



Slab-derived halogens and noble gases illuminate closed system processes controlling volatile element transport into the mantle wedge



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ABSTRACT

Halogen and noble gas systematics are powerful tracers of volatile recycling in subduction zones. We present halogen and noble gas compositions of mantle peridotites containing H₂O-rich fluid inclusions collected at volcanic fronts from two contrasting subduction zones (the Avacha volcano of Kamchatka arc and the Pinatubo volcano of Luzon arcs) and orogenic peridotites from a peridotite massif (the Horoman massif, Hokkaido, Japan) which represents an exhumed portion of the mantle wedge. The aims are to determine how volatiles are carried into the mantle wedge and how the subducted fluids modify halogen and noble gas compositions in the mantle. The halogen and noble gas signatures in the H₂O-rich fluids are similar to those of marine sedimentary pore fluids and forearc and seafloor serpentinites. This suggests that marine pore fluids in deep-sea sediments are carried by serpentine and supplied to the mantle wedge, preserving their original halogen and noble gas compositions. We suggest that the sedimentary pore fluid-derived water is incorporated into serpentine through hydration in a closed system along faults at the outer rise of the oceanic, preserving Cl/H₂O and ³⁶Ar/H₂O values of sedimentary pore fluids. Dehydration–hydration process within the oceanic lithospheric mantle maintains the closed system until the final stage of serpentine dehydration. The sedimentary pore fluid-like halogen and noble gas signatures in fluids released at the final stage of serpentine dehydration are preserved due to highly channelized flow, whereas the original Cl/H₂O and ³⁶Ar/H₂O ratios are fractionated by the higher incompatibility of halogens and noble gases in hydrous minerals.

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1. Introduction

Water is one of the most important volatiles in many processes studied in earth sciences. It is a major component degassed from the Earth's interior through volcanism at mid-ocean ridges, hot spots, and arcs and is returned via subduction processes. Hydrous minerals in subducting slabs transport water by incorporating it as OH groups. The water is released from the subducting slabs to the mantle wedge through dehydration of those hydrous minerals. Even a relatively small amount of water may result in major changes to the chemical and physical properties of mantle

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rocks, influencing mineral phase assemblages, melting temperatures, viscosities, seismic wave velocities, and electrical conductivities (Bolfan-Casanova, 2005; Kawamoto et al., 2015). Volcanism and seismicity associated with subduction zones is also linked to the dehydration processes and release of water from the subducting slabs (Mitsui and Hirahara, 2009; Tatsumi, 1989), although the detail of hydrous mineral and water release mass balance remains debated (e.g., Iwamori, 2007; van Keken et al., 2011; Wada et al., 2012).

Concentrations of heavy halogens (chlorine, bromine, and iodine) and noble gases in the Earth's surface reservoirs are significantly higher than in the mantle. For example, ^{36}Ar and chlorine concentrations in the depleted mantle are 6×10^{-11} ccSTP $^{36}\text{Ar}/\text{g}$ (Holland and Ballentine, 2006) and <6 ppm Cl (John et al., 2011) respectively, whereas in seawater they are orders of magnitude higher at 1.3×10^{-6} ccSTP $^{36}\text{Ar}/\text{g}$ (Ozima and Podosek, 2002) and 19400 ppm Cl (Bruland and Lohan, 2006). Noble gases are strongly partitioned into gas- and fluid-phases relative to minerals (Ozima and Podosek, 2002) and heavy halogens are also strongly partitioned into aqueous fluids (Bureau et al., 2000, 2016). The large contrast in concentrations between the surface and interior of the Earth means that halogens and noble gases are potentially powerful tracers of slab-derived aqueous fluids in the mantle. Furthermore, the distinct elemental and/or isotopic compositions of halogens and noble gases (e.g., Ballentine and Holland, 2008; Chavrit et al., 2016; Holland and Ballentine, 2006; John et al., 2011; Kendrick et al., 2011, 2012, 2013, 2015; Ozima and Podosek, 2002; Porcelli and Ballentine, 2002; Staudacher and Allègre, 1988; Sumino et al., 2010) can be used to reveal the origin and/or the subduction path of subducted water.

Subducted materials in slabs are recycled into the deep mantle, but volatiles including halogens and noble gases are often assumed to be returned to the surface through arc volcanism with little, if any transferred to the deep mantle (Staudacher and Allègre, 1988). Despite this "subduction barrier", the ratios of non-radiogenic isotopes of heavy noble gases (argon, krypton, and xenon) in the convecting mantle are similar to those of seawater and distinct from other subducted materials (Ballentine and Holland, 2008; Holland and Ballentine, 2006). In addition, evidence for subducted noble gases in mantle peridotites has been found from many regions (e.g., Hopp and Ionov, 2011; Matsumoto et al., 2001; Sumino et al., 2010). Evidence of halogen recycling into the deep mantle has also been found in plume related volcanic rocks (e.g., John et al., 2010). Sumino et al. (2010) studied halogens and noble gases in mantle wedge peridotites from the Higashi-akaishi peridotite body in the Sanbagawa metamorphic belt, Shikoku Island, Japan, in which slab-derived H_2O -rich fluids were trapped just above the subducting slab at ≥ 100 km depth. These peridotites contain noble gas compositions similar to those of seawater, however their high I/Cl values indicate the presence of a marine sedimentary pore fluid. This aqueous fluid originates as seawater trapped in the pores of marine sediments that is subsequently enriched in iodine by the decomposition of organic materials in the sediments (e.g., Fehn et al., 2006). Similar sedimentary pore fluid-like signatures have also been found in fluid inclusions in a quartz vein in metapelites from the Besshi, Sanbagawa metamorphic belt (Sumino et al., 2011). These fluid inclusions are considered to represent fluids captured during the prograde path, or near the peak metamorphic stage of subduction (Yoshida and Hirajima, 2012). John et al. (2011) and Kendrick et al. (2011, 2013) have shown that serpentinites in the oceanic lithosphere contain substantial amounts of sedimentary pore fluid-like noble gases and halogens, suggesting that serpentine may be an important carrier of pore fluid-derived water.

In this study, we report halogen and noble gas compositions in mantle xenoliths collected at the volcanic fronts from two different

subduction zones (the Kamchatka and Luzon arcs), and orogenic peridotites from a peridotite massif (the Horoman peridotite massif, Japan), that latter represents a portion of the mantle wedge infiltrated with slab-derived H_2O - CO_2 rich fluids. We consider the extent to which the mantle wedge signature is preserved in orogenic peridotite samples that are subject to modification processes during exhumation. In contrast, the rapid ascent of mantle xenoliths has favored retention of a direct record of metasomatic processes in the mantle wedge. We discuss how slab-derived fluids are transferred into the mantle wedge and how they modify the mantle halogen and noble gas compositions.

2. Samples

Mantle xenoliths are from the Avacha volcano, the Kamchatka peninsula, Russia and the Pinatubo volcano, Luzon island, in the Philippines. These volcanoes are located at the volcanic fronts of the Kamchatka and Luzon arcs, respectively. The old and cold Pacific plate is subducting beneath the Avacha volcano (Minster et al., 1974), whereas the young and hot South China Sea plate is subducting beneath the Pinatubo volcano (Briais et al., 1993). The xenolith lithologies are spinel-harzburgites with textures and chemical compositions that reflect differing extents of metasomatism (Ishimaru and Arai, 2009; Ishimaru et al., 2007; Kawamoto et al., 2013; Yoshikawa et al., 2016). There are two subtypes of Avacha peridotites characterized by either the presence or absence of fine-grained (<100 μm) olivine domains (Arai et al., 2003). All Avacha samples examined in this study are the coarse-grained type, except for Avx-1, which contains domains of fine-grained olivine (Avx-1 F-part). One Pinatubo sample (P2) contains fine-grained domains, whereas the other sample (P3) is of the coarse-grained type. The Avacha and Pinatubo harzburgites contain H_2O -rich fluid inclusions (Fig. 1) having salinities of 5.1 ± 1.0 wt% NaCl-equivalent for Pinatubo (Kawamoto et al., 2013) and 2–8 wt% NaCl-equivalent for Avacha (Ishimaru, unpublished results). Hopp and Ionov (2011) reported atmospheric noble gases present in fluid inclusions in Avacha xenoliths, arguing for their incorporation into the mantle wedge via slab-derived fluids. Hereafter we refer to atmospheric noble gases as those that show isotopic ratios similar to the air (elemental ratios can vary from those in the air).

The orogenic peridotite studied is from the Horoman peridotite massif in Hokkaido, Japan. The sample is a fragment of a peridotite block from which a powder has previously been prepared and distributed by the Geological Survey of Japan as the geochemical reference material JP-1. Hereafter we refer to this sample as JP-1. Although JP-1 is described as a dunite by Imai et al. (1995), it consists of olivine, orthopyroxene, clinopyroxene, and chromian spinel indicating it more appropriately classified as a harzburgite (Appendix A). Hirai and Arai (1987) have suggested that the Horoman peridotite massif represents an exhumed portion of the mantle wedge infiltrated with H_2O - CO_2 rich fluids, the latter based on finding relic fluid inclusions in Horoman dunites. A mantle wedge origin is supported by trace element patterns and Nd-Sr isotopes of Horoman harzburgites and lherzolites (Yoshikawa and Nakamura, 2000). Horoman lherzolites and harzburgites including JP-1 have atmospheric noble gas compositions (Ikeda et al., 2001; Matsumoto et al., 2001; Miura and Nagao, 1991) and Matsumoto et al. (2001) showed that the atmospheric ^{36}Ar concentrations correlate with mantle-derived ^3He , indicating that the atmospheric noble gases are a recycled component derived from the subducting slab.

3. Experimental methods

The peridotite samples were coarsely crushed into 0.5–2 mm mineral grains (or aggregates of fine-grained minerals in the case

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