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# Simulation of nonisothermal metasomatism of peridotite from mantle wedge beneath the Avacha group of volcanoes (*Kamchatka*)

V.N. Sharapov [a,b,*], G.V. Kuznetsov [a], T.Yu. Timina [a], A.A. Tomilenko [a], K.V. Chudnenko [c]

[a] *V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences,*
*pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*
[b] *Novosibirsk State University, ul. Pirogova 2, Novosibirsk, 630090, Russia*
[c] *A.P. Vinogradov Institute of Geochemistry, Siberian Branch of the Russian Academy of Sciences, ul. Favorskogo 1a, Irkutsk, 664033, Russia*

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## Abstract

Comprehensive studies of mineralogy, fluid and melt inclusions, and gas phase in minerals from a representative collection of peridotite xenoliths that underwent metasomatism and convective partial melting in the mantle wedge beneath Avacha Volcano were used to simulate interactions between mantle wedge material and magmatic fluids of constant and variable compositions at different depths, as well as metasomatic effects of fluids derived from subduction slabs. The obtained virtual dynamic patterns of metasomatic zoning across the mantle wedge show how composition variations of fluids and *PT* conditions at their sources influence the facies of metasomatized mantle wedge harzburgite. The compositions of the Avacha xenoliths and crustal rodingite from Kamchatka compared with results of physicochemical modeling suggest that eruptions of Avacha Volcano brought metasomatized material of the upper mantle wedge to the surface. The rocks underwent multistage metasomatism along cracks in a relatively narrow temperature range. Such processes are apparently common to seismically deformed permeable lithosphere above magma reservoirs. However, the mineralogical zoning of the Kamchatka crustal rhodingites differs from that in cracked metasomatic peridotite above the sources of magmatic fluids in the mantle wedge beneath the Kamchatka arc.

*Keywords:* infiltration metasomatism; dynamics; zoning; mantle wedge

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## Introduction

Mantle wedge peridotites from volcanic arcs in the western Pacific margin bear signatures of Ca–Mg–Si metasomatism (Arai and Ishimaru, 2008; Arai et al., 2003, 2007) exhaustively documented in xenoliths found in pyroclastics from the Avacha group of volcanoes (Ishimara and Arai, 2011; Ishimaru et al., 2007). They attract attention being presumably produced by interaction of mantle wedge material with fluids released from a subducting slab of oceanic lithosphere (Malaspina et al., 2009; van Keken, 2003; and others), by melting during thermal and mechanic slab-mantle interaction (Coltorti et al., 2009; Grégoire et al., 2008; and others), or by thermal effects of a mantle diapir (Antonov, 2006; Moroz and Gontovaya, 2003).

The Avacha peridotite xenoliths, with their massive to veined structures, diverse textures, assemblages and chemistry of minerals and their inclusions (Koloskov et al., 2001; Timina et al., 2010, 2012), make a continuous series from dunites to pyroxenites (Koloskov, 1999; Koloskov and Khotin, 1978). The rocks have been interpreted as a crust-mantle mixture (Koloskov et al., 2001) produced by metasomatism and partial melting of mantle wedge above a subducting slab (Ionov et al., 2011; Ishimaru et al., 2011; Sharapov et al., 2009; Timina et al., 2014, 2015; Tomilenko et al., 2010). Kimura et al. (2009) suggested a software for simulating slab dehydration and fluid-fluxed mantle melting for arc basalts (Arc Basalt Simulator or ABS, version 2), but the metasomatic processes in the slab and in the mantle wedge beneath the Avacha group of volcanoes have not been quantified in terms of approximations used in the ABS modeling scheme.

The theory of infiltration metasomatism (Golubev, 1981; Korzhinsky, 1968), which is applicable to the diverse peridotitic xenoliths of Avacha, implies vertical zoning in the metasomatized mantle wedge across the lithospheric mantle. The existing controversy about the compositions of fluids and depths of their sources (Ishimaru et al., 2011; Koloskov et al., 2001) can be resolved by quantitative modeling of nonisother-

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[*] Corresponding author.
*E-mail address*: vik@igm.nsc.ru (V.N. Sharapov)

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mal Ca-Mg-Si metasomatism of the mantle wedge fluxed with fluids rising from different sources at different depths. Such modeling should consider metasomatic facies which correspond to depth variations and zoning of metasomatic columns which accounts for the compositional diversity. In this respect, comparison of mantle and crustal processes is relevant (Seliverstov and Osipenko, 1998) in view of metasomatic Si enrichment of peridotites. Below we estimate the boundary conditions of metasomatism in mantle wedge peridotites fluxed by fluids above magma reservoirs at different depths.

## Boundary conditions of mantle wedge metasomatism beneath the Avacha group of volcanoes

Simulation of a crust-mantle fluid system beneath the Avacha group of volcanoes requires specifying the sources of fluids, the geometry and size of the permeable zone, and the boundary *PT* conditions of heat and mass transfer in the system. This knowledge can be obtained from synthesis of known geological and geophysical data and comprehensive studies of the representative collection of more than 600 samples from the southwestern and northeastern parts of the Avacha edifice.

### *Tectonophysical setting of fluid and magmatic systems in mantle wedge beneath the Avacha area*

The tectonophysical setting of fluid and magmatic systems in the mantle wedge beneath the volcanic arc (including the Avacha group of volcanoes) was discussed in detail in our latest publication (Sharapov et al., 2017). The present paper focuses mainly on the dynamics of nonisothermal metasomatism. According to published evidence (Abkadyrov et al., 2014; Gontovaya et al., 2008; Koulakov et al., 2014; Moroz and Gontovaya, 2003; Sharapov et al., 1984, 1992), the mantle wedge structure can be imaged as in Fig. 1*a*, with two zones of fluid fluxing under compression below and extension in seismically deformed crust above. This structure has bearing on effective permeability of rocks and is relevant to fluid dynamic modeling.

The main difficulty is to estimate the depths of xenoliths entrapment by melts. Xenoliths in volcanics hardly can originate deep below the top of magma reservoirs that maintain volcanism (Fig. 1*a*). Petrogenetic modeling (Koloskov, 1999) predicts the existence of a crust-mantle mixture within the interval between 30 and 60 km below volcanoes, while the tectonophysical model shows seismogenic depths reachin 70 km, which may correspond to magma storage at the crust/mantle boundary (Fig. 1*a*).

Deep hot fluids can discharge through flat fractured zones occupying the upper 20 km of the crust, with their parameters as suggested by Abkadyrov et al. (2014). Possible fracture patterns in the permeable mantle wedge section may look as in the models of Nikolaevsky (1996) for lithospheric deformation. The structures and textures of large peridotitic xenoliths indicate various fracturing styles in zones of magma conduits above magma reservoirs: open cavities, fracture planes intersecting at 23° to 45°, contortion, lumping, chaotic micro-cracks, and other features of seismic deformation.

The depths of magma reservoirs and respective fluid sources (Fig. 1*a*), estimated by Gontovaya et al. (2008) for the Avacha system, hardly could change much (Sharapov and Sotnikov, 1997) within the lifespan of post-Miocene magmatic systems of Kamchatka (Bindeman et al., 2010; Koloskov and Kovalenko, 2009). Thus, the dynamic models of heat and mass transfer in the systems 'fluid source—permeable zone' of 120–150, 100, 70, and 50 km high and 4 km wide, span the time interval from 0 to 100 kyr (Bazanova et al., 1998, 2003, 2004; Melekestsev et al., 1991).

### *Compositions and textures of peridotitic xenoliths*

The Avacha xenoliths have harzburgite, dunite, pyroxenite, wehrlite, and cortlandite compositions of dunite-harzburgite and pyroxenite-cortlandite types (Koloskov, 1999; Koloskov and Khotin, 1978). Large xenoliths form three groups of harzburgites distinguished by optical and scanning electron microscopy, XRD, XRF, and mineral chemistry and thermobarometry (Sharapov et al., 2009; Tomilenko et al., 2010). Group 1: harzburgite composed of fine-grained olivine, orthopyroxene, and accessory spinel. Olivine lacks fluid or melt inclusions but encloses minute spinel crystals (Fig. 2*a*, *b*). Olivine chemistry (Table 1, 1) differs in high Mg# (0.90–0.89) and NiO (0.35–0.37 wt.%) but low CaO and MnO (0.06–0.10 and 0.10–0.16 wt.%, respectively). Orthopyroxene contains 56.3 wt.% $SiO_2$, 1.2 wt.% $Al_2O_3$, 5.4 wt.% FeO, 0.4 wt.% $Cr_2O_3$, 35.4 wt.% MgO, 0.14 wt.% MnO, and 0.36 wt.% CaO; it exists as aggregates of radiating or prismatic crystals free from fluid or melt inclusions (Table 1, 4). Accessory spinel occurs as fine particles of 10–40 μm (Timina et al., 2010, 2012; Tomilenko et al., 2010), has high Mg# (0.69–0.71) and $Al_2O_3$ (26.2–27.1 wt.%), and is likewise free from fluid or melt inclusions. Thus, the rocks of this group are primary harzburgites composed of primary olivine, orthopyroxene, and spinel (Tomilenko et al., 2010).

Group 2: a fine harzburgite matrix with speckles, bands or veinlets of coarse olivine-orthopyroxene-spinel aggregates from a few tens of microns to a few cm in size (Fig. 3*a*) (Timina et al., 2012; Tomilenko et al., 2010). Fresh zones have compositions and textures of primary harzburgite while all secondary phases differ markedly in compositions from their counterparts in unaltered peridotite. Recrystallized harzburgite (Table 1) contains secondary olivine (with higher FeO of 8.9 to 14.1 wt.%) and spinel (with lower $Al_2O_3$ of 27.1 to 18.1 wt.% but higher $Cr_2O_3$ of 37.5 to 43.4 wt.%) (Timina et al., 2012; Tomilenko et al., 2010). Secondary spinel, unlike the primary variety, occurs mainly as large interstitial lamelli at olivine boundaries or between olivines and orthopyroxenes (Fig. 3*a*, *b*). Some harzburgite xenoliths locally preserve structures and textures corresponding to different alteration stages. Zones of strong metasomatic recrystallization coexist in some samples with those of primary harzburgite.