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Petit-spot geology reveals melts in upper-most asthenosphere dragged by lithosphere

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ABSTRACT

Petit-spot volcanism is a phenomenon ubiquitous on Earth. It originates from melt in the upper-most mantle asthenosphere, occurring where the plate flexes and fractures before subduction. Recent geochemical and petrological studies of petit-spot volcanism lava have shown that understanding this form of volcanism can contribute to the investigation of mantle dynamics and CO_2 degassing of Earth. However, geological information constraining the magma source of petit-spot remains limited. Here, we present a comprehensive dataset of geochemistry (major and trace elements, and Sr and Nd isotopic compositions) and $^{40}Ar/^{39}Ar$ ages of alkaline basaltic rocks and glasses to define the geological characteristics of petit-spot volcanoes in the northwestern Pacific. The geochemical and geochronological variations of the basalts indicate that petit-spot volcanism is characterized by a petrogenetically and temporally isolated magma system for each volcano. The basalt geochemistry further indicates that the magmas at the volcanoes were derived from the melting of a heterogeneous regional-scale source under a range of conditions. In addition, slight temporal intra-field migration of petit-spot vent fields against the plate motion was detected. These features indicate that the magma originates from isolated melt ponds at the lithosphere–asthenosphere boundary, and that the speed at which the melt ponds are dragged by the plate is only slightly slower than that of the plate motion. Our results provide detailed insight into eruption processes of asthenosphere melts induced by plate-flexure, and also suggest the complete coupling of the lithosphere to the upper-most asthenosphere in the case of large plate subduction.

1. Introduction

Petit-spot volcanism originates from melt in the upper-most mantle asthenosphere, occurring where the plate flexes and fractures before subduction, and forms diminutive volcanoes compared to large volcanoes on hotspots and large igneous provinces (Hirano et al., 2006; Yamamoto et al., 2014). Hirano et al. (2008, 2013), Valentine and Hirano (2010), Uenzelmann-Neben et al. (2012), and Taneja et al. (2015) have shown that petit-spot volcanism is a phenomenon ubiquitous to plate flexure. Geochemical studies have revealed that alkaline basalt lava from petit-spot volcanoes has high concentrations of incompatible trace elements, indicating extreme enrichment in highly incompatible elements (e.g., Rb, Ba, U, Th, and Nb) and light rare earth elements (REEs), and depletion in heavy REEs (Hirano et al., 2006), and extreme Enriched Mantle 1 (EM-1)-like Sr–Nd–Pb isotopic compositions (Machida et al., 2009). Thus, Machida et al. (2009) proposed that melting of small-scale recycled plate material produces petit-spot magma. Moreover, Okumura and Hirano (2013) suggest that petit-spot volcanism plays an important role in Earth's CO_2 emission because of the enrichment of CO_2 in the primary magma. To achieve the further understanding of petit-spot geology, six sampling cruises were conducted over three petit-spot volcanic fields (Fig. 1), and 623 samples of lava and volcanic breccia were collected and described. Here, the description of a comprehensive compositional

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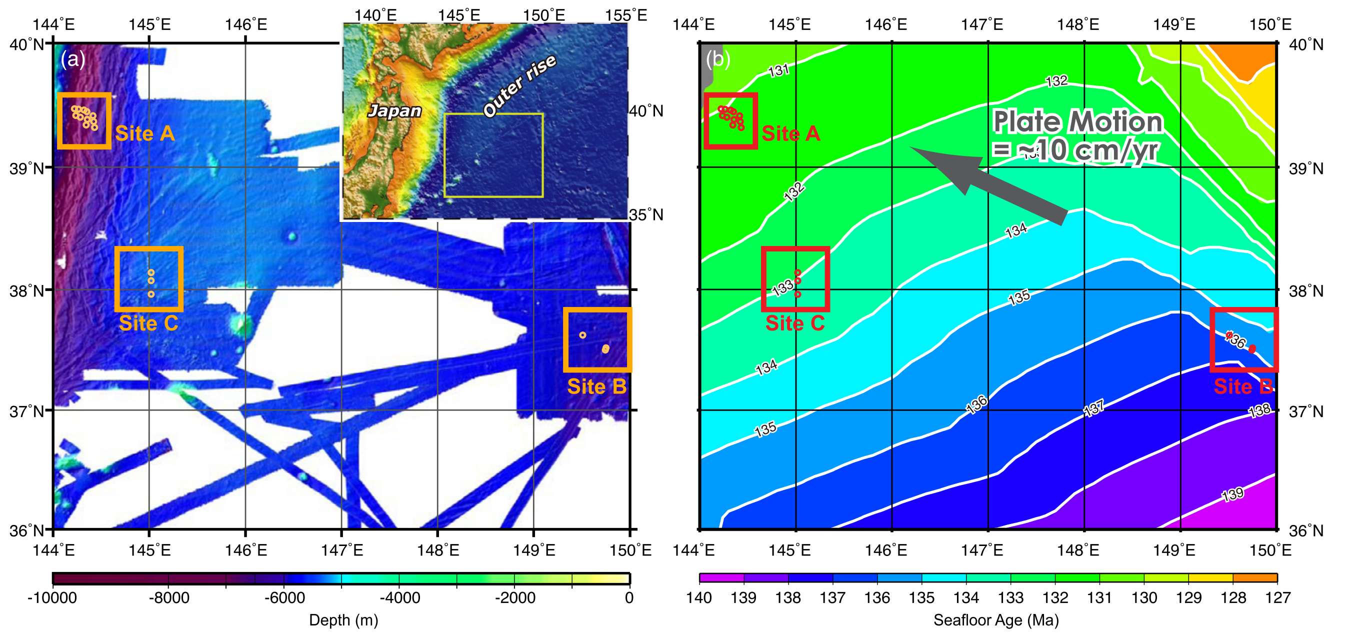

Fig. 1. (a) Distribution of three petit-spot volcanic fields in the northwestern Pacific. (b) Seafloor age of the northwestern Pacific Plate. In (a), bathymetric map by multibeam surveys is modified from Fig. 2 of Hirano et al. (2008); bathymetric data for inset map are from ETOPO2 (NOAA National Geophysical Data Center; http://www.ngdc.noaa.gov/); yellow box shows area of central map; orange boxes show Sites A, B, and C (shown in detail in Figs. S1, S2, and S3, respectively). In (b), seafloor age gridded data for GMT software are from Müller et al. (2008), and gray arrow illustrates the present absolute motion of the Pacific Plate (10.29 cm/yr toward 295.26°; Gripp and Gordon, 1990).

data set, including major and trace element compositions and Sr and Nd isotopes in addition to $^{40}Ar/^{39}Ar$ ages, is made to define the detailed geological picture of petit-spot volcanism in the NW Pacific. The data set presents an age trend for each group of petit-spot volcanoes exhibiting the same geochemical feature, in which the position of inter-regional eruption fields slightly migrates contrary to the northwest movement of region due to the Pacific Plate motion. We suppose that the migration of the volcanoes is in fact the movement of the melt ponds in the upper-most asthenosphere—the magma source of petit-spot is unrelated to an active mantle plume—slightly slower than or close to the speed of the plate. This observation indicates a coupling between lithosphere and asthenosphere. To make this interpretation, we present a three-step approach in this report: (1) we identify and describe several geochemical groups on the basis of bulk-rock chemical compositional features; (2) then, the correlation between bulk-rock chemical compositional features and isotopic composition was investigated in order to evaluate the relationships among magma systems at different monogenetic volcanoes; and (3) finally, to determine the location of eruption, we examine the correlation between the eruption age and plate motion, and reveal systematic spatial geochemical variations.

2. Background

Hirano et al. (2008) defined the type morphology of petit-spot volcanoes, which are characterized by irregular shapes, <2 km in diameter and 100–200 m in height. The estimated volume of the volcanoes ranges between 0.001 and 1.06 km^3 (Hirano et al., 2008). Such diminutive volcanoes have been also found along the oceanward slopes of the Tonga Trench (Hirano et al., 2008), the Chile Trench (Hirano et al., 2013), and the Sunda Trench (Taneja et al., 2015), in the Basin and Range Province of North America (Valentine and Hirano, 2010), offshore from southern Greenland (Uenzelmann-Neben et al., 2012), and in the Santa Rosa Accretionary Complex of Costa Rica (Buchs et al., 2013). These occurrences indicate that petit-spot volcanism is a ubiquitous phenomenon in region of plate flexure arising from factors such as plate subduction (Hirano et al., 2001, 2006, 2008, 2013; Taneja et al., 2015) and glacial melting (Uenzelmann-Neben et al., 2012).

Petit-spot volcanoes in the northwestern Pacific are located on the oceanward slope of the Japan Trench (Site A), ∼600 km east-southeast of the Japan Trench (Site B) (Fig. 1; Hirano et al., 2001, 2006), and ∼200 km south of Site A (Site C; Fig. 1; Hirano et al., 2006). Sites A, B, and C are located on the Cretaceous Pacific Plate formed at ∼131, ∼136, and ∼133 Ma, respectively. During our six research cruises over these three volcanic fields and subsequent descriptions of the sampled lavas, we identified the following characteristic geological and petrological features of petit-spot volcanism in the northwestern Pacific. (1) Knolls at Sites A, B, and C commonly consist of highly vesicular (up to 60 vol.%) pillow lavas and volcanic breccias, and massive sheet-flow lavas were observed in outcrops along the fault wall at Site A (Fig. 3A in Hirano et al., 2006). (2) Petit-spot lava is commonly glassy and aphyric (or containing sparse olivine micro-phenocrysts), with the exception of samples containing olivine xenocrysts or peridotite xenolith (Hirano et al., 2004; Yamamoto et al., 2009; Harigane et al., 2011). (3) The lavas contain high concentrations of alkaline elements and are classified as potassic trachybasalt, shoshonite, and basanite (Hirano et al., 2006). We also observed these general geological and petrological features on petit-spot lavas from off the central Chile Trench, which were first reported by Hirano et al. (2013).

3. Materials and methods

3.1. Sampling from three petit-spot volcanic fields in the NW Pacific

Site A (Fig. 2c, 2f, and Fig. S1, and Table S1) rock samples were collected by dredge or submersibles at seven locations during the KR97-11 (Kaiko 10000), KR03-07 (dredge), KR04-08 (dredge), and KR07-06 (Kaiko 7000II) cruises by R/V Kairei, and the YK05-06 (Shinkai 6500) cruise by R/V Yokosuka (Table S1). The locations of submersible sampling correspond to each volcanic edifice (knoll or fault wall), except for dive #880 of Shinkai 6500 submersible. During dive #880, two different lava locations of fault wall and knoll were found, and sampling was conducted at two points in