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Noble gas and carbon isotopic compositions of petit-spot lavas from southeast of Marcus Island

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ABSTRACT

We measured noble gas isotopic compositions of quenched lavas sampled from seamounts, so-called petit-spot volcanoes, on the 160-million-year-old northwestern Pacific Plate. The samples $^3He/^4He$ and $^{40}Ar/^{36}Ar$ ratios were, respectively, 2.5–8.3 Ra and up to 1735, where Ra stands for atmospheric $^3He/^4He$, which are analogous to or lower than those of MORB. Considering narrow sampling regions, a secondary effect might be responsible for variation of the data.

During ascent and subsequent cooling of magma in the oceanic lithosphere, chemical components in the magma will be assimilated with those in the lithosphere. Correlation between $CO_2/^3He$ ratios and carbon isotopic ratios suggests that carbon was affected by the incorporation of seafloor carbonate. The same would be true of noble gases. The mixing of noble gases among a mantle source, an atmospheric component dissolved in seawater and a radiogenic component can explain the data distribution. No $^3He/^4He$ ratio exceeds the MORB-like value. The mantle source of the petit-spot magma was likely to have had a MORB-like $^3He/^4He$ ratio originally. The eruption of petit-spot magma shows a close relation with the bending of subducting oceanic plates. The MORB-like $^3He/^4He$ ratio supports the hypothesis that the petit-spot magma is derived from the lithosphere–asthenosphere boundary.

1. Introduction

The occurrence of partial melts in the lithosphere–asthenosphere boundary (LAB) is an attractive hypothesis to explain a seismic low velocity zone and the high-electric conductive layer in the upper mantle (Kawakatsu et al., 2009; Kumar and Kawakatsu, 2011; Schmerr, 2012). Moreover, this hypothesis is supported by results of high-pressure experiments conducted to assess peridotite solidus (Sifré et al., 2014; Wyllie, 1988) and the viscosity of silicate magma (Sakamaki et al., 2013).

If partial melt exists in asthenosphere, then it would migrate upward by its own buoyancy and pool beneath the lithosphere (LAB). Later, it might erupt as intraplate volcanoes. Batiza (1982) presents data related to the abundance, size, and crustal age of volcanoes of the Pacific Ocean. The sizes of the largest seamounts are related to the age of the sea floor on which they formed. Large seamounts can form on a thick lithosphere, but only small seamounts form on a thin lithosphere (Hillier and Watts, 2007; Wessel, 1997), implying that the maximum volume and the rate at which magma can ascend from the asthenosphere increases with the depth to which lithosphere-traversing fractures must penetrate to reach the ponded melt (Foulger, 2010).

As some reports have already suggested (Hirano et al., 2006; Valentine and Hirano, 2010), vertical transport of the ponded melt becomes prominent when the stress state at the base of the lithosphere becomes extensional, generating fractures within the lithosphere. The melt will ascend through the fracture and engender volcanism along the concavely flexed zone of the outer rise, outboard of the zone of plate subduction. Additionally, horizontal migration of the ponded melt occurs because of the horizontal pressure gradient induced by the topographic head of the outer rise, sustaining a continuous melt supply to the volcanism (Yamamoto et al., 2014).

Young basalts have been discovered beside the outer rise on the northwestern Pacific Plate: so-called petit-spot volcanoes (Hirano et al., 2006). They erupted at the oceanward base of the outer rise of the descending Pacific Plate where flexure of the subducting plate causes fractures in the lithosphere (Hirano et al., 2001, 2004, 2006, 2008; Machida et al., 2015; Sato et al., 2018). Based on their geochemical signatures, these lavas presumably originated from partial melts in the asthenosphere, but the original depth of the petit-spot magma remains uncertain.

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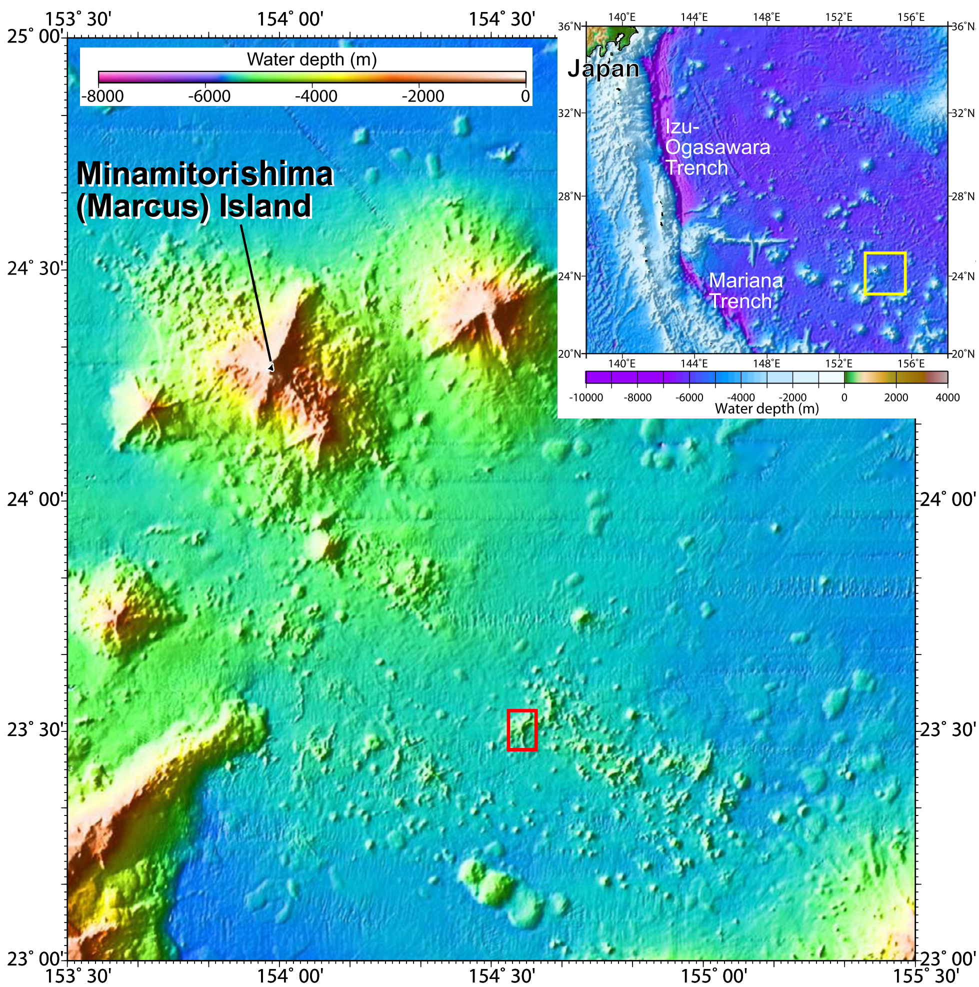

Fig. 1. Bathymetric map of the study area. The red square represents the sampling area. Topographic data are from Amante and Eakins (2008). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

A key question is whether the petit-spot volcanoes represent LAB magma or hot spots fed by a mantle plume. Obayashi et al. (2006) studied the slow seismic velocity anomaly beneath the ocean-ward side of the Japanese subduction zone. Based on their interpretation of the seismological images, they proposed the existence of a hot thermal anomaly at the 410-km discontinuity near the Honshu subduction zone. They concluded that it is mainly an association of occurrence of fractional melt or a thermal anomaly with magnitude of approximately 200 °C. The tomographically imaged low-velocity region is interpreted as a remnant of past activity of the Pacific superplume (Honda et al., 2007). However, the possible occurrence of plumes is just one interpretation of the tomographic image. Direct investigation of the magma must be conducted to settle the provenance of petit-spot magmatism.

Applying the $^3He/^4He$ ratio is effective for identification of the origin of petit-spot magma. Mid-ocean ridge basalts (MORB) show a uniform $^3He/^4He$ ratio of 8.0 ± 1.5 Ra, where Ra is atmospheric $^3He/^4He$ ratio, but $^3He/^4He$ ratios of ocean island basalts (OIB) vary widely (Sano and Fischer, 2013). Although values of 20–30 Ra are common on some ocean islands (i.e., Hawaii (e.g., Kaneoka et al., 2002; Valbracht et al., 1996), Iceland (e.g., Moreira et al., 2001; Trieloff et al., 2000), Samoa (e.g., Farley et al., 1992; Jackson et al., 2007), and Galapagos (e.g., Kurz and Geist, 1999; Kurz et al., 2009)), higher $^3He/^4He$ values have been obtained for Baffin Island (e.g., up to 50 Ra; Stuart et al., 2003). Moreover, enriched and HIMU-type OIBs show $^3He/^4He$ ratios lower than 8 Ra (Hanyu and Kaneoka, 1997; Hanyu et al., 2011). If petit-spot magma were originated from LAB, then it would have a MORB-like $^3He/^4He$ ratio because the original depth is comparable to that of MORB.

Although Hirano et al. (2006) once analyzed noble gas isotopic compositions of petit-spot basaltic glasses sampled from the northwestern Pacific Plate, they did not ascertain the $^3He/^4He$ ratio because of the samples low He contents and the low sensitivity of the mass spectrometer for He. Recently, swarm petit-spot volcanism was discovered southeast of Marcus (Minamitorishima) Island (Yokosuka YK10-05 Cruise Data). The basaltic glasses have high vesicularities up to 64%, indicating higher amounts of gases including He. For this study, we analyzed the $^3He/^4He$ ratios of the glasses using a mass spectrometer with particular sensitivity for $^3He/^4He$ ratio. The device enables us to address the origin of petit-spot magma.

2. Samples

During a survey (YK10-05 cruise) of the area on the northwestern Pacific Plate (Fig. 1) by the Japan Agency for Marine–Earth Science and Technology (JAMSTEC), basaltic rocks with glassy rims were recovered from petit-spot volcanoes using the manned research submersible Shinkai 6500 (Table 1). Basalts used for this study were recovered during two dives, 6K#1203 and 6K#1206, at locations about 100 km southeast of Marcus Island. Information related to sampling sites is reported in a cruise report (Yokosuka YK10-05 Cruise Data). Site 6K#1203 is located about 10 km north–northeast of the site 6K#1206. Each site covers a region with a ma-