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Early stages in the evolution of Izu–Bonin arc volcanism: New age, chemical, and isotopic constraints

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Abstract

A remarkable record of early arc volcanism in the Izu–Bonin–Mariana (IBM) arc is exposed in and around the Bonin Islands, an uplifted segment of the IBM forearc. New $^{40}Ar/^{39}Ar$ dating results imply that the boninitic volcanism on Chichijima Island occurred in a brief period during Eocene time, between 46–48 Ma. A slightly younger volcanic succession is identified along the Bonin Ridge, including 44.74 ± 0.23 Ma high-Mg andesite from the Mikazukiyama Formation, the youngest volcanic sequence on Chichijima, 44.0 ± 0.3 Ma tholeiitic to calcalkaline andesite from Hahajima Island, and 3 samples of andesite collected by the submersible SHINKAI 6500 from the Bonin Ridge Escarpment (BRE) that range in age from 41.84 ± 0.14 to 43.88 ± 0.21 Ma. Four SHINKAI 6500 dives (YK 04–05) on the BRE mapped an elongated constructional volcanic ridge atop the escarpment; we observed steeply west-dipping volcaniclastic debris flows shed from the summit of this ridge into the Ogasawara Trough to the west. These dives recovered fresh andesitic clasts from debris flows along the northern segment of the ridge, and high-Mg andesite lava blocks and Nummulitic limestone of middle Eocene age from the escarpment northwest of Chichijima. Our results also confirm previous inferences that melting of depleted mantle at shallow levels beneath the length of the arc with the aid of hydrous fluids from newly subducted slab to produce boninitic volcanism occurred nearly simultaneously along the entire length of the IBM arc system during the earliest stage of arc evolution. BRE–Mikazukiyama Formation–Hahajima andesites represent a transitional stage from forearc spreading (represented by ODP site 786-Chichijima boninites) and the stable, mature arc that developed in the Oligocene. These OPX-bearing high-Mg or tholeiitic to calcalkaline andesites were erupted along the BRE, as the arc magmatic axis localized and retreated from the trench.

Keywords: Infant arc; Izu–Bonin–Mariana arc; $^{40}Ar/^{39}Ar$ dating; Boninite; Igneous geochemistry

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1. Introduction

Recent advances in understanding crustal structure and composition of oceanic arcs demonstrate that such arcs could represent the building blocks of continental crust formation [1,2]. In order to understand the formation of arc and continental crust, it is necessary to estimate growth rates of arc crust coupled with petrological and chemical evolution. Oceanic arcs, where thickened arc crust has formed on oceanic lithosphere provide a unique opportunity to investigate this problem. The Izu–Bonin–Mariana (IBM) arc is an outstanding example of such an arc system.

Forearcs with thin sediment cover are particularly valuable for understanding how subduction zones begin [3]. For example, Stern and Bloomer [4] and Bloomer et al. [5] recognized that forearc basement formed in the initial phases of arc volcanism nearly synchronously over a zone up to 300 km wide and thousands of kilometers long, at igneous production rates much higher than those of current arcs.

The Bonin Ridge is an unusually prominent forearc massif in the IBM arc that exposes early arc volcanic rocks on islands of Chichijima, Hahajima, and smaller islands (e.g. [6–9]). Submarine parts of the ridge, which could complement the record of volcanism preserved on the islands, have not been extensively investigated.

During the YK 04–05 expedition in May 2004, we carried out the first manned submersible (SHINKAI 6500) diving survey of the western escarpment of the Bonin Ridge. This effort–along with new $^{40}Ar/^{39}Ar$ ages for Bonin island samples–provided new information about the duration of infant arc volcanism and how this progressively reorganized into a typical magmatic arc by Early Oligocene time.

2. Geological background

The IBM arc is an intra-oceanic convergent margin system that trends south for ~2500 km from Japan and is bounded by the IBM Trench to the east and back-arc basins to the west (Fig. 1). The central part of the IBM arc is characterized by a well-preserved forearc massif, the Bonin Ridge. The Bonin Ridge trends N–S for about 400 km, with a maximum width of ca.110 km. The Bonin Ridge is bounded by the Ogasawara Trough forearc basin to the west and the Izu–Ogasawara trench to the east. The western margin of the Bonin Ridge is a steep escarpment exceeding 3000 m of relief and probably formed at the same time as rifting to create the Ogasawara Trough, which Taylor [10] argued occurred during Oligocene time. The active magmatic arc is situated well to the west of the Ogasawara Trough.

Subaerial exposures on the Bonin Islands have been studied extensively, and are where boninites were first described (e.g. [11]) Chichijima and Mukojima Islands are large piles of boninite and slightly younger andesite and dacite. On Chichijima, the Maruberiwan, Asahiyama, and Mikazukiyama Formations (from oldest to youngest), expose over 500 m of Eocene boninite flows, breccias, felsic lavas and tuffaceous sediments. 45 km south of Chichijima, Hahajima has Eocene high-Mg and low-Mg tholeiitic andesites, but boninite is not reported (e.g. [12,13]).

Strata atop the Bonin Ridge dip gently and show combinations of an open anticline and syncline so that a limited range of stratigraphic levels is exposed. For example, Eocene units on the eastern side of Chichijima dip gently westward, although in some western locations, these units dip slightly east [8,9,14]. An anticline axis trends through Minamijima off the southern coast of Chichijima, and also along the western side of Hahajima.

The submarine portion of the IBM forearc has been studied mainly by dredging (e.g. [15,16]) and drilling (DSDP leg 60, and ODP legs 125 and 126; e.g. [10,17–22]), although ROV and manned submersible observations continue. Dredging of the western Bonin Ridge Escarpment recovered low- and high-Mg tholeiites, similar to lavas exposed on Hahajima [16].

At ODP site 786 north of the Bonin Ridge, boninites were observed in the lowermost drilled section, where they are intimately associated with bronzite andesites, andesites and felsic rocks in the vicinity of an eruption center [21]. The boninites were dated by $^{40}Ar/^{39}Ar$ method to be 45.3–46.7 Ma except for one older age with large uncertainty [23], indicating an Eocene age for the drilled volcanic section, consistent with the record exposed in the Bonin Islands.

Infant arc sequences also make up much of the Mariana fore-arc. DSDP sites 458 and 459 recovered a sequence of boninites underlain by tholeiitic basalts [24]. The tholeiites have compositions that are similar to those found on the inner slope of the Izu–Bonin trench [25] and therefore may represent a fragment of the Philippine Sea basaltic crust [26]. The boninites have $^{40}Ar/^{39}Ar$ ages that are about the same (ca. 45–49 Ma, [23,26]) as the low-Ca boninites of the Bonin Ridge. The basement of the forearc island of Guam consists of ca. 44 Ma [27] boninite series pillow lavas and associated sediments. These are capped by ca. 41 Ma arc tholeiites and 38–35 Ma calcalkaline andesites [26–28]. High-Si rhyolites erupted on Saipan at 44.6–46.6 Ma [23] have an uncertain relationship to other IBM infant arc sequences. As pointed out by [29], these lavas have REE concentrations consistent of a derivation by crystal fractionation of boninites. However, concentrations of other trace elements are transitional to the more

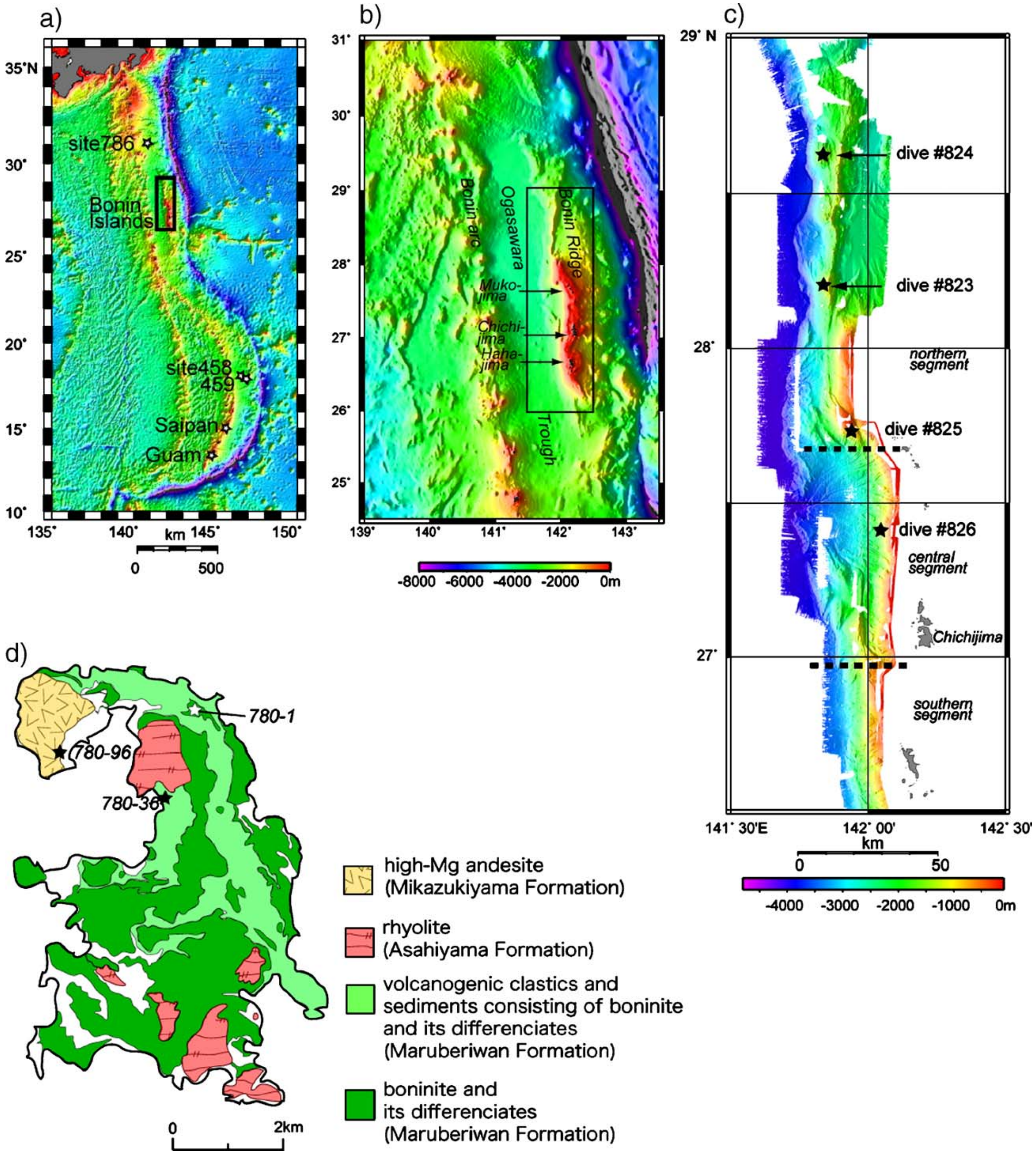

Fig. 1. a) Overview of the Izu–Bonin–Mariana arc with locations of Eocene volcanics (bathymetric data from [64]. b) Overview of the Bonin ridge with locations of the Bonin islands (bathymetric data from JTOPO30 published by Japanese Coast Guard). (c) Detailed bathymetric map of the Bonin Ridge Escarpment obtained during the YK 04–05 cruise. Bathymetric data were acquired using SEABEAM 2112 multinarrowbeam echosounder system fitted to M/V Yokosuka. Dive sites (#823–#826) are designated on the maps. These maps show that NW–SE fabric is superimposed on the overall N–S trend of the Bonin Ridge. (d) Simplified geological map of Chichijima (after [8]) and locations of dated samples.

typical arc volcanic rocks erupted in the late Eocene and Oligocene [26].

3. Bathymetry, paleontology, and petrography

The western escarpment of the Bonin Ridge (BRE, hereafter) stretches at least 400 km between the Ogasawara Trough to the west and the Bonin Ridge to the east. The BRE can be subdivided into three (N, central, S) segments (Fig. 1), offset 5–15 km E–W. The northern segment, or N-BRE, where SHINKAI 6500 dives #823 to #825 were conducted, is associated with a narrow ridge trending 010° atop the escarpment. This ridge is surmounted by relatively small, discrete conical features that could be the remnants of old volcanoes. The dives in the northern segment recovered volcanic debris flows (supplement Fig. 1). These contain blocks of mostly intermediate lavas. Clasts are polymictic and generally subangular to rounded, suggesting that they were redeposited as gravity flows, as opposed to being primary volcaniclastics. N-BRE debris flow samples are similar to rocks described in the Mikazukiyama Formation exposed in the northwestern part of Chichijima. We infer that the N-BRE ridge and seamounts were the source of the volcanic material in the debris flows.

Dive #826 was conducted on the central segment, NNW of Chichijima. This dive recovered mafic volcanic rocks, sediments, and limestones including samples with large foraminifera. These are identified as *Nummulites boninensis Hanzawa*, similar to those reported from upper Middle Eocene (Biarrizian to upper Lutesian) shallow-water, unconsolidated sands at Hahajima [30]. The Nummulitic limestone is thick and interbedded with pillow lavas, indicating that the lavas are also Eocene in age.

All outcrops encountered during the northern 2 dives were covered by Mn-oxide crusts that were 5–7 cm thick. In contrast, the Mn-crusts on rocks collected during the southern 2 dives were uniformly less than 2 mm thick (supplement Fig. 1). At these dive sites, bedding of volcaniclastic on the decimeter to several meter scale was observed. These beds were dipping at angles consistent with the original deposition of sediment on a pre-existing escarpment slope.

Volcanic rock samples collected during dives #823–#825 have clinopyroxene (3–6%), orthopyroxene (1–3%), plagioclase (5–40%) phenocrysts; they may also have Fe–Ti oxide (0–1%), and olivine (0–1%) phenocrysts (supplement Fig. 1). Reaction textures are common, including complex zoning in plagioclase phenocrysts, clinopyroxene rimming orthopyroxene, and orthopyroxene rimming olivine. The groundmass is generally composed of plagioclase, pyroxene, Fe–Ti oxide, and interstitial glass showing intersertal texture. Samples from dive #826 are OPX–CPX–phyric andesite with rare

Table 1
Results of $^{40}Ar/^{39}Ar$ dating of volcanic rocks from the Bonin Islands and western escarpment of the Bonin Ridge

Analysis no.	Sample no.	Rock type	Total age (±1σ)				Plateau age (±1σ)				
			Integrated age (Ma)	Inv. isochron age (Ma)	$^{40}Ar/^{36}Ar$ intercept	MSWD	Weighted average (Ma)	Isochron age (Ma)	$^{40}Ar/^{36}Ar$ intercept	MSWD	Fraction of ^{39}Ar (%)
Chichijima											
U02211	780-1	Bronzite andesite	47.9±0.4	48.8±1.0	293±5	1.46	48.2±0.3	48.7±0.7	293±3	1.46	100.0
U02212	780-25	Boninite	46.9±0.3	45.2±0.7	323±9	1.87	46.0±0.3	46.5±0.5	279±9	0.66	96.7
U02210	780-36	Boninite	46.0±0.6	49.1±0.5	156±18	0.63	47.5±0.4	47.5±2.0	288±191	0.51	85.0
U02209	780-96	Andesite	45.29±0.22	44.7±0.7	306±14	1.62	44.74±0.23	45±4	298±101	2.19	65.7
Hahajima											
U02279	780-30	Andesite	45.1±0.3	43.1±0.5	415±21	0.76	44.0±0.3	43.7±0.7	337±71	0.75	89.3
Bonin Ridge Escarpment											
U05015	#823 R8	Andesite	44.36±0.21	43.7±0.7	311±15	1.95	43.88±0.21	44.1±0.5	291±13	1.22	82.3
U04468	#824 R9	Andesite	42.24±0.12	41.7±0.6	392±47	2.94	41.84±0.14	48±4	<490	0.53	72.6
U05001	#826 R8	High-Mg andesite	42.57±0.20	42.0±0.8	307±10	2.35	42.86±0.18	43.2±0.5	291±7	1.32	93.1

$\lambda b=4.962\times10^{-10}$ y^{-1}, $\lambda e=0.581\times10^{-10}$ y^{-1}, $^{40}K/K=0.01167\%$ [71].
inv. isochron age: inverse isochron age. MSWD: mean square of weighted deviates ((SUMS/(n−2))^0.5) in York [34].
Integrated ages were calculated using sum of the total gas released.
Weighted average ages and uncertainties are calculated using the following equations [72].
$Tav=\Sigma(Ti/\sigma i^2)/\Sigma(1/\sigma i^2)$
$\sigma av=(\Sigma(1/\sigma i^2))^{-0.5}$
Tav: weighted average age, Ti: individual ageσav: uncertainty for the average age, σi: uncertainty for the individual age.

olivine phenocrysts and significantly less plagioclase (1–4%) than other dive samples (supplement Fig. 1).

4. Analytical procedure

4.1. $^{40}Ar/^{39}Ar$ dating

Age determinations were conducted using $^{40}Ar/^{39}Ar$ dating facility at the Geological Survey of Japan/AIST. Details of analytical procedure are reported by Ishizuka et al. [31]. Laser step-heating experiments were conducted on 5–10 mg groundmass samples. The samples were treated ultrasonically in 3 N HCl for 10–15 min to remove possible alteration products (clays and carbonates) prior to irradiation. Sanidine separated from the Fish Canyon Tuff (FC3) was used for the flux monitor and assigned an age of 27.5 Ma [32].

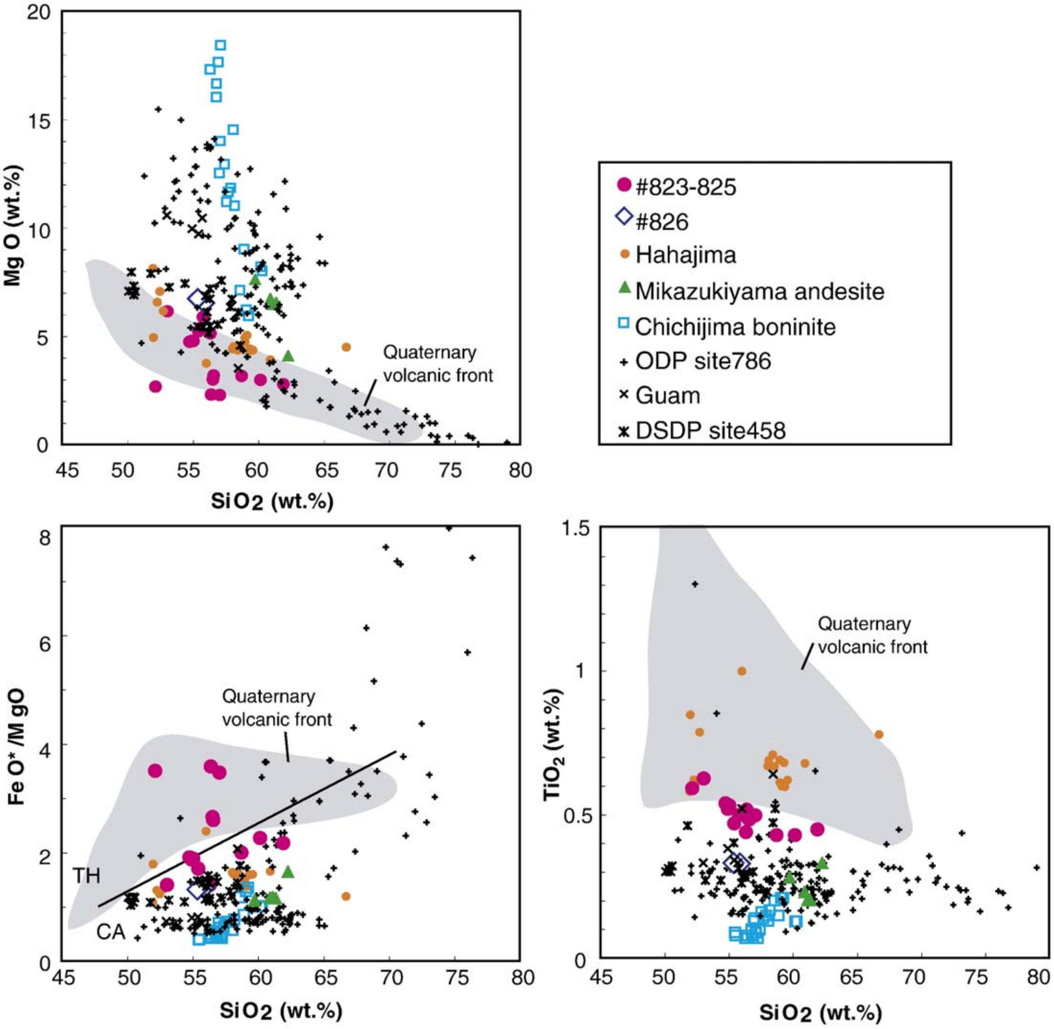

Fig. 2. a) FeO*/MgO diagram for Bonin Ridge samples (after [65]). Samples from dive #826 and Chichijima boninites are calcalkaline. Hahajima tholeiites plot on the boundary between tholeiitic and calcalkaline suites. Dives #823–#825 samples scatter in tholeiitic and calcalkaline fields, partly overlapping the field for Hahajima and partly overlapping the field for the Quaternary volcanic front of the Izu–Bonin arc (shaded field). Data source for Eocene lavas; site 458: [49,66], Chichijima (including high-Mg andesite from the Mikazukiyama Formation) and Hahajima: [7,13], Taylor et al. in prep., Guam: [42], ODP site 786: [21]. b) MgO vs. SiO_2 diagram. Dive #826 boninites have similar MgO contents with low-MgO boninites from the ODP Sites. Tholeiites from dives #823–#825 fall between Hahajima and Quaternary volcanic front tholeiites. c) TiO_2 vs. SiO_2 diagram for Bonin Ridge samples shows the increasing TiO_2 values from Chichijima boninites to Hahajima tholeiites to Quaternary volcanic front tholeiites. High-Mg andesites from dive #826 falls in the field for ODP site 786 and show slightly higher TiO_2 than Chichijima boninites. TiO_2 values for tholeiites from dives #823–#825 are lower than for Hahajima tholeiites but higher than Chichijima boninites.

Correction for interfering isotopes was achieved by analyses of $CaFeSi_2O_6$ and $KFeSiO_4$ glasses irradiated with the samples. The blank of the system including the mass spectrometer and the extraction line was 7.5×10^{-14} ml STP for ^{36}Ar, 2.5×10^{-13} ml STP for ^{37}Ar, 2.5×10^{-13} ml STP for ^{38}Ar, 1.0×10^{-12} ml STP for ^{39}Ar and 2.5×10^{-12} ml STP for ^{40}Ar. A blank analysis was done every 2 or 3 steps of the analyses.

All errors for ^{40}Ar/^{39}Ar results are reported at one standard deviation. Errors for ages include analytical uncertainties for Ar isotope analysis, correction for interfering isotopes and J value estimation. An error of 0.5% was assigned to J values as a pooled estimate during the course of this study.

The age plateaus were determined following the definition by Fleck et al. [33]. Inverse isochrons were calculated using York's least-squares fit, which accommodates errors in both ratios and correlations of errors [34].

4.2. Whole rock composition and isotopes

Only the least altered rocks from the SHINKAI 6500 dive sites were chosen for whole rock geochemical analysis. Whole rock compositions were determined using a Rigaku 3270 X-ray fluorescence (XRF) spectrometer at the Ocean Research Institute, University of Tokyo, Japan. Samples were cut into slabs, washed with distilled water, and finely ground in an agate ball mill. One gram of powdered sample was dried at 110 °C for ~10 h and weighed to obtain weight percent H_2O loss. The dried samples were then ignited at 950 °C for ~4 h and weighed to obtain loss on ignition (LOI). Major-element analyses were conducted using glass beads. Fused disks were prepared with a lithium tetraborate (Li_2B_4O7) flux at a dilution ratio of 1:10. Trace element analyses were performed using pressed powder pellets (~4 g of sample) made with a polyvinyl acetate ring holder (after [35]).

Table 2
Summary of analytical results of Shinkai dive samples from the Bonin Ridge Escarpment

Sample name (in ppm)	#823 R8	#824 R9	#824 R10	#824 R11A	#824 R11B	#824 R12	#824 R13	#824 R14	#824 R15	#825 R3	#825 R5	#825 R6	#825 R7	#825 R13	#826 R7	#826 R8
Li	13.37	4.84	5.63	12.53	3.72	6.36	6.62	5.46	4.81	10.35	7.00	10.89	7.94	8.55	7.06	8.48
Be	0.42	0.40	0.35	0.42	0.34	0.42	0.40	0.40	0.35	0.44	0.50	0.47	0.39	0.36	0.33	0.32
Rb	9.50	7.48	7.57	4.32	7.91	6.68	7.80	7.63	7.92	8.82	5.66	9.78	7.80	8.72	8.77	7.51
Sr*	357	249	235	258	235	241	248	241	233	285	313	262	288	293	164	171
Y	15.33	14.57	12.56	17.50	13.74	18.24	14.66	13.79	12.82	11.17	11.19	11.82	13.52	11.15	7.26	8.31
Zr	49.72	41.11	32.10	41.54	29.41	38.73	38.59	36.47	32.24	44.21	49.69	51.45	38.95	42.83	27.69	29.07
Nb	1.97	1.55	0.93	0.90	0.71	1.11	0.84	1.08	0.68	1.32	1.39	1.91	1.20	1.26	0.59	0.60
Sb	0.12	0.57	0.23	0.38	0.11	36.78	0.23	0.29	0.12	0.13	0.06	0.07	0.11	0.09	0.12	0.16
Cs	0.24	0.28	0.30	0.08	0.28	0.29	0.32	0.35	0.34	0.09	0.02	0.11	0.20	0.22	0.31	0.22
Ba*	121.9	63.1	49.1	66.6	40.6	54.4	49.1	50.3	42.7	74.6	76.8	129.0	58.2	59.1	35.2	34.9
La	7.35	6.29	3.15	4.66	3.09	5.28	3.57	4.10	2.60	4.31	3.89	4.99	4.54	3.80	1.54	1.82
Ce	14.44	20.35	8.76	8.82	6.06	13.52	8.42	12.03	5.87	10.11	9.20	10.86	9.60	8.50	3.49	3.80
Pr	1.95	1.84	1.13	1.48	1.08	1.58	1.21	1.30	0.98	1.38	1.37	1.57	1.39	1.22	0.56	0.65
Nd	8.81	8.39	5.49	7.43	5.56	7.56	6.08	6.40	4.99	6.32	6.53	7.03	6.62	5.79	2.72	3.03
Sm	2.26	2.34	1.63	2.09	1.67	2.14	1.75	1.81	1.51	1.68	1.74	1.85	1.81	1.60	0.86	0.96
Eu	0.77	0.77	0.60	0.76	0.61	0.70	0.61	0.64	0.55	0.56	0.60	0.60	0.59	0.55	0.32	0.35
Gd	2.55	2.62	1.97	2.55	1.95	2.60	2.07	2.13	1.82	1.90	1.88	2.04	2.02	1.77	1.03	1.14
Tb	0.43	0.45	0.35	0.46	0.35	0.46	0.39	0.38	0.35	0.31	0.31	0.34	0.34	0.31	0.19	0.22
Dy	2.77	2.94	2.30	3.06	2.39	3.08	2.51	2.53	2.28	2.01	2.05	2.15	2.23	2.09	1.27	1.47
Ho	0.57	0.59	0.48	0.67	0.52	0.66	0.55	0.54	0.48	0.43	0.42	0.45	0.48	0.41	0.26	0.30
Er	1.56	1.60	1.38	1.89	1.45	1.91	1.57	1.47	1.39	1.20	1.18	1.23	1.38	1.22	0.81	0.88
Tm	0.24	0.26	0.21	0.30	0.23	0.30	0.24	0.24	0.22	0.19	0.19	0.19	0.22	0.19	0.13	0.14
Yb	1.61	1.79	1.46	1.98	1.58	2.03	1.70	1.61	1.56	1.30	1.33	1.29	1.51	1.30	0.89	0.96
Lu	0.25	0.27	0.22	0.32	0.25	0.32	0.27	0.26	0.25	0.20	0.21	0.21	0.23	0.20	0.14	0.15
Hf	1.44	1.13	1.00	1.35	0.96	1.20	1.13	1.07	1.01	1.22	1.41	1.54	1.17	1.36	0.81	0.82
Ta	0.10	0.05	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.06	0.07	0.10	0.06	0.06	0.04	0.04
Tl	0.07	1.06	0.40	0.75	0.05	0.62	0.20	0.42	0.07	0.22	0.04	0.05	0.10	0.05	0.07	0.09
Pb	2.90	21.78	5.36	2.72	0.55	10.91	3.81	11.62	0.71	4.91	1.29	1.28	3.52	1.87	1.25	2.49
Th	1.03	0.86	0.37	0.35	0.23	0.59	0.33	0.52	0.22	0.51	0.47	0.65	0.45	0.58	0.16	0.18
U	0.32	0.32	0.16	0.18	0.21	0.21	0.16	0.18	0.16	1.68	0.60	1.01	0.21	0.24	0.12	0.13

Full dataset is presented in supplemental Table 1.
*For the determination of Sr and Ba JB2 was used as a calibration standard.

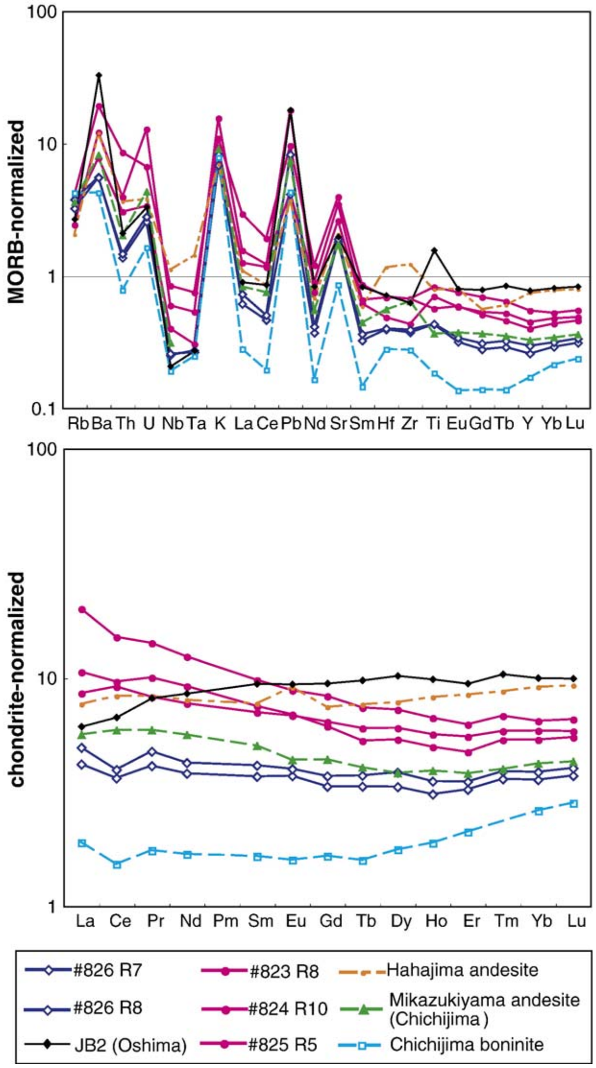

Fig. 3. a) MORB-normalized trace element patterns for the least-altered Bonin Ridge volcanics (normalized to N-MORB composition of [67]). Data for the Northern Izu–Bonin volcanic front (JB2; Oshima) is shown for comparison. High-Mg andesites from dive #826 have lower HFSEs and Sm/Zr and show relatively similar pattern to Chichijima boninites and other boninitic lavas from the IBM arc. Tholeiitic to calcalkaline andesites from dives #823–#825 are enriched in LILEs and light REEs relative to Hahajima tholeiites. All the andesites and boninites are depleted in Nb and show positive spikes in Ba and Sr (fluid signature). Data source for Chichijima (including high-Mg andesite from the Mikazukiyama Formation) and Hahajima: [7,13], Taylor et al. in prep. b) REE pattern of the Bonin Ridge volcanics normalized to chondrite composition of [67]. High-Mg andesites from dive #826 show weak middle REE depletion (even though not as obvious as that of Chichijima boninite). Tholeiitic to calcalkaline samples from dives #823–#825 are light REE-enriched relative to Hahajima tholeiites.

For determination of trace element concentrations samples were crushed by iron pestle to millimeter size and washed in sub-boiled deionized water over 3 days by refreshing the water each 5 h. The samples were pulverized by agate motor for 30 min. Trace elements were analyzed using inductively coupled plasma mass spectrometry (Thermo ELEMENTAL, VG PQ-3 at Shimane University) by the standard addition technique and using normal concentric nebulizer [36]. The acid digestion process was partly modified using 1:1 $HClO_4$ and HF mixture for digestion and mixed acid (HNO_3, HCl, with trace HF) used for recovery process [37]. Acid regents used were EL-grade nitric acid (Kanto Chemicals) and HF (Tama Chemicals) and precise analysis grade $HClO_4$ (Wako Chemicals). Experimental water was distilled and subsequently ion exchanged with a Milli Q filter (Millipore).

Pb isotopic composition was determined on 200 mg of hand-picked rock chips with a grain size of 0.5–1 mm. The rock chips were leached in 6 M HCl at 140 °C for 2 to 5 h prior to dissolution in HF–HNO_3, followed by the isolation of Pb using AG1-X8 200–400 mesh anion exchange resin. Procedural Pb blanks were <30 pg, and considered negligible relative to the amount of sample analyzed.

Isotopic data were acquired using a VG Sector 54 mass spectrometer at the National Oceanography Centre, Southampton, UK (NOC). Pb isotopic measurements were made in multi-dynamic collection mode. The measurements were achieved using the double spike (Southampton–Brest–Lead 207-204 spike (SBL74: [38]). Natural (unspiked) run measurements were made on 60–70% of collected Pb, giving beam intensities of $2.5–3\times10^{-11}$ A of ^{208}Pb. The true Pb isotopic compositions were obtained from the natural and mixture runs by iterative calculation adopting an modified linear mass bias correction [39]. The reproducibility of this Pb isotopic measurement (external error: 2 s.d.) by double spike is <200 ppm for all ^{20x}Pb/^{204}Pb ratios. Measured values for NBS SRM-981 during the measurement period were ^{206}Pb/^{204}Pb = 16.9414 ± 26, ^{207}Pb/^{204}Pb = 15.4997 ± 30 and ^{208}Pb/^{204}Pb = 36.726 ± 9 (2σ, n = 9).

Sr and Nd isotope ratios were measured at the NOC on a seven-collector VG Sector 54 mass spectrometer. Sr was isolated using Sr resin (Eichrom Industries, Illinois, USA). For Nd isotopic analysis, the REE were initially separated from major elements and Ba by cation exchange, before isolation of Nd on Teflon powder columns coated with HDEHP. Sr and Nd isotope ratios were determined as the average of 150 ratios by measuring ion intensities in multi-dynamic collection mode. Isotope ratios were normalized to

Table 3
Sr, Nd and Pb isotopic compositions of Shinkai dive samples from the Bonin Ridge Escarpment

Sample name	#823 R8	#824 R9	#824 R10	#824 R11A	#824 R11B	#824 R13	#824 R14	#825 R5	#825 R7	#825 R13	#826 R7	#826 R8
$^{87}Sr/^{86}Sr$	0.703352	0.703550	0.703543	0.703513	0.703576	0.703583	0.703588	0.703648	0.703519	0.703512	0.703876	0.703817
±2 s.e.	8	13	8	8	8	8	10	13	8	8	10	8
$^{143}Nd/^{144}Nd$	0.512960	0.512976	0.512979	0.512998	0.512987	0.512978	0.512967	–	0.512956	0.512973	0.512944	0.512962
±2 s.e.	5	7	10	8	6	7	7	–	5	18	8	6
$^{206}Pb/^{204}Pb$	19.0772	18.7950	18.7891	18.7629	18.7984	18.7708	18.7629	18.8121	18.7270	18.7569	18.6991	18.7075
±2 s.e.	9	9	10	23	7	9	11	8	13	6	8	12
$^{207}Pb/^{204}Pb$	15.5476	15.5322	15.5305	15.5244	15.5319	15.5312	15.5326	15.5215	15.5169	15.5181	15.5254	15.5250
±2 s.e.	8	8	10	21	6	8	10	7	12	6	7	11
$^{208}Pb/^{204}Pb$	38.706	38.417	38.413	38.373	38.416	38.399	38.393	38.339	38.349	38.381	38.336	38.333
±2 s.e.	25	26	30	65	19	26	30	22	37	18	23	35
$\Delta^{207}Pb/^{204}Pb$	−1.1	0.4	0.3	0.0	0.3	0.5	0.8	−0.9	−0.4	−0.6	0.7	0.6
$\Delta^{208}Pb/^{204}Pb$	1.4	6.7	7.0	6.1	6.2	7.8	8.2	−3.2	8.1	7.7	10.1	8.9

$^{86}Sr/^{88}Sr=0.1194$ and $^{146}Nd/^{144}Nd=0.7219$. Measured values for NBS SRM-987 and JNdi-1 ([40]; $^{143}Nd/^{144}Nd=0.512115$) were $^{87}Sr/^{86}Sr=0.710249\pm18$ (2σ, $n=3$) and $^{143}Nd/^{144}Nd=0.512097\pm12$ (2σ, $n=3$), respectively during the measurement period. This corresponds to a $^{143}Nd/^{144}Nd=0.511840$ for the La Jolla Nd standard [40].

5. Results

5.1. $^{40}Ar/^{39}Ar$ Geochronology

Crystalline groundmass of samples from the Bonin Islands and the BRE were dated using the $^{40}Ar/^{39}Ar$ laser-heating technique described above. Sample selection was based on thin section examination and observation of individual grains under a binocular microscope. Three samples collected during the diving were chosen for dating. In addition we selected 5 samples for dating out of ca. 120 samples from the Bonin Islands (4 samples from Chichijima and one sample from Hahajima). Petrography and geochemistry of these subaerial samples were reported by Taylor et al. [7] and Taylor and Nesbitt [13].

Two boninites and one bronzite andesite were dated from the Maruberiwan Formation, the oldest rocks exposed on Chichijima (Fig. 1). The boninites gave similar plateau ages of 46.0±0.3 Ma and 47.5±0.4 Ma (supplement Fig. 2, Table 1). The bronzite andesite gave a well-defined plateau age of 48.2±0.3 Ma, which is within 2σ error of the older age obtained for the boninites. One andesite block from the Mikazukiyama Formation, the youngest volcanic sequence exposed on Chichijima, gave a plateau age of 44.74±0.23 Ma, which is ca. 1–3 m.y. younger than the boninite ages (supplement Fig. 2, Table 1). A OPX–CPX andesite lava from the Motochi Formation [12] exposed on Hahajima gave a plateau age of 44.0±0.3 Ma (supplement Fig. 2, Table 1), suggesting that Hahajima andesite correlates with Mikazukiyama andesites on Chichijima.

An andesite block from dive #823 (the northernmost dive location) yielded a plateau age of 43.88±0.21 Ma (supplement Fig. 2, Table 1), which is essentially the same as 44.0±0.3 Ma for the Hahajima andesite. Another andesite from dive #824 (R9) produced a plateau age of 41.84±0.14 Ma. The inverse isochron for this sample gave large errors for age and $^{36}Ar/^{40}Ar$ intercept because the data cluster at the radiogenic end. Even so, consistency between the isochron age and the plateau age and the relatively undisturbed age spectra imply that the plateau age is reliable. High-Mg andesite

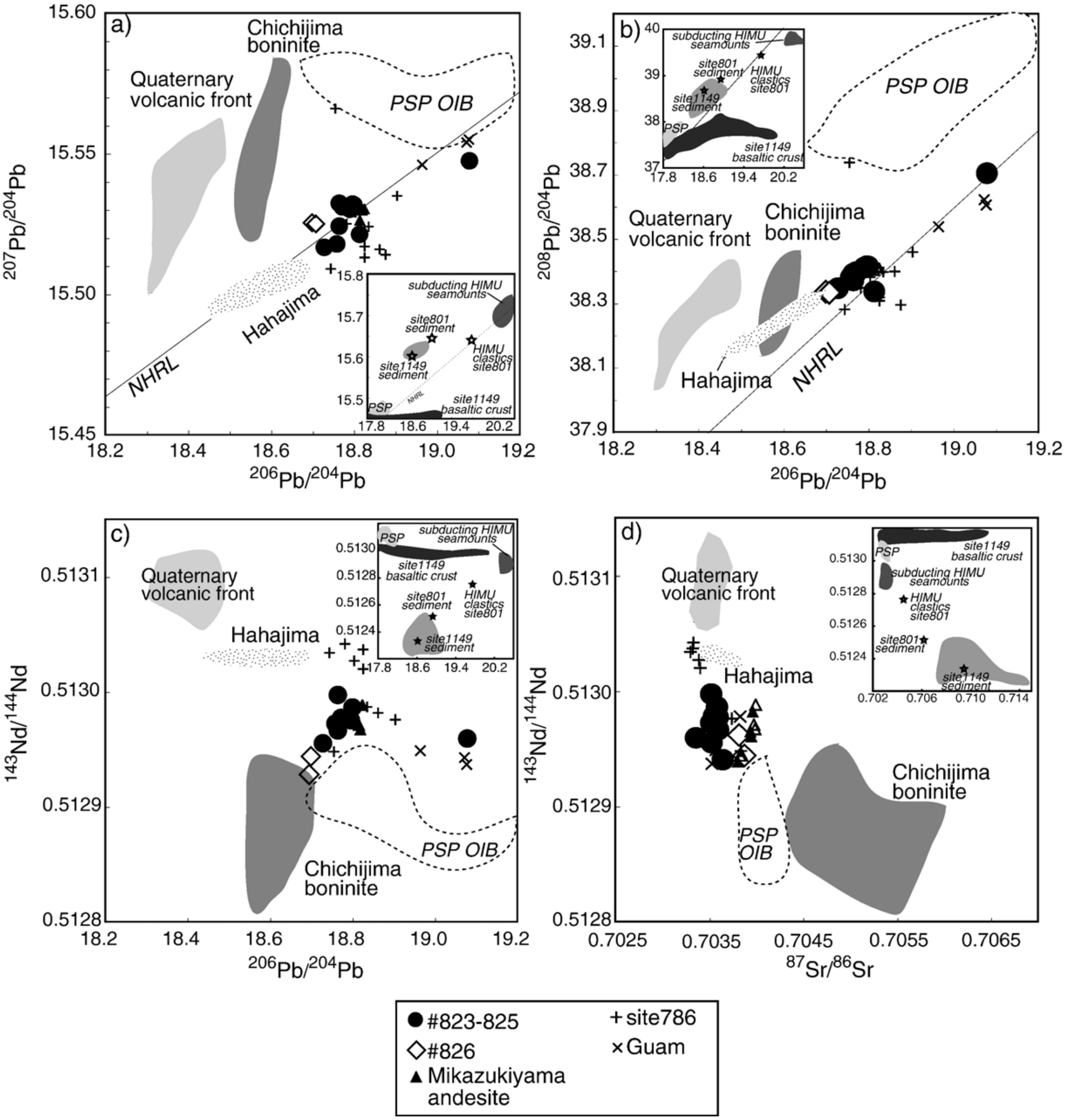

Fig. 4. Isotopic composition of samples from the Bonin Ridge. The data range for Eocene lavas from Chichijima and Hahajima [7,13], Guam [42], ODP site 786 [21] and PSP OIB (oceanic island basalt from the Philippine Sea Plate; [62]) are shown for comparison. The isotopic compositions are not corrected for age. Isotopic range and/or average compositions (star symbols) of the possible slab-derived components for the southern Izu–Bonin arc, including ODP site 1149 sediment and basaltic crust [68], subducting HIMU seamounts [69], are shown as an inset. (a) plots of $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$, (b) $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$, (c) $^{206}Pb/^{204}Pb$ vs. $^{143}Nd/^{144}Nd$ and (d) $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$.

(#826 R8) returned a well-defined plateau age of 42.86 ± 0.18 Ma. These results indicate that the lavas that make up the narrow volcanic ridge of the northern BRE are Eocene, comparable in age to lavas of the Mikazukiyama Formation of Chichijima and the Hahajima andesites, and are a few million years younger than the boninites and bronzite andesites of the Maruberiwan Formation on Chichijima.

5.2. Geochemistry of volcanics from the BRE

Samples collected from the N-BRE (dives #823–#825) are tholeiitic to calcalkaline basaltic andesites, and andesites with major element compositions (Fig. 2, Table 2 and supplement Table 1) that span the range of compositions between Hahajima andesites and Late Eocene to Early Oligocene "first-arc" [41] samples from other

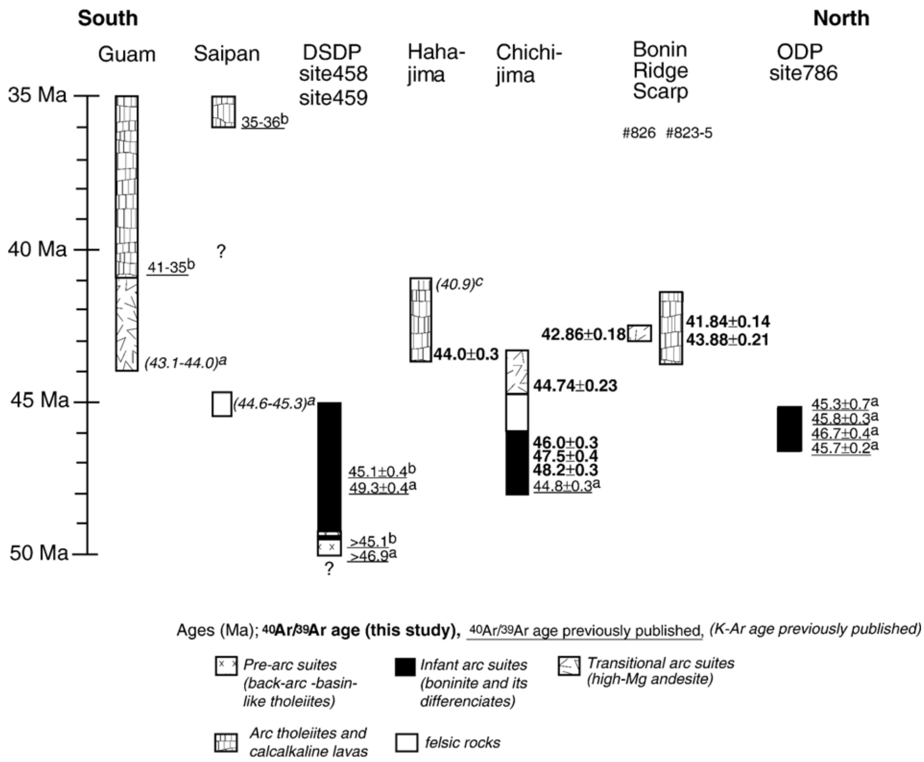

Fig. 5. Compilation of $^{40}Ar/^{39}Ar$ dating results on volcanics from the IBM forearc. These results imply that there is no systematic difference in age between boninites from Chichijima and ODP site 786. A boninite from the Mariana arc (DSDP site 458) also shows a similar age to these boninites. Boninite volcanism appears to have ceased before 46 Ma and characteristics of volcanism in the Izu–Bonin forearc seems to have changed at 45–46 Ma. Date source other than this study; a: [23], b: [26], c: [70]. $^{40}Ar/^{39}Ar$ age of Cosca et al. [23] is calculated using an age of 520.4 Ma for MMHB-1. $^{40}Ar/^{39}Ar$ age of Reagan et al. [26] is calculated using an age of 27.84 Ma for FC-2 Fish Canyon Tuff.

locations in the IBM arc system (cf. [28,42,43]). Samples from dive #826 are high-Mg andesites (andesites with MgO > 6 wt.%) with lower MgO and higher TiO_2 than the Chichijima boninites.

Samples from dives #823–#825 are enriched in LILEs (large ion-lithophile elements) and light REEs (rare earth elements), but depleted in heavy REE relative to tholeiitic andesites from Hahajima (Fig. 3). These dive samples also are relatively depleted in Nb and enriched in fluid-mobile elements such as Sr, Ba, U, and Pb consistent with an arc setting and implying contribution of a subduction-related fluid to their mantle source. The high-Mg andesites from dive #826 are similar in trace element characteristics to high-Mg andesites from the Mikazukiyama formation on Chichijima and relatively enriched boninitic lavas from ODP site 786 and Guam, such as higher Sm/Zr at given Zr content, and higher REE and Ti concentrations (Fig. 3) compared to Maruberiwan Formation boninites (cf., [7,18,42]).

The isotopic characteristics of BRE lavas are listed in Table 3 and shown on Fig. 4. On Pb isotope diagrams (Fig. 4a and b), samples from all BRE dives plot with other Eocene lavas from the IBM arc (except the Chichijima boninites) near the Northern Hemisphere Reference Line (NHRL; [44]). This trend is characterized by low or negative $\Delta^{207}Pb/^{204}Pb$ and $\Delta^{208}Pb/^{204}Pb$ with higher $^{206}Pb/^{204}Pb$, trending towards the composition of the HIMU mantle reservoir (Fig. 4a and b: [7,13,42]). In Pb–Nd and Sr–Nd isotopic plots (Fig. 4c and d) andesitic samples from dives #823–#825 have relatively constant $^{87}Sr/^{86}Sr$ and slightly increasing $^{143}Nd/^{144}Nd$ with increasing $^{206}Pb/^{204}Pb$. Sample #823 R8 has lower $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ but higher $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than other N-BRE samples. BRE tholeiitic to calcalkaline andesites are remarkably similar in isotopic composition to ODP site 786 boninites. The #826 high-Mg andesites have isotopic compositions that are intermediate between BRE tholeiitic andesite and Chichijima boninites, which form a trend extending to high $\Delta^{207}Pb/^{204}Pb$ and $\Delta^{208}Pb/^{204}Pb$ (Fig. 4a and b). In Pb–Nd and Sr–Nd isotopic plots, BRE high-Mg andesites are distinct from other BRE andesites from #823–#825 in having slightly lower $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ and higher $^{87}Sr/^{86}Sr$. BRE high-Mg andesites thus plot between other BRE andesites and

Chichijima boninites, confirming their transitional geochemical characteristics.

6. Discussion

6.1. Age and duration of boninitic volcanism

The new dating results from the Bonin islands show that the boninitic volcanism on Chichijima was active between 48 and 46 Ma (Fig. 5). This age range is much smaller than previous estimates based mainly on K–Ar dating results (e.g., [45,46]), which range from 8 to 48 Ma (Fig. 4: [14,45]). The new data is slightly older than a weighted mean plateau age of 44.8±0.3 Ma by Cosca et al. [23]. The ages we obtained correspond with the oldest published ages, indicating that younger K–Ar ages reflect Ar loss caused by alteration and loss of Ar from glassy boninite samples.

Another important result is that the age of Chichijima bronzite andesite (780-1) is indistinguishable from the ages of true IBM boninites. This implies that these two rock types coexisted during the earliest stage of arc evolution. This is also consistent with their mode of occurrence [8], similarity in their source [7] and petrogenetic interpretation [7,9].

Another boninite locality in the Izu–Bonin forearc is ODP site 786 [21]. K–Ar ages for samples from this site [47] range between 12–41.1 Ma for boninites and between 37.9–43.9 Ma for bronzite andesite; these ages are sometimes inconsistent with stratigraphic relationships. More reliable $^{40}Ar/^{39}Ar$ plateau ages obtained for bronzite andesites from ODP site 786 are 45.8±0.3 and 46.7±0.4 Ma (Fig. 5; [23]). The wider and younger range of K–Ar ages result from alteration and Ar loss. If we assume that the associated boninites from site 786 are contemporaneous with the bronzite andesite as is the case for Chichijima, the timing of boninite volcanism at ODP site 786 (32° N) is almost identical to that of Chichijima boninite.

The slightly younger age (44.74±0.23 Ma) of high-Mg andesite from the Mikazukiyama Formation indicates that this volcanism postdated boninitic volcanism by 1–2 m.y. The $^{40}Ar/^{39}Ar$ age is significantly older than a K–Ar age of 29 Ma [48], but is consistent with radiolarian biostratigraphic age of Early Middle Eocene [8]. The age is also consistent with stratigraphic relation between the boninitic dacite lavas of the Maruberiwan Formation and the Mikazukiyama Formation, i.e., the Mikazukiyama Formation unconformably overlies the boninitic dacite [8]. The new $^{40}Ar/^{39}Ar$ age indicates that the time between eruption of the boninites and the Mikazukiyama andesites was much smaller than previously estimated. Since no younger boninitic volcanism has been recognized, the eruption of boninite in the Bonin sector of IBM appears to have ceased between 44.7 and 46 Ma.

The 44.0 Ma radiometric age of Hahajima tholeiitic andesite is consistent with the estimated biostratigraphic age of 43–47 Ma for radiolaria from interpillow sediment [49]. Along with ages of 41.8–43.9 Ma for BRE andesites, it is clear that tholeiitic to calcalkaline andesitic volcanism postdates boninitic volcanism and this confirms our assertion that boninitic volcanism ceased after 45–46 Ma in the Bonin Ridge area.We conclude that in the Bonin sector, Eocene infant arc boninitic volcanism occurred between ca. 46–48 Ma. We also conclude that after 45–46 Ma, volcanism shifted to compositions ranging from high-Mg andesites to tholeiitic and calcalkaline andesites. These observations suggest that boninitic volcanism in the Izu–Bonin forearc had a much shorter duration than previously thought [45]. In the southern IBM arc (Mariana sector), the shift from true low-Ti boninitic volcanism at DSDP site 458 to the higher-Ti "boninite series" volcanism on Guam occurred at about the same time as the shift from boninite to high-Mg andesite volcanism on the Bonin Ridge (Fig. 5; [24,26]). However, the appearance of tholeiitic to calcalkaline volcanism postdates 41 Ma in this part of the arc [26,27]. The shorter duration of infant arc volcanism also implies a much higher rate of crustal production during this stage than the ~120–180 km^3/km-Ma inferred earlier [4].

6.2. Origin of volcaniclastics on the Bonin Ridge Escarpment

Our results indicate that andesitic volcanism along the BRE postdates Chichijima boninites, and that the BRE is constructed on slightly older infant arc crust. There are at least two explanations for this. The Bonin Ridge is known to have been uplifted and exposed above sealevel prior to the Oligocene [50]. It is possible that the central part of the ridge (where the islands are) was uplifted most. In this case, younger BRE–Mikazukiyama–Hahajima andesites might have been eroded away after the ridge was exposed above sealevel, whereas the same units along the BRE might have remained preserved below sealevel. Another possibility, which we prefer, is that BRE volcanism represents transitional stage in localizing the magmatic arc away from trench along the edge of the Ogasawara Trough. The dips of the volcaniclastic layering observed during diving suggest that BRE–Ogasawara Trough bathymetry was present before 44–42 Ma volcanism. The volcaniclastics of the

Mikazukiyama Formation were transported to topographic lows and formed slump deposits [8], since no eruption center for this younger Mikazukiyama andesite has been recognized on Chichijima or on the small island east of Chichijima. Furthermore the ridge where the 3 dives (#823–#825) were conducted is located west of the extension of the trend of the northern Bonin Islands (Mukojima Islands) where boninites have been reported [51]. These lines of evidence imply that the location of younger volcanism (<45 Ma) was west of vents for the boninite volcanism. In this case, BRE–Mikazukiyama–Hahajima volcanism occurred under extensional stresses that localized eruption of andesite along an elongate ridge rather than discrete volcanic centers. Eruption from chains of vents forming volcanic ridge at the earliest stage of rifting have been reported from other rift basins (Okinawa Trough: [52]; Sumisu Rift: [53]). This interpretation implies, in turn, that the Ogasawara Trough formed in late Eocene time behind the arc and thus was the first back-arc basin of the IBM arc. This interpretation for the age of the Ogasawara Trough contrasts with an interpretation of Oligocene age by Taylor [10].

The significant change in compositions between the Chichijima boninite and the BRE–Mikazukiyama–Hahajima andesites tempts us to propose that the change from shallow and high-degrees of melting required for generating boninites (e.g. [4,54,55]) to conditions similar to those for normal arc volcanism began after 45 Ma. Taylor and Nesbitt [13] proposed that andesitic volcanism exposed on Hahajima, whose chemical characteristics are similar to BRE andesites, was associated with intra-arc rifting. Further studies of Ogasawara Trough crustal structure and the distribution and nature of volcanism in Eocene and Oligocene time on the Bonin Ridge is necessary to test these hypotheses.

6.3. Implications for the tectonic setting for boninitic volcanism and development of transitional arc magmatism

In the IBM arc boninite has been found at several widely separated locations along the entire ~2500 km length of the forearc. The results of this study and earlier studies (e.g. [23,26]) indicate that boninite volcanism occurred almost contemporaneously along the entire length of the IBM arc system beginning at about 48 Ma and continuing until ~45 Ma. The wide dispersal of boninite volcanism throughout the IBM forearc rule out point heat source (e.g., subducting ridges, the Central Basin Spreading Center, a mantle plume) for genesis of boninite magma. Boninite series lavas from Guam with compositions that are similar to those of lavas from the

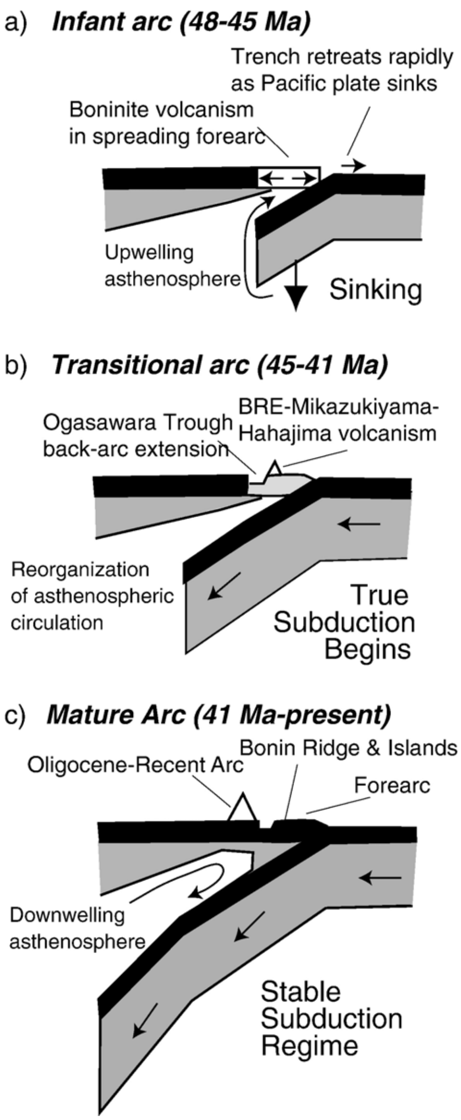

Fig. 6. Schematic cartoon for evolution of arc magmatism and subduction in the Bonin sector of the IBM arc system. a) Sinking of Pacific plate causes spreading at the site of the modern forearc; flux of water from sinking slab to upwelling asthenosphere melts harzburgite to form boninite magmas. b) Beginning of down-dip motion of Pacific plate leads to reorganization of mantle circulation above subducting slab and forearc extension is greatly reduced. This allows the forearc to cool and the locus of magmatism retreats from the trench. Magmas erupt from fissures, not point sources. This is the environment of the BRE–Mikazukiyama Formation–Hahajima igneous activity. Continued (if reduced) extension of the overriding plate results in back-arc basin extension to form the Ogasawara Trough. c) Stable subduction regime is established, with further retreat of the magmatic arc. Back-arc basin extension to form the Shikoku–Parece Vela Basin at 25 Ma occurs behind the magmatic arc.

Mikazukiyama Formation and dive site #826 (i.e., high-Mg andesite) erupted at about 44 Ma [26,27], suggesting that eruption of high-Mg andesites with higher REE and

TiO_2 concentrations also are contemporaneous along the length of the arc. This change in composition apparently was associated with the migration of the locus of volcanism away from the trench and towards the position of the modern magmatic front. Along the IBM arc, the completion of the transition to "normal" arc volcanism occurred at about this same time. Any model for the tectonic setting of boninite production is required to address these observations.

Several models have been proposed to explain IBM boninites. Stern and Bloomer [4] proposed that boninitic volcanism in the IBM forearc began with nucleation of a subduction zone along a fracture zone, accompanied by adiabatic upwelling of asthenosphere and aided by fluids released from the sinking Pacific plate. This model of subduction initiation was shown recently to be the likely consequence of convergence between an old and young plate [56]. This scenario can explain the occurrence of boninite volcanism along the length of the initial convergent margin, if the required temperature (~1280 °C) for mantle melting of depleted mantle is reached (e.g., [21]). In the scenario, upwelling of asthenosphere to form boninite by forearc spreading (Fig. 6a) was vigorous at 46–48 Ma. A transition to true subduction began about 44–45 Ma, causing a reorganization of asthenospheric circulation that allowed the forearc to cool and forced the arc magmatic axis to retreat (Fig. 6b). This generated high-Mg andesites like those found in the Mikazukiyama Formation on Chichijima, the Facpi Formation on Guam, and dive #826 by still shallow, but somewhat lower degrees of melting. The opening of the Ogasawara Trough accompanied by the nearly simultaneous switch to typical arc volcanism near the northern dive sites suggests that mantle counterflow and deeper melting started about this time in this part of the arc, whereas this transition may have occurred later in the southern IBM system. Establishment of a stable subduction zone was completed sometime after 41 Ma but before 35 Ma (Fig. 6c).

Subduction of an active spreading ridge beneath young lithosphere also has been proposed as a way to produce boninites [21]. This scenario reasonably explains the short duration of boninitic volcanism. However, subduction of young oceanic crust results in slab melts or adakites, which are quite different from boninites (e.g., [57–60]). Furthermore, for ridge subduction to explain simultaneous boninite volcanism along the IBM arc, the ridge would need to trend subparallel to the trench and there is no evidence for this orientation from magnetic anomalies in the Pacific or Philippine Sea plates.

Macpherson and Hall [61] suggest that the high temperatures needed for boninitic volcanism require a mantle plume beneath the Philippine plate at the time of subduction initiation. However, we contend that high mantle temperatures at shallow levels are a natural consequence of subduction initiation [56], and additional heat from a mantle plume is not needed. In addition, there is little concrete petrochemical evidence for the presence of a plume-related source mantle during the early evolution of the IBM system. For example, Pb and Nd isotopic compositions for IBM boninites are distinct from Philippine Sea plate OIB ([62]; Fig. 4) and appear largely to be mixtures of subducted reservoirs associated with the Pacific plate. Chichijima boninites have high $\Delta^{207}Pb/^{204}Pb$ and low $^{143}Nd/^{144}Nd$, suggesting important contributions from subducting pelagic sediment. Pb isotopes for these boninites trend from pelagic sediment toward the NHRL (Fig. 4), which probably reflects the presence of Pb from altered Pacific MORB in its source [7,63].

The Pb isotopic characteristics of the IBM arc boninites thus do not seem to be consistent with involvement of a Philippine Sea plate OIB source. The mantle provenance is predominantly Indian rather than Pacific mantle provenance, as indicated by Hf–Nd isotope considerations [43], i.e., the same mantle component as Philippine Sea Plate MORB.

Another recent hypothesis assumes interaction between subduction and a spreading ridge [46]. This model may need to be modified because it assumes that boninite volcanism lasted for more than 10 Ma, which is much longer than the 2–3 m.y. that our data indicates.

A process which enables melting of depleted mantle (harzburgite) along the length of the arc such as upwelling of asthenosphere as a result of a sinking plate, aided by fluids released from the newly subducted

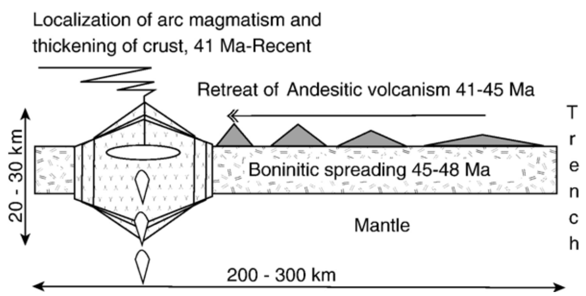

Fig. 7. Generalized cross-section across IBM arc system showing mode of crustal growth for juvenile IBM arc inferred from this study. Broad swatch of crust forms by seafloor spreading during first 3 Ma of arc infancy, including boninites. Transitional volcanism at 45–42 Ma changes composition and style to erupt along linear ridges like that atop Bonin Ridge Escarpment (parallel to arc). Mature arc volcanism begins as focus of magmatic activity retreats to independent edifices near locus of present volcanic front, ~200 km from trench.

slab and sediments seems to satisfy constraints of volcanic history and chemical characteristics of boninite and associated volcanic rocks. Models which require localized heat source such as ridge subduction and plume-induced melting do not satisfy these constraints and thus are not preferred.

7. Summary

New constraints on the earliest stage of volcanism in the Izu–Bonin arc were obtained on Eocene volcanic rocks from the Bonin Islands and Bonin Ridge Escarpment. $^{40}Ar/^{39}Ar$ dating results imply that the boninitic volcanism in the vicinity of Chichijima Island was active for a shorter period than previously thought, i.e, 46–48 Ma. Tholeiitic andesite from Hahajima Island appears to be 2–3 m.y. younger than Chichijma boninites. Tholeiitic to calcalkaline andesite and high-Mg andesite from the western escarpment of the Bonin Ridge erupted at 41.8–43.9 Ma and appear to be contemporaneous with the volcanism on Hahajima. Thus, the compositions of the subarc mantle and conditions of melting seem to have changed in both time and space at 45–46 Ma. These data indicate that boninite volcanism occurred almost contemporaneously along the length of the IBM arc system. This implies that any model for the tectonic setting for early IBM arc volcanism needs to explain the synchronous boninitic magmatism several thousand km of arc length. A process which enables melting of depleted mantle along the length of the arc, aided by flux from sinking slab best fulfills requirements from volcanic history and chemical characteristics of boninite and associated volcanic rocks. Catastrophic sinking of the Pacific Plate and forearc spreading [4] following a period of convergence between the Philippine and Pacific plates [56] is the most likely such process.

One of our most interesting results is the recognition of a transitional stage in the development of the magmatic arc, from forearc spreading to the localization of magmatism during the Early Oligocene at a chain of discrete edifices located 200 km west of the trench system. The transitional stage consists of fissure eruptions halfway between the trench and the present magmatic axis and is represented by the 44–42 Ma BRE–Mikazukiyama Formation–Hahajima andesite association. These OPX-bearing high-Mg (Mikazukiyama Formation and #826) and tholeiitic to calcalkaline (#823–#825 and Hahajima) andesites were erupted along the BRE, as the arc magmatic axis localized and retreated from the trench. The change from shallow near-trench hydrous melting of the mantle to more typical arc magma generation occurring further away from the trench and deeper in the mantle appears to have been well underway in the Bonin ridge area by about 42 Ma. This evolution is summarized in Fig. 7. This interpretation and the observation that breccias containing 44–42 Ma clasts flowed westward off the BRE into a depression to the west implies that the Ogasawara Trough opened before about 44–42 Ma, significantly older than previously thought. We note that the identification of a transitional magmatic stage early in the evolution of the IBM arc system is a new inference but some intermediate stage between boninitic spreading during arc infancy and establishment of a stable arc volcanic front seems inescapable.

The model depicted in Fig. 7 requires confirmation at the same time that it should be taken into consideration by geodynamic models for how lithospheric descent and mantle circulation respond to the initiation of subduction zones.

This interpretation further implies that the Ogasawara Trough is the oldest back-arc basin in the IBM arc system and is significantly older than previously thought. The identification of a transitional magmatic stage early in the evolution of the IBM arc system has important constraints for understanding how mantle circulation responds to the initiation of subduction zones.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2006.08.007.

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