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Crustal Contamination Versus Subducted Components: An Example from The West Java Arc, Indonesia and Its implications in Magma Genesis

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Abstract - New Sr isotope and K_2O data are presented for Papandayan and Cikuray Volcanoes in West Java. The data are combined with published Sr isotope and K_2O data, and compared with arc that has a similar geological setting, namely Northeast Japan Arc (NJA, N 38° ~ 41°) to constrain the relative importance of crustal assimilation and subducted input of crustal material in magma genesis beneath West Java Arc (WJA). New strontium isotope and K_2O data from fifty-four Quaternary volcanic rocks from WJA were collected and compared to forty-six Quaternary volcanic rocks from NJA. The increasing K_2O and decreasing of $^{87}Sr/^{86}Sr$ ratios with distance from trench have been found in NJA, but there are rough and no across arc variation of K_2O and Sr isotopic ratios in WJA. This study shows that the across arc variation of magma chemistry on the WJA is attributed to the crustal assimilation and the involvement of subducted sediments and slab fluids from altered oceanic crust.

Keywords: West Java Arc, Northeast Japan Arc, magma genesis, crustal assimilation, subducted sediments, slab fluid

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Introduction

Background

The magma genesis in convergent margin such as on WJA, Indonesia, can be examined by whole rock geochemistry and isotopic compositions. However, these data are not always indicative of actual magma source characteristics, as they have commonly undergone through complicated processes such as mafic recharge, magma mixing, mingling, assimilation, and fractional crystallization. Furthermore, the geochemical variations of the mantle wedge, subducted oceanic crust, subducted sediments, or melts and slab configuration also play an important role in magma genesis.

Past studies place some constraints on magma genesis in WJA. They believed that there is across arc variation on WJA (Whitford, 1975; Whitford *et al.,* 1979; Soeria-Atmadja *et al.,* 1991; Abdurrachman, 2012; Abdurrachman and Yamamoto, 2012). Although much geological data have been reported in Java, the main cause of the rough across arc variation of magma chemistry on the WJA is not clearly defined. This study provides further constraints on magma genesis beneath WJA.

Here whole-rock Sr isotope and K_2O data for WJA and new data from Papandayan and Cikuray Volcanoes were presented. The new data are combined with previously published geochemical and isotopic data and with other published WJA and NJA volcanic rock data to increase the understanding of the relative importance of both crustal assimilation and subduction input of crustal material in WJA

Regional Geology

Tectonic Settings

Indonesia is located at the boundaries of three plates, Eurasia, Indian-Australia, and Pacific-Philippine Plates (Hamilton, 1979). The Indian-Australia Plate moves northward and is being subducted beneath Eurasian Plate with convergent rate about 7 cm/year (Turner and Foden, 2001).

On the Late Cretaceous, a microcontinental fragment (Argoland) was detached from Gondwana and drifted northeastward approaching the subduction zone (Metcalfe, 2011). The collision of microcontinent fragment was believed as the cause of termination of Late Cretaceous subduction as well as the one which shifted the subduction to the south of Java. According to Katili (1975), the suture zone may exist beneath Papandayan and Cikuray Volcanoes (Figure 1a).

Volcanism in West Java

Volcanic arc on Java Island has existed on present position at least since 10 Ma (Carn and Pyle, 2001). On the WJA, number of Quaternary volcanoes formed a group of volcanoes that are referred to the Triangular Volcanic Complex (TVC) along three fault zones (Figure 1b). Some of those volcanoes, such as Papandayan and Cikuray Volcanoes, are located in the volcanic front of TVC, West Java, and lie within the boundary of Late Cretaceous to Early Tertiary suture zone (Figure 1a).

METHODS

Thirty-five samples from early to late stages of Papandayan and also from Cikuray were collected during field campaign in August 2008 to February 2009, and cut to obtain fresh interior and crushed using an automatic agate pestle and mortar system to <40 μm. They were then analyzed for the major elements (SiO_2 and K_2O) and trace elements (Zr and Nb) using a Rigaku 3270 X-ray fluorescence spectrometer (XRF) at Akita University, Japan. Powdered samples were ignited in a muffle furnace for two hours at 900°C before the preparation of fused glass beads containing 1.8 g of sample and 3.6 g of alkali flux (1:2). The alkali flux was a mixture of lithium metaborate ($LiBO_2$) and lithium tetraborate ($Li_2B_4O_7$) in a ratio of 1:4. Analytical precision is better than 2% for major elements and better than 10% for trace elements (Kimura and Yamada, 1996).

Thirty selected samples were analyzed for Sr isotope using a Finnigan MAT 261 at Akita University, Japan. The methods for extraction and acquisition were adapted from Kagami *et al.* (1982) and Yamamoto and Maruyama (1996) . NBS-987 and La Jolla standards were also measured in the same runs, yielding values of $^{87}Sr/^{86}Sr = 0.710241 \pm 0.000008$ (2σ).

RESULTS

SiO_2, K_2O, and Sr isotopic ratios of basaltic to dacitic volcanic rocks from Papandayan and Cikuray area are listed in Table 1. The $^{87}Sr/^{86}Sr$ ratios of Papandayan plot in the fourth quadrant; they range from 0.705243 to 0.705907. Early stage exhibits the widest range in $^{87}Sr/^{86}Sr$ (0.705243-0.705907), extending well outside the 2σ error, whereas in each subsequent stages and Cikuray, $^{87}Sr/^{86}Sr$ ratios are more constant, varying by 0.705539-0.706133 for Papandayan middle and late stages and 0.704172 to 0.704257 for Cikuray.

DISCUSSION

The ranges of SiO_2 wt.% are 54.03-58.10 (early stage), 58.66-61.35 (middle stage), 63.58-75.81 (late stage), and 55.05-29.20 (Cikuray),

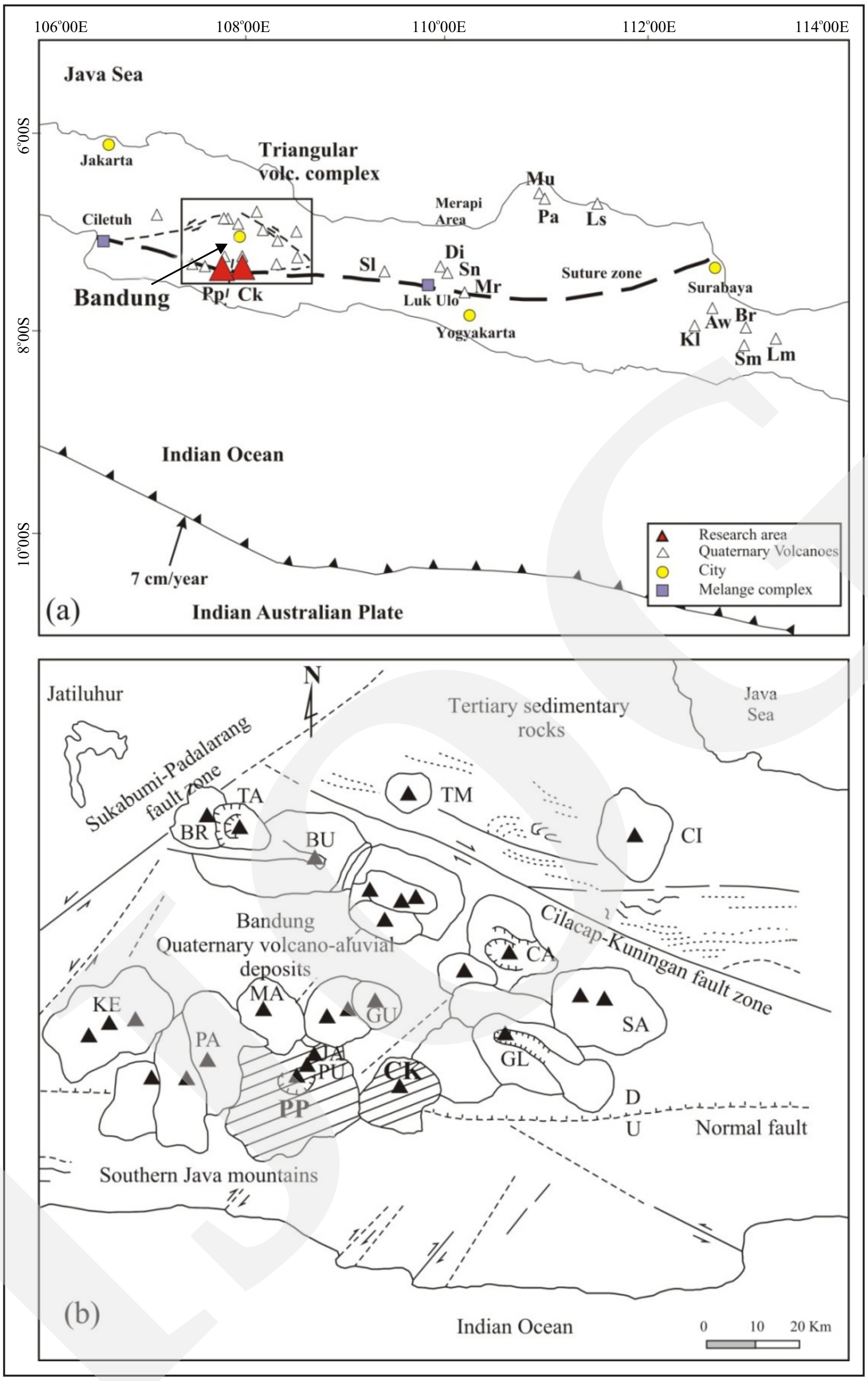

Figure 1. Historical earthquakes in Sumatra. Yellow star symbols indicate historical GSF earthquakes with M>6. Blue star symbols indicate historical megathrust earthquakes with M≥6.5 after 2004. Colour straight lines indicate the GSF segmented by geometrical irregularities into nineteen major segments by Sieh and Natawidjaja (2000). (Br: Burangrang; TA: Tangkuban Prahu; BU: Bukit Unggul; TM: Tampomas; CI: Ciremai; CA: Cakrabuana; SA: Sawal; CI: Ciremai; GL: Galunggung; CK: Cikuray; PP: Papandayan; PU: Puntang; JA: Jaya; GU: Guntur; MA: Malabar; PA: Patuha; KE: Kendeng; U: Hanging wall; D: Foot wall.

implying that fractional crystallization is probably not the only process in the evolution of Papandayan. Crustal contamination and magma mixing could also be involved. Previous studies on the WJA suggested that Sr isotope and K_2O contents increased from the trench side to the backarc side volcanoes (Whitford, 1975; Whitford *et al*., 1979; Soeria-Atmadja *et al*., 1991; Abdur-

Table 1. SiO_2, K_2O, And Sr Isotopic Ratio of Papandayan and Cikuray Volcanoes

Volcano	Stage	Sample No	SiO_2	K_2O	$^{87}Sr/^{86}Sr$	2σ
Papandayan	Early	MA-1	55.88	1.00	0.705243	8
		AK-3	57.67	1.26	0.705793	8
		AK-1	57.44	1.23	0.705264	8
		AK-13	54.69	0.96	0.705431	8
		AK-14	54.84	0.71	-	-
		MA-8A	54.34	0.81	0.705287	9
		MA-3B	54.07	0.78	0.705311	12
		MA-2A	58.10	1.38	0.705907	7
		MA-5B	54.03	0.72	0.705324	6
		IM2-3A	56.57	1.11	0.705811	9
		MH-7	52.98	0.79	0.705509	8
		IM2-5A	57.40	1.23	0.705905	8
		MIL-5	57.88	1.31	0.705902	8
		MH-1	54.20	0.60	-	-
		A21-B	54.08	0.58	-	-
	Middle	AK-5	60.93	1.47	0.705593	6
		AK-11	61.35	1.67	0.70559	9
		MC-2	58.66	1.72	0.705803	7
		MMK-2	59.37	1.48	0.705539	8
		IN-22	60.93	1.70	0.705696	9
	Late	AK-7	64.09	1.88	0.705891	19
		MM-7B	71.07	2.93	0.705802	9
		MZ-1	65.50	2.40	0.705924	7
		CRG-TJL	67.39	2.91	0.705849	7
		MZ-9	63.58	2.05	0.706133	8
		IN 4	75.82	1.00	0.705618	8
		A-23	63.62	2.30	0.70569	9
		IP2-7	65.03	2.25	-	-
		IN 13	67.26	2.92	-	-
Cikuray		IM-5	56.86	0.74	0.704182	8
		5.1	55.40	0.70	0.704184	8
		IM-3B	57.54	0.73	0.704172	8
		MH-9	55.05	0.32	0.704236	17
		MH-12	55.97	0.70	0.704257	9
		IM-7	59.20	0.82	0.704223	8

rachman, 2012; Abdurrachman and Yamamoto, 2012). In detail, however, when the normalized of K_2O wt.% to SiO_2= 55 wt.% from the WJA are closely examined and compared with the NJA, the WJA shows rough across-arc variation and more diverse in K_2O, especially in the volcanic front (Figure 2a). The decreasing of $^{87}Sr/^{86}Sr$ ratios with distance from trench has been found in NJA (*e.g*. Notsu 1983; Shibata and Nakamura, 1997), but there is no across arc variation of Sr isotopic ratios in WJA (Figure 2b).

Papandayan and Cikuray volcanic rocks are not the only end members of K_2O and Sr-Nd isotopic ratios in TVC but also the whole Java volcanoes (Figure 3). Therefore, the genetic relationship between these volcanoes is suitable to explain the diversity of all the TVC and Java volcanic rocks.

Mantle Source Characteristics

Immobile trace elements are generally assumed to be unmodified by the subduction processes (*e.g.* Wood *et al*., 1979). In order to identify the mantle source beneath Papandayan and Cikuray, immobile element ratios of Zr/Nb were employed. Table 2 and Figure 4 show that Zr/Nb ratios do not change significantly with differentiation and are relatively homogeneous in both Papandayan and Cikuray. The Zr/Nb ratios

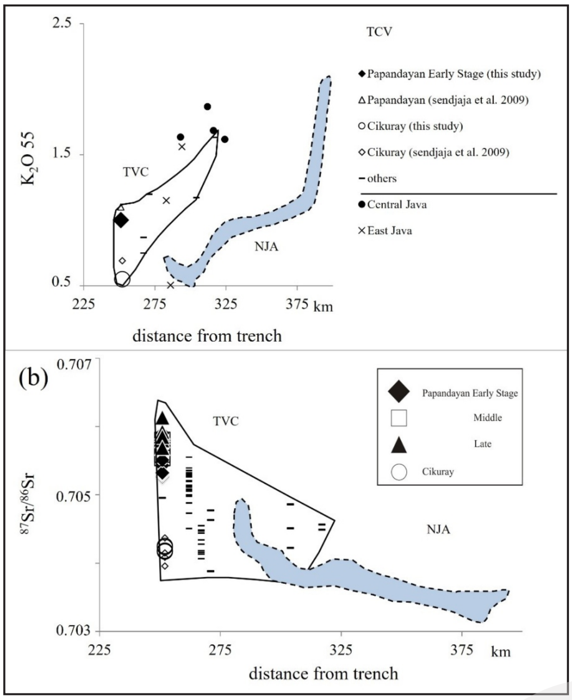

Figure 2. Diagram showing across-arc variation of (a) K_2O contents, (b) $^{87}Sr/^{86}Sr$ ratios in TVC (fifty-four samples from eight volcanoes) compared with NJA (forty-six samples from six volcanoes). The K_2O content of each volcanoes is normalized to SiO_2= 55 wt.% on the empirically determined regression curve. (Data sources of Java volcanoes: Whitford, 1975; Gerbe *et al*., 1992; Bourdier *et al*., 1997; Carn and Pyle, 2001; Reubi *et al*., 2002; Gertisser and Keller, 2003; Bernard and Mazot, 2004; Sendjaja *et al*., 2009; this study. NJA: Katsui *et al*., 1979; Ishikawa *et al*., 1984; Sakuyama and Koyaguchi, 1984; Yoshida and Aoki, 1984; Maruyama *et al*., 1988; Fujimaki *et al*., 1990; Ohba and Umeda, 1999; Kimura and Yoshida, 2006; Yamamoto *et al*., 2010.

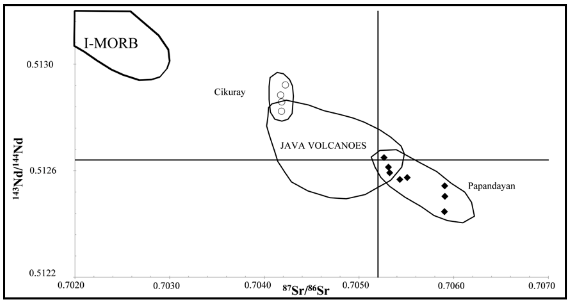

Figure 3. $^{87}Sr/^{86}Sr$ *vs*. $^{143}Nd/^{144}Nd$ isotope ratio diagram showing ~~the~~ Papandayan and Cikuray data compared to basaltic rocks of Java volcanoes, symbols as in Figure 2. I-MORB (Chauvel and Blichert-Toft, 2001); Java volcanoes: (Edwards *et al*., 1991; Gerbe *et al*., 1992; Edwards *et al*., 1994; Carn and Pyle, 2001; Turner and Foden, 2001; Gertisser and Keller, 2003; Chadwick *et al*., 2007; Handley *et al*., 2009; Sendjaja *et al*., 2009; Abdurrachman and Yamamoto, 2010; this study).

Table 2. Average Zr/Nb Ratio of Papandayan and Cikuray compared to I-MORB, N-MORB, NJA. Data sources: I-MORB (Chauvel and Blichert-Toft, 2001), N-MORB (Sun and McDonough, 1989), NJA (Shibata and Nakamura, 1997)

Ratio	I-MORB	N-MORB	NJA	Papandayan	Cikuray
Zr/Nb	26	32	19-37	20-32	18-29

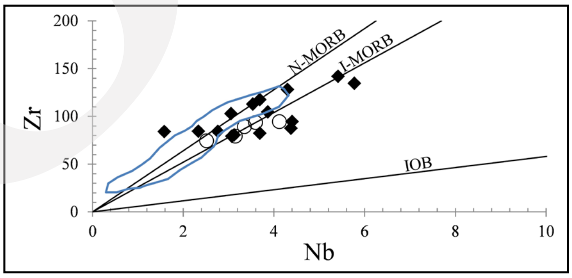

Figure 4. *Zr vs*. Nb for Papandayan and Cikuray compared to NJA. Symbols as in Figure 2. Data sources: I-MORB (Chauvel and Blichet-Toft, 2001), N-MORB and OIB (Sun and McDonough, 1989), NJA (blue solid line curve; Shibata and Nakamura, 1997).

are similar to Indian Mid- Oceanic Ridge Basalt (I-MORB). When they are compared to NJA (Figure 4), they are flatter and nearly identical to I-MORB rather than N-MORB. Considering these evidences, magma sources beneath Papandayan and Cikuray are nearly identical in term of Zr and Nb compositions indicating that the mantle wedge beneath both volcanoes is similar to the source of I-MORB.

The Role of Crustal Contamination

The summits of Papandayan and Cikuray Volcanoes are contiguous (~ 14 km, Figure 1), therefore the local tectonic settings under these volcanoes are expected to be constant (convergent rate of Sunda Arc: Turner and Foden, 2001; the depth of the Wadati-Benioff Zone: Abdurachman *et al*., 2015; distance to the trench axis and crustal thickness: Gasparone and Varne, 1998) and the chemical diversities of the mantle wedge by subducted inputs as proposed by Edwards *et al*. (1991) also to be constant.

The new Sr isotope and K_2O data of Papandayan and Cikuray volcanic rocks provide surprising observation, that volcanic rocks from both volcanoes have distinctively differences in K_2O and Sr isotopic ratios showing end members of TVC (Figure 3). These seem to be related to other condition, *e.g.* local crustal composition.

Sr-Nd Isotopic Mixing Model: I-MORB + AOC + Granites + Sediment

Figure 5a shows a mixing model, where I-MORB is contaminated by altered oceanic crust (AOC) fluid and Indian Ocean sediments end members. Mixing curves fail to provide a good fit to isotopic variation of the TVC, and could not explain the steep mixing line, also the downward bend of Papandayan isotopic trend, suggesting that an additional isotopically distinct component is needed.

The mixture of basaltic andesite of Cikuray, AOC fluid, and crustal contaminants of older crust (*e.g.* Australian granites) have been added to produce steep mixing lines. The involvement of AOC fluid is clearly shown by the starting points of Cikuray which are not on I-MORB (Figure 5b).

The involvement of subducted sediment to the source of I-MORB mantle wedge is evidence since the most Nd radiogenic rocks of Cikuray are still below than I-MORB-AOC line (Figure 5b). The basaltic andesite of Cikuray represents the least evolved sample with the highest Nd isotopic ratio in the TVC area. The crustal contaminant represents Australian granites as a possible microcontinent beneath southern Java as proposed by zircon study (Clements and Hall, 2007; Smyth *et al.*, 2007) which collided to the eastern margin of Sunda Land during Late Cretaceous to Early Tertiary (Sribudiyani *et al.*, 2003). The ages of contaminant granites range from Silurian to Devonian (SE Australian, McCulloch and Chappell, 1982) and Pre-Cambrian (SW Australian, Bickle *et al.,* 1989, 1993). The contaminants used in the mixing modelling are listed in Table 3. They are older than the initial age of the segregation of Gondwana Supercontinent (Late Devonian), also the formation of microcontinent fragments (Late Jurassic) (Metcalfe, 1996). Papandayan and Cikuray are located at the boundary of Late Cretaceous to Early Tertiary suture zone (Katili, 1975) (Figure 1) and on the extension of East Java continental fragment to West Java (Clement and Hall, 2007; Abdurrachman *et al.*, 2018). Therefore, it is appropriate to use Australian granites as candidates for crustal contaminant.

The results show that many mixing curves of granitic rocks produce reasonable fit to the TVC trends compared to Indian Ocean sediments (Figure 5b). Considering this mixing model we argue that the presence of "Argoland" beneath southern West Java was responsible for Sr-Nd isotopic ratios diversity in Papandayan area as well as in the TVC as illustrated in Figure 6.

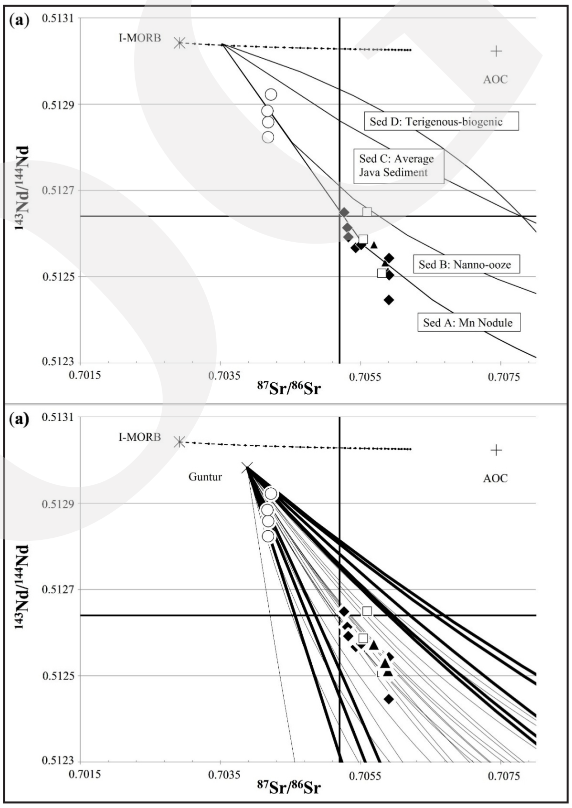

Figure 5. Sr-Nd isotopic mixing model; symbols as in Figure 2. (a) Mixture of I-MORB (I-MORB*0.1, assuming 10% melting) and AOC fluid and sediments. (b) Mixture of basaltic andesite of Cikuray with crustal contaminant from Australia (SE: thin line; SW: thick line) and Data sources: I-MORB (Chauvel and Blichert-Toft, 2001); basaltic andesite of Cikuray (this study. Sediment A, Mn Nodule, V34-62 (White and Dupré, 1986; Ben Othman *et al.,* 1989); B, nanno-ooze, DSDP site 211 (Gasparon and Varne, 1998); C, average Java sediment (Plank and Langmuir, 1998); D, terrigenous-biogenic average of V33-75, -77, -79 (Ben Othman *et al.*, 1989; Gasparon and Varne, 1998); AOC fluid (Handley *et al.*, 2007); AOC (Staudigel *et al.*, 1995); SE Australian granites (McCulloch and Chappell, 1982); SW Australian granites (Bickle *et al.,* 1989, 1993); TVC volcanoes (dashed line curve): (Whitford, 1975; Gerbe *et al.*, 1992; Sendjaja *et al.*, 2009; this study).

Table 3. End-member Compositios Used in the Mixing Calculation for Figure 5

	Sr (ppm)	Nd (ppm)	Sr/Nd	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$
I-MORB source	13.5	0.97	13.92	0.702915	0.513042
Basaltic member of Guntur	225	10.3	21.84	0.703882	0.512982
AOC fluid	22.42	0.697	32.17	0.704584	0.513070
Sediment					
A	857	187.9	4.561	0.709117	0.512236
B	126	51.9	2.428	0.716430	0.512228
C	218	33.95	6.421	0.716820	0.512160
D	398	15.36	25.911	0.708875	0.512411
SE Australian Granites					
Tingaringy granodiorite	30.34	168	0.18	0.728400	0.511252
Numbla Vale adamelite	25.31	97	0.26	0.752810	0.511246
Cooma granodiorite	70.13	127	0.55	0.738900	0.511111
Cooma gneiss	44.74	114	0.39	0.758390	0.511193
Jillamatong granodiorite	22.29	139	0.16	0.737890	0.511186
Ingebyrah granodiorite	32.23	163	0.20	0.730180	0.511255
Kalkite adamelite	27.96	117	0.24	0.744050	0.511242
State Circle shale	39.3	23	1.71	0.879330	0.511094
Buckley Lake adamellite	191	37.12	5.15	0.723520	0.511483
Buckley Lake adamellite	175	33.18	5.27	0.725550	0.511514
Tara granodiorite	252	24.51	10.28	0.712030	0.511441
Namungo adamelite	33	8.98	3.67	0.808030	0.511640
Delegate adamellite	131	34.39	3.81	0.729060	0.511520
Iona granodiorite	264	22.36	11.81	0.713570	0.511452
Wullwye granodiorite	189	42.26	4.47	0.716170	0.511596
Maffra adamellite	121	25.5	4.75	0.729860	0.511595
Bimbimbie granodiorite	243	28.48	8.53	0.717630	0.511282
Currowong granodiorite	231	23.8	9.71	0.717110	0.511339
Merumbago granodiorite	139	18.42	7.55	0.726910	0.511160
Finister granodiorite	123	19.79	6.22	0.729480	0.511213
Jindagyne tonalite	254	17.96	14.14	0.713620	0.511393
Grosses Plain granodiorite	256	13.95	18.35	0.709020	0.511479
SW Australian Granites					
Porphyritic granites					
SB 599	398	39	10.21	0.738310	0.510432
Y1-5	364	48	7.58	0.741870	0.510520
Y1-7	376	48	7.83	0.739930	0.510650
Leuco-adamellite					
SB 437	203	42	4.83	0.709113	0.510245
SB 450	199	50	3.98	0.81437	0.510248
Contact tonalite					
SB 611	739	28	26.39	0.710580	0.510208
SB 615	815	35	23.29	0.709150	0.510191
SB 616	777	32	24.28	0.709970	0.510319

Data Sources: I-MORB (Chauvel and Blichert-Toft 2001), basaltic member of Guntur (Sendjaja *et al*., 2009); sediment: A, Mn nodule, V34-62 (White and Dupré, 1986; Ben Othman *et al*., 1989); B, nanno-ooze, DSDP site 211 (Gasparon and Varne, 1998); C, average Java sediment (Plank and Langmuir, 1998); D, terrigenous-biogenic average of V33-75, -77, -79 (Ben Othman *et al.*, 1989; Gasparon and Varne, 1998); AOC fluid (Handley *et al.*, 2007); AOC (Staudigel *et al*., 1995); crustal contaminant: SE Australian granites (McCulloch and Chappell, 1982), SW Australian granites (Bickle *et al*., 1989, 1993).

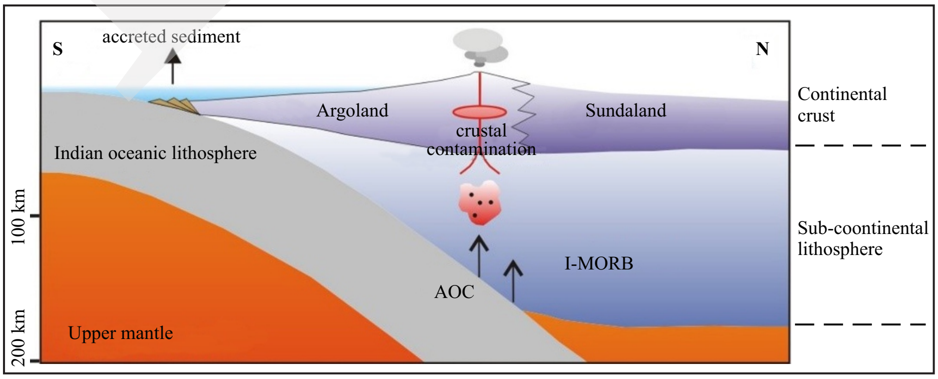

Figure 6. Illustration of magma genesis beneath Papandayan Volcano (no scale). AOC: altered oceanic crust; S: south; N: north.

Conclusion

The WJA shows rough across-arc variation and more diverse in K_2O and no across arc variation for Sr isotopic ratio especially in the volcanic front, it is due to Papandayan data. The contrasting Sr-Nd isotopic ratios in Papandayan area can be explained by the mixing of clear mantle wedge (I-MORB + AOC ± Indian Sediments) with Paleozoic to Pre-Cambrian Australian Granites as the missing "Argoland" which have separated from Western Australia in the Late Jurassic and collided to SE Sundaland in the Late Cretaceous. We note that the presence of "Argoland" beneath southern West Java is thought to contribute significantly to the spatial geochemical source input variations exhibited by TVC volcanoes.

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