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Author(s)	Johnson, Kevin T.M.
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MAJOR, TRACE, AND RARE EARTH ELEMENT ABUNDANCES IN BONINITIC LAVAS FROM THE OGASAWARA FOREARC

by

Kevin T. M. Johnson*

(with 7 text-figures and 1 table)

Abstract

Dredged andesites and dacites from the Ogasawara forearc contain high abundances of MgO at high SiO₂, high K₂O, low rare earth element abundances and flat patterns, and very low TiO₂ contents. The chemical character and geologic setting support the interpretation that these lavas are evolved members of the boninite series formed by high degrees of partial melting of a previously depleted arc source, followed by enrichment in K, Th, and large-ion lithophile elements, and finally differentiated to higher SiO₂ contents than are usually found in boninites. This is consistent with existing tectonic models of the Izu-Mariana arc system in which young, hot Philippine Sea crust produced high geothermal gradients in this region from the Tertiary.

Introduction

The Ogasawara (Bonin) volcanic arc extends south-southeast between 26°N and 28°N, 142°E, about 1000 km south of Tokyo (Text-fig. 1). The Bonin Islands comprise the outer arc of the Izu-Mariana arc-trench system in this area and are chiefly Eocene to Miocene in age (Kaneoka et al., 1970; Kuroda and Shiraki, 1975). Several authors have described high-magnesium, bronzite bearing igneous rocks dredged from the Mariana forearc or from Chichi-jima in the Bonin Islands (Dietrich et al., 1978; Bloomer et al., 1979; Meijer, 1980; Hussong and Uyeda, 1981; Ishii et al., 1981). These rocks are rare in the world and are found mainly in the island arcs of the western Pacific. They are characterized by high SiO₂ and MgO, and low TiO₂ and incompatible trace elements in a rock series ranging from basalts through dacites that have been called the "boninite series" (Meijer, 1980).

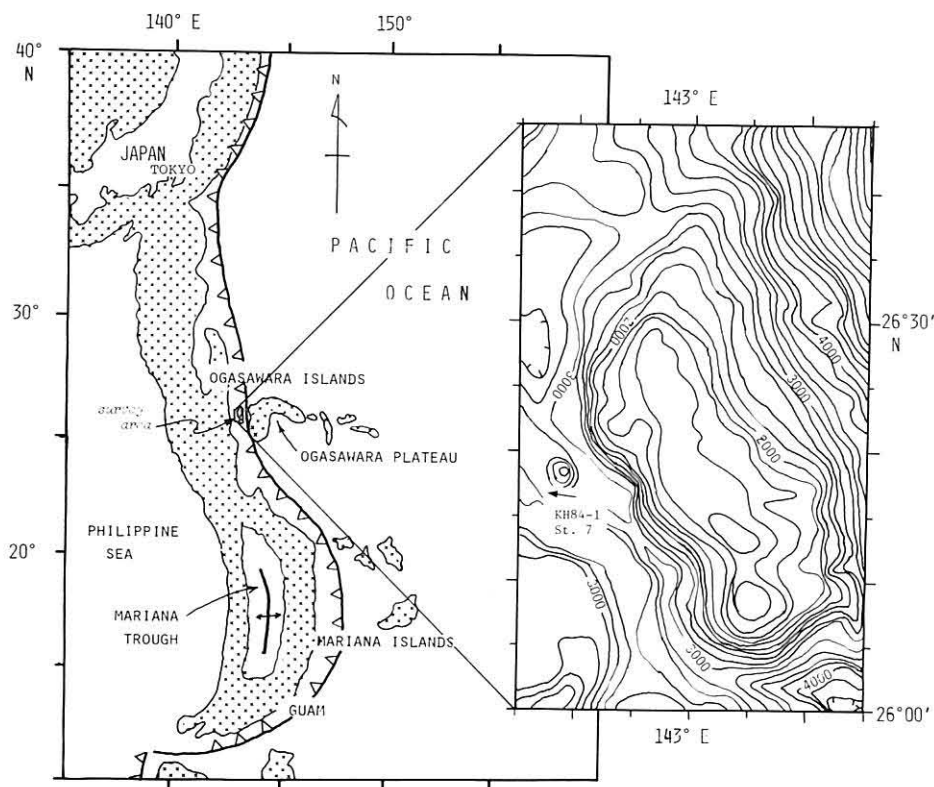
In this paper I report major, trace, and rare earth element analyses for five boninitic rocks recovered in dredge 7 (Text-fig. 1) of the cruise KH84-1 of the R/V HAKUHO-MARU from the Ogasawara forearc and discuss the results in light of the tectonic and petrogenetic processes likely in this region.

Sample Analysis

Thin sections were made and fresh samples were chosen for analysis. Chips were soaked in deionized water for 10 days until the water remained clear upon addition of

Contribution from the department of Geology and Mineralogy, Faculty of Science, Hokkaido University, No. 1856.

* Present address: Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543 U.S.A.



Text-fig. 1 Map of KH84-1 station 7 dredge location. Patterned areas on larger map indicate depths less than 4 km. Barbed line is Izu-Mariana Trench. Inset map modified after Kobayashi (1983).

AgNO_3 . This was to remove as much seawater contamination as possible. The chips were then crushed in a WC mill for XRF and atomic absorption analyses and in an Fe mill for INAA analyses. XRF analyses for SiO_2 , TiO_2 , Al_2O_3 , FeO^* , CaO , K_2O , and P_2O_5 were carried out at the facilities of the National Agricultural Research Center in Sapporo. Atomic absorption analyses for MnO , MgO , and Na_2O were carried out at Hokkaido University. INAA for REE, Ba, Co, Cr, Hf, Sc, Ta, and Th was performed at the University of Tokyo's Faculty of Science, Laboratory for Earthquake Chemistry.

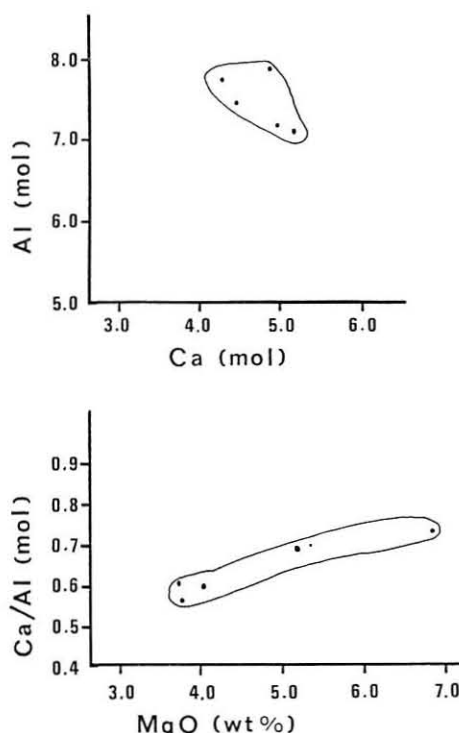
Petrography

Provisional petrographic groups were determined on board ship according to mineralogy, texture, and alteration. Five fresh, representative samples from four of the groups were chosen for chemical analysis. Orthopyroxene phenocrysts with $2V = 80^\circ$ were found in samples 7-745 and 7-851 and are probably bronzites, the remaining opx being hypersthene. Relict grains of altered, resorbed olivine were found in trace quan-

ties in 7-851. Quartz was found in the groundmass of samples 7-721, 7-772, and 7-803 and as rounded phenocrysts in 7-772 (dacite). Plagioclase is present in all of the samples and though the type boninites are glassy and plagioclase-free (Kuroda and Shiraki, 1975; Meijer, 1980), their SiO_2 contents are lower and their MgO contents slightly higher and are less evolved than our samples. Plagioclase microphenocrysts and laths were found mantling tabular clinopyroxene in samples 7-851 and 7-745 and according to phase relationships noted by Natland (1981) this is the most characteristic feature of boninite petrography. This is because in boninites the liquids fall within the diopside field in Di-An-Ab space due to suppression of plagioclase crystallization in the presence of H_2O (Yoder, 1969) and since the water present in subduction environments also enhances melting, more mafic magmas are produced. Hence cpx is on the liquidus before plagioclase and this texture results.

Major Elements

Table 1 lists the major and trace element compositions and the molecular norms of the samples. Noteworthy are the consistently low values of TiO_2 ($\leq 0.28\%$) and the high concentrations of MgO (3.67–6.87%) at high SiO_2 (60.22–65.15%). The K_2O contents range from a low of 0.3% in the MgO -rich sample, 7-851, to 1.22% in the dacite, 7-772. Al_2O_3 increases slightly with decreasing MgO , but CaO and FeO^* decrease suggesting cpx and opx fractionation. Late stage plagioclase crystallization probably ac-



Text-fig. 2 (a) Ca vs. Al (mol %), (b) Ca/Al vs. MgO. The diagrams show the increase in Al content relative to Ca with differentiation in dredge 7 lavas, even in more evolved stages indicating suppression of plagioclase crystallization in favor of cpx.

Table 1 Major and trace element analyses — Ogasawara Forearc

Sample No.	7-721	7-745	7-772	7-803	7-851
SiO ₂	63.29	61.32	65.15	62.52	60.22
TiO ₂	0.27	0.24	0.28	0.28	0.23
Al ₂ O ₃	14.14	13.59	14.60	15.01	13.42
FeO*	6.49	7.26	5.72	6.67	7.91
MnO	0.11	0.12	0.07	0.11	0.13
MgO	4.01	5.18	3.77	3.67	6.87
CaO	6.27	6.96	6.05	6.84	7.20
Na ₂ O	2.58	2.39	2.94	2.56	2.33
K ₂ O	1.12	0.93	1.22	0.89	0.30
P ₂ O ₅	0.05	0.05	0.06	0.05	0.11
H ₂ O ⁺	0.85	2.31	0.86	1.82	1.34
H ₂ O ⁻	0.38	0.29	0.42	0.58	0.70
Total	99.57	100.64	101.14	101.02	100.76
Mg #	33	36	34	30	40
Trace Elements (ppm):					
Ba*	73	47	47	34	29
Sc	26.1	29.1	25.3	27.5	32.7
Co	22.7	26.5	18.1	23.1	36.7
Cr	124	227	122	105	356
Hf	1.72	1.39	1.78	1.69	1.44
Ta*	0.044	0.038	0.046	0.037	0.051
La	1.93	1.65	2.20	2.06	4.71
Ce	5.03	4.65	5.75	5.16	11.36
Sm	1.16	0.90	1.15	1.16	2.24
Eu	0.37	0.27	0.35	0.34	0.55
Tb	0.27	0.21	0.26	0.24	0.46
Yb	1.25	0.87	1.07	0.99	2.04
Lu	0.19	0.15	0.18	0.17	0.29
Th	0.18	0.14	0.19	0.15	0.15
Cation Norms:					
Q	21.8	19.0	21.8	21.2	17.2
Or	7.0	6.0	7.2	5.4	1.8
Ab	24.0	22.0	26.2	23.7	21.2
An	24.3	24.0	24.4	27.4	25.7
Wo	3.0	4.5	2.7	2.8	4.0
En } Di	1.9	3.1	1.8	1.8	2.9
Fs } Di	1.1	1.4	0.9	1.1	1.1
En } Hy	9.5	11.9	8.6	8.7	16.6
Fs } Hy	5.3	5.5	4.3	5.3	6.5
Mt	2.0	2.3	1.6	2.0	2.3
Il	0.4	0.3	0.4	0.4	0.3
Ap	0.1	0.1	0.1	0.1	0.2

Analyses: major elements — XRF except MgO, MnO, Na₂O by atomic absorption, analyst — K. Johnson; trace elements — INAA, analysts — Y. Nakamura and K. Johnson; H₂O — Penfield method.

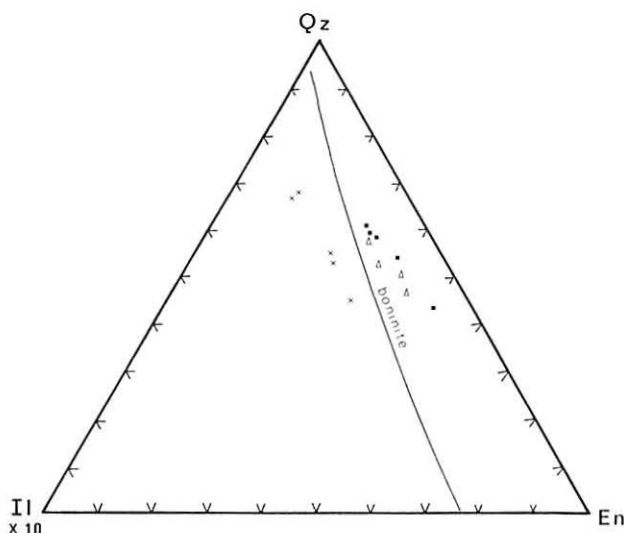
FeO*: total iron as FeO.

Mg #: Mg/100/(Mg+Fe*), Fe*: total iron as Fe.

Ba* and Ta*: Accuracies are very poor (generally > ±60%) due to low concentrations.

counts for the increase in Al_2O_3 with decrease in MgO and CaO (see Petrography discussion above and Text-fig. 2). The low $\text{CaO}/\text{Al}_2\text{O}_3$ (0.41–0.54) in the sampled lavas and the hypothetically lower plagioclase crystallization temperature (Yoder, 1969) supports a lower An content of plagioclase, and this should be tested.

The dredged rocks are highly quartz normative and on a quartz-enstatite-ilmenite normative diagram (Text-fig. 3) they all plot within the field of boninites as defined by Meijer (1980). At the same time, $\text{Mg\#}$ [$\text{Mg} \times 100 / (\text{Mg} + \text{Fe}^*)$] are as high as 40, which is quite high for lavas with these silica concentrations, and are consistently higher at a given SiO_2 than andesites of the arc tholeiite series (Jacks and White, 1972).



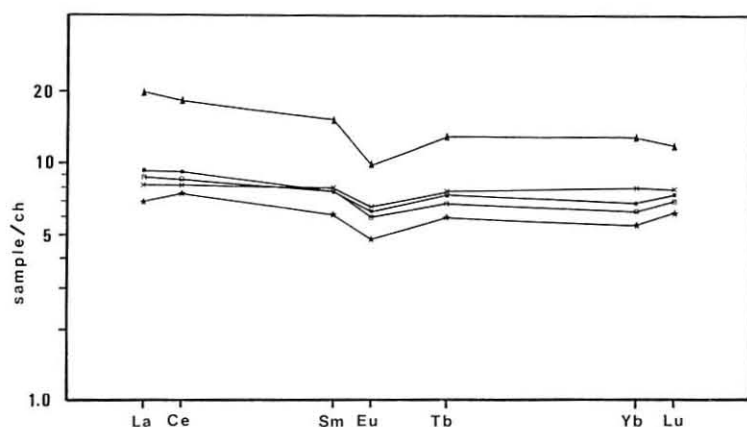
Text-fig. 3 Normative (cation) Qz (quartz), En (enstatite), and Ilx10 (ilmenite) showing the field of boninite as defined by Meijer (1980). The diagram emphasizes the highly quartz- and enstatite-normative nature of boninitic rocks. Squares, dredge 7 rocks; X, Palau arc tholeiite series (Johnson, unpublished data); triangles, DSDP site 458 rocks (Hussong and Uyeda, 1981).

Experiments on wet melting of mantle peridotites have shown that SiO_2 saturated liquids of high MgO content, similar to the compositions of boninites, are produced under H_2O -saturated or near saturated conditions at pressures of 14–17 kb (Green, 1975; Kushiro and Sato, 1978; Howard and Stolper, 1981). Furthermore, the major element variation of these lavas is controlled by crystallization of $\text{opx} + \text{cpx} \pm \text{olivine}$ as liquidus phases. The major element compositions of the sampled lavas from the Ogasawara forearc in this study are consistent with this scheme.

Trace Elements

Chondrite-normalized rare earth element (REE) abundances are presented in Text-fig. 4. The samples all show flat to slightly LREE enriched patterns [$(\text{La}/\text{Sm})_N = 1.0$ –1.3; $(\text{La}/\text{Yb})_N = 1.04$ –1.56]. Small Eu anomalies are also present, reflecting the presence of plagioclase fractionation in these lavas. In a rough sense, the patterns resemble those of lavas from the Bonin Islands and the Mariana trench (Hickey and Frey, 1982), but with a less developed U-shape. The patterns are subparallel, with the

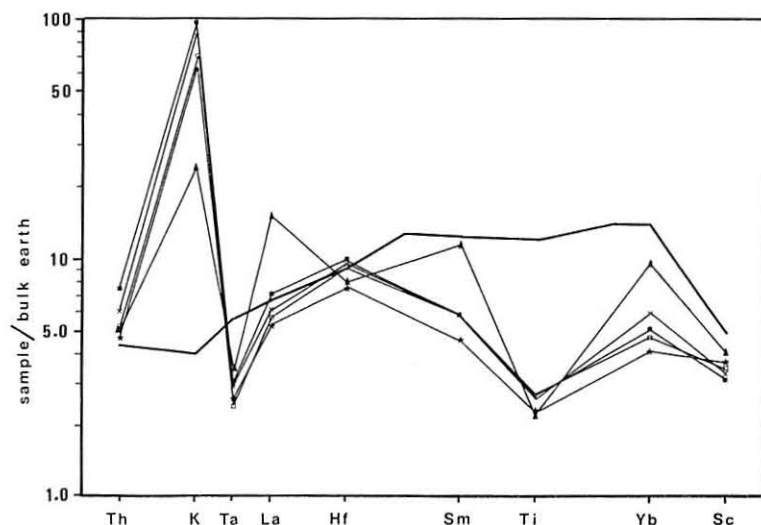
FeO^* : total iron as FeO , Fe^* : total iron as Fe .



Text-fig. 4 Cl chondrite normalized REE abundances. Normalization values from Anders and Ebihara (1982). X, 7-721; star, 7-745; solid square, 7-772; open square, 7-803; triangle, 7-851.

exception of 7-721 which has greater LREE depletion than the others (1.0 vs. 1.3-1.5). Compared to REE abundance patterns of boninite series lavas from other locations, our patterns resemble those from Chichi-jima in the Bonin Islands and dredge site 1403 in the southern portion of the Mariana trench (Hickey and Frey, 1982), but have slightly higher relative abundances probably due to shallow level fractionation.

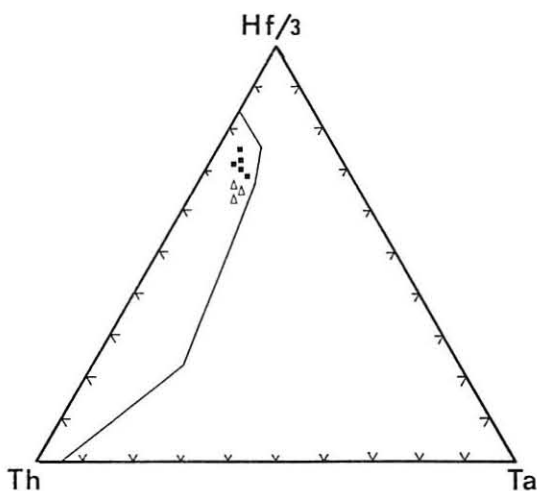
Text-fig. 5 shows an extended REE diagram with normalized abundances of Th, K,



Text-fig. 5 REE diagram extended to include other incompatible elements. Note the consistent anomalies of K, Ta, and Ti relative to MORB (heavy line). Bulk earth normalization values from Hickey and Frey (1982). Symbols as in Text-fig. 3.

Ta, Hf, Ti, and Sc along with La, Sm, and Yb. The notable enrichment in K, slight enrichment in Th and the marked depletion in Ti relative to MORB abundances are clearly illustrated in this diagram. REE abundances are also low with respect to MORB with the exception of sample 7-851. K/Ti ratios are high in all samples, ranging from 2 to 6, which contrasts with typical island arc ratios of ≤ 2 (Perfit et al., 1980).

Hygromagmatophile (HYG) elements are generally very low in concentration, but their depletion is irregular compared to MORB (Text-fig. 5). On a Hf-Th-Ta diagram (Text-fig. 6), the lavas plot in the upper end of the island arc field as defined by Wood

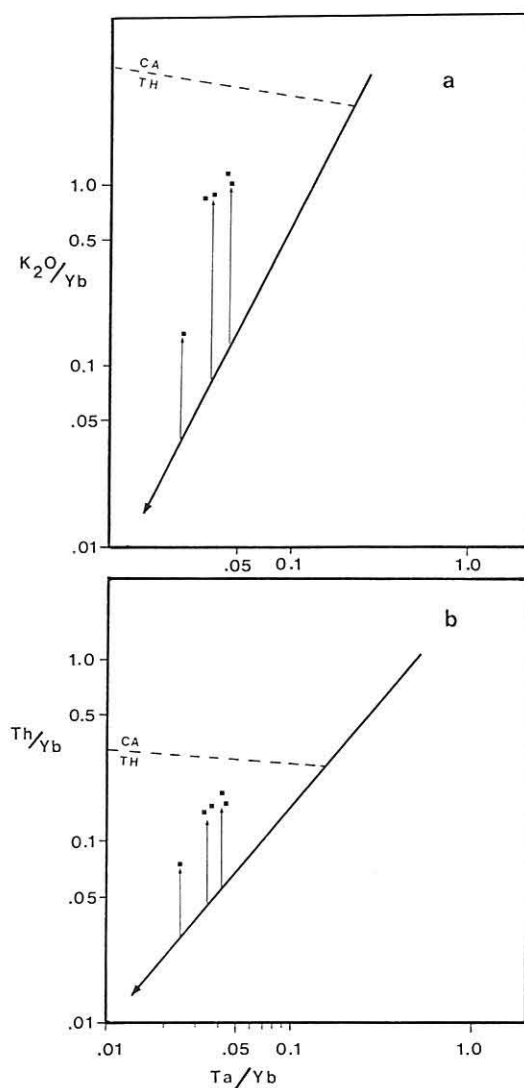


Text-fig. 6 Hf/3-Th-Ta diagram with destructive plate margin field expanded to include boninites (Wood et al., 1979). Symbols as in Text-fig. 2.

et al. (1981). They are enriched in Hafnium relative to Th and Ta, a characteristic noted in other boninitic lavas (Bougault et al., 1981). Th/Yb and K_2O/Yb vs. Ta/Yb diagrams have been used (Pearce, 1982) to identify contributions from the subducted slab and mobilization of Th and K_2O in hydrous fluids. Text-fig. 7 shows that the lavas of this study plot in the island arc tholeiite field indicative of the early stages of island arc development in which the degree of enrichment of Th and K is lower relative to more advanced calc-alkalic volcanism.

Summary of geochemical features:

1. High SiO_2 contents (59–65%) with high MgO, Cr, and Co contents.
2. Extremely low Ti and Ta and depletion of Ti relative to Sc below chondritic values.
3. Low REE abundances with slight but variable LREE enrichment and low HYG abundances relative to MORB.
4. Marked enrichments of K relative to MORB similar to other primitive arc rocks.
5. H_2O contents ranging from 1.2% to 4%.



Text-fig. 7 (a) K_2O/Yb vs. Ta/Yb , and (b) Th/Yb vs. Ta/Yb discrimination diagrams for dredge 7 lavas. Heavy lines with arrows indicate direction of source depletion while fine lines indicate subduction-related element enrichment. CA, calc-alkaline; TH, tholeiitic (after Pearce, 1982).

Discussion

Most models of boninite formation invoke mixing of magmas from at least two sources, a depleted sub-arc mantle wedge and a LREE enriched component. Meijer (1980) noted that REE total abundances decrease and La/Sm ratios increase up section in lavas drilled at site 458. This is contrary to fractionation from a unique source since La/Sm from later derived melts should also decrease up section. In the present study there is no stratigraphic control on the sampled lavas, but the sample which is most enriched in REE also contains the lowest concentration of TiO_2 and K_2O and highest concentration of MgO and Cr . So the sampled lavas are obviously not related by any

simple melting or fractionation process.

The high MgO contents of these lavas at high SiO₂ indicates the involvement of an ultramafic source in their genesis. It has been shown that hydrous melting of peridotite at pressures of 14-17 kb produces SiO₂ saturated liquids with high MgO content (Green, 1976; Kushiro and Sato, 1978). These melts resemble primitive boninites from site 458 and Chichi-jima (Kushiro, 1981). The normative clinopyroxene and orthopyroxene and the CaO and MgO contents of lavas in Kushiro's (1981) experimental study and those of lavas reported here are quite similar, especially samples 7-721, 7-745, and 7-851. Kushiro found that the site 458 lavas were not in equilibrium with mantle peridotites, i.e. they were not primary melts, but evolved from high-Mg boninitic melts by removal of cpx + opx ± spinel at pressures ≥ 8 kb under H₂O saturated conditions. Hickey and Frey (1982) noted that melting of fertile peridotite will produce magmas with Ti and HREE concentrations at least as high, but probably higher than boninite series lavas. It seems clear then that the source area for boninite lavas is depleted in incompatible elements by a prior melting episode (e.g. Meijer, 1980; Cameron et al., 1983). Similarities between REE patterns of refractory dunite and harzburgite and boninite (Frey, 1983) lend support to this interpretation; high degrees of melting of such a source would tend to produce REE patterns that mimic the source patterns.

The depletions in Ta and Ti (Text-fig. 5) are present in other island arc lavas as well (Briqueu et al., 1984). One explanation to account for these anomalies involves the presence of small amounts of sphene or titanate minerals which hold Ti, Ta, Nb, and middle REE (Hellman and Green, 1979; Wood et al., 1979). However, the stability range of the titanate minerals may be out of the range of likely boninite magma genesis (Haggerty, 1983). An alternative explanation is that these elements were removed by previous melting and their low mobility in vapor transfer processes prevented them from being reconcentrated in the source for boninites along with other more mobile elements.

In order to produce Qz-normative liquids from peridotite we have seen that H₂O is needed. Furthermore, to produce the high degrees of partial melting needed for the MgO enrichment, temperatures of 1100° to 1200° are needed (Green, 1976). Even under H₂O saturated conditions this would require depths of over 70 km (Sclater and Francheteau, 1970). However, depths in this range would not yield Qz-normative liquids so a higher geothermal gradient is needed to produce boninitic melts.

Meijer (1980) suggested that boninites were produced during the early stages of opening of the Philippine Sea when the Pacific plate was subducted beneath the young, hot Philippine Sea plate in late Eocene to Oligocene. Though ages are not known for the dredged lavas, this age is consistent with the age of volcanism along the Bonin ridge. The generalized model looks like this: initial arc volcanism producing arc tholeiites (present on some of the Bonin Islands) whose formation depleted the source mantle in incompatible elements and REE. The depleted, refractory mantle is increasingly melted due to the introduction of water with the descending slab and the water-rich vapor carries with it K, Th and other LIL elements.

Conclusions

The sampled lavas carry geochemical signatures typical of boninite series lavas and may be classified as boninitic andesites to dacites. These characteristics are:

1. High SiO_2 contents along with high MgO contents typical of much more primitive magmas.
2. High K and Th typical of other island arc volcanics.
3. Low REE abundances and nearly flat to slightly U-shaped REE patterns.
4. Very low TiO_2 contents.

The sampled lavas fit models of boninite generation by hydrous melting of a previously depleted (probably by earlier arc tholeiitic magmatism) subarc mantle peridotite source. This depleted residue was subsequently enriched in K, Th, and LIL elements from metasomatic volatile transfer from the subducted slab. LREE enrichment may have been accomplished by introduction of components from surrounding undepleted mantle by hydrous melting. The high heat flows needed to produce sufficient melting may have prevailed during the early stages of Izu-Mariana arc formation when the young, hot Philippine Sea plate was just forming and geothermal gradients at the site of Pacific plate subduction were high.

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