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A trapped Philippine Sea plate origin for MORB from the inner slope of the Izu–Bonin trench

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Abstract

Basement outcrops sampled by submersible and dredge from the inner slope of the Izu–Bonin trench at 32°N and 6200–6700 m water depth have a distinct mid-ocean ridge basalt (MORB) chemistry unlike any other rocks previously sampled in the Izu–Bonin arc. They are low K tholeiites with moderate TiO_2 (0.7–1.8 wt%), extremely low Ba (1.5–7 parts per million), low Ba/La (1.2–3) and are depleted in light rare-earth elements. These samples could represent either an accreted piece of subducting Pacific plate or a trapped remnant of Philippine Sea plate on which the Izu–Bonin arc was built. Although their major and trace element chemistry do not help to distinguish their source, the Sr, Nd and Pb isotopes clearly support a Philippine Sea plate origin. The isotopic signature of the inner trench slope samples matches that of Philippine Sea plate lavas, with $^{87}Sr/^{86}Sr = 0.70321–0.70373$, $^{143}Nd/^{144}Nd = 0.513057–0.513077$ and $^{206}Pb/^{204}Pb = 18.2–18.5$. The samples have elevated $^{207}Pb/^{204}Pb$ (15.3–15.5) and $^{208}Pb/^{204}Pb$ (38.0–38.2) values compared to the Northern Hemisphere reference line (NHRL) and their isotopic signature is distinct from the Mesozoic Pacific MORB being subducted. These are the first samples of trapped Philippine Sea oceanic crust discovered in the Izu–Bonin–Mariana arc. They require that models for the formation of intra-oceanic arc crust account for pre-existing oceanic crust and that estimates of arc magma production rates are lowered accordingly.

Keywords: Izu–Bonin Arc; mid-ocean ridge basalts; magmatism; basement

1. Introduction

Three dives to between 6100 and 6500 m water depth were made on the inner trench slope of the Izu–Bonin arc at 31°59′N (Fig. 1) using the manned Japanese submersible, Shinkai 6500. The primary goal was to recover arc basement from the trench slope. Seismic reflection profiles [1,2] show that the steep inner slope of the Izu–Bonin trench likely exposes arc basement below 5 km water depth, above and possibly below a terrace of serpentinite seamounts (Fig. 1). This is corroborated by two SeaMARC II sidescan swaths near 32°N (Fig. 2) that reveal high amplitude acoustic backscatter from the slope between 5200 and 6700 m. Together with the seismic reflection profiles, the sidescan data indicate that

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basement rocks are at, or within a few meters of, the surface. Surprisingly, the central Izu–Bonin inner trench slopes were virtually unsampled prior to our dives, though the potential existed at 32°N to sample a basement section up to 1500 m thick.

The rationale for these dives was to exploit the extremely rare opportunity to study in situ the basement of an intra-oceanic island arc. Our aim was to make a composite stratigraphic and structural profile of the basement section above 6500 m water depth and to sample the deepest and most seaward section of the central Izu–Bonin arc basement reachable by submersible (only 35–45 km from the trench axis) (Fig. 1). Ocean Drilling Program (ODP) Site 786, on the outer arc high just upslope from our dive sites, sampled boninitic and tholeiitic volcanic rocks similar to those exposed subaerially on the Bonin Islands. Diving on the trench slope ~40 km east and 3000 m lower than ODP Site 786 could sample the plutonic roots to these volcanic systems (Fig. 1).

An additional goal of these dives was to test alternate models of forearc evolution and inner trench slope tectonism. It has been thought that only very minor, and probably ephemeral, tectonic accretion occurs (along the very base of the slope) at the Izu–Bonin–Mariana and Tonga–Kermadec trenches. In the Mariana trench, arc lavas drilled at great depths on the inner trench slope were explained as the result of extreme subsidence resulting from tectonic erosion of the forearc by high-angle normal faulting [3]. In contrast, in the Tonga trench, an apparently coherent crustal and upper mantle section on the inner slope was interpreted to reflect flexural uplift of the arc footwall beneath a low angle normal fault [4].

Our dives produced surprising results. Instead of finding arc-related volcanic rocks or plutonic basement rocks that would support either of the two forearc evolutionary models proposed above, we recovered N-MORB-type diabase and basalt. These findings presented two likely possibilities, that the forearc includes remnant Philippine Sea plate crust or that Pacific plate crust has been accreted. In either case, the forearc clearly does not consist solely of arc-related rocks. The forearc may comprise trapped segments of Philippine Sea plate MORB that are interspersed among younger, arc-related boninitic and tholeiitic volcanic rocks or the forearc may have grown by episodic, previously unrecorded accretion events from the Pacific plate [5]. The isotopic results that we present in this paper strongly support the former.

2. Geologic setting and tectonic history of the Izu–Bonin arc

The Izu–Bonin arc, south of the island of Honshu in the Japan archipelago (Fig. 1), is one of the best-surveyed intra-oceanic volcanic arcs as a result of studies by Japanese, American and international (i.e. ODP) agencies. The trench is well developed and extends to nearly 10 km water depth. The 200 km wide forearc region includes an inner trench slope with a basal terrace formed by sediments ponded behind and between serpentinite seamounts, an outer arc high that becomes subaerial in the Bonin Islands and a thick forearc sedimentary basin east of the active arc volcanoes. The backarc region includes active rift basins as well as cross-chains of submarine arc volcanoes that extend into the Shikoku Basin.

The history of the Izu–Bonin arc system has been described in detail by B. Taylor [6]. The earliest arc volcanism occurred during the middle and late Eocene, when a vast terrane of boninites and island arc tholeiites (> 300 km wide) was formed. Development of a modern-style volcanic arc began by the early Oligocene, accompanied by intense tholeiitic and calcalkaline volcanism that continued until 27 Ma. The Eocene–Oligocene arc massif was stretched during protracted Oligocene rifting. Arc volcanism decreased in intensity at 27 Ma and was at a minimum from 23 to 17 Ma, with no record of volcanic ash from 23 to 20 Ma. This minimum corresponds to early spreading of the Shikoku backarc basin (24–15 Ma). Middle Miocene to Holocene Izu–Bonin volcanism developed a volcanic front oriented 3° counter-clockwise from the Oligocene frontal arc and has increased in intensity to a Pliocene–Quaternary maximum. Neogene magmatism along the volcanic front has been focused on bimodally

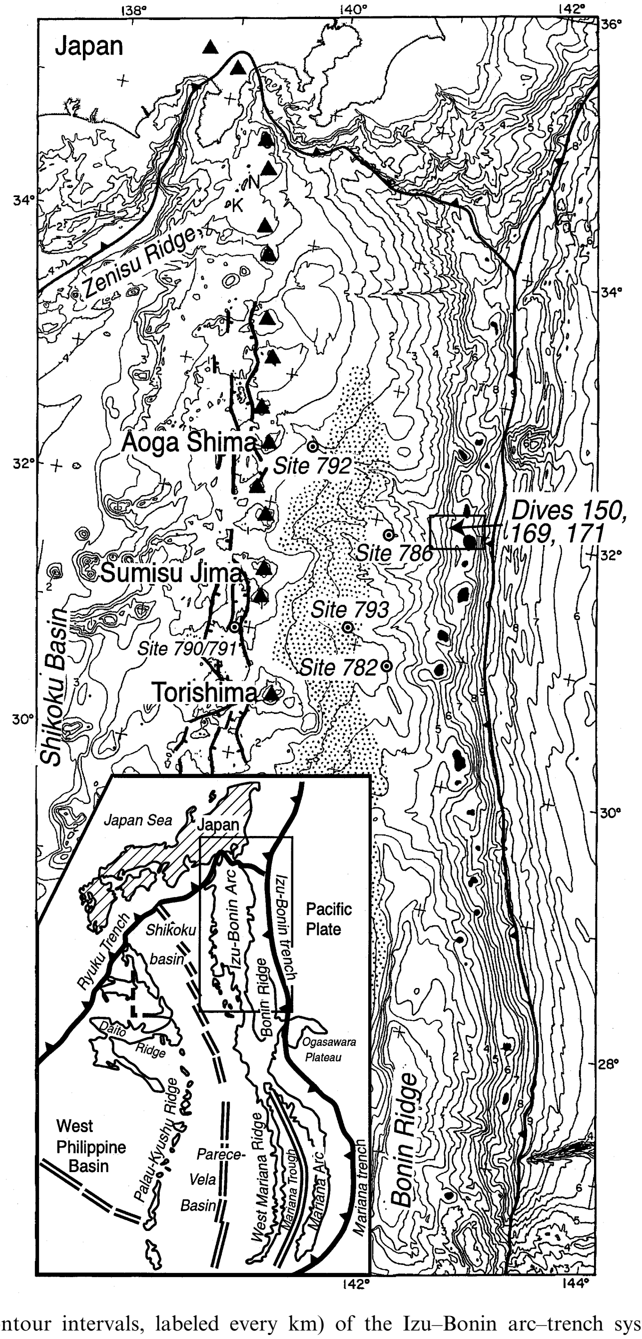

Fig. 1. Bathymetry (500 m contour intervals, labeled every km) of the Izu–Bonin arc–trench system modified after Taylor [6]. Barbed heavy lines locate trench axes, filled bathymetric contours locate serpentinite seamounts on the trench inner slope, filled triangles locate frontal arc volcanoes, ticked heavy lines locate active normal faults and the thickly sedimented forearc basin is stippled. ODP drill sites are numbered and an arrow points to the dive area on the trench slope at 32°N. A box shows the location of Fig. 2. The inset shows simplified tectonic setting and location, basins and ridges are outlined by the 4 km bathymetric contour, except for the Izu–Bonin arc, West Mariana Ridge and Mariana arc, which are outlined by the 3 km contour.

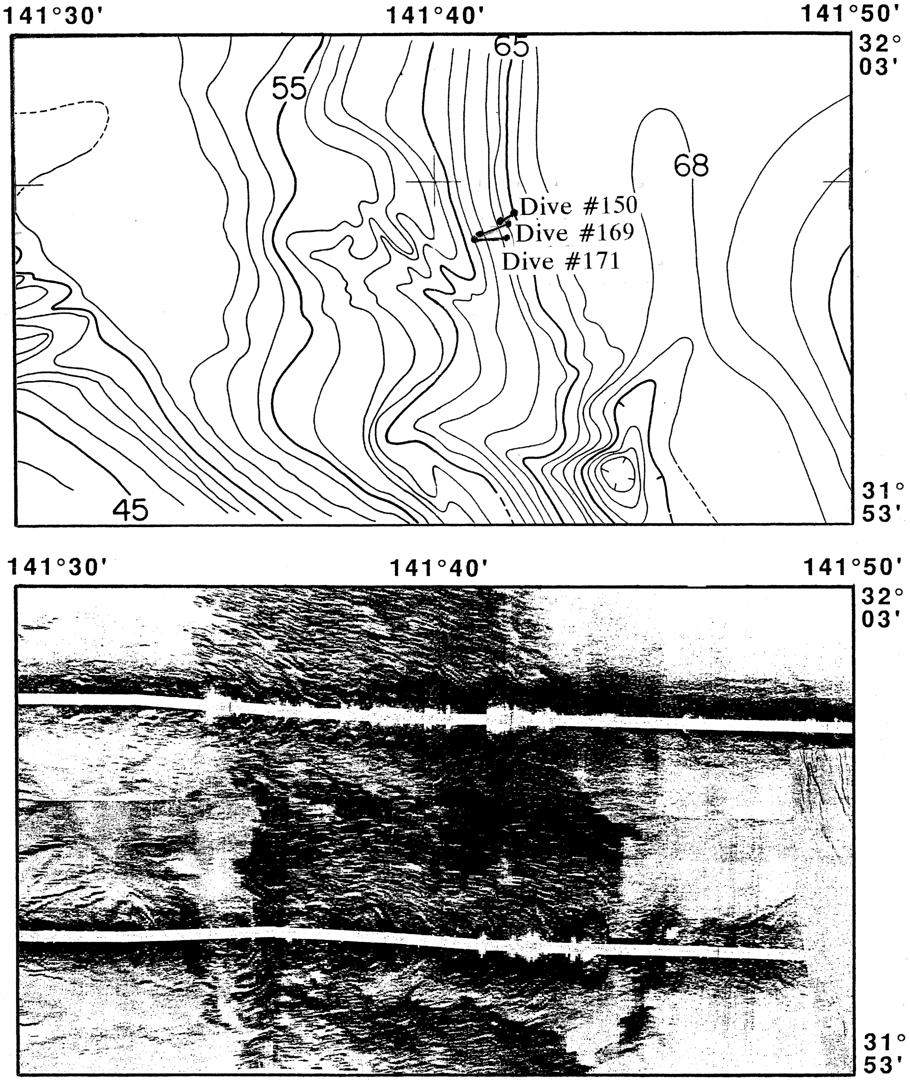

Fig. 2. SeaMARC II bathymetry (100 m contours, top) and acoustic imagery (bottom) of the Izu–Bonin trench inner slope at 32°N (see Fig. 1 for location). On the acoustic image, note the highly reflective slope between 5200 and 6700 m, where seismic reflection records also indicate that arc basement is exposed. Locations of the dives are marked with heavy lines.

spaced, long-lived centers, but arc tholeiites have also occasionally intruded the forearc [7]. The present rifting of the central Izu–Bonin arc (including Sumisu Rift) began about 2–3 Ma and extends from 27.5° to 33.5°N (Fig. 1). The Sumisu Rift at ODP Sites 790 and 791 is floored with synrift volcanics that are geochemically distinct from contemporary arc volcanics. The oldest (>1.1 Ma) to the youngest (Holocene) Sumisu Rift lavas are backarc basin basalts, whereas pre- and synrift arc volcanism is mostly low K, subalkaline rhyolite and andesite.

The basement of the Izu–Bonin forearc area was studied during the drilling programs of ODP Legs 125 and 126 (Fig. 1). At Site 786 (31°52′N), low Ca boninites and bronzite andesites overlain by intermediate Ca boninites, bronzite andesites and a fractionated series of andesites, dacites and rhyolites were recovered from a core that penetrated to 661 m [8]. Site 786 is

Table 1
Description of samples collected from the inner trench slope

Sample	Lithology	Phenocrysts	Groundmass/texture	Alteration	Water depth
150-01a	Devitrified lava clast in breccia	Acicular, fine plag, cpx	90% glass, intersertal	Actinolite, chlorite	6491 m
150-01b	Devitrified lava clast in breccia	Absent	Vitrophyric	None	6491 m
150-02	Diabase	Absent	Fine grained, 40% cpx, 50% plag, 10% oxides	Actinolite, chlorite	6420 m
150-03	Devitrified basalt	$<5\%$ cpx, $<5\%$ plag	Vitrophyric	None	6390 m
169-01a	Fine grained basalt	5% plag, 5% cpx	Crypto-crystalline	None	6192 m
169-01b	Fine grained basalt	5% plag, 5% cpx	Crypto-crystalline	None	6192 m
BT-1	Diabase	None	Ophitic, 60% plag, 30% cpx, $\sim$1% oxide, $\sim$1% olivine	Chlorite replacing cpx	6400–6700 m
BT-2	Diabase	None	Ophitic, 55% plag, 43% cpx, 2% oxide, $\sim$1% olivine	Chlorite replacing cpx	6400–6700 m

located on the forearc basement high, the southward continuation of which is exposed above sea level in the Ogasawara (or Bonin) Islands (Fig. 1), the type locality for boninites. New $^{40}Ar/^{39}Ar$ ages, consistent with biostratigraphic ages of immediately overlying sediments, indicate that the Site 786 basement formed by at least 47–45 Ma [9].

3. Petrology and geochemistry of inner trench slope samples

3.1. Dive descriptions and sample petrography

Samples described in this study were collected during two research cruises of the Japan Marine Science and Technology Center (JAMSTEC) ship R/V *Yokosuka* with the Shinkai 6500 submersible. Three manned submersible dives were completed and six samples were collected from the trench inner slope in the region of 31°59′N and 141°41′–141°42′E (Figs. 1 and 2) from water depths of 6499–6190 m. Recovery of more samples was inhibited by the cohesiveness of the outcrop. Complete dive descriptions can be found in [5].

Outcrop is excellent and ranges from well bedded flows that dip –20° into the slope to steep cliff faces (tens of meters) with megascale layering striking approximately N30°W and dipping gently southwest into the cliff. Columnar jointing in cliff faces is common, as are megascale (1–4 m) pillow structures. Steep cliffs alternate with flat muddy steps and may represent successive trench-parallel fault blocks [5]. No exposures of plutonic rocks were observed.

Samples collected during the dives consist of fine diabase (samples 150-01, 150-02), devitrified glass (sample 150-03) and basalt (sample 169-01) (Table 1). Two additional diabase samples (BT-1 and BT-2, Table 1) are included in this study. These samples were recovered on a R/V *Kana Keoki* cruise (KK84-04-27 Leg 3) in 1984 by the second author while dredging the trenchward side of Myojin forearc seamount at 31°58′N, 141°56–57′E, just east of the edge of Fig. 2. The dredge recovered dominantly serpentinized ultramafic rocks plus the two diabase samples analyzed here. It is not known whether the diabase was incorporated from deeper levels by the rising serpentinite or whether they were transported down Aoga Shima canyon and up and over the crest of the seamount.

Petrographic characteristics of the samples are summarized in Table 1. In general, phenocrysts are rare to absent and all samples have some alteration, from solely devitrification at the lower end to lower greenschist facies at the upper end.

Table 2
Geochemical analyses of samples from the Izu–Bonin inner trench slope

	Myojin Seamount		Dive #150				Dive #169	
Sample:	BT-1	BT-2	150-01a	150-01b	150-02	150-03	169.01a	169.01b
Description:	Coarse gr. diabase	Coarse gr. diabase	Devitrified basalt clast	Devitrified basalt clast	Fine gr. diabase	Devitrified glass	Fine gr. basalt	Fine gr. basalt
Minerals:	cp, op, pl, ol	cp, pl, ol, opq	pl, cp	–	cp, pl, opq	pl, cp	pl, cp	pl, cp
SiO_2	50.50	51.52	52.73	51.3	52.31	49.92	50.46	49.95
TiO_2	0.67	1.19	1.80	1.12	1.44	1.71	0.83	0.82
Al_2O_3	15.33	13.98	13.89	14.23	13.95	13.67	16.21	16.17
FeO[a]	8.63	11.51	13.17	12.23	12.97	14.03	8.77	8.74
MnO	0.18	0.26	0.29	0.23	0.23	0.25	0.16	0.17
MgO	9.73	8.15	5.96	7.48	7.87	6.55	7.94	7.85
CaO	12.72	10.31	7.68	10.01	6.42	9.68	12.33	12.53
Na_2O	1.69	2.46	3.03	2.48	3.08	3.26	2.31	2.3
K_2O	0.08	0.08	0.42	0.14	0.2	0.19	0.29	0.27
P_2O_5	0.04	0.10	0.15	0.08	0.13	0.12	0.06	0.05
Total	99.57	99.55	99.12	99.31	98.6	99.39	99.35	98.85
Mg/(Mg+Fe)	66.8	55.8	44.7	52.2	52.0	45.4	61.7	61.6
Ni	115	62	43	42	44	30	98	109
Cr	407	152	147	59	95	50	353	353
Sc	44	49	50	50	51	52	48	46
V	264	355	431	360	384	496	288	276
Rb	0.7	0.7	7.6	2.7	1.1	1.2	7.0	5.0
Sr	54	70	81	74	80	80	79	78
Zr	37	73	96	60	93	91	47	47
Y	18	31	36	28	38	40	22	23
Nb	0.4	0.8	2.0	1.3	1.1	1.1	4.3	2.1
Ga	15	19	20	17	19	19	17	13
Cu	125	144	38	119	96	97	133	146
Zn	41	120	151	102	91	116	64	66
Ba	1.5	4.2	6.9	5.4	5.2	3.0	4.0	2.0
Th	0.04	0.07	0.18	0.2	0.12	0.11	0.08	0.05
Hf	0.81	1.68	2.54	1.47	2.34	2.27	1.16	1.07
Ta	0.04	0.07	0.15	0.1	0.11	0.1	0.04	0.04
Rb	0.66	0.66	7.55	2.72	1.06	1.17	4.86	4.19
Cs	0.02	0.01	0.41	0.15	0.02	0.01	0.14	0.12
La	0.95	1.81	2.84	1.79	2.56	2.47	1.40	1.33
Ce	2.73	5.84	9.08	5.29	8.19	7.81	3.99	3.77
Pr	0.55	1.05	1.59	0.93	1.44	1.45	0.75	0.70
Nd	3.05	6.16	8.96	5.28	8.40	8.40	4.31	4.20
Sm	1.41	2.66	3.69	2.33	3.58	3.61	1.84	1.83
Eu	0.60	1.01	1.39	0.93	1.29	1.36	0.79	0.77
Gd	2.06	3.59	4.88	3.28	5.03	5.04	2.77	2.75
Tb	0.43	0.76	1.00	0.69	1.01	1.04	0.54	0.54
Dy	2.95	5.33	6.68	4.82	6.88	7.06	3.84	3.81
Ho	0.66	1.15	1.41	1.04	1.50	1.56	0.85	0.85
Er	2.00	3.52	4.25	3.19	4.63	4.66	2.42	2.44
Tm	0.28	0.49	0.60	0.45	0.65	0.67	0.36	0.35
Yb	1.70	3.17	3.77	2.79	3.98	4.14	2.21	2.25
Lu	0.27	0.48	0.61	0.44	0.61	0.65	0.35	0.35

cp = clinopyroxene, opq = opaque minerals, pl = plagioclase, ol = olivine

[a] All Fe as FeO.

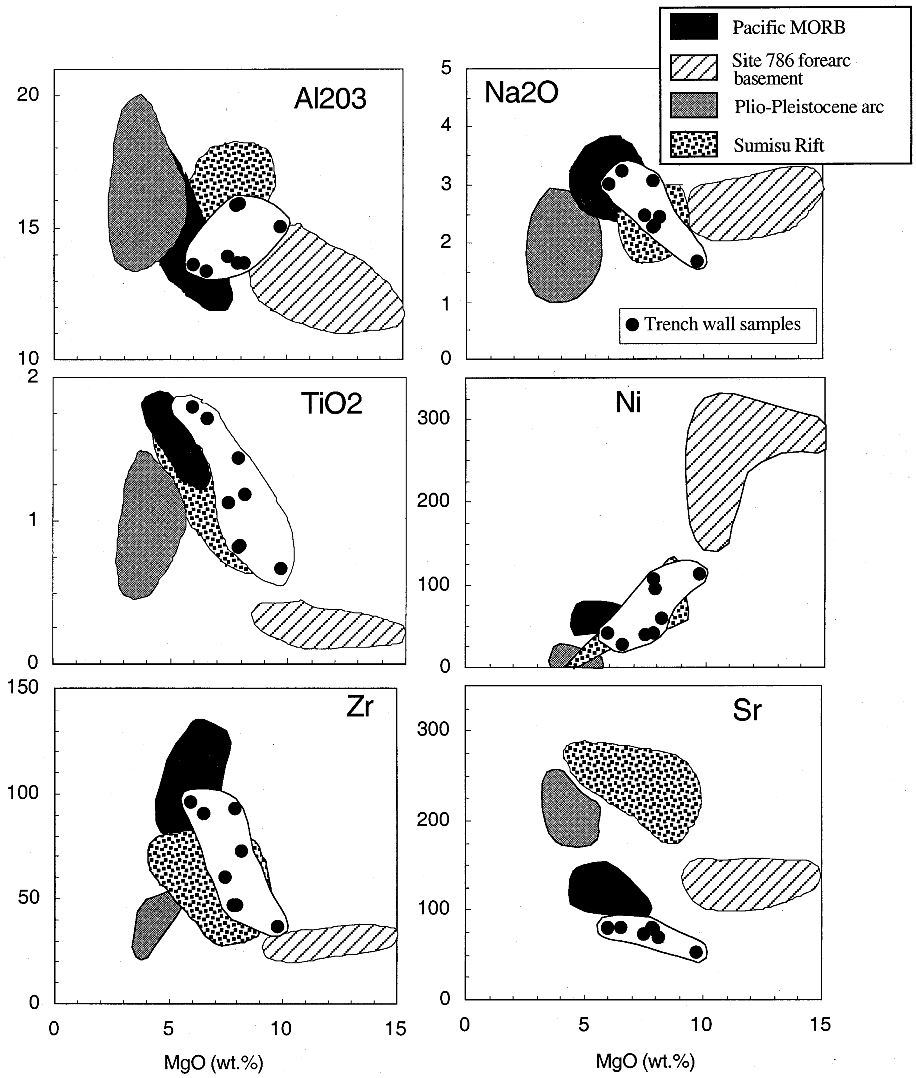

Fig. 3. Variation diagrams of selected major and trace elements vs. MgO for the inner trench slope samples. Also included for comparison are Pacific plate MORB [16], Site 786 boninites [8,13], basalts from the Quaternary arc [14,15] and basalts from the Sumisu Rift [17].

3.2. Analytical methods

Samples were analyzed for major elements and Ni, Cr, Sc, V, Rb, Sr, Y, Nb, Zr, Ga, Cu and Zn by a Rigaku 3370 XRF spectrometer at the Washington State University GeoAnalytical Lab according to the procedures of Johnson et al. [10]. Precision was tested by multiple analyses of a single specimen. Major element precision is $< 2\%$ of the absolute abundance. Trace element precision is $< 5\%$ except for Rb and Nb, which are 10% in low abundance samples. The rare-earth elements (REE) and trace elements Ba, Th, Hf, Ta, U, Pb, Rb and Cs were also analyzed at Washington State University by a Sciex Elan model 250 ICP-MS equipped with a Babington nebulizer, water-cooled spray chamber and Brooks mass flow controller. The precision on in-house standards

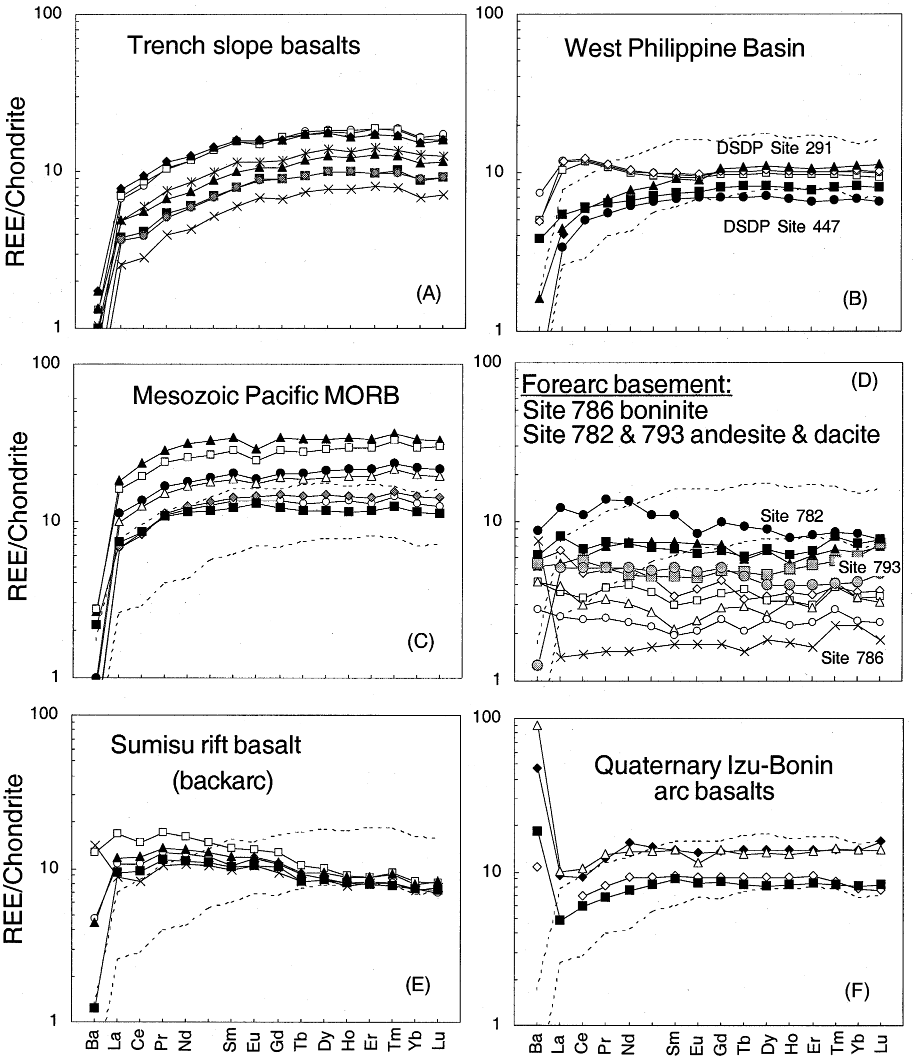

Fig. 4. REE patterns of (A) inner trench slope samples, (B) West Philippine Basin [20], (C) Mesozoic Pacific MORB [16], (D) Forearc basement drilled by ODP at Sites 786, 782 and 793B [13,18,19], (E) Sumisu Rift [17] and (F) active arc basalts from the Shichito Ridge and Torishima knoll [15,17]. Normalization values are from Taylor and McLennan [39].

BCR-P basalt is better than 1.5% for Ce, Pr, Nd, Gd, Tb, Dy, Ho, Er, Tm, Yb, Y and Hf, better than 2.5% for Ba, La, Sm, Eu, Lu, Rb, Y and Nb, better than 3.5% for Ta, Cs and Pb and better than 10% for Th and U. Reported ICP-MS detection limits are 0.1–0.5 times chondrite values (Charles Knaack, personal communication).

Isotope analyses were performed at the University of Hawaii. Forty–sixty mg of sample powders was processed from acid-washed rock chips and analyzed for Sr, Nd and Pb isotopes in the SOEST Mass Spectrometry Lab. Lead was purified on anion-exchange resin using HBr-HNO_3 chemistry under class-100 conditions. The non-Pb fraction was collected and processed sequentially to isolate Sr and the REE on HCl columns. This was followed by Nd purification from other REE on cation resin using 2-methyllactic acid.

Table 3
Isotopic analyses of selected samples from the Izu–Bonin inner trench slope

	Myojin Seamount	Dive #150	Dive #169
Sample	BT-1	150-02	169.01a
Description	Coarse gr. diabase	Fine gr. diabase	Fine gr. basalt
Pb (ppm)	0.093	0.196	0.139
$^{206}Pb/^{204}Pb$	18.21	18.42	18.46
$^{207}Pb/^{204}Pb$	15.51	15.53	15.50
$^{208}Pb/^{204}Pb$	38.03	38.16	38.04
$^{143}Nd/^{144}Nd$	0.513077	0.513057	0.513063
ε_{Nd}	8.5	8.1	8.3
$^{87}Sr/^{86}Sr$ (unleached)	0.70346	0.70428	0.70359
$^{87}Sr/^{86}Sr$ (leached)	0.70333	0.70373	0.70321

Leached Sr analyses were obtained by subjecting a split of the sample powders to a harsh, multi-step technique using repeated attacks of 6 N HCl during sonification, in order to remove a seawater Sr signature from altered rocks [11].

Samples were analyzed on a Micromass Sector mass spectrometer in multicollector mode. Sr was analyzed in dynamic mode, loading approximately 100 ng Sr onto finely ground tantalum powder on a tungsten filament. Nd ($\sim$25 ng) and Pb ($\sim$6–8 ng) were analyzed using silica-gel phosphoric acid on a Re filament, Nd in dynamic and Pb in static mode.

Isotopic fractionation factors are $^{148}Nd/^{144}Nd = 0.241572$, $^{86}Sr/^{88}Sr = 0.1194$. The lab's value for LaJolla Nd is $^{143}Nd/^{144}Nd = 0.511843 \pm 0.000009$, or $\sim$0.15 epsilon units, and for SRM 987, it is $^{87}Sr/^{86}Sr = 0.71024 \pm 0.00002$ (both $2 \times$S.D.). Pb isotopes are corrected for fractionation using the values of Todt [12] and the total ranges measured on NBS 981 are ± 0.008 for $^{206}Pb/^{204}Pb$, 0.008 for $^{207}Pb/^{204}Pb$ and 0.030 for $^{208}Pb/^{204}Pb$. In-run errors for individual samples are less than the stated uncertainties on standards. Total procedural blanks are < 40 pg for Pb, < 20 pg for Nd, < 120 pg for Sr. Zero-age epsilon Nd corresponds to $^{143}Nd/^{144}Nd = 0.51264$ for $^{147}Sm/^{144}Nd = 0.1967$.

3.3. Geochemistry

Whole-rock compositions of the trench inner slope samples (Table 2) define a tholeiitic trend on an AFM diagram, with 8.5–14.0 wt% (wt.%) FeO. They are all basaltic, except for sample 150-01a, which is a basaltic andesite (52.7% SiO_2). They have low to moderate Al_2O_3 (13.5–16 wt.%), moderate MgO (6–10 wt.%) and TiO_2 (0.7–1.8 wt.%) and low K_2O (< 0.5 wt.%). They are distinctive in their extremely low Ba contents (1.5–7 parts per million (ppm)). None of the samples are boninitic. They bear no geochemical resemblance to the Eocene boninitic samples recovered just upslope from the forearc basement in Site 786 of ODP Leg 125. They also do not resemble tholeiitic basalts of the modern Izu–Bonin arc or backarc.

The relative variations of the major elements and some of the minor elements of the inner trench slope samples are plotted on MgO variation diagrams in Fig. 3. They are compared to forearc basement recovered at Site 786 of ODP Leg 125 [8,13], basalts from the Quaternary Izu–Bonin arc [14,15], Pacific plate MORB [16] and basalts from the Sumisu Rift [17]. Although only data for Al_2O_3, Na_2O, TiO_2, Ni, Zr and Sr are shown, a decreasing MgO content in the trench slope samples correlates with increasing K_2O, P_2O_5, TiO_2, FeO and Na_2O and scattered CaO, Al_2O_3 and SiO_2. The compatible minor elements Cr and Ni decrease with decreasing MgO, whereas the incompatible elements Ba, Zr, Nb, Rb and Y increase with decreasing MgO. Values of Sr increase slightly.

As seen in Fig. 3, these trench slope samples are distinct from the ODP Site 786 forearc basement samples. The latter have much more MgO and SiO_2, lower Al_2O_3, FeO, TiO_2 and P_2O_5 but sim-

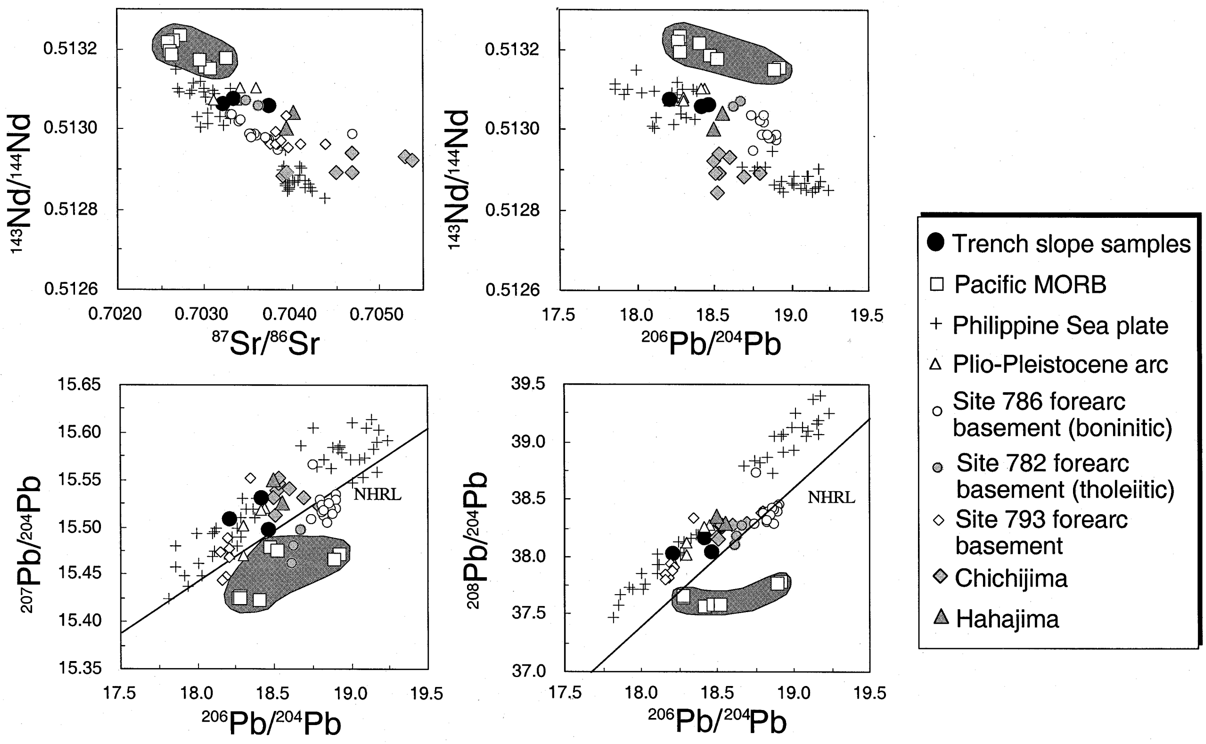

Fig. 5. Isotopic systematics (present-day ratios) for the inner trench slope samples compared to Pacific plate MORB [16], forearc basement drilled from ODP Site 786 [18], Site 792 [18] and Site 793 [19] (see Fig. 1), boninite from the islands of Chichijima [23] and Hahajima [22], Plio-Pleistocene Izu–Bonin arc volcanics from Torishima and Miyakejima volcanoes [14] and other Philippine Sea plate submarine lavas including the West Philippine, Parece Vela and Shikoku Basins [20,21] and the Sumisu Rift [40].

ilar CaO, Na_2O and K_2O. They are also distinctive in their trace elements: trench slope samples have lower Ba, Rb, Sr, Ni and Cr and higher Zr, Y and Nb than the boninite samples. The trench slope samples also do not look like modern-day arc magmas erupted from Izu–Bonin volcanoes. They have much lower Sr and higher Ti, Nb, Ni and Cr. They do not show the marked enrichment in large-ion lithophile elements such as K, Rb and Ba relative to MORB, nor other trace element characteristics typical of island arc tholeiites. They are quite depleted in Ba (1.5–7 ppm) and have low Ba/La (1.2–3) and Ti/Zr (93–112), more typical of MORB.

Chondrite-normalized REE patterns for the inner trench slope samples (Fig. 4) show depletion of the light REE and Ba, with values of La/Yb_{CN} from 0.4 to 0.6. The patterns for each of the samples are strikingly parallel, even for the samples dredged from Myojin forearc seamount. The samples do not have the typical enrichment of large-ion lithophile elements (such as Ba) that is so characteristic of island arc magmas, including basalts from the Quaternary Izu–Bonin arc [14,15], boninites from the forearc basement [13,18,19] and Neogene sills from the Mariana and Izu–Bonin forearcs [7]. They also do not share REE characteristics with backarc basin basalts of the Sumisu Rift [17] or the Shikoku Basin [5,20]. The REE patterns do, however, show similarities to Mesozoic Pacific MORB [16] and MORB from the West Philippine Basin [20], although the Pacific plate samples show flatter patterns with generally higher abundances for a given MgO content than the trench slope samples (Fig. 4). West Philippine Basin MORB sampled at Deep Sea Drilling Program Site 447 [20] have REE patterns most closely related to the trench slope samples.

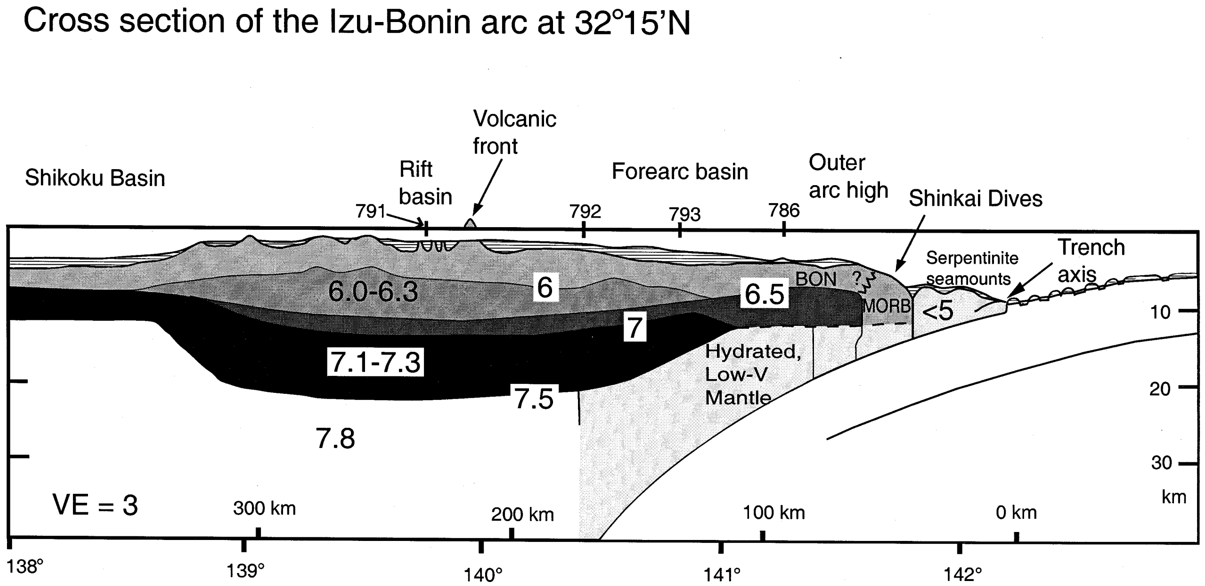

Fig. 6. Schematic west-east section across the Izu–Bonin arc-trench system after Suyehiro et al. [30]. Numbers 791, 792, 793 and 786 refer to ODP Sites (positions projected along strike). Large numbers are seismic velocities in km/s. BON region is boninitic crust sampled at Site 786, MORB region is mid-ocean ridge crust sampled by Shinkai dives.

One sample in particular, 21-1 (filled triangles in Fig. 4), has a pattern identical to several of the inner trench slope samples.

3.4. *Isotope geochemistry*

Strontium, neodymium and lead isotopes were analyzed on three of the Izu–Bonin trench slope samples (BT-1, 150-02 and 169-01a) (Table 3). The samples have a very consistent $^{143}Nd/^{144}Nd$ (0.513057–0.513077), but more variable $^{87}Sr/^{86}Sr$ (unleached samples: 0.70346–0.70428; leached samples: 0.70321–0.70373). Acid leaching to remove Sr added by seawater exchange significantly lowered Sr isotopic ratios. Lead isotopic ratios are fairly limited in range, with $^{206}Pb/^{204}Pb = 18.21$–18.46, $^{207}Pb/^{204}Pb = 15.3$–15.5 and $^{208}Pb/^{204}Pb =$ 38.0–38.2.

The trench slope samples are compared to Pacific plate MORB and a variety of Philippine Sea plate samples in Fig. 5. It is clear that the trench slope samples have a lower $^{143}Nd/^{144}Nd$ and higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$ than Pacific plate MORB. They fall above the Northern Hemisphere reference line (NHRL), whereas Pacific plate MORB characteristically plot on or below this line [16]. Their values do fall on a trend that is characteristic of a variety of lavas from the Philippine Sea plate. These include MORB-type basalt from the West Philippine, Parece Vela and Shikoku Basins [20,21], as well as arc-related lavas from the Palau Kyushu ridge [21], the modern arc front [14] and forearc boninites [18,19,22,23]. This characteristic isotopic signature of Philippine Sea plate rocks is the same as that from Indian Ocean spreading ridges and is interpreted to be due to a shared asthenospheric mantle domain [20,24]. This Indian Ocean mantle domain is distinct from that of Pacific plate MORB [20,24].

Interestingly, although the trench slope samples shown in Fig. 5 are similar in Pb isotopic ratios to samples from the Quaternary arc [14,15] and some Philippine Sea plate MORB, they are distinct from boninitic and tholeiitic samples drilled during ODP Leg 125 (Sites 786 and 782). Leg 125 is located just 3 km shallower on the outer arc high east of the dive site (Fig. 1). These latter forearc basement samples plot on or just below the NHRL and lie very close to Pacific MORB mantle. Surprisingly, this odd isotopic signature is not shared by the subaerially exposed Eocene tholeiites and boninites from Hahajima [22] and Chichijima [23], also on the outer arc high. Pearce et al. [18] interpreted the Pb isotopic trends of Site 782 and 786 samples to be due to simple mixing between Pacific MORB mantle and Pacific hotspot component or volcanogenic sediment. Because they plot near the NHRL, they have little or no Pb derived from subducted pelagic sediment in their source. Hence, although spatially very close, the trench slope samples and the outer arc high forearc basement must be derived from very distinct sources.

4. Discussion

The presence of massive cliffs of pillowed lavas on the inner trench slope for at least 400 vertical meters (6100–6500 m water depth), and probably much more (Fig. 2), suggests that a good portion of the inner trench slope of the Izu–Bonin arc is not plutonic. These lavas are present at least 3000 m deeper than the volcanic material drilled from the outer arc high at ODP Site 786 (Fig. 1). More surprising, however, is the fact that these inner trench slope lavas have a geochemical signature that does not resemble those drilled lavas, nor do they resemble any typical arc magma. The REE patterns shown in Fig. 4 and other tectonic discrimination diagrams [5] argue that these trench slope samples are indistinguishable from N-MORB.

What is the origin of these N-MORB basalts? Specifically, were they accreted from the Pacific plate or are they a remnant of trapped Philippine Sea plate? In the Mariana arc, MORB-like lavas were also dredged from the outer forearc [25]. However, an 85 Ma minimum K-Ar age and associated chert with Valanginian (131–138 Ma) and Albian (97–112 Ma) foraminifers conclusively supported an accreted origin for these rocks [26]. The chert and volcanic rocks are too old to have formed in situ or to be part of trapped West Philippine Basin crust. The samples discussed in this study have some similar characteristics to the Mariana MORB-like samples. However, there is no associated chert that could adequately discern rock ages. Ubiquitous glass devitrification and small sample size preclude analysis by K-Ar or ^{40}Ar/^{39}Ar. The alternative test, isotopic signatures, proved to be equally conclusive. Because Pacific plate MORB has distinctly different Nd, Sr and Pb isotopic characteristics than almost all rocks from the Philippine Sea plate, the isotopic signature of the trench slope basalts analyzed herein provides a definitive test (Fig. 5). The isotopic characteristics of these basalts are distinct from those of Pacific plate MORB but overlap the fields for Philippine Sea plate rocks (Fig. 5).

This conclusion is significant for two reasons. Firstly, it constrains the physical structure and composition of the Izu–Bonin arc. To date, no trapped MORB oceanic crust has been recovered from drilling, on-land sampling or dredge hauls from the Izu–Bonin arc [27]. This led to the assumption that no pre-existing crust exists and that the entire arc infrastructure is made up of new, supra-subduction magmatic addition. Hence, interpretive cross sections of the arc do not take into account the fate of pre-existing crust [28–30]. The discovery of trapped MORB on the inner trench slope suggests that the structure of the arc may need to be re-evaluated. This trapped crust may exist in other parts of the arc, but as with the inner trench slope, it may have been passed over by previous sampling campaigns. In Fig. 6, we present a simplified cross section of the Izu–Bonin arc that also shows the ODP drill sites projected along strike and the location of the MORB sampled by the Shinkai dives. We interpret the low velocities in the forearc above the subducted plate as hydrated low velocity mantle. In this interpretation, the crustal structure (thickness and velocities) beneath Site 786 is similar to that of oceanic crust and may represent an in situ ophiolite [27]. We do not know how much trapped MORB crust may exist. If the early arc formed under extension, much of the pre-existing oceanic crust could be rifted away, but some could be trapped within the arc as isolated crustal sections or slivers. These sections, with seismic velocities of

4.5–7 km/s, would be surrounded and/or intruded by new arc products from which they would be difficult to distinguish seismically.

If we assume that the early arc formed under extension and that much of the pre-existing MORB crust was rifted away to form the modern arc and forearc, then, the boundary between the boninitic forearc basement and the MORB basalts on the inner trench slope represents the eastern 'edge' of the Izu–Bonin arc. Where then is the western edge? Reconstruction of the early arc by closing of the rift and backarc basins suggests that the western edge should be just to the west of the Palau Kyushu ridge, north of the Daito Ridge (region enclosed by dashed right-angle triangle in Fig. 1). This East Amami Triangle oceanic basin is unsampled, but is likely to be the counterpart to the trapped MORB on the inner trench slope. Future drilling could test this hypothesis.

The presence of trapped oceanic crust also has implications for calculation of magma production rates in the early Izu–Bonin arc. Bloomer et al. [27] suggest that magma production rates were as high as 80–180 km^3/km Ma in the first 10–15 million years of arc growth. These rates are much higher than those estimated for magma production at mature arcs and are comparable to crustal production rates at slow-spreading oceanic ridges. Their calculations are based on the assumption described above that the entire forearc represents arc-related magmatic addition and that there is no trapped oceanic crust. They assume a 200–300 km wide arc and a crustal thickness of 6 km. If, however, a significant volume of trapped oceanic crust does exist within the forearc, magma production rates will necessarily be lower.

Models for the physical structure and composition of arc basement vary in their proportions of new magmatic addition, trapped oceanic crust and accreted oceanic sections. The velocity structure within 100 km of the volcanic front of the Izu–Bonin arc is consistent with the formation of felsic middle crust in the arc (Fig. 6) [30]. In contrast, trapped oceanic crust and a more mafic arc crust are inferred from velocity models to be present in the Aleutian arc [31,32] and have been found within uplifted sections of island arcs [33,34]. Accreted oceanic slivers [35,36] have been sampled within the Mariana forearc [26] and imaged within the Sulu forearc [37,38]. Clearly, the varying proportion of these three components must be determined before the physical structure of arcs and magma production rates within them can be adequately quantified.

5. Conclusion

Samples collected from 6200–6700 m water depth in the Izu–Bonin trench represent the first samples of trapped Philippine Sea plate oceanic crust discovered in the Izu–Bonin–Mariana arc to date. They have no affinity with the Eocene boninitic rocks drilled upslope in the forearc at ODP Site 786, nor are they similar to rocks from the active arc or backarc. Their geochemistry more closely resembles typical MORB. Isotopic and geochemical characteristics point to an origin within the Philippine Sea plate and preclude a genetic relationship to subducting Pacific plate crust. We suggest here that these N-MORB rocks represent a remnant piece of Philippine Sea plate oceanic crust that was unaffected by arc magmatism. They represent pre-existing crust that may be interspersed throughout the forearc with unknown extent. They require that models for the formation of intra-oceanic arc crust account for pre-existing oceanic crust and that estimates of arc magma production rates are lowered accordingly.

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