ABSTRACT

High field strength elements (HFSEs: Nb, Ta, Zr, Hf, Ti) relative to large-ion lithophile elements (LILEs: e.g., Rb, Ba, Sr) and rare earth elements (REEs) are commonly observed in lavas from subduction zones. One of the possible explanations for HFSE depletion is that trace quantities of residual minerals in subducting slab, such as rutile and zircon, conserve HFSEs during the slab dehydration process (Elliott et al., 1997; Rubatto and Hermann, 2003). In the Izu-Bonin-Mariana arc (northwest Pacific Ocean), slab-derived fluids that contributed material with breakdown of residual zircon in the slab (Okamura et al., 2016). These studies imply that the behavior of residual zircon in the slab must be an important constraint on the thermal structure of the mantle wedge. In this study, two types of basalts with different Zr contents were identified in the active rift zone of the Izu arc, which is the first stage of the backarc basin. We propose that their origin is related to the breakdown of residual zircon in the slab caused by high slab-surface temperatures related to the injection of asthenospheric material.

INTRODUCTION

Depletion of high field strength elements (HFSEs; Nb, Ta, Zr, Hf, Ti) relative to large-ion lithophile elements (LILEs: e.g., Rb, Ba, Sr) and rare earth elements (REEs) are commonly observed in lavas from subduction zones. One of the possible explanations for HFSE depletion is that trace quantities of residual minerals in subducting slab, such as rutile and zircon, conserve HFSEs during the slab dehydration process (Elliott et al., 1997; Rubatto and Hermann, 2003). In the Izu-Bonin-Mariana arc (northwest Pacific Ocean), slab-derived fluids that contributed material with breakdown of residual zircon in the slab (Okamura et al., 2016). These studies imply that the behavior of residual zircon in the slab must be an important constraint on the thermal structure of the mantle wedge. In this study, two types of basalts with different Zr contents were identified in the active rift zone of the Izu arc, which is the first stage of the backarc basin. We propose that their origin is related to the breakdown of residual zircon in the slab caused by high slab-surface temperatures related to the injection of asthenospheric material.

GEOLOGICAL BACKGROUND AND SAMPLES

The backarc rifting of the Izu arc began at ca. 2.8 Ma and continues today (Taylor, 1992; Ishizuka et al., 2003). It is suggested that the active rifting and rifting-related volcanism migrated eastward in response to steeping of the subducting slab (Ishizuka et al., 2003). The current active rift zone is located just behind the volcanic front; from north to south, it consists of the Aogashima, Myojin, and Sumisu rifts (Fig. 1). The seafloor is deeper at the Sumisu rift than at the Aogashima and Myojin rifts. Subsidence of the basement by normal faulting is greatest in the southern part of the backarc region (Ishizuka et al., 2002), and thus the water depths may reflect asymmetric development of the active rift zone in the north and south.

The 27 fresh lavas analyzed in this study were collected from the active rift zone and from

Figure 1. Bathymetric map of the active rift zone and sample locations, Izu arc. Open star indicates the position of the active rift zone of the Izu-Bonin arc. Gray circles denote sample locations for the Myojinsho volcano. Bathymetric data from Smith and Sandwell (1997) were used for drawing the bathymetric map. SB—Shikoku Basin, WPB—West Philippine Basin, HZB—high-Zr/Y basalt, LZB—low-Zr/Y basalt.
one frontal volcano (Myojinsho) by R/V *Boseimaru* of Tokai University (Japan) (Fig. 1). Major and trace elements, Sr-Nd-Hf isotope data, and locations for these samples are presented in the GSA Data Repository1. These lavas contain normally zoned olivine + plagioclase ± clinopyroxene, range from basalt to basaltic andesite (48.3–54.4 wt% SiO2; herein referred to as basalts), have >5 wt% MgO, and belong to the low-K tholeiitic series (Gill, 1981). Although Ba/Nb in basalts from the active rift zone are lower than in arc front basalts, they are obviously higher than in mid-oceanic ridge basalts (MORBs), indicating that they have been affected by subduction components (Fig. DR1 in the Data Repository). In this study, our data for basalts from the active rift zone are presented with published data filtered to exclude samples with MgO <5 wt%, in order to minimize the effect of fractional crystallization.

**TWO GEOCHEMICAL TYPES IN THE ACTIVE RIFT ZONE**

The active rift basalts can be divided into two geochemical types. We found that some basalts from the Sumisu Rift show higher Zr/Y values than MORB-like basalts from the West Philippine Basin (WPB MORB; Pearce et al., 2005), whereas the other lavas from the active rift zone are lower than in mid-oceanic ridge basalts (MORBs), indicating that they have been affected by subduction components (Fig. DR1). The previous studies (Ikeda and Yuasa, 1989; Fryer et al., 1990; Hochstaedter et al., 1990a, 1990b, 2001; Gill et al., 1992; Tollstrup et al., 2010) denote the range of basalts from the volcanic front (Tamura et al., 2005, 2007). The previous studies (Ikeda and Yuasa, 1989; Fryer et al., 1990) compared the Zr contents of primary magma. We compared the Zr/Y and Nb/Y values in the two types of basalts from the Izu backarc with the slab melts in the mantle wedge (MW) followed by 15% batch melting of oceanic crust. See the Data Repository (see footnote 1) for details of the slab melting model and the end-member compositions and partition coefficients from ocean-floor basaltic glasses for the active rift basalts. Orange dots denote compositions of ocean-floor basaltic glasses from Jenner and O’Neill (2012). Curved line with black dots represents the compositional change of primary melts generated by a batch melting model using depleted mid-oceanic ridge basalt (MORB) mantle (DMM) compositions and partition coefficients from Workman and Hart (2005); percentages indicate the degree of melting. C: 143Nd/144Nd versus 176Hf/177Hf; the Indian-Pacific mantle discriminant boundary is from Pearce et al. (1999). D: 176Hf/177Hf versus 143Nd/144Nd; the 176Hf/177Hf versus 143Nd/144Nd discriminant boundary is from Pearce et al. (1999).
ocean-floor basaltic glasses (Jenner and O’Neill, 2012; Fig. 3B). Most of the ocean-floor basaltic glasses were collected from non-subduction-related tectonic settings and contain low subduction components (Ba/Nb <10), and thus these ocean-floor basaltic glasses are assumed to represent global heterogeneity in the upper mantle (Jenner and O’Neill, 2012). Interestingly, the HZBs plot above the range of ocean-floor basaltic glasses in Figure 3B, whereas the LZBs and volcanic front basalts plot within the range. The upward shift of the HZBs suggests that basalt similar to the HZB, showing depleted Nb/Yb with enriched Zr/Yb, does not occur in non-subduction-related settings, whereas basalt similar to the LZB can occur. Moreover, if the HZBs are originally derived from enriched mantle relative to the source of the LZBs, only the HZB shifts toward less-radiogenic compositions in Nd-Hf isotope space, also suggesting that the difference of fertility in the source mantle cannot explain the variations between the LZBs and HZBs.

The degree of melting of a source mantle also expands the potential range in concentrations of incompatible elements in the primary magma. However, if the different Zr contents between the HZBs and LZBs are caused by different degrees of melting, concentrations of other incompatible elements (e.g., Na_2O, K_2O, and Nb) may also be distinguishable; however, they are not distinguishable for the samples studied here. Moreover, the melting model of depleted MORB mantle (DMM) composition (Workman and Hart, 2005) cannot produce the high Zr/Yb values in the HZBs, whereas that model may be suitable to explain the Zr/Yb-Nb/Yb trend formed by the LZBs (Fig. 3B).

Tollstrup et al. (2010) proposed that hydrous partial melts of the slab in equilibrium with residual rutile and zircon contributed to the source mantle of the Izu backarc region, including the active rift zone. The presence of rutile and zircon in the residual phase was presumed to explain the large Nb-Ta and Zr-Hf anomalies in basalts from the Izu backarc region. Therefore, the addition of such hydrous partial melts to the source mantle may explain the geochemical variation in the LZBs, but cannot explain the minimal Zr and Hf anomalies in the HZBs (Fig. 3A).

To estimate the effect of residual minerals, we constructed three mixing lines between the mantle wedge and slab melts in equilibrium with different proportions of residual zircon (0.05%, 0.01%, and 0%) (Fig. 3). We assumed that rutile (1%) and monazite (0.001%) are stable as residual phases during slab melting based on experimental results (e.g., Skora and Blundy, 2010), where rutile and monazite were stable even when temperatures exceeded that at which zircon breaks down. The presence of rutile in the residual phase does not allow Nb and Ta to be mobile in slab melts, and thus the contribution of the slab melts does not significantly change Nb/Yb values in primary magma (Fig. 3B). The absence of residual zircon results in high Zr contents and Zr/Yb values in the slab melts. Therefore, if the same amount of slab melt is added to the source, the addition of a slab melt that is not in equilibrium with residual zircon to the source may result in the highest Zr/Yb values in the primary magma. This indicates that the contribution of slab melts in equilibrium with rutile, but not zircon, explain the enriched Zr/Yb and depletion of Nb/Yb in the HZBs.

The mixing models with 0.05% and 0.01% residual zircon cause high Nd/Hf values in the slab melts, generating a curved variation in Nd-Hf isotope space (Fig. 3C) and a sharp decrease in Hf/Hf* (Fig. 3D), which is consistent with variations in the LZBs. In contrast, 0% residual zircon provides low Nd/Hf values in the slab melts, and thus generates a mixing line that is not as curved as the other two curves in Nd-Hf isotope space (Fig. 3C), and a gradual decrease in Hf/Hf* (Fig. 3D), which can explain the Nd-Hf isotopic variations displaced from the LZBs and the minimal negative Hf anomaly in the HZBs.

In summary, the addition of ~2% slab melts that are not in equilibrium with residual zircon can explain the geochemical characteristics of the HZBs. We interpret that the slab melts were extracted at high slab-surface temperatures, sufficient to break down residual zircon, but not rutile. On the other hand, the slab melts that contributed to the source of the LZBs must have been in equilibrium with trace quantities of rutile and zircon, as suggested by Tollstrup et al. (2010).

**IMPLICATIONS FOR THE ORIGIN OF BACKARC RIFTING**

Experiments with oceanic crustal materials under sub-arc pressure-temperature (P-T) conditions have shown that temperatures need to exceed 900 °C for slab melts to fully dissolve zircon (e.g., Hermann and Rubatto, 2009). In contrast, geodynamic thermal models estimate that the slab surface temperatures beneath the Izu arc are not high enough to break down residual zircon in the slab (710–770 °C; Syracuse et al., 2010). A candidate model that can explain the high slab-surface temperatures pertains to the estimates obtained from P-T paths of exhumed subduction-related metamorphic rocks (Penniston-Dorland et al., 2015), which are ~300 °C hotter than the geodynamic models, although it may not be able to explain the limited distribution of the HZBs in the active rift zone.

Another possibility is the presence of additional heat sources in the mantle wedge. Isse et al. (2009) showed three low-velocity anomalies in the mantle wedge along the Izu-Bonin-Mariana arc, and pointed out that the southernmost low-velocity anomaly beneath the Mariana Trough is only related to active backarc spreading (Fig. DR4A). On the other hand, the northernmost low-velocity anomaly is located beneath the Torishima and was also observed in a study conducted in the area adjacent to the active rift zone (Fig. DR4B; Obana et al., 2010). Applying the seismic velocity structure to the active rift zone, which is located only 20 km west of the volcanic front, the low-velocity anomaly would be more obvious beneath the Sumisu Rift. Moreover, the range of occurrence of the HZBs corresponds with the range of low-velocity anomalies in the upper slab beneath the Sumisu Rift. In contrast, low-velocity anomalies were not observed beneath the Myojinsho mantle wedge, indicating that the Aogashima and Myojin rifts are not associated with low-velocity anomalies in the mantle wedge.

It has been suggested that an injection of asthenospheric material, which would have steepened the dip of the subducting slab, is a possible cause for backarc opening (e.g., Tatsumi et al., 1989; Okamura et al., 1998). The eastward migration of backarc volcanism in the Izu arc (Ishizuka et al., 2003) suggests the steepening of the slab melts does not significantly change the seismic velocity structure to the active rift zone, the northernmost low-velocity anomaly beneath the Mariana Trough is only related to active backarc spreading (Fig. DR4A). On the other hand, the northernmost low-velocity anomaly is located beneath the Torishima and was also observed in a study conducted in the area adjacent to the active rift zone (Fig. DR4B; Obana et al., 2010). Applying the seismic velocity structure to the active rift zone, which is located only 20 km west of the volcanic front, the low-velocity anomaly would be more obvious beneath the Sumisu Rift. Moreover, the range of occurrence of the HZBs corresponds with the range of low-velocity anomalies in the upper slab beneath the Sumisu Rift. In contrast, low-velocity anomalies were not observed beneath the Myojinsho mantle wedge, indicating that the Aogashima and Myojin rifts are not associated with low-velocity anomalies in the mantle wedge.

**ACKNOWLEDGMENTS**

This work was supported by a Japan Society for the Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (B) 17H02987 to Tamura. We thank the captain and crew of R/V *Bosei Maru* for their support and skill during the sampling cruises. The helpful comments from H. Marshall improved the manuscript. We thank Pamela Kempton, Oliver Nebel, and Stephen Turner for their insightful reviews. This manuscript benefited from constructive discussions with K. Wada and M. Aizawa. We also thank Y. Adachi and S. Oshiro for supporting the isotope measurements.

**REFERENCES CITED**


