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Oxygen- and strontium-isotopic investigations of subduction zone volcanism: the case of the Volcano Arc and the Marianas Island Arc

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Recent, fresh, volcanic rocks of the intra-oceanic Mariana and Volcano Arcs were analyzed for O and Sr isotopic compositions in order to determine the source of these magmas. Fresh, non-arc, volcanic rocks from the regions surrounding the Mariana-Volcano Arcs and some DSDP sediments were also analyzed for comparison. The oxygen isotopic ratios of the arc lavas (5.5–6.8‰) exhibited a small *inter-island* variation that cannot be entirely explained by fractional crystallization. The Sr isotopic composition of the arc lavas is remarkably uniform (0.70332–0.70394 for the Marianas). Three models are considered in order to explain the observed isotopic characteristics: (1) bulk mixing and melting of MORB-type mantle with (a) subducted sediments, and (b) subducted oceanic crust (excluding sediments); (2) melting of a mixture of sediment-derived fluids and MORB-type mantle; and (3) melting of a mixture of sediment-derived fluids and oceanic island or “hot-spot” type mantle. The last model fits the data best. The conclusion that very small, and variable, amounts of sediment-derived fluid ($\leq 1\%$) are required to explain the observed *inter-island* O isotopic variation, is consistent with that of other workers who used different isotopic and trace element methods. The generation of magmas in the Mariana-Volcano Arcs involves very little sediment and the source region of Mariana lavas is *isotopically* indistinguishable from that of hot-spot basalts.

1. Introduction

The origin of magmas at convergent margins is a question that must be answered if we are to understand not only the geochemical evolution of arcs but also more global questions such as the fate of subducted material and the growth rates of continents. Many investigators think that in subducted zones at least some crustal (sedimentary) materials are transported down to 100–150 km beneath the volcanoes where they are involved in the generation of subduction zone magmas, either by direct melting or by releasing volatiles into the overlying mantle, thereby reducing its eutectic temperature and causing it to melt (e.g., [1]). Confirmation of the slab-derived component is not always easy. Part of the problem is that in many subduction zones, magmas that have erupted through continental crust have been contaminated by it (e.g., [2]). In other words, the presence of continental crust beneath volcanic arcs complicates the interpretation of trace element and isotopic characteristics such that it is very difficult

to evaluate the slab-derived component. For this reason, the origin of primary magmas at convergent margins is best evaluated in arcs built on more refractory oceanic crust (intra-oceanic arcs). For some intra-oceanic arcs, it has been argued that the geochemical or isotopic signature of subducted material, particularly of sediments, can be identified (e.g., [3,4]). In other intra-oceanic arcs, investigators have argued that such a contribution is difficult to demonstrate unequivocally (e.g., [5,6]).

In this study, we report the results of an $^{18}\text{O}/^{16}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ investigation of lavas sampled from 1000 km of the intra-oceanic Volcano and Mariana Arcs and of related sediments and volcanic rocks from the western Pacific (Fig. 1). The Mariana-Volcano Arc system is built on a thickened (17–20 km), late to Middle Miocene oceanic crust (see [7]), and older arc rocks, perhaps similar to the boninites and arc tholeiites that have been recovered from the inner wall of the Marian Trench [8]. Nevertheless, as we have discussed elsewhere [8], the extent and effects of shallow-level

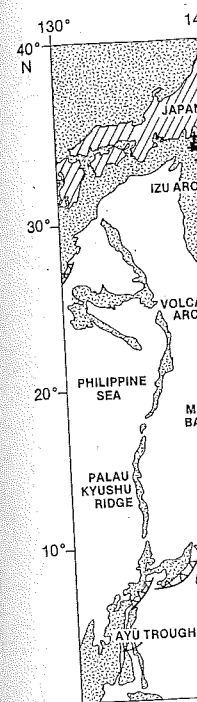


Fig. 1. A map of the islands and sear 1 = Iwo Jima; 2 = Agrigan; 5 = Pag Bank; 9 = Guam shown.

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2. Samples

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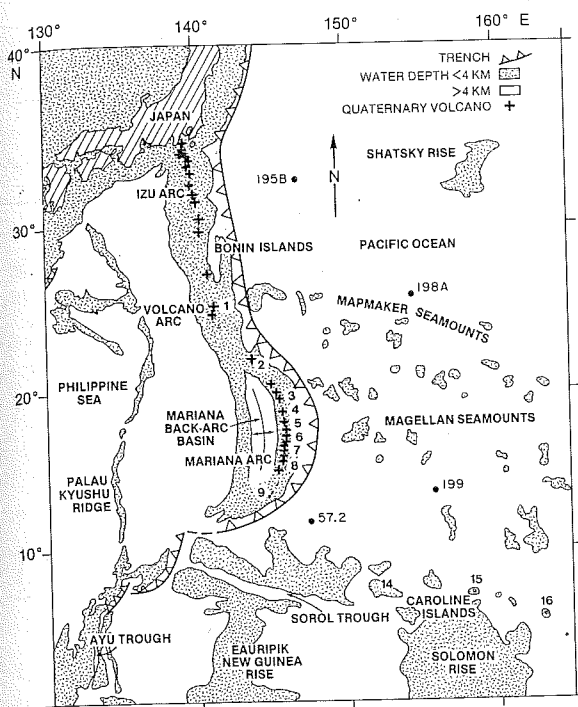


Fig. 1. A map of the western Pacific. The numbers indicate the islands and seamounts included or discussed in the study. 1 = Iwo Jima; 2 = Fukujin Seamount; 3 = Asuncion; 4 = Agrigan; 5 = Pagan; 6 = Guguan; 7 = Sarigan; 8 = Esmeralda Bank; 9 = Guam. The locations of the DSDP Sites are also shown.

crustal contamination should be minimal in this system. The study of fresh rocks from this system gives us an outstanding opportunity to determine the isotopic composition of magmas uncontaminated during ascent through the crust and thus to attempt to resolve the role of any slab-derived component.

2. Samples

Volcanic rocks from active and dormant volcanoes of the Volcano and Mariana Arcs range in composition from calc-alkalic [10,11] to shoshonitic [12] in their differentiation trends. Samples in this study include basalts and andesites from the active Mariana Arc and trachyandesites from the Volcano Arc. Samples analyzed were restricted to fresh vitrophyres or crystalline rocks without traces of altered minerals, especially of olivine. The analyzed DSDP sediment core sam-

ples are from the western Pacific seafloor just east of the arc and include carbonates, cherts, clays and tuffs as likely representatives of subducted sediments [13,14].

3. Analytical procedure

Oxygen was quantitatively extracted from ground rock powders by reaction with BrF_5 and converted to CO_2 using a procedure similar to the one described by Clayton and Mayeda [15]. The working standard or reference gas used was a bottled CO_2 having a $\delta^{18}\text{O}$ of 5.40 (average of ~150 analyses) against SLAP of -55.5‰ as measured in Dr. T. Coplen's laboratory at the U.S. Geological Survey. NBS 28 quartz measures 9.60 based on this calibration. Strontium was separated from dissolved ground rock powders using standard cation-exchange resin-column techniques, and was analyzed on single Ta filaments [6].

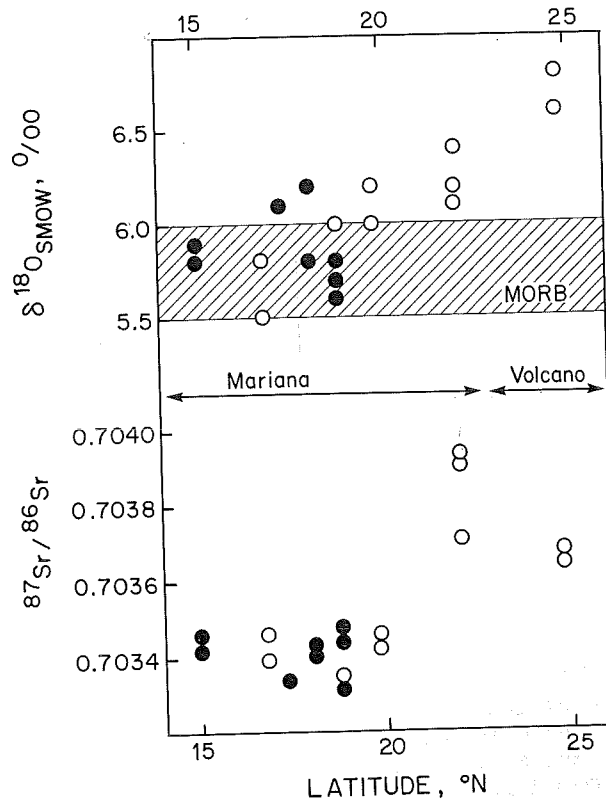


Fig. 2. The $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ compositions of the arc rocks are shown against their latitudes. General range of $\delta^{18}\text{O}$ composition for MORB is indicated. Symbols: ● = $\text{SiO}_2 < 53 \text{ wt.}\%$; ○ = $\text{SiO}_2 > 53 \text{ wt.}\%$.

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TABLE 1
Sr and O isotopic composition

Sample	Sr (ppm)	SiO ₂ (wt.%)	K ₂ O (wt.%)	⁸⁷ Sr/ ⁸⁶ Sr	δ ¹⁸ O (‰)
<i>Island arc lavas</i>					
Volcano arc					
Iwo Jima	450	60	4.33	0.70365 ± 6	6.6
Iwo Jima Suribachi	459	60	4.21	0.70368 ± 4	6.8
Mariana Arc					
Fukujin					
MV15146	347	56.7	1.32	0.70394 ± 5	6.1
MV15117	364	60.6	1.48	0.70392 ± 6	6.4
MV1580	359	59.7	1.66	0.70371 ± 4	6.2
Asuncion					
A-1B ^a	256	55.1	0.58	0.70346 ± 6	6.2
A-4A	268	56.1	0.62	0.70342 ± 5	6.0
Agrigan					
Ag1-3 ^b	342	50.9	0.73	0.70344 ± 6	5.6
Ag4-4 ^b	274	51.9	0.72	0.70348 ± 4	5.7
Ag8-4 ^b	294	57.4	1.80	0.70344 ^b	6.0
Ag7-1 ^b	314	60.1	2.06	0.70335 ^b	5.8
Ag10-1 ^a	397	51.6	0.93	0.70332 ± 6	5.8
Pagan					
P-4 ^a	323	52.4	0.69	0.70344 ± 5	5.8
P-5 ^a	320	50.5	0.70	0.70343 ± 8	6.2
Guguan G-2 ^a	281	50.5	0.42	0.70334 ± 8	6.1
Sarigan					
SRGN 2 ^a	341	59.1	0.92	0.70347 ± 8	5.5
SRGN 5 ^a	331	59.8	1.02	0.70339 ± 6	5.8
Esmeralda Bank					
M45g ^c	377	51.0	0.90	0.70342 ^c	5.9
M46-10T ^c	326	52.2	0.92	0.70346 ^c	5.8
<i>Non-arc lavas</i>					
Mariana Back-Arc Basin					
T11 D-2 glass ^d	159	50.8	0.20	0.70303 ± 9	5.9
T11 D-6 glass ^d	133	50.1	0.25	0.70287 ± 5	5.9
T16 D-3 glass ^d	180	49.5	0.28	0.70313 ± 6	5.8
M41	-	-	-	0.70309 ± 5	6.0
Mariana Trench ^e					
1402 D2-11 glass	440	49.4	4.06	0.70281 ± 6	5.9
Sorol Trough ^f					
D19-2 glass	255	49.1	1.70	0.70305 ± 5	5.9
D19-3 glass	-	49.3	0.97	0.70324 ± 5	5.8
Ayu Trough ^f					
D22-2 glass	-	51.1	0.31	0.70300 ± 7	5.6
S22-4 glass	-	51.5	0.02	0.70279 ± 5	5.6
<i>Sediments (to be subducted)</i>					
DSDP Leg 6					
59.2, 1-3, 99-100, tuff	-	-	4.70	0.70526 ± 9	-
59.2, 4-1, 109-111, tuff	-	-	2.01	0.70554 ± 8	-
DSDP Leg 20					
195B, 3-1, 129-130, chalk	-	-	0.31	0.70758 ± 8	27.4
195B, 3-1, 124-125, chert	-	-	0.06	-	25.7
198A, 2-2, 103-104, clay	-	-	3.75	0.71499 ± 4	-
198A, 3-3, 77-78, clay	-	-	3.70	0.71230 ± 8	-

TABLE 1 (continuation)

Sample
198A, core catch
199, 1-2, 92-93,
199, 10-2, 38-39
199, 11-1, 29-31
Major element cor
by isotope dilutor
^a Chow et al. [18].
^b Stern [10].
^c Stern and Bibee
^d Stern [6].
^e Sample donated
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^f Fornari et al. [2

4. Results

The range of δ¹⁸O (Fig. 2) is from the Volc 18O, ranging Mariana lavas oxygen isotop overlaps, but the range for 6.0‰).

Fig. 3. Calculated from -2.1‰, Δ (Open triangles) represents the less fractionated assumed parent compositions and the s

TABLE 1 (continued)

Sample	Sr (ppm)	SiO ₂ (wt.%)	K ₂ O (wt.%)	⁸⁷ Sr/ ⁸⁶ Sr	δ ¹⁸ O (‰)
198A, core catcher, chert	—	—	0.31	0.71056 ± 4	—
199, 1-2, 92-93, foram ooze	—	—	1.05	0.70841 ± 5	30.1
199, 10-2, 38-39, chalk	—	—	0.46	0.70763 ± 5	28.4
199, 11-1, 29-31, limestone	—	—	0.90	0.70807 ± 6	29.5

Major element concentrations for volcanic rocks are from published and unpublished sources. K₂O for DSDP samples was obtained by isotope dilution.

^a Chow et al. [18].

^b Stern [10].

^c Stern and Bibee [45].

^d Stern [6].

^e Sample donated by Dr. R.G. Coleman and collected during the 17th cruise of "Dmitry Mendeleev", as a part of the U.S.S.R. participation in the IG CP. Major element data from Dietrich et al. [21].

^f Fornari et al. [20].

4. Results

The range of δ¹⁸O for all volcanic rocks (Table 1, Fig. 2) is from 5.4 to 6.8‰. Andesitic rocks from the Volcano Arc are relatively enriched in ¹⁸O, ranging from 6.1 to 6.8‰, compared with Mariana lavas which range from 5.5 to 6.4‰. The oxygen isotopic composition of all the arc lavas overlaps, but extends to slightly higher values than the range for other, nearby, non-arc lavas (5.6 to 6.0‰).

It has been shown [16,17] that fractionation of ferromagnesian minerals from basaltic melts can cause an enrichment of ¹⁸O in residual liquids. This seems to be the case for the 4 pre-caldera samples from a differentiation sequence on Agrigan (Fig. 3) [10]. We suspect this effect may partially be responsible for the high-δ¹⁸O rocks (δ¹⁸O = 6.1-6.8; SiO₂ ~ 60%) from Fukujin and the Volcano Arc. However, some rocks from the Marianas have δ¹⁸O up to 6.2‰ even though they only contain about 50% SiO₂. These rocks from

Sample	Ag 9-1A	Ag 1-3	Ag 4-8	Ag 8-4	Ag 7-1
δ ¹⁸ O calc. (%) obs.	---	5.6 ¹	5.7	5.8	5.9
liquid % ³ liquid % ⁴	100%	61.5% 100%	43.05% 70% 100%	28.23% 65.57% 100%	24.37% 86.33%
solid % ⁵	7.29% Cpx 0.1 % Mt (Usp 9.9) 26.86% An96 4.29% Fo85	10.64% Cpx 2.7 % Mt (Usp 9.9) 16.19% An82 0.51% Fo83	9.76% Cpx 2.17% En82 2.36% Mt 16.92% An86 3.25% Fo65	1.20% Cpx 4.34% En 1.4 % Mt 6.75% An68	
Σχ ² ⁶	0.09	0.069	0.059	0.056	

Fig. 3. Calculated and observed δ¹⁸O of lavas from Agrigan. Mineral-melt fractionation values at magmatic temperatures were calculated from published values to be Δ (An₈₀-melt) = +0.10‰, Δ (Cpx-melt) = -0.45‰, Δ (Ol-melt) = -0.70‰, Δ (Mt-melt) = -2.1‰, Δ (Opx-melt) = -0.45‰. The portions of minerals removed from the successive melts were taken from Stern [10]. Notes: ¹ The analyzed composition was adopted as the starting value. ² Ag 4-8 was not analyzed. The value shown is that of Ag 4-4, a slightly less fractionated lava having a SiO₂ = 51.9% and K₂O = 0.72%. ³ Percent liquid remaining from the crystal fractionation of the assumed parent 9-1A. ⁴ Percent liquid remaining from the fractionation of immediately preceding liquid composition. ⁵ The compositions and amounts of the modelled removed solids found to best mimic the observed compositional variations. ⁶ Σχ² represents the sum of the squares of residuals between observed and modelled liquids.

TABLE 2
Composition of western Pacific sediments

Rock type and age	Thickness (m)	Density (g/cm ³)	Mass (%)	$\delta^{18}\text{O}$ (‰)	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$
Tertiary tuff	140	1.2	22	13 ^a	218	0.7054
Mesozoic and Lower Tertiary chalk	220	1.6	45	29	471	0.7078
Mesozoic clay	120	1.6	25	16 ^b	168	0.7140
Mesozoic chert	20	2.3	6	26	1	0.7106
Total	500	1.5	100	24	360	0.7083

^a Garlick and Dymond [46].

^b Savin and Epstein [47].

the islands of Pagan and Guguan are neither altered nor petrologically unusual. It thus appears that there is a minor inter-island variation in the O isotopic composition of the lavas, indicating subtle variations in the source of individual volcanoes along the arc, as previously noted on the basis of incompatible element ratios [18].

The range of $^{87}\text{Sr}/^{86}\text{Sr}$ for the Mariana rocks up to but not including Fukujin Seamount is very narrow (0.70332–0.70348; Table 1), comparable to or narrower than the range of $^{87}\text{Sr}/^{86}\text{Sr}$ variations that have been observed in an equivalent length of a mid-ocean ridge [19]. Fukujin and Iwo Jima lavas show more elevated $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70365–

0.70392). Submarine basalt glasses from the Mariana Back-arc Basin, Sorol and Ayu Troughs [20] and Mariana Trench [21], i.e., submarine basalts from the areas surrounding the Marianas, have less radiogenic Sr than the arc lavas (0.70279–0.70313), and are similar to fresh MORB in terms of $^{87}\text{Sr}/^{86}\text{Sr}$ or $\delta^{18}\text{O}$ [22,23].

5. Discussion

In this section we examine possible causes of the observed O and Sr characteristics of the Mariana and Volcano arc lavas in terms of two likely processes: (1) direct melting of subducted material; and (2) melting in the mantle wedge caused by the volatiles released from the subducted slab.

It is clear that there is extreme variability in the composition of the subducted sediments [9,24]. Moreover, we do not know how much of and what part of the sediment pile is subducted. Assuming that the entire pile is subducted, we calculate that *on the average* the subducted sediments should have: $\delta^{18}\text{O} \sim 22\text{‰}$; $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.7080$; and Sr ~ 310 ppm (Table 2, also see [9]). The isotopic compositions are considerably different from those of the lavas from the Volcano and Mariana Arcs (Fig. 4). Calculation of bulk mixing of pelagic sediments with MORB-type mantle ($\delta^{18}\text{O} \sim 5.5\text{‰}$, $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.7025$, and Sr ~ 20 ppm) to form a mixture which would then melt to produce unfractionated basaltic arc magmas ($\delta^{18}\text{O} = 5.6\text{‰}$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7033\text{--}0.7039$, Sr = 350 ppm) shows that not more than 1% bulk mixing of sediment can be involved even for the lavas of Fukujin and Iwo Jima. Oceanic crust now being subducted beneath the Volcano and Mariana Arcs

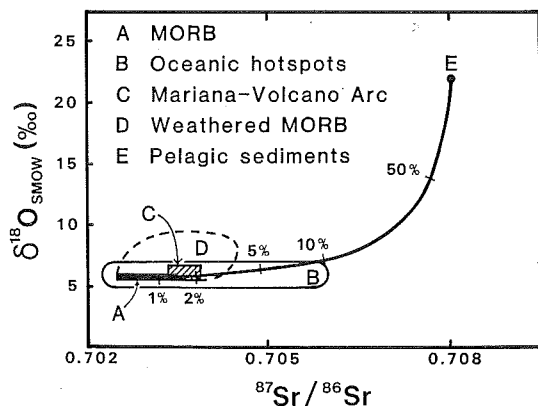


Fig. 4. The $\delta^{18}\text{O}$ - $^{87}\text{Sr}/^{86}\text{Sr}$ relationships among fresh MORB, fresh Mariana and Volcano Arc lavas, "weathered" MORB (i.e., altered by halmyrolysis), oceanic island volcanic rocks, and western Pacific pelagic sediments are shown. The composition of the pelagic sediments was derived as shown in Table 2. The expected effect of bulk mixing and melting of the pelagic sediments and MORB-type mantle to form arc magmas is indicated as a mixing curve. The calculated isotopic compositions for 50%, 10%, 5%, 2%, and 1% bulk mixing are shown.

is Mesozoic in a 1/2 to 1 km thick section. The $^{87}\text{Sr}/^{86}\text{Sr}$ is 7–9‰, and the subface amphibolite has $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7025–0.7030, 6–6.5 km section is unchanged although its average is ~ 0.7035 . The subducted oceanic crust on the Sr is fractionated by the Volcano Arcs and the subface crust affected perhaps 5–25% and (2) if the crust is melted, let alone isotopes alone the fact that subducted material are probably [5,27].

The main elements is that they fine-scaled variations observed along bulk mixing such models variation in Sr isotopes to the south two-step process during the and second, mantle where

The concentration one major measured Sr isotopes clays are typically 2); the Sr carbonates (variation of high into porewater reduced to le depth after prism [28]. calcite at th to aragonite coefficients

is Mesozoic in age and should be altered: the top 1/2 to 1 km by halmyrolysis ($\delta^{18}\text{O} = 7-9\%$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7025-0.7045$, Sr = 130 ppm), and the subjacent 1/2 to 2 km to greenstone and amphibolite ($\delta^{18}\text{O} = 4-6\%$, $^{87}\text{Sr}/^{86}\text{Sr} = 0.7025-0.7030$, Sr = 130 ppm) [25,26]. The entire 6-6.5 km section of oceanic crust, however, may be unchanged in its bulk O isotopic composition, although its average $^{87}\text{Sr}/^{86}\text{Sr}$ may be raised to ~ 0.7035 . The possible effects of bulk mixing of subducted oceanic crust with MORB-type mantle on the Sr and O isotopic ratios of the unfractionated basaltic magmas of the Mariana and Volcano Arcs are: (1) if just the upper part of the crust affected by the halmyrolysis is melted, perhaps 5-25% weathered crust could be involved, and (2) if the entire thickness of the subducted crust is melted, its contribution cannot be detected, let alone assessed, by using Sr and O isotopes alone. This uncertainty is exacerbated by the fact that about 4% of the mass of the subducted material is composed of seamounts which are probably isotopically similar to the arc lavas [5,27].

The main shortcoming of the bulk mixing models is that they do not readily explain the relatively fine-scaled variation in O isotopic composition observed along the arc. There is no reason why bulk mixing cannot cause such a variation, but such models would require a corresponding variation in Sr isotopes. This is not observed, especially to the south of 20°N . Hence, we considered a two-step process: first, the release of hydrous fluids during the dehydration of subducted materials; and second, the mixing of fluids with MORB-type mantle where melting occurs.

The concentration of Sr in released volatiles is one major uncertainty in this model. The measured Sr isotopic ratios of DSDP carbonates and clays are typically very high (0.708-0.715; Table 2); the Sr concentrations are also high in the carbonates (~ 470 ppm). The in-situ recrystallization of high-Mg calcite on the seafloor expels Sr into porewater, and the porosity should be reduced to less than 10% within a few kilometers' depth after the sediments enter the accretionary prism [28]. In addition, the massive carbonates are calcite at the time of subduction and should invert to aragonite at about 5 kbar [29]. The distribution coefficients of Sr in aragonite are six times that of

calcite [30], so that Sr should be retained during this phase transition until decarbonation. Using dolomite as an analogue [31], decarbonation should not occur during any part of P - T trajectory of the slab at least down to 30 kbar [29]. Since sediments do not seem to be accreted on to the inner wall of the Mariana Trench [8], and since the subducted and over-riding plates are seismically decoupled [32], it seems likely that the sediments (and their Sr contents) are carried relatively intact (except for any fluids) down to depths directly beneath the arc volcanoes. Any Sr contained in silicate minerals may not partition effectively into aqueous fluid phase during dehydration reactions, or those minerals may remain stable in the pertinent P - T range. However, in the case of bulk mixing or the direct melting of sediments, the elevated $^{87}\text{Sr}/^{86}\text{Sr}$ of the sediment *must* show up in the resulting melt, and a variation in the sediment composition large enough to manifest itself in the O isotopic composition would surely affect the Sr isotopic composition as well unless it were fortuitously compensated for by the heterogeneity of the mantle.

The oxygen isotopic variation *between* islands is not large. Small but variable amounts of fluid from the dehydration of the slab added to a uniform source in the mantle wedge can bring about such a variation. For example, every 1% (by mass) addition of sediment-derived fluid (assumed $\delta^{18}\text{O} = 15-20\%$) to the mantle source region will increase the bulk $\delta^{18}\text{O}$ by 0.2%. In other words, the observed inter-island variation in $\delta^{18}\text{O}$ can be explained by the addition of 1% to 3% fluid to a uniform mantle source, i.e., as a function of differences in the water-to-rock ratio in the source region. The inter-island variation in the shapes of the REE pattern can also be explained by a small variation in the degree of partial melting (10-20% partial melting, [33]) which may be a consequence of the different degrees of solidus depression due to the addition of variable amounts of fluid.

We also considered the possibility that the small isotopic variation in O isotopes which is not faithfully mimicked in Sr isotopes might be a result of the differences in the diffusion rates of O and Sr in the melt. However, in a mixture of crystals and melt, crystals will not flow at the same velocity as the melt due to differences in their densities. Isotopic homogenization will then occur by turbu-

lence or by convection caused by the differential movement of crystals, and will be much faster than by diffusion. In this case, both O and Sr isotopes are likely to be homogenized in the source region. Nevertheless, if diffusive mixing is the only homogenization process, and if the magma contains water, the diffusivity of cations in melt would be 10^3 – 10^5 times faster than for oxygen [34,35]. For a stagnant sphere of pure melt with a diameter of 100 m, Sr and Pb will homogenize in about 0.4 Ma whereas O will need about 400 Ma, which is much longer than the timescale between subduction and eruption (~ time required for a segment of a slab just entering the Mariana Trench to reach the depth of 100–150 km), and therefore, much longer than any reasonable duration for magmas to remain trapped in the source region. Hence, if diffusion is the only mechanism, the small variation in the O isotopic composition probably reflects the incomplete homogenization of fluid-derived and mantle-derived oxygen [35].

Finally, we note that the combined O and Sr isotopic data are also consistent with the derivation of Mariana and Volcano Arc magmas from an oceanic island-type source that has been modified, albeit insignificantly, by slab-derived fluids. The range of $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ for Mariana arc lavas (excluding Fukujin) is consistent with observations by other workers that Mariana Arc lavas are indistinguishable from hot-spot basalts on the basis of K/Rb, K/Ba, and Ba/Sr [18], Pb isotopes [5,36], and Sr, Nd and Hf isotopes [37,38]. This interpretation is supported by the observation that the range of $\delta^{18}\text{O}$ in these arc magmas is also similar to that of basalts from oceanic islands [39,40]. It is further supported by the lack of a subducted-slab component in ^{10}Be [41]. The only undoubtedly slab-derived signature is the low K/Cs for this arc [38], a feature which can be explained by an extremely small slab-derived component ($< 1\%$).

The small variation in $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ observed between 15° and 20°N of this arc system contrasts markedly with the more variable and elevated $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ of lavas observed between 20° and 25°N (Fukujin and Iwo Jima). The first data set indicates that these arc lavas are derived from a remarkably homogeneous source. The development and preservation of such a homogeneous source as a result of incremental and

variable additions of slab-derived fluids to a MORB-type mantle seems unlikely. We think the bulk isotopic characteristics of the source region of the Mariana (15 – 20°N) Arc magmas do not, for the most part, reflect ongoing processes of slab-derived mantle metasomatism. It seems more likely that the bulk isotopic characteristics were developed prior to the present episode of subduction, and thus were developed by processes and time-scales comparable to those responsible for the formation of oceanic island or hot-spot basalts [42,43], while the fine-scale isotopic characteristics (inter-island variation in $\delta^{18}\text{O}$) were developed by more recent, small but variable amounts of slab-derived fluids added to the uniform mantle source. The characteristics of Fukujin and Iwo Jima may be manifestations of magmagenesis related to very early stages of back-arc rifting [44] representing unique and short-lived petrogenetic conditions.

6. Conclusions

The results of our discussion can be summarized as follows:

(1) O and Sr isotopic compositions range from 5.5 to 6.8‰ and 0.70332 to 0.70394, respectively, over 1000 km of the Mariana-Volcano Arcs. Fresh, non-arc basalts from this region have slightly lower values for $\delta^{18}\text{O}$ (5.6–6.0‰) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70279–0.70313). Western Pacific sediments have much higher and more variable $\delta^{18}\text{O}$ (up to 30‰) and $^{87}\text{Sr}/^{86}\text{Sr}$ (0.70526–0.71499).

(2) Sr and O isotopic data are consistent with the bulk mixing of about 1% or less subducted sediment in the magmas of the Mariana-Volcano Arc, but do not easily explain the uniformity of Sr ratios in the interval 15 – 20°N and the apparent lack of uniformity of O isotopic ratios in the same interval.

(3) It is possible but unlikely that the different diffusion rates of O and Sr caused the observed isotopic variations.

(4) We find that O and Sr isotopic compositions along the arc are best explained by a process involving the mixing of variable but almost insignificant amounts of the slab-derived fluids with the overlying mantle reservoir of an oceanic island or hot-spot type.

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