Chapter 7

Dynamics of Convective Heat and Mass Transfer in Permeable Parts of Seismofocal Zones of the Kamchatka Region and Conjugated Volcanic Arcs

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Abstract

This chapter considers the dynamics of convective heating of mantle and crustal rocks in the seismic focal zone of Kamchatka region and associated volcanic arcs, which are characterized by the predominance of compressive stresses and the compaction of the heterophase medium. Features of heating, determining the dynamics of metasomatic transformations and convective melting, are studied on the basis of nonisothermal hydrodynamic model of heating of lithospheric rocks above the magmatic chambers.

Keywords: mantle wedge, convective heat and mass transfer, infiltration metasomatism, zoning, mathematical model

1. Introduction

The problem statement arose out of consideration of the nature of porphyritic deposits (porphyritic formation PF) as paleosystems [1], similar to existing fluid systems in transitional areas of the Pacific Ocean (PO) [2]. In the canonic model of these ore-forming systems, the fluid mass transfer is determined by the retrograde boiling of magma in mesoabyssal intrusive cameras. The analysis of time characteristics of formation [3, 4] and the cyclic nature of porphyritic deposits of active margins of PO have showed that more than 70% of the described deposits are formed with the participation of mantle-crustal ore-magmatic systems [5]. Building quantitative models, it is necessary to rely on the data on tectonophysical characteristics of mantle-crust systems of modern volcanic arcs. This chapter takes into account the data on the dynamics and structure of the seismic focal zone (SFZ) of Kamchatka and the Kuril Island arc, and data on the nature of the volcanic groups of the Japan Islands, their spatial structure, and time cycles of formation [6, 7]. Physical models of convective heat and mass transfer in the fluid mantle-crust systems associated with magmatic chambers are discussed taking into account the already developed schemes of convective heat transfer in the earth's crust for tensile phases [1, 8] as well as the specifics of regions of the SFZ, where the conditions of compression prevail [9, 10].

2. On tectonophysical conditions of development of the magmatogene fluid systems under terrestrial and submarine volcanoes of Kamchatka and the Kuril Islands

The considered problems of convective heat and mass transfer in the mantle wedge beneath volcanic arcs of the Japanese Islands, the Kuril Island arc, the Kamchatka region, and the Aleutian Island arc result from tectonophysical developments, distinguishing regions of SFZ with a predominance of conditions of compression and extension [11–14]. Problems of existing models of the mechanics of development of morphostructures of active marginal continents are discussed in the review of works on canonic models of subduction [15]. New geological and geophysical information about the structures of northwest part of PO, which appeared in the last two decades [16–24], contains the actual data, which has not received explanation in the framework of the discussion in the above review. Among them are research data that are not considered within the canonic model of subduction: (1) before the frontal part and in the rear area of the coastal stripe of volcanoes in the linear and arc permeable zones, there are cyclically occurring and ongoing processes of magmatism with certain geochemical trends [1, 5–7, 18, 25–28]; (2) in the northern and southern sectors of the Kuril-Kamchatka volcanic arc in the upper part of the lithosphere, there is a fixed splitting of the SFZ into the western and eastern branches with orthogonal drop of fracture zones [17, 29] in the area of development of grouping (swarm) earthquakes [12, 30–31]; (3) central parts of volcanic arcs of the northern and northwest areas of PO fall into segments with different structural characteristics of transition zones and back-arc basins; (4) time harmonics of development of tectonic and magmatic processes [5, 17] and stages of formation of PF deposits [2–4] allow assuming that within the seismic focal regions in the continental lithosphere, there have been previously and there are now permeable zones with periodically functioning mantle-crustal ore-magmatic systems. No correct physical models of heat-mass transfer have been proposed for such zones yet; (5) in these segments, there is no "frontal" volcanic zone, since magmatic and hydrothermal events have developed and still occur in the faults that are longitudinal and transverse to the axis of the ocean trench, in the strip of the modern subaerial volcanoes, considered to be the "frontal" volcanic area above the lithospheric wedge; and (6) there are latitudinal fault zones, in which all dated magmatic events in the interval 0–75 million years are recorded [6, 18, 26, 28].

The last point is significant: the analysis of time harmonics of PF formation in the PO margins has found several characteristic dynamic features: (1) the existence of multistage mono- and polycyclic deposits [2–4] and (2) the duration of the formation of individual deposits ranges from a few tens of thousands of years to tens of millions of years, while maintaining thermodynamically close conditions of ore formation [1, 5]. Over the observed period of less than 100 years within the SFZ of the Kamchatka region, the significant seismic activity has a cycle with a period of about 10–12 years [17]. From this, we can conclude that since the formation of deep ocean trenches in the northern half of PO, the tectonophysical characteristics of the SFZ did not remain stationary [18, 22, 25] that is similar to the position of permeable zones in the lithosphere section. As a consequence, it is necessary to clarify the direction of the evolution of tectonophysical characteristics of the structure of the SFZ in the Kamchatka region and the conditions for the development of fluid magmatic systems associated with magmatic chambers under the morphological structures typical for the transition region of "ocean continent."

3. On the structure of the ocean: Continent transition zones of the Kamchatka region and associated volcanic arcs

The structure of the earth's crust to the west of the axis of ocean trenches of the continental sector of the N-W margins of PO is considered in detail in the above-cited works. The most detailed discussion of the crustal structure of the transition area of the Kamchatka region (in its submarine part) may be found in [32]. At that, the structure of the jointing region (ocean trench), as a rule, is beyond the scope of the description of its geophysical characteristics and a real form and distribution of lineaments, submarine volcanic structures and configuration of magma bodies in the crust.

These data may be found using the GIS complex GIS-ENDDB [33], in particular, to clarify the distribution of volcanic bodies in lineaments in the lithosphere structure of the Kamchatka region for the "ocean-continent" transition region (**Figure 1**), and the distribution of density and magnetization of rocks (**Figures 2** and **3**), to correlate earthquake epicenters with the gravimetric map of inhomogeneities in the crust (**Figure 4**), and to determine heat flow values (**Figure 5**) and positions of compression and extension in SFZ on the basis of modern catalogs of seismic events (**Figure 6**).

The most important factor of the development of magmatogene fluid systems is a fixed blocky structure of the Kamchatka lithosphere [27, 34] and its compliance with the current blocky structure of SFZ. The blocky structure of the lithosphere within the SFZ of the Kamchatka region was determined by two methods: (1) estimating the size and shape of areas with similar characteristics of strains, separated by bands of unstable seismicity [11, 35] and (2) monitoring the bands of seismic activity with changing ratios of velocities of longitudinal and transverse waves [30–31]. The development of the first approach using laboratory simulation of stress fields of optically anisotropic media allowed simulating the "restored" continuous stress fields for the relevant mechanisms of earthquakes in the selected region of the energy spectrum [12]. The development of the second approach allowed investigating the structure of SFZ in the depth interval of 0–70 km, where about 90% of seismic events take place and define the

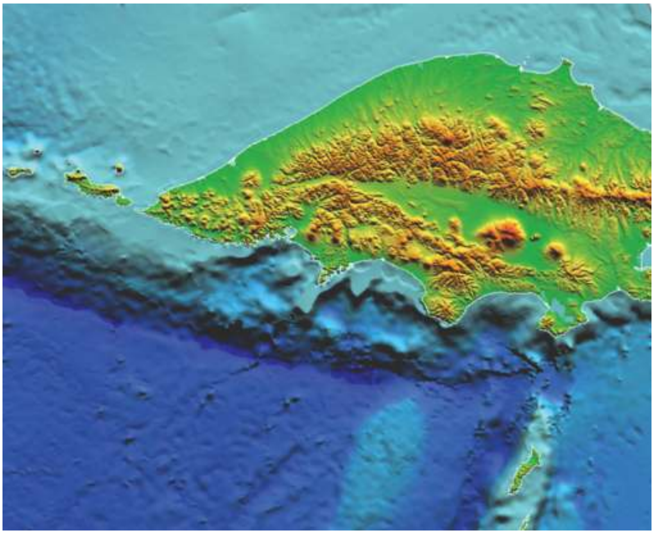

Figure 1. The morphological structures and lineaments of the "ocean-continent" transition zone in the Kamchatka region.

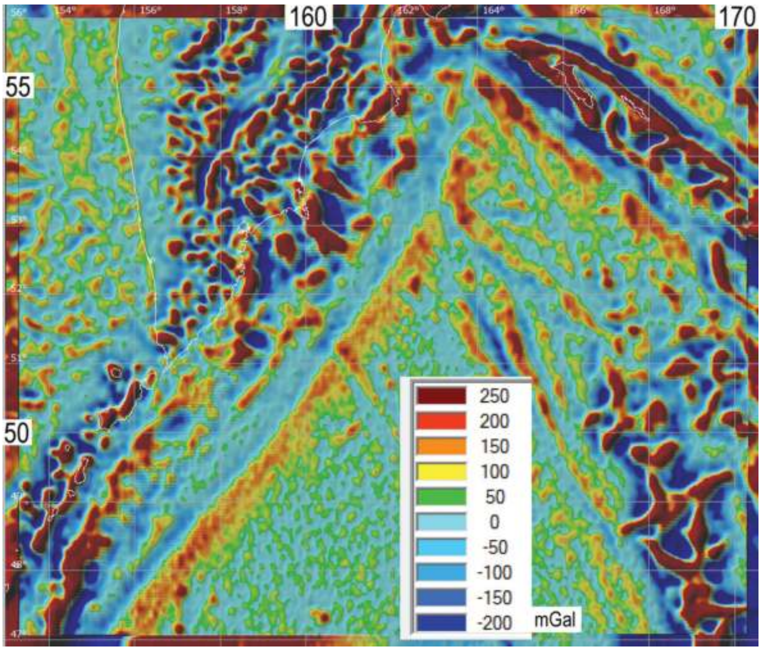

Figure 2. The structure of local variations in the density of the crust of the Kamchatka region and associated volcanic arcs.

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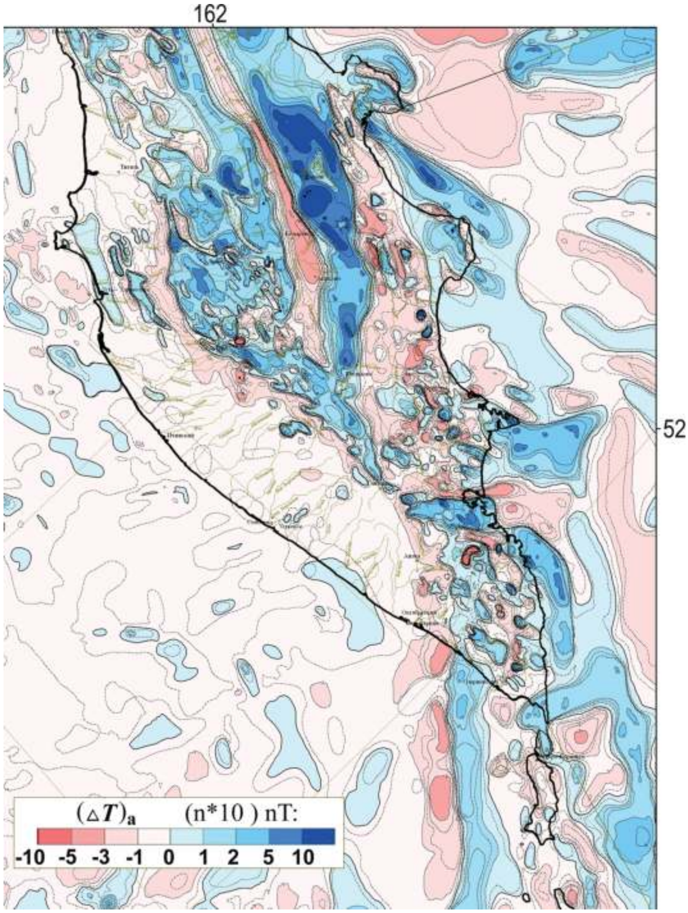

Figure 3. Sequences of positively (basite) and negatively (granite) magnetized asynchronous (Cretaceous—Present) magmatic bodies, part of which has higher density (basite intrusions). (Litvinova TP, editor. Map of anomalous magnetic field of Russia. Scale 1:2500000. Moscow: VSEGEI; 2010).

tectonic appearance of the volcanic zones, the surface morphology of the earth's crust, and its lineament system [17]. It should be noted that under active volcanoes, the morphology of permeable zones in the crust is distinguished experimentally. Thus, according to the study of the crust structure under the Avacha volcano [36], they represent linear fracture zones with a width of 2–4 km. Such zones are conductors of melts and magmatogene fluids, originating from the magma chambers [19, 37].

The distribution of subaerial and submarine volcanic structures of Kamchatka region may be added with the known scheme of structural control of volcanism in Kamchatka [27, 38], built on the basis of tectonophysical data [39], and a structural scheme of satellite data interpreting for the area under consideration [40–41]. This allowed obtaining data on the junction of

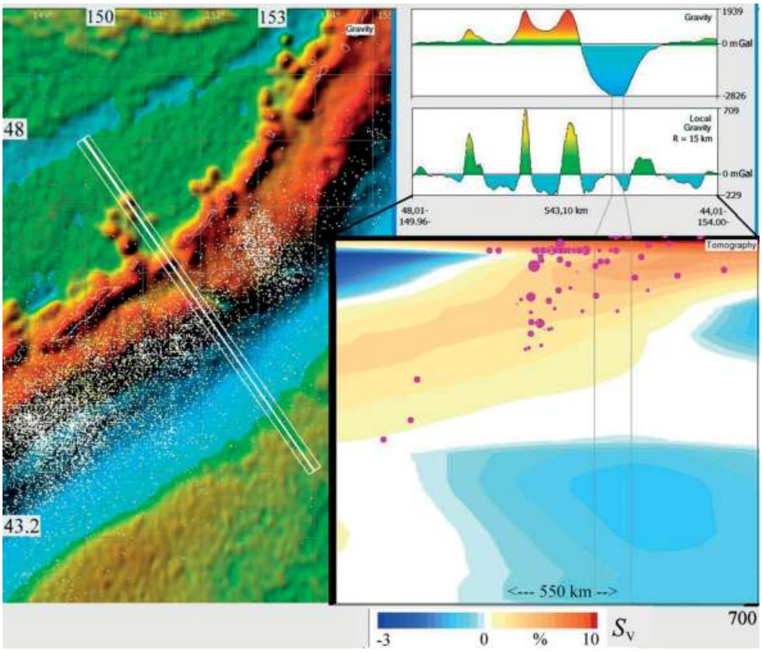

Figure 4. Distribution of epicenters of earthquakes (white dots) in the Kurile region and adjacent volcanic arcs, rendered on the regional map of the gravitational field of the earth's crust. The axial region of the trench is characterized by low seismicity. In the inserted picture: The gravitational cross section, its local part, and tomographic cross section are shown. The axial region of the trench is marked by vertical lines.

lineaments of ground surface and seabed. These data on structural elements, when compared with variations of parameters of different geophysical fields based on the results of satellite observations and ground measurements, serve to correlate the appearance of faults, deformations of the earth's crust and formation of magmatic bodies in the permeable zones. This greatly increases the reliability of geological-genetic schemes of the above-cited papers when compared with the results of the structural analysis and tectonophysical schemes from [12, 17, 19–20, 30–31, 37, 40–41].

The analysis of morphology and position of volcanic structures, location, and extent of tectonic and geomorphic elements in the Kamchatka region (**Figure 1**) suggests that: (1) linear volcanic ridges may cross the structural elements from the edge of the continental shelf to the area of occurrence of volcanic ridges of the oceanic plate, parallel to the axis of the deep trench, (2) these transverse ridges may cross some arc volcanic ridges on the shelf of the continental slope and oceanic plates, (3) the mentioned ridges may cross tectonic terraces of the continental slope up to the limits of the shelf, and (4) linear submarine ridges may be located on the continuation of arc and line faults, controlling the volcanic groups of terrestrial volcanoes of Eastern and Southern Kamchatka.

Based on the found values of tectonic cycles of development and manifestation of magmatic systems of the Okhotsk Sea basin and the Kuril Island arc [18, 22] and the data of Kamchatka

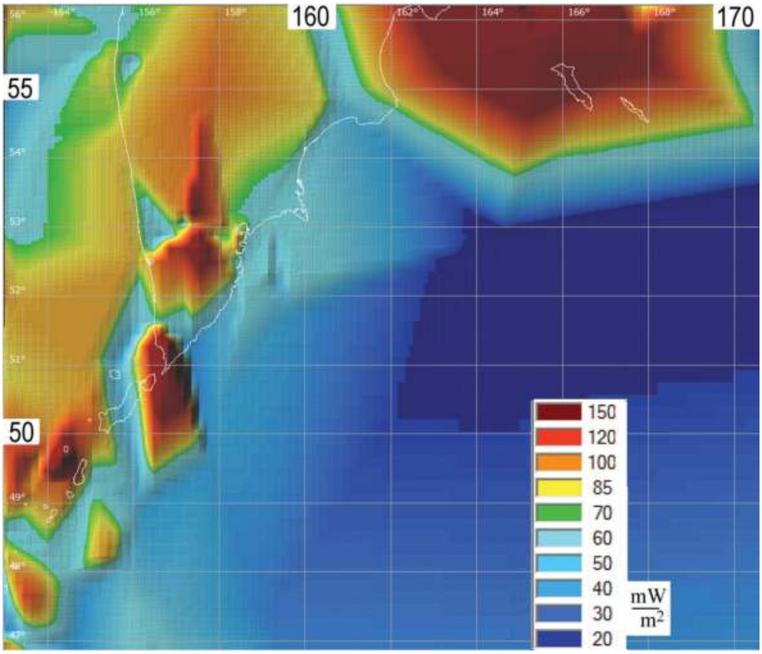

Figure 5. The regional thermal field in the morphostructures of the Kamchatka region and associated volcanic arcs.

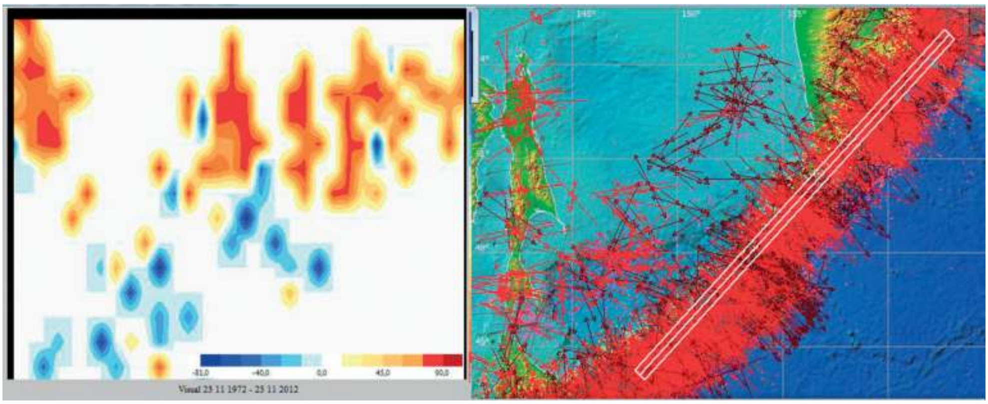

Figure 6. Distribution of compression and stretching regions along the continental slope in the seismic focal zone of Kamchatka region and the southeastern part of the Okhotsk Sea. The structure of vertical and inclined destruction zones of mantle rocks in the lithosphere and in the upper mantle appears above the perovskite transition.

terrestrial magmatic systems dating [26, 28, 42], it is possible to make some assumptions about the sequence of magmatic events, recorded in **Figures 1-3**. After forming the ocean trench offspur, in the "ocean-continent" transition region, there were cyclic processes of tension and shear with their development over arc and line faults of volcanic structures. In the grabens of the bays, in the direction from the trench axis to the volcanic groups of Eastern and Southern

Kamchatka, from about 8 to 14 tectonic and tectonic-magmatic events were detected. With regard to the fixed scale of magmatic events in the vicinity of deep-sea trenches and submarine conditions, the most significant is thought to be the latest magmatic phase [28], which developed within the boundaries and geodynamic conditions of the actual SFZ. Therefore, the model of heat and mass transfer dynamics for mantle-crust magmatic systems should be built taking into account tectonic and physical data, as shown in **Figures 4-6**, and tomographic data of the work [19].

4. Problem statement and mathematical model

Note the main structural and mineralogical and thermo-dynamic effects that may be assumed in the fields of compaction of heterophase media under volcanoes. The correct model of heat and mass transfer dynamics in orthomagmatic systems under volcanoes was developed [5, 8], assuming the predominance of tension conditions in such systems [12]. This assumption was based on then available statistical data on the identified mechanisms of earthquakes [11–12]. Results of processing of seismic data of Kuril-Kamchatka SFZ accumulated since then and shown in **Figures 5** and **6** give reason to significantly adjust the specified assumption. As can be seen from **Figures 5** and **6**, in the section of the earth's crust of Kamchatka, the condition of tension prevails in the western and eastern parts of the SFZ, whereas in the vertical section of the central region of SFZ, there are alternating regions of compression and tension. At that, at the junction of blocks, there are regions with changing configuration, characterized by the conditions of compression. It is obvious that for such areas, the developed hydrodynamic model of magmatic fluid filtering [5, 8] is not quite correct. Therefore, we are developing a more correct model of heat and mass transfer in compressible heterophase media as discussed below.

It should be noted that for mantle rocks, we have already seen experimental evidence of the complexity of such "fluid-rock" interactions. So in mantle rocks, in the field of compression predominance, processes of percolation are assumed in the formation of recrystallization margins along the boundaries of the rock matrix crystals in the presence of a fluid phase [43]. On the other hand, in the models of catastrophic eruptions of andesite volcanoes, it was discovered that heating of the heterophase medium might occur in the zone of tension in the volcanic channel in a heterophase flow in the presence of mechanical interaction of phases [44]. Considering the interaction of compressible phases when filtering fluids in the fractured media [10] apparently can detect a similar effect. Note that under crustal tectonophysical conditions in metasomatic debasification of ultrabasites of Kamchatka, there is the effect of rodingite melting in the areas of ophiolite plate protrusion [32]. Similar effects of local heating in compacted heterophase medium should be expected when filtering the fluid in terms of compaction of the heterophase medium in permeable zones of the lithospheric mantle.

Keeping in mind the above, the physical model of heat and mass transfer in the lithosphere under continental and submarine volcanoes in its governing equations will take into account the main effects of interfacial interaction in the compacted heterophase medium in permeable zones above the magmatic source of fluids. Equations of the mathematical model of such fluid system evolution in the lithosphere were obtained in the framework of the laws of conservation, which

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is based on the compliance of the first principles of thermodynamics, conservation laws, and group invariance of the equations [45]. The used phenomenological method ensures thermodynamic consistency of equations of the nonlinear mathematical model of the heterophase medium dynamics. In the framework of this approach, different models were obtained for saturated porous media [46] and two-phase media under the assumption of phase equilibrium in pressure and temperature [47]. The nonlinear model of two-phase media is based on the assumption of the lack of phase equilibrium in pressure, but with phase equilibrium in temperature.

The unit volume of the heterophase medium is characterized by density ρ, velocity $\mathbf{v}$, mass density of the entropy s, and mass content of one of the phases c. The relative motion of phases in such a heterophase medium is characterized by velocity $\mathbf{w}$. The selected parameters of the heterophase medium are connected with parameters of the phases: partial densities and velocities of the phases ρ_s, ρ_f, $\mathbf{u}_s$, $\mathbf{u}_f$ by ratios: $\rho = \rho_s + \rho_f$, $\mathbf{v} = c\,\mathbf{u}_s + (1-c)\mathbf{u}_f$, $\mathbf{w} = \mathbf{u}_s - \mathbf{u}_f$. Thermodynamics of such a medium is fixed by the choice of the functional dependence of energy $E = E(\rho, c, \mathbf{v}, \mathbf{w}, s)$. Governing equations of two-velocity hydrodynamics of heterophase medium with two pressures include the laws of conservation of total mass and mass of one of the phases:

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \mathbf{v}) = 0,\ \frac{\partial \rho c}{\partial t} + \operatorname{div}\left(\rho c\,\mathbf{v} + \rho\left(c - c^2\right)\mathbf{w}\right) = 0, \tag{1}$$

the entropy transfer equation

$$\begin{gathered} T\frac{\partial \rho s}{\partial t} + T\operatorname{div}(\rho s \mathbf{v}) = \operatorname{div}(\kappa \nabla T) + \operatorname{div}(\nu \mathbf{w}) + , \\ +\rho(1-c)b\,\mathbf{w}^2 + \eta_v v_{ik}^2 + \eta_m v_{ik} w_{ik} + \eta_w w_{ik}^2 \end{gathered} \tag{2}$$

transferred with an average velocity of the two-phase flow $\mathbf{v}$, satisfying the conservation law

$$\frac{\partial \rho v_i}{\partial t} + \partial_k\left(\rho v_i v_k + \rho\left(c - c^2\right) w_i w_k + p\delta_{ik}\right) = \partial_k\left(\eta_v v_{1ik}\right) - \partial_k\left(\eta_w w_{1ik}\right) + \rho g_i, \tag{3}$$

and the equation describing the relative motion

$$\begin{gathered} \frac{\partial w_i}{\partial t} + (\mathbf{v}, \nabla) w_i + (\mathbf{w}, \nabla) v_i + (1-2c)(\mathbf{w}, \nabla) w_i = -\partial_i q + (\mathbf{w}, \mathbf{w})\partial_i c + \\ + \nu\left(c - c^2\right)^{-1} \nabla T - bc^{-1} w_i + c^{-1}\partial_k\left(\mu_v v_{1ik}\right) - (1-c)^{-1}\partial_k\left(\mu_w w_{ik}\right) \end{gathered} \tag{4}$$

Here, $v_{ik} = \frac{1}{2}\left(\partial_k v_i + \partial_i v_k - \frac{2}{3}\delta_{ik}\operatorname{div}\mathbf{v}\right)$, $w_{ik} = \frac{1}{2}\left(\partial_k w_i + \partial_i w_k - \frac{2}{3}\delta_{ik}\operatorname{div}\mathbf{w}\right)$ are tensors of deformation rates, $\mathbf{g}$ is the acceleration, T is the temperature, p is the pressure, and q is the parameter of interfacial interaction, introducing a second pressure in the two-phase medium. Kinetic coefficients of interfacial friction b, dynamic viscosity η_i, thermal conductivity of the medium κ, and the coefficient ν are functions of thermodynamic parameters. Effects of bulk viscosity in this model are not taken into account.

The equation of state and closing dynamic equations (1–4) in the linear approximation [48] are taken as follows:

$$\frac{\delta\rho}{\rho} = \alpha\,\delta p - \beta\,\delta T,\ \ \delta s = c_p\frac{\delta T}{T} - \beta\frac{\delta p}{\rho},\ \ \frac{\rho_0}{\rho}\frac{\delta c}{c} = \rho(1-c)\alpha_q\,\delta q. \quad (5)$$

Coefficients of volumetric compression α, α_q, and thermal expansion β, as well as the specific heat c_p of the heterophase medium introduced here are additive on subsystems. Full density of the heterophase medium and density of entropy are, assumingly, associated with temperature and pressure and do not depend on the second pressure.

The constructed model was analyzed numerically. The difference approximation of the equations (1–4) of nonlinear two-velocity model was realized in the framework of the method of control volume [49–50], whose essential advantage for solving the hydrodynamic problem is that discrete analogs of differential equations satisfy exact integral balance relationships even on rough grids. Application of the control volume method to nonlinear nonstationary equations (1–4) features the choice of assumptions, concerning the change in the dependent variables at a time step, determining the appropriate method to discretize the convective terms at the faces of control volumes, building the algorithm for calculating the pressure field and the consistent velocity field, and satisfying the continuity equation. To determine the values of dependent variables at a new time layer, we have chosen a fully implicit scheme in time, which allows eliminating restrictions on the time step [51–52] and enables making calculations on large time scales characteristic of the problem under consideration. For discretizing the convective terms to determine the values of dependent variables on the faces of control volumes, the nonlinear scheme of the second order HLPA was implemented [53–54]. This scheme

Parameters	**Values**
Fluid viscosity, η_f (Pa · s)	4.5×10^{-5}
Fluid density, ρ_f (kg/m^3)	120
Fluid thermal conductivity, κ (W/m K)	32
Fluid specific heat capacity, c_p (J/kg K)	0.17
Fluid initial temperature in source, T_0 (°C)	1000–1200
Fluid compressibility, β_f (m^2/N)	8.07×10^{-5}
Density of crust rocks, ρ_f (kg/m^3)	2600
Density of lithospheric rocks, ρ_f (kg/m^3)	3000
Specific heat capacity of lithospheric mantle rocks, c_p (J/kg K)	1000
Thermal conductivity of lithospheric mantle rocks, κ (W/m K)	2.4
Fluid heat transfer coefficient on the side of the fluid conductor (W/m^2 K)	0.005–0.05
Fluid conductor length, L	50–150
Fluid conductor width, L_2	4
Effective porosity along the fluid conductor	0.01–0.03
Effective permeability along the fluid conductor, (m^2)	10^{-16}–10^{-13}

Table 1. Physical parameters.

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Medium	Composition
Earth's crust rocks, H_1 (0–10 km)	Basalts
Earth's crust rocks, H_2 (10–40 km)	Andesites
Lithospheric mantle rocks, H_3 (40–150 km)	Harzburgites
Magmatogenic fluid in the reservoir (source), R_0 (mol)	C: 0.01-1, H: 0.02-2, O: 0.03-3, N: 0.01, S: 0.003-0.01, Cl: 0.01-0.5, F: 0.003-0.1, Si: 0.125-0.8, Ca: 0.01-0.3, K: 0.001-0.02, Na: 0.01-0.03, Al: 0.01-0.3, Fe: 0-0.2, Ti: 0-0.01
Gas in the reservoir, average content, R_1 (%)	Gas: 0.5-5
Rock in the reservoir, initial composition, $R_{1,\ldots,40}$ (mol)	Si: 6.248, Ca: 0.112, K: 0.006, Na: 0.019, Al: 0.082, Fe: 0.583, Ti: 0.006, Mg: 10.705, Mn: 0.023, Cr: 0.034, P: 0.004, O: 25.52

Table 2. Mineralogical composition.

ensures the monotonicity and the required accuracy of the solutions and meets the convective boundedness criterion (CBC).

The feature of this model is the presence of two pressures in a heterophase medium. For the calculation of consistent velocity fields and pressure fields, the iterative algorithm SIMPLE was adapted [50, 55]. The general iterative approach to the construction of the computational algorithm, based on the method of simple iteration that includes local iterations at solving

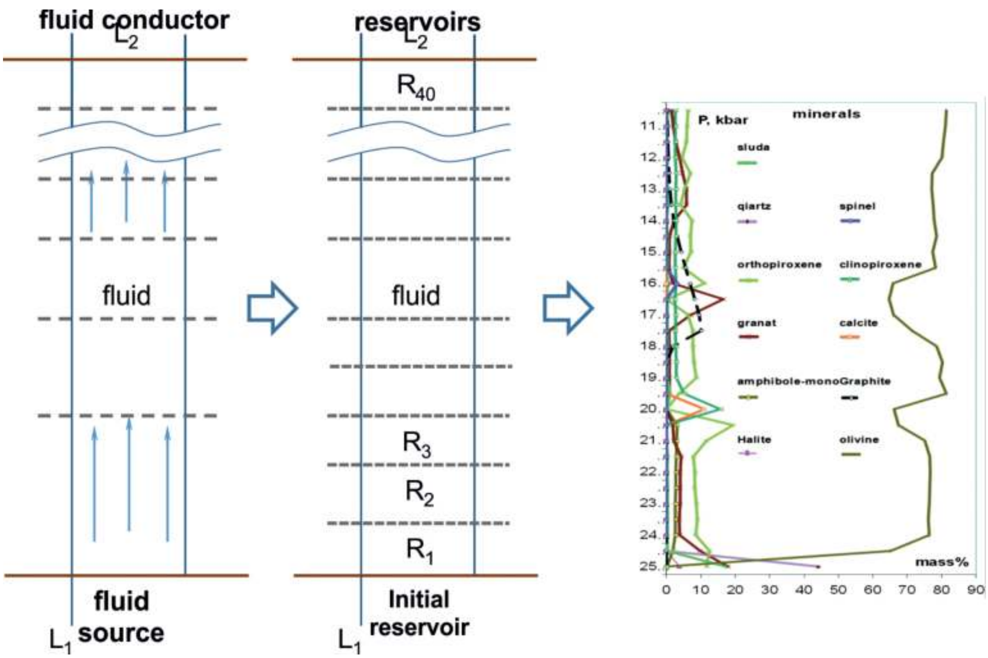

Figure 7. Model of convective heating of lithosphere rocks over a deep chamber of basite magma by the fluid flow over the permeable zone (left), general scheme of a multireservoir thermodynamic model, and distributions of minerals in metasomatic columns (right).

each of the equations and closes with global iterative procedure SIMPLE with recalculation of thermodynamic parameters at each step, takes into account the nonlinearity of the model. All numerical calculations are performed on uniform rectangular grids with a staggered arrangement of nodes. To solve the discrete analogs of differential equations (1–4) obtained by the method of control volume, the following is used: a combination of the direct method of three-point sweep with the iterative method of Gauss-Seidel method of variable directions [50]; direct and iterative methods, optimized to account for the matrix sparsity and implemented in the IMSL and IMKL libraries, used for numerical solution of the system of linear algebraic equations, arising in the calculation of pressure correction [56]. Physical values used in numerical calculations are given in **Tables 1** and **2**, and the problem geometry is shown in **Figure 7**.

5. Numerical modeling of heat exchange dynamics at compacting the heterophase medium

The general structural and geological scheme of mantle-crustal magmatic and local fluid systems under the Avacha group of volcanoes is built on the basis of seismotectonic data; for each of them, the dynamic model of flow-through many-vessel reactor is presented. The physical and chemical analyses of the emergence of substrates, whose convective melting may lead to the formation of carbonatite, basite, and other magmas, are based on the coordinated use of the model of nonstationary nonlinear dynamics of heat and mass transfer in heterophase media and the nonisothermal model of a flow-through many-vessel reactor, describing processes of equilibrium metasomatic transformation of depleted ultrabasic rocks. The problem geometry is shown in **Figure 7**. Pressure in the magma source is taken to be equal to a lithostatic one. Pressure distribution in the field of fluid filtration is set consistently with the distribution of porosity and permeability. According to the study of anisotropy of rocks in the lithosphere [16, 57] and tectonic conditions of formation of volcano-plutonic deposits, one of the main petrophysical characteristics of fluid systems is significant variation in the permeability over the section of the mantle wedge. In the problem, it is assumed that permeability (k_p) and porosity (m_p) decrease with depth (Z = 0–100 km) according to the power law from $k_p\ (Z_0) = 10^{-15}$ m^2, m_p = 2%, or are set piecewise constant for individual layers in the range 10^{-13}–10^{-17} m^2. Temperature over the border of the mantle magmatic source at lithosphere thickness of 100 km changes from T_0 = 1330 to 1100°C.

The results of numerical simulation of convective heat and mass transfer, taken into account when modeling the dynamics of equilibrium infiltration metasomatism, not accompanied by partial or complete melting of some of the zones in the metasomatic column, show that in the quasi-stationary stage of the fluid system evolution, the temperature distribution in the lower part of the conductor is always higher than in the fluid source by tens of degrees. The magnitude of this effect depends on the values of effective permeability. When considering the dynamics of metasomatic processes, it is possible to explore the temperature range, in which melting in some areas of the emerging column is not expected.

We investigated the types of metasomatic columns at fluid temperature variation in magmatic source from 1330 to 1100°C for constant and variable content of petrogenic components and at the following ratio of molar contents of independent components in the source fluid: C (1),

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O (2), H (2), Cl (0.25–0.5), F (0.1–0.25), S (0.01), N (0.01). The variation of molar quantities of petrogenic components in the fluid was consistent with the previously defined area of harzburgites' wehrlitization. The differences in the dynamics of metasomatic zoning development for single- and two-speed models in the fluid systems of the lithospheric mantle come to a much longer duration of the metasomatic zone formation at realized compaction, and to facies differences in the composition and ratios of mineral assemblages, involving pressure increase in the fluid system at compaction of heterophase media. Furthermore, at pressures above 20 kbar for temperatures below 1150°C, the rate of synthesis of clinopyroxene at the same intensity of olivine decomposition is about two times larger than that of orthopyroxene. Thus, in the fluid system at wehrlitization in high temperature zones, the content of orthopyroxene in associations is higher than in the upper part of emerging metasomatic columns. When a quasi-steady-state temperature distribution is not reached, differences in the mineral associations of the metasomatic zones, formed with and without compaction of heterophase media, are minimum. If $T_0 \leq 1300°C$, there are a number of detected mineralogical effects, related to variations of fluid composition in the source: at different ratios of Si/Ca in the fluid debasification of ultrabasites is implemented with the lines of compositions of metasomatites from carbonatite to grospydites; and complete replacement of olivine by orthopyroxene is realized at ≈975°C. At compaction of heterophase medium with $T \geq 1330°C$, an anomalous development of wehrlitization is realized for a range of ratios in the fluid $1 \leq Si/Ca \leq 5$. At abnormal wehrlitization, the content of petrogenic components significantly changes, which is reflected in the mineral composition of zones of a metasomatic column.

Simulating the dynamics of metasomatic transformation of mantle ultrabasites on the basis of the hydrodynamic model of compaction of heterophase media reveals complete dissolution of olivine in the external front of temperature growth in the range 1326–1330°C with the formation of clinopyroxene and carbonate, as well as with the formation of a zone of garnet lherzolites above the column section. In realizing such a " transformation column of originally homogeneous depleted ultrabasic rocks," there may be up to three formed regions of melting of simultaneously existing magma chambers, meeting virtually the entire spectrum of mantle magmatic melts in the "ocean-continent" transition zone in the volcanic arcs of the Pacific Ocean. This allows understanding the reason for the existence of the above-mentioned magma chambers at different depths in areas of SFZ compression.

That is, there may appear three levels of changes in the mineral composition of the initial depleted ultrabasite substrate, where melting zones may show up with the formation of basite liquids. In the lower part of the earth's crust, the heating temperature may reach values that are necessary for melting of granitoid magmas.

6. Applying the obtained results to the description of the isothermal dynamics of metasomatic processes in the mantle wedge at compacting the heterophase medium

Numerical simulation of the equilibrium dynamics of nonisothermal fluid systems beneath the volcanoes of the frontal zone of Kamchatka using single-velocity hydrodynamics in the area of predominance of tensile stresses is considered in [58]. As shown in **Figure 8** in SFZ, in the zones of the meridional shear (at a depth of fluid sources ≥ 100 km for initial temperatures of magmatic fluids 1000 ÷ 1200°C) in metasomatic zoning of altered ultrabasites, there are facies variations in the ratios of minerals of wehrlite rocks [1, 58].

In the mantle wedge of the geodynamic northwestern margin of the Pacific Ocean, over which epicontinental volcanic arcs developed at postmiocene stage, products of asynchronal and multilevel magmatic systems may be combined in the same permeable zones in the "crust-lithospheric mantle" transition area. So, geodynamics of consistently developed types of ore-magmatic systems (from back-arc basin of the Manus type to the formation of the epicontinental volcanic structures of bimodal series) is described in ore deposits of porphyritic formation of one of the Aleutian Islands. Temperature values of the melting centers of the lithospheric mantle in the presence of ultrabasite matrix wehrlitization must be at least 1300°C for this kind of systems [59]. According to the model [25, 36], "cratonization" of the main volcanic sections of the continental earth's crust in such systems, typical for post-Cretaceous geodynamic history of Kamchatka, has to be realized according to the scheme of "metasomatic granitization," the initial element of which is wherlitization of ultrabasic rocks of the mantle wedge. This is why in the framework of the model of compaction in the fluid systems associated with compression and tension areas, we have simulated processes of equilibrium metasomatic

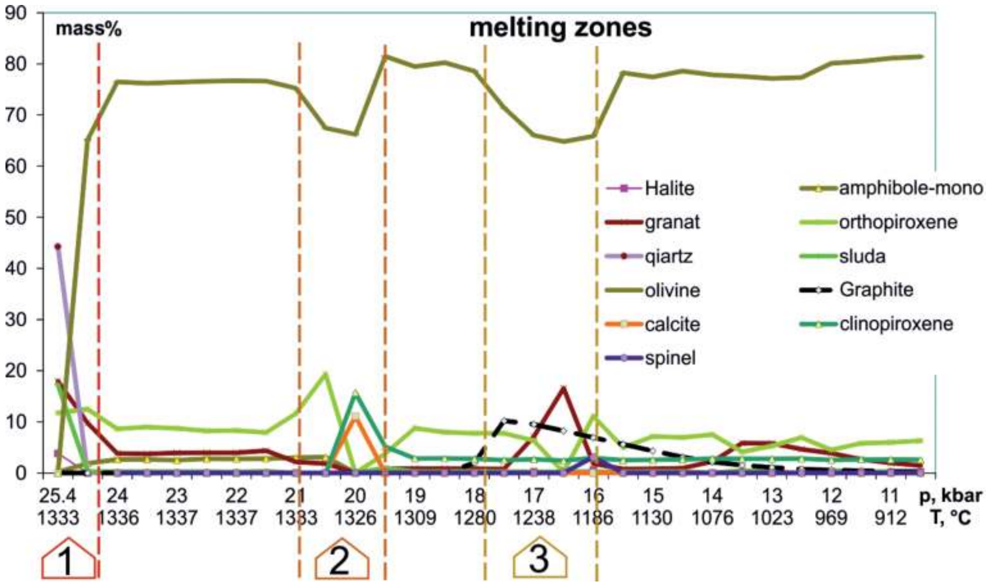

Figure 8. The formation of complex metasomatic columns, which may be the cause of appearance of mantle magma chambers with different levels [59]. (1) Alkaline magma formation area, (2) carbonatite melting area, and (3) basic magma melting area.

debasification of rocks of the mantle wedge, using the approximation of the flow-through many-vessel reactor [60, 1]. The hydrodynamic basis for the numerical description of the dynamics of convective heat and mass transfer in this report are the results given in the previous section.

It should be noted that the value of "thermal effect" obtained in the calculations meets some reasonable assumptions, but cannot be experimentally verified in respect of possible maximum values. However, even the obtained underestimated value of temperature growth of about 30°C leads to a very significant physical and chemical "reactivation" of fluids at the exit of the secondary zone of basification, which results in a fundamental change in the nature of dynamics in the metasomatic column (**Figure 8**). Further in the modeling of volcanic ore-magmatic systems in terms of heat and mass transfer in the zones of active seismicity, we should move from the analysis of steady motion of the melts and gas mixtures over permeable zones in the areas of compression dominance and associated areas of the predominance of tension in the seismic focal zone to solving problems of multispeed dynamics of heterophase media. This also applies to hydrodynamic models of nonisothermal motion of heterophase media in flat [8] and tubular [44] channels. Such hydrodynamic models of mantle-crust magmatic systems should be applied to the areas with predominance of compressive stresses within the continental slope of Kamchatka or under volcanoes of the Southern Kuril Islands [12]. The presence of "asthenospheric layer" under the continental slope of Kamchatka [19, 35], of volcanic linear and arc ridges, and the discharge of submarine thermal systems [15] indicate the necessity of using multivelocity hydrodynamics in the description of the dynamics of ore-forming fluid systems of Kamchatka and Kurile volcanic arc.

7. Conclusion

Hydrodynamics of heat and mass transfer in heterophase systems with and without the account for compaction may vary significantly. In seismically active areas of the lithosphere of the transition zone of PO, the presence of the depth zone with compaction should lead to the emergence of specific conditions of heating over the mantle magmatic sources of fluids. Metasomatic columns in such fluid systems can have at least three possible levels of convective melting of metasomatized substrates of the mantle wedge, and the region of high-temperature "fluid" processing of basite intrusions in the crust. This chapter shows some of the reported effects in the implementation of metasomatic processing of the rocks of the mantle wedge. Some mineralogical primitivity of obtained mineral associations is determined by the insufficiency of the used database of thermodynamic characteristics of minerals in the solid phase (rocks of the lithospheric mantle) for a more complete description of metasomatic processing of the depleted ultrabasites of the mantle wedge. The broadening of this information will allow us to proceed (with diagrams of state of obtained mineralogical associations) to the description of a rather complete picture of the formation of magma chambers in the lithospheric mantle and the related ore-forming systems of PF.

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