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Tracing partial melting and subduction-related metasomatism in the Kamchatkan mantle wedge using noble gas compositions

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ABSTRACT

We determined noble gas composition of minerals separated from mantle-derived xenoliths hosted by andesites in the active Avacha volcano, Kamchatka peninsula, Russia in order to better constrain the provenance and nature of fluids involved in partial melting and metasomatism in the mantle wedge. The lithospheric mantle beneath Avacha mainly consists of spinel harzburgites produced by high degrees of melt extraction. Data on coarse olivine separated from seven harzburgite xenoliths constrain fluid regime during flux melting in arc settings. Pyroxenes from two websterite veins cross-cutting the harzburgites characterize post-melting metasomatism by subduction-related melts or fluids. $^3He/^4He$-ratios of 5.2 ± 0.6 to 8.1 ± 0.3 R_A obtained on both olivines and pyroxenes overlap the highest values reported for volcanic rocks from Kamchatka and fall into the typical range of continental lithospheric mantle worldwide. This rules out significant contributions of slab-derived radiogenic $^4He^*$. The highest $^{40}Ar/^{36}Ar$ ratios are 400; Ne and Xe isotope ratios are indistinguishable from those in the air. We consider the slab as the initial source of a major portion of these 'atmospheric' gases. Element composition of noble gases in olivine differs markedly from that in vein pyroxene indicating that the composition of the fluid phase involved in partial melting was distinct from that during metasomatism. In particular, the harzburgites and veins define distinct linear trends on plots of $^3He/^{36}Ar$ vs. $^{40}Ar/^{36}Ar$ and of $^{132}Xe/^{36}Ar$ vs. $^{40}Ar/^{36}Ar$. Estimates of 'mantle' $^{132}Xe/^{36}Ar$ values by extrapolating $^{40}Ar/^{36}Ar$ to 40 000 yield unrealistically high values of 0.5–0.8 (olivine) and 4–5 (vein pyroxene) ruling out a simple two-component mixing of mantle and atmospheric noble gases. Rather a two-stage mixing process applies: (1) Changes in relative proportions of slab-derived element-fractionated atmospheric gases and 'mantle' produce two hybrid mixtures dominated by atmospheric gases. This may reflect interaction of slab fluids with mantle wedge fluids on a regional scale within the melting zone. (2) Subsequently mixing of these mantle-atmosphere "hybrids" occurred shortly before the entrapment of the fluids and possibly represents locally restricted compositional variations within the source region of the xenoliths.

1. Introduction

The mantle in subduction zones is affected by various, multi-stage melt extraction and metasomatic enrichment processes. This is reflected in a broad range of chemical variation in island arc magmas containing variable contributions of different slab-derived and asthenospheric components. These components and their sources may be difficult to identify and characterize based on bulk compositions of volcanic rocks, which are products of complex mixing processes on a regional scale.

Xenoliths in volcanic rocks may carry petrologic and geochemical information on small-scale, multi-stage melting and metasomatic processes in supra-subduction mantle. Mantle xenoliths from active continental margins and those hosted by alkali basalts in arc regions are not uncommon (e.g. Yamamoto et al., 2004) but the share of subduction-related vs. asthenospheric or continental components in such rocks is uncertain. Peridotite xenoliths hosted by andesitic magmas in active island arc settings are unequivocal samples of supra-subduction oceanic mantle. Such xenoliths are very rare, in particular large and fresh samples appropriate for geochemical studies. Much of earlier work focused on strongly metasomatised or recrystallized arc-related xenoliths (e.g. Arai et al., 2003; Ishimaru et al., 2007), which provide insights into late-stage processes but do not represent normal mantle wedge lithosphere (Ionov, 2010).

Published data indicate that most of the noble gases from subducting slabs are not recycled to the deep mantle beyond the zone of arc magma generation but efficiently return back to the surface (e.g. Hilton et al., 2002). The recycled noble gases develop characteristic fractionated elemental ratios during their passage through the mantle wedge because of different solubility and partitioning behaviour during melting and fluid percolation. Noble gas studies of xenoliths from island arc settings are limited (Ikeda et al., 2001;

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Kaneoka et al., 1978; Nagao and Takahashi, 1993; Patterson et al., 1994; Sumino et al., 2000; Tolstikhin et al., 1974). Little data is available for xenoliths in andesites, in particular for harzburgites, which are the most common rock type in supra-subduction mantle likely produced by flux melting. Here, we report noble gas compositions in xenoliths from the andesitic Avacha volcano in Kamchatka, NE Russia (Fig. 1, Tables 1 and 2; Supplementary Tables 1 and 2) including residual harzburgites and metasomatic veins (Ionov, 2010; Soustelle et al., 2010). We show that noble gas data can be used to provide additional constraints on the sources and nature of fluids present at different stages in the history of a typical supra-subduction zone environment.

2. Geological context and sample description

2.1. Tectonic setting

The Kamchatka peninsula in far eastern Russia is one of the most active volcanic regions in the world. The ~80 Ma old Pacific lithosphere subducts at the Kurile–Kamchatka trench under the Okhotsk plate at a rate of ca. 8 cm/a (De Mets et al., 1990). The Avacha volcano in southern Kamchatka (part of the East Volcanic Front; Fig. 1) is situated ca. 120 km above the slab surface. Activity started in late Pleistocene; exposed volcanic products consist of ash-fall and pyroclastic flow deposits with compositions evolving from K-poor andesite (carbon-14 age 7250–3500 a BP) to basaltic andesite (Braitseva et al., 1998). Some pyroclastic deposits contain small peridotite xenoliths. Their earlier studies mainly concerned rare strongly metasomatised and recrystallized rocks (Arai et al., 2003; Ishimaru et al., 2007; Kepezhinskas et al., 2002) or focused on the Re–Os isotope system (Saha et al., 2005; Widom et al., 2003).

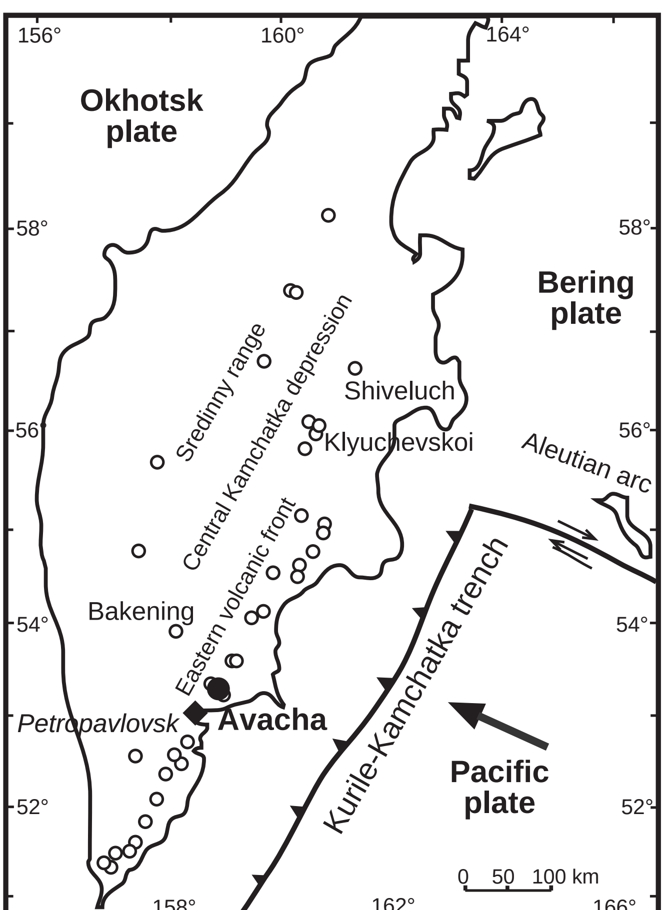

Fig. 1. Location map of major Holocene volcanoes (empty circles) in Kamchatka including Avacha and of the Kuril-Kamchatka trench (modified after Ionov, 2010).

2.2. The Avacha xenolith suite

This work deals with a suite of particularly large and fresh peridotite xenoliths emplaced in a recent tephra fallout. These xenoliths were also studied for petrography and major and trace element compositions (Ionov, 2010), mineral orientation and water contents (Soustelle et al., 2010), Os isotopes and PGE (Ionov et al., 2007), Li and Fe isotopes (Ionov and Seitz, 2008; Weyher and Ionov, 2007); studies of pyroxene-rich veins in the peridotites (Bénard and Ionov, 2009) are under way. The xenoliths are medium to coarse-grained spinel harzburgites containing interstitial clinopyroxene (cpx) and amphibole. Based on major, minor and trace element data these highly refractory rocks may have been formed by 28–35% of melt extraction from a fertile source, possibly in water-rich conditions (Ionov, 2010). Ionov (2010) and Soustelle et al. (2010) proposed a three-stage evolution history for these rocks: (1) partial melting in the asthenosphere, (2) slow cooling to ≤900–1000 °C during the emplacement to the lithosphere, and (3) local fracturing, recrystallization and infiltration of hydrous fluids shortly before the transport of the xenoliths to the surface. Metasomatism took place at stages (2) and (3) to precipitate late-stage interstitial phases and rare cross-cutting pyroxene-rich veins in the melting residues.

Noble gas data in this study were obtained on coarse olivine separated from seven peridotites and on pyroxene separated from coarse websterite veins in two xenoliths. A sample list and a summary of petrological data on the xenoliths are given in Supplementary Table 1. The peridotites are free of alteration based on petrographic data and negative loss on ignition values (LOI: −0.53 to −0.65%, Ionov, 2010) for the bulk-rock powders (i.e., mass gain due to oxidation of FeO to Fe_2O_3). The LOI analyses were also done on olivine powders left after our crushing experiments; these values are negative as well (−0.4 to −0.5%) confirming negligible degrees of alteration.

3. Sample processing and experimental details

Peridotite xenoliths >10 cm in size were sawn to remove their outer parts that may have been affected by host magma; fresh material from central parts of the xenoliths was crushed (Fig. 2 in Ionov, 2010). An aliquot of each crushed rock was used to produce bulk-rock powder, the remaining material was sieved, and pure olivine grains were hand-picked under binocular microscope from 0.5 to 1 mm size fraction. All mineral separates were cleaned with deionised water and ethanol in an ultrasonic bath. Noble gases in those separates are likely hosted mainly by fluid inclusions (Fig. 2a,b), which are common in the majority of the samples. Thus far no microthermometric or Raman data are available for the inclusions which could constrain their compositions and P–T conditions of entrapment. The olivine separates contain no or very little of fine-grained, late-stage olivine and orthopyroxene formed by metasomatism and deformation shortly before the transport of the xenoliths to the surface (stage 3 as defined above), thus the olivine separates most likely carry signatures of ancient partial melting events.

One of the two veins in this study is from xenolith Av-8 (Ionov, 2010). The vein (1–2-cm thick) and adjacent peridotite were sawn, vein material was extracted and crushed to hand-pick pyroxene; homogeneous harzburgite from the remaining part of the xenolith was used to separate olivine. The vein in xenolith Av-25 is thicker (2–3 cm) and is more coarse-grained (5–10 mm); no bulk-rock sample of the host peridotite was made for Av-25 because the xenolith is too small. Vein pyroxene separated from Av-8 and Av-25 is mainly orthopyroxene (opx) but contains some cpx because the two minerals are intergrown, and coarse opx contains cpx exsolution lamellae. We