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Sr and Nd isotopic compositions of mafic xenoliths and volcanic rocks from the Oga Peninsula, Northeast Japan Arc: Genetic relationship between lower crust and arc magmas

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ABSTRACT

Whole-rock and constituent hornblende and plagioclase geochemical and isotopic compositions of 52 mafic xenoliths from the Ichinomegata maar in the Oga Peninsula, located on the backarc side of Northeastern Japan, were investigated to further understand the nature of lower crustal materials beneath the Oga Peninsula. The inter-rock variations in isotopic compositions ($^{87}Sr/^{86}Sr$ ratios of 0.703245–0.705246 and $^{143}Nd/^{144}Nd$ ratios of 0.512910–0.512608) correlate negatively with $^{87}Rb/^{86}Sr$ and $^{147}Sm/^{144}Nd$ ratios. A continuous and arcuate trend in a Sr–Nd isotope diagram suggests a two-component mixing curve is present; at lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ ratios, this trend extends towards and partly overlaps Quaternary volcanic rock compositions from the Toga, Ichinomegata (xenolith-hosting pumice), and Kampu volcanoes on the Oga Peninsula (herein, Oga volcanic rocks). This overlapping suggests a common control on the isotopic variations within both xenoliths and volcanic rocks. This common control is most likely to be the metasomatism of intact original lower crustal material by parental magmas of the Oga volcanic rocks, herein termed the Oga parental magma, in addition to the contamination of the Oga parental magma by the crustal material after contact between the two. This metasomatism also caused isotopic re-homogenization of these constituent minerals, meaning hornblende and plagioclase within individual xenoliths have the same Sr–Nd isotopic compositions; i.e., they show no intra-rock variations, suggesting thermal re-setting.

However, inter-rock variations imply that full metasomatism and destruction of the original isotopic and geochemical characteristics of the lower crust did not occur. These inter-rock variations are consistently present as changes in the geochemistry of constituent minerals, with K_2O, Rb, Sr, Sm, and Nd concentrations varying in hornblende, and anorthite contents (An %) varying in plagioclase. The original lower crustal material, as one end-member of a mixing curve, is assumed to have a $^{87}Sr/^{86}Sr$ ratio of 0.705250 and a $^{143}Nd/^{144}Nd$ ratio of 0.512570, whereas the Oga parental magma, forming the other end-member on the mixing curve, has a $^{87}Sr/^{86}Sr$ ratio of 0.702958 and a $^{143}Nd/^{144}Nd$ ratio of 0.512933, as represented by Oga volcanic rocks with the lowest $^{87}Sr/^{86}Sr$ and highest $^{143}Nd/^{144}Nd$ ratios (stage 3 lavas from Kampu volcano near Ichinomegata maar). The isotopic compositions of other Oga volcanic rocks vary from the most contaminated Toga rhyolitic pumices ($^{87}Sr/^{86}Sr$ of 0.703723–0.703885 and $^{143}Nd/^{144}Nd$ of 0.512906–0.512847) through to the Ichinomegata host pumice ($^{87}Sr/^{86}Sr$ of 0.703398 and $^{143}Nd/^{144}Nd$ of 0.512895). This research indicates that both the Ichinomegata mafic xenoliths and the Oga volcanic rocks have undergone isotopic changes, creating an overlap in compositions caused by metasomatism and contamination, respectively. This relationship between lower crustal and volcanic rocks can be also be applied to trench-side volcanic rocks. If the Ichinomegata lower crustal material extends to the trench side of the NE Japan Arc, the island-arc tholeiites typically found within the volcanic front probably also contain a similar, if not identical, lower crustal component.

1. Introduction

The nature of the sub-volcanic lithosphere can be determined by investigating the lithology of xenoliths within volcanic rocks; however,

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crustal xenoliths are not always indicative of the actual lithosphere through which magmas migrate, as they commonly interact with magma prior to emplacement (Graham et al., 1990; Gruender et al., 2010; Salvioli-Mariani et al., 2005). One example of this is provided by lower crustal xenoliths in Syria that have altered chemical compositions due to partial melting and contamination by the hosting alkali magmas (Al-Safarjalani et al., 2009). These secondary processes are therefore important, not only during the development of the sub-volcanic lithosphere but also during magma genesis.

The nature of the lithosphere beneath Ichinomegata maar, on the Oga Peninsula in the NE Japan Arc, has been characterized based on the lithology of xenoliths (Aoki, 1971, 1987; Arai, 1980; Takahashi, 1978). These lithological models suggest that the Ichinomegata mafic hornblende gabbro and amphibolite xenoliths were originally derived from the lower crust. If so, the lower crustal materials that these xenoliths were derived from are isotopically heterogeneous, as the Ichinomegata mafic xenoliths have a wide range of Sr and Nd isotopic compositions, with $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of 0.7030–0.7054 and 0.5127–0.5129, respectively, although pumiceous host rocks have $^{87}Sr/^{86}Sr$ values of 0.7033 (Kagami et al., 1999; Zashu et al., 1980). This isotopic heterogeneity in the xenoliths therefore either reflects the original characteristics of the lower crust or suggests that the isotopic composition of the xenoliths changed during interaction with the host magma.

Here we focus on isotopic and geochemical variations within the Ichinomegata mafic xenoliths and examine the relationship between Sr–Nd isotopic characteristics and geochemical compositions of hornblende, plagioclase, and their whole-rock. These isotopic characteristics are compared with volcanic rocks from the Oga Peninsula (host pumice and other volcanic rocks; herein, Oga volcanic rocks) to determine whether secondary processes contributed to the isotopic variations present in both xenoliths and volcanic rocks.

The Ichinomegata mafic xenoliths are derived from the lower crust beneath the backarc side of the NE Japan Arc; however, they are geochemically more similar to trench-side tholeiites than the volcanic rocks within the backarc side of the arc (Aoki and Yoshida, 1986). This study will therefore finally investigate the relationship between island-arc tholeiitic magmas and the Ichinomegata mafic xenoliths.

2. Geological setting and sampling

Five Quaternary volcanoes (the Toga, Sannomegata, Ninomegata, Ichinomegata, and Kampu volcanoes) form a 15 km-wide east–west oriented cluster on the Oga Peninsula along the Japan Sea coastline of Japan (Fig. 1). These volcanoes are part of the backarc-side volcanoes (the Chokai volcanic chain on the backarc side: Tatsumi et al., 2008; or the rear-arc volcanoes: Kimura and Yoshida, 2006) of the NE Japan Arc. The Toga tuff-ring is formed of rhyolitic pyroclastic surge deposits (0.42 Ma, fission-track age; Kano et al., 2002), whereas the Kampu volcano (formed after 0.022 Ma, ^{14}C age; Kano et al., 2011) is mainly composed of lavas with lithic pyroclastic deposits and one pumice fall deposit sheet (Maruyama et al., 1988). The Megata volcanoes comprise the Ichinomegata, Ninomegata, and Sannomegata maars, with the youngest maar forming at 0.024 Ma (^{14}C age; Kano et al., 2011). These maars are formed from scoria and pumice fall, mudflow, and base surge deposits (Katsui et al., 1979), and are one of the localities where ultramafic–mafic xenoliths are found within the SW and NE parts of the Japan Arc. The abundant xenoliths in Ichinomegata pyroclastic deposits are thought to relate to the passage of magma through subvolcanic lithosphere. The majority of xenoliths (99%) are derived from the surface or near-surface and are sedimentary, volcanic, and plutonic rocks, with a much smaller population of upper mantle-derived spinel lherzolite and websterite or lower crust-derived amphibolite and hornblende gabbro xenoliths (Aoki, 1987). Mafic and ultramafic xenoliths are rimmed by thin gray pumice, while no rims are present on shallow-derived sedimentary, volcanic, and plutonic xenoliths, indicating that the shallow xenoliths were captured in a multiphase flow comprising a spray of magma and steam, immediately following a phreatomagmatic explosion.

We collected 52 mafic (amphibolite and hornblende gabbro; Aoki, 1971) xenoliths from the Ichinomegata pyroclastic deposits during four differing sampling expeditions, here termed “A”, “YAM”, “090430”, and “TKD”. The size of these xenoliths ranges from a few millimeters (glomerocrysts) up to ~10 cm in diameter. For comparison, four cognate cumulus hornblende gabbro inclusions were collected from Oshima-Oshima volcanic island, about 180 km north of the Oga Peninsula (Fig. 1a). This study focuses on the mineral chemistry of the Ichinomegata mafic xenoliths and Oshima-Oshima cognate inclusions, primarily because whole-rock chemical variations are controlled by the modal proportions of minerals present, especially in small samples. Fukuyama (1985) analyzed 57 Ichinomegata mafic hornblende gabbro and amphibolite xenoliths, and reported a very wide range of whole-rock compositions (SiO_2 36–52 wt.%, Al_2O_3 12–29, total Fe_2O_3 3–24, MgO 2–15, CaO 7–16, Na_2O 0.8–4.7, and K_2O 0.01–0.61), and indicated that these variations were dependent on the variable modal abundances of plagioclase and hornblende. In addition to the Ichinomegata xenoliths, volcanic rocks were collected from the Oga Peninsula (Oga volcanic rocks: Ichinomegata host pumice, Toga rhyolitic pumices, and Kampu basalt–andesite lavas) and from Oshima-Oshima (basalt–basaltic andesite lavas and dyke).

3. Petrography of the Ichinomegata mafic xenoliths

Mineral assemblages and significant petrographic features of the “YAM” and “090430” series xenoliths are listed in Table 1. These xenoliths are dominated by hornblende and plagioclase with minor pyroxene and opaque minerals, and can be classified into three types based on their mineralogy and textures. The dominant xenolith type (type A) is characterized by greenish brown or brown hornblende with plagioclase and magnetite, whereas other xenolith types (B and C) contain polygonal aggregates of pyroxene in addition to hornblende and plagioclase. Type B xenoliths are characterized by dark green vermicular spinel associated with polygonal aggregates of pyroxene surrounded by light greenish–brown hornblende. Type C xenoliths are characterized by dark, holly leaf-shaped hornblende; the dark color is caused by dusty inclusions and films of opaque minerals along cleavage planes.

The majority of hornblende contains abundant dusty inclusions, whereas plagioclase contains thin films defined by dusty and fern-like glass inclusions; these inclusions are especially common in type A xenoliths, whereas type C xenoliths contain plagioclase with deformation textures, such as wedge-shaped twins and undulose extinction. Coarse-grained hornblende and pyroxene (>0.3 mm in diameter) have undulose extinction and pyroxenes contain exsolution lamellae, whereas smaller crystals are homogeneous and pyroxenes and plagioclases have polygonal mosaic textures. Interstitial spaces between coarse grains are filled with thin films (<0.03 mm wide) of minute pyroxene, plagioclase, hornblende, magnetite, and glass; hornblende and plagioclase crystals adjacent to these spaces have finely jagged rims.

4. Analytical techniques

Samples of the Ichinomegata mafic xenoliths, the Oshima-Oshima cognate inclusions and volcanic rocks were crushed using a tungsten pestle and mortar. Crushed samples of the Ichinomegata mafic xenoliths and the Oshima-Oshima inclusions were ultrasonically agitated in distilled water to remove any contamination introduced during sampling and crushing, and were then leached with warm 7% HCl for 30 min. After rinsing with distilled water and drying, five Ichinomegata mafic xenolith samples were powdered for whole-rock analysis. Plagioclase and hornblende crystals from Ichinomegata mafic xenoliths and Oshima-Oshima