

Genesis of Mariana shoshonites: Contribution of the subduction component

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Abstract. The Izu-Bonin-Mariana arc contains a unique group of shoshonitic volcanoes from along the magmatic front of this intraoceanic arc. Shoshonites are greatly enriched in incompatible elements compared to lavas typically found in primitive arc settings but have fractionations of lithophile (LIL) and high-field strength (HFSE) incompatible elements characteristic of convergent margin magmas and thus are characterized by an unusually large "subduction component." New geochemical and isotopic data for Izu-Bonin-Mariana shoshonites and related rocks are presented and interpreted to examine the origin of these enrichments. Enrichments are associated with distinctive isotopic compositions, including the most radiogenic Pb ($^{206}\text{Pb}/^{204}\text{Pb} \sim 19.47$) and least radiogenic Nd ($\epsilon\text{Nd} \sim -5.6$) from along the magmatic front of the arc. Despite highly elevated concentrations of fluid-mobile lithophile elements in the lavas, the similarity of diagnostic element ratios (e.g., Ba/La, Pb/Ce, and U/Th) to those in mid-ocean ridge basalts and ocean island basalts indicates little role for fluid-induced elemental fractionation in the generation of these shoshonites. Modeling isotopic data allows up to 6% subducted sediments to be involved, but oxygen isotopic evidence limits this to < 3%. Low- P fractionation explains most of the chemical variations observed in these shoshonites. Removal of < 2% Ti-rich phases could fractionate HFSE from LIL, indicating an important role for low- P fractionation. Although many features of these shoshonites are consistent with a greater role for subducted sediments, such a role is not accompanied by an unequivocal and universal signal in both isotopic compositions and trace element abundances and fractionations. This signifies a large role for both equilibration of these melts with mantle and for low-pressure fractionation.

1. Introduction

Arc magmatism is a result of subducting lithosphere and sediments interacting with overlying mantle asthenosphere. Arc lavas generally are enriched in large ion lithophile (LIL) and light rare earth elements (LREE) relative to mid-ocean ridge basalts (MORB) and oceanic island basalts (OIB). High field strength elements (HFSE) are commonly depleted in most arc lavas compared with MORB and OIB. The high LIL/HFSE along with variable isotopic compositions in arc volcanics implies a major role for a "subduction component" in generating arc melts. The subduction component has several potential origins in the mantle wedge and subducted plate. These include enriched mantle, zone refining of the mantle wedge, melts from subducted crust or sediments, and hydrous fluids released from dehydration of subducted materials (Figure 1). The latter two factors are particularly important because adding such enriched components to depleted mantle source regions may reproduce significant features of arc melts, such as high LIL/HFSE.

The shoshonite series is one of the three principal rock series in convergent margins [Jakes and Gill, 1970; Jakes and White, 1972] and may indicate an advanced evolutionary stage of arc volcanism, unusual tectonic setting, or unusually enriched sources. Shoshonitic lavas have an unusually large "dose" of the subduction component, as has been inferred from trace element and isotopic compositions of shoshonitic rocks from Papua New

Guinea [Woodhead and Johnson, 1993], Sunda [Edwards *et al.*, 1991], Aeolian Arc [Ellam *et al.*, 1989], Puerto Rico [Jolly *et al.*, 1998], and Fiji islands [Gill and Whelan, 1989].

The principal objective of this study is to understand which sources and what processes cause the unusual chemical enrichments in arc melts by examining how these factors affect the generation of shoshonitic series lavas in the Izu-Bonin-Mariana arc system. This shoshonitic volcanism are particularly important because it is currently active, allowing parallel construction of tectonic setting. In addition, the arc is built on oceanic crust, obviating the role that contamination by granitic crust might have in fostering these enrichments.

To assess the contribution of subduction component in the genesis of this shoshonitic province, petrogenetic models are tested with geochemical and isotopic data. Trace elements, such as Th, Pb, and HFSE, and radiogenic isotopes are emphasized since they act as important petrogenetic fingerprints.

2. Geological Background and Previous Studies

The 2500-km-long Izu-Bonin(Volcano)-Marana arc system results from the subduction of the Pacific plate beneath the Philippine Sea plate (Figure 2a). Volcanic rocks from this active magmatic arc have predominantly tholeiitic and calc-alkaline affinities, with subordinate shoshonitic occurrences. Some shoshonites erupt from rear-arc volcanoes, such as the Kasugas [Fryer *et al.*, 1997], but there is also a 150-km-long segment along the magmatic front which erupts shoshonitic lavas. Bloomer *et al.* [1989a] called this the "Alkalic Volcano Province," which extends from Iwo Jima in the Volcano Arc through the Hiyoshi Volcanic Complex to South Hiyoshi in the northern Mariana arc

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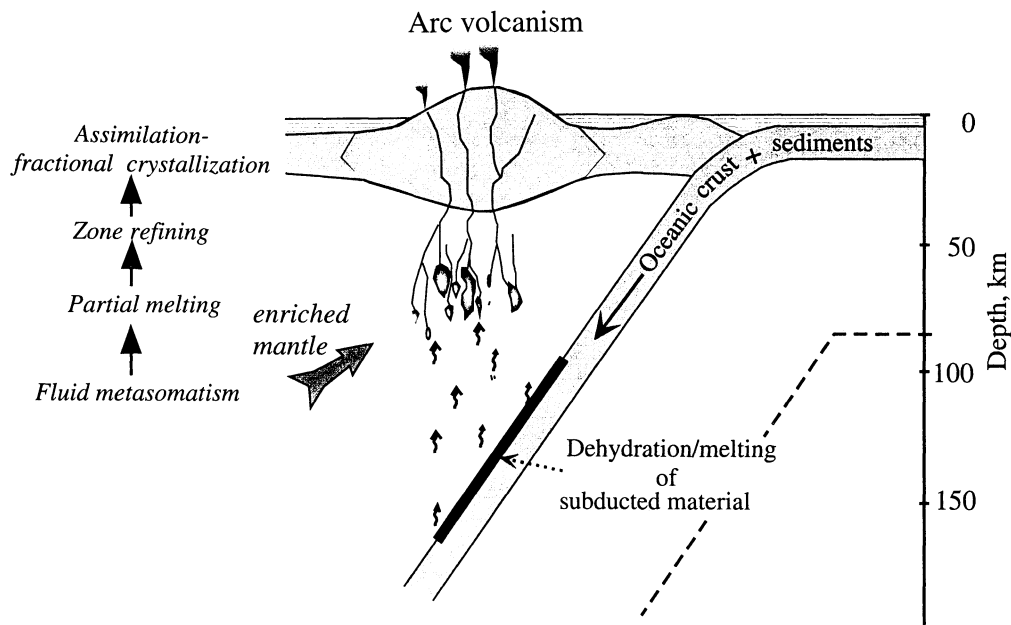


Figure 1. Schematic illustration for the origin of the “subduction component” in the subduction environment. The subduction component is manifested by the unusual geochemical signatures of arc melts and results from a complete interaction of subducted and mantle sources as well as processes accompanying magma ascent, storage, and fractionation.

(Figure 2b). The Alkalic Volcano Province is noteworthy for several reasons: First, unlike Kasuga cross-chain seamounts, volcanic edifices in the Alkalic Volcano Province are aligned along the magmatic front. Their distinctive compositions do not correlate with the thickness of arc crust or depth to the Benioff zone. Second, there is no known compositional transition from tholeiitic to calc-alkaline to shoshonitic series with time in any individual edifice of the province. In fact, these shoshonitic edifices appear to be among the youngest in the arc system [Stern *et al.*, 1988]. Third, the relationship of these shoshonites to tectonic setting can be studied. This alkalic province is associated with the northern termination of a propagating back arc basin rift axis in the Mariana Trough, which may provide unusually fertile sources or trigger an unusual process of melt generation [Stern *et al.*, 1984]. Also, a colliding oceanic plateau (the Ogasawara Plateau) intersects the Izu-Bonin trench just north of the Alkalic Volcano Province and the alkalic province lies along a portion of the arc where convergence is highly oblique [Seno and Maruyama, 1984].

Geochemical characteristics of the shoshonites are unusual among Izu-Bonin-Marian arc lavas. Incompatible element abundances can be up to 10 times that found for other volcanoes along the magmatic front but are still associated with elevated LIL/HFSE. Models for the origin of this alkalic province, as well as those of ordinary Bonin and Mariana arc lavas, have attributed these enrichments and fractionations to a subduction component. A number of authors [Lin *et al.*, 1989; Elliott *et al.*, 1997] suggest that the abundances of hydrous fluid-mobile elements in these lavas result from mantle metasomatism by fluids from dehydrating subducted materials. A sedimentary component has been emphasized by Woodhead and Fraser [1985], who infer that up to 70% of the Pb in Mariana arc lavas is derived from subducted sediments. Mass balance calculations [Plank and Langmuir, 1993] indicate that the sedimentary input into the subduc-

tion zone substantially enriches Mariana arc volcanics in certain incompatible elements (e.g., Rb, Ba, K, Cs, La, Th, and U). Elliott *et al.* [1997] argued that a sediment-derived melt, rather than hydrous fluids, enriched the source of some Mariana arc lavas and caused the highly fractionated LIL/HFSE ratios. Much controversy has been centered upon the OIB-like isotopic composition of lavas in the Mariana arc. Stern and coworkers [Stern, 1981, 1982; Ito and Stern, 1986; Lin *et al.*, 1989] noted the affinities of Sr, Nd, and O isotopic compositions between ordinary Mariana arc lavas in general and the shoshonitic lavas in particular and OIB mantle sources. A similar conclusion was reached by Morris and Hart [1983] for arc volcanics worldwide using Sr, Nd, and Pb isotopic compositions and incompatible element ratios.

3. Analytical Techniques

Submarine samples were dredged by R/V *Thomas G. Thompson* during cruise TT192 in 1985. Locations, bathymetric maps, and geochemical and isotopic data of a small suite of samples are reported by Bloomer *et al.* [1989a, 1989b], Lin *et al.* [1989, 1990], and Peate and Pearce [1998]. Iwo Jima samples were collected by R.J.S. in 1981.

Thirty-eight samples were analyzed. Major and trace elements (including Nb, Ta, Hf, Th, and REE) were determined at the Plasma Analytical Laboratory of the University of Kansas by inductively coupled plasma atomic emission spectrometry (ICP-AES) and inductively coupled plasma mass spectrometry (ICP-MS), respectively. (Analytical procedures for ICP-MS and ICP-AES can be found at <http://www.geo.ukans.edu/icpmain.html>.) Analytical precision for major elements was generally within 4%. For most trace elements the analytical error was usually better than 5%, and less than 7% for Nb and Ta.

Sr, Nd, and Pb isotopic compositions were measured on a Fin-

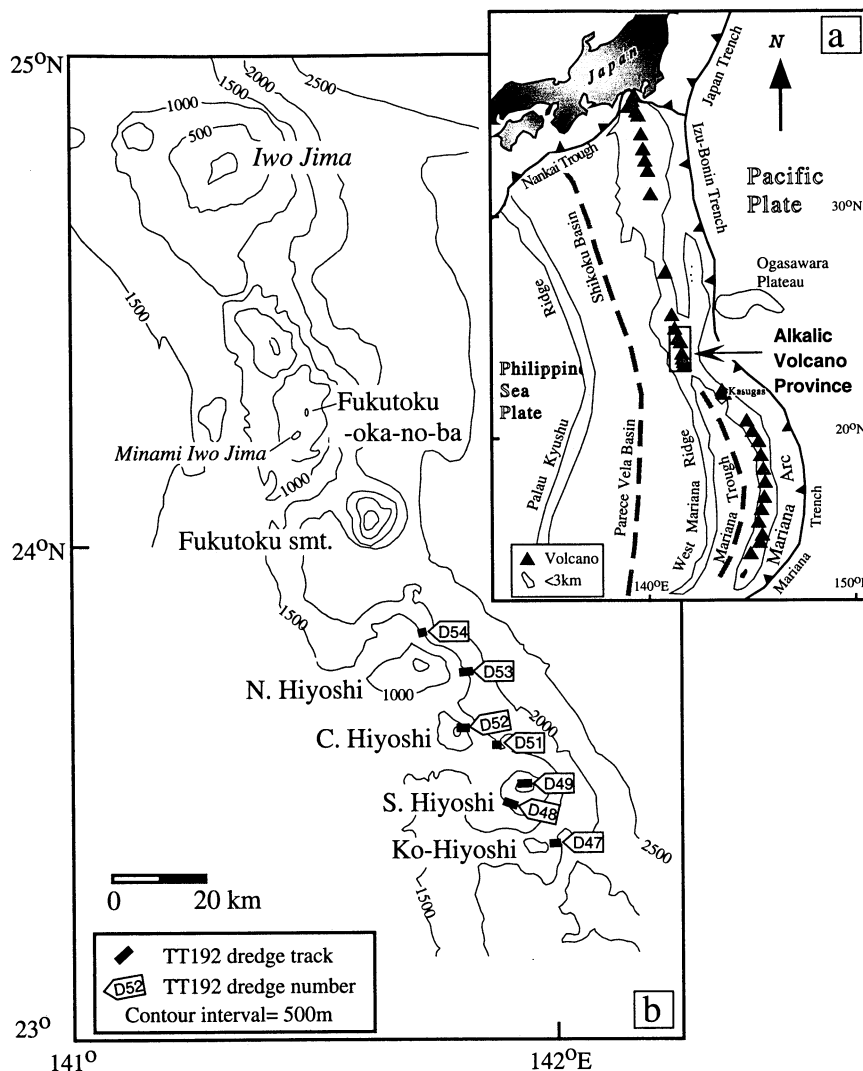


Figure 2. (a) Map of the Izu-Bonin-Mariana arc system. (b) Detailed locality map for the Alkalic Volcano Province.

nigan MAT261 multicollector mass spectrometer at the University of Texas at Dallas. A subset was leached in 6 N HCl for 2 hours before dissolution for comparison with unleached samples. Twenty analyses of E+A SrCO₃ during the course of this study gave a mean $^{87}\text{Sr}/^{86}\text{Sr} = 0.708063 \pm 0.000031$ (one standard deviation). All Sr isotopes were corrected for mass fractionation to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and normalized to a value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.70800$ for the E+A SrCO₃ standard. The ratio $^{143}\text{Nd}/^{144}\text{Nd}$ were fractionation normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Nineteen analyses of the La Jolla standard gave a mean $^{143}\text{Nd}/^{144}\text{Nd} = 0.511863 \pm 0.000012$. Pb isotopes were analyzed at 1350°C and corrected for thermal fractionation using 0.15% per amu. Twenty eight analyses of NBS-981 yielded a mean $^{206}\text{Pb}/^{204}\text{Pb} = 16.944 \pm 0.008$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.500 \pm 0.009$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.743 \pm 0.031$. Total processing blanks for Sr, Nd, and Pb are <0.1, <0.3, and <0.3 ng, respectively.

4. Results

4.1. Petrography

Lavas from the Alkalic Volcano Province are characterized by plagioclase porphyritic textures with glassy or microcrystalline

groundmass (Table 1). Other major phenocrysts include olivine (Ol), clinopyroxene (Cpx), and titanomagnetite (Mt). Subordinate hornblende is found in Central Hiyoshi, North Hiyoshi, and Iwo Jima. Biotite appears in some North Hiyoshi samples.

The samples typically consist of 2 to 40% vesicles. Lavas from Iwo Jima show a ductile flow structure, probably corresponding to their more siliceous compositions. Most studied samples are fresh; however, a few are slightly altered. In some cases (e.g., D48-5-1 and D52-3-1), olivine margins display incipient alteration to iddingsite.

Most samples do not have the mineral assemblage of typical shoshonite series defined by *Iddings* [1895]. Coexistence of calcic plagioclase and potash feldspar (sanidine) is only reported for one example (3K350-1) from North Hiyoshi [Sun *et al.*, 1999].

4.2. Bulk Rock Compositions

Tables 1 and 2 list the major and trace element compositions of the analyzed samples. For a more comprehensive treatment of the Alkalic Volcano Province in the following discussion, we include data previously published for Fukutoku-oka-no-ba [Sun *et al.*, 1998] and a subset of North Hiyoshi lavas collected with a remotely operated vehicle in 1997 [Sun *et al.*, 1999].

Table 1. Bulk Rock Compositions and Petrographic Features of Alkalic Volcano Province Lavas ^a

Sample	Ko-Hiyoshi				South Hiyoshi										
	D47-IN	D47-1-4	D47-2-1	D47-2-2	D48-5-1	D48-5-2	D48-5-3	D48-5-4	D48-5-5, 5-6, 6-2		D48-6-1	D49-3-2, 4-4, 6-3, 6-4, 6-5, 6-6, 6-7		D49-6-2	
									av	sd			av	sd	
SiO ₂	51.99	49.14	51.25	52.10	53.51	52.96	55.36	51.83	52.25	0.82	55.12	52.80	0.37	56.61	
TiO ₂	0.74	0.79	0.83	0.75	0.76	0.73	0.79	0.91	0.94	0.02	0.72	0.94	0.04	0.88	
Al ₂ O ₃	20.09	18.82	18.55	19.71	20.22	16.94	19.57	18.68	18.44	0.27	19.96	18.63	0.19	16.55	
Fe ₂ O ₃ [†]	9.25	10.19	10.50	9.36	7.36	9.41	6.77	9.56	10.10	0.26	6.99	9.86	0.20	9.02	
MnO	0.20	0.17	0.23	0.21	0.13	0.17	0.14	0.17	0.18	0.01	0.13	0.18	0	0.21	
MgO	3.27	5.47	4.66	3.47	2.60	5.25	1.76	3.02	3.23	0.30	1.59	3.05	0.09	2.19	
CaO	10.03	13.18	10.38	10.03	10.02	9.88	7.43	8.95	8.90	0.13	7.96	8.89	0.12	5.31	
Na ₂ O	3.34	2.35	3.21	3.53	3.38	3.18	4.20	3.45	3.57	0.07	4.06	3.56	0.05	4.24	
K ₂ O	0.98	0.91	0.98	1.08	2.59	1.94	2.98	2.10	2.22	0.12	2.87	2.13	0.05	3.55	
P ₂ O ₅	0.23	0.22	0.19	0.26	0.38	0.26	0.50	0.38	0.39	0.01	0.40	0.40	0.02	0.58	
Total	100.13	101.23	100.78	100.50	100.96	100.71	99.50	99.05	100.22	1.14	99.8	100.44	0.48	99.14	
LOI	0.50	0.59	2.30	1.33	1.30	0.58	1.78	0.70	0.75	0.35	1.72	0.32	0.18	0.20	
Mg # ^b	44	54	49	45	44	55	36	41	41		33	41		35	
Groundmass	G	G	G	G	G	G	G	M	G		G	G		G	
Alteration	S				S			S			S	S			
Vesicles	15	40	40	20			T	5	2~20		20	2		T	
Plag	40	15	8	35	30	15	25	15	20~25		30	40		5	
Cpx	2	3	5	5	1	2	<1	2	1~7		2	<1		1	
Ol	2	2	4	3	3	3	T	2	1~3		T	T		T	
Hb															
Bio															
Mt	1		1	T			T	T	T		T	T		T	

Sample	Central Hiyoshi			North Hiyoshi				Iwo Jima						
	D51-5-1	D52-1-2, 6-1, 6-2, 6-3, 6-4		D53-E, -F		D54-E, F, G		D54-H	D54-K	IJ-2C, 19		IJ-6B	IJ-11	IJ-12
		av	sd	av	sd	av	sd			av	sd			
SiO ₂	52.42	50.76	0.26	56.27	0.33	47.93	0.02	47.75	48.07	59.83	0.10	59.84	59.79	59.21
TiO ₂	0.68	0.80	0.02	0.64	0.02	0.95	0.00	0.91	0.91	0.89	0.00	0.91	0.79	0.84
Al ₂ O ₃	17.67	18.73	0.16	17.85	0.11	17.43	0.69	17.62	17.54	16.55	0.09	16.75	16.83	16.78
Fe ₂ O ₃ [†]	9.69	9.77	0.23	7.29	0.21	11.79	1.07	11.78	11.94	7.10	0.11	7.09	6.93	6.76
MnO	0.23	0.20	0.01	0.15	0.00	0.21	0.04	0.20	0.19	0.22	0.01	0.22	0.22	0.21
MgO	4.61	4.23	0.16	2.92	0.13	6.13	0.53	6.23	6.43	1.45	0.05	1.55	1.61	1.64
CaO	8.64	9.72	0.26	6.58	0.18	11.23	0.07	12.08	12.05	3.07	0.06	3.21	3.16	3.43
Na ₂ O	3.36	3.11	0.04	3.75	0.03	2.59	0.11	2.36	2.41	5.91	0.09	6.08	5.82	5.97
K ₂ O	1.40	2.57	0.05	4.15	0.14	1.44	0.02	1.20	1.15	4.09	0.09	4.18	4.04	3.86
P ₂ O ₅	0.34	0.41	0.03	0.35	0.03	0.36	0.02	0.34	0.37	0.47	0.03	0.50	0.51	0.47
Total	99.0	100.30	0.73	99.95	0.17	100.07	0.78	100.47	101.05	99.58	0.13	100.35	99.7	99.18
LOI	0.44	0.73	0.30	0.87	0.05	0.67	0.35	0.23	0.32	0.56	0.18	0.00	0.60	0.46
Mg #	51	49		47		54		54	54	31		33	34	35
Groundmass	G	G		G		M		M	M	M		M	M	M
Alteration	S	S						S						
Vesicles	20	~5				15~25		20	15					
Plag	5	25~35		15		20~35		20	35	7		5	4	10
Cpx	8	2~4		5		6~10		10	8	3		2	T	<3
Ol	T	<1		2		2~4		3	2	5		2	T	3
Hb										T		1		4
Bio				1										
Mt	1	<1		1		1		1	1	2		T	T	2

^aThe average compositions of several samples are expressed as av; standard deviation of the average is indicated by sd. For description of sample texture, G is glass groundmass; M is microcrystalline groundmass; S is slightly altered. Vesicle and the proportions (in percent) of each phenocryst phase in the samples are estimated visually. T, trace amount; Plag, plagioclase; Cpx, clinopyroxene; Ol, olivine; Hb, hornblende; Bio, biotite; Mt, titanomagnetite.

^bMg # = 100Mg/(Mg + Fe²⁺); Fe³⁺/Fe²⁺=0.1.

All lavas are evolved, with Mg # (= 100Mg/(Mg + Fe²⁺); Fe³⁺/Fe²⁺=0.1) less than 57. Most have low Ni (1.5~32 ppm) and Cr (<65 ppm), except for a Fukutoku-oka-no-ba sample (FO92-1) which has 188 ppm Cr [Sun *et al.*, 1998]. The higher K₂O in the studied lavas at any given SiO₂ distinguishes them from subalka-

lic counterparts elsewhere in the arc (Figure 3). Shoshonitic samples are highlighted by half-shaded patterns in Figure 3 and in subsequent figures. Both calc-alkaline to shoshonite series lavas were collected from North Hiyoshi and South Hiyoshi. Whether or not related by fractional crystallization, calc-alkaline lavas

Table 2. Trace Element Contents and Ratios of Alkalic Volcano Province Lavas^a

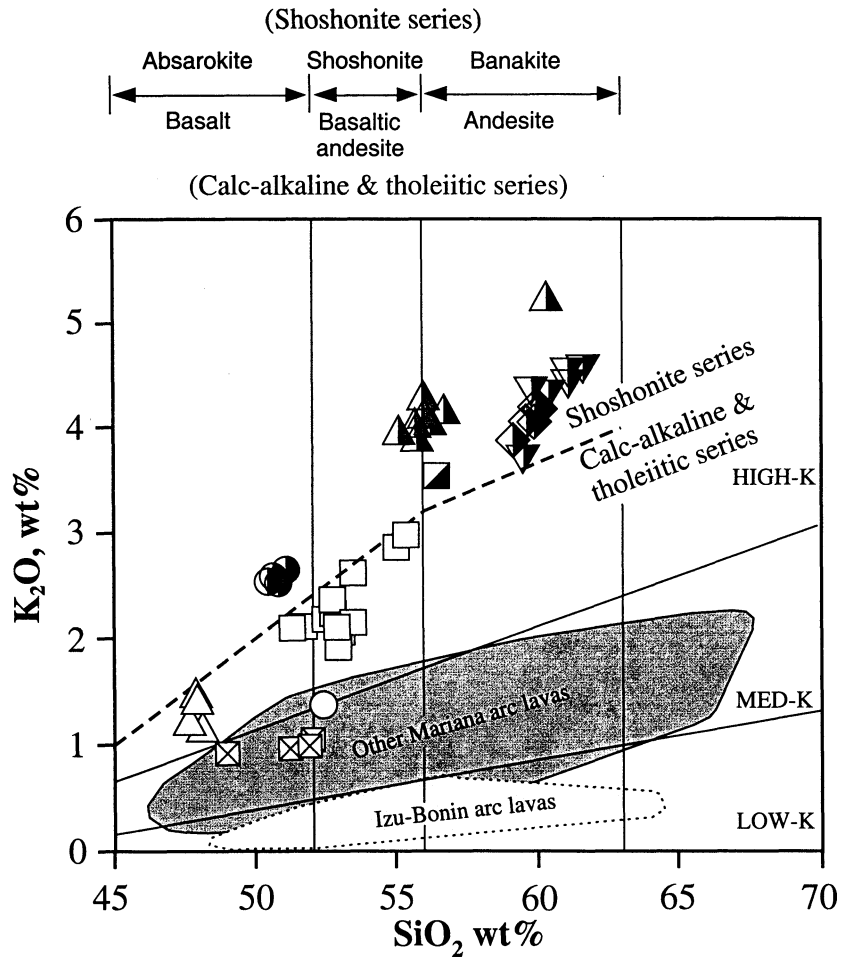
Sample	Ko-Hiyoshi				South Hiyoshi										
	D47-IN	D47-1-4	D47-2-1	D47-2-2	D48-5-1	D48-5-2	D48-5-3	D48-5-4	D48-5-5, 5-6, 6-2		D48-6-1	D49-3-2, 4-4, 6-3, 6-4, 6-5, 6-6, 6-7			D49-6-2
									av		sd	av		sd	
Rb	14.9	17.3	14.0	19.4	54.1	40.5	73.3	46.2	59.2	3.6	80.9	56.2	2.2	103	
Sr	713	811	660	715	727	547	784	667	691	32	635	676	6	511	
Ba	518	467	453	467	707	604	945	680	694	8	868	699	18	1056	
Zr	73.8	58.6	67.0	86.9	187	142	239	165	168	8	227	167	5	277	
Y	24.5	20.8	23.0	27.8	28.9	24.6	40.3	31.1	30.3	1.2	31.7	31.9	1.1	43.6	
La	17.8	18.8	16.0	22.3	34.3	27.2	48.5	33.9	40.6	1.2	46.8	39.7	1.2	62.6	
Ce	34.6	36.3	31.5	42.9	63.2	50.2	89.8	63.4	74.0	1.8	82.8	72.8	2.3	114	
Pr	4.56	4.80	4.19	5.53	7.53	6.10	10.8	7.79	8.85	0.13	9.56	8.72	0.32	13.3	
Nd	18.9	19.8	17.5	22.4	28.3	23.3	41.2	30.1	33.7	0.3	35.1	33.8	1.0	49.5	
Sm	4.08	4.11	3.88	4.67	5.36	4.55	7.76	5.85	6.43	0.14	6.43	6.52	0.18	9.28	
Eu	1.35	1.32	1.28	1.50	1.49	1.29	2.15	1.67	1.79	0.05	1.74	1.80	0.04	2.30	
Gd	3.92	3.66	3.79	4.43	4.75	4.11	6.91	5.22	6.29	0.25	6.22	6.30	0.22	8.93	
Tb	0.68	0.60	0.66	0.76	0.81	0.70	1.15	0.89	0.97	0.05	0.97	0.98	0.03	1.37	
Dy	3.78	3.19	3.72	4.23	4.41	3.84	6.32	4.85	5.36	0.27	5.35	5.39	0.18	7.62	
Ho	0.80	0.64	0.77	0.89	0.90	0.80	1.29	0.99	1.07	0.05	1.09	1.09	0.04	1.54	
Er	2.21	1.74	2.15	2.49	2.58	2.28	3.65	2.79	2.91	0.14	3.03	2.96	0.09	4.20	
Yb	2.16	1.60	2.09	2.42	2.57	2.31	3.61	2.76	2.88	0.13	3.07	2.93	0.09	4.24	
Lu	0.35	0.26	0.33	0.39	0.42	0.37	0.59	0.45	0.46	0.02	0.49	0.47	0.01	0.68	
Hf	1.72	1.40	1.60	1.97	3.57	3.00	4.78	3.35	3.69	0.09	4.80	3.67	0.11	6.00	
Nb	3.38	2.18	3.12	4.43	9.14	6.46	10.3	7.51	9.42	0.41	12.8	8.89	0.32	16.2	
Ta	0.18	0.09	0.16	0.24	0.47	0.33	0.51	0.37	0.40	0.03	0.56	0.39	0.01	0.68	
Pb	4.22	3.25	3.89	4.63	7.96	6.38	16.9	7.75	8.50	0.39	9.95	8.01	0.21	12.4	
Sc	22.1	37.0	29.2	23.0	22.0	28.7	21.5	25.4	23.3	1.1	18.0	24.3	1.0	19.4	
V	239	332	287	240	231	228	176	265	256	10	173	262	8	128	
Cr	2.61	22.9	16.8	4.64	11.4	37.6	8.82	14.1	7.32	0.82	2.42	7.37	1.09	BDL	
Co	24.8	37.7	31.7	27.6	21.3	31.1	14.9	24.8	25.0	2.3	17.9	24.1	0.5	18.2	
Ni	3.22	23.9	12.0	4.40	8.87	20.5	1.52	7.51	10.4	1.0	5.85	9.97	0.32	2.70	
Cu	131	120	118	121	165	97.1	95.1	223	204	26	62.0	228	9	75.4	
Zn	86.7	68.1	87.3	95.9	98.8	78.0	125	96.8	92.0	1.1	88.6	95.1	2.0	112	
Ga	20.8	18.6	20.3	21.5	22.1	18.2	23.1	22.1	21.2	0.1	21.8	21.8	0.5	20.7	
Cs	0.34	0.26	0.32	0.41	0.75	0.74	1.26	0.85	0.95	0.06	1.29	0.93	0.03	1.63	
Th	2.18	2.77	2.15	3.25	8.33	7.08	10.9	7.75	8.63	0.42	12.3	8.15	0.31	14.9	
U	0.74	0.89	0.60	1.06	2.50	1.91	5.77	2.12	2.36	0.10	3.95	2.25	0.08	4.07	
K/Rb	547	437	583	463	398	397	337	377	311		294	315		285	
K/Ba	16	16	18	19	30	27	26	26	27		27	25		28	
Cs/Rb	0.023	0.015	0.023	0.021	0.014	0.018	0.017	0.018	0.016		0.016	0.017		0.016	
Sr/Nd	37.8	40.9	37.8	32.0	25.7	23.4	19.0	22.2	20.5		18.1	20.0		10.3	
Ba/La	29.1	24.8	28.3	21.0	20.6	22.2	19.5	20.1	17.1		18.5	17.6		16.9	
U/Th	0.34	0.32	0.28	0.33	0.30	0.27	0.53	0.27	0.27		0.32	0.28		0.27	
Pb/Ce	0.122	0.090	0.123	0.108	0.126	0.127	0.188	0.122	0.115		0.120	0.110		0.109	
Th/Nb	0.64	1.27	0.69	0.73	0.91	1.10	1.07	1.03	0.92		0.96	0.92		0.92	
U/Nb	0.219	0.408	0.192	0.239	0.274	0.296	0.563	0.282	0.250		0.308	0.253		0.252	
Zr/Nb	21.8	26.9	21.5	19.6	20.4	22.0	23.4	22.0	17.8		17.7	18.8		17.2	
Ti/V	18.5	14.3	17.3	18.7	19.9	19.1	26.9	20.5	22.0		24.9	21.5		41.2	
Ce/Yb	16.0	22.7	15.1	17.7	24.6	21.7	24.9	23.0	25.7		27.0	24.8		26.8	
(La/Yb) _N	5.6	8.0	5.2	6.2	9.0	7.9	9.1	8.3	9.5		10.3	9.2		10.0	
Ce/Ce*	0.90	0.89	0.90	0.91	0.92	0.91	0.92	0.91	0.92		0.92	0.92		0.92	
Eu/Eu*	1.03	1.04	1.02	1.01	0.90	0.91	0.90	0.92	0.86		0.84	0.86		0.77	

Table 2. (continued)

Sample	Central Hiyoshi			North Hiyoshi						Iwo Jima				
	D51-5-1	D52-1-2, 6-1, 6-2, 6-3, 6-4		D53-E, -F		D54-E, F, G		D54-H	D54-K	IJ-2C, 19		IJ-6B	IJ-11	IJ-12
	av	sd	av	sd	av	sd	av	sd	av	sd	av	sd	av	sd
Rb	27.6	70.5	7.6	124	0	31.0	4.8	23.1	25.6	63.9	2.1	62.8	61.9	57.4
Sr	811	1024	14	950	4	1031	62	973	973	459	23	484	506	552
Ba	631	830	14	844	9	742	35	486	488	1115	11	1131	1148	1115
Zr	93.0	144	6	329	3	79.7	0.5	70.4	78.5	237	11	234	224	217
Y	24.9	24.7	1.10	29.5	0	20.7	0.7	19.8	21.5	40.6	1.5	40.6	38.6	37.9
La	32.5	44.3	2.30	60.8	0.5	30.7	1.5	27.7	31.6	61.7	0.2	60.5	58.8	57.5
Ce	60.8	78.7	3.6	108	1	58.7	2.7	57.1	64.0	116	0.2	114	111	108
Pr	7.49	9.29	0.37	12.0	0.1	7.35	0.30	7.53	8.29	15.4	0	15.2	14.7	14.3
Nd	29.4	35.5	1.40	43.5	0.3	29.9	1.0	31.6	34.6	60.0	0.2	59.2	57.0	55.8
Sm	5.81	6.66	0.27	7.58	0.04	5.97	0.19	6.46	7.05	10.6	0.1	10.5	10.1	9.90
Eu	1.73	2.05	0.09	2.02	0.01	1.86	0.06	2.04	2.15	2.54	0	2.49	2.47	2.47
Gd	5.53	5.95	0.44	6.45	0.04	5.41	0.22	5.70	6.13	8.04	0.04	8.00	7.67	7.50
Tb	0.84	0.90	0.04	0.96	0.01	0.80	0.03	0.81	0.88	1.29	0	1.28	1.23	1.21
Dy	4.49	4.59	0.21	4.89	0.03	4.05	0.15	4.06	4.40	6.79	0.01	6.73	6.47	6.36
Ho	0.87	0.87	0.04	0.91	0	0.76	0.02	0.75	0.81	1.34	0.01	1.33	1.28	1.25
Er	2.34	2.31	0.07	2.46	0.01	1.98	0.08	1.89	2.07	3.81	0.01	3.80	3.63	3.56
Yb	2.27	2.16	0.08	2.50	0.02	1.79	0.07	1.67	1.84	3.76	0.03	3.75	3.59	3.50
Lu	0.36	0.34	0.01	0.40	0	0.27	0.01	0.26	0.28	0.61	0	0.61	0.58	0.57
Hf	2.28	3.13	0.24	6.11	0.04	2.05	0.05	1.86	1.96	5.57	0.09	5.53	5.29	5.11
Nb	4.66	7.31	0.69	14.9	0.2	4.29	0.13	3.43	3.66	8.30	0.13	8.15	7.84	7.57
Ta	0.19	0.32	0.03	0.66	0.01	0.17	0.01	0.12	0.13	0.40	0	0.40	0.38	0.37
Pb	6.16	7.37	0.16	12.7	0	5.42	0.29	4.12	3.84	12.3	0.4	12.3	11.5	14.9
Sc	25.5	21.7	0.7	17.7	0.9	32.7	0.6	40.2	36.7	12.6	0.9	13.2	12.0	13.2
V	204	293	14	226	3	388	6.87	378	387	90.7	4.6	96.6	82.5	94.5
Cr	21.3	8.90	3.45	1.83	0.23	36.0	1.73	64.4	45.4	1.58	0.69	1.72	29.2	1.91
Co	27.8	29.7	1.2	22.8	0.1	44.7	2.43	43.2	41.8	9.68	0.51	10.2	9.65	10.1
Ni	15.0	9.52	1.31	9.51	0.01	29.6	1.75	32.1	28.0	2.80	0.61	2.77	15.7	2.68
Cu	52.2	102	25	69.1	2.7	152	11	87.2	132	28.8	1.9	29.4	33.7	31.1
Zn	90.4	85.3	6.0	75.4	1.4	78.7	2.0	77.0	75.9	133	1	132	126	130
Ga	18.9	20.0	1.2	20.1	0	18.5	0.4	17.6	18.2	20.0	1.8	20.8	19.6	19.4
Cs	0.41	0.70	0.11	1.78	0	0.71	0.38	0.10	0.13	0.24	0.04	0.67	0.84	0.48
Th	4.59	7.37	0.12	18.3	0.1	3.70	0.19	2.49	2.70	11.3	0.2	11.2	10.7	10.3
U	1.09	1.77	0.08	5.47	0.04	0.98	0.08	0.57	0.76	3.70	0.11	3.90	3.47	3.37
K/Rb	420	302		277		366		430	371	532		553	543	559
K/Ba	18	26		41		16		20	19	30		31	29	29
Cs/Rb	0.015	0.010		0.014		0.020		0.004	0.005	0.004		0.011	0.014	0.008
Sr/Nd	27.6	28.8		21.8		35.9		30.8	28.1	7.6		8.2	8.9	9.9
Ba/La	19.4	18.7		13.9		25.1		17.5	15.4	18.1		18.7	19.5	19.4
U/Th	0.24	0.24		0.30		0.26		0.23	0.28	0.33		0.35	0.33	0.33
Pb/Ce	0.101	0.094		0.117		0.094		0.072	0.060	0.106		0.108	0.104	0.137
Th/Nb	0.98	1.01		1.22		0.84		0.73	0.74	1.36		1.37	1.36	1.36
U/Nb	0.234	0.242		0.366		0.222		0.166	0.208	0.446		0.479	0.443	0.446
Zr/Nb	19.9	19.6		22.1		18.4		20.5	21.4	28.6		28.8	28.6	28.7
Ti/V	20.0	16.4		17.1		14.6		14.5	14.1	58.6		56.3	57.6	53.3
Ce/Yb	26.8	36.4		43.4		32.5		34.2	34.8	30.9		30.4	30.8	31.0
(La/Yb) _N	9.7	13.8		16.5		11.5		11.2	11.6	11.1		10.9	11.1	11.1
Ce/Ce*	0.91	0.91		0.94		0.91		0.93	0.93	0.88		0.88	0.88	0.88
Eu/Eu*	0.93	0.99		0.88		1.01		1.03	1.00	0.84		0.83	0.86	0.88

*Mean compositions of several samples are expressed as av; standard deviation of the mean is indicated by sd.

BDL: below detection limit.



	Calc-alkaline	Shoshonitic
Iwo Jima		◊
Fukutoku-oka-no-ba		▼
N. Hiyoshi	△	▲
C. Hiyoshi	○	●
S. Hiyoshi	□	◼
Ko-Hiyoshi	⊠	

Figure 3. K_2O versus SiO_2 plot for volcanic rocks of the Izu-Bonin-Mariana arc. Each volcanic edifice from the Alkalic Volcano Province is assigned to a specific symbol; shoshonitic and calc-alkaline lavas are discriminated by half-shaded and open patterns, respectively. Data for Fukutoku-oka-no-ba are from *Sun et al.* [1998]; some data for North Hiyoshi are from *Sun et al.* [1999]. The shaded field represents calc-alkaline and tholeiitic lavas from the rest of the Mariana arc and are compiled from various sources [*Bloomer et al.*, 1989a; *Woodhead*, 1989; *Elliott et al.*, 1997]. Izu-Bonin arc lavas [*Taylor and Nesbitt*, 1998] are outlined by dotted line and are shaded. The boundary between shoshonitic series and calc-alkaline series is from *Peccerillo and Taylor* [1976].

from the Alkalic Volcano Province clearly have genetic links to their shoshonitic relatives. For this reason, shoshonitic and non-shoshonitic samples are discussed together.

K/Rb in these lavas has a relatively low average of 365 ± 90 (one standard deviation), typical of arc volcanics and much lower than normal MORB (1070 [*Sun and McDonough*, 1989]). The K/Rb for Alkalic Volcano Province lavas is also lower than the mean K/Rb of 456 ± 85 for other Mariana arc lavas [*Lin et al.*, 1989]. More depleted Izu-Bonin arc lavas have much higher

K/Rb, with a mean value of 693 ± 105 [*Taylor and Nesbitt*, 1998]. K/Ba is approximately constant along the entire Izu-Bonin-Mariana magmatic front. The mean K/Ba of 27 ± 8 in the studied samples is a similar range to that of depleted Izu-Bonin arc tholeiites (27 ± 8 [*Taylor and Nesbitt*, 1998]) and other Mariana arc lavas (27 ± 7 [*Lin et al.*, 1989]).

Fractional crystallization may have affected some element ratios in these alkalic lavas. Sr/Nd in the samples negatively covaries with SiO_2 , probably reflecting removal of plagioclase from

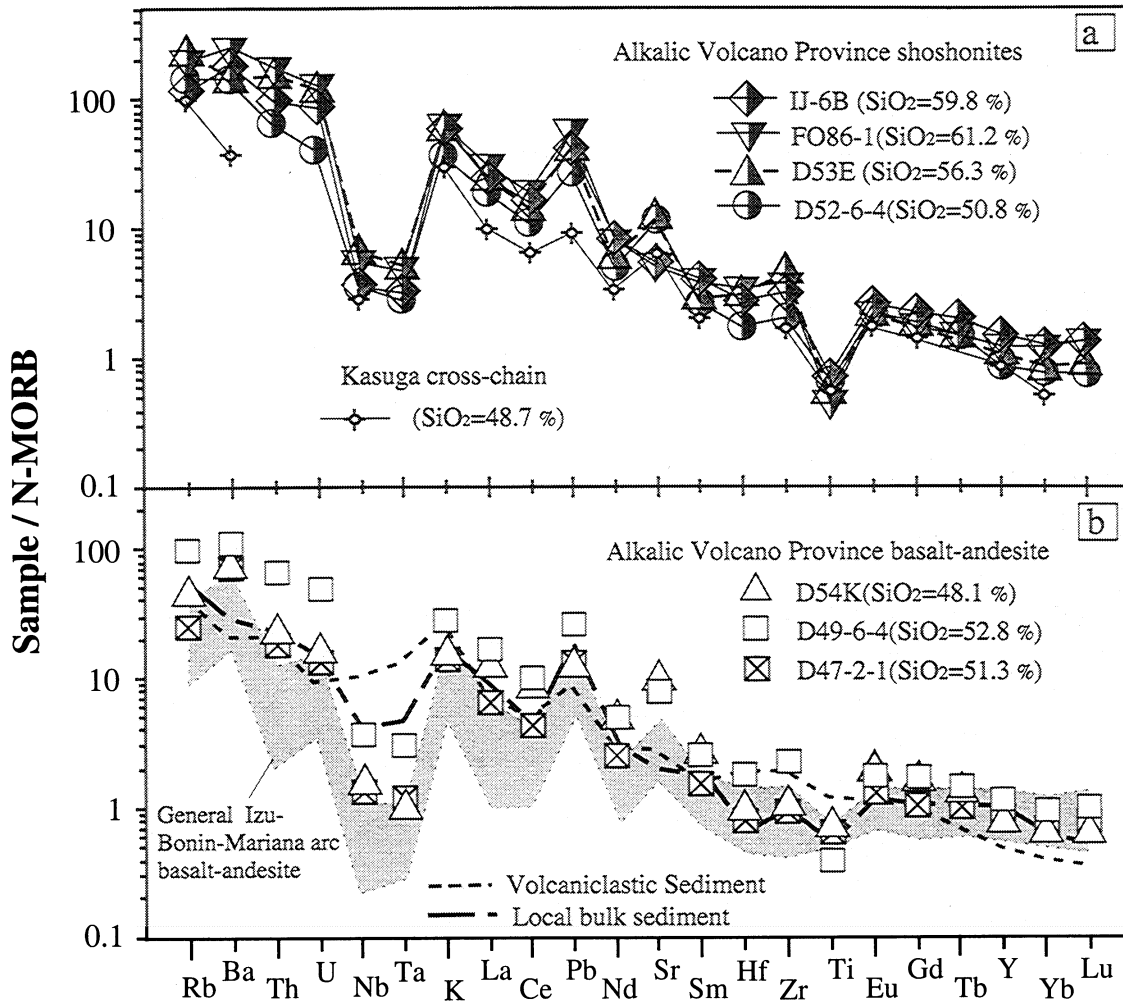


Figure 4. NMORB normalized spidergrams illustrating the distinctively enriched compositions of studied Alkalic Volcano Province lavas compared with Izu-Bonin [Taylor and Nesbitt, 1998] and other Mariana arc [Peate and Pearce, 1998] basalts and andesites and a Kasuga cross-chain shoshonite (R.J. Stern, unpublished data, 1999). (a) Alkalic Volcano Province and Kasuga shoshonites. (b) Non-shoshonitic Alkalic Volcano Province lavas.

melt. Sr/Nd ranges from 7 to 41 with a mean of 22 ± 9 , less than 28 ± 13 of the mean Mariana arc and 37 ± 18 of the mean Izu-Bonin arc.

Although the samples exhibit greater enrichment in incompatible elements than ordinary lavas in the arc, some incompatible element ratios show restricted ranges and approach mantle values. The ratios of Cs/Rb (0.003–0.034) and U/Th (0.22–0.53) in these rocks are similar to mantle values (0.0125 and 0.26–0.39; [Sun and McDonough, 1989]). In contrast, the more depleted lavas in the arc have distinctly higher means and wider ranges of these ratios [Lin et al., 1989; Elliott et al., 1997; Taylor and Nesbitt, 1998].

Chemical characteristics of the alkalic lavas relative to depleted Mariana arc lavas are summarized on MORB-normalized spidergrams (Figure 4). Shoshonitic samples show elevated concentrations of highly incompatible elements (Rb, Ba, and Th), up to 200 times MORB, and manifest a Nb-Ta trough. A Nb-Ta trough is a negative anomaly relative to the adjacent elements and is a common characteristics of arc volcanics. U/Nb in some samples (up to 0.56) is slightly higher than that in general subalkaline lavas in the arc (0.13–0.43 [Elliott et al., 1997; Peate and Pearce,

1998; Taylor and Nesbitt, 1998]), regardless of the absolute concentration of Nb. Th/Nb in Alkalic Volcano Province lavas range from 0.64 to 1.84 compared with the range of 0.24 to 1.37 in the rest of the arc [Elliott et al., 1997; Peate and Pearce, 1998; Taylor and Nesbitt, 1998]. Such high Th/Nb is uncommon, especially in island arc volcanism. Some Fiji shoshonites have Th/Nb up to 2.7 [Gill and Whelan, 1989]. Th/Nb up to 6.14 in shoshonites from the northwestern Alps of Italy [Venturelli et al., 1984] may be partially due to crustal contamination.

Zr, Hf, Nb, and Ta are typical high field strength elements. Samples analyzed in this study have a mean Zr/Hf of 45.1 ± 4.1 which is significantly higher than the mantle value (36 [Sun and McDonough, 1989]). It is also higher than the Zr/Hf of 31 ± 3 in the Izu-Bonin arc [Taylor and Nesbitt, 1998] and that of 38 ± 2 in the rest of Mariana arc [Elliott et al., 1997; Peate and Pearce, 1998].

The mean Nb/Ta of 22.3 ± 2 in the lavas is above the mantle value (17.8 [Sun and McDonough, 1989]) and also above that reported for other Mariana lavas (16.1 ± 3.4 [Elliott et al., 1997; Peate and Pearce, 1998]). This element pair has similar bulk/melt partition coefficients in mantle peridotites. Fractiona-

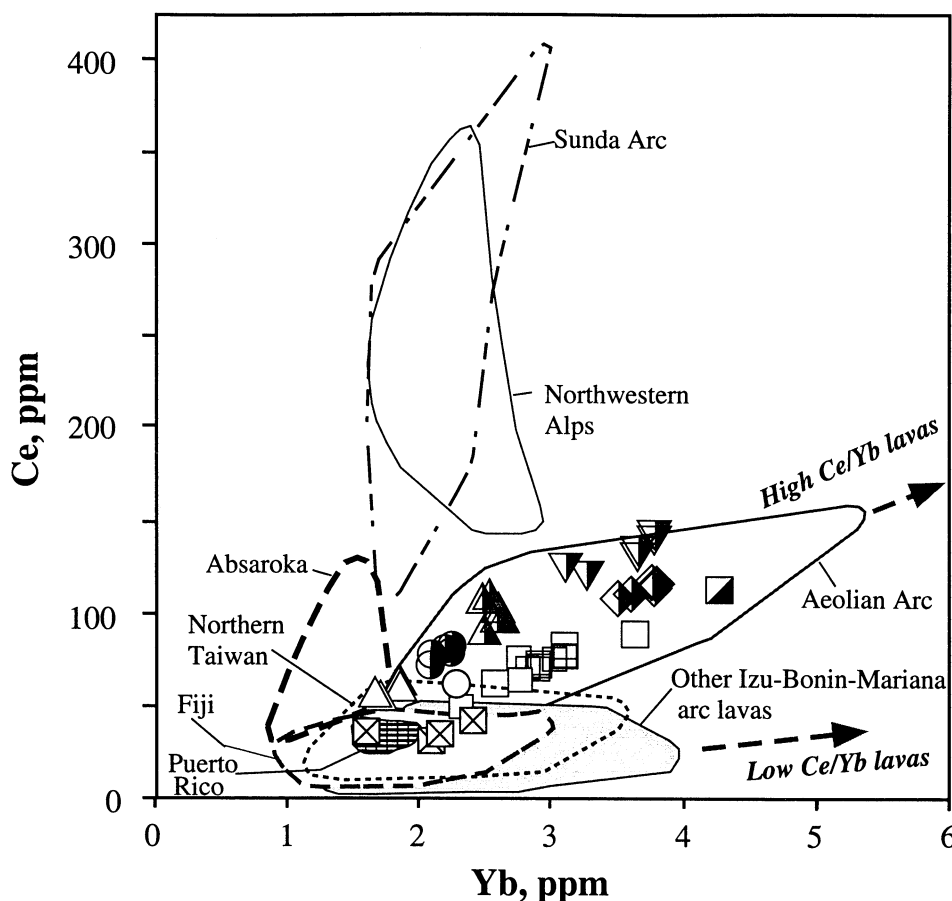


Figure 5. Ce-Yb variation diagram for volcanic rocks from the Alkalic Volcano Province and shoshonites from around the world. Alkalic Volcano Province lavas define a trend similar to that of Aeolian arc and belong to the high-Ce/Yb group defined by *Hawkesworth et al.* [1991]. The trend for the studied samples can be distinguished from other intraoceanic arc shoshonites in Fiji islands. Data for Absaroka are taken from *Meen* [1987]; for northern Taiwan from *Chen* [1984]; for Sunda from *Edwards et al.* [1991]; for the Aeolian arc from *Ellam et al.* [1989]; for Puerto Rico from *Jolly et al.* [1998]; and for Fiji islands from *Gill and Whelan* [1989]. The field defined by other Izu-Bonin-Mariana arc lavas consists of data published by *Lin et al.* [1989], *Elliot et al.* [1997], *Taylor and Nesbitt* [1998], and *Peate and Pearce* [1998].

tion of this ratio is possible if Ti-bearing phases are residual after melt generation, during fractionation, or during crustal contamination, since such phases have different partition coefficients for Nb and Ta [e.g., *Green and Pearson*, 1987].

Another notable geochemical characteristic of the alkalic lavas is their negative Ce anomaly. Ce/Ce* in the Alkalic Volcano Province varies from 0.88 to 0.98 with a mean of 0.90 ± 0.02 . Ce anomalies have been previously reported for Mariana-Volcano arc lavas [*Hole et al.*, 1984; *White and Patchett*, 1984; *Woodhead*, 1989; *Lin et al.*, 1989]. Their presence in arc lavas have been attributed to the involvement of pelagic sediments into the region of melt generation in the mantle wedge, although other factors (e.g., oxidizing environment) may also fractionate Ce from the other REE.

Hawkesworth et al. [1991] subdivided rocks from destructive plate margins into two groups, based on variations of Ce/Yb (Figure 5). The low Ce/Yb group has a restricted range of non-radiogenic Sr and Pb isotopes and radiogenic Nd. In contrast, the high Ce/Yb group has elevated Ce contents and variable Sr, Nd, and Pb isotopic compositions, implying crustal contamination, involvement of subducted sediments or an enriched mantle

source. A comparison of Alkalic Volcano Province shoshonites with global shoshonites is shown in Figure 5. Note that shoshonites from northern Taiwan, Puerto Rico, and Fiji islands belong to the low Ce/Yb group [*Hawkesworth et al.*, 1991]. The Sunda arc, northwestern Alps, and Absaroka shoshonitic suites have high abundances of Ce at nearly constant Yb contents; this probably reflects the role of residual garnet in these continental arcs. Alkalic Volcano Province shoshonites have Ce/Yb characteristics that are similar to Aeolian arc shoshonites, which were defined as typical members of the high-Ce/Yb group.

4.3. Isotopic Compositions

Sr, Nd, and Pb isotopic compositions are listed in Table 3 and plotted along with previously reported Alkalic Volcano Province samples [*Sun et al.*, 1998, 1999] and MORB and OIB in Figures 6 and 7. The $^{87}\text{Sr}/^{86}\text{Sr}$ variations are less than 0.0002 between leached and unleached samples, while $^{143}\text{Nd}/^{144}\text{Nd}$ show negligible differences. Slightly different Pb isotopic compositions before and after acid leaching are found for samples D47-2-2, D48-5-3, D49-4-4, D49-6-2, and D54-H but these are mostly attributed to

Table 3. Isotopic Compositions of Alkalic Volcano Province Lavas

Edifice	Sample ^a	⁸⁷ Sr/ ⁸⁶ Sr ^b	¹⁴³ Nd/ ¹⁴⁴ Nd ^c	ε _{Nd} ^d	²⁰⁸ Pb/ ²⁰⁴ Pb ^e	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²⁰⁴ Pb	
Ko-Hiyoshi	D47-IN	0.70402±2	0.51284±2	3.90	38.730	15.625	18.906	
		0.70392±1	0.51286±2	4.31	38.698	15.613	18.891	
	D47-1-4	0.70402±2	0.51286±1	4.33	39.005	15.685	19.041	
		0.70391±2	0.51282±1	3.55	-	-	-	
	D47-2-1	0.70398±1	0.51288±3	4.66	38.750	15.627	18.893	
		0.70389±2	0.51288±1	4.60	-	-	-	
	D47-2-2	0.70393±1	0.51286±1	4.31	38.895	15.647	19.052	
		0.70387±2	-	-	38.811	15.621	19.035	
	South Hiyoshi	D48-5-1	0.70396±1	0.51282±1	3.43	38.777	15.615	18.947
			0.70388±3	-	-	38.771	15.612	18.943
D48-5-2		0.70374±2	0.51285±1	4.12	38.805	15.614	18.977	
D48-5-3		0.70387±2	-	-	38.778	15.612	18.973	
		0.70380±1	0.51285±1	3.98	38.842	15.632	18.990	
D48-5-4		0.70381±3	-	-	38.881	15.632	18.994	
D48-5-5		0.70386±1	0.51284±1	3.90	38.810	15.615	18.982	
D48-5-6		-	-	-	38.858	15.629	19.012	
D48-6-1		0.70385±1	-	-	38.816	15.613	18.981	
D48-6-2		-	-	-	38.836	15.624	18.988	
D49-3-2		0.70384±1	0.51286±1	4.23	38.784	15.606	18.968	
D49-4-4		0.70393±2	0.51285±1	4.10	39.002	15.672	19.032	
		0.70375±3	-	-	38.801	15.609	18.977	
D49-6-2		0.70382±1	0.51284±1	3.88	38.763	15.599	18.958	
(leached)		0.70384±2	0.51285±1	4.14	38.857	15.630	18.992	
D49-6-3		-	-	-	38.822	15.619	18.987	
D49-6-4		0.70371±1	0.51286±1	4.19	38.853	15.627	18.996	
D49-6-5		-	-	-	38.806	15.612	18.980	
D49-6-6		-	-	-	38.814	15.617	18.988	
D49-6-7		0.70379±1	0.51284±1	3.90	38.841	15.622	18.991	
Central Hiyoshi	D51-5-1	0.70369±2	0.51290±1	5.11	38.906	15.626	19.087	
		0.70362±2	0.51285±1	4.10	38.922	15.630	19.092	
	D52-1-2	0.70371±1	0.51280±1	3.08	38.829	15.635	18.865	
		0.70385±4	-	-	38.804	15.632	18.866	
	D52-6-1	-	-	-	38.786	15.624	18.857	
	D52-6-2	0.70382±5	-	-	38.786	15.625	18.860	
	D52-6-3	-	-	-	38.849	15.643	18.872	
	D52-6-4	0.70393±3	0.51279±1	2.89	38.891	15.657	18.881	
North Hiyoshi	D53-E	0.70373±3	0.51279±1	2.89	38.825	15.626	18.982	
		0.70373±1	0.51281±1	3.24	38.859	15.640	19.001	
	D53-F	0.70387±1	0.51282±2	3.45	38.772	15.605	18.959	
	D54-E	0.70388±1	0.51284±1	3.86	38.751	15.612	18.893	
	D54-G	0.70386±1	0.51280±2	3.10	38.733	15.614	18.886	
	D54-H	0.70366±2	0.51285±1	4.10	38.802	15.600	19.048	
		0.70371±4	0.51287±1	4.53	38.893	15.638	19.110	
	D54-K	0.70380±1	0.51287±1	4.39	39.054	15.672	19.123	
	0.70374±3	-	-	-	-	-		
Iwo Jima	IJ-2C	0.70376±2	0.51292±1	5.44	39.057	15.627	19.454	
	IJ-6B	0.70356±3	0.51293±1	5.52	39.079	15.635	19.460	
	IJ-11	0.70365±2	0.51289±1	4.76	39.086	15.635	19.465	
	IJ-12	0.70386±3	0.51293±2	5.62	39.002	15.629	19.366	
	IJ-19	0.70359±1	0.51292±1	5.50	39.083	15.634	19.463	

^a Leached samples were treated with 6 N HCl for 2 hours prior to dissolution.

^b Twenty analyses of E+A SrCO₃ gave a mean ⁸⁷Sr/⁸⁶Sr = 0.708063±0.000031 (one standard deviation).

^c Nineteen analyses of the La Jolla standard gave a mean ¹⁴³Nd/¹⁴⁴Nd = 0.511863±0.000012.

^d ε_{Nd} values are calculated by using ε_{Nd} = -19.2 for La Jolla Nd standard determined at the University of Texas at Dallas.

^e Twenty eight analyses of NBS-981 yielded a mean ²⁰⁶Pb/²⁰⁴Pb = 16.944±0.008, ²⁰⁷Pb/²⁰⁴Pb = 15.500±0.009, ²⁰⁸Pb/²⁰⁴Pb = 36.743±0.031.

thermal fractionation during analysis. We conclude that the isotopic compositions reported here closely approximate those of the lavas at the time of eruption. The lavas have ⁸⁷Sr/⁸⁶Sr ranging from 0.70356 to 0.70403, similar to previously reported results of *Lin et al.* [1989], and are slightly higher than the rest of the Izu-Bonin-Mariana arc. The alkalic province is distinct from its calc-alkaline counterparts in having different Nd and higher Pb iso-

topic compositions. Nd isotopic compositions vary significantly from north to south along the 2500-km-long arc, with the lowest ε_{Nd} in the Alkalic Volcano Province. The ε_{Nd} drops abruptly from nearly MORB-like values in the Izu arc (8.2 ~ 9.4 [*Taylor and Nesbitt*, 1998]) to 5.5 in Iwo Jima, the northernmost member of the Alkalic Volcano Province, then reaches the lowest value (2.8) in North Hiyoshi within a distance of 200 km; ε_{Nd} in-

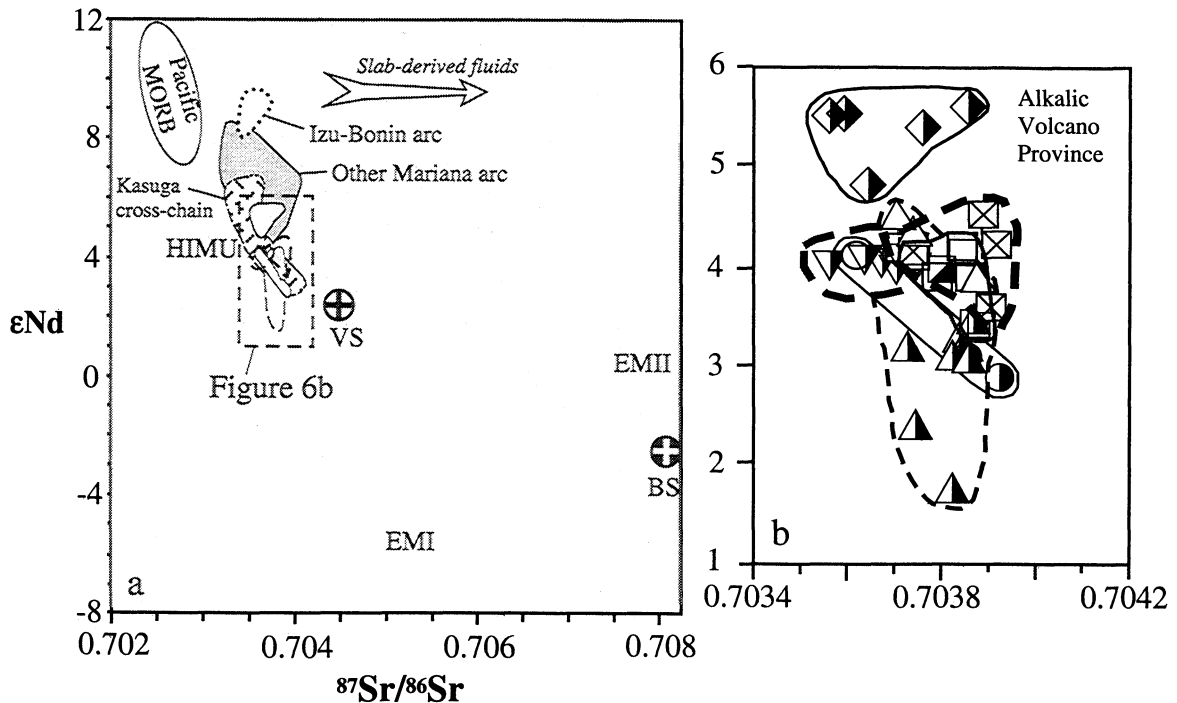


Figure 6. (a) Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus ϵNd . The alkalic lavas have $^{87}\text{Sr}/^{86}\text{Sr}$ comparable with those of depleted counterparts from the rest of the arc [Lin *et al.*, 1989; Woodhead, 1989; Elliot *et al.*, 1997; Taylor and Nesbitt, 1998] but generally have lower ϵNd than the latter. (b) Detail of Sr and Nd isotopic variations. Note that significant variations are observed among lavas recovered from Central and North Hiyoshi seamounts, where shoshonitic samples have lower ϵNd than calc-alkaline samples. These lavas have Sr and Nd isotopic compositions similar to shoshonitic lavas from the Kasuga crosschain [Stern *et al.*, 1993].

creases slowly from the Alkalic Volcano Province to the south. Similarly, Pb isotopic compositions demonstrate variations along the arc. Most samples in the Alkalic Volcano Province have more radiogenic Pb isotopic compositions than other Izu-Bonin and Mariana arc lavas except for the Kasuga cross chain, the other shoshonitic occurrence in this arc system (Figure 7).

5. Discussion

We first discuss the roles of batch melting and fractional crystallization. A fractional crystallization model is presented and used to forward model trace element evolution. Incompatible trace element ratios and isotopic compositions are then employed to evaluate the contribution of the possible enriched inputs and subsequently to estimate the quantity of the enriched source(s). In addition, we test the hypothesis of residual refractory phases in the magma source by monitoring interelemental variations among HFSE.

5.1. Interelement Fractionations by Magmatic Processes

5.1.1. Constraints on melting. One of the most distinctive chemical characteristics that distinguish Alkalic Volcano Province lavas from ordinary Izu-Bonin-Mariana arc lavas is their strong enrichments in LREE. Strong fractionation of LREE relative to heavy REE (HREE) in melts can be due to the involvement of certain refractory phases (e.g., garnet). Melting with residual garnet should exhibit not only greater LREE enrichment but also steeper HREE patterns at smaller extent of partial melting because of the extremely high HREE partitioning coefficient

of garnet [e.g., Hanson, 1980]. This may explain shoshonites from continental arcs such as Sunda, NW Alps, and Absaroka (Figure 5), but the relatively flat HREE patterns of most Alkalic Volcano Province lavas are inconsistent with significant residual or cumulate garnet.

Model calculations by Lin *et al.* [1989] predicted REE evolution in melts of spinel peridotite. Melts generated from a spinel peridotite source after different extents of melting have variable LREE enrichment but rather flat HREE patterns, which are common to all Mariana arc lavas. The model attributed the geochemical variations along the magmatic front to the degrees of melting in a homogeneous subarc mantle. In contrast, Bloomer *et al.* [1989a] argued that melts in the southern part of the Izu-Bonin-Mariana magmatic front were generated by similar degrees of partial melting. Peate and Pearce [1998] confirmed that most Mariana lavas can be reproduced by 25–30% melting in the spinel peridotite field. Accordingly, the distinctive compositions of these alkalic lavas relative to other Izu-Bonin-Mariana arc lavas, and perhaps the interedifice variations within the Alkalic Volcano Province, are interpreted to reflect heterogeneous sources rather than different degrees of partial melting of a homogeneous mantle source.

5.1.2. Fractional crystallization. Model calculations using a mafic North Hiyoshi sample (D54-H; 47.75 wt % SiO_2 , Mg # = 54) as the starting magma demonstrates systematic evolution in major element compositions controlled by fractional crystallization of plagioclase, clinopyroxene, olivine, and magnetite (Table 4). A 4% increase in SiO_2 requires 65% crystallization, while to reproduce the most siliceous Fukutoku-oka-no-ba lavas ($\approx 61\%$

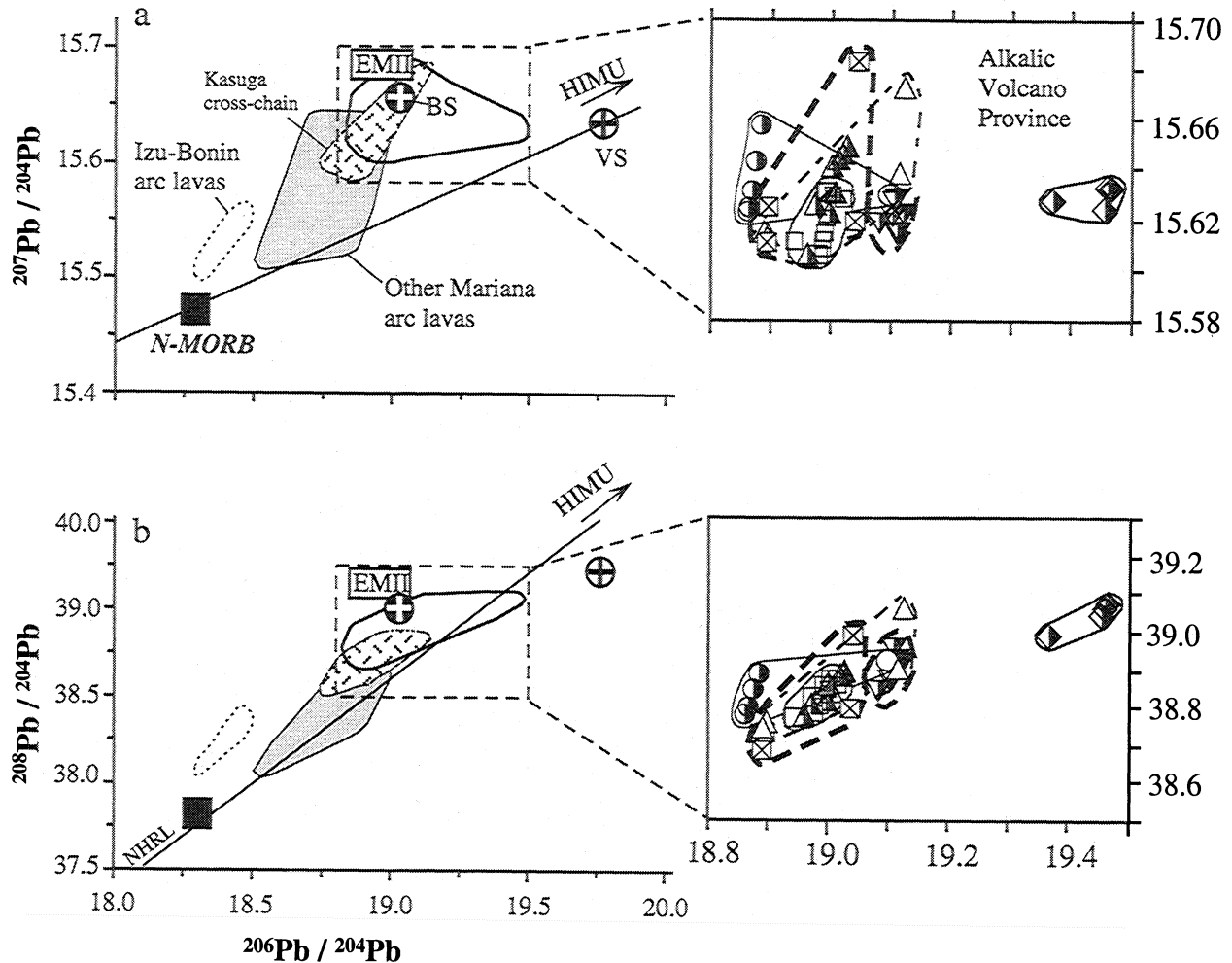


Figure 7. Plots of $^{206}\text{Pb}/^{204}\text{Pb}$ versus (a) $^{207}\text{Pb}/^{204}\text{Pb}$ and (b) $^{208}\text{Pb}/^{204}\text{Pb}$ illustrating the more radiogenic Pb isotopic compositions of Alkalic Volcano Province lavas compared to other Izu-Bonin-Mariana arc lavas [Woodhead, 1989; Elliott et al., 1997; Taylor and Nesbitt, 1998]. Note the similarity of Alkalic Volcano Province lavas and Kasuga crosschain shoshonites [Stern et al., 1993].

SiO_2), the system requires up to 78% crystallization. The proportion of phases is relatively constant throughout the various extents of fractionation. The calculated phases consist of 48–56% plagioclase, 27–35% clinopyroxene, 7–10% olivine, and 7.5–9.5% magnetite. These phases are observed in the lavas and define a low-pressure assemblage.

The fractionation model is further examined using incompatible trace element ratios which are little affected during fractional crystallization. By using the fractionation model and appropriate partition coefficients, trace element ratios are calculated for the residual melts from the model magma parent (Table 4). The calculated melts show only a slight increase in $(\text{La}/\text{Yb})_N$ over the modeled range of fractionation, reflecting similar bulk partition coefficients of La and Yb during low-P fractionation. The samples show no correlation between SiO_2 and $(\text{La}/\text{Yb})_N$ and some have even lower $(\text{La}/\text{Yb})_N$ than the model melts (Figure 8a).

Evidence supporting the effect of fractional crystallization for fractionating LIL/HFSE of these alkalic lavas is found in a strong correlation of Th/Nb with increasing SiO_2 (Figure 8b). Causing this covariation by fractional crystallization requires significantly different bulk partition coefficients for Th and Nb than those used

in the fractionation model that we have developed. A similar behavior of U/Nb can be also observed from the covariation of Th/Nb and U/Nb (Figure 8c). Elevated and covarying U/Nb and Th/Nb in the Alkalic Volcano Province requires fractionating phases with high D_{Nb} .

The presence of Ti-rich phases (rutile, sphene, ilmenite, and magnetite) in the magma is an attractive mechanism to account for HFSE depletion in arc volcanism due to the high partition coefficients of Nb in these phases. Experimental data by Green and Pearson [1987] confirm that fractionation of minor amounts of these minerals can strongly affect on the HFSE distribution in derivative magmas. Our fractionation model was modified to include crystallizing 0.7–2% rutile from the model magma. Using the partition coefficients of Nb (29.8) from the partition coefficients of Nb (29.8) for rutile by Green and Pearson [1987] and assuming $D_{\text{Nb}} \gg D_{\text{Th}}$ for rutile (no D_{Th} data are available at present), the model can generate the observed Th/Nb variations (Figure 7b). Similarly, presence of residual rutile in the magma source would cause high Th/Nb in equilibrium. Whether rutile is responsible for the HFSE depletion in Alkalic Volcano Province lavas remains to be demonstrated because we have not found rutile or similar phases in thin sections. In addi-

Table 4. Model Calculation Assuming Most Alkalic Volcano Province Lavas Were Fractionated From a Starting Magma Which Has Chemical Compositions Similar to That of Sample D54-H

	D54-H	D48-5-4	D49-6-2	D52-1-2	D53-F	3K350-2	FO86-2	IJ-6B
Phase proportions ^a								
Plag (%)		48.2	53.4	48.9	51.9	56.1	52.9	52.8
Cpx		34.4	31.4	35.0	32.1	27.0	31.5	32.0
Ol		8.3	7.4	7.5	6.9	8.0	6.4	6.7
Mt		9.1	7.8	8.6	9.1	8.9	9.2	8.4
Degrees of crystallization		65.7	72.4	47.9	59.6	62.2	77.6	77.4
Sum of squares of residual		0.09	0.08	0.05	0.10	0.10	0.14	0.15
Observed ratios								
SiO ₂	47.75	51.83	56.61	50.52	56.27	56.26	61.15	59.84
Ba/La	17.50	20.06	16.87	20.42	13.91	14.08	17.64	18.69
Th/Nb	0.73	1.03	0.92	1.18	1.23	1.13	1.77	1.37
U/Nb	0.17	0.28	0.25	0.26	0.37	0.35	0.52	0.48
U/Th	0.23	0.27	0.27	0.22	0.30	0.31	0.29	0.35
(La/Yb) _N	11.20	8.30	9.98	13.22	16.48	14.90	13.18	10.90
Model ratios ^b								
Ba/La		18.63	19.33	18.46	19.26	18.88	19.74	19.67
Th/Nb		0.76	0.79	0.76	0.79	0.78	0.81	0.80
U/Nb		0.17	0.18	0.17	0.18	0.18	0.18	0.18
U/Th		0.23	0.23	0.23	0.23	0.23	0.23	0.23
(La/Yb) _N		12.06	12.17	11.90	12.19	11.60	12.35	12.40

^a In order to produce the observed major elements in the selected Alkalic Volcano Province lavas, the phases and their proportions shown here need to be separated from the residual melts.

^b Model trace element ratios are calculated from the model starting magma based on the phases and their proportions above. Partition coefficients for olivine: $D_{Ba}=0.01$, $D_U=0.04$, $D_{Th}=0.02$ [Villemant, 1988], $D_{La}=0.0067$, $D_{Yb}=0.0468$ [Fujimaki et al., 1984], $D_{Nb}=0.009$ [Larsen, 1979]; clinopyroxene: $D_{Ba}=0.02$, $D_{La}=0.11$, $D_U=0.02$, $D_{Th}=0.02$ [Villemant, 1988], $D_{Yb}=0.65$ [Schnetzler and Philpotts, 1970], $D_{Nb}=0.025$ [Larsen, 1979]; Plagioclase: $D_{Ba}=0.19$ [Ewart et al., 1973], $D_{La}=0.24$, $D_U=0.02$, $D_{Th}=0.02$ [Villemant et al., 1981], $D_{Yb}=0.098$ [Nagasawa, 1973], $D_{Nb}=0.045$ [Dunn and Sen, 1994]; titanomagnetite: $D_{Ba}=0.028$ [Okamoto, 1979], $D_{Nb}=0.7$ [Green and Peterson, 1987], $D_{La}=0.29$, $D_{Yb}=0.26$, $D_U=0.12$, $D_{Th}=0.06$ [Luhr et al., 1984].

tion, this model has difficulty explaining the relatively constant Nb/Ta in these lavas (Figure 9). Rutile has $D_{Nb/Ta} \approx 0.65$ with andesitic melt, [Green and Peterson, 1987] so that the fractionation of this phase should raise Nb/Ta in the derivative melt. The crystallization of rutile in the magma source would also cause a positive slope as observed on Figure 9, which is not in agreement with the data. Buffering the high Nb/Ta by crystallizing other minor phases (e.g., ilmenite) might be possible. This phase has high $D_{Nb/Ta}$ and should reduce Nb/Ta in the residual magma. Further modeling of element fractionation by these Ti-rich phases requires more experimental data for other trace element partition coefficients.

5.1.3. Magma mixing. Additional magmatic processes have been postulated to explain the variously enriched chemical compositions of Alkalic Volcano Province lavas. Meen et al. [1998] argued that Central Hiyoshi lavas may be hybrid melts due to mixing of alkaline and subalkaline magmas. A complex magmatic history combining magma mixing and fractional crystallization might have occurred on other Hiyoshi volcanoes. Moreover, glass inclusion studies on North Hiyoshi lavas [Sun et al., 1999] suggest magma mixing between a highly siliceous melt and a silica-undersaturated alkaline magma. The formation of

Alkalic Volcano Province melts could have involved a multistage process including fractional crystallization and magma and/or mantle source mixing. A more detailed discussion of mixing is presented in section 5.2.

5.2. A Limited Role for Hydrous Fluids

Mantle metasomatism by fluids released from the subducted lithosphere may modify the composition of the mantle wedge as fluids trigger melting. Such a process has been proposed to explain the high LIL/LREE in Mariana arc lavas [Lin et al., 1989; Lin, 1992; Woodhead, 1989; Elliott et al., 1997]. The argument is supported by inferences derived from flux melting models [Stolper and Newman, 1994]. LIL/LREE fractionations are especially marked for depleted arc lavas such as Izu [Taylor and Nesbitt, 1998] or Tonga [McDermott and Hawkesworth, 1991], reflecting the greater effect of fluid metasomatism on the compositions of very depleted mantle sources.

To examine the influence of fluid induced mantle metasomatism on the Alkalic Volcano Province magma source, incompatible element ratios Ba/La, Pb/Ce, Cs/Rb, and U/Th are used because of the higher fluid mobility of the numerator with respect

to the less fluid-mobile denominator. This behavior of these elements has been confirmed by high-pressure experiments [Tatsumi *et al.*, 1986; Brenan *et al.*, 1995a, 1995b; Keppler, 1996; You *et al.*, 1996; Kogiso *et al.*, 1997]. Accordingly, lavas with higher ratios of these elements are likely to have sources that were strongly affected by fluid-induced enrichments.

In Figure 10, relatively constant LIL/LREE, Cs/Rb and U/Th in the Alkalic Volcano Province are associated with variably elevated Ce/Yb. The alkalic samples contrast with their tholeiitic and calc-alkaline counterparts in the arc in having restricted ranges of Ba/La, Pb/Ce, and U/Th, while having a large range of Ce/Yb. The ratios of Ba/La and Pb/Ce in Alkalic Volcano Prov-

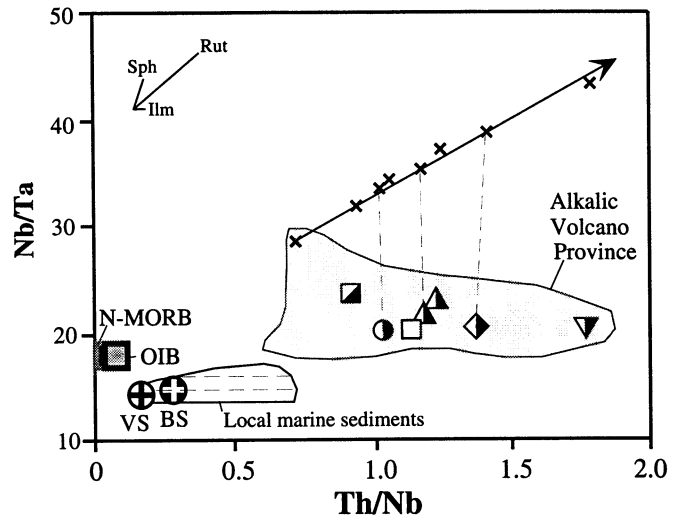
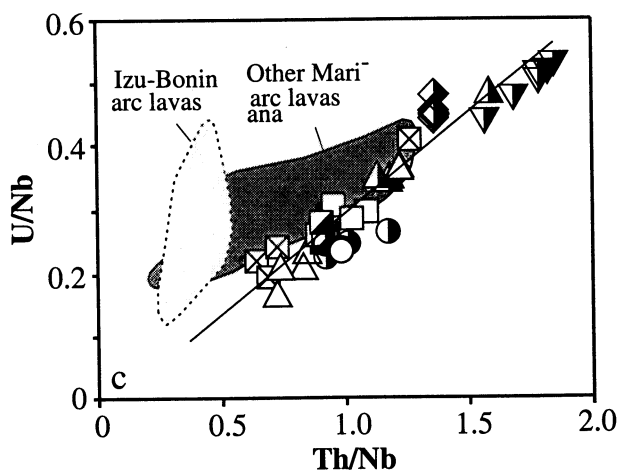
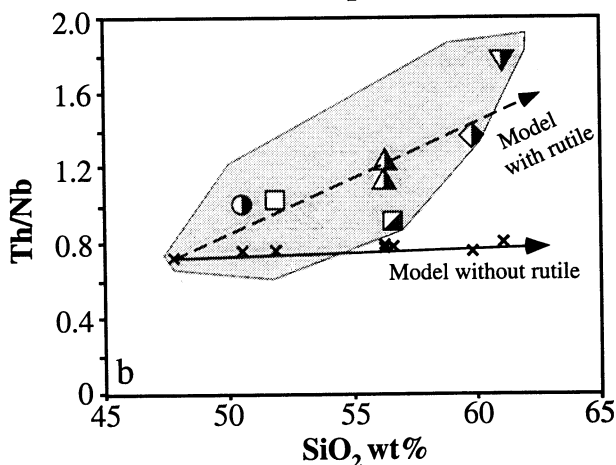
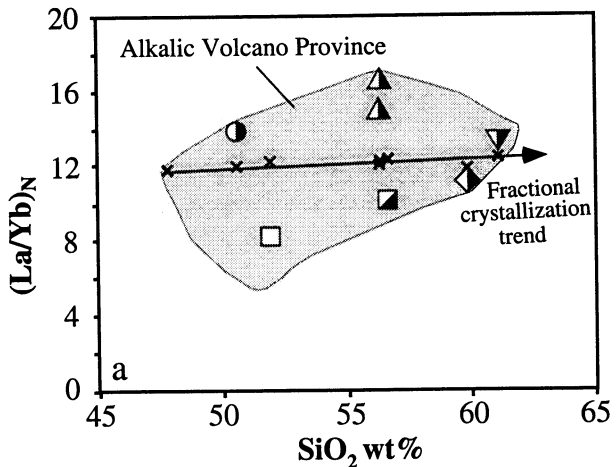


Figure 9. Plot of Th/Nb versus Nb/Ta for Alkalic Volcano Province lavas. The samples have higher Nb/Ta than local marine sediments and mantle. The arrow predicts model magma evolution (expressed as cross) controlled by rutile fractionation. Also shown are evolutionary trends for sphene (Sph), and ilmenite (Ilm) at 2% crystallization for each phase. Partition coefficients for rutile: $D_{Nb}=29.8$, $D_{Ta}=44.7$ [Green and Peterson, 1987], $D_{Nb,Ta} \gg D_{Th} \sim 0$; Sphene: $D_{Nb}=5.4$, $D_{Ta}=14$ [Green and Peterson, 1987], $D_{Nb,Ta} \gg D_{Th} \sim 0$; ilmenite: $D_{Nb}=2.7$, $D_{Ta}=2.3$, [Green and Peterson, 1987], and $D_{Nb,Ta} \gg D_{Th} \sim 0$.

ince lavas are only slightly higher than those in MORB and OIB, indicating that the origin of these enrichments in Alkalic Volcano Province lavas is not due to fluid-induced metasomatism of the mantle source. In contrast, the predicted effects of fluid metasomatism on elevating these ratios are best observed in depleted arc volcanics such as in the Izu-Bonin and other Mariana arc lavas (insets in Figure 10). It should be noted that hydrous fluids are not the significant mechanism raising Ce/Yb.

The mantle-like U/Th in the lavas further constrains the contribution of fluid metasomatism. Under normal redox conditions in the mantle, both U and Th are tetravalent and have similar chemical behaviors. In the hydrous subduction environment, U may be oxidized from U^{4+} to U^{6+} and form uranyl complexes that are

Figure 8. Model magmatic evolution due to fractional crystallization. The model assumes a starting magma having major elements similar to a North Hiyoshi basaltic sample (D54H). (a) (La/Yb)_N for selected samples are compared with predicted derivative melts (expressed as cross) which are calculated from major element fractionation model. (b) Model calculation demonstrating that the unusual high Th/Nb in Alkalic Volcano Province lavas is unlikely a result of fractional crystallization using its model parameters of Table 4. It could be developed by crystallizing additional rutile from the starting magma. The amounts of rutile required to generate the model derivative melts are 1.1, 0.7, 2, 2, 1.6, 2, and 1.5% for samples D48-5-4, D49-6-2, D52-1-2, D53F, 3K350-2, FO86-2, and IJ-6B, respectively. The R^2 of regression line for the model with rutile is 0.72. (c) Th/Nb versus U/Nb plot of Alkalic Volcano Province samples compared with ordinary Izu-Bonin-Mariana arc lavas. The R^2 of the regression line for Alkalic Volcano Province lavas is 0.81. Sources of data for Izu-Bonin and Mariana arc lavas are given in Figure 3 caption.

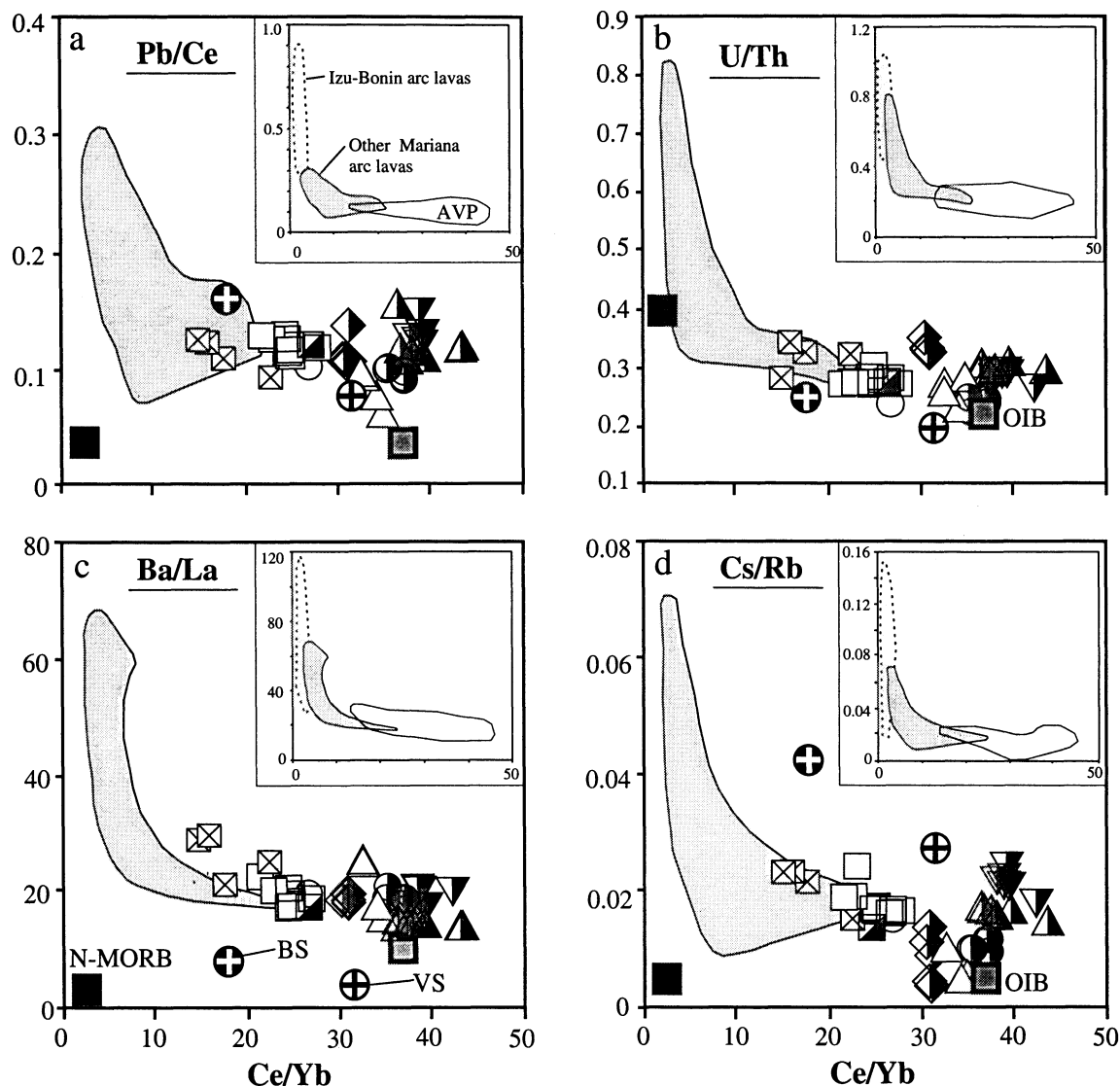


Figure 10. Fluid-sensitive element ratios (a) Pb/Ce; (b) U/Th; (c) Ba/La; and (d) Cs/Rb plotted against Ce/Yb. BS, local bulk sediments; VS, volcanoclastic sediment. Data sources include Elliott et al. [1997] and Peate and Pearce [1998] for other Mariana arc lavas, Taylor and Nesbitt [1998] for Izu-Bonin arc lavas, Plank and Langmuir [1998] for volcanoclastic sediment and bulk sediment and Sun and McDonough [1989] for NMORB and OIB.

mobilized in hydrous fluids [Brenan et al., 1995b]. Interaction between a high U/Th fluid and depleted sub arc mantle should enrich the latter in U as well as other fluid-mobile LIL elements, as discussed earlier. Hence the relatively low and constant U/Th in these lavas is inconsistent with fluid fluxing. Instead, elevated Th and other incompatible elements together may reflect enriched mantle or slab-derived components obtained without fluid mediation, such as melting. Similar geochemical features found in other enriched arcs, such as the Aeolian islands [Ellam et al., 1989] and the Philippines [McDermott et al., 1993], were interpreted to indicate involvement of a sedimentary component rather than a hydrous fluid [Hawkesworth et al., 1997].

Isotopic data limits any role for subducted oceanic crust. Strontium isotopic compositions in altered oceanic basalts are raised by seawater alteration [Menzies and Seyfried, 1979], so that altered MORB should have a wide range of $^{87}\text{Sr}/^{86}\text{Sr}$, while Nd and Pb isotopic compositions may remain unchanged [e.g., Castillo et al., 1992]. Fluids and melts derived from altered oce-

anic crust should inherit these isotopic characteristics. Given the isotopic compositions of altered MORB, fluids or melts derived from altered oceanic crust could not be the primary factor responsible for the isotopic characteristics of the lavas.

Alternatively, hydrous fluids released from dehydration of subducted seamounts and sediments on oceanic crust could provide appropriate isotopic compositions for the Alkalic Volcano Province source. Very little is known about OIB- and sediment-derived fluids. These fluids should behave similarly to other slab-derived fluids in having undisturbed Nd and Pb isotopic compositions but elevated LIL/HFSE and fluid-sensitive element ratios. However, there is little correlation between isotopic compositions and fluid-sensitive ratios Pb/Ce and U/Th (Figure 11). Unless the original U/Th from subducted OIB and subducted sediments was not significantly fractionated during dehydration (which seems unlikely), the wide range of ϵNd but relatively low and constant U/Th in these alkalic lavas does not indicate involvement of a hydrous fluid derived from either subducted OIB and sediment.

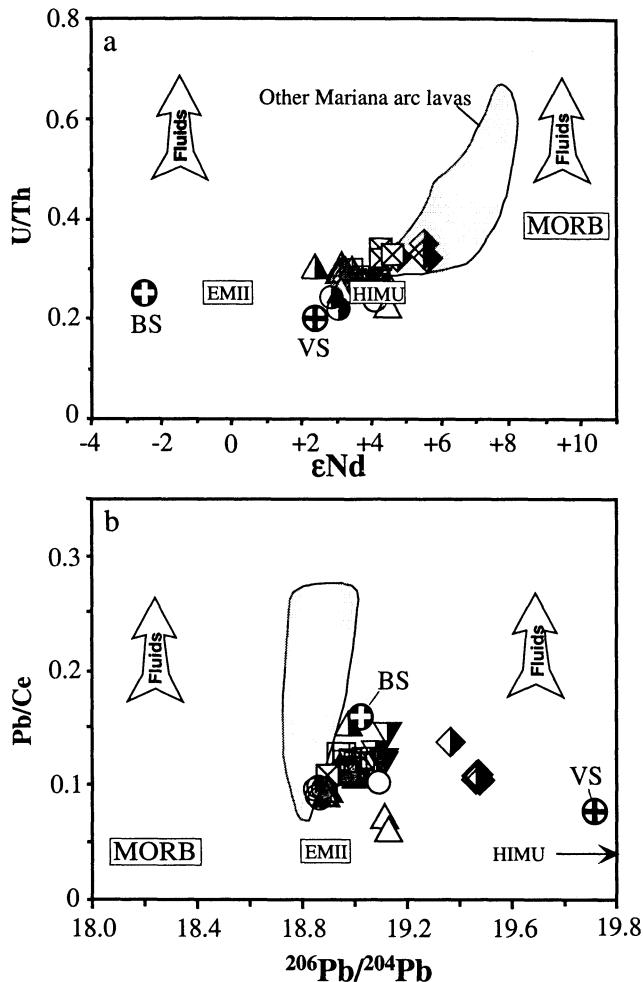


Figure 11. (a) The ϵ_{Nd} versus U/Th and (b) $^{206}Pb/^{204}Pb$ versus Pb/Ce . Arrows indicate possible trends which predict compositional variations of melts when slab-derived fluid is added into the mantle source. Data for other Izu-Bonin-Mariana arc lavas are compiled from Lin et al. [1990], Elliott et al. [1997], and Peate and Pearce [1998].

5.3. Constraints on the OIB Mantle Source

Here we consider the possibility that enriched mantle alone produces the alkalic lavas. The two-component mixing model previously proposed by Stern and coauthors [Ito and Stern, 1986; Stern et al., 1993; Lin et al., 1989, 1990] implies that a LREE- and LIL-enriched OIB-like mantle source mixed with a metasomatized MORB-type mantle. Hickey-Vargas [1992] suggested that a mixture of a depleted mantle and a high U/Pb-type (HIMU) component may be responsible for Izu-Bonin-Mariana arc magmas, especially for the Mariana arc. Furthermore, the mantle-like oxygen isotopic compositions of olivine [Eiler et al., 2000] and pyroxene phenocrysts (E. Ito et al., unpublished data, 1999) in selected lavas from the Alkalic Volcano Province gives strong support for the OIB model. This may reflect a petrogenetic process which only includes OIB mantle or incorporates less than a few percent of subducted sediment.

Mixing NMORB with HIMU (high U/Pb) mantle sources fails to explain the isotopic compositions in the studied samples (Figure 12). Both source components have higher ϵ_{Nd} (>4) but lower $^{87}Sr/^{86}Sr$ (<0.703) than these lavas. Iwo Jima lavas are more similar to HIMU than any other of the arc lavas. A MORB man-

tle source mixed with an enriched mantle II (EMII-type) OIB source is unlikely because both sources have less radiogenic Pb isotopic compositions than most the lavas. Mixtures of MORB-source, EMI, and HIMU can explain the isotopic compositions of Mariana shoshonites shown in Figure 12.

A model advocating an OIB-like mantle source for the enrichments faces geochemical objections. The negative Ce anomalies observed in these alkalic lavas has not been reported from OIB. Hydrous, oxidizing fluids could cause Ce anomalies [White and Patchett, 1984], but we have demonstrated the evidence against fluid involvement. Another argument against the OIB mantle source model is that OIB does not have a Nb-Ta trough and shows smooth incompatible element pattern in spidergrams. One may argue that the Nb-Ta trough could appear as a result of metasomatizing an OIB-like or OIB-hybridized mantle source with highly LIL-enriched hydrous fluids, but again the arguments against fluid metasomatism are strong. Elevated U/Nb may be explained by such a process, but this process is unlikely to fractionate Th/Nb due to the low fluidmobility of Th. Therefore unless there are residual phases retaining Nb and the other HFSE in the melting region, magma generated from an OIB-type mantle source should not have significant Nb-Ta depletion.

5.4. Geochemical Evidence for a Sedimentary Component

Marine sediments have many characteristics of arc magmas, including high concentrations of LIL, high LIL/HFSE, and Ce and Nb anomalies (Figure 4b) [e.g., Plank and Langmuir, 1993; 1998]. The sedimentary column adjacent to the Mariana Trench has an average thickness of about 400m [Plank and Langmuir, 1998] and there is no accretionary prism. As a result, sediments entering the trench are introduced into the mantle, where they may be another potential source to account for the enriched incompatible element budget in the mantle source of Alkalic Volcano Province.

To recognize the involvement of marine sediments in the mantle source, incompatible elements with limited fluid mobility are preferred since their chemical features should not be confused with the effects of hydrous fluids. In Figure 13 the entire Izu-Bonin-Mariana arc system defines a hyperbola extending from a MORB-like high ϵ_{Nd} and low Ce/Yb component towards a low ϵ_{Nd} and high Ce/Yb component. The latter has chemical characteristics similar to volcanogenic sediments but not pelagic "bulk" sediment. The inverse correlation of Ce/Yb and ϵ_{Nd} in the lavas agrees with the model of Hawkesworth et al. [1994], which predicts the antivaration of LREE enrichment and ϵ_{Nd} as sediment is involved in the source region of arc melts.

A negative Ce anomaly ($Ce/Ce^* < 1$) is a common feature of arc volcanics, but its significance is debatable. In most cases, the Ce anomaly is associated with high LIL and REE abundances, more radiogenic Sr and Pb isotopes, and lower ϵ_{Nd} in arc lavas. The correlation is well recognized in depleted Mariana arc lavas and has been linked to sedimentary input [Woodhead, 1989]. However, the samples do not show significant correlation between Ce/Ce^* and any isotopic compositions. This implies that the magnitudes of negative Ce anomalies is not simply related to the amount of sediments introduced into the source.

Sr, Nd, and Pb isotopic compositions of these lavas may be explained by mixing a MORB mantle source with bulk marine sediments, as inferred from ODP Site 800 [Plank and Langmuir, 1998]. The model shown in Figure 12 indicates that < 6% of bulk sediment mixed with a MORB source can generate the Sr and Nd isotopic characteristics of most Alkalic Volcano Province lavas.

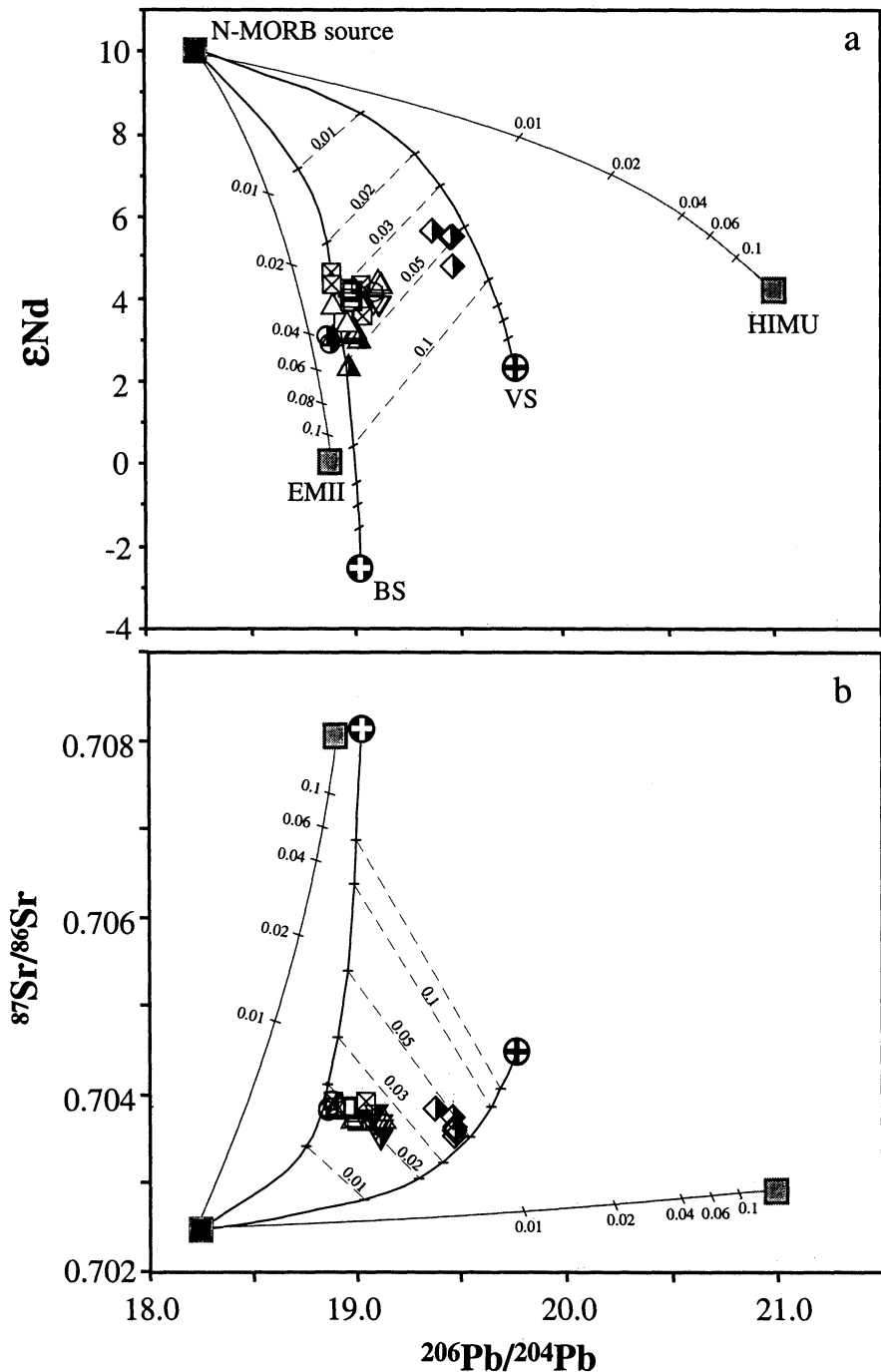


Figure 12. Models for mixing a MORB source with variable proportions of sediment or OIB-like mantle sources shown as (a) ϵNd vs. $^{206}Pb/^{204}Pb$ and (b) $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$. The lavas can be reproduced by mixing the MORB source with 1~6% local sediments. Higher $^{206}Pb/^{204}Pb$ for Iwo Jima samples might reflect a greater proportion of volcanoclastic sediment.

Pb isotopic compositions in Iwo Jima samples are significantly more radiogenic than predicted from mixing MORB and bulk sediment and require another component. The isotopic compositions in Iwo Jima could represent a mixture of a MORB mantle source and ~5% sediments shed from OIB seamounts, which are common on the Pacific seafloor east of the Mariana Trench. The northward increase in Pb isotope compositions may indicate progressively greater involvement of volcanoclastic sediments northward in the region of melt generation. This interpretation of Sr, Nd, and Pb isotopic models may also reconcile the discrepan-

cies that resulted from correlating Ce anomaly with isotopic compositions. The nonsystematic variations between Ce anomalies and isotopic data may not be caused by mixing either the calculated bulk sediment or volcanoclastic sediment solely with a MORB mantle source; mixing of different types of marine sediments may be necessary.

The quantity of sediment added to the mantle source must be very small. Marine sediments generally have high $\delta^{18}O$, for instance, ~22‰ for the bulk western Pacific sediments [Ito and Stern, 1986]. Recent oxygen isotope analyses of olivine and py-

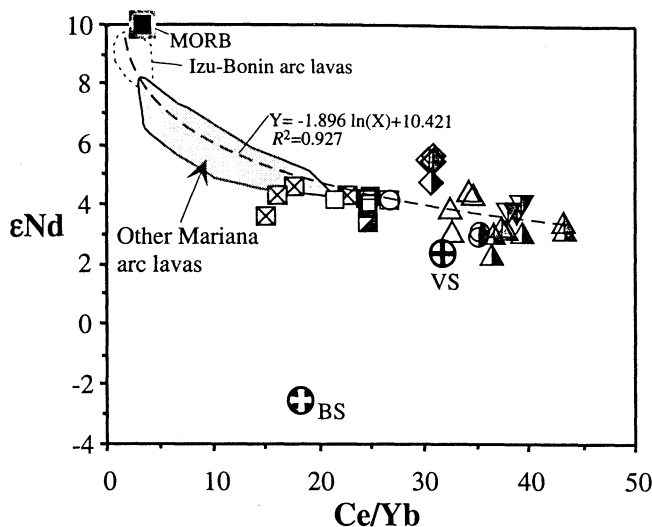


Figure 13. Plot of Ce/Yb versus ϵNd for Alkalic Volcano Province lavas. Also shown in the insets are fields for other Mariana [Elliott et al., 1997], Izu-Bonin arc [Taylor and Nesbitt, 1998], local sediments [Plank and Langmuir, 1998], and MORB [Sun and McDonough, 1989]. The R^2 of the regression curve for lavas from the Alkalic Volcano Province and the rest of the Izu-Bonin-Mariana arc is 0.93.

roxene phenocrysts [Eiler et al., 2000; E. Ito et al., unpublished data, 1999] in Alkalic Volcano Province lavas show mantle-like $\delta^{18}\text{O}$. The inferred parental melts in equilibrium with olivine and pyroxene phenocrysts of the lavas have $\delta^{18}\text{O}=5.4\text{--}6.3\text{‰}$ which are not significantly distinct from mantle $\delta^{18}\text{O}$ (5.71‰). Marine sediments thus may contribute less than 3% of the oxygen in the Alkalic Volcano Province. Resolving the debate may require additional data on oxygen isotopic compositions of volcanoclastic sediments. The latter may have oxygen isotopic compositions similar to the mantle, allowing a larger proportion of such sediment to mix into in the mantle source region of Alkalic Volcano Province lavas.

6. Conclusions

Major element evolution of the alkalic magma can be achieved by low-pressure fractional crystallization with subordinate magma mixing. Neither inherent source signature nor crystallization of common phases alone can account for the highly fractionated LIL/HFSE in the lavas. The fractionation model in this study yielded limited variations for these ratios although the degrees of the depletion correlate with SiO_2 . Crystallization of rutile and other minor Ti-rich phases during magmatic processes may be responsible for HFSE depletions, and that decoupling of LIL/HFSE in Alkalic Volcano Province lavas reflects source enrichments of incompatible elements and depletion in HFSE caused by fractionation of minor Ti-rich phases.

Although lavas from the Alkalic Volcano Province show elevated concentrations of fluid-mobile elements as well as other LIL, fluid-sensitive element ratios for these lavas show limited variations and are lower than that for ordinary Izu-Bonin-Mariana arc lavas. We conclude that the enriched compositions of the shoshonitic samples did not result from melting mantle that has been metasomatized by hydrous fluids.

Although isotopic compositions of Alkalic Volcano Province lavas are similar to OIB, an OIB-like mantle source for generat-

ing the alkalic magma is not preferred because the HFSE depletions and Ce anomalies in these lavas are unlikely to result from melting any OIB-type mantle source.

Geochemical and isotopic modeling permits the incorporation of a sedimentary component in the mantle source as long as it is not introduced as a hydrous fluid. Isotopic models suggest that up to 6% of the Sr, Nd, and Pb in the lavas can be obtained from marine sediments. Marine sediments may be also responsible for enrichments of other incompatible elements (e.g., Th, REE, HFSE). This sedimentary component does not necessarily have homogeneous compositions for the entire Alkalic Volcano Province; progressively higher ratios of volcanoclastic to pelagic sediments must be added to the mantle source northward along this portion of the arc to explain especially the Pb isotopic variations. The mantle-like oxygen isotopic composition restricts the contribution of subducted sediments to < 3%. Although many features of these shoshonites are consistent with a greater role for subducted sediments, such a role is not accompanied by an unequivocal and universal signal in both isotopic compositions and trace element abundances and fractionations. This signifies a large role for both equilibration of these melts with mantle and for fractionations developed during low-pressure fractionation.

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