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GEOCHEMISTRY

Contact Metamorphism and Metasomatism near the Talnakh Intrusion: Fluid Convection and Heat Transfer Modeling on the Basis of the Finite-Difference Method

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The zonal contact-metamorphic aureoles around intrusions provide insight into the thermal impact of magma on country rocks. In [1–3], the issue of conductive heating of rocks without the participation of fluid was scrutinized. The duration of cooling and temporal temperature distribution versus distance from the contact were estimated. However, in many cases, the conductive heat transfer turns out to be insufficient to form thick complexes of thermally metamorphosed rocks. As was shown for a number of geological and theoretical models, convective heat-and-mass transfer near magmatic bodies is of great importance [3–5]. The country rocks of intrusions in the Noril'sk ore district at the northwestern margin of the Siberian Craton are one such case. In this communication, mathematical modeling is used to describe the heat redistribution and fluid convection in the volcanosedimentary sequence at the contact with the Talnakh ore-bearing intrusion. The objective of this study was to simulate the temperature and hydrodynamic fields that would fit the location of isotherms and isograds, as well as the distribution of metasomatic rocks near the intrusion.

The problem of modeling of heat transfer and convective flows of a two-phase fluid is solved in the 2D setting in the Cartesian coordinate system on the basis of time-dependent equations of nonisothermal hydrodynamics with account of vapor–liquid phase transition. The following assumptions are accepted: (1) the Darcy relationship is fulfilled for two-phase flow; (2) effects of capillary pressure are ignored; (3) all phases, including matrix (solid framework of rock), liquid, and gas, are considered to be in the state of local thermal equilibrium; (4) mechanical reaction of the solid rock framework to the fluid motion is negligibly small; and (5) metasomatic processes are beyond the scope of consideration. The problem boils down to the solution of a system of equations of energy-and-mass balance for convection of two-phase liquid through a porous medium [6]. The state equation of fluid $P = P(T, \rho)$ that controls the interrelation of thermodynamic variables (pressure, temperature, and density) closes the system of equations. The Haar–Gallaher–Kell equation, which describes the properties of pure aqueous fluid within a temperature range of 0–1200°C and a pressure interval of 1–10 kbar, was used in calculations. The computing algorithm is built on the basis of an implicit finite-difference scheme with iterations by the Newton–Raphson method realized in the Hydrotherm software [7, 8].

To solve the problem of convective heat-and-mass transfer near the Talnakh intrusion at the boundary of the Yenisei–Khatanga sedimentary basin at the northwestern margin of the Siberian Craton, we elaborated a geological model of this district. An area at the boundary of the Kharaelakh syncline and Kayerkan–Pyasina anticline is considered. The model vertical section is oriented across the Talnakh intrusive body and the Noril'sk–Kharaelakh fault, which represents the boundary normal fault in the Kharaelakh syncline. The modeled fragment of the basin is limited in depth by the upper 5.5 km of volcanosedimentary cover. The geological structure of the Upper Talnakh intrusion and its framework are shown in Fig. 1 on the basis of the data reported in [9, 10] and simplified for purposes of mathematical modeling. According to the geological and geophysical data, the model section consists of the following rocks (from bottom to top): (1) Devonian carbonate rocks (thickness >1600 m, porosity $n = 0.025$, permeability $k = 2 \cdot 10^{-17}$ m^2, thermal conductivity $\lambda = 2.5$ W/(m · K), and density $\rho = 2850$ kg/m^3 [11]); (2) Middle Carboniferous–Upper Permian coaliferous terrigenous rocks of the Tunguska series (thickness 680 m, $n = 0.07$, $k = 5 \cdot 10^{-15}$ m^2, $\lambda = 1.66$–4.0, $\rho = 2450$), which are country rocks of the Talnakh intrusion ($n = 0.004$; $k = 10^{-18}$ m^2; $\lambda = 3.1$, $\rho = 2650$); and (3) Upper Permian–Middle Triassic volcanic rocks of trap association (thickness 3200 m, $n = 0.03$, $k = 10^{-17}$–$5 \cdot 10^{-15}$ m^2, $\lambda = 3.0$, $\rho = 2750$). The thickness of the tuff and lava

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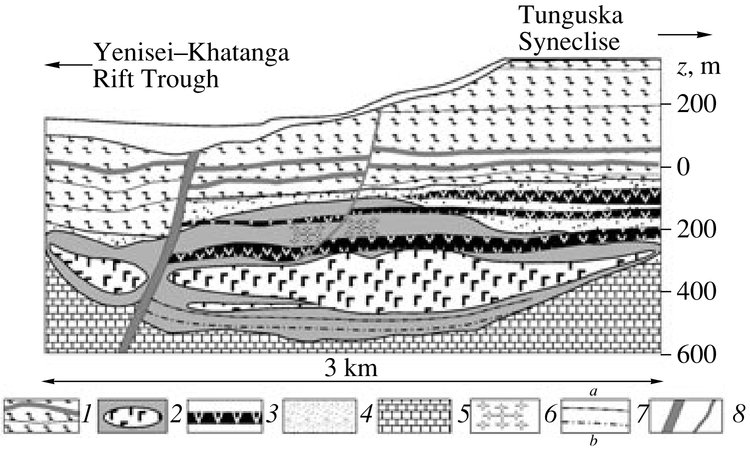

Fig. 1. Contact aureole of the Talnakh intrusion, simplified after [9, 10]. (*1*) Basaltic lavas and tuffs of trap sequence; (*2*) differentiated mafic–ultramafic intrusion and its contact aureole; (*3*) dolerite sill; (*4*) sedimentary rocks of the Tunguska series (sandstone and siltstone transformed into hornfels); (*5*) Devonian carbonate rocks; (*6*) metasomatic zones; (*7*) periclase (*a*) and tremolite (*b*) isograds; (*8*) suture of the Noril'sk Kharaelakh Fault and faults of the second order.

complex (screen) is 500–3800 m [10]. In hydrostatic approximation, this thickness corresponds to the fluid pressure of 0.5–1.0 kbar. The heat capacity of all rocks is accepted to be 1 kJ/(kg · K) except for the crystallizing magma (see below). It is assumed that magma with an initial temperature of 1200°C instantly intrudes in sedimentary rocks of the Tunguska series as a lenticular (in cross section) chonolith-shaped body 2 km wide and 280 m thick. The intrusion is presumably 3500 m deep. According to the geological data, the intrusive body extends parallel to the Noril'sk–Kharaelakh fault. The model assumes that this fault served as a magma conduit [9, 10] and afterward was a zone of increased permeability 60 m wide. Estimates of filtration properties of faults show that the faults range from fluid-conducting to fluid-confining structures. In our case, these properties were estimated from the measured inflows to wells in the fault zone. The porosity and permeability of the fault zone were accepted to be constant ($n = 0.10$ and $k = 10^{-14}$ m^2, respectively). The thermal conductivity and density values were accepted the same as in the rocks crossed by the fault.

We elaborated several versions of the model, beginning from the simplest basic model, which was complicated at each subsequent step by the addition of different factors in the following sequence: (i) model with uniform permeability of country rocks; (ii) model of low-permeable trap complex (confining bed); (iii) model taking into account the latent heat of magma crystallization; (iv) model with a vertical fault that crosscuts and bounds the intrusion; and (v) model with magmatic fluid that releases during magma crystallization or ascends along a permeable fault zone. The geometry of the problem and its boundary conditions are shown in Fig. 2.

The modeling results forecast the development of metamorphic and metasomatic zoning in a wide range of parameters. Permeability of rocks, composition of fluid, and depth of magma emplacement are the major parameters. The thermal conductivity, heat capacity (except the model of magma crystallization), and initial magma temperature remained unchanged.

The location of isotherms (isograds) is an obvious characteristic of the thermal impact of intrusion on country rocks. We can compare the position of periclase and tremolite isograds recorded by the first appearance of these minerals with calculated isotherms. According to experimental data on the CaO–MgO–SiO_2–CO_2–H_2O system, the temperature of the mineral equilibrium 5 talc + 6 calcite + 4 quartz = 3 tremolite + $6CO_2$ + $2H_2O$ as a function of $P_{H_2O + CO_2}$ is 400–520°C at 1 bar and 330–420°C at 0.5 kbar [12]. The equilibrium 5 dolomite + 8 quartz + H_2O = tremolite + 3 calcite + $7CO_2$ is achieved at 300–450°C at $P_{H_2O + CO_2}$ = 0.50–0.75 kbar [12, 13]. Dolomite is decomposed with the formation of periclase, calcite, and CO_2 at a temperature no lower than 570–620°C at $P = 0.5$ and 1 kbar. In this process, the mole fraction of CO_2 in a fluid should be <0.05 [14]. The thickness of metamorphosed rocks at the upper and lower contacts of intrusion is variable and averages 25–90 m at the roof and 13–30 m at the base. The thickness of metasomatic rocks reaches 150–200 m (40–60 m, on average) above the upper contact and is not greater than 30–45 m below the lower contact depending on the thickness of the intrusive body and/or occurrence of faults. According to [9], the periclase isograd is recorded at a distance of 7–10 to 50 m from the contact of the Upper Talnakh intrusion, while the tremolite isograd is traced at a distance of 40–75 m from the contact (Fig. 1). These data serve as a criterion for testing the models and may be used for estimation of the fluid composition and lithostatic pressure (depth) of magma emplacement.

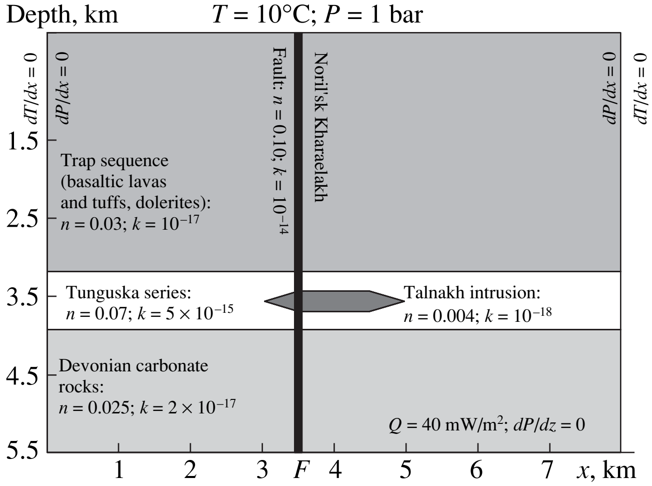

Fig. 2. Model region, boundary conditions, and properties of rocks in the mathematic model. Porosity (*n*) and permeability (*k*) of sedimentary rocks, intrusion, and permeable zone ($k = 10^{-n}$ corresponds to 10^{-n} m^2). *Q, T, P,* and *F* designate heat flow, temperature, pressure, and fluid flow, respectively.

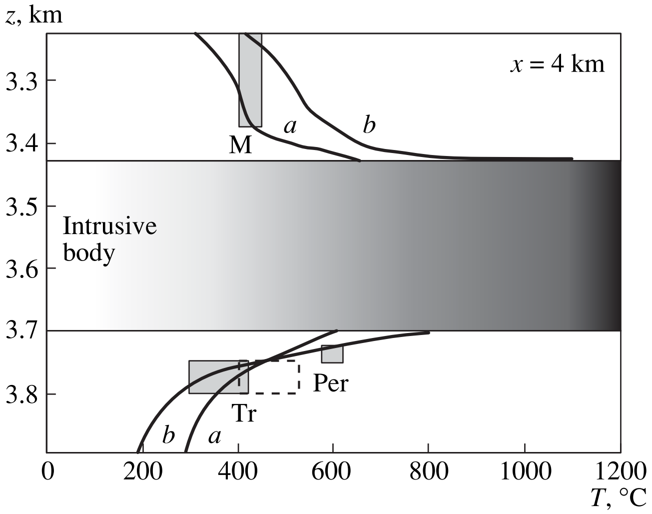

Fig. 3. Maximal temperatures at the contact of intrusion with country rocks. Vertical sections are drawn across the central part of the intrusion. Model *a* does not, but model *b* does account for the latent heat of magma crystallization (200 kJ/kg) within a temperature range of 1200–1100°C at the thermal conductivity of country rocks equal to 4.0 and 1.66 W/(m · K), respectively. The intrusion is shaded. Boxes indicate the temperature at P = 0.5 kbar and location of tremolite (Tr) and periclase (Per) isograds and temperature of metasomatic alteration (M) taking the uncertain composition of the fluid into account. The box made by dashed line indicates the appearance of tremolite at P = 1 kbar.

Figure 3 shows the distribution of the maximal temperature in the section for different models. The maximal temperatures for different times are drawn as enveloping curves. As follows from calculations, the temperature reaches 600–800°C at the lower contact and 650–1100°C at the upper contact. Curves *a* in Fig. 3 correspond to the basic model without taking the latent heat of crystallization of ultramafic magma into account. In both versions, the heat is transferred more efficiently across the upper contact. The highest contact temperature was obtained in the model that makes allowance for the latent heat of crystallization (Fig. 3, curves *b*). The heat of crystallization was taken into account by setting the variable heat capacity. In a temperature range of 1000–1200°C (interval of crystallization), the heat capacity was set as 2 kJ/(kg · K), i.e., two times higher than the nominal value [2, 7]. In the model accounting for the heat of crystallization at a lower thermal conductivity of country rocks, the temperature near the contact exceeds 570°C in agreement with the position of the periclase isograd. At a greater distance from the contact, the temperature falls more rapidly and the shape of the curve of maximal temperature is in poor agreement with the suggested position of the tremolite isograd. The effect of latent heat of crystallization raises temperature at the upper contact by 100–150°C. Another shape of curves for the lower contact is accounted for by the difference in the thermal conductivity of country rocks: 4.0 and 1.66 W/(m · K) for versions *a* and *b*, respectively (Fig. 3).

Metasomatic rocks are distributed nonuniformly at contacts of intrusive bodies of the Noril'sk–Talnakh type [9]. The same pattern is observed in the 2D modeling that demonstrates a cellular structure of fluid convection and nonuniform temperature field. To simulate the conditions that produce metasomatically altered rocks, the problem of convective heat transfer with sources of heat and fluid was solved. We considered three models with different fluid sources: (i) the basic model with formation water as a source; (ii) model with account for magma crystallization (volatile components dissolved in magma); and (iii) model of a deep magma chamber (not shown in the figure), where the fluid ascends along the fracture zone (fault). The modeling results are shown in Figs. 4a–4c as distribution of isotherms and vector field of filtration velocity at selected times.

In the *first model*, highly permeable fault zones are absent. Effects of supplementary heat sources related to the magma crystallization and the release of dissolved volatile components are eliminated. As follows from the calculations, the efficiency of heat transfer depends on the permeability of country rocks pertaining to the Tunguska series and the trap igneous complex. The results of downhole measurements of filtration coefficients recalculated to permeability are $4.87 \cdot 10^{-15}$ – $7.2 \cdot 10^{-13}$ m^2 for terrigenous rocks and $6.9 \cdot 10^{-16}$ – $4.64 \cdot 10^{-14}$ m^2 for the volcanic complex. The modeling permeability ($5 \cdot 10^{-15}$ and 10^{-17} m^2, respectively) is somewhat underestimated relative to the real values in order to reduce the efficiency of convective heat transfer.

Tests with uniform/nonuniform permeability have shown that the heat transfer is nonuniform in various places near the intrusion. Convective flows above the intrusion considerably disturb the temperature field. The localized ascending fluid flows make up hydrothermal "protuberances." They arise above inhomogeneities of the contact with country rocks, in particular, at bends of the roof. Beneath the intrusions, the isotherms are conformal to the contact, thus indicating that heat conduction is predominant [3]. The permeability of the overlying tuff and lava cover varied in models from 10^{-17} to $5 \cdot 10^{-15}$. Figure 4 demonstrates the modeling results when permeability of rocks above the intrusion is constant and equals $5 \cdot 10^{-15}$ m^2. An ascending flow is formed, and the arising plume penetrates the tuff–lava sequence. If the permeability of volcanic rocks is low (no higher than 10^{-17} m^2), the thermal anomaly is limited by the terrigenous rocks of the Tunguska series.

The *second model* makes allowance for a permeable zone that crosscuts the intrusion, the release of volatile components, and the thermal effect of magma crystallization. It was accepted that magma solidifies at 1000–1200°C. The latent heat of phase transition was taken into account by setting the doubled heat capacity. The permeability of rocks within a fracture zone was assumed to be 1.5 order higher than in the adjacent rocks. According to the modeling results, the magma chamber that corresponds to the Talnakh intrusion in volume crystallized over 300 yr. The temperature field and fluid flows are formed in the course of convection and under the influence of the permeable zone. The results of modeling are shown in Fig. 4b for 100 yr after magma emplacement. The melt is retained in the central portion of the intrusion limited by isotherm of 1000°C. The heat advection along the fracture zone produces an anomaly (>400–450°C, 300–500 m wide) above the intrusion. Thus, the region of elevated temperature is 5–8 times wider than the permeable zone.

In the *third version* of the model, the fluid with an inflow temperature of 500°C and discharge F = 0.6 m^3/(m$^2 \cdot$ yr) [13] is transported along the permeable zone from the inferred underlying magma chamber, which is located at a depth of 12–15 km and has a thickness of 4.5 km. These parameters are consistent with results of 3D modeling based on the data of aeromagnetic survey [15]. Figure 4c illustrates the postmagmatic stage of the formation of the hydrothermal system after the complete cooling of the intrusion. When ascending along the conduit, the juvenile fluid mixes with formation water of sedimentary rocks near the intrusion. The ascent of fluid along the fracture zone creates a hydrothermal anomaly with a temperature of 370–380°C. Above the intrusion, the mixed fluid dis-

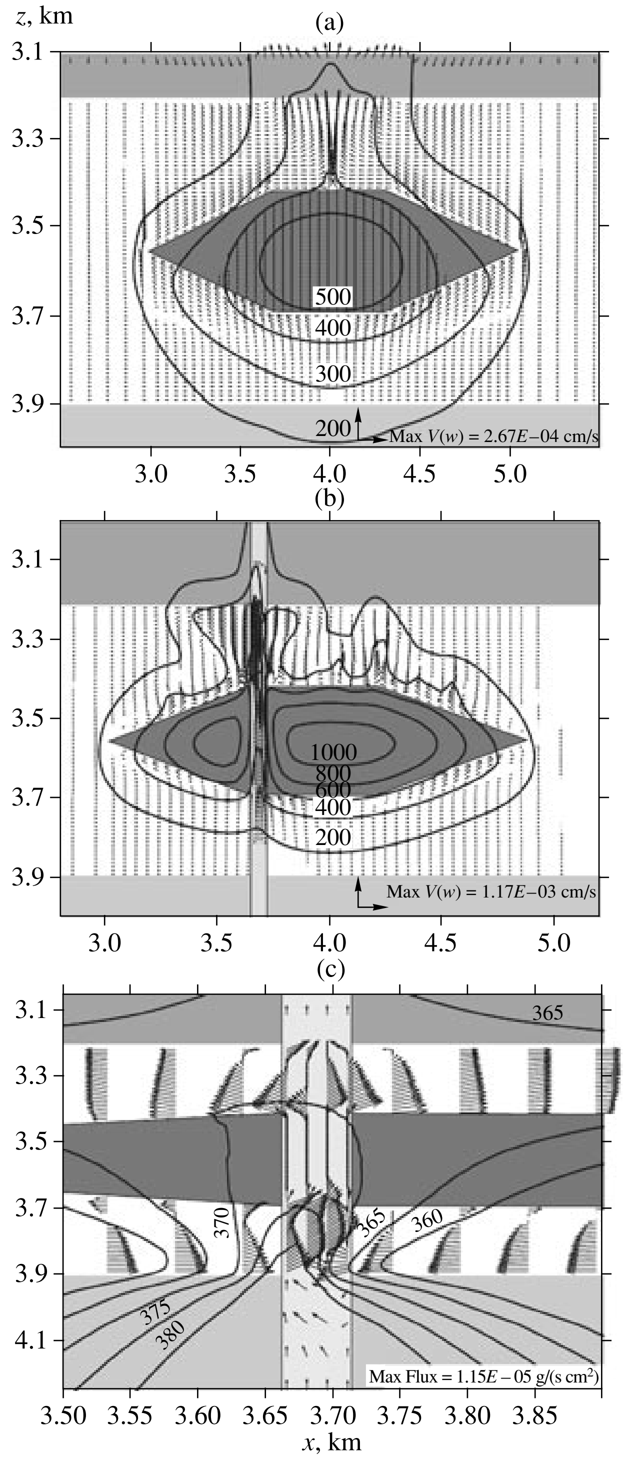

Fig. 4. Temperature fields and convective fluid flows for different versions of modeling. Numerals at curves (isotherms) denote temperature, °C. The scale of filtration velocity (cm/s) is shown in each panel. The dark lens is the intrusive body at initial temperature of 1200°C. The dark gray pattern denotes rocks of the trap lava–tuff complex; no fill pattern, rocks of the Tunguska series; and light gray pattern, Devonian carbonate rocks (see Fig. 2). (a) Model with uniform permeability, 500 yr after the intrusion; (b) model with a vertical permeable conduit, temperature, and filtration velocity of fluid, 100 yr after the intrusion; the section is drawn across the central part of the lenticular intrusive body crossed by a fault; (c) closeup of the model with a fluid flow ascending along a permeable zone (vertical box); the postmagmatic stage of intrusion cooling 200 ka after the emplacement of magma (dark gray). The scale of fluid flow is $1.15 \cdot 10^{-5}$ g/(c $\cdot$ cm^2).

charges into the country rocks and ascends further toward the surface. The hydrodynamic anomaly is accompanied by a temperature anomaly (360–380°C) produced by convection around the low-permeable intrusive body. A slight asymmetry of the thermal anomaly relative to the fault axis is caused by pinching out of the intrusive lens. As the modeling results show, metasomatic zoning may arise at the postmagmatic stage within a zone 150–200 m thick above the intrusion and no more than 30–40 m thick below the lower contact.

CONCLUSIONS

Patterns of fluid flow in the hydrothermal system with a permeable vertical zone that crosscuts the intrusion were obtained through a numerical modeling. The suggested mechanism of mixing of magmatic fluid with formation water may be efficient only at sufficiently high permeability of the rocks. The zones of increased permeability in the Noril'sk ore district were formed either as a result of tectonic deformation or mineral transformation. According to the thermodynamic calculations [13], the decarbonation reaction has a large negative volumetric effect (–16.16 cm^3/mol) and may be responsible for the higher porosity of carbonate rocks in the contact zone and thus lead to the growth of permeability at the prograde stage. The modeling results are confirmed by the real arrangement of isograds. To estimate the metasomatic alteration in quantitative terms, it is necessary to examine the thermochemical convection of fluid with variable properties and composition.

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