MORB-type Basalts on the Inner Wall of the Izu -Bonin Trench—Accreted Pacific Plate or Pre -existing Crust?

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Three dives in the "Shinkai 6500" submersible were made on the inner trench wall of the Izu Bonin arc at 32°N in order to sample arc basement and test models of forearc evolution. Our dives were focused on basement outcrops exposed between 5,500 and 6,500m water depth in a region considered to lack an accretionary wedge. Six samples were collected and analyzed and provided an unexpected result: a distinct mid-ocean ridge basalt (MORB) chemistry unlike any other rocks previously sampled in the Izu Bonin arc. These rocks are distinctly different from forearc basement (boninitic) rocks drilled from Site 786 of ODP Leg 125 on the outer arc high just upslope from our dive sites. They are also unlike any of the active arc or backarc volcanic rocks. They are tholeiitic with moderate TiO_2 (0.8 to 1.8 wt.%), extremely low Ba (1.5 to 7 ppm), low Ba/La ratios (2 to 5), and are light-REE depleted. The origin of these MORB-like rocks is problematic. They may either represent an early accretion event of subducting Pacific plate, or they may represent a trapped piece of remnant Philippine Sea plate.

Key words: Island arc, Igneous petrology, Mid-ocean ridge basalt, Izu Bonin, "Shinkai 6500"

1. Introduction

In 1992 and 1993 three dives to between 6,100 and 6,500m water depth on the inner trench wall of the Izu-Bonin arc at 31°59′N were made in the "Shinkai 6500" (Fig.1). The dives were part of a Japan - United States cooperative deep-sea research program. The primary goal of these three dives was to collect samples from the trench wall in an attempt to recover arc basement. Seismic reflection profiles (Honza and Tamaki, 1985; Horine et al., 1990) show that the steep inner wall of the Izu-Bonin trench likely exposes arc basement below 5km, above and possibly below a terrace of serpentinite seamounts (Fig.2). This is corroborated by two SeaMARC II sidescan swaths near 32° N (Fig.3) that reveal high amplitude acoustic backscatter from the slope between 5,200-6,700m. Together with the seismic reflection profiles, the sidescan data indicate that 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 1,500m thick.

The rationale for these "Shinkai" dives was to exploit the extremely rare opportunity to study in situ the basement of an intra-oceanic island arc. Two "Shinkai" dives in 1992 and two in 1993 were proposed in order to make a traverse and composite stratigraphic and structural profile of the basement section above 6,500m, with the aim of sampling both the structurally deepest and most seaward section of the central Izu-Bonin arc basement (~40km east of

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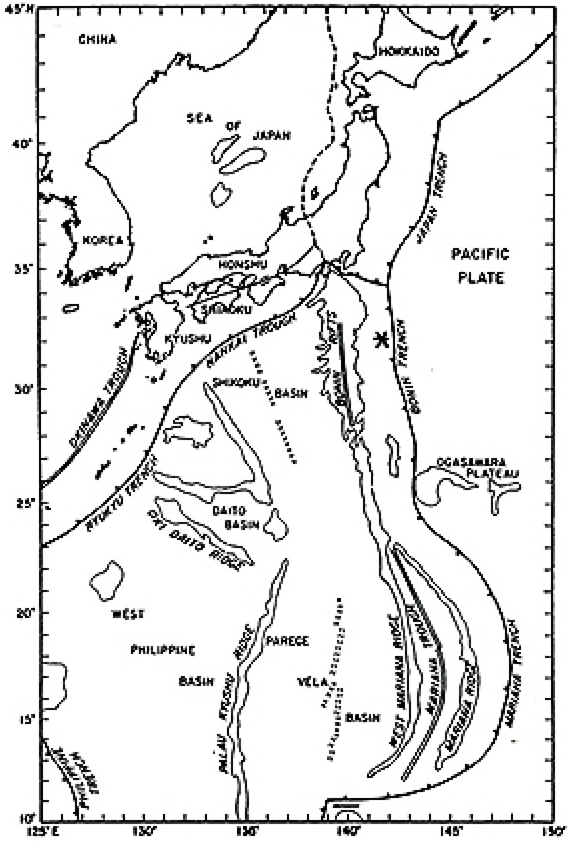

Fig.1 Location map of "Shinkai 6500" dive site showing bathymetry and geologic features in the Philippine Sea region (from Taylor, Fujioka et al., 1992). Basins and ridges are outlined by the 4km bathymetric contour, except for the Izu-Bonin arc, West Mariana Ridge, and Mariana arc, which are outlined by the 3km contour. Filled triangles mark trench axes; medium double lines show active spreading centers; dashed double lines show relict spreading centers.

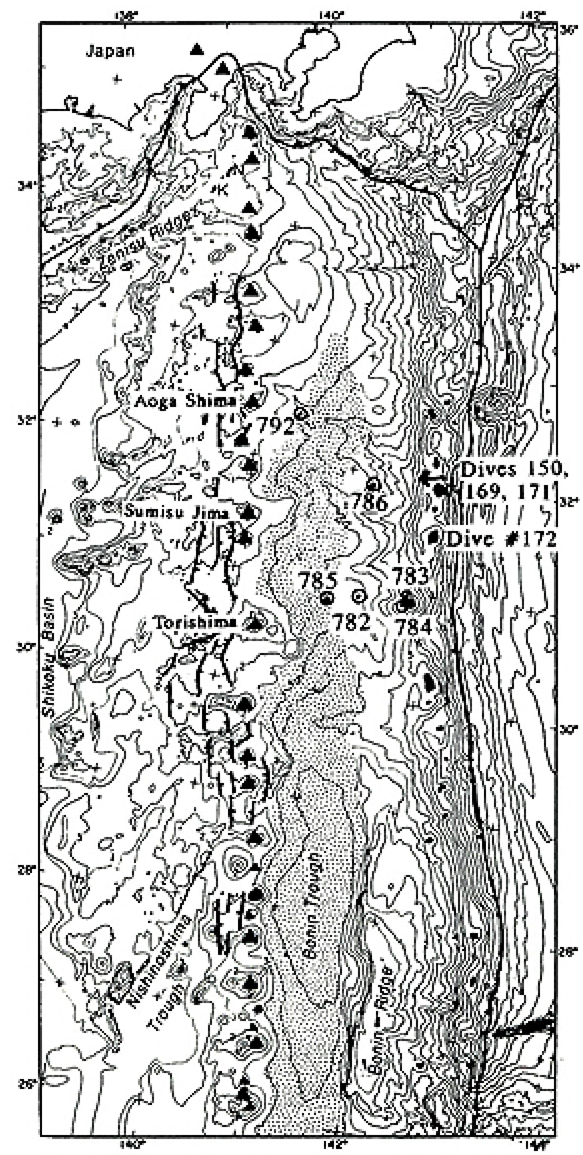

Fig.2 Bathymetry (500-m contour intervals, labeled every kilometer) of the Izu-Bonin arc trench system modified after Taylor (1992). Barbed heavy lines locate trench axes, filled bathymetric contours locate serpentinite seamounts on the trench inner wall, filled triangles locate frontal arc volcanoes, 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 wall at 32°N.

ODP Site 786 and only 35-45km from the trench axis) (Fig.2). We hoped to directly examine and sample the deep plutonic roots that feed the surficial boninitic and arc tholeiitic volcanic systems that form the outer-arc high (which were sampled about 3,000m higher at Site 786 and are exposed on the Bonin Islands) in order to better understand the formation of island arcs and of continental crust formed by their accretion.

An additional goal of these dives was to test between the alternate models of forearc evolution and inner trench wall tectonism proposed by Hussong and Uyeda (1981) and Bloomer and Fisher (1987). 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, Hussong and Uyeda (1981) explained the presence of arc lavas, and their apparent subsidence to great depths on the inner trench wall, to be the result of tectonic erosion of the forearc by high-angle normal faulting. In contrast, in the Tonga Trench Bloomer and Fisher (1987) found an apparently coherent crustal and upper mantle section on the inner wall and appealed to flexural uplift of the arc footwall beneath a low angle normal fault to explain this occurrence.

Our dives produced surprising results. Instead of finding boninitic or arc-related volcanic rocks, or plutonic basement rocks that would support either of the two forearc evolutionary models proposed above, the samples recovered were MORB-like diabase and basalt. These findings present two likely possibilities, that the forearc includes remnant pieces of Philippine Sea plate basalts or that pieces of the downgoing Pacific plate have been accreted.

2. Geologic Setting

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 the result of studies by the Geological Survey of Japan, the Ocean Research Institute of the University of Tokyo, the Hydrographic Department of Japan, JAMSTEC, JNOC and JAPEX, the Hawaii Institute of Geophysics, and the Ocean Drilling Program. Fig.4 shows

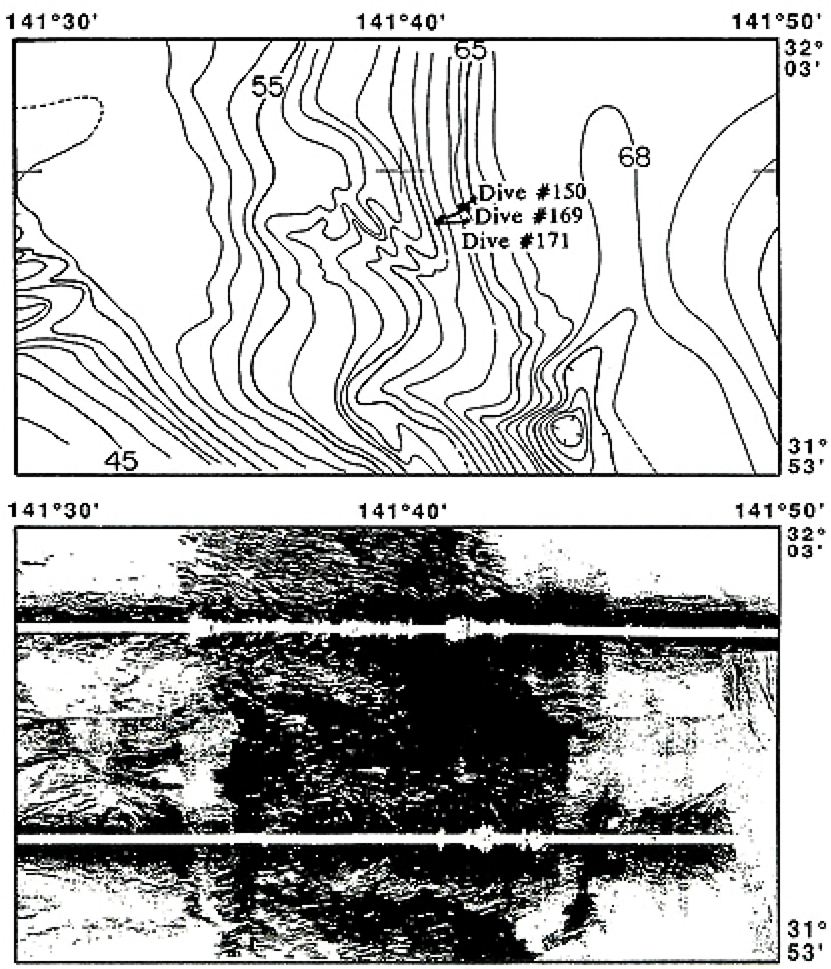

Fig.3 Previously unpublished SeaMARC II bathymetry (100m contours, top) and acoustic imagery of (bottom) of the Izu-Bonin trench inner wall at 32 N (see Fig.2 for location). On the acoustic image, note the highly reflective slope between 5,200 to 6,700m, where seismic reflection records also indicate that arc basement is exposed. Locations of the dives are marked with heavy lines.

details of the arc system discerned from Geological Society of Japan single-channel seismic profiles from the Pacific Basin to the Shikoku Basin. The trench is well-developed and extends to nearly 10,000m water depth. The 200-km-wide forearc region includes an inner-trench slope with a terrace formed by sediments ponding behind and between spaced serpentinite seamounts. Further west there is an outer arc high, which becomes subaerial in the Bonin Islands, and then a thick forearc sedimentary basin east of the linear active volcanic chain. The backarc region includes active rift basins as well as cross-chains of submarine arc volcanoes that extend WSW into the Shikoku basin.

The history of the Izu-Bonin arc system has been described in detail by Taylor (1992). The earliest arc volcanism occurred during the middle and late Eocene, when a vast terrane of boninites and island arc tholeiites (>300km wide) was formed. This early arc terrane is unlike any modern arc systems but is similar to many ophiolites (Bloomer et al., 1995). 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, creating sags and half grabens in the forearc and backarc. The arc volcanism decreased in intensity at 27 Ma and was a minimum 23-17 Ma, with no record of volcanic ash 23-20 Ma during 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 spaced (27 and 47km), long-lived centers, but arc tholeiites have occasionally intruded the thermally cool forearc. The present rifting of the central Izu-Bonin arc (Sumisu rift) began about 2 Ma and extends from 27.5°-33.5°N (Fig.2). Syn-rift sediments are pervasively faulted and often intruded. Both the Sumisu rift at ODP Sites 790 and 791 and the forearc basin at ODP Site 793 are floored with syn-rift volcanics that are geochemically distinct from their contemporary frontal arc volcanics. The oldest (>1.

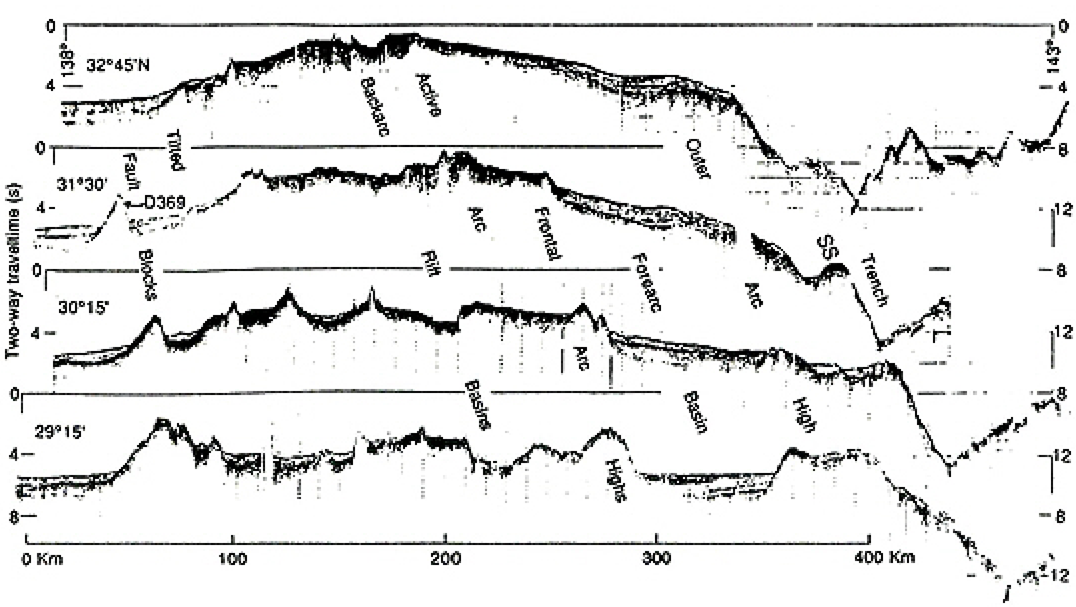

Fig.4 Geological Survey of Japan single-channel seismic profiles across the Izu-Bonin arc trench system, from the Pacific Basin (143°E) on the right to the Shikoku Basin (138°E) on the left, from Taylor (1992). The vertical exaggeration is 10.

1 Ma) to the youngest (Holocene) Sumisu Rift lavas are backarc basin basalts, whereas pre- and syn-rift arc volcanism is mostly low K, subalkaline, rhyolite and andesite. The Oligocene forearc volcanics are dominantly high-Mg, low Ti, two-pyroxene basaltic andesites and andesites, similar to the Eocene volcanics of the outer arc high (e.g. Bonin Islands).

3. Previous work

The basement of the Izu-Bonin forearc adjacent to our dive area was extensively studied during the drilling program of ODP Leg 125 (Fryer and Pearce et al., 1992) and Leg 126 (Taylor, Fujioka et al., 1992) (Fig.2). At Site 786 (31°52N), a complex suite of igneous basement rocks was recovered from a core that penetrated to 661m (Arculus et al., 1992). Site 786 is located on the forearc basement high, the southward continuation of which is exposed above sea level in the Ogasawara (or Bonin) Islands (Fig.2). The Ogasawara islands are famous for their exposures of boninitic volcanic rocks. The dominant rock type recovered from Site 786 is also boninite, indicating that boninitic volcanism occurred along strike for a long distance. Three types of boninites and their differentiates were recovered (Murton et al., 1992). They were erupted during two episodes of magmatism, an early episode at 41-48 Ma that produced low-Ca boninites and bronzite andesites overlain by intermediate -Ca boninites, bronzite andesites and a fractionated series of andesites, dacites, and rhyolites. The later episode at 35 ma produced high -Ca boninites and intermediate-Ca boninites (Murton et al., 1992). Murton et al. (1992) suggest that all of the evolved chemical groups at Site 786 can be related back to the three boninite groups, high-, medium-, and low-calcium boninites, which represent distinct parental magmas. Relative to MORB, the boninites have low Ti, Y, and HREE, but are enriched in LIL elements, LREE and selected HFS (Zr, Hf). This latter enrichment reflects the addition of a subduction component to the boninite source region.

The calc-alkaline lavas drilled at Sites 792 and 793, and dredged from the frontal arc highs, and the Eocene tholeiites and boninites exposed on the Bonin Ridge along strike to the south, had previously provided the only in situ samples of the Izu-Bonin arc basement. All are shallow extrusives and dikes. The only samples of Izu-Bonin middle crustal or plutonic rocks are the late Miocene diorites, tectonically exposed by accretion, in the Tanzawa Mountains west of Tokyo (Taira et al., 1989).

It was our intent that sampling the inner trench wall at the same latitude as Site 786, but at much deeper levels (6,500m below sea level), would provide the deeper plutonic roots to the boninite series. When it became clear that the samples we collected were volcanic rocks not at all related to boninites, we recognized some similarities to samples collected from the outer-arc high of the Mariana trench (Johnson and Fryer, 1990; Johnson et al., 1991). These workers found radiolarian cherts and foraminifers with Cretaceous ages, together with MORB-like volcanic rocks, that they interpreted as allochthonous fragments of Cretaceous oceanic crust that had been accreted to the Mariana forearc.

4. Results of this study

4.1 Dive descriptions

The submersible "Shinkai 6500" was utilized on two research cruises of the JAMSTEC ship R/V "Yokosuka" in the Izu-Bonin area during September of 1992 and 1993. In total, three dives were completed and five samples were collected on the trench inner slope in the region of 31°59'N and 141°41' to 141°42'E (Fig.2 and 3). A greater sampling load was inhibited by the cohesiveness of the outcrop. The robust mechanical arm of "Shinkai" was in many cases unable to remove pieces of the abundant outcrop.

The 1992 dive (#150) made observations from 6,491 to 6,383m water depth between 31°59.221'N, 141°42.198'E and 31°59.043'N, 141°41.785'E. Dive #150 had 2 hours 2 minutes of total bottom time; however, we had only one hour of bottom sampling/observation time as a result of a power leakage from the number 2 camera strobe. The second dive was lost due to bad sea and weather conditions and so our planned traverse of the inner wall was severely curtailed.

Two dives (#169 and #171) were completed in 1993.

Table 1a Geochemical analyses of samples from the Izu Bonin inner trench wall.

	Myojin Sho samples		Dive #150				Dive #169	
	BT-1 diabase	BT-2 diabase	150-01a clast	150-01b clast	150-02 diabasic	150-03 devitrified glass	169.01a	169.01b
SiO_2	50.5	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*	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
Q	-	0.5	3.4	0.6	1.8	-	-	-
C	-	-	-	-	-	-	-	-
Or	0.5	0.5	2.5	0.8	1.2	1.1	1.71	1.60
Ab	14.3	20.8	25.6	21.0	26.1	27.6	19.55	19.46
An	34.0	26.9	23.1	27.3	23.6	22.1	33.00	33.00
Di	23.4	19.4	11.7	18.0	6.1	20.9	22.67	23.51
Hy	22.5	27.2	27.1	27.4	34.9	12.4	14.22	11.90
Ol	2.2	-	-	-	-	9.7	5.18	6.41
Mt	1.4	1.9	2.1	2.0	2.1	2.3	1.41	1.41
Il	1.3	2.3	3.4	2.1	2.7	3.2	1.57	1.55
Ap	0.1	0.2	0.3	0.2	0.3	0.3	0.12	0.12
Mg/(Mg+Fe)	66.8	55.8	44.7	52.2	52.0	45.4	61.7	61.6
Sr	54	70	81	74	80	80	79	78
Rb	0.7	0.7	7.6	2.7	1.1	1.2	7.0	5.0
Nb	0.4	0.8	2.0	1.3	1.1	1.1	4.3	2.1
Zr	37	73	96	60	93	91	47	47
Y	18	31	36	28	38	40	22	23
Ni	115	62	43	42	44	30	98	109
Cr	407	152	147	59	95	50	353	353
V	264	355	431	360	384	496	288	276
Ba	1.5	4.2	6.9	5.4	5.2	3	4	2
Ta	0.04	0.07	0.15	0.1	0.11	0.1	0.04	0.04
Hf	0.81	1.68	2.54	1.47	2.34	2.27	1.16	1.07
La	2.84	1.79	2.56	2.47	0.95	1.81	1.4	1.33
Ce	9.08	5.29	8.19	7.81	2.73	5.84	3.99	3.77
Pr	1.59	0.93	1.44	1.45	0.55	1.05	0.75	0.7
Nd	8.96	5.28	8.4	8.4	3.05	6.16	4.31	4.2
Sm	3.69	2.33	3.58	3.61	1.41	2.66	1.84	1.83
Eu	1.39	0.93	1.29	1.36	0.6	1.01	0.79	0.77
Gd	4.88	3.28	5.03	5.04	2.06	3.59	2.77	2.75
Tb	1	0.69	1.01	1.04	0.43	0.76	0.54	0.54
Dy	6.68	4.82	6.88	7.06	2.95	5.33	3.84	3.81
Ho	1.41	1.04	1.5	1.56	0.66	1.15	0.85	0.85
Er	4.25	3.19	4.63	4.66	2	3.52	2.42	2.44
Tm	0.6	0.45	0.65	0.67	0.28	0.49	0.36	0.35
Yb	3.77	2.79	3.98	4.14	1.7	3.17	2.21	2.25
Lu	0.61	0.44	0.61	0.65	0.27	0.48	0.35	0.35

Table 1b Geochemical analyses of samples from other parts of the Izu Bonin arc system.

	Dive #172 - Sumisu forearc seamount					Dive #177 - Shikoku basin (rift)				
	172-01d	172-02a	172-02b	172-02g	172-04a	177-01a	177-01c	177-02a	177-02b	177-04b
SiO_2	67.51	46.67	50.97	54.34	47.34	49.68	49.53	49.02	48.83	50.02
TiO_2	0.60	2.02	0.57	1.20	2.68	1.07	1.06	1.04	1.06	1.18
Al_2O_3	13.33	12.86	15.17	15.69	13.51	18.41	18.99	19.66	19.73	18.36
FeO*	4.51	11.5	10.16	10.9	11.97	8.72	9.55	9.5	9.62	9.64
MnO	0.17	0.23	0.19	0.15	0.37	0.12	0.12	0.17	0.22	0.17
MgO	2.96	7.7	7.99	3.99	5.59	4.96	3.71	4.21	3.98	3.85
CaO	0.99	10.53	13.03	8.11	10.9	12.61	12.38	12.39	12.37	11.38
Na_2O	2.56	3.39	1.74	4.16	3.58	2.61	2.65	3	2.93	2.85
K_2O	2.77	0.71	0.25	0.57	0.81	0.39	0.39	0.42	0.43	0.52
P_2O_5	0.09	0.19	0.13	0.19	0.26	0.38	0.18	0.18	0.19	0.11
Total	95.48	95.79	100.19	99.3	97.01	98.96	98.56	99.59	99.36	98.08
Q	32.84	-	0.15	1.77	-	-	-	-	-	-
C	4.53	-	-	-	-	-	-	-	-	-
Or	16.37	4.20	1.48	3.37	4.79	2.30	2.30	2.48	2.54	3.07
Ab	21.66	21.32	14.72	35.20	23.53	22.08	22.42	25.39	24.79	24.12
An	4.33	17.78	32.84	22.45	18.40	37.37	38.77	38.94	39.41	35.77
Di	0.00	27.28	25.39	13.90	28.16	18.77	18.01	17.82	17.33	16.70
Hy	13.74	0.00	22.70	18.25	0.00	11.62	12.06	0.13	1.27	14.02
Ol	-	15.24	-	-	10.98	2.58	1.14	11.02	10.13	0.46
Mt	0.73	1.85	1.64	1.76	1.93	1.41	1.54	1.53	1.55	1.55
Il	1.13	3.83	1.07	2.28	5.09	2.04	2.01	1.98	2.01	2.23
Ap	0.19	0.41	0.28	0.41	0.57	0.83	0.38	0.39	0.41	0.24
Mg/(Mg+Fe)	53.9	54.4	58.4	39.5	45.4	50.4	40.9	44.1	42.4	41.6
Sr	332	128	114	214	109	181	177	194	194	184
Rb	64.0	11.0	5.0	8.0	11.0	7.0	7.0	26.0	21.0	9.0
Nb	9.1	8.8	2.5	3.3	7.6	3.4	4.7	3.8	5.1	4.9
Zr	123	125	36	86	168	71	70	71	74	85
Y	37	47	20	33	60	31	36	28	28	32
Ni	64	54	40	32	28	25	11	75	64	30
Cr	79	200	279	30	57	266	276	338	308	245
V	71	395	309	472	449	284	307	306	304	262
Ba	183	43	16	200	16	16	19	31	33	24
Ta	0.48	0.34	0.04	0.08	0.33	0.1	0.1	0.09	0.09	0.11
Hf	3.43	2.77	0.75	2.41	4.33	1.75	1.78	1.69	1.69	1.96
La	16.19	5.33	1.68	6.41	6.25	6.45	8.04	4.76	4.87	12.03
Ce	33.84	13.51	3.52	15.13	18.27	9.47	9.24	8.87	9.06	10.07
Pr	4.21	2.18	0.68	2.22	2.97	1.84	2.2	1.67	1.72	2.99
Nd	17.28	11.51	3.79	11.55	16.7	9.44	10.83	8.53	8.68	14.67
Sm	4.94	4.35	1.57	3.92	6.46	3.39	3.66	3.07	3.04	4.56
Eu	1.25	1.52	0.61	1.25	2.19	1.23	1.31	1.14	1.17	1.53
Gd	5.08	5.38	2.19	4.79	8.35	4.38	4.52	3.84	3.82	5.29
Tb	0.99	1.08	0.44	0.91	1.67	0.84	0.87	0.75	0.76	0.99
Dy	6.52	6.97	3.01	5.93	10.89	5.5	5.76	4.87	4.88	6.32
Ho	1.42	1.49	0.67	1.26	2.31	1.21	1.25	1.05	1.05	1.27
Er	4.13	4.25	2.05	3.72	6.72	3.49	3.57	3.04	3.03	3.6
Tm	0.61	0.6	0.29	0.53	0.93	0.49	0.52	0.42	0.44	0.48
Yb	3.88	3.7	1.75	3.22	5.86	3.05	3.1	2.59	2.64	2.92
Lu	0.64	0.6	0.29	0.53	0.91	0.5	0.49	0.42	0.43	0.46

The 2 hours 38 minutes of bottom sampling/observation on dive #169 was from 6,390 to 6,145m water depth between 31°59.100′N, 141°41.810′E and 31°58.952′N, 141°41.293′E. Dive #171 had 3 hours 13 minutes of bottom sampling/observation time from 6,107 and 6,344m water depth between 31°58.986′N, 141°41.603′E and 31°58.999′N, 141°41.101′E.

Dive #150 in 1992 provided the full spectrum of outcrop coverage. The deepest section that we traversed (6,491 to 6,420m water depth) was blanketed by bioturbated, muddy sediments and no outcrop was seen. An isolated boulder near the landing site, a volcanic breccia (150-01), was sampled. Above water depths of 6,420m, the abundance of boulders increased and outcrops were observed. A fresh diabase (150-02) was collected from this region. The outcrops appeared to be well bedded, dipping approximately 20° into the slope of the trench wall and forming steep faces. Sampling of these rocks retrieved small pieces of fine-grained diabase. Further up section, between 6,400 and 6,383m, outcrop became plentiful. The outcrops formed steep cliffs up to 10m high with fresh, exposed faces that proved difficult to sample. A sample retrieved from the base of the cliffs was a devitrified basalt (Sample 150-03, Table 1). Megascale layering in the cliffs was observed, striking approximately N30°W and dipping gently into the cliff approximately 20° SW. At the top of the cliffs there was a jointing that resembled columnar jointing. Steep cliffs alternated with flat muddy areas in this region and may be due to alternating fault surfaces and fault blocks. Only a thin veneer of mud covers the cliff outcrops. Interestingly, no talus slopes or loose rubble were found at the base of the cliffs. No exposures of plutonic rocks were observed anywhere along the traverse.

"Shinkai" Dive #169 in 1993 landed at 6,390m, near the takeoff point of Dive #150. At the landing, there was no visible outcrop, just bioturbated mud and a few boulders. The sea bottom was fairly flat in this region. Further upslope (6,310 to 6,190m), the seafloor became much steeper and huge cliffs (5 to 40 meters in height) appeared. It was very difficult to sample these cliffs as there was no talus slope at the base and the rock was quite solid on the cliff faces. The outcrop appeared to be massive flows or sills; no structure such as bedding, pillows, or columnar jointing was observed. However, there appeared to be an alternating pattern between steep cliff faces and flat muddy steps, which again may represent successive fault blocks. The final part of the area surveyed (6,190-6,150m) had a more gentle slope.

Sampling was successful in only one location at 6,192m water depth (Table 1). This was at a relatively flat area where there was the rare occurrence of some talus at the base of overhanging cliffs. Several samples of fine-grained volcanic rock with very fine-grained mafic phenocrysts were collected here (Samples 169-01a and 169-01b). Once again, no plutonic rocks were observed or recovered in the area traversed.

Dive #171 traversed excellent cliffy exposures during almost all of the observation time. Exposures observed in the cliffs were comprised of very large pillow lavas (1 to 4m wide), dikes, and columnar jointed dikes or flows. As in previous dives, no talus slopes or loose rubble piles were exposed at the base of the cliffs. Alternating with the cliffs were extremely steep sided gullies oriented at NNW-SSE to NNE-SSW. On climbing the cliffs, the submersible would reach a very flat top which then descended into a very steep walled canyon. Crossing the canyons (10 to 30m wide), steep cliffs were encountered at the opposite side. These canyons and gullies are probably fault controlled, indicating that there are trench-parallel faults that cut the inner trench wall. These may be related to subsidence along trench-parallel normal faults. No plutonic rocks were observed at the localities sampled. Although much effort was made, no samples were collected during this dive.

Two additional diabase samples (BT-1 and BT-2, Table 1 and Fig.2) 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. This dredge (KK84-19) was the first (and successful) test of Taylor and Smoot's

(1984) hypothesis that the seamounts along the Izu-Bonin trench inner-wall terrace are formed by serpentinite protrusions similar to those then known in the Mariana forearc. The dredge recovered dominantly serpentinised ultramafics plus the two diabase samples analyzed here. It is not known whether the diabases were 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.

4.2 Petrography of samples collected

Sample 150-01a is a devitrified lava clast in a volcaniclastic breccia. The clast is comprised of approximately 90% devitrified glass with sparse, acicular, very fine-grained phenocrysts of plagioclase and altered clinopyroxene. The clinopyroxene has been converted to actinolite and chlorite. The texture is intersertal.

Sample 150-01b is another clast in the same breccia. It is comprised of almost 100% devitrified glass with some unidentified cryptocrystalline phenocrysts.

Sample 150-02 was collected at the base of very cliffy outcrops. It has diabasic texture and is extremely fine grained. It consists of pyroxene (40%) and plagioclase (50%); however the cpx has been altered to actinolite and chlorite in places. Oxides are also present (8 to 10%).

Sample 150-03 is a partially devitrified glass with sparse (less than 5%) phenocrysts of clinopyroxene and plagioclase.

Sample BT-1 (dredge sample) is a medium-grained diabase containing plagioclase (60%), clinopyroxene (30%), an oxide phase (1%), and perhaps minor olivine. Clinopyroxene has been replaced by chlorite and is somewhat oxidized. The texture is ophitic.

Sample BT-2 (dredge sample) is also medium-grained diabase containing plagioclase (55%), clinopyroxene (43%), opaques (2%), and minor olivine. Pyroxene has been replaced by chlorite, minor actinolite, and some Fe-oxide.

Samples 169-01a and 169-01b are fine-grained basalt with 10% micro- to cryptocrystalline phenocrysts of clinopyroxene and plagioclase and a cryptocrystalline groundmass.

4.3 Geochemistry

Whole-rock compositions of the samples collected from the trench inner wall ("Shinkai" dives #150 and 169 and the R/V Kana Keoki dredge) are given in Table 1a. Table 1b lists data for samples collected by K. Fujioka during dive #172 on the Sumisu forearc seamount and dive #177 on the Kinan escarpment in the Shikoku Basin. Major and trace elements were analyzed by XRF at Washington State University. Selected trace elements and the Rare-Earth elements were analyzed by ICP-MS, also at Washington State University.

The trench inner wall samples define a tholeiitic trend on an AFM diagram, with Fe varying between 8.5 and 14.0 wt.%. They are all basaltic in composition, except for sample 150-01a which is a basaltic andesite at 52.7% SiO_2. They have low to moderate Al_2O_3 content, moderate MgO and TiO_2 contents, and low K_2O contents. They are distinctive in their extremely low Ba contents. None of the samples are boninitic; they bear no geochemical resemblance to the Eocene to Oligocene boninitic samples recovered from the forearc basement in Hole 786 of ODP Leg 125. They also do not resemble modern basalts of the Izu-Bonin arc. The following description of these samples will include comparisons to rocks sampled from other parts of the Izu-Bonin-Mariana arc system.

The relative variations of the major elements and some of the minor elements of the inner trench wall samples are plotted on MgO variation diagrams in Fig.5. Trends for volcanic forearc basement recovered at Hole 786 of ODP Leg 125 (Arculus et al., 1992; Murton et al., 1992) and MORB-like dredge samples from the Mariana outer forearc (Johnson and Fryer, 1990; Johnson et al., 1991) are plotted for comparison. Fig.5 shows that decreasing MgO content in our samples is correlated with increasing K_2O, P_2O_5, TiO_2, FeO, and Na_2O; decreasing Al_2O_3; and scattered CaO and SiO_2. The compatible minor elements Cr and Ni decrease with decreasing MgO, whereas the incompatible elements Ba, Zr, Nb, Rb, and Y

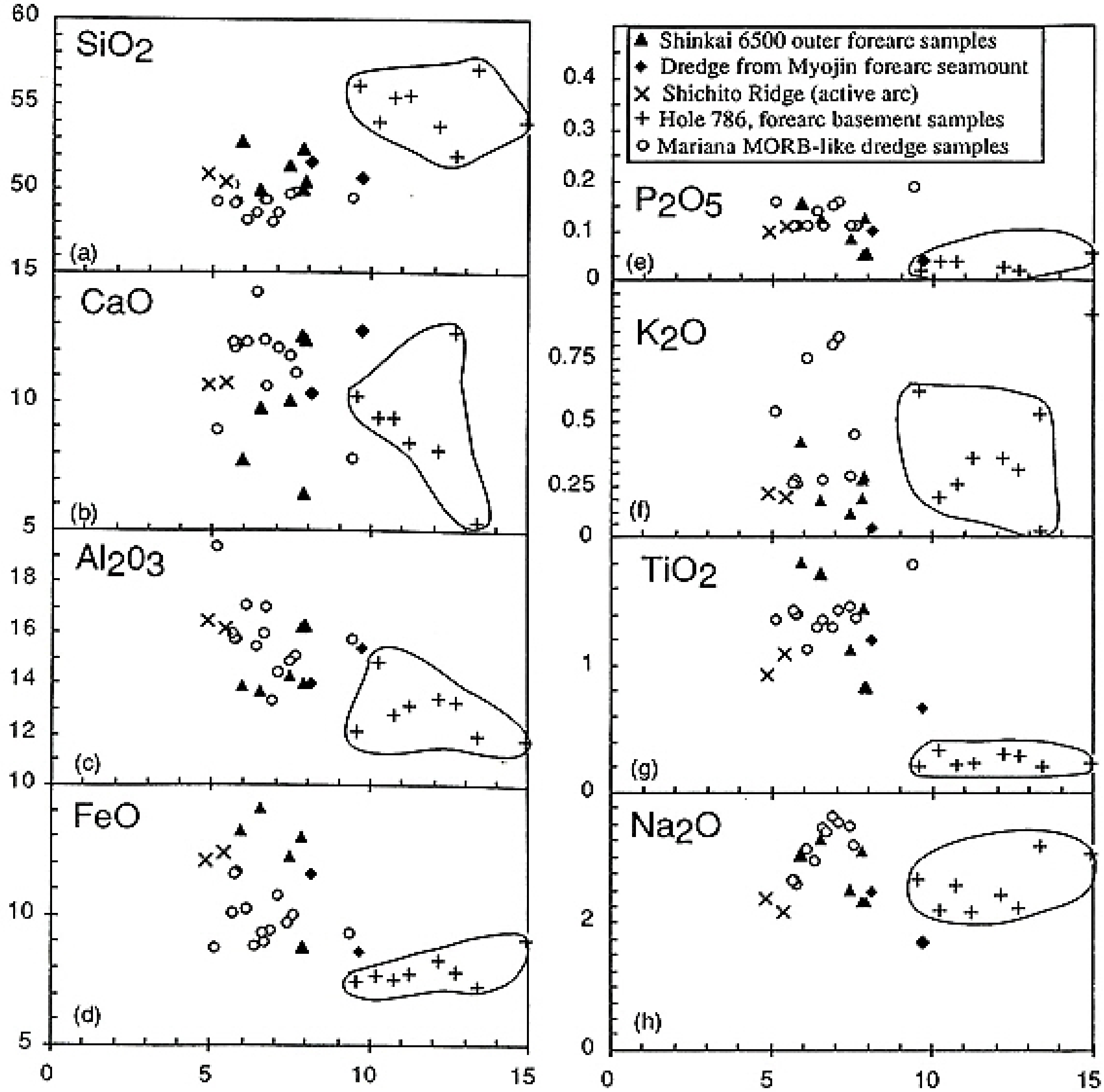

Fig.5 Variation diagrams of major elements (a-h) and trace elements (i-p) vs. MgO in the inner trench wall samples. Also included are Hole 786 boninites recovered from the outer arc high upslope from the "Shinkai" dive (Arculus et al., 1992; Murton et al., 1992), basalts from the active arc (Ikeda and Yuasa, 1989), and MORB-like samples dredged from the Mariana trench inner wall (Johnson and Fryer, 1990). Fields for the Hole 786 data are circled for clarity.

increase with decreasing MgO. Values of Sr are constant. Fig.5 also shows that our samples are quite distinct from the forearc basement sampled just upslope at Hole 786 (Arculus et al., 1992; Murton et al., 1992). They have much less MgO and SiO_2; higher Al_2O_3, FeO, TiO_2, and P_2O_5; and similar CaO and K_2O. They are also distinctive in their trace elements; our samples have lower Ba, Rb, Sr, Ni, and Cr; and higher Zr, Y, and Nb than the boninite samples. The inner-trench slope samples also do not look like modern-day arc magmas erupted from Izu-Bonin volcanoes. They have much lower Ba, and Sr, and higher Ti, Nb, Ni, and Cr.

Chondrite-normalized rare-earth element (REE) patterns for the inner trench wall samples (Fig.6) show depletion of the light REE and Ba, with values of La/YbCN from 0.4 to 0.6. The patterns are strikingly parallel for each of the samples, even for the samples dredged from Myojin forearc seamount. The samples do not have the typical enrichment of large

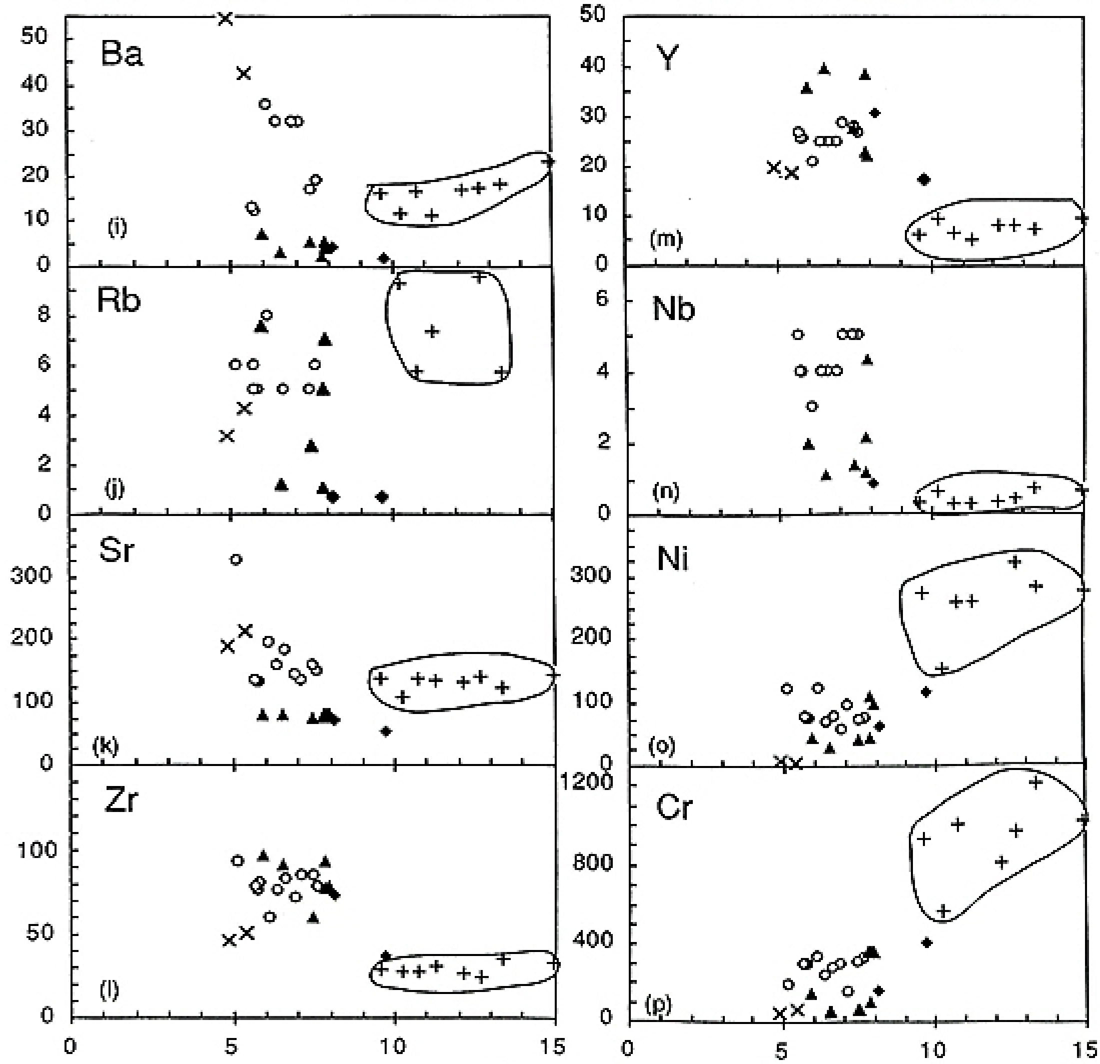

Fig.5 (Continued)

-ion lithophile elements (such as Ba) that is so characteristic of island arc magmas. Also plotted on Fig.6 for comparison are REE patterns for basalts from the Sumisu backarc rift (Gill et al., 1992), boninites from Hole 786 forearc basement (Murton et al., 1992), and basalts from the active arc (Shichito Ridge) (Ikeda and Yuasa, 1989).

Fig.7 shows REE patterns for the samples collected during two other "Shinkai" dives to the Sumisu forearc seamount and the Shikoku basin whose analyses are given in Table 1 (Dives #172 and 177, respectively). The Shikoku basin samples have REE patterns almost identical to those of the Sumisu rift except for the presence of negative Ce anomalies. These Ce anomalies are probably caused by alteration by seawater, which would explain the constant Ce values for all of the samples regardless of other REE abundances. These rift-related samples are distinct from the inner trench wall samples. In contrast, some of the samples from the Sumisu forearc seamount have REE patterns that are similar to our trench wall samples, except for higher Ba.

Our trench wall samples 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

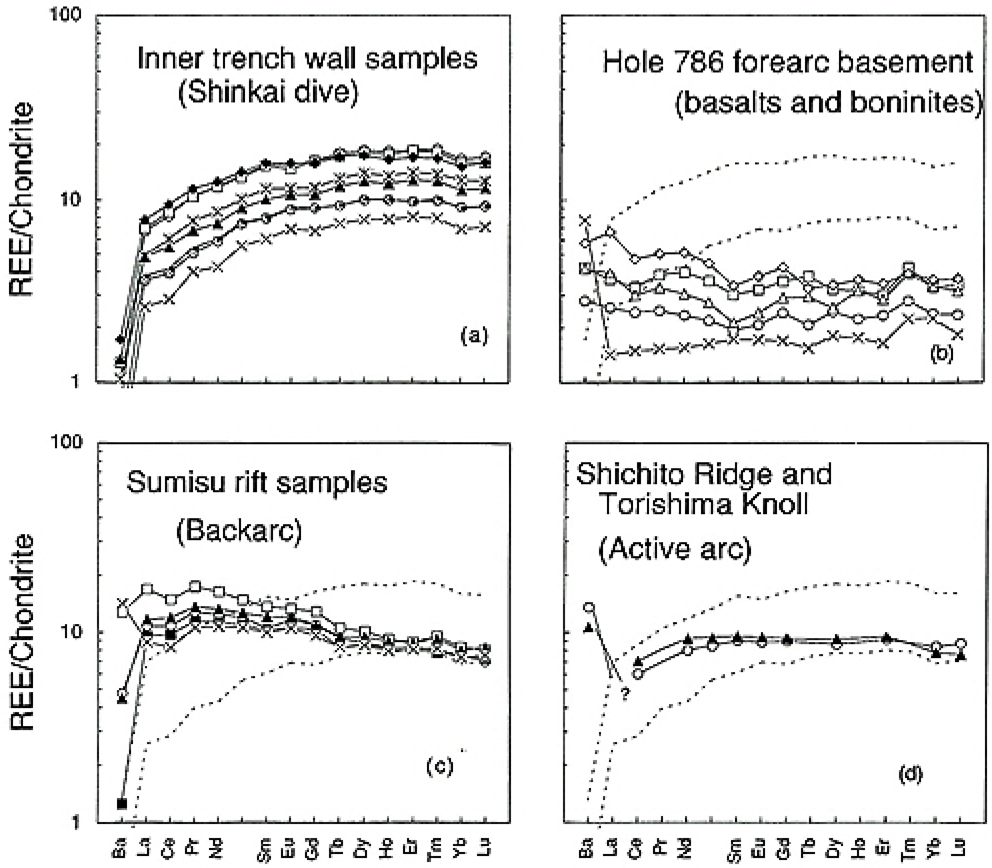

Fig.6 REE patterns of (A) inner trench wall samples from "Shinkai" dives 150 and 169 and KK84-19 dredge samples, (B) Hole 786 forearc basement (Murton et al., 1992), (C) Sumisu rift (Fryer et al., 1990), and (D) active arc basalts from the Shichito Ridge and Torishima knoll (Ikeda and Yuasa, 1989).

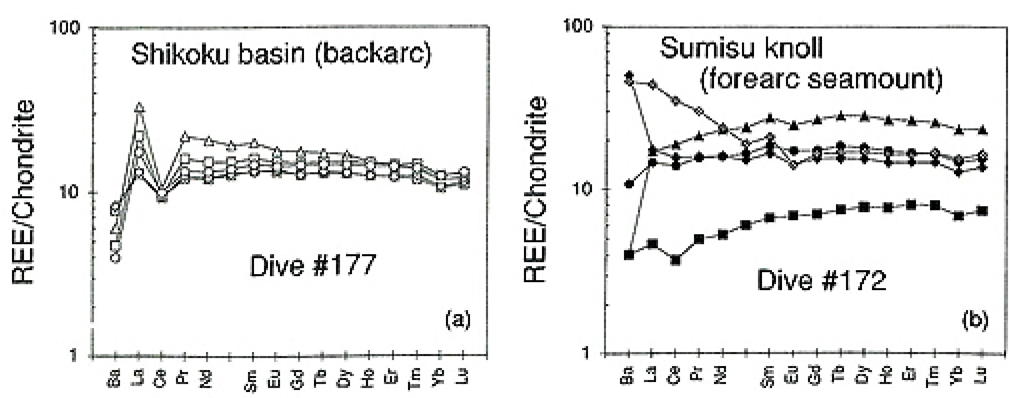

Fig.7 REE patterns of samples collected during dives 177 (Sumisu rift) and 172 (Sumisu forearc seamount).

tholeiites. They are quite depleted in Ba (3 to 7 ppm) and have low Ba/La ratios (2 to 5) and Ti/Zr ratios (93 to 112) more typical of MORB.

5 . Discussion

The most surprising result from geochemical analyses of the samples collected on the trench inner wall from the Izu-Bonin arc is that they do not resemble other samples of forearc basement (boninites) drilled from ODP Leg 125 just upslope on the outer arc high, nor do they resemble any typical island arc magma. This is true for both the samples collected during the "Shinkai" dive as well as the samples collected from the dredge of Myojin forearc Sea mount.

Fig.8 shows various tectonic discrimination diagrams that illustrate that the chemistry of these trench-wall samples is MORB-like. Other samples from the Izu Bonin arc system have been plotted for comparison, including the boninitic samples of the outer forearc at Hole 786 of ODP Leg 125 and samples of the Sumisu rift lavas. It is clear that the trench-wall samples are not related to the boninitic samples that crop out further up the trench slope. On a plot of Ti versus Zr (Fig.8a) the trench-wall samples plot well within the field of MORB. MORB-like dredge samples studied by Johnson and Fryer (1990) from the Mariana trench wall have also been plotted for comparison in Fig.8a and Fig.8c. They plot in the

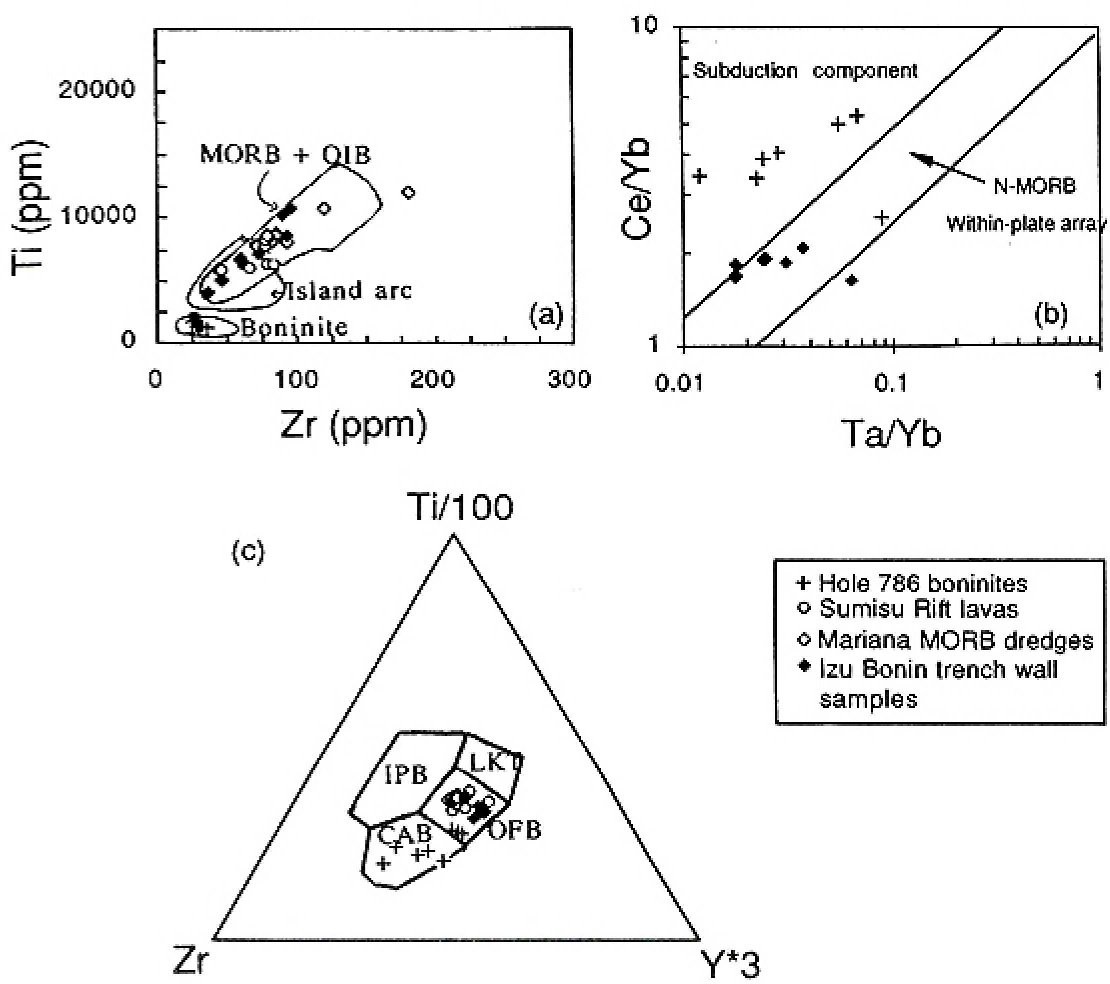

Fig.8 Plots of various discrimination diagrams for tectonic setting; (A) Ti versus Zr (Pearce and Cann, 1973), (B) Ce/Yb versus Ta/Yb, and (C) Ti/100-Zr-Y ＊3 ternary (Pearce and Cann, 1973). Abbreviations: IPB = intra-plate basalts, CAB = calcalkaline basalts, OFB = ocean floor basalts, and LKT = low K tholeiites. Note that the Izu Bonin trench wall samples plot well within the field for MORB in all diagrams.

same fields as the Izu Bonin trench wall samples. Other tectonic discrimination diagrams, such as the Th-Hf/3-Ta ternary (not presented here), also clearly point to a MORB source.

In addition to tectonic discrimination diagrams, a useful approach is to compare the concentration of a characteristic oxide in volcanic samples collected across strike of the arc system. This has been done previously by R. Taylor et al. (1992) for TiO_2 across the Izu-Bonin arc. When the trench wall samples are plotted on this diagram of TiO_2 versus distance from the trench (Fig.9), it is clear that they have too much TiO_2 to fit into the general trend. Excluding the trench-wall samples, there is a steady trend of increasing TiO_2 from east to west across the arc from the forearc to the backarc. The forearc boninitic rocks are extremely depleted in TiO_2, and the values rise steadily from the arc to the backarc. The trench-wall samples display values of TiO_2 that are as high as those in the backarc rift. This indicates that a very different mantle source was responsible for these basalts than what fed the forearc boninites. What was this source?

Johnson and Fryer (1990) presented evidence for MORB-like lavas dredged from the outer Mariana forearc. They were unable to conclusively distinguish whether these samples represented trapped pieces of Philippine oceanic plate or accretion of downgoing Pacific plate. However, in a subsequent paper, Johnson et al. (1991) presented evidence that strongly supported an accreted origin for these rocks based on age determinations. A dredged MORB-like lava recorded a (minimum) K-Ar age of 85 Ma, and associated chert yielded Valanginian (131-138 Ma) and Albian (97-112 Ma) foraminifers. The chert and volcanic rocks are thus too old to have formed in situ or to be part of trapped West Philippine Basin crust. The samples discussed in this study have many similar characteristics to the Mariana MORB-like samples. However, there is no associated chert that could adequately discern rock ages and the rocks are too altered to be analyzed by K-Ar.

It is not possible to distinguish without ambiguity the source of the Izu Bonin MORB-like rocks. The two most reasonable scenarios are (1) these rocks represent a piece of accreted Pacific plate. As the Pacific plate subducted beneath the Philippine plate, some of the basaltic crust was scraped off and accret-

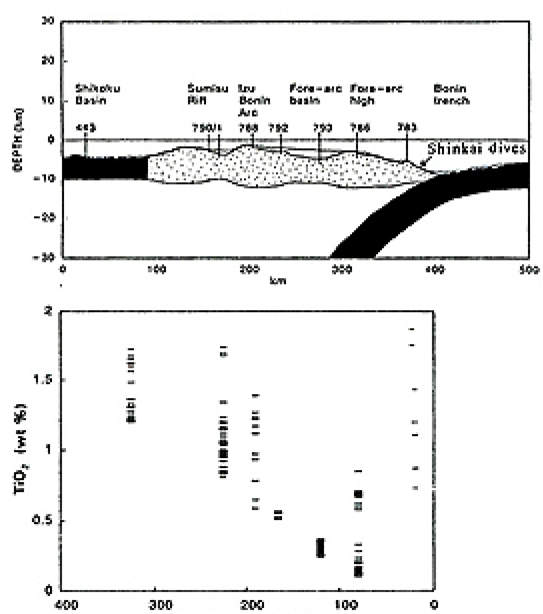

Fig.9 (A) Schematic west-east section across the Izu-Bonin arc-trench system. Numbers refer to DSDP and ODP sites. Shaded regions are MORB-type crust. Stippled regions are arc-related crust. (B) TiO_2 contents of lavas from the Izu Bonin arc-trench system plotted versus distance from the trench. Fig.modified after R. Taylor et al. (1992).

ed to the inner trench wall at deep levels. Somewhere above 6,000m water depth but below approximately 4,000m would have to mark the boundary between this accreted crust and the intact 650-m-thick boninitic sequence drilled in Hole 786 of ODP Leg 125 at 3,500m water depth (see Fig.2). In order for this to be true, the accretion must have occurred early in the history of the Izu Bonin system, before development of serpentinite seamounts that are trenchward of our dive sites (see Figures 2 and 4). (2) These MORB-like rocks represent a remnant piece of Philippine plate oceanic crust that has been unaffected by arc magmatism. This could only be true if the Eocene an younger arc magmatism was not pervasive enough to obliterate the older oceanic crust that it was built on. In this scenario, the rocks that we sampled on the inner trench wall would be a fossilized piece of older crust.

An avenue for future study to distinguish between these two scenarios would be to utilize the radiogenic isotopes Nd, Sr, and Pb. Hickey-Vargas (1991) has shown that the West Philippine basin MORB have Pb ratios that are distinct from Pacific Ocean MORB. K-Ar or ^{40}Ar-^{39}Ar age dating would not necessarily work given the altered nature of these rocks. It would also be less discriminatory, given that Philippine Basin crust in this region could be as old as Cretaceous, whereas in the Mariana region where Johnson and Fryer (1991) worked, the Philippine Plate crust was much younger.

6. Conclusion

Three dives in the "Shinkai 6500" submersible were made to 6,500m on the trench inner wall of the Izu-Bonin arc system at 32° N in order to study a vertical traverse of island arc basement. Samples collected from this traverse are quite surprising in that they are uncharacteristic of any other rocks collected from the Izu Bonin arc. They are basaltic in composition, with moderate MgO contents. They have no affinity with the Eocene boninitic rocks drilled upslope in the forearc at Hole 786 of ODP Leg 125. They are also unlike rocks from the active arc and the backarc. Their geochemistry more closely resembles typical mid ocean ridge basalt. We suggest here that these MORB-like rocks represent either accreted Pacific plate rocks or a remnant piece of the Philippine plate that was unaffected by arc magmatism. If these rocks are accreted Pacific plate, they represent the first piece of evidence for any accretion of Pacific plate material in the IZU-Bonin trench which was previously characterized by subduction erosion.

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