholls, 1974b). Trace element concentrations were determined by X-ray fluorescence spectrometry on pressed powder samples (Rb, Sr, Zr, Y) (Norrish and Chappell, 1967), emission spectroscopy (Cr, V, Sc, Ni, Co, Cu, Ba) (Ahrens and Taylor, 1961; Taylor et al., 1970) and spark-source mass spectrography (Th, U, Pb, Hf, REE, Ba, Cs, Sn, Nb) (Taylor, 1965, 1971; Taylor and Gorton, 1977)

Table 2. Averaged major and trace element concentrations in Quaternary calc-alkaline lavas from Java and Bali (as in Table 1)

Calc-Alkaline Series												
	Basalt			Basaltic Andesite			Andesite			Dacite		
		1 σ	n		1 σ	n		1 σ	n		1 σ	n
SiO ₂	50.8	0.6	17	54.6	1.4	56	59.0	1.4	45	65.6	1.8	7
TiO ₂	1.27	0.3	17	0.85	0.2	56	0.74	0.1	45	0.64	0.1	7
Al ₂ O ₃	18.7	1.1	17	18.8	0.8	56	18.1	0.7	45	16.1	0.8	7
FeO*	9.7	0.6	17	8.3	0.7	56	6.8	0.7	45	5.3	0.7	7
MnO	0.12	0.05	17	0.12	0.05	56	0.10	0.04	45	0.09	0.04	7
MgO	5.0	0.6	17	3.7	0.8	56	2.9	0.5	45	1.6	0.7	7
CaO	9.5	0.5	17	8.4	0.7	56	6.7	0.7	45	4.1	1.1	7
Na ₂ O	3.3	0.3	17	3.4	0.3	56	3.5	0.3	45	4.2	0.9	7
K ₂ O	1.44	0.4	17	1.57	0.4	56	1.84	0.4	45	2.47	0.4	7
P ₂ O ₅	0.32	0.08	17	0.26	0.07	56	0.22	0.06	45	0.17	0.02	7
Mg/(Mg+Fe ²⁺)	0.52			0.48			0.47			0.38		
Cs	1.5	1.3	4	3.3	2.2	6	4.4	2.1	4	9.4		1
Rb	32	9.8	17	43	20	56	62	18	45	81	32	7
Ba	340	120	8	390	150	28	420	140	15	450	23	3
Sr	400	110	17	460	110	56	360	91	45	240	64	7
Pb	9.3	7.5	3	11	5	5	11	1.3	4	17		1
K/Rb	377			300			248			253		
K/Cs($\times 10^{-3}$)	8.0			3.9			3.5			2.2		
K/Ba	35			33			36			46		
Rb/Sr	0.080			0.094			0.17			0.33		
Th	3.6	1.5	4	5.6	3.2	6	6.7	1.7	4	13		1
U	0.75	0.2	4	1.4	0.7	6	1.6	0.6	4	2.6		1
Zr	129	51	17	119	34	55	151	33	45	195	52	7
Hf	2.6	1.1	4	2.9	1.0	6	3.6	0.4	4	4.7		1
Sn	4.1	5.9	4	2.8	1.8	6	1.4	0.3	4	2.1		1
Nb	5.8	4.1	4	4.8	2.1	6	9.4	3.8	4	6.1		1
Th/U	4.8			4.0			4.2			5.0		
K/U($\times 10^{-4}$)	1.6			1.9			0.95			0.79		
Zr/Hf	50			41			42			41		
Zr/Nb	22			25			16			32		
Cr	57	38	8	32	79	25	19	33	16	3.4	1.3	3
V	320	63	8	240	61	25	130	36	16	50	38	3
Sc	35	10	8	24	7	25	16	4.7	16	12	2.6	3
Ni	23	9	8	12	19	25	8	7.6	16	<2		3
Co	31	6	8	21	3.5	25	14	3.3	16	8.2	3.9	3
Cu	111	52	8	62	38	25	31	25	16	29	11	3
V/Ni	14			20			16					
Cr/V	0.18			0.13			0.15			0.07		
Ni/Co	0.74			0.57			0.50					
La	14.6	2.7	4	15.3	5.9	6	19.4	5.0	4	30.9		1
Ce	32.1	6.8	4	34.8	12	6	40.9	11	4	58.9		1
Pr	4.0	0.9	4	4.0	1.3	6	4.9	1.2	4	8.4		1
Nd	17.6	4.0	4	17.4	5.4	6	19.4	4.9	4	28.8		1
Sm	4.0	1.2	4	4.0	1.1	6	3.5	0.7	4	5.0		1
Eu	1.3	0.3	4	1.3	0.3	6	1.0	0.2	4	0.97		1
Gd	4.0	1.2	4	3.8	1.0	6	3.3	0.5	4	3.7		1
Tb	0.68	0.21	4	0.66	0.2	6	0.53	0.1	4	0.68		1
Dy	4.0	1.1	4	3.9	1.0	6	3.3	0.7	4	4.0		1
Ho	0.89	0.3	4	0.87	0.2	6	0.73	0.1	4	0.86		1
Er	2.5	0.9	4	2.5	0.7	6	2.2	0.4	4	2.5		1
Yb	2.4	0.8	4	2.5	0.6	6	2.1	0.3	4	2.4		1
La/Yb	6.1			6.0			9.1			12.9		
Y	28	6.1	17	27	4.1	55	28	6.5	45	39		7

Table 3. Averaged major and trace element concentrations in Quaternary high-K calc-alkaline lavas from Java

High-K Calc-Alkaline Series									
	Basalt			Basaltic Andesite			Andesite		
		1 σ	n		1 σ	n		1 σ	n
SiO ₂	49.6	1.0	5	54.9	2.0	5	59.1	1.6	7
TiO ₂	1.15	0.07	5	0.91	0.13	5	0.86	0.2	7
Al ₂ O ₃	18.2	0.6	5	18.3	0.2	5	17.3	0.6	7
FeO *	9.8	0.4	5	7.9	0.9	5	7.1	0.8	7
MnO	0.20	0.01	5	0.17	0.02	5	0.17	0.02	7
MgO	5.1	0.8	5	3.4	0.5	5	2.8	0.6	7
CaO	10.2	0.9	5	7.8	0.9	5	6.0	1.0	7
Na ₂ O	3.0	0.3	5	3.5	0.2	5	3.6	0.4	7
K ₂ O	2.18	0.4	5	2.8	0.1	5	2.8	0.5	7
P ₂ O ₅	0.40	0.06	5	0.33	0.02	5	0.30	0.1	7
Mg/(Mg+Fe ²⁺)	0.52			0.47			0.45		
Cs	4.1		1	6.2		1	6.6		2
Rb	61	16	5	85	12	5	93	23	7
Ba	480		1	600		2	470	130	6
Sr	540	68	5	490	48	5	360	54	7
Pb	5.7		1	12		1	19		1
K/Rb	297			270			250		
K/Cs ($\times 10^{-3}$)	4.4			3.7			3.5		
K/Ba	38			38			49		
Rb/Sr	0.11			0.18			0.26		
Th	6.5		1	11		1	12		2
U	1.2		1	2.2		1	2.6		2
Zr	113	18	5	152	58	4	181	43	7
Hf	2.0		1	3.7		1	4.6		2
Sn	1.2		1	1.0		1	2.2		2
Nb	11		1	10		1	11		2
Th/U	5.4			5.0			4.6		
K/U ($\times 10^{-4}$)	1.5			1.0			0.89		
Zr/Hf	56			41			39		
Zr/Nb	10			15			16		
Cr	39	28	3	8.1		1	12	7.9	5
V	280	10	3	160		1	130	28	5
Sc	27	4.6	3	12		1	16	4.8	5
Ni	19	5	3	8		1	4.2	3.2	5
Co	32	4	3	15		1	15	3.0	5
Cu	110	24	3	30		1	26	10	5
V/Ni	15			20			31		
Cr/V	0.14			0.05			0.09		
Ni/Co	0.59			0.53			0.28		
La	23.1		1	30.6		1	35.1		2
Ce	53.6		1	66.2		1	68.0		2
Pr	5.5		1	7.8		1	7.9		2
Nd	21.3		1	27.8		1	33.8		2
Sm	4.1		1	4.8		1	7.3		2
Eu	1.3		1	1.5		1	2.0		2
Gd	3.5		1	3.9		1	6.4		2
Tb	0.54		1	0.68		1	0.99		2
Dy	3.0		1	3.8		1	5.9		2
Ho	0.67		1	0.83		1	1.4		2
Er	1.77		1	2.3		1	4.0		2
Yb	1.5		1	2.2		1	3.8		2
La/Yb	15			14			9.1		
Y	28	2.7	5	32	9.3	4	36	14	7

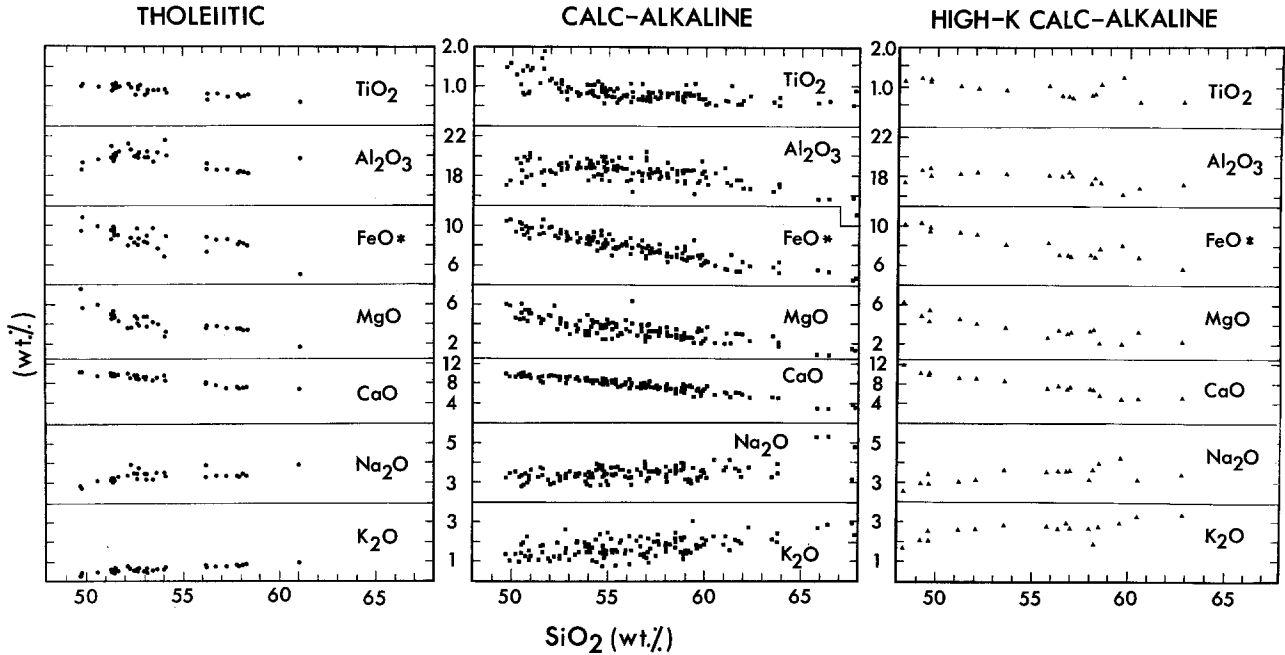


Fig. 3. Variation diagrams illustrating the major element compositions of rocks of the normal island arc association in Java and Bali

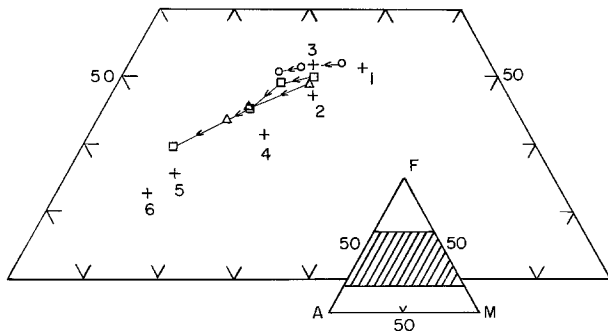


Fig. 4. AFM ($\text{Na}_2\text{O} + \text{K}_2\text{O}$, FeO^* , MgO) diagram illustrating the variation in average rock compositions. The Fe-rich character of the Indonesian lavas is shown by comparison with the average andesitic and related calc-alkaline rocks from Taylor (1969) denoted by the symbol +. Symbols: \circ : tholeiitic series; \square : calc-alkaline series; \triangle : high-K calc-alkaline series

arcs. The large lithophile ions (Cs, Rb, Ba), the small high valency cations (U, Th, Zr, Hf, Nb) and the light REE vary sympathetically with K. The concentrations of compatible transition elements such as Cr, Ni, Co, Sc, and V vary directly with those of Mg and Fe. Of major importance are the low concentrations of Ni and Cr in all but a few samples which argue strongly against the idea that any of the analyzed lavas represent primary mantle-derived liquids (Taylor, 1969; Nicholls and Whitford, 1976).

For some elements such as Sr the pattern is more complex. Whereas there is an increase in Sr concentration from the tholeiites to the high-K calc-alkaline

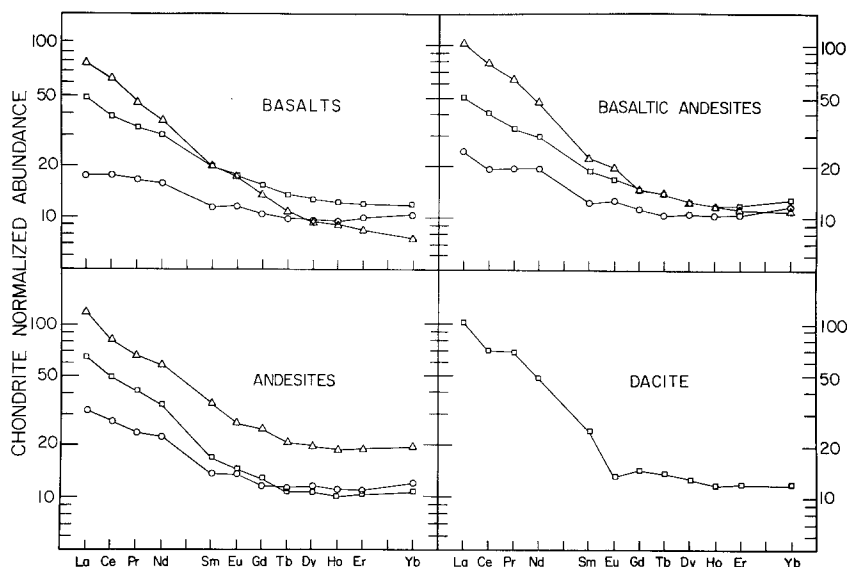
lavas, there is little consistent variation within these groups. This appears to reflect low-pressure plagioclase fractionation (Whitford and Nicholls, in preparation), although Eu variation indicates that this is extensive only in intermediate to acid compositions.

REE patterns of the rock averages are plotted in Fig. 5. Within the sequence from basalt to andesite (and dacite) the total REE abundances increase (Tables 1–3), due largely to increasing light REE abundances. From the tholeiites to the high-K calc-alkaline lavas there is an increase in the fractionation of the REE patterns. For example in the basalts the ratio La/Yb varies from 2.5 in the tholeiites to 15 in the high-K calc-alkaline lavas. The heavy REE abundances show less variation than those of the more incompatible light REE and generally lie within the range of 10–20 times chondritic. Although plagioclase is a prominent phenocryst phase in these lavas and appears to have been involved in low-pressure fractionation, only the dacite shows a significant negative Eu anomaly.

Geochemical Variations Across the Sunda Arc in Java and Bali

Figure 6 shows the variation in concentration of major and selected trace elements with depth to the Benioff zone (h) for all analysed basaltic andesites including those of the high-K alkaline association. In

Fig. 5. Chondrite normalized rare earth element abundance patterns of average rock compositions as in Fig. 4



lavas from individual volcanoes, the variation of almost all major and trace elements correlates with the SiO_2 content and to avoid the problems of distinguishing inter- from intra-volcano effects only element abundances in basaltic andesites (52–57% SiO_2) are shown in Fig. 6. This range of SiO_2 was chosen because basaltic andesites are the predominant rock type in the Sunda arc.

In lavas of the normal island arc association this range in SiO_2 concentration corresponds approximately to the same level of fractionation as indicated by MgO and FeO^* contents, $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios and by the concentrations of trace elements such as Ni and Cr (Tables 1–3, Fig. 3). Alkaline lavas with the same SiO_2 contents from Muriah are generally more evolved and are characterized by lower contents of MgO, Ni and Cr and lower $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios. Therefore, the trends on Fig. 6 which are largely controlled by the results from Muriah alone ($h = 360$ km) are probably not significant. Benioff zone depths (h) beneath particular volcanoes have been interpolated from the Preliminary Tectonic Map of Indonesia (Hamilton, 1972). Hamilton (1974b) slightly altered his previous Benioff zone depth contours along the Sunda arc, but those changes do not affect our conclusions.

From Tables 1–3 and Fig. 6 a number of chemical trends across the Sunda arc are obvious. With the notable exceptions of *K* and *P*, the major elements show little if any significant variation from Papandajan ($h = 130$ km) to Ungaran ($h = 240$ km). The atomic ratio $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ also shows little consistent variation. Both *K* and *P* abundances show a positive correlation with depth to the Benioff zone, with that for *K* somewhat better defined.

The trace element results are characteristically more scattered. As might be expected from their correlations with *K*, the Rb, Ba, and Sr abundances increase with increasing h (Fig. 6, Tables 1–3). The limited La data show a good positive correlation with increasing h whereas Y, which behaves as one of the heavy REE, remains essentially constant across the arc. This contrasts with Gill and Gorton's (1973) trend of decreasing concentrations of the heavy REE with increasing h . Nb, Th, *U* and less clearly, Hf exhibit a trend of increasing concentration with increasing h which is particularly pronounced between the high-K calc-alkaline and alkaline lavas. Th/*U* ratios increase with h from approximately 3 to 6 while *K*/*U* and Zr/Nb decrease (Tables 1–3) over the same interval.

Both Cr and Ni concentrations are very scattered (Fig. 6), whereas concentrations of V, Sc, Co, and less clearly Cu, display a slight increase with increasing depth to the Benioff zone from $h = 140$ – 180 km, which is followed by a decrease in concentration which for Sc, for example, continues to $h = 360$ km (Muriah).

Discussion

The Role of the Subducted Oceanic Crust

The close correlation between incompatible element geochemistry and Benioff zone depth immediately raises the question of the role of the subducted lithosphere, and more particularly the subducted crust, in processes of magma genesis. Recent studies in experimental petrology strongly suggest high water con-

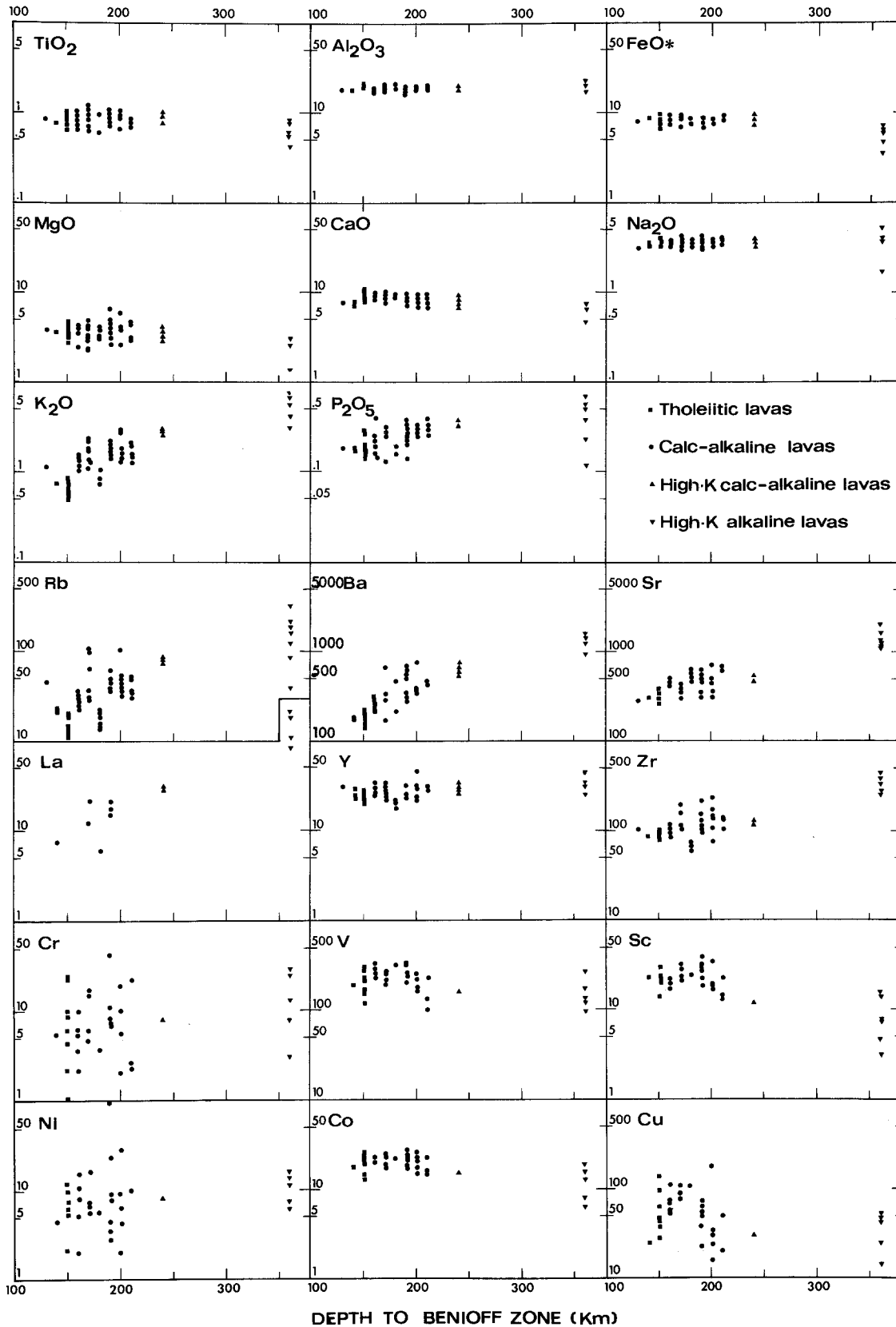


Fig. 6. Variation in major and trace element abundances in basaltic andesites (52–57 wt.% SiO_2) with depth to the underlying Benioff zone across the Sunda arc in Java and Bali

tents in the ultimate source regions of island arc magmas (Yoder, 1969; Ringwood, 1974) and it is generally agreed that subduction of hydrous oceanic crust is responsible in some way (McBirney, 1969).

Many attempts to explain the relationship between potassium and depth to the Benioff zone for island arc lavas have stressed the possible importance of subducted oceanic crust as a source for potassium in island arc magmas (Jakeš and White, 1970; Marsh and Carmichael, 1974; Ringwood, 1974; Nicholls, 1974a). T. Green and Ringwood (1968) and T. Green (1972) proposed that andesitic magmas were produced directly by partial melting of quartz eclogite. On this basis, Jakeš and White (1970) proposed that the K_2O/SiO_2 ratio in andesitic magmas increased as a function of depth of partial melting, due to the progressive reduction in the stability of phlogopite with increasing depth. Marsh and Carmichael (1974) have proposed a similar model in which the K-bearing phase is sanidine.

Explanations involving the progressive breakdown of selected minerals alone, quantitatively fail to explain the observed incompatible element abundances. Breakdown of phlogopite could explain the variations in K, Rb, and Cs but could not account for the increasing abundances of elements such as U, Th, Ba, Sr, and the light REE. Boettcher (1973) and Forbes and Flower (1974) claimed that the breakdown of titan-phlogopite at depths greater than 150 km was responsible for the 'concomitant increase in K and Ti' observed in orogenic magmas. The fact that Ti remains at constant concentration while K increases, suggests that this mineral alone is not the key. The progressive breakdown of sanidine faces similar problems and to explain the data these models require some revision. Perhaps there is more than one phase contributing significantly to the incompatible element abundances or, more likely, the degree of partial melting may decrease with increasing h . If the degree of partial melting is the primary control, the importance of individual incompatible element-bearing minerals decreases.

The correlation between incompatible element abundances and h implies some involvement of the slab and raises the questions of whether the slab melts, serves only as a source of water or acts simply as a thermal perturbation which affects melting in the overlying mantle. The thermal effects caused by the sinking of the relatively cool lithospheric slab into the mantle have been widely studied (e.g., Toksöz et al., 1971) but models remain very crude. Geochemical studies on volcanic rocks from the Banda arc (Whitford et al., 1977; Magaritz et al., 1978; Whitford and Jezek, 1979) have shown that subducted sediments have melted during magma genesis at Be-

nioff zone depths of approximately 150 km. This implies probable temperatures of at least 750° C at the top of the subducted lithospheric slab, temperatures very close to the 'wet' melting temperature of eclogite at such pressures. Although sediment subduction may not be a widespread phenomenon, that it appears to have occurred in the Banda arc implies that island arc lavas can reflect melting at the top of the subducted lithospheric slab, and that temperatures are probably high enough to cause melting of the basaltic component of the slab at depths of approximately 150 km.

Knowledge of the composition of liquids formed by small degrees of partial melting of hydrous quartz eclogite is clearly important. Gill (1974) calculated that the products of low to moderate degrees of melting ($\leq 40\%$) of eclogite of average oceanic tholeiite composition should be enriched in Na and depleted in K and related elements. In addition, such melts would be depleted in the heavy REE (see also Nicholls and Whitford, 1976). Partial melting experiments on quartz eclogite with the composition of a typical oceanic tholeiite have been performed at 30 kbar (K.L. Harris, personal communication). The liquid is silicic (~ 70 wt.% SiO_2) and is characterized by high Na (~ 7 wt.% Na_2O) and a correspondingly high Na/K ratio (~ 6) and bears little or no resemblance to any of the compositions listed in Tables 1–3. From partial melting experiments on olivine tholeiite at 30 kbar, Stern (1974) reached the similar conclusion that liquids produced in such a manner do not resemble natural calc-alkaline compositions.

In summary, it appears that the slab alone cannot be responsible for the observed spatial variations in geochemistry. Partial melting of the crustal component of the subducted lithosphere seems likely to occur but the compositions of such melts do not resemble those of typical lavas from island arcs. Moreover, progressive breakdown of specific minerals such as phlogopite or sandine fails to explain all the incompatible element variations without invoking a concomitant variation in degree of melting. A speculative account of what might happen to any slab melt formed follows in a later section.

Mantle Melting

The strong objections to the eclogite-melting hypothesis to explain the origin of island arc lavas indicates that the ultimate origin of these lavas must be within the mantle above the slab. It is possible to examine variations in the composition of that mantle wedge using the composition of its partial melting products although it is important to recognize that this portion

of the mantle may have been modified by reaction with a melt component derived from the underlying slab.

Green (1972, 1973) argued that changing the conditions of partial melting of homogeneous mantle results in significant variations in major element abundances. Green (1972) presented a petrogenetic grid which attempts to relate magma composition to depth and degree of partial melting for pyrolite containing 0.1% water – a level of water perhaps low for the mantle over the shallow parts of the Benioff zone although the general trends appear to remain the same under more hydrous conditions (Green 1973). With increasing pressure and decreasing degrees of partial melting, magmas become more alkaline and mafic in terms of the relative proportions of (FeO + MgO) and (Na₂O + K₂O) to SiO₂ resulting in a greater degree of undersaturation. For melting at depths at which garnet will not remain in the residue (< 60 km), a decrease in the degree of partial melting could lead to a decrease in Ca/Al ratios due to preferential retention of Ca in residual Ca-rich clinopyroxene in the mantle (D.H. Green, personal communication). At greater depths where pyropic garnet is stable Ca/Al ratios could increase.

The average major element compositions of basaltic lavas of the normal island arc association of Java and Bali show only slight variations in elements other than *K* and *P*. Nevertheless, there is a decrease in Al₂O₃, and increases in (MgO + ∑FeO) and CaO with increasing depth to Benioff zone (Tables 1–3) and these trends continue into the high-K alkaline association. The ratios (MgO + ∑FeO)/SiO₂, (Na₂O + K₂O)/SiO₂ and CaO/Al₂O₃ all increase progressively. In terms of Green's petrogenetic grid, these changes are most compatible with simultaneous increase in the depth of partial melting of peridotitic mantle and decrease in the degree of melting.

It is clearly important to know of any of the analyzed lavas represent primary unfractionated partial melts of the mantle. Nicholls and Whitford (1976) argued on the basis of Mg/Fe relationships between olivine-host-rock pairs that few if any of the observed most-mafic basalts could be primary mantle-derived melts. Addition of 10–15 wt.% of olivine to liquids of the bulk composition of the analyzed basalts is required before that liquid could be in equilibrium with mantle olivine. The low abundance of Ni leads to a similar conclusion (Taylor, 1969). If the basalts are primary, the average Ni concentration of about 20 ppm implies a partition coefficient of Ni between mantle olivine and coexisting liquid of approximately 100 (based on a widely accepted concentration of approximately 2,000 ppm Ni in the mantle – Boyd and Nixon, 1972). This is grossly in excess of those measured in several recent studies (Hart and Davis, 1978;

Mysen, 1976; Leeman and Scheidegger, 1977) where the dependence of the partition coefficient on such variables as pressure, temperature and bulk composition have been recognized together with the problems surrounding attainment of equilibrium during experiments. The highest values quoted by these authors are 20 to 30 (Hart and Davis, 1978) in an andesitic liquid (high Si/O, low Mg/O). Coefficients for basaltic liquids are typically 20 or less. The Ni concentrations therefore reinforce the argument that even the most mafic basalts observed are derivative, and cannot represent primary mantle melts.

Understanding magma genesis in the Sunda arc or in most other island arcs involves two extrapolations – one to derive primary liquid compositions (Nicholls and Whitford, 1976) and, based on these results, another to derive compatible mantle compositions.

The first of these extrapolations has been attempted for the lavas of some volcanoes of Java and Bali (Nicholls and Whitford, 1976). In terms of the 'basalt tetrahedron' classification of Green and Ringwood (1967), (based on that of Yoder and Tilley, 1962), the 'primary magma' compositions for most volcanoes belonging to the normal island arc association are olivine tholeiites with 5 to 27% normative olivine (Fig. 7). Two primary compositions based on basalt to basaltic andesite lavas of Papandajan and Tjerimai are quartz-normative (2–5% Qz). The neighboring volcanoes Merapi and Merbabu yield olivine basalt compositions (1–3% normative Hy), Slamet yields alkali olivine basalts (0.5–1.0% normative Ne) and Ungaran, compositions on the boundary between alkali olivine basalt and basanite (4–5% Ne). The most mafic analyzed lava of the high-K alkaline volcano Muriah has a primitive compatible element geochemistry (high Mg/Fe, Ni, Cr), and is a K-rich basanite (11% normative Ol, 12% Ne, 11% Lc). There is thus an overall, but not consistent, trend of decreasing silica-saturation with increasing depth to Benioff zone.

When these 'primary magma' compositions are used, in conjunction with the petrogenetic grid of Green, to estimate the depth and percent partial melting of a water-undersaturated peridotitic source, the results define an overall, but again not consistent, decrease in percent partial melting and an increase in depth of melting. The calculated olivine tholeiite magmas for Galunggung and Guntur indicate 20–25% melting at depths of 30–40 km, while the alkali olivine basalt or basanite magmas of Slamet and Ungaran indicate 5–15% melting at 40–60 km. The proposed high-K basanite magma for Muriah indicates around 5% melting at 80–90 km.

The two quartz-normative 'primary magma' compositions of Papandajan and Tjerimai suggest either 10–15% melting of water-undersaturated mantle at

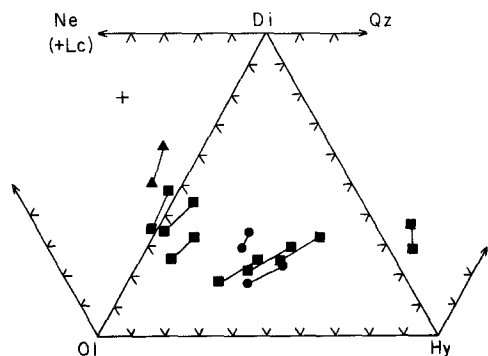


Fig. 7. Plot of calculated primary magma compositions in the expanded normative 'basalt tetrahedron' for selected volcanic centers of Java. Tielines join compositions which could be in equilibrium with Fo_{88} (nearer O1 apex) and Fo_{86} or Fo_{84} (see Nicholls and Whitford, 1976; 1978). +: high-Kalkaline; \blacktriangle : High-K calc-alkaline; \blacksquare : calc-alkaline; \bullet : tholeiitic

very shallow depths (<10 km), or 20–30% melting of hydrous mantle at depths of 20–40 km. The close similarity between the suggested magma composition for Tjerimai and estimated liquid compositions for melting of hydrous peridotitic assemblages at pressures of around 10 Kbar (Green, 1973; Nicholls, 1974a) has already been noted (Nicholls and Whitford, 1976). The depth-% melting relationships derived in this way are compared with the distribution of crust, lithosphere and subducted lithosphere in Fig. 8.

The petrogenetic grid of Green, and experimental studies by Green (1973), Nicholls (1974a) and Mysen and Boettcher (1975a and b) also yield information on the nature of residual crystalline phases in equilibrium with partial melts of peridotitic mantle in the presence of water. Magmas produced by >20% partial melting are likely to be in equilibrium with olivine and orthopyroxene, or olivine alone, while those produced by 10–20% partial melting should include clinopyroxene in the residual assemblage. Those magmas produced by <10% melting are likely to be in equilibrium with olivine, orthopyroxene, clinopyroxene, amphibole and possibly phlogopite for pressures less than 20–25 Kbar, while amphibole and clinopyroxene will be partly replaced by garnet at higher pressures.

The nature of these residual phases is critical for estimations of the content of alkali elements, Ti, P and incompatible trace elements in the mantle source of basaltic magmas. In the case of the tholeiitic volcanoes of Java, the suggested olivine tholeiite primary magmas probably were in equilibrium with only olivine and orthopyroxene, and they should therefore possess K/Na and La/Yb ratios similar to those of the mantle source. On the other hand, primary magmas for centres such as Slamet and Ungaran were

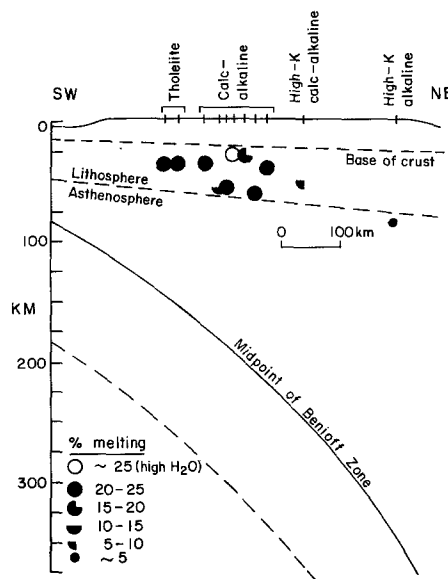


Fig. 8. Diagrammatic cross-section of the crust and upper mantle beneath Java showing the position of selected volcanoes together with the depths of final equilibration of primary magmas with peridotitic upper mantle sources (see text). Depths to the base of the crust have been extrapolated from the seismic profiles of Ben Avraham and Emery (1973). Depths to the base of the lithosphere correspond to the beginning of partial melting of peridotitic mantle under conditions of water saturation beneath the arc and water undersaturation behind the arc (see Nicholls and Whitford, 1978)

probably in equilibrium with clinopyroxene and amphibole, as well as olivine and orthopyroxene. Since K/Na ratios for amphiboles in experimentally crystallized peridotitic assemblages at 10–20 Kbar are around 0.10–0.20 (Green, 1973; Nicholls, 1974a, Mysen and Boettcher, 1975a), and the corresponding values for amphibole megacrysts and phenocrysts in calc-alkaline lavas of Java are 0.20–0.25 (Whitford, 1975b), these magmas should have K/Na ratios higher than those of their mantle sources. As an example the 'primary magma' composition for the high-K calc-alkaline volcano Ungaran has 1.4% K_2O and 2.2% Na_2O ($K/Na=0.41$). Assuming it to represent a 10% partial melt, in bulk equilibrium with 10% residual amphibole (0.5% K_2O , 2.0% Na_2O , $K/Na=0.16$) and clinopyroxene, orthopyroxene and olivine in a peridotitic source, the K/Na ratio of this source will be at most 0.30. If the proportion of residual amphibole is increased to 20%, K/Na of the source becomes 0.25 (see also Nicholls and Whitford, 1978).

Similar estimates for rare earth elements are uncertain, since the magnitudes of experimental amphibole/basaltic liquid partition coefficients range from <1 (e.g. Mysen, 1978) to >1 (Harris, and Nicholls, 1979). Concentrations of La and Yb in amphibole phenocrysts (La 25 ppm, Yb 10 ppm) and megacrysts (La 3.0 ppm, Yb 1.8 ppm) from lavas of Java

(Whitford, 1975b) also differ greatly, but the La/Yb ratios of around 2, compared with La/Yb of 15 for the 'primary magma' composition for Ungaran, indicate that this magma will have higher La/Yb than its source.

In spite of the uncertainties in the above approach, it is probable that the mantle sources of tholeiitic basaltic magmas of south-western Java have values of K/Na (~ 0.10) and La/Yb (~ 3) similar to those of 'primitive' peridotitic mantle; K/Na a maximum of around 0.08 (Sun and Nesbitt, 1977); La/Yb around 1.6 (Lopez-Escobar et al., 1977), while the sources for the calc-alkaline and particularly high-K calc-alkaline series have appreciably higher K/Na (a maximum of around 0.3) and La/Yb (possibly as great as 5). These estimates suggest that the lithosphere beneath Java is geochemically zoned. A possible explanation of such zoning is the modification of this lithosphere by the addition of partial melts from the underlying subducted oceanic crust.

Modification of the Mantle Source

Evidence that the mantle source has been modified by the influx of slab derived melts also comes from the study of Sr isotopes. Whitford (1975a) showed that in Recent lavas across the Sunda arc in Java and Bali, $^{87}\text{Sr}/^{86}\text{Sr}$ ratios increase from approximately 0.7043 in the tholeiites to 0.7049 in the high-K calc-alkaline lavas. Although there is some overlap, especially among the calc-alkaline lavas, these differences imply that the source regions producing the range of lavas is heterogeneous at least with respect to $^{87}\text{Sr}/^{86}\text{Sr}$, and may be regularly zoned.

As suggested by Nicholls (1974a) and Ringwood (1974), such zoning may be related to the assimilation into the mantle of silicic melts derived from the underlying slab. The principal chemical effects would be enrichment of the mantle in Si, Al, Na, K and related elements and water, and a depletion in Fe and Mg. The mineralogical effects would be an increase in the proportions of pyroxene and garnet relative to olivine (Nicholls, 1974a; Ringwood, 1974).

Subsequent partial melting of the modified mantle composition and fractionation of magma produced must be capable of producing basalts of the type found in the Sunda arc. Residual phases during partial melting of modified mantle are likely to be olivine, orthopyroxene, and perhaps clinopyroxene and amphibole which, except for orthopyroxene are generally less silicic than basalt. This suggests that basalts cannot be produced by melting of a silicic mantle such as that derived by 1:1 mixing (55–60 wt.% SiO_2) and implies that mixing in the proportions of one part

slab melt to either two or three parts peridotite probably represents the upper limit of slab involvement. A greater degree of slab involvement would also produce unreasonably high incompatible trace element abundances in the mantle.

The pattern of incompatible trace element abundances of the modified mantle will closely resemble that of the slab melt although the absolute abundances will be lower. The compatible trace elements will have similar concentrations to those in the unmodified mantle. In this model the variations in the incompatible element geochemistry in lavas of the normal island arc association are primarily a reflection of chemical variations within the source region although they may also be influenced by differences in the conditions of melting or perhaps subsequent fractionation.

Melting of modified mantle can explain the spatial variations in incompatible element geochemistry across the Sunda arc and island arcs in general. It is recognized that the explanations are ad hoc and none is entirely satisfactory. There are four processes which may act in concert:

1. A regular increase in the proportions in which any slab melt mixes with the primary unmodified mantle with increasing depth to the Benioff zone could account for the observed variations. Why such an increase should occur is not clear, but it could be related to the thermal structure of the mantle wedge above the subducted slab. Perhaps the relative volume of mantle melt to slab contribution falls off as temperature contrast between the slab and overlying mantle decreases. A simple increase in the volume of slab melt with depth seems unlikely because both the volumes of undepleted oceanic crust and water probably decrease with increasing depth.

2. If the degree of partial melting of the slab decreases with increasing pressure (Jakeš and White, 1972; Miyashiro, 1974) then that melt might be expected to become increasingly fractionated with higher concentrations of the incompatible elements. This model assumes that undepleted oceanic crust is still available to melt at deeper levels (Wyllie, 1973).

3. Hydrous fluids derived from the subducted lithosphere rise into the overlying mantle wedge 'scavenging' incompatible elements during their migration (Ninkovich and Hays, 1972; Best, 1975). Progressively greater thicknesses of this wedge are reflected in increasing concentrations of K and related elements in the lithosphere. In many ways this process is analogous to the upward zone refining model developed by Harris (1957).

4. A decreasing proportion of partial melting of modified mantle over the deeper parts of the Benioff zone, with amphibole becoming more important in

the residue, leads to enhancement in the magmas of the spatial variations already present in their lithosphere sources. Such a model is consistent with the decrease in K/Rb ratios that is observed across the arc.

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