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Migration of fluids and melts in subduction zones and general aspects of thermophysical modeling in geology

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Abstract

Modeling of fluid-magmatic systems in a suprasubduction mantle wedge is considered for the case of Kamchatka with reference to data on peridotites from other known subduction and oceanic rock complexes. This modeling has to take account of magma storage in several intermediate reservoirs at different depths, up to six such reservoirs, as in the case of Avacha Volcano. Comparison of available data on melt inclusions in spinels indicates crystallization of the Avacha peridotites in magmatic systems progressively decreasing in temperature (>1200 °C → 1100 °C → 900 °C) and pressure (from 13.8 to 4.5 kbar) in intermediate reservoirs at depths of 30–40 and 15–20 km. The Avacha harzburgites do not belong to primary oceanic mantle as they lack both signatures of high-temperature plastic flow and effects of mantle melts known for sheared mantle peridotites from ophiolite suites. The v_P/v_S ratio estimated from jointly analyzed *P*- and *S*-wave velocities (v_P and v_S, respectively), an important indicator for seismic tomographic reconstructions of subduction zones, allows discriminating between regions saturated mainly with liquid (melts) and gas phases beneath volcanoes. Only specially tested tomographic data can provide reliable reference for modeling of mantle wedge processes.

Keywords: fluid; melt; subduction zone; mantle wedge; magma reservoir; peridotite; melt inclusion; seismic tomography; Avacha Volcano; Kamchatka

Introduction

Numerous publications have been appearing lately on numerical or less often physical modeling of processes in lower crust and upper mantle. However, many features of these processes remain overlooked: extent in space and time, poor accessibility for direct observations, combinations of occasional observations and finds (e.g., animal and plant fossils) or random events such as volcanic eruptions with variations in heat flux, sea level, and other continuous long-term trends.

Modeling for subduction zones has received much recent attention (Gerya, 2011; Sharapov et al., 2017; and others). Modeling of this kind is a challenge because subduction-related processes have multiple controls and are variable in space and time, which leads to multiple solutions for melt sources, with several intermediate reservoirs on the way of rising melts. Gerya (2011) reviewed about 100 publications on various aspects of modeling and mentioned more than ten topical problems. Sharapov et al. (2017) discussed local problems of metasomatism and filtration of fluids in the mantle beneath volcanoes in subduction zones and referred to more than 50 relevant publications. However, it is difficult to highlight mainstream issues among the wealth of published evidence.

In our previous review (Dobretsov et al., 2015) concerning the deep carbon cycle, we tried to formulate key problems related to subduction with reference to data of geology, experimental petrology and geochemistry, and geophysics (especially, seismic tomography). They are, namely:

(1) critical role of andesite melting in subduction of oceanic crust as a basic element of material turnover in the crust and upper mantle;

(2) necessity of three-velocity modeling of flows for subduction zones with independent migration of fluids and melts and slab motion, which has never been undertaken

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before; only two-velocity models were obtained, but as a specific case (Dorovsky et al., 1998);

(3) critical role of magma storage in intermediate reservoirs at depths 50–80 and ~30 km, and special role of shallow (10–15 and 2–5 km) reservoirs at the final pre-eruption stage.

Migration of fluids, though not considered as a key issue, has important implications for metallogeny of subduction zones.

Another general methodological approach in geodynamic modeling (Dorovsky et al., 1998) is to perform inversion as a series of forward problems based on fitting of initial and boundary conditions in numerical experiments, to cover the whole possible range of their variations.

Inversion is always ambigous and often provides multiple opinions instead of certain knowledge (Dobretsov, 2011; Dobretsov et al., 2001). The best approach to inversion is to (i) use methods of mechanics, thermophysics, and physical chemistry, (ii) apply fitting at the preliminary stage of geological-geophysical analysis of field data, (iii) combine numerical and physical (laboratory) modeling, and (iv) check modeling results against observations.

Sharapov et al. (2017) touched upon another essential point of methodology, that approximation of mass transfer in the context of the similarity theory imposes more rigorous constraints on the modeling results than the Darcy approximation (Dorovsky et al., 1998; Gukhman, 1974). The principal theorem of similarity (Gukhman, 1974), or the theorem of Kirpichev–Gukhman, can be formulated as follows (Dobretsov et al., 2001; Mikheev, 1947): similar phenomena should have similar conditions and criteria of uniqueness. Therefore, the criteria of similarity should base on parameters that can provide unique solutions, such as the Rayleigh or Reynolds numbers for convection and fluid flow, respectively, or the Nusselt criterion, etc. Meanwhile, the cited authors (Dorovsky al., 1998; Sharapov et al., 2017) did not use them.

Intermediate melting sources and pathways of fluids and melts

The structure of crust and upper mantle and pathways of migrating melts beneath the Avacha group of volcanoes (Kamchatka) and Chokai–Kurikoma volcanoes (Japan) were imaged and compared (Fig. 1) based on different models: by Gontovaya et al. (2010) and Sharapov et al. (2017) (Fig. 1*a*) and by Kogiso et al. (2009) and Nakajima et al. (2001, 2009) (Fig. 1*b*); seismic tomography data from the latter publication were discussed in (Dobretsov et al., 2015). Both panels shows six intermediate magmatic zones, at the depths 25–30 km, ~50–80 km and 120–150 km, and two melt conduits: (1) from a greater depth of ~150 km via an intermediate source at 30 km to Chokai or Proto-Avacha Volcanoes and (2) from 100–120 km via sources at 50–90 km to Avacha and Kurikama Volcanoes. These conduits are simialar to the magma pathways in subduction zones suggested by Ivanov (2008). Theoretically, another conduit may be traceable by the surface hydrothermal front (No. 3 in Fig. 1*a*, in the field of the aqueous fluid in Fig. 1*b*).

The different models for geographically dispersed areas (Fig. 1*a*, *b* and Fig. 39.2 in (Ivanov, 2008)) must be realistic as they predict similar magma reservoirs and melt conduits. Their pattern accounts for the combiantion and intermittence of andesitic (Avacha, Bezymiannyi, and Shiveluch Volcanoes) and basaltic (Klyuchevskoy and Tolbachik) magmatism in Kamchatka. Large amounts of andesitic magma mostly erupts during episodes of high volcanic activity recurrent at ~500–600 kyr in Kamchatka and Japan (Dobretsov et al., 2015; Laverov et al., 2005), while less voluminous basaltic volcanism acts between these episodes (Dobretsov, 2010; Dobretsov et al., 2015; Kelemen et al., 2004). Note that dacite-andesite volcanism was predominant hundreds of thousand to millions of years ago in Kamchatka (Laverov et al., 2005) and Japan (Dobretsov et al., 2015) but never repeated in Holocene or historic time. The estimated amounts of erupted material in Kamchatka are 8700 km^3 for the past 130–150 kyr (mainly dacites and andesites); 6700 km^3 for 730–850 kyr (about 50% andesites), 15,400 km^3 in total for 250 kyr and only 2200 km^3 for the remaining 600 kyr (mainly basalts). However, the quality of these estimates remains poorly constrained.

Erupting andesite magma (Fig. l) rises from the subduction zone and experiences almost no change in intermediate reservoirs at 25–30 km. The respective rocks preserve geochemical signatures of melting at large depths: Ta and Nb minimums corresponding to rutile residue, a garnet trend of lanthanides, discrete Ba, Rb, and Zr ratios, etc. (Dobretsov, 2010; Dobretsov et al., 2015).

The idea that batches of hydrothermal and/or gaseous fluids can pass through several connected reservoirs, like in a flow reactor (Sharapov et al., 2017), does not contradict Fig. 1, but migration of hydrothermal fluids through intermediate zones is possible only for flow 3 (Fig. 1) within the aqueous fluid field. However, more rigorous geological and geophysical constraints on the number of reservoirs are required in this case (50 are too many and unreasonable). Furthermore, the flow has to be extended into the crustal domain till emergence of hydrotherms (0–30 km) to compare it with the belt of solfataric alteration before the magmatic front in Kamchatka (e.g., Karpov, 1976; Naboko, 1958).

Complicated iterative calculations for 50 reservoirs, at every 1 kyr till 50 kyr (Sharapov et al., 2017), led to a mineral-depth profile from 100 to 40 km at temperatures 1330 to 1230 °C shown at the margin of Fig. 1*a*. These temperatures are generally lower than the values at the respective depths in Fig. 1*b*. Note that unlike Fig. 1*a*, the temperature pattern of Fig. 1*b* includes a low level corresponding to the cold slab and a conjugate high level of >1400 °C at depths of 150–100 km (left) and 75–30 km (center). Most of the profile (Sharapov et al., 2017) records wehrlitization of peridotite with the ranges 55–70% olivine and 10 to 15% clinopyroxene and orthopyroxene at 94–88 km or 3–5% clinopyroxene and 5–7% orthopyroxene at 86–40 km. The variations are stronger only in reservoir No. 1 at the depth 100–95 km, where olivine reduces to 0–3% while orthopyroxene and clinopyroxene increase, respectively, to 50% and 35–40% during wehrlite formation for the first 20 kyr (Sharapov et al., 2017, Fig. 11).