

## Thematic Article

# Fukutoku-oka-no-ba Volcano: A new perspective on the Alkalic Volcano Province in the Izu–Bonin–Mariana arc

CHIH-HSIEN SUN,<sup>1</sup> ROBERT J. STERN,<sup>1</sup> TAKEYOSHI YOSHIDA<sup>2</sup> AND JUN-ICHI KIMURA<sup>3</sup>

<sup>1</sup>Center for Lithospheric Studies, University of Texas at Dallas, Box 830688, Richardson, Texas 75083–0688, USA,

<sup>2</sup>Institute of Mineralogy, Petrology & Economic Geology, Graduate School of Science, Tohoku University, Kawauchi, Aoba-Ku, Sendai, 980–77, Japan and <sup>3</sup>Regional Sciences Laboratory, Faculty of Education, Fukushima University, Asakawa Sugumichi 2, Fukushima City, 960–12, Japan

**Abstract** Pumice samples from Fukutoku-oka-no-ba in the Izu–Bonin–Mariana (IBM) arc were analysed for 40 trace elements and Sr, Nd, and Pb isotopic compositions. These samples are shoshonites (59.4–61.8 wt% SiO<sub>2</sub>), characterized by high contents of K<sub>2</sub>O (3.74–4.64 wt%), Ba (1274–1540 p.p.m.), Rb (91–105 p.p.m.), and light rare earth elements. The characteristics of alkali-element enrichment are similar to those of other parts of the Alkalic Volcano Province (AVP) in the northern Mariana and southernmost Volcano arcs. Sr (<sup>87</sup>Sr/<sup>86</sup>Sr = 0.7036–0.7038) and Pb isotopic compositions (<sup>206</sup>Pb/<sup>204</sup>Pb = 19.08–19.11, <sup>207</sup>Pb/<sup>204</sup>Pb = 15.62–15.63, <sup>208</sup>Pb/<sup>204</sup>Pb = 38.85–38.91) of Fukutoku-oka-no-ba pumice are relatively radiogenic, whereas Nd is unradiogenic (<sup>143</sup>Nd/<sup>144</sup>Nd = 0.51283–0.51286). Fukutoku-oka-no-ba is isotopically distinct from Iwo Jima and is similar to the Hiyoshi Volcanic Complex, suggesting that Fukutoku-oka-no-ba might have a magma source similar to that of the Hiyoshi volcanic complex. Plots of Pb and Nd isotopes for AVP lavas trend toward the fields of ocean island basalt (OIB) source and pelagic sediments, which are possible sources of AVP enrichments.

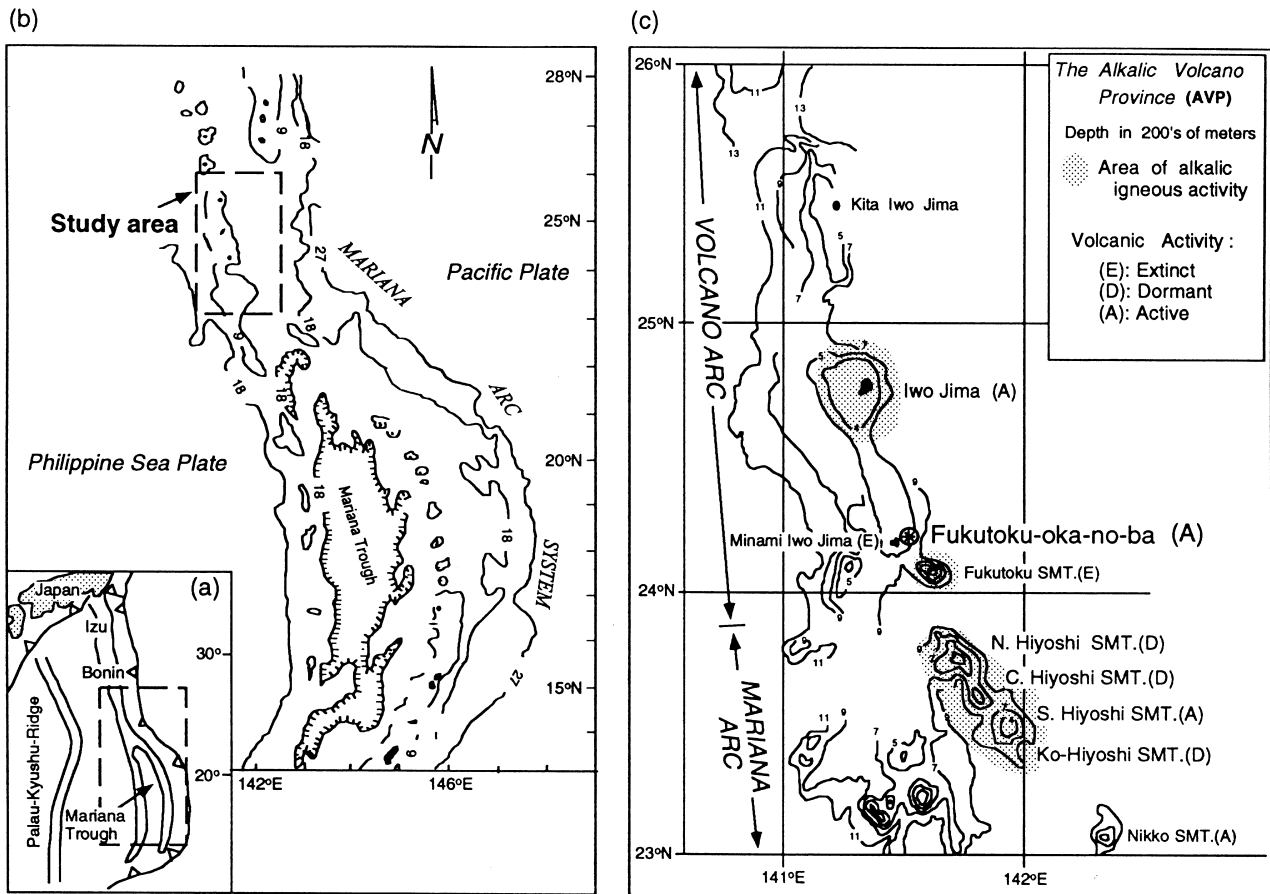
**Key words:** Fukutoku-oka-no-ba, igneous rocks, island arc, Izu–Bonin–Mariana arc, shoshonites.

## INTRODUCTION

The Volcano and Mariana arcs are the southern parts of the 3000-km-long Izu–Bonin–Mariana (IBM) arc system formed by the subduction of the Pacific plate beneath the Philippine Sea plate. Two different magma series, alkalic and calc-alkalic-tholeiitic, are recognized in the IBM arc system. Lavas from most of the IBM arc are calc-alkalic to tholeiitic (Stern *et al.* 1984; Meijer 1976; Stern 1979; Dixon & Batiza 1979; Meijer & Reagan 1981, 1983; Hole *et al.* 1984; Dixon & Stern 1983; Stern *et al.* 1988), while the northernmost Mariana and southern Volcano arcs are dominated by high-K calc-alkaline to shoshonitic lavas (Stern *et al.* 1984; Bloomer *et al.* 1989; Lin *et al.* 1989). The volcanoes of Iwo Jima, Fukutoku-oka-

no-ba, and the Hiyoshi volcanic complex comprise the Alkalic Volcanic Province (AVP).

Fukutoku-oka-no-ba Volcano is located at 24°17'N, 141°29'E, ~70 km south-southeast of Iwo Jima and just east of Minami Iwo Jima (Fig. 1). Five eruptions (1904–05, 1914, 1973, 1986 and 1992) and several other events producing discoloration of seawater have been recorded this century (Ossaka 1991; Furukawa 1995). Our understanding of this volcano is limited because it is submarine. One analysis of pumice from the 1914 eruption showed geochemical similarities to Iwo Jima lavas (Tsuya 1937). Samples studied here were collected from pumice rafts formed by the 1986 and 1992 eruptions. Petrography, mineral chemistry, major elements and 13 trace elements analysed by photo-activation technique are reported elsewhere (Yoshida *et al.* 1987; Kato 1988; Ossaka 1991; Furukawa 1995). Yoshida *et al.* (1987) show that these pumices have



**Fig. 1** Locator map. (a) Izu–Bonin–Mariana (IBM) arc system. Dashed box shows the location of (b). (b) Mariana and Volcano arcs (modified after Chase *et al.* 1968). The Alkalic Volcanic Province (AVP) lies in the northernmost Mariana and southern Volcano arcs. The study area is shown in the dashed box. (c) Location of AVP volcanoes. Only Kita Iwo Jima, Iwo Jima, and Minami Iwo Jima are above sea-level. SMT, seamount. Isobaths in hundreds of fms.

clear island arc signatures with a negative Nb anomaly on mid-ocean ridge basalt (MORB)-normalized element abundance diagrams. In this contribution, analyses of Nd-, Sr-, and Pb- isotopic ratios and of 40 trace elements are presented and interpreted to reveal petrogenetic relationships between Fukutoku-oka-no-ba and lavas from other IBM arc volcanoes.

## METHODS

Pumice samples in the present study are vesicular and contain mafic inclusions. The host pumices and their inclusions have similar mineral assemblages of clinopyroxene, olivine, and plagioclase  $\pm$  magnetite. Even though pumice and inclusions are suggested to be derived from the same magma source (Kato 1988), careful separation was done to reduce the possible contamination from inclusions.

Major and trace elements were analysed in the Regional Sciences Laboratory, Fukushima University, Japan using X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS), respectively. Analytical procedures are reported by Kimura *et al.* (1995) and Kimura and Yamada (1996). Isotopic compositions of Sr, Nd, and Pb were determined on the Finnigan MAT261 multicollector mass spectrometer at the University of Texas at Dallas (UTD), USA. Since these samples had drifted in the ocean for periods from a few days to 9 months before being collected, they may have been contaminated by interaction with seawater and so were analysed before and after leaching with 6 mol/L HCl for 2 h. The Sr data are normalized to  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70800$  for E&A SrCO<sub>3</sub> standard. Seven analyses of the E&A SrCO<sub>3</sub> during the present study yielded a mean  $^{87}\text{Sr}/^{86}\text{Sr}$  value of  $0.708014 \pm 0.000035$  (total range). The  $^{143}\text{Nd}/^{144}\text{Nd}$  value was normalized to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$ . The mean  $^{143}\text{Nd}/^{144}\text{Nd}$

value was  $0.511856 \pm 0.000018$  for five measurements of the UCSD Nd standard.  $\epsilon_{\text{Nd}}$  was calculated by using the data of Pier *et al.* (1989) for the UCSD Nd standard to compute the bulk earth  $^{143}\text{Nd}/^{144}\text{Nd}$  value appropriate for the UTD lab. Pb was purified by the single-bead technique after a conventional anion exchange technique (Manton 1988). Pb isotopes were analysed at 1350 °C and the ratios were corrected for a 0.15%/a.m.u. thermal fractionation. Nine analyses of NBS-981 gave mean values of  $^{206}\text{Pb}/^{204}\text{Pb} = 16.948 \pm 0.008$  (total range),  $^{207}\text{Pb}/^{204}\text{Pb} = 15.507 \pm 0.015$ , and  $^{208}\text{Pb}/^{204}\text{Pb} = 36.766 \pm 0.042$ .

## RESULTS

Chemical data for six Fukutoku-oka-no-ba pumices are listed in Tables 1 and 2. No significant differences are observed between the products of the two successive eruptions, except that pumice from the 1992 eruption (FO92-1) has higher MgO, CaO, Cr, and Ni, but lower V and Pb contents than 1986 pumices (FO86-1-5). It is believed that the chemical differences between the two eruptions may be due to a higher proportion of mafic inclusions in FO92-1.

Lavas in the AVP have high concentrations of large ion lithophile (LIL) and light rare earth elements (LREE). Fukutoku-oka-no-ba pumices are the most siliceous of all AVP lavas, and have high K<sub>2</sub>O contents (3.74–4.64 wt%) and high K<sub>2</sub>O/Na<sub>2</sub>O values (0.79–0.90). These samples are called shoshonites on the basis of the K<sub>2</sub>O–SiO<sub>2</sub> diagram (Fig. 2) but would be ‘trachytes’ by the

classification scheme of Irvine and Baragar (1971). The pumice samples are chemically similar to other AVP lavas and are even more enriched in elements such as Rb (91–105 p.p.m.), Ba (1274–1540 p.p.m.), Th (17.2–22.5 p.p.m.), U, Nb, and Pb than are other AVP rocks. A Nb–Ta ‘trough’, characteristic of arc lavas, is clearly visible on an element compatibility diagram (Fig. 3a).

Incompatible element ratios K/Rb, K/Ba, and Ba/La reflect the composition of the magma source. The K/Rb, K/Ba, and Ba/La values in Fukutoku-oka-no-ba pumices are 341–374, 21–28, and 17–21, respectively, indistinguishable from the values ( $406 \pm 84$ ,  $28 \pm 7$ , and  $19 \pm 3$ ; Lin *et al.* 1989) of other AVP lavas but lower than those of calc-alkalic–tholeiitic series lavas (e.g. values are  $469 \pm 84$ ,  $31 \pm 9$ , and  $37 \pm 13$  for the Central Island Province; Lin *et al.* 1989). The REE patterns of the pumices are shown in Fig. 3(b). These rocks are strongly LREE enriched ((La/Yb)<sub>n</sub> = 13.4–15.5), with negative europium anomalies (Eu/Eu\* = 0.81–0.86). Low-pressure fractional crystallization involving plagioclase may have caused the negative europium anomalies. The flat heavy rare earth element (HREE) patterns observed for the samples are common for IBM arc lavas and indicate that mantle melting involving residual garnet is not important for the evolution of these magmas.

The Sr, Nd, and Pb isotopic compositions of Fukutoku-oka-no-ba pumices are listed in Table 3. The Sr isotopic data show significant lowering of  $^{87}\text{Sr}/^{86}\text{Sr}$  following 6 mol/L HCl leaching. For example, the  $^{87}\text{Sr}/^{86}\text{Sr}$  values in FO86-4 for

**Table 1** Major element chemical analyses from Fukutoku-oka-no-ba Volcano

Sample no.	FO86-1*	FO86-2*	FO86-3*	FO86-4*	FO86-5*	FO92-1†
SiO <sub>2</sub> (wt%)	61.22	61.15	59.71	60.52	61.82	59.42
TiO <sub>2</sub>	0.55	0.57	0.52	0.54	0.55	0.60
Al <sub>2</sub> O <sub>3</sub>	16.67	16.59	16.09	16.53	16.29	14.83
Fe <sub>2</sub> O <sub>3</sub>	1.87	2.24	1.50	1.68	1.73	5.67‡
FeO	2.80	2.78	2.99	2.98	2.91	—
MnO	0.17	0.18	0.17	0.17	0.17	0.16
MgO	2.16	1.96	2.19	1.99	1.48	3.47
CaO	3.34	3.38	3.57	3.70	3.45	5.25
Na <sub>2</sub> O	5.36	5.21	5.97	5.24	5.12	4.73
K <sub>2</sub> O	4.44	4.33	4.31	4.24	4.64	3.74
H <sub>2</sub> O+	1.14	1.28	2.56	2.12	1.53	—
H <sub>2</sub> O–	0.10	0.13	0.25	0.11	0.14	—
P <sub>2</sub> O <sub>5</sub>	0.19	0.19	0.17	0.19	0.19	0.21
Total	100.01	99.99	100.00	100.01	100.02	98.04

\*Yoshida *et al.* (1987); † analysed in the present study.

‡Total Fe calculated as Fe<sub>2</sub>O<sub>3</sub>.

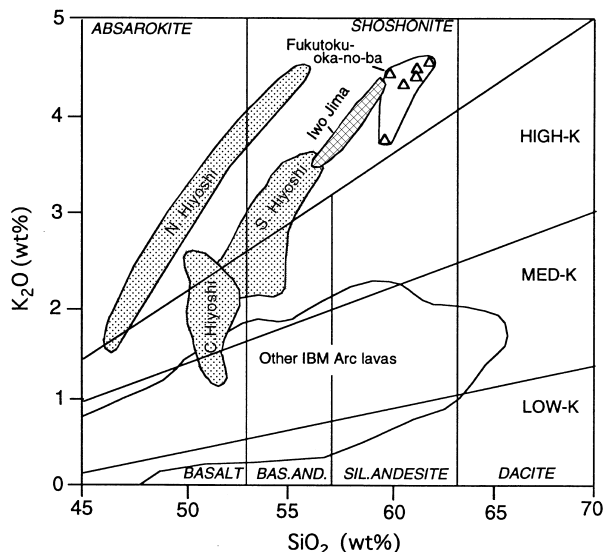
**Table 2** Trace element analyses of Fukutoku-oka-no-ba pumices

Sample no.	FO86-1	FO86-2	FO86-3	FO86-4	FO86-5	FO92-1
Rb (ppm)	105	98.7	99.9	94.3	103	91.1
Sr	448	427	421	403	421	566
Ba	1540	1307	1274	1405	1418	1472
Zr	274	243	246	236	246	254
Y	33.4	32.4	31.4	30.7	32.4	29.6
La	73.1	74.1	71.8	67.4	76.0	70.5
Ce	140	145	137	126	147	130
Pr	15.8	16.6	15.8	14.9	17.1	14.2
Nd	56.7	59.1	55.2	51.8	58.5	50.9
Sm	9.6	10.1	9.3	9.1	10.1	8.6
Eu	2.2	2.4	2.2	2.1	2.3	2.1
Gd	6.6	7.4	6.6	6.6	7.2	7.3
Tb	1.0	1.1	1.0	1.0	1.1	1.0
Dy	6.0	5.9	5.8	5.2	6.0	5.1
Ho	1.2	1.2	1.2	1.1	1.3	1.0
Er	3.2	3.4	3.2	3.0	3.5	3.1
Tm	0.5	0.5	0.6	0.5	0.6	0.5
Yb	3.6	3.8	3.6	3.2	3.8	3.1
Lu	0.6	0.6	0.6	0.5	0.6	0.5
Hf	6.8	6.7	6.7	5.8	7.2	5.7
Nb	12.3	11.7	11.6	11.2	12.2	9.4
Ta	0.6	0.6	0.6	0.5	0.6	0.5
Pb	17.4	21.9	17.5	15.5	19.4	6.5
Li	22.4	20.8	21.4	19.0	21.6	18.6
Be	2.8	2.8	2.8	2.5	3.0	2.3
Sc	11.6	14.7	13.8	13.3	10.8	22.0
V	73.0	80.0	67.4	74.8	76.5	22.9
Cr	32.2	23.0	31.1	36.5	18.5	188
Co	10.5	10.3	10.4	9.8	8.5	14.1
Ni	10.3	7.2	11.1	9.2	6.5	23.2
Zn	—	—	82	—	—	—
Ga	20.4	20.3	19.5	18.6	20.0	1.1
Mo	5.0	4.2	4.3	4.1	4.8	3.9
Cd	0.7	0.5	0.4	0.6	0.6	0.6
Sn	1.6	1.7	1.5	1.5	1.9	1.4
Sb	0.3	0.25	0.23	0.23	0.3	0.2
Cs	2.2	2.2	2.2	2.4	2.2	1.7
W	0.9	1.0	1.0	0.9	1.1	0.9
Th	20.8	20.9	20.7	17.6	22.5	17.2
U	5.9	6.1	5.9	5.0	6.5	4.9
K/Rb	352	354	358	373	374	341
K/Ba	24	28	28	25	27	21
Ba/Rb	15	13	13	15	14	16
Cs/Rb	0.02	0.02	0.02	0.03	0.02	0.02
Ba/La	21.1	17.6	17.7	20.9	18.7	20.9
Sr/Nd	7.9	7.2	7.6	7.8	7.2	11.1
Y/Zr	0.12	0.13	0.13	0.13	0.13	0.12
Pb/Ce	0.02	0.02	0.02	0.03	0.02	0.02
Th/U	3.53	3.43	3.52	3.53	3.44	3.50
Ce/Ce*	0.97	0.97	0.95	0.93	0.96	0.98
Eu/Eu*	0.86	0.86	0.86	0.81	0.83	0.81
(La/Yb) <sub>N</sub>	13.6	13.4	13.4	14.1	13.7	15.5

$$\text{Ce/Ce}^* = \text{Ce}_N / [(\text{La}_N) \cdot (\text{Pr}_N)]^{1/2}; \quad \text{Eu/Eu}^* = \text{Eu}_N / [(\text{Sm}_N) \cdot (\text{Gd}_N)]^{1/2}.$$

unleached and leached samples are 0.70453 and 0.70372, respectively. Examination of the pumice revealed small gastropods occupying many of its voids. Acid leaching removes shell materials which contain Sr with the isotopic composition of seawater, and thus reduces  $^{87}\text{Sr}/^{86}\text{Sr}$  values in

leached samples to magmatic values. The Nd isotopic compositions are similar for leached and unleached pumice samples. The  $^{143}\text{Nd}/^{144}\text{Nd}$  values range from 0.51283 to 0.51286, corresponding to  $\epsilon\text{Nd}$  of +3.7 to +4.3. Pb isotopic variations between leached and unleached sam-



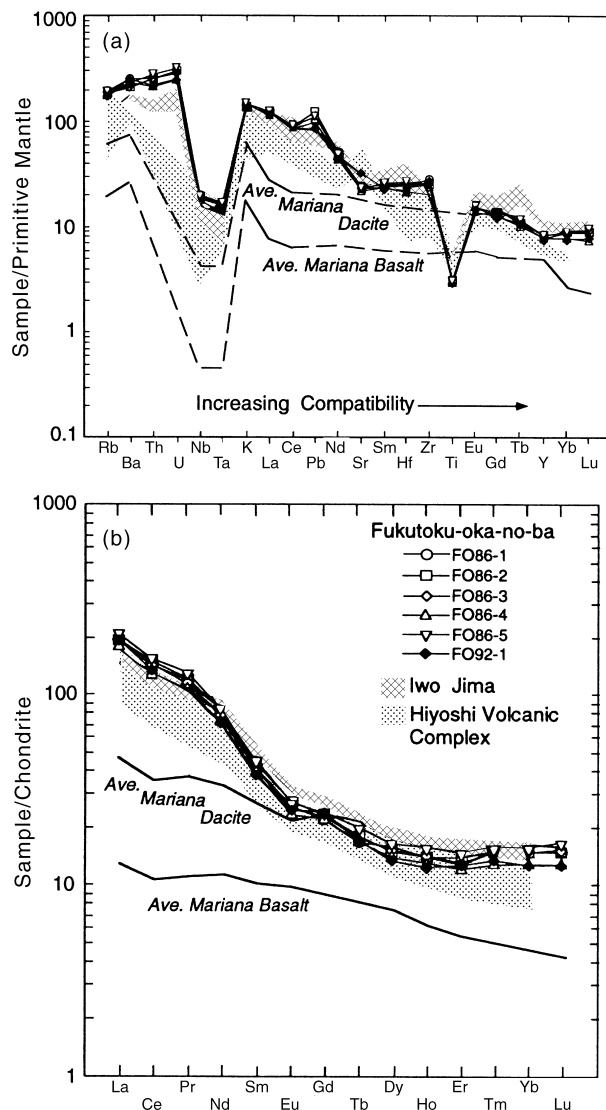
**Fig. 2** Potassium-silica classification diagram (Gill 1981). Reference data for Fukutoku-oka-no-ba are taken from Yoshida *et al.* (1987) and Furukawa (1995). Data for Iwo Jima, Hiyoshi volcanic complex, and other Izu-Bonin-Mariana arc lavas are taken from Bloomer *et al.* (1989) and Lin *et al.* (1989).

ples are less than the deviation due to thermal fractionation (0.15%/a.m.u.). Leaching is not expected to alter the isotopic compositions of Nd or Pb because of the low Nd ( $<10^{-2}$  p.p.b.) and Pb (0.04 p.p.b.; Walton-Smith 1974) concentrations of seawater, with which the shells had equilibrated.

A plot of Sr versus Nd isotopic compositions demonstrates that leached Fukutoku-oka-no-ba samples overlap with the field of Hiyoshi volcanic complex lavas and are distinct from Iwo Jima lavas (Fig. 4). Pb isotopic compositions of Fukutoku-oka-no-ba pumices are plotted on Fig. 5 and are compared with those of the other IBM arc lavas. These pumices have  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  values slightly higher than those from the Hiyoshi volcanic complex but are less radiogenic than Iwo Jima, which has the highest values ( $^{206}\text{Pb}/^{204}\text{Pb} = 19.4$  and  $^{208}\text{Pb}/^{204}\text{Pb} = 39.3$ ; Morris *et al.* unpubl. data) in the IBM arc system.

## DISCUSSION

Recent efforts to understand the mineralogical, geochemical, and isotopic compositions of the IBM arc system have yielded important petrogenetic insights (Lin *et al.* 1989, 1990; Bloomer *et al.* 1989; Stern *et al.* 1993; Meen *et al.* 1998). The origin of LIL and LREE enrichments is one of the most important aspects that need to be understood for this arc system. It was proposed by Lin *et al.*



**Fig. 3** Element compatibility diagram, with sequences and normalizing abundances taken from Hofmann (1988). Note the similar patterns for all Alkalic Volcanic Province (AVP) lavas, in which more mafic Hiyoshi volcanic complex samples have lower concentrations of incompatible elements. (b) Rare earth element pattern. Data for Iwo Jima are taken from R. N. Thompson (unpubl. data), data for Hiyoshi Volcanic Complex are from D. Peete (unpubl. data), and data for average Mariana basalt and dacite are from Woodhead (1988).

(1989, 1990) that the distinctive geochemistry and isotopic compositions in the IBM arc system require mixing between depleted and enriched magma/mantle sources. The data presented here allow us to refine the mixing models.

## MIXING BETWEEN MAGMA SOURCES

Mixing of sources or melts is implied by the isotopic composition of Fukutoku-oka-no-ba pumice, which is intermediate between Iwo Jima and Hiyoshi volcanic complex lavas. A binary

**Table 3** Sr, Nd, and Pb isotopic compositions of pumices from Fukutoku-oka-no-ba

Sample	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\Delta 207/204\text{Pb}$	$\Delta 208/204\text{Pb}$
F086-1								
Unleached	0.70367	0.51286	+4.3	19.113	15.625	38.887	6.2	15.2
Leached	0.70355	0.51284	+3.9	19.109	15.614	38.865	5.2	13.5
F086-2								
Unleached	0.70372	0.51285	+4.1	19.075	15.624	38.835	6.5	14.6
Leached	0.70364	0.51284	+3.9	19.119	15.627	38.894	6.4	15.2
F086-3								
Unleached	0.70434	0.51285	+4.1	19.099	15.619	38.873	5.8	15.5
Leached	0.70370	0.51284	+3.9	19.109	15.616	38.866	5.4	13.6
F086-4								
Unleached	0.70385	0.51283	+3.7	19.129	15.649	38.963	8.5	22.0
Leached	0.70366	0.51284	+3.9	19.080	15.626	38.852	6.7	15.7
F086-5								
Unleached	0.70453	0.51286	+4.3	19.095	15.620	38.862	5.9	14.9
Leached	0.70372	0.51285	+4.1	19.079	15.619	38.854	6.0	16.0
F092-1								
Unleached	0.70379	—	—	19.119	15.636	38.931	7.3	18.9
Leached	0.70381	—	—	19.115	15.633	38.912	7.0	17.5

Leached samples were treated with warm 6 mol/L HCl for 2 h prior to dissolution.

Values of Sr isotopes are adjusted for E&A  $\text{SrCO}_3 = 0.70800$ . Mean  $^{87}\text{Sr}/^{86}\text{Sr}$  for seven analyses of E&A  $\text{SrCO}_3 = 0.708014 \pm 0.00035$  (total range).

Values for  $\epsilon\text{Nd}$  are calculated using Bulk Earth and  $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{Bulk Earth}} = 0.512636$ .

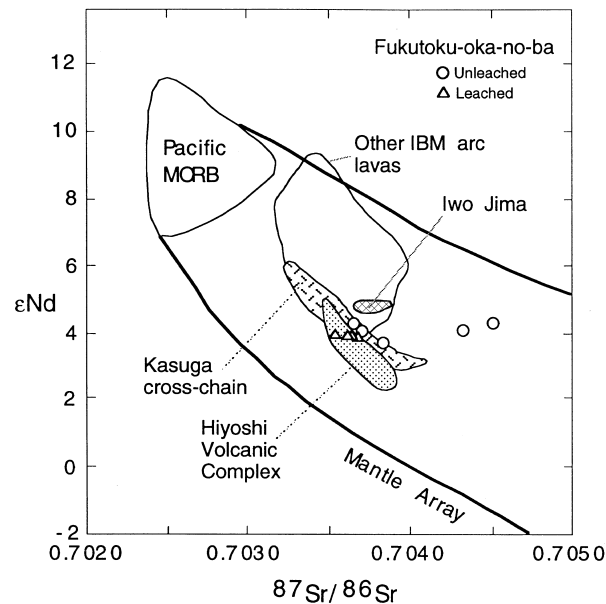
Nine analyses of NBS-981 gave mean  $^{206}\text{Pb}/^{204}\text{Pb} = 16.948 \pm 0.008$  (total range),  $^{207}\text{Pb}/^{204}\text{Pb} = 15.507 \pm 0.015$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 36.766 \pm 0.042$ .

magma-mixing model, based on Sr, Nd, and Pb isotopic data, is proposed in the present study. Model isotopic compositions of mixing end-

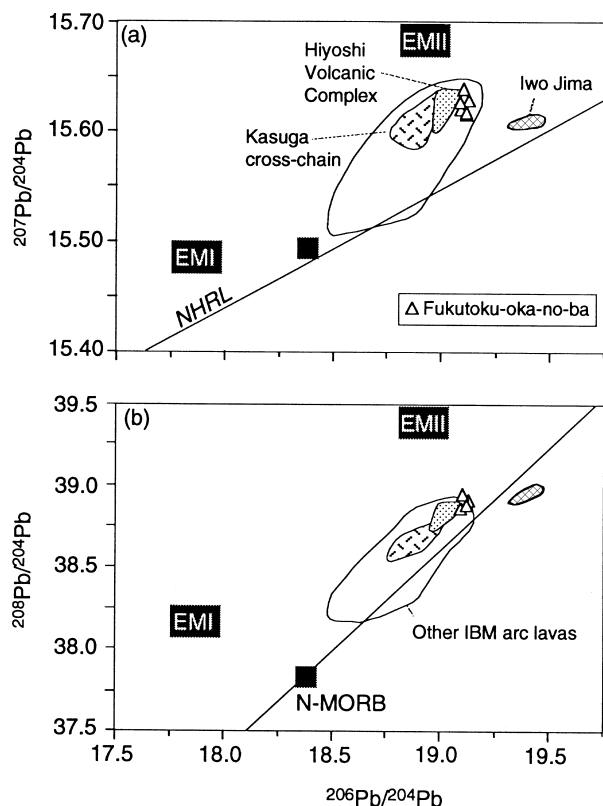
members A and B in Table 4 are taken from mean compositions of Hiyoshi volcanic complex and Iwo Jima lavas, respectively (after Lin *et al.* 1990; Morris *et al.* unpubl. data). End-member B has more radiogenic Sr ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.70374$ ), Nd ( $^{143}\text{Nd}/^{144}\text{Nd} = 0.51290$ ) and Pb ( $^{206}\text{Pb}/^{204}\text{Pb} = 19.407$ ,  $^{208}\text{Pb}/^{204}\text{Pb} = 39.295$ ) than end-member A. Calculations indicate that Fukutoku-oka-no-ba lavas have Pb and Nd isotopic characteristics which consist of  $\sim 80\%$  end-member A and  $20\%$  end-member B magma sources (Fig. 6). The  $^{87}\text{Sr}/^{86}\text{Sr}$  value for end-member A needs to be near 0.70367. The value is slightly lower than the average Hiyoshi volcanic complex (0.70377), but still within the range (0.70350–0.70392; Lin *et al.* 1990).

#### ORIGIN OF ENRICHED MANTLE SOURCE

Another important objective for studying AVP lavas is to recognize the origin of the enriched mantle. Lavas in the IBM arc system are suggested to be generated by similar degrees of partial melting (Bloomer *et al.* 1989). Therefore, source heterogeneity instead of magma processes (e.g. partial melting and crystal fractionation) may be the major factor controlling relative enrichments in LIL and LREE for IBM arc lavas. The observation led Lin *et al.* (1989) to construct



**Fig. 4**  $\epsilon\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$  variation diagram. Data for the fields of Iwo Jima and Hiyoshi Volcanic Complex are from Lin *et al.* (1989). Data for Kasuga cross-chain are from Stern *et al.* (1993). The other Izu–Bonin–Mariana (IBM) arc field is compiled from various sources (Dixon & Stern 1983; Stern & Bibee 1984; DePaolo & Wasserburg 1977; Woodhead & Fraser 1985; Ito & Stern 1986; Woodhead 1989; Lin *et al.* 1990).



**Fig. 5** Pb isotopic compositions of leached Fukutoku-oka-no-ba and shoshonitic series compared to the field for other Izu-Bonin-Mariana (IBM) arc volcanoes. Data for Iwo Jima, Hiyoshi Volcanic Complex, and other IBM arc lavas are taken from Meijer (1976), Woodhead *et al.* (1987), Stern *et al.* (1993), and Morris *et al.* (unpubl. data). Mantle components EM I, EM II, and normal-mid-ocean ridge basalt (N-MORB) are from Hart (1988). (a)  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ . (b)  $^{208}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ .

a two-component mixing model for the petrogenesis of the Mariana-Volcano arc magmas based on incompatible element ratios, and Sr and Nd isotopic characteristics. The model of Lin *et al.* (1989) is shown in Fig. 7, with Fukutoku-oka-no-ba data included. End-member 1 is de-

**Table 4** Inferred isotopic compositions of mixing end-members A and B

	End-member A	End-member B	Fukutoku- oka-no-ba
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70367	0.70374	0.70368
$^{143}\text{Nd}/^{144}\text{Nd}$	0.51283	0.51290	0.51284
$^{206}\text{Pb}/^{204}\text{Pb}$	19.003	19.407	19.115
$^{207}\text{Pb}/^{204}\text{Pb}$	15.621	15.610	15.623
$^{208}\text{Pb}/^{204}\text{Pb}$	38.825	39.295	38.874

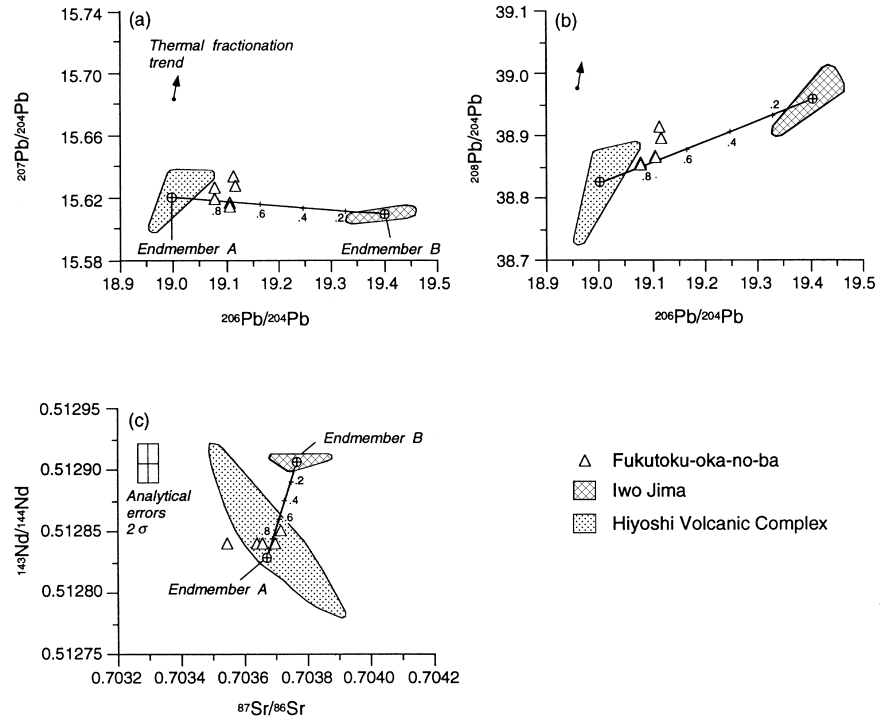
The isotopic compositions of end-members A and B are the average values of Hiyoshi Volcanic Complex and Iwo Jima lavas, respectively. Reference data for Sr and Nd are taken from Lin *et al.* (1990); data for Pb are from Morris *et al.* (unpubl. data).

pleted mantle (or equivalent melt) which has been metasomatized by Ba-rich, REE-poor fluids. End-member 2 represents a LIL- and LREE-enriched mantle (or equivalent melt). End-member 1 has  $\text{Ba}/\text{La} = \sim 80$  and  $(\text{La}/\text{Yb})_n = \sim 15$ , while end-member 2 has low  $\text{Ba}/\text{La}$  ( $\sim 15$ ) and high  $(\text{La}/\text{Yb})_n$  ( $\sim 20$ ). Fukutoku-oka-no-ba and the other AVP data fit the mixing curve in a  $\text{Ba}/\text{La}$  versus  $(\text{La}/\text{Yb})_n$  plot and approach the enriched end-member 2.

What is the origin of end-member 2? In an attempt to understand the origin of the observed enrichments, our binary magma-mixing model is extended to address the issue. Isotopic compositions provide a clue and reveal that the enriched mantle sources for the Hiyoshi volcanic complex and Iwo Jima are distinct. The significant trends toward EM II and pelagic sediments in  $\Delta^{208}/^{204}\text{Pb}$  versus  $\Delta^{207}/^{204}\text{Pb}$  (Fig. 8a) and  $^{206}\text{Pb}/^{204}\text{Pb}$  versus  $^{143}\text{Nd}/^{144}\text{Nd}$  (Fig. 8b) diagrams indicate that either an EM II mantle source or pelagic sediments are responsible for the enrichment in Hiyoshi volcanic complex magmas. Fukutoku-oka-no-ba lavas are isotopically very similar to those of the Hiyoshi volcanic complex. Iwo Jima lavas, in contrast, are characterized by higher  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  values and manifest a tendency towards a HIMU source. The HIMU characteristic of Iwo Jima coincides with the ocean island basalt (OIB)-like enriched mantle originally postulated by Lin *et al.* (1989).

Subducted pelagic sediment has long been thought to be important for LIL- and LREE-enrichments observed in arc volcanics. Woodhead *et al.* (1987) reported that Mariana arc lavas have higher  $\delta^{34}\text{S}$  (+2.0–+20.7‰) relative to oceanic basalts (–0.5–+0.1‰), and trend toward marine sediments, which have an average  $\delta^{34}\text{S}$  value of +20‰. Other studies (Hole *et al.* 1984; Woodhead 1989; Elliott *et al.* 1997) reveal that small amounts of recycled sediments are required to develop slightly negative Ce anomalies in IBM arc lavas.

Highly incompatible elements and elemental ratios are used to recognize the role of subducted sediment component in arc volcanics. Pelagic sediments are enriched in Pb (25–44 p.p.m.; Chow & Patterson 1962), while the mantle has Pb contents of  $\sim 0.2$  p.p.m. (Vidal *et al.* 1989). Assuming that mixing has happened between a pelagic sediment component and a mantle source, one can expect that a small amount of recycling pelagic sediments may bring the Pb concentra-

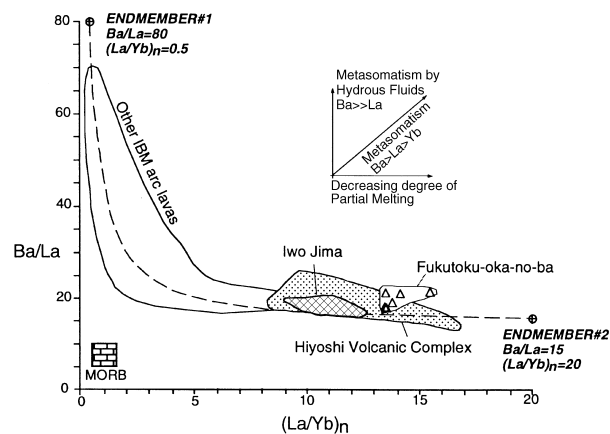


**Fig. 6** Mixing model for Sr-, Nd-, and Pb isotopic compositions of Alkalic Volcanic Province (AVP) lavas. The solid lines indicate the mixing trajectories between end-member A (Hiyoshi Volcanic Complex) and end-member B (Iwo Jima). The numbers shown on the mixing curves indicate the fraction of end-member A involved in the hybrid magma source. (a)  $^{207}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ . (b)  $^{208}\text{Pb}/^{204}\text{Pb}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ . (c)  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$ . Reference data for Pb are taken from Morris *et al.* (unpubl. data); and those for Sr and Nd are from Lin *et al.* (1990).

tion of the resulting magma up to the order of a few p.p.m. The Pb content of Fukutoku-oka-no-ba lavas (6.5–22 p.p.m.) then may reveal evidence of sediments.

Sediments have significantly higher Pb/Ce (~0.4; Ben Othman *et al.* 1989) and Cs/Rb (0.02–0.1; Hofmann & White 1983) ratios than the suboceanic mantle. The estimated Pb/Ce and Cs/Rb values in the suboceanic mantle are 0.04 (Sun

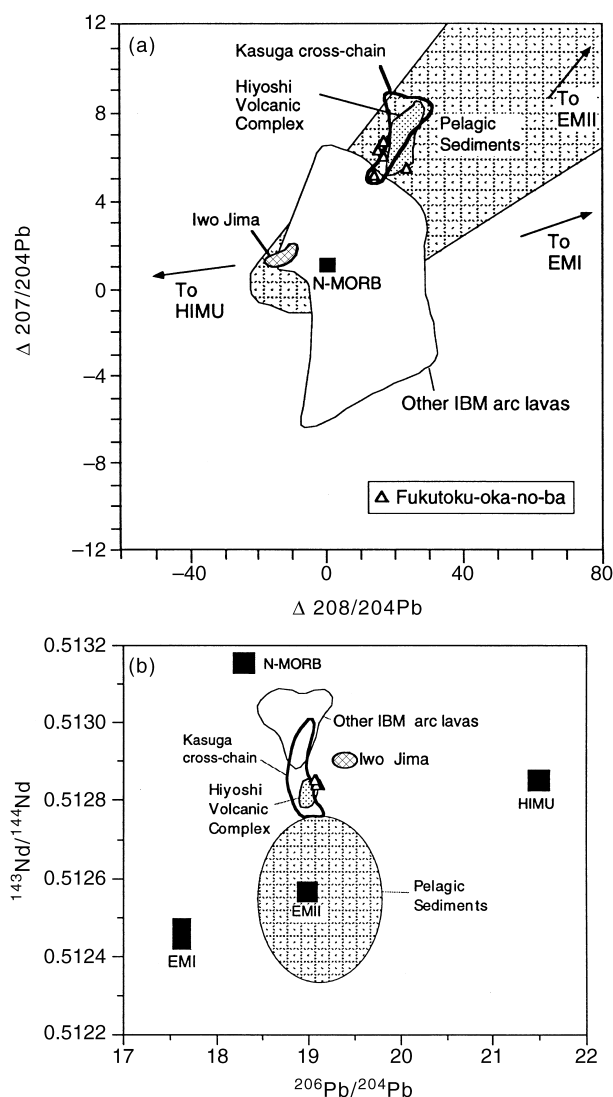
& McDonough 1989; Ben Othman *et al.* 1989) and 0.013 (Hofmann & White 1983), respectively. The suboceanic mantle alone is unlikely to evolve the moderately high Pb/Ce and Cs/Rb lava observed in Fukutoku-oka-no-ba pumice (Pb/Ce = 0.05–0.15, Cs/Rb = ~0.02). The involvement of subducted sediments in the source region may be responsible. However, the limited variation of Pb/Ce and Cs/Rb values in Fukutoku-oka-no-ba pumices suggests that the involvement of pelagic sediments is limited. The possibility of a subducted sediment component in Fukutoku-oka-no-ba pumices also allows the possibility that Hiyoshi volcanic complex magmas contain a sediment component based on our early binary magma-mixing model. Further data will help to resolve the assumption.



**Fig. 7** Ba/La vs  $(\text{La}/\text{Yb})_n$  plot (after Lin *et al.* 1989). Mariana and Alkalic Volcanic Province (AVP) lavas approximate a mixing trajectory between a metasomatized mid-ocean ridge basalt (MORB) source or melt (end-member 1) and an enriched end-member with composition appropriate to ocean island basalt (OIB)-like mantle or melt (end-member 2). The AVP lavas have more of the latter source relative to other Mariana arc lavas. Inset shows different possible trajectories for modification of mantle source region.

## CONCLUSIONS

Fukutoku-oka-no-ba pumices provide a new perspective on the origin of the alkalic province in the IBM arc system. Fukutoku-oka-no-ba pumices are highly enriched in LIL and LREE. Their alkali contents and element ratios such as K/Rb, K/Ba, and Sr/Nd are similar to other AVP volcanoes. The most important observation from the present study is the recognition of intermediate isotopic characteristics of Fukutoku-oka-



**Fig. 8** Plots of Nd and Pb isotopic compositions for Izu-Bonin-Mariana (IBM) arc lavas compared with the major mantle sources. (a)  $\Delta 208/204\text{Pb}$  vs  $\Delta 207/204\text{Pb}$ . (b)  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $^{206}\text{Pb}/^{204}\text{Pb}$ . Data for Iwo Jima, Hiyoshi Volcanic Complex, and other IBM arc lavas are taken from Meijer (1976), Woodhead (1989), Lin *et al.* (1990), and Morris *et al.* (unpubl. data); data for the Kasuga cross-chain are from Stern *et al.* (1993); data for pelagic sediments are from Woodhead and Fraser (1985) and Lin (1992). Mantle components HIMU, EMI, EMII, and N-MORB are from Hart (1988).

no-ba pumices between Hiyoshi volcanic complex and Iwo Jima lavas. Major and certain elements (e.g. HFSE and LREE) indicate that Fukutoku-oka-no-ba lavas resemble Iwo Jima shoshonites, while isotopic data for Fukutoku-oka-no-ba lavas are closer to Hiyoshi volcanic complex lavas. A hybrid magma source composed of 80% Hiyoshi volcanic complex and 20% Iwo Jima magma sources explains the Fukutoku-oka-no-ba isotopic data.

Judging from Nd and Pb isotopic compositions, we may reconsider the possible enriched mantle

sources for each edifice in the AVP. The Nd and Pb isotopic compositions of Hiyoshi Volcanic Complex and Fukutoku-oka-no-ba lavas are displaced toward the fields of EMII mantle source and pelagic sediments. However, neither EMII nor pelagic sediments can be clearly discriminated. On the other hand, Iwo Jima shoshonites may be derived from mantle sources with HIMU affinities.

## ACKNOWLEDGEMENTS

We thank H. Furukawa for providing 1992 pumice sample (FO92-1) and appreciate the critical comments of referees.

## REFERENCES

- BEN OTHMAN D., WHITE W. M. & PATCHETT J. 1989. The geochemistry of marine sediments, island arc magma genesis, and crust-mantle recycling. *Earth and Planetary Science Letters* **94**, 1-21.
- BLOOMER S. H., STERN R. J., FISK E. & GESCHWIND C. H. 1989. Shoshonitic volcanism in the Mariana Arc, 1. Mineralogic and major and trace element characteristics. *Journal of Geophysical Research* **94**, 4469-96.
- CHASE T. E., MENARD H. W. & MAMMERICKX J. 1968. Bathymetry of the North Pacific, Chart 6. *Institute for Marine Research Technical Report Series TR-11*.
- CHOW T. J. & PATTERSON C. C. 1962. On the occurrence and significance of lead isotopes in pelagic sediments. *Geochimica et Cosmochimica Acta* **26**, 263-308.
- DEPAOLO D. J. & WASSERBURG G. J. 1977. The sources of island arcs as indicated by Nd and Sr isotopic studies. *Geophysical Research Letters* **4**, 465-68.
- DIXON T. H. & BATIZA R. 1979. Petrology and chemistry of recent lavas in the Northern Marianas: Implications for the origin of island arc basalts. *Contributions to Mineralogy and Petrology* **70**, 167-81.
- DIXON T. H. & STERN R. J. 1983. Petrology, chemistry and isotopic composition of submarine volcanoes in the southern Mariana arc. *Geological Society of America Bulletin* **94**, 1159-72.
- ELLIOTT T., PLANK T., ZINDLER A., WHITE W. & BOURDON B. 1997. Element transport from slab to volcanic front at the Mariana arc. *Journal of Geophysical Research* **102**, 14991-15019.
- FURUKAWA H. 1995. Annual report of world volcanic eruptions in 1992, Fukutoku-oka-no-ba. *Bulletin of Volcanology* **57**, 81-2.

- GILL J. 1981. *Orogenic Andesites and Plate Tectonics*. Springer-Verlag, Berlin.
- HART S. R. 1988. Heterogeneous mantle domains: Signatures, genesis and mixing chronologies. *Earth and Planetary Science Letters* **90**, 273–96.
- HOFMANN A. W. & WHITE M. W. 1983. Ba, Rb, and Cs in the Earth's mantle. *Zeitschrift für Naturforschung* **38**, 256–66.
- HOFMANN A. W. 1988. Chemical differentiation of the Earth: The relationship between mantle, continental crust, and oceanic crust. *Earth and Planetary Science Letters* **90**, 297–314.
- HOLE H. J., SAUNDERS A. D., MARRINER G. F. & TARNEY J. 1984. Subduction of pelagic sediments: Implications for the origin of Ce-anomalous basalts from the Mariana Islands. *Journal of the Geological Society of London* **141**, 453–72.
- IRVINE T. N. & BARAGAR W. R. A. 1971. A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences* **8**, 523–48.
- ITO E. & STERN R. J. 1986. Oxygen- and Strontium-isotopic investigations of subduction zone volcanism: The case of the Volcano Arc and the Mariana Island Arc. *Earth and Planetary Science Letters* **76**, 312–20.
- KATO Y. 1988. Gray pumice drifted from Fukutokuoka-no-ba to Ryukyu Islands. *Bulletin of the Volcanological Society of Japan Series 2* **33**, 21–30 (in Japanese).
- KIMURA J., YOSHIDA T. & TAKAKU Y. 1995. Igneous rock analysis using ICP-MS with internal standardization, isobaric ion overlap correction, and standard addition methods. *Science Reports of Fukushima University* **56**, 1–12.
- KIMURA J. & YAMADA Y. 1996. Evaluation of major and trace element XRF analyses using a flux to sample ratio of two to one glass beads. *Journal of Mineralogy, Petrology and Economic Geology* **91**, 62–72.
- LIN P. N. 1992. Trace element and isotopic characteristics of western Pacific pelagic sediments: Implications for the petrogenesis of Mariana Arc magmas. *Geochemica et Cosmochimica Acta* **56**, 1641–54.
- LIN P. N., STERN R. J. & BLOOMER S. H. 1989. Shoshonitic volcanism in the northern Mariana Arc: 2. Large-ion lithophile and rare earth element abundances: Evidence for the source of incompatible element enrichments in intraoceanic arcs. *Journal of Geophysical Research* **94**, 4497–514.
- LIN P. N., STERN R. J., MORRIS J. & BLOOMER S. H. 1990. Nd- and Sr-isotopic compositions of lavas from the northern Mariana and southern Volcano arcs: implications for origin of island arc melts. *Contributions to Mineralogy and Petrology* **105**, 381–92.
- MANTON W. I. 1988. Separation of Pb from young zircons by single-bead ion exchange. *Chemical Geology (Isotope Geoscience Section)* **73**, 147–52.
- MEEN J. K., STERN R. J. & BLOOMER S. H. 1998. Evidence for magma mixing in the Mariana Arc system. *The Island Arc* **7**, 000–000.
- MEIJER A. 1976. Pb and Sr isotopic data bearing on the origin of volcanic rocks from the Mariana island-arc system. *Geological Society of America Bulletin* **87**, 1358–69.
- MEIJER A. & REAGAN M. 1981. Petrology and geochemistry of the island of Sarigan in the Mariana Arc: Calc-alkaline volcanism in an oceanic setting. *Contributions to Mineralogy and Petrology* **77**, 337–54.
- MEIJER A. & REAGAN M. 1983. Origin of  $K_2O-SiO_2$  trends in volcanoes of the Mariana arc. *Geology* **11**, 67–71.
- OSSAKA J. 1991. *Eruptions of Submarine Volcanoes around Japan*. Tokai University Press, Tokyo (in Japanese).
- PIER J. G., PODOSEK F. A., LUHR J. F., BRANNON J. C. & ARANDA-GOMEZ J. J. 1989. Spinel-lherzolite-bearing Quaternary volcanic centers in San Luis Potosi, Mexico. 2. Sr and Nd isotopic systematics. *Journal of Geophysical Research* **95**, 7941–51.
- STERN R. J. 1979. On the origin of andesite in the northern Mariana Island arc: Implications from Agrigan. *Contributions to Mineralogy and Petrology* **68**, 207–19.
- STERN R. J. & BIBEE L. 1984. Esmeralda Banks: Geochemistry of an active submarine volcano in the Mariana Island arc. *Contributions to Mineralogy and Petrology* **86**, 159–69.
- STERN R. J., SMOOT N. C. & RUBIN M. 1984. Unzipping of the Volcano Arc, Japan. *Tectonophysics* **102**, 153–75.
- STERN R. J., BLOOMER S. H., LIN P. N., ITO E. & MORRIS J. 1988. Shoshonitic magmas in nascent arcs: New evidence from submarine volcanoes in the northern Marianas. *Geology* **16**, 426–30.
- STERN R. J., JACKSON M. C., FRYER P. & ITO E. 1993. O, Sr, Nd, and Pb isotopic composition of the Kasuga Cross-Chain in the Mariana Arc: A new perspective on the K-h relationship. *Earth and Planetary Science Letters* **119**, 459–75.
- SUN S. S. & MCDONOUGH W. F. 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Geological Society Special Publication* **42**, 313–45.
- TSUYA H. 1937. On the volcanics of the Huzi Volcanic zone, with special reference to the geology and petrology of the Idu and the Southern Islands. *Bulletin of Earthquake Research Institute* **15**, 215–357.
- VIDAL P., DUPUY C., MAURY R. & RICHARD M. 1989. Mantle metasomatism above subduction zones: Trace-element and radiogenic isotope characteristics of peridotite xenoliths from Batan Island (Philippines). *Geology* **17**, 1115–18.
- WALTON-SMITH F. G. ed. 1974. *Handbook of Marine Science*, vol. 1. CRC Press, Cleveland.

- WOODHEAD J. D. 1988. The origin of geochemical variations in Mariana lavas: A general model for petrogenesis in Intra-oceanic Island Arcs? *Journal of Petrology* **29**, 805–30.
- WOODHEAD J. D. 1989. Geochemistry of the Mariana arc (Western Pacific): Source composition and processes. *Chemical Geology* **76**, 1–24.
- WOODHEAD J. D. & FRASER D. G. 1985. Pb, Sr and  $^{10}\text{Be}$  isotopic studies of volcanic rocks from the Northern Mariana Island. Implications for magma genesis and crustal recycling in the Western Pacific. *Geochemica et Cosmochimica Acta* **49**, 1925–30.
- WOODHEAD J. D., HARMON R. S. & FRASER D. G. 1987. O, S, Sr, and Pb isotope variations in volcanic rocks from the Northern Mariana islands: Implications for crustal recycling in intra-oceanic arcs. *Earth and Planetary Science Letters* **83**, 39–52.
- YOSHIDA T., FUJIWARA S. & AOKI K. 1987. Geochemistry of Fukutoku-oka-no-ba submarine volcano, Izu-Ogasawara arc. *Research Report of Laboratory of Nuclear Science, Tohoku University* **20**, 202–15 (in Japanese).