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Simulation of the Geochemical Structure of the Ioko-Dovyren Layered Intrusion, Northwestern Baikal Area

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Abstract—The processes of differentiation in the magmatic chamber of the Ioko-Dovyren layered dunite–troctolite–gabbro–gabbronorite massif were simulated using the COMAGMAT-3.5 software package, which is based on the convection–accumulation model for the crystallization of magmatic intrusions. The initial magma composition was assumed to be equal to the weighted mean composition of the rocks composing the intrusion (wt %: 43.92 SiO_2, 9.72 Al_2O_3, 10.53 FeO, 27.88 MgO, 6.99 CaO, 0.59 Na_2O, 0.07 K_2O, and 0.11 TiO_2). The results obtained by simulating the crystallization of this composition within a pressure range of 0–10 kbar indicate that the crystallization sequence determined for the rocks $Ol + Chr \longrightarrow Ol + Pl + Chr \longrightarrow Ol + Pl + CPx \longrightarrow \pm Ol + Pl + CPx + LowCaPx$ in an anhydrous system takes place under pressures of 0–2 kbar. A series of simulations for a system closed with respect to oxygen yielded estimates for the phase and chemical composition of the emplaced magma and the parameters of the optimum model, which reproduces accurately enough the geochemical structure of the Ioko-Dovyren intrusion: the naturally occurring distributions of minerals and components in its vertical section. The correlation coefficients between the concentrations of oxides determined in the rocks and calculated within the model are $r_{\mathrm{MgO,\,Al_2O_3,\,CaO}} \geq 0.9$ and $r_{\mathrm{FeO,\,SiO_2,\,Na_2O}} \geq 0.6$. The simulated phase composition of the magma during its emplacement corresponded to melt + olivine (Fo_{89}). The crystallinity of the parental magma was determined to have been equal to approximately 40 vol % at an assumed cumulus density of 90% near the lower contact and 70% near the upper one. The temperature of the magma during its emplacement was close to 1340°C at a pressure of 1 kbar. In the model, plagioclase and clinopyroxene appear on the liquidus at $T \cong 1255$°C at $T \cong 1210$°C, respectively, and the crystallization sequence of cumulus minerals corresponds to that observed in nature. The liquid phase (melt) of the parental magma during its emplacement had the following composition (wt %): 45.95 SiO_2, 15.93 Al_2O_3, 14.49 MgO, 10.88 FeO, 11.46 CaO, 0.97 Na_2O, 0.11 K_2O, and 0.18 TiO_2. Our results confirm the plausibility of the hypothesis that the inner structure of the Ioko-Dovyren intrusion was formed by the emplacement and differentiation of a single magma portion with no less than 40 vol % crystallinity.

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INTRODUCTION

The interpretation of the inner structure and mechanisms that formed layered intrusions is one of the most interesting and extensively studied petrological problems because it is directly related to the problems of magmatic evolution and the reasons for the diversity of magmatic rocks. The concepts invoked to explain the modal and compositional layering of intrusive bodies of basic and ultrabasic rocks included the emplacement of already layered magma, gravitational diffusion, magmatic replacement, liquid immiscibility of silicate melts, multiple melt injections, various variants of crystallization differentiation, etc. The exhaustive comparison of these hypotheses and the identification of the most plausible of them requires detailed physicochemical analysis, development of quantitative models, and their verification. These models should be able to reproduce principal relations in the structure of layered massifs, such as (1) the chemical diversity of their rocks, which is determined by the compositions of the solid phases and coexisting melts depending on temperature, pressure, and degree of fractionation; and (2) the spatial relations between discrete structural elements, which were controlled by the dynamics of the process. The distinguishing of these structural units includes the identification of the layered series and the upper and lower contact zones, in which the compositional evolution of the rocks was opposite to that in the layered series, the strong structural asymmetry, which is expressed in the pervasive succession of rock-forming mineral assemblages in the rocks from high-temperature ones in the bottom portion of the intrusion to low-temperature ones near its roof [1–4]. The simulation of processes forming layered basic–ultrabasic intrusions provides important information for the testing of hypotheses concerning the character of the magmatic evolution, the genesis of various magmatic rocks, and the differentiation mechanisms that resulted in the spatial geochemical structure of these bodies. These simulations make it possible to establish relations between ore-generating processes and the solidification mechanism of the intrusion.

The hypothesis that the origin of layered complexes is largely controlled by the mechanisms of crystallization differentiation is now one of the most thoroughly developed concepts. It was further modified in the form of the convection–accumulation model of differentiation in a magmatic chamber, which was developed in the 1980s by researchers from the Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, and the Department of Geochemistry at Moscow State University [4–6], and the COMAGMAT program complex [7–10], which is based on the principles of this model and enables the researcher to numerically model the processes of the cooling and chemical differentiation of basic magmas, including naturally occurring intrusive bodies. The program includes a routine for solving problems related to the crystallization of a basaltic magma layer with regard for the gravitational redistribution of phases and convective heat and mass transfer. The model simulates the principal characteristic parameters of layered intrusions: quantitative relations in the variations of the chemical composition of the rocks composing the intrusion, which are expressed as systematic variations in the assemblages of rock-forming minerals and the chemistries of these minerals, as well as the variations in the distributions of elements and minerals in the vertical section of the layered complexes. This information can be obtained in the course of the geological study of natural magmatic bodies, and hence, the consistency (within the accuracies of the employed methods) of the simulation results and natural observations serves as a convincing argument for the plausibility of the model. The model was previously verified in application to the flood basalts of the Siberian Platform [6, 4] and the Burakovskii and Kivakka intrusions in Karelia [11].

When simulating magmatic systems, the researcher may face two aspects of the problem: thermodynamic and dynamic. The thermodynamic aspect is related to the analysis of the driving forces of melt evolution: it is necessary to determine what kind of a physicochemical system should magma have been to enable the modeled processes to occur in it (for example, the mechanism of the crystallization differentiating of the material) and what the characteristics were of the system (pressure, modal and chemical composition, etc.). This enables the researcher to identify the crystallization sequences of mineral phases and the possible rock associations. The dynamic aspect involves the analysis of the mechanisms of magma evolution, i.e., a search for the means of the operation of a given differentiation mechanism in the space of the system. The analysis of the heat and mass transfer in space and time leads to the development of a model reproducing the spatial relations of the rocks.

Significant progress in petrological research was achieved with the development of a model for the crystallization of basaltic magmas. This model made it possible to calculate the chemical and modal composition and variations in the phase proportions during fractional and equilibrium crystallization in natural systems as functions of temperature and pressure [12–20]. Solving the thermodynamic part of the problem, these models could not directly reproduce the processes forming the geochemical structure of the magmatic bodies because they did not involve the description of the differentiation dynamics. In spite of its certain limitations (see below), an advantage of the COMAGMAT model was its systematic character, which combines the thermodynamic description of phase equilibria with the simulation (although fairly primitive) of the heat transfer dynamics in the magmatic chamber.

Attempts to include mass transfer dynamics in the mathematical description of the evolution of magmatic systems were undertaken by Golubev and Sharapov [21, 22] first in the form of analytical and then numerical models. To calculate mass transfer, the formulation of the models was appended only with the mathematical description of the diffusion-controlled transport of some components. However, the framework of the analytical solutions of the problem significantly constrained the spectrum of models potentially interesting for the description of natural petrological processes.

An important step toward understanding the dynamics of magmatic evolution was the elucidation of conditions favorable for the onset of convection in a magmatic chamber. Shimazu [23, 24], Vinogradov and Yaroshevskii [25], Kadik and Khitarov [26], and, later, Bartlett [27], Irvine [28], McBirney [29], Trubitsyn and Kharybin [30, 31], and other researchers have demonstrated that convection should inevitably develop in large magmatic chambers. Convection regimes were thought to be responsible for the origin of cyclic layering [32, 33]. Difficulties arising when these simple models were correlated with the actual inner structures of natural cyclically layered magmatic bodies led to the complication of the models with the involvement of the concepts that crystallization fronts should be associated with fronts of concentration—thermal convection developing within the double diffusion layer. This interesting model was developed and discussed in numerous experimental and theoretical works [34–41 and others]. However, practically none of these models enabled the researcher to immediately reproduce empirical relations observed in the spatial structure of layered complexes.

Another disputable issue is still the mechanisms of crystal nucleation in a magmatic chamber (homogeneous or heterogeneous nucleation). In application to the genesis of layered intrusions, the mechanism of heterogeneous nucleation implies nucleation near the bottom and walls of the chamber and the formation of rocks via the directed crystallization of the melt starting from its lowermost portions and shitting toward the chamber roof, without any significant contribution of the redistribution of the solid phases [42, 28, 43–45]. Later variants of this hypotheses allow for the occurrence of a boundary heterogeneous layer between the crystallizing rocks and melt that is devoid of crystals and forms the rocks [3, 46–48, and others]. It should be mentioned that the mechanism controlling the chemical evolution of melt in this situation is the diffusion-mediated transport of components between the front of complete solidification and the main volume of convecting melt, and this alone already points to the very limited potential of the crystallization evolution of magma in this situation. With reference to any scheme of directed crystallization, this was first understood by Bowen [49] and quantitatively demonstrated by Frenkel' and Yaroshevskii [50].

The hypothesis of homogeneous nucleation maintains that crystals nucleate in melt in the chamber volume and settle from the convecting (or, as in the earlier variants of the hypothesis, from pooled) magma. Campbell [43] noted that the degree of undercooling needed for homogeneous nucleation should be much greater than that required for heterogeneous nucleation, because the activation energy of homogeneous nucleation is much higher than that of the heterogeneous process. This conclusion was later confirmed by experiments conducted by Martin [51] with aqueous solutions of potassium nitrate that were cooled from above. These experiments have demonstrated that the process of crystallization is heterogeneous at the bottom of the vessel if the cooling rate is low (the degree of undercooling is also insignificant) or simultaneously heterogeneous and homogeneous at high cooling rates (i.e., high degrees of oversaturation). Moreover, the probability of homogeneous nucleation increases with increasing viscosity of the liquid.

The possibility of differentiation as a result of redistribution of crystals homogeneously nucleating near the roof was questioned. For example, according to Marsh [52], crystals nucleating near the roof due to magma cooling at the upper contact cannot settle and should dissolve because of the high temperature of the magma, and hence, differentiation cannot proceed via this mechanism. In fact, Marsh repeated the arguments put forth by Niggli [53] against the universal applicability of Bowen's concept of crystallization differentiation. However, as was demonstrated by Frenkel' and Yaroshevskii [54], this argument is not valid because crystal settling in a superheated melt leads to the rapid cooling of the whole melt volume (because of heat sink during the melting of these crystals) to the liquidus temperature. This is, however, at the sacrifice of the first crystals and the lower velocity of the frontal boundary of the cloud of sinking crystals as compared to the sinking velocity of single crystals because the sinking velocity of the front of crystals is limited by heat balance.

Neither is the sinking of crystals hampered by the convective stirring of the melt. In contrast to artificial systems in which convection of any intensity can be induced by an external source of energy (for example, when the liquid and crystals are placed into an agitator), no such situation can take place in nature. There are two possible reasons that can lead to the density inversion of the boundary melt layer and bring about convective motions in a magma mass from which heat sinks into the roof rocks: the cooling of the melt, a process that can result in free thermal convection, and the origin of suspended solid phase in the melt, which should cause so-called sedimentation convection. In our earlier publications [55, 4, 56, see also 57, 30, 31, 58], it was demonstrated that convection instability due to the accumulation of suspended crystals is a much more efficient driving force of motions in the magmatic mass, which can suppress (if induced) free thermal convection (for this reason, for example, Bartlett's model [27] is inapplicable to processes occurring in natural crystallizing magmatic systems, and its petrological implications are thus invalid). Thereby convective motions themselves do not hamper crystal sedimentation [59]. In fact, Wager [32, 1] and Hess [33] were the first to point out the role of this (sedimentation) convection in the formation of layered magmatic complexes.

However complicated and disputable the processes of homogeneous or heterogeneous crystal nucleation and the problems of the origin and spatial structure of convective motions in solidifying magmatic masses are, it is clear that the sinking of crystals formed near the roof of a magmatic chamber (or buoyantly ascending, if their density is lower than the density of the melt) can explain mass transfer sufficient for the development of profoundly layered magmatic complexes. Because of this, the convection–accumulation model of the crystallization differentiation dynamics of magma is now the only physically consistent model that can be employed to develop a general physicochemical theory for the dynamics of magmatic processes and providing insight, for example, into the mechanisms responsible for the origin of magmatic layering. Accurate solutions of these problems require the comparison of the simulation results with relations observed in the inner structures of naturally occurring layered complexes. A contribution to the solution of these problems is our simulations of magma differentiation in the chamber of the Ioko-Dovyren differentiated complex and the genesis of the spatial geochemical structure of this layered intrusion.

GENERAL PRINCIPLES AND CONSTRAINTS OF THE CONVECTION–ACCUMULATION MODEL

The modeled system is a horizontal layer of polycomponet magma, which approximates the chamber of a tabular intrusion that was initially filled with compositionally homogeneous magma with temperatures equal throughout its volume. Upon its emplacement, the magma starts to cool because of the difference between its temperature and that of the host rocks, and cooling triggers its crystallization. Single crystals (and/or mixtures of crystals and melt) produced thereby settle or buoyantly ascend depending on the relative densities of the solid and liquid phases and form crystalline mass (mush) at the chamber bottom. The mush consists of a framework of solid phases and residual melt in between.

A detailed mathematical description of the model, its algorithm, and simulation principles can be found in [7, 4, 56, 10], and below we present only general characteristics of the model and its major postulates and constraints. The convection–accumulation model assumes the homogeneous nucleation of crystals in response to heat losses through the roof of the intrusion within a thin magmatic layer near the upper boundary of the chamber. The elevated density of this suspension of crystals and melt compared to the density of the magma in the underlying portion of the chamber induces active convection, which does not, however, hamper crystal settling and the development of cumulus rocks at the chamber bottom. Solid phases appearing near the lower boundary of the solidifying magmatic mass are not involved in the spatial redistribution and thus do not contribute to the chemical evolution of the melt.

Any rock of the intrusion can be represented as a combination of certain volumetric fractions of cumulus (F_{cum}) and intercumulus ($1 - F_{\text{cum}}$), which are understood as the melt that was in equilibrium with the settled crystals of minerals and solidified *in situ*. In contrast to the process of ideal crystallization differentiation, melt is not completely separated from the forming crystals, i.e., contains a certain amount of the suspended phase, whose amount is the smaller, the greater the chamber volume and the lower its cooling rate (thus providing sufficient time for crystals to settle). The mechanism of ideal fractionation acts in the model at high settling rates of crystals.

The simulation technique utilized in the algorithm of the COMAGMAT program generates the modal composition of the system and the compositions of all phases occurring on the liquidus. After magma emplacement, the chamber is regarded as a closed system, and the host rock suffer only diffusion-controlled heat (but not mass) transfer. It is postulated that a material flux occurs in the system in the form of the free motions of suspended crystals simultaneous with the convection of the melt. It is also assumed that heat transfer in the chamber is both conductive and convective, and the mass transfer is only convective (the settling of crystals and the motions of the suspension as a whole). Thus, heat and material fluxes through an arbitrarily chosen surface oriented perpendicular to the transfer direction have two components: conductive and convective (sedimentation). This convective mass transfer of crystals relative to the melt is the only acting differentiation mechanism able to reproduce the observed spatial geochemical structure of the intrusion and its chemical and modal layering. It is thereby assumed that the high intensity of convection ensures the homogeneity of the magma throughout the whole chamber volume (from its roof to the cumulus surface) in terms of composition, temperature, and the content of the suspended solid phase at each crystallization step. It is also thought that the cumulus framework is excluded from convective motions after the solid phase reaches a certain limiting concentration in this cumulus. After this cumulus evolves (solidifies) as a closed system.

The model consists of dynamic and thermodynamic parts. The *dynamic part* of the simulation problem, which accounts for the movements of crystals in the gravity field, is devised to trace the variations in the following characteristics with time:

(1) the velocities of the crystallization fronts during their shifts from the upper to lower boundaries of the intrusion;

(2) the appearance rates of solid phases in the volume of the convecting melt;

(3) the supply rates of solid phases suspended in the melt to cumulus; and

(4) the velocity of the upper boundary of cumulus in the lower part of the magmatic chamber.

These parameters are calculated during each crystallization step. The region of the convective stirring of melt with suspended crystals is believed to be constrained between the lower boundary of the upper sticking zone and the upper cumulus boundary.

The state of the system as a whole at any moment of time is completely determined by the initial and boundary conditions. The boundary conditions are specified by the heat fluxes through the upper and lower boundaries of the convecting melt layer. The assumed initial conditions are as follows:

* the thickness of the intrusive magma layer;

* the composition of the emplaced magma (bulk concentrations of components);

* the difference between the temperatures of the magma and host rocks;

* the initial position of the boundaries of the convecting layer, which are assumed to be the upper and lower boundaries of the intrusion; and

* the content of the intratelluric solid phase suspended in the intrusive melt.

It is also believed that the composition and thermal characteristics of the emplaced magma are homogeneous. Knowing these parameters, it is possible to calculate all other values describing the differentiation dynamics of magma. Inasmuch as data needed for the simulations include parameters found via the variation optimizing of the results within physically permissible ranges of their values (these fitting parameters are the modal composition of the emplaced magma, which determines its initial heat content and temperature, the effective sinking velocities of the solid phases, and the porosity of the cumulus), this model is semiempirical.

The *thermodynamic part* of the convection–accumulation model is designed for the calculation of the trajectories of equilibrium or fractional crystallization of melt. It determines the proportions of the liquidus phases, their compositions, and equilibrium temperatures as functions of the degrees of fractionation at each crystallization step. The degree of fractionation is, in turn, uniquely determined by the heat lost from the magmatic system per time unit.

The COMAGMAT computer program based on this model makes use of a number of geothermometers (temperature functions of the equilibrium constants of reactions forming mineral solid solutions from melt components) as an empirical approximation of the system of equations for equilibrium between the melt and rock-forming minerals. This structure of the algorithm makes it possible to use the results of quenching experiments with mineral equilibria in basaltic melts and their synthetic analogues at various temperatures and pressures as the thermodynamic basis.

The computational routines in the solution of thermodynamic equilibria involve the minimization of the free energy, when the phases of the equilibrium association are selected. The simulations are conducted in the multiphase polycomponet system SiO_2–TiO_2–Al_2O_3–FeO–MnO–MgO–CaO–Na_2O–K_2O–P_2O_5–trace components, which is described by the following set of geothermometers: olivine–melt, plagioclase–melt, augite–melt, pigeonite–melt, orthopyroxene–melt, magnetite–melt, and ilmenite–melt [10, 60]. The distribution of trace elements between phases is specified by distribution coefficients. With regard for the potential of the modern experimental basis, the main geothermometers are regarded as rigorously specified parameters, whereas the distribution coefficients of trace elements are assumed to be variable within ranges permitted by isomorphism laws and the uncertainties of the experimental data.

The numerical values of the initial conditions (the chemical composition of the emplaced initial magma, the thickness of the intrusion, and the temperatures difference between the emplaced magma and host rocks) are specified based on geological observations. The values of the physical and physicochemical parameters of the model (the heat capacities and densities of phases, heat conductivity, melting heats of minerals, and the density and viscosity of the melt) are assumed based on experimental data. The parameters of the model determined in the process of calculations are, first, the fluxes of solid phases crystallizing near the roof of the intrusion (which are determined by the rate of heat sink and phase proportions on the liquidus of the system) and, second, the crystallinity of the emplaced magma (the fraction of the intratelluric phase F_{int}), the maximum possible porosity of the cumulus $1 - F_{max}$, and relations between the solid phase fluxes into the magma during its cooling and crystallization and from the magma into cumulus as a consequence of crystal settling (these are determined by means of selecting solution variants within the physically permissible ranges of values). Other optimization parameters are the pressure, H_2O concentration in the melt, and O_2 fugacity. The criteria of the necessary and sufficient consistency between the model and naturally occurring magmatic body are as follows:

(1) reproduction of the qualitative characteristics of the intrusion (the crystallization sequence, which determines the order in which cumulus phases appear in the vertical section of the intrusion);

(2) consistency of the quantitative characteristics of the modeled and naturally occurring intrusions (proportions of cumulus minerals, levels at which various mineral assemblages appear, thicknesses of zones containing these assemblages, and the distributions of components in the vertical section of the intrusion). The simulations are conducted in the following succession: first, the reproduction of the qualitative characteristics of a given natural intrusion and, then, the variation optimization of its characteristics.

INNER STRUCTURE OF THE IOKO-DOVYREN INTRUSION

The Ioko-Dovyren Massif is a thoroughly examined intrusion [61–70 and others]. Morphologically, it is a lens-shaped body up to 3.5 km thick and approximately 26 km long, which almost conformably rests in Late Proterozoic carbonate–terrigenous rocks (Fig. 1). Tectonic motions have exposed the massif from its roof to bottom, which makes it convenient for petrological examination and modeling.

The geochemical structure of the massif was studied based on materials (369 samples) collected in the course of sampling of the massif along three profiles across the trends of its rocks. The geochemical structure of the massif was described in much detail in our earlier paper [71]. The body is made up of intercalating dunites, plagiodunites, troctolites, olivine gabbro, olivine gabbronorites, quartz-bearing gabbronorites with rare wehrlites and anorthosites occasionally occurring at various levels in the layered series. The latter contains a number of units with low-sulfide PGE ore mineralization [70]. The rocks were determined to contain mineral associations of structural group I (assemblages of cumulus minerals), which were used to distinguish the following zones of predominant cumulus assemblages: dunite, troctolite, olivine gabbro, gabbronorite, as well as lower and upper contact zones. This rock succession is complicated by cyclically intercalating rocks of neighboring mineral assemblages, which are usually constrained to the boundaries of zones and are consid-

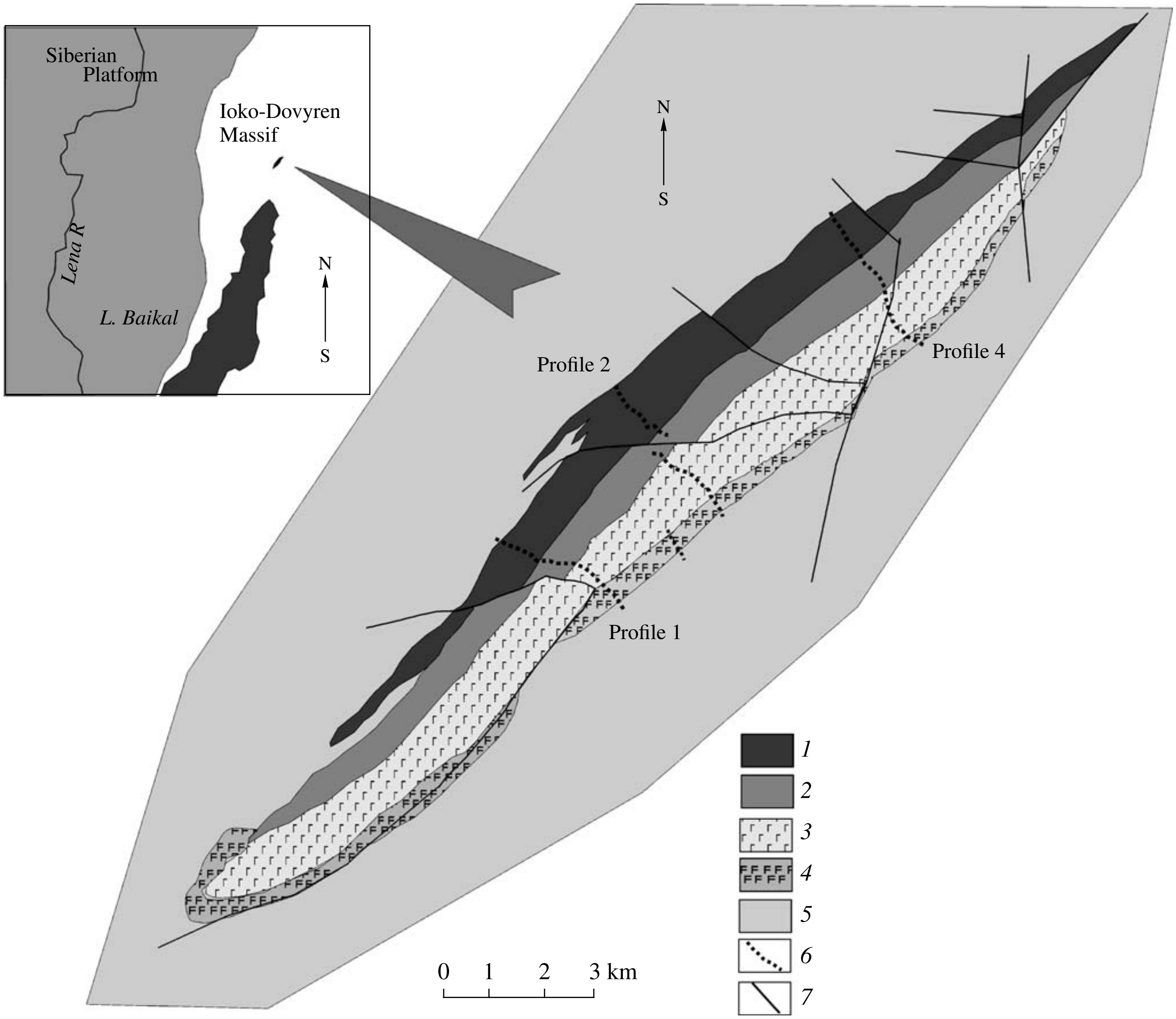

Fig. 1. Schematic geological map of the Ioko-Dovyren intrusion (modified after M.I. Grudinin and S.A. Gurulev). (*1*) Dunite zone; (*2*) troctolite zone; (*3*) olivine gabbro zone; (*4*) olivine gabbronorite zone; (*5*) host rocks; (*6*) reference profiles; (*7*) faults.

ered to be a phenomenon complicating but not disturbing the general succession [71]. According to the evolution of mineral assemblages, the crystallization sequence of the magma was determined to be as follows: olivine + chromite ⟶ olivine + plagioclase + chromite ⟶ olivine + plagioclase + augite ⟶ ±olivine + plagioclase + augite + low-Ca pyroxene. This crystallization sequence is consistent with the tendencies of the fractionation crystallization of tholeiitic magmas and an experimentally established sequence in which phases appear on the liquidus in systems of this composition. No intrusive contacts between any rocks of the massif were found.

As a representative vertical section of the central part of the intrusion whose systematically repeated rock relations can be quantitatively simulated, we chose profile 4 (Fig. 2), which covers a rock interval approximately 3 km in thickness and which includes a lower contact zone approximately 150 m thick and a layered series. The latter consists of a dunite zone (~750 m thick), troctolite zone (1030 m), gabbro zone (630 m), and gabbronorite zone (550 m). The thicknesses of the zones vary along their strikes and reach maximum values in the central part of the intrusion, where the greatest thicknesses are typical of the gabbro and dunite zones. This does not modify the principal relations between the zones. The relations most important for our simulations are those between the ultrabasic and basic parts of the massif because they determine the calculation of the weighted mean composition of the intrusion.

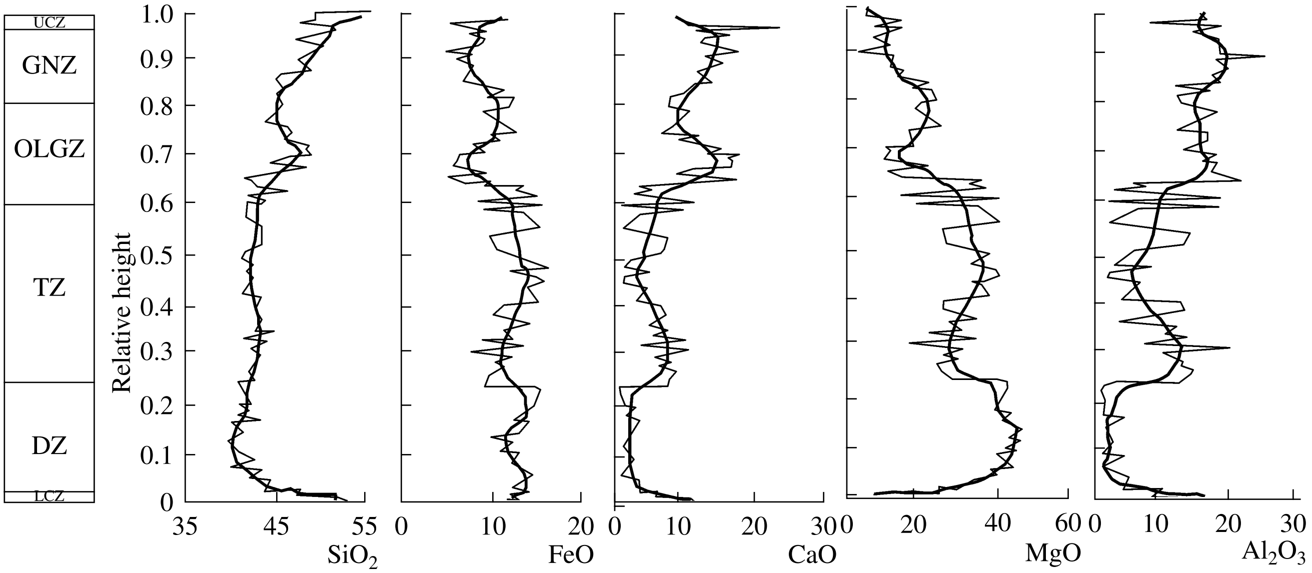

Fig. 2. Distribution of components in profile 4 across the Ioko-Dovyren intrusion. Polygonal lines—primary data; smooth lines—concentrations after ten-fold smoothing by the sliding window technique. LCZ—lower contact zone; DZ—dunite zone; TZ—troctolite zone; OLGZ—olivine gabbro zone; GNZ—olivine gabbronorite zone; UCZ—upper contact zone.

SIMULATION OF THE SOLIDIFICATION OF THE IOKO-DOVYREN INTRUSION AND CONSTRAINING THE PARAMETERS OF THE OPTIMUM MODEL

The aim of our simulations was to test the hypothesis of the possible formation of the geochemical structure of the Ioko-Dovyren Massif by the mechanism of fractional crystallization with regard for the gravitational redistribution of phases simultaneously with convective heat and mass transfer without additional magma injections. The simulations were conducted by the successive studying of the reaction of the system to variations in certain parameters and the subsequent fitting of optimum values of the parameters in order of their decreasing influence on the system.

One of the limitations of the algorithm of the COMAGMAT model is the primitive description of the convection regime in the chamber, which enables the researcher to model only the general phase and chemical structure of the pluton disregarding the cyclic character of this process. Because of this, a crucial issue in selecting the parameters of the model was the distribution of minerals in the vertical section of the body smoothed by the sliding window technique. This vertical section reflects the principal geochemical structure of the intrusion: the succession of mineral assemblages and systematic variations in the thicknesses of zones with various cumulus assemblages (Fig. 2).

We believe that the differentiation (fractionation) of the parental melt, a process that controlled the structure of the intrusion as a whole, and the cyclic layering of its rocks were controlled by various processes: the cyclic intercalation complicates the crystallization sequence of the massif but does not perturb its general trends and relations. Hence, the cyclic layering of the intrusion is considered to be produced by a superposition of the general evolutionary course and some dynamic process. In this publication we did not focus on the genesis of the cyclic layering itself.

Estimation of the Thermodynamic Parameters of Crystallization

The pressure and H_2O concentration during the crystallization of the intrusion. An important parameter of the model is the pressure in the magmatic chamber, because it affects the appearance sequence of mineral phases on the liquidus. The model includes a routine designed to simulate equilibrium crystallization with an arbitrarily specified pressure step within a predetermined range of values. This makes it possible to trace changes in the crystallization sequence at various total pressures in the system and to evaluate the pressure (or its range) corresponding to the observed crystallization sequence. The simulations were conducted for anhydrous environments, because the rocks of the intrusion contain very little hydroxyl-bearing minerals, and hence, the parental magma should have been low in water. This also follows from gas analyses of the rocks [72, 70].

Approximate estimates of the pressure from geological data indicate that the intrusion solidified under a low pressure. For example, according to Pertsev and Shabynin [73], who examined magnesian skarns developing in carbonate rocks, the Ioko-Dovyren Massif solidified near the surface at a depth of about 1.5 km, and thus, at a thickness of the intrusion of 3–3.5 km, the pressure near the floor of its magmatic chamber did not exceed 1.5 kbar.

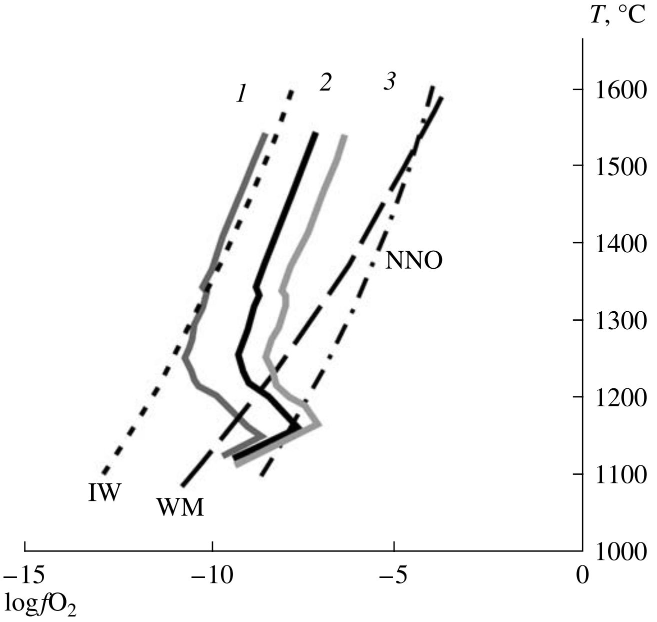

Fig. 3. Dependence of oxygen fugacity on temperature in the optimal model at the following initial FeO/(Fe_2O_3 + FeO) ratios: (*1*) 0.99, (*2*) 0.98, (*3*) 0.97. Buffers: IW—iron–wuestite; WM—wuestite–magnetite, NNO—Ni–NiO.

The results of the calculation of the equilibrium crystallization of a composition corresponding to the evaluated composition of the parental anhydrous melt at 0–10 kbar indicate that the crystallization sequence observed in nature corresponds to pressures of 0–2 kbar. Under higher pressures, orthopyroxene appears on the liquidus simultaneously with clinopyroxene and crystallizes earlier than plagioclase under pressures above 7 kbar. In modeling the solidification of the intrusion, we assumed an average pressure in the magmatic chamber equal to 1 kbar and that the pressure increase with depth in the chamber insignificantly affects the phase proportions on the liquidus and the composition of these phases.

Oxygen fugacity. A distinctive feature of the Ioko-Dovyren intrusion is the absence of rocks with cumulus titanomagnetite, which was used as a criterion in selecting the optimum values of oxygen fugacity during the crystallization of the intrusion. The calculations were conducted in a system closed with respect to oxygen, whose fugacity was specified through the proportion of bivalent to total iron in the parental magma. Metallic Fe appeared on the liquidus of the crystallizing magma at FeO/(FeO + Fe_2O_3) values in the parental melt (weighted mean composition of the intrusion) higher than 0.99, and magnetite appeared on the liquidus when this ratio was lower than 0.97. In our calculations, we assumed an initial value of this ratio equal to 0.98, which corresponded to $\log f O_2$ = –7.14. During the magmatic evolution, this ratio in the melt varied because of various incorporation of Fe^{2+} and Fe^{3+} in minerals (it was postulated that no Fe^{3+} is incorporated into any of the crystallizing phases before magnetite appeared). This led to an increase in this ratio and $\log f O_2$, whose value systematically varied from –8.80 during the emplacement of the melt to –7.96 when magnetite appeared on the liquidus (Fig. 3).

Estimation of the Initial Conditions

Chemical composition of the parental magma. As an estimate of the composition of the parental magma, we assumed the weighted mean composition of the rocks of the intrusion sampled along profile IV. This estimate was close to the weighted mean composition calculated for the other profiles and to the results obtained by other researchers [74, 68, 75] (table). The selection of experimental data from the INFOREX thermodynamic database [76] indicates that olivine is the first to appear on the liquidus during the crystallization of compositions closest to our calculated weighted mean composition under a low pressure (< 5 kbar) [77].

Temperature difference between the magma and host rocks during the emplacement of the intrusion. When cooling, magma loses its heat through the upper and lower contacts of the chamber. The temperature gradient between the emplaced magma and host rocks controls the heat flux from the intrusion into these rocks. The heat flux through the upper boundary of the chamber J_U determines the rate with which the solid phase is supplied to the melt, and the heat flow J_L through the floor of the intrusion to the host rocks controls the velocity of the lower boundary motion of the

Estimated average composition of the Ioko-Dovyren Massif

Reference	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
this paper	43.92	0.11	9.72	10.53	0.17	27.88	6.99	0.59	0.07	0.02
Konnikov, 1986	43.2	0.2	9.86	10.51	–	24.31	6.87	0.78	0.28	–
Ionov, 1984	44.54	0.09	10.64	10.05	0.14	26.57	7.35	0.54	0.07	–
Ariskin et al., 2003	47.71	0.36	9.11	10.37	0.15	24.71	6.03	0.94	0.54	0.04

Note: The compositions are normalized to 100%, all Fe is recalculated to FeO.

growing cumulus layer (the surface of complete solidification) near the chamber floor. The flux of the solid phase forming near the roof into the main magma volume and the induced sedimentation convection lead to the continuously maintained flow of melt with a higher heat content toward the upper boundary of the convecting mass and thus predetermines the elevated heat flux through the roof of the massif. This is a principal feature of the model that results in an asymmetry of the heat fluxes, with the bulk of heat released through the intrusion roof. The simulation of flood basalts [4] has demonstrated that the heat fluxes through the upper and lower boundaries of intrusions is described (as an approximation accurate enough for the model) by the equation $J_L = J_U \cdot t^{1/3}$, where t is the time elapsed from the moment of emplacement.

The simulations are started with the reproduction of the transition boundary from the lower contact zone to the layered series. The structure of the lower contact zone reflects the dynamics (velocity) of the upward movement of the lower surface of complete solidification and depends on the solid phase flux from the main magma volume. It was determined that the thickness of the lower contact zone and the distribution of the first liquidus phase are controlled during the solidification of an intrusion primarily by the temperature difference between the magma and host rocks, the percentage of intratelluric phases (F_{int}), and the sinking velocity of crystals. We conducted a series of simulations within a temperature range of 1600–800°C and selected a value of 1200°C at which the thickness of the lower contact zone and the olivine distribution in it are close to those observed in nature and do not contradict the possible temperature difference in the intrusive magma (approximately 1300°C) and the host rocks at a depth of about 1.5 km (100°C).

Fraction of intratelluric phase in the parental magma. Our simulations indicate that, if the emplaced magma was homogeneous and did not contain phenocrysts (i.e., had a zero initial crystallinity) cumulus plagioclase and clinopyroxene appear in the vertical section of the layered series at a much higher level than in nature. In this case, the thickness of the modeled dunite zone is almost twice as high as that in nature, the thicknesses of other zones are, conversely, strongly underestimated, and the boundary between the dunite and troctolite zones becomes less sharp. Conversely, if the initial crystallinity is high and the content of phenocrysts in the emplaced magma reaches 50 vol %, plagioclase and clinopyroxene appear in the modeled vertical section earlier than is observed in nature. Simulations of different variants of the model demonstrate that the parental magma of the Ioko-Dovyren intrusion should have contained about 40 vol % intratelluric olivine crystals during emplacement.

In the variant of the model in which the emplaced magma contained no crystals and the sinking velocities of crystals are constant, the boundaries between zones of different mineralogical composition are very sharp and stepwise. An increase in F_{int} within the range of 0–40 vol % results in progressively less sharp boundaries between the zones.

The concentration of the intratelluric phase in the emplaced magma, in addition to the distribution of cumulus minerals in the lower part of the vertical section, notably affects the solidification time of the intrusion. When model variants with phenocryst contents within the range of 0–60 vol % were simulated, the solidification time decreased by almost one order of magnitude, and the relations between regions of various phase composition also varied (Fig. 4). This significant decease in the solidification time of magmatic melt was related to the fact that the bulk of heat lost thereby was accounted for by the latent heat of crystallization, whose amount decreases with increasing contents of intratelluric phases in the emplaced magma.

The dependence of the quantitative parameters of the structure of the intrusion on the percentage of the intratelluric solid phase is an important characteristic of the model, which makes it possible to evaluate the temperature of the emplaced magma independently of other methods. This is because the proportion of liquid and solid phases in magma in a given solution algorithm of the problem is an independent variable parameter, which is uniquely related to its heat content, but the temperature is calculated by the equations for equilibria between solid phases and melt (geochemical thermometers) and is not an independent variable.

Dynamic Parameters of the Model

Velocities of crystal sinking. One of the most important parameters controlling the modeled distribution of rock compositions (proportions of minerals in rocks) is the effective velocities of crystal motion, because the accumulation ratio of cumulus phases in the course of crystallization is controlled in the model by these velocities. The latter determine, along with the contents of solid phases in the magma, the weighted mean flux of minerals into the cumulus within a given time span.

The manifestations of megacyclicity remaining after the smoothing of the natural distribution of minerals in the vertical section highlighted the necessity of postulating periodical variations in the velocities of crystals relative to the magma during the origin of the rocks that were needed to realistically reproduce, for example, maxima and minima of olivine and plagioclase in the troctolite and gabbro zones. For example, the model specified a decrease (to zero) of the plagioclase flux from magma to cumulus within a certain interval in the troctolite zone. This issue of our simulations requires some comments.

The point is that the proportions of solid phases received by the cumulus are determined, within the scope of the model, by three parameters: their cotectic

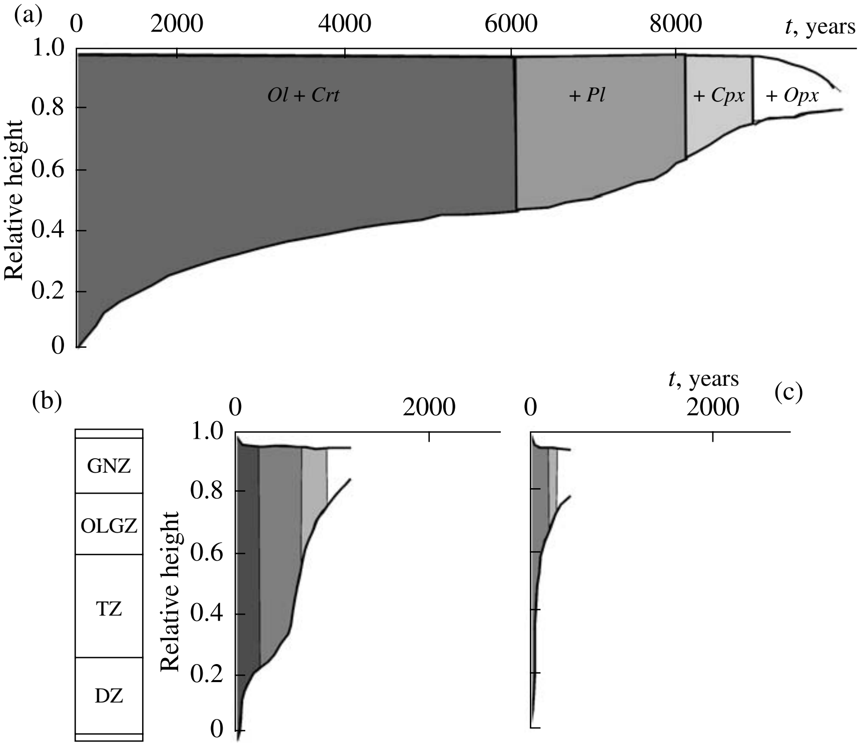

Fig. 4. Dependence of the solidification time of the Ioko-Dovyren intrusion on the content of the intratelluric phase (F_{int}): (a) $F_{\text{int}} = 0$ (the emplaced magma contained no suspended solid phase); (b) $F_{\text{int}} = 40$ vol % (optimal model); (c) $F_{\text{int}} = 54$ vol %. The lower boundary corresponds to the displacement of the upper boundary of cumulus with time. Mineral symbols indicate liquidus phases in equilibrium with the melt: *Ol*—olivine; *Crt*—chromite; *Pl*—plagioclase; *Cpx*—clinopyroxene; *Opx*—orthopyroxene.

proportions in the course of crystallization and the relations between the velocities and concentration of phases suspended in the melt (which are a function of the sinking velocities). The first parameter is uniquely specified by thermodynamic data (diagram of state) and cannot be arbitrarily varied in the process of solidification. At the same time, the other two parameters, which determined the flux of solid phases into cumulus, are parameters of the model, whose numerical values cannot be exactly evaluated beforehand. We selected and fitted their values in order to make the simulated distributions of minerals consistent with those observed in nature (within physically permissible ranges of values). Within the framework of this simplified model, there is no possibility to reflect variations, including cyclic ones, in the proportions of the cumulus phases in zones composed of the same mineral assemblages other than to vary the sedimentation flux. We realize that this is an artificial procedure and thus believe that our results merely demonstrate the possibility of understanding this cyclicity but are not its only possible explanation.

Cumulus porosity. The porosity of the cumulus is one of the parameters of the model that is fitted in the course of simulations by means of comparing modeled and naturally occurring maximum concentrations of cumulus and intercumulus phases in the rocks. The petrographic examination of the rocks indicates that the rocks of the dunite zone contain very little intercumulus and have textures close to adcumulus ones. Farther up the vertical section, the amount of intercumulus phases in the rocks increases and reaches a maximum in the gabbro zone.

Our simulations indicate that the best consistency between the simulated and natural trends can be reached when the cumulus porosity is assumed to be 5–10 vol % for the lower portion of the intrusion and close to 30 vol % for the upper part of the chamber, in the gabbroid zone. These estimates are confirmed by petrographic data. The variations in the cumulus porosity in various variants of the model demonstrates that the cumulus density at the lower contact controls the enrichment of the lower zone of the layered series in the first cumulus mineral.

Thus, varying the material flux from the magma to cumulus (sinking velocities of the solid phases), the initial crystallinity of the emplaced magma, and the density of the cumulus, we managed to reproduce the quantitative distribution of minerals observed in the Ioko-Dovyren layered intrusion and to develop an optimum model for its solidification. The simulations were conducted until magma crystallinity equal to 94–96% was reached. In the course of these simulations, we determined that the model is highly sensitive to variations in the fitting parameters. The difference between the temperatures of the magma and host rocks, the percentage of the intratelluric solid phase, the sinking velocities of crystals, and, to a lesser degree, the density of the cumulus are interrelated parameters of the model. It was most efficient to vary the numerical values of different parameters.

SIMULATION RESULTS

The series of our simulations allowed us to determine the following parameters of the optimal model for the solidification of the Ioko-Dovyren intrusion and to evaluate the conditions of its solidification:

* the phase composition of the magma during its emplacement corresponded to melt + olivine (Fo_{89});

* the crystallinity of the parental magma was close to 40 vol %;

* the temperature of the magma during its emplacement was approximately 1340°C;

* the pressure in the magma chamber was 1 kbar;

* the volumetric fraction of cumulus phases in the cumulus was 90–95 vol % in the lower part of the chamber and 70 vol % in its upper part;

* the effective sinking velocities of minerals $V_{\sin}$ varied within the range of 0.7–2.5 m/yr; and

* the concentration of the suspended solid phase in the convecting melt ranged during various solidification stages from 35 to 50 vol % (Fig. 5).

At the values of parameter assumed in the model, plagioclase appeared on the liquidus at a temperature of 1255°C, clinopyroxene appeared at 1216°C, orthopyroxene at 1156°C (Fig. 6), and the crystallization sequence of the cumulus minerals corresponded to that observed in nature. The liquid phase (melt) contained during its emplacement 45.95 wt % SiO_2, 15.93 wt % Al_2O_3, 14.49 wt % MgO, 10.98 wt % FeO, 11.46 wt % CaO, 0.97 wt % Na_2O, 0.11 wt % K_2O, and 0.18 wt % TiO_2. This composition of the melt corresponded to magnesian basalt or plagiopicrite.

Figures 7 and 8 display the ability of the optimal model to reproduce the principal relations in the spatial geochemical structure of the Ioko-Dovyren intrusion: the distributions of normative minerals and chemical elements in the vertical section. The model most accurately reproduces the evolutionary trends of MgO, Al_2O_3, and CaO. The correlation coefficients between the concentrations of these components in nature and the model are 0.95, 0.93, and 0.91, respectively. The correlation coefficients for SiO_2, FeO, and Na_2O are lower: 0.61, 0.59, and 0.70, respectively (Fig. 9).

The possibility of reproducing the parameters of the geochemical structure of the Ioko-Dovyren Massif are demonstrated in Fig. 10, which compares the characteristic correlations between the concentrations of elements reflecting the general tendencies in the fractionation of the melt in the process of crystallization differentiation and the calculated data.

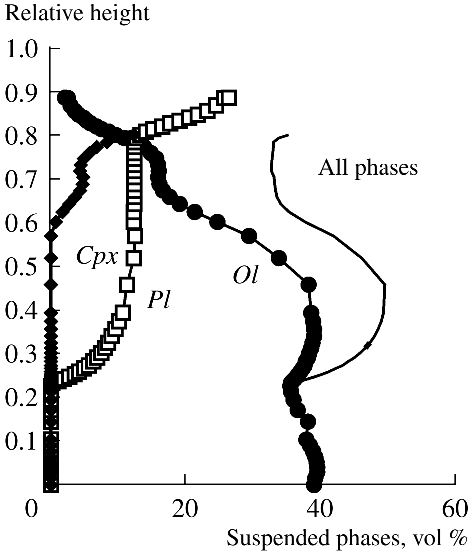

Fig. 5. Content of solid phases suspended in the convecting melt as a function of the position of the cumulus surface. See Fig. 4 for symbol explanations.

An independent criterion of the plausibility of our evaluations of the parameters of the solidification process is the consistency of the evolutionary trends of the simulated and observed mineral chemistries. The comparison indicates that the model fairly realistically

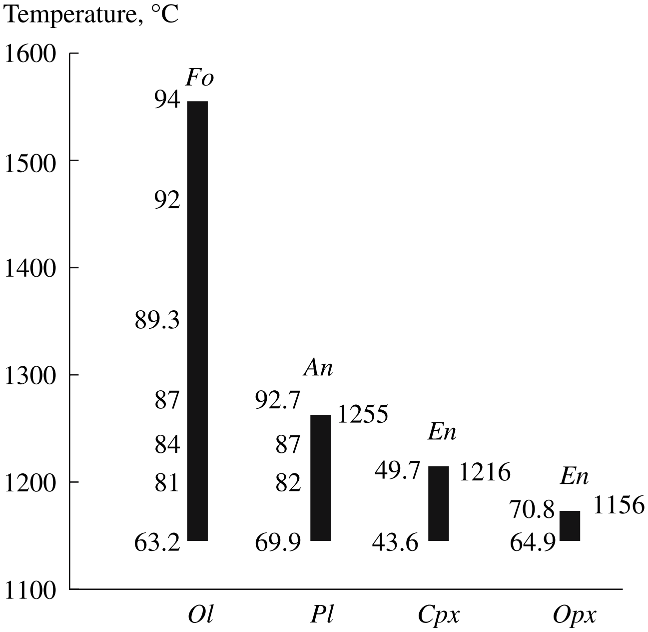

Fig. 6. Crystallization succession of liquidus phases with decreasing temperature of a melt corresponding to the composition of the Ioko-Dovyren intrusion. Numerals near the bars indicate the temperature and concentration of the forsterite end member (*Fo*, mol %) in olivine, anorthite end member in plagioclase (*An*, mol %), and enstatite end member in clinopyroxene and orthopyroxene (*En*, mol %).

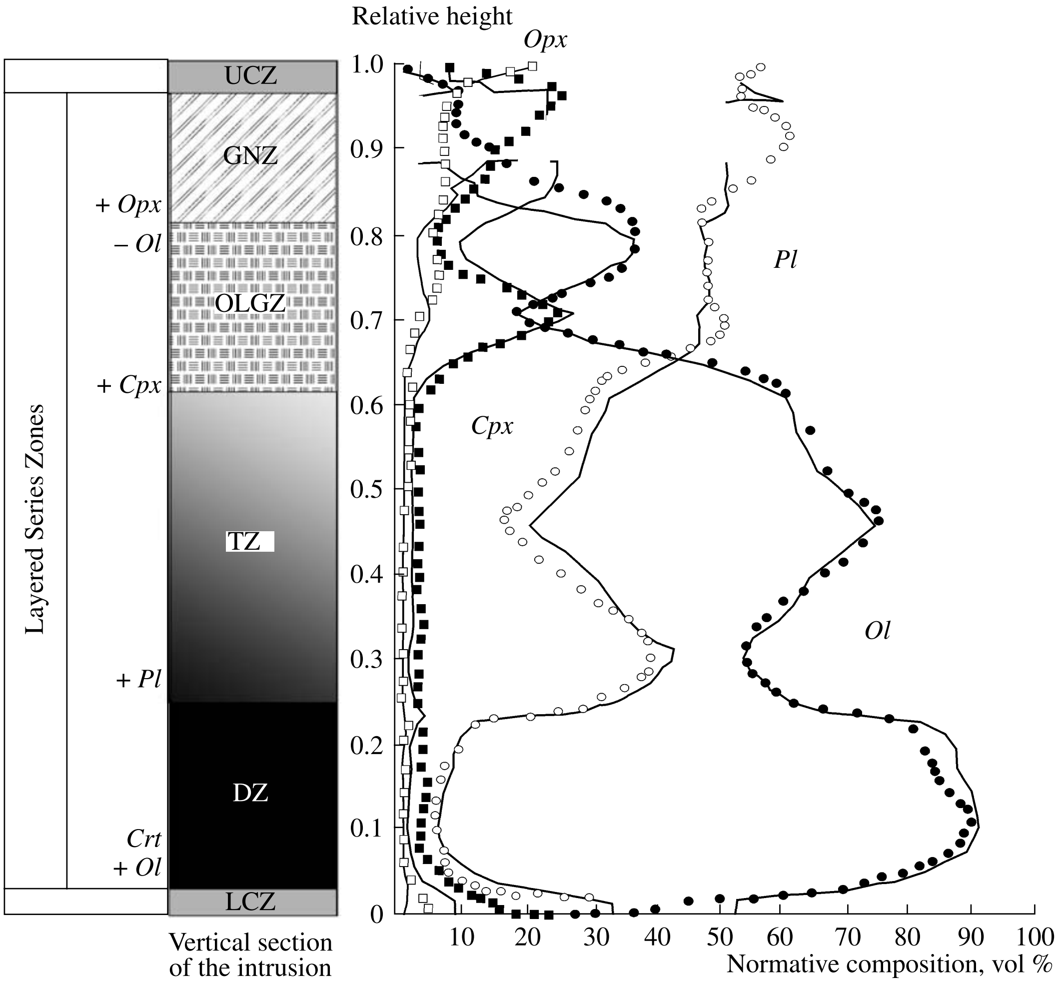

Fig. 7. Distributions of normative minerals in the vertical section of the smoothed natural (symbols) and modeled (lines) intrusion. See Fig. 4 for symbol explanations.

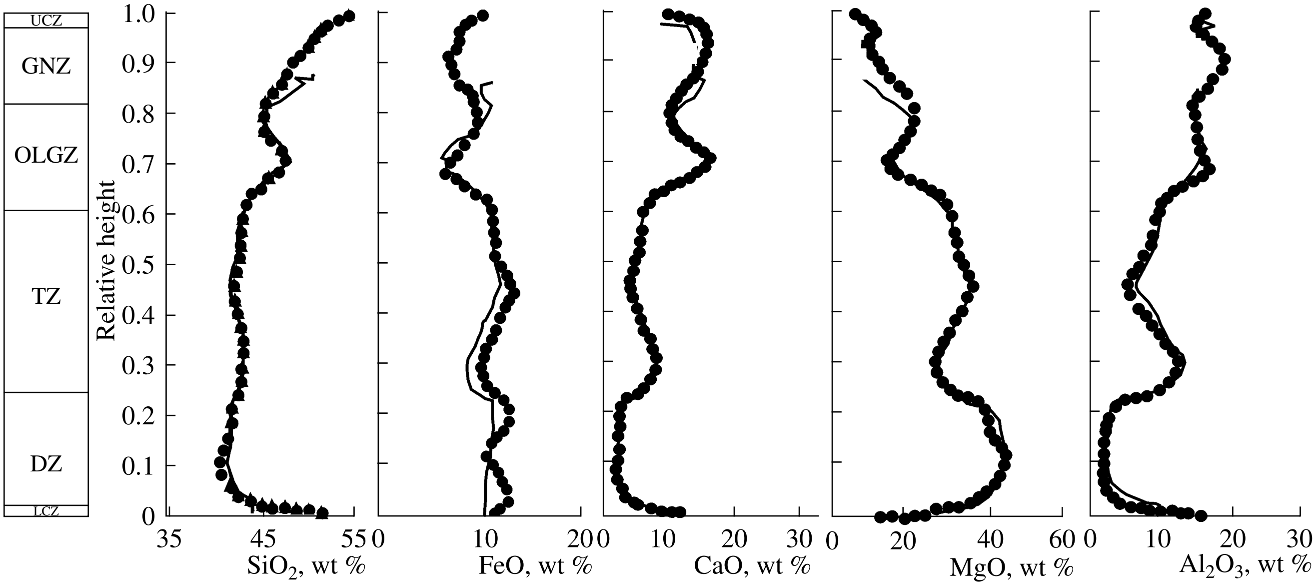

Fig. 8. Distributions of components in the vertical section of the smoothed natural (symbols) and modeled (lines) intrusion.

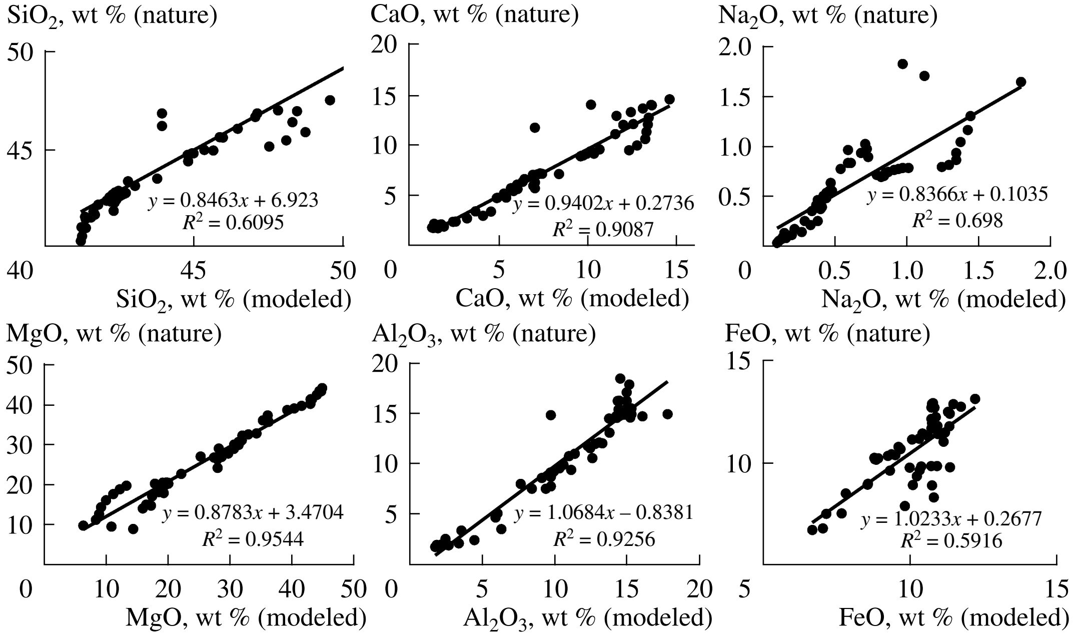

Fig. 9. Correlation between the modeled and observed (natural) concentrations of components in the vertical section of the intrusion.

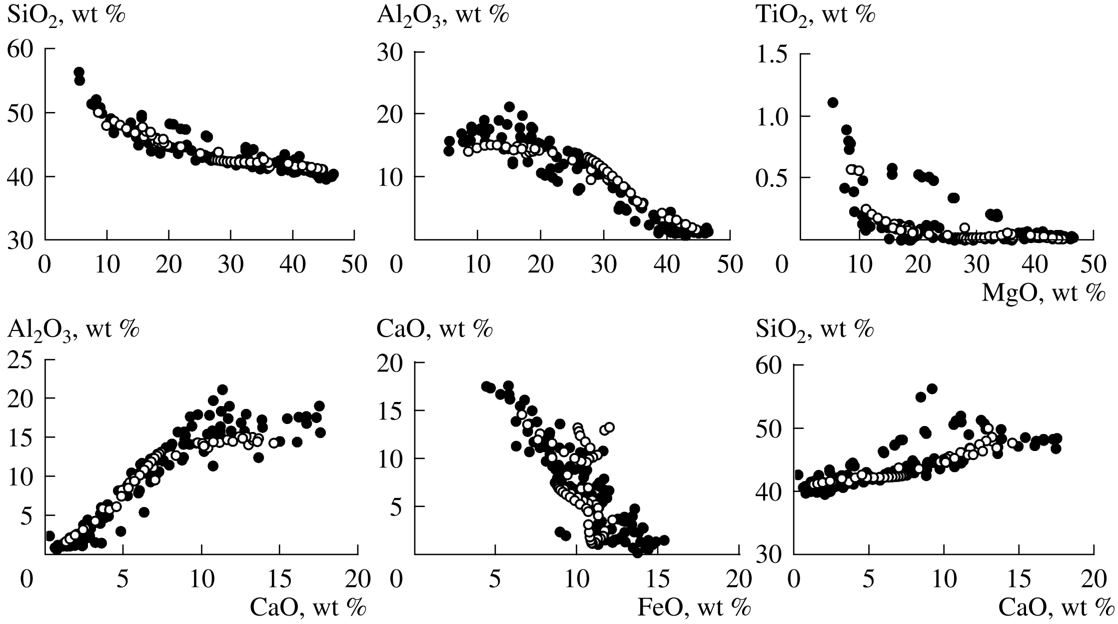

Fig. 10. Correlation between the contents of components in the rocks of the natural (solid circles) and modeled (open circles) intrusion.

describes the evolution of the compositions of olivine, plagioclase, and clinopyroxene (Fig. 11). In the optimal model at a content of the intratelluric solid phase of 40–45%, the composition of olivine varies from 89.2 to 88.6 mol % of the forsterite end member at oxygen fugacity from 10^{-10} to $10^{-7.5}$, which falls within the range of the composition of this mineral in the lower part of the dunite zone.

DISCUSSION

The results of our simulations, namely, the ability of the model to reproduce the naturally occurring geochemical structure of the Ioko-Dovyren intrusion, testify to the validity of the postulates underlying this model that homogeneous nucleation played the leading role in the genesis of the massif and that it was sig-

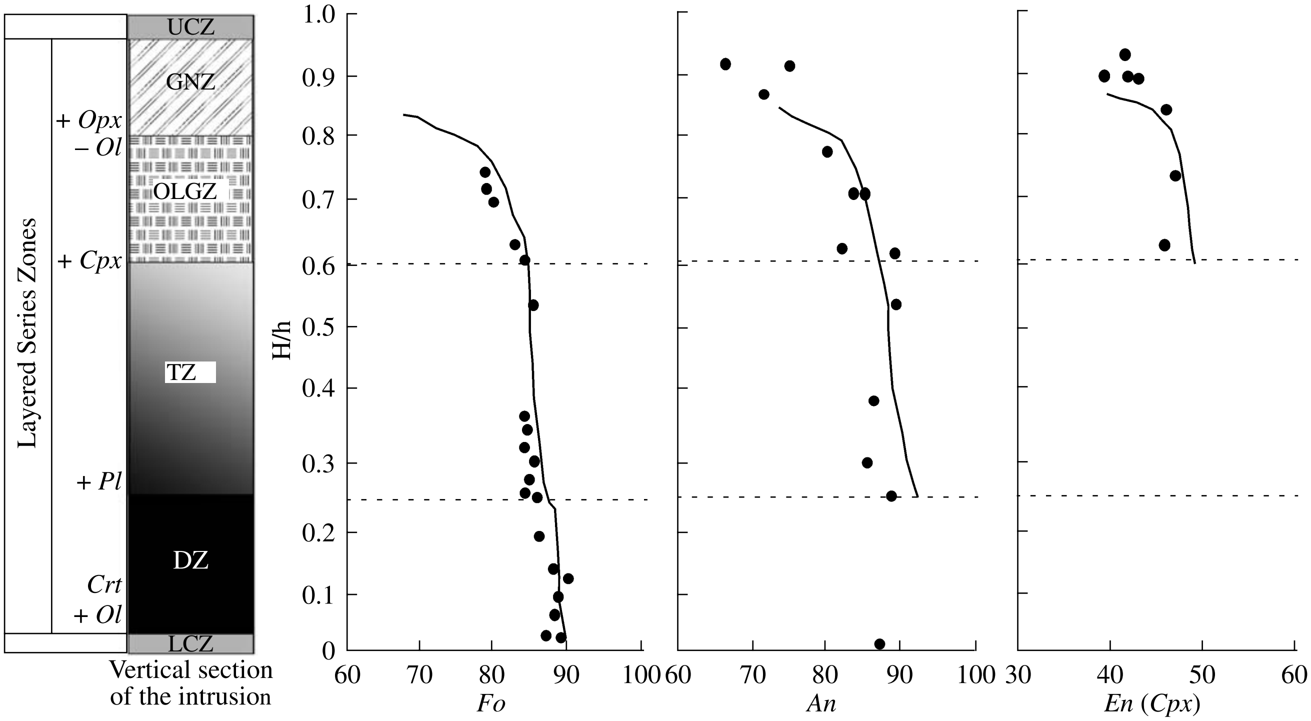

Fig. 11. Comparison of the naturally occurring (circles, based on data from [78]) and modeled (lines) compositional trends of olivine (*Fo*, mol %), plagioclase (*An*, mol %), and clinopyroxene (concentration of the enstatite end member *En*, mol %). See Figs. 2 and 4 for the explanation of the symbols of zones and cumulus minerals.

nificantly contributed by the motions of suspended crystals simultaneously with convection in the magmatic chamber.

Our evaluations of the phase and chemical composition of the emplaced magma show high contents of suspended intratelluric olivine crystals during the emplacement (approximately 40 vol %). This means that, in the simulated vertical section of the intrusion, the rocks of the dunite zone were produced mainly by the settling and subsequent compaction of intratelluric olivine. The troctolite and gabbro zones were formed with the participation of remaining suspended intratelluric crystals at the predominance of newly formed phases. The natural relations of rocks composed of various cumulus assemblages could be formed only if plagioclase and pyroxene started to crystallize after the emplacement of the magma and its cooling in the magmatic chamber and after the origin of the dunite zone.

The accuracy of the estimated crystallization parameters of the intrusion depends on the plausibility of the evaluations of parameters related to the thermal history of the magmatic system. The simulations of various variants of the model conducted to examine the stability of the solutions indicate that the major factor controlling the numerical value of the content of the solid intratelluric phase and the sinking velocities of crystals is the temperature differences between the emplaced magma and host rocks. This dependence is stable in the sense that variations in the ΔT values lead to proportional variations in F_{int} and V_{sin} (recall that the temperature difference itself is not an independent variable but is specified through the selected optimum values of F_{int} and V_{sin}). It was thereby determined that the optimal solution is unique: at a given ΔT value, no more than one solution variant can exist in which variations in F_{int} are compensated by variations in V_{sin}, because different parameters of the vertical section are sensitive to variations in F_{int} and V_{sin}. The position of the boundary between the olivine (dunite) and olivine–plagioclase (troctolite) cumulates is controlled, first of all, by F_{int}, whereas the variations in the content of cumulus olivine in the transition zone from the lower contact to dunites depends largely on V_{sin}. This stability of the solutions was earlier demonstrated by Koptev-Dvornikov and Mitoyan [79] and is a nontrivial feature of the model.

It should be emphasized that the actual structural relations of the intrusion can be reproduced only by the model in which a significant content of the solid phase suspended in the melt remains during all solidification stages. This means that both the equilibrium crystallization and the ideal fractionation model, which inevitably follows from the model of directed (from below upward) crystallization, cannot be adequate to the natural process.

The examination of the model indicates that the main qualitative feature in the spatial structure of the intrusion (the succession of zones with various cumulus mineral assemblages) is controlled by the chemical composition of the parental magma and pressure and is independent of the effective sinking velocities of crystals. The qualitative characteristics, such as the thicknesses of zones, proportions of cumulus minerals in the rocks (the quantitative mineral and chemical composition of the rocks), and their variations in the vertical section, depend on relations between the fluxes of the solid phase into the magma (owing to the crystallization) and the fluxes of crystals from the magma into cumulus (because of the difference between the densities of the solid phase and melt), i.e., are controlled by the dynamics of the process.

The dynamic parameters affect the spatiotemporal geochemical structure of the intrusion in such a way that changes in some of these parameters can be counterbalanced by variations (within certain ranges) of others, but there are limits beyond which no ideal model can be developed. An estimate of the fraction of the solid phase during the emplacement of the intrusion was determined to be only insignificantly dependent on the sinking velocities of mineral crystals specified in the model. If the velocity is increased by factors of 4–5, the optimum value of the fraction of intratelluric phenocrysts changes by no more than 2%. An insignificant (within 200°C) increase in the temperature difference between the magma and host rocks during magma emplacement (which results in an increase in the fraction of the intratelluric phase) can be compensated by an increase in the sinking velocities.

The thermal conductivity and heat capacity of the host rocks and the temperature difference during the emplacement predetermine the solution of the thermal problem. The heat flux through the upper contact of the intrusion predetermines the dynamics of the solid phase flux into the melt, and the heat flux through the lower contact controls the velocity of the lower boundary of cumulus (the complete solidification surface).

The thickness of the lower contact zone and the enrichment of the rocks in olivine (both intratelluric and crystallizing in the chamber) within the near-contact layer are controlled by the duration of the chilling regime and the relations between the upward velocity of the lower crystallization front and the intensity of material flux from the magma into cumulus, i.e., is determined by the values of ΔT, F_{int}, and the sinking velocity of olivine crystals. The criterion for determining the value of F_{int} is, first of all, the thickness of the dunite zone (whose rocks contain no cumulus plagioclase) with an insignificant correction made for the sinking velocity of olivine. Thus, for each intrusion and a given sinking velocity of minerals, the fraction of intratelluric phenocrysts in the magma can be uniquely determined.

The distributions of minerals in the vertical section of the intrusion results from a balance of the flux of the solid phase into magma as a consequence of crystallization and the flux from the magma due to crystal sinking. The study of the contribution of different parameters in the behavior of fluxes in the magmatic chamber indicates that the rate of solid phase supply to the magma is controlled by the heat loss rate from the intrusion, which depends on the temperature difference between the magma and host rocks during the emplacement, the thermal conductivity and heat capacity of the minerals and host rocks, and the time elapsed after the emplacement. The behavior of material fluxes from the magma to cumulus depends immediately on the content of the suspended solid phase in the melt and the sinking velocities of the crystals. The content of the suspended solid phase in the melt is controlled by the balance between the flux of the solid phase into the chamber from its upper boundary and the flux of crystals from the convecting melt into cumulus. In this sense, the flux of the solid phase into the cumulus does not depend on the "thermal" parameters of the system. As was mentioned above, variations in the flux of crystals from the convecting magma into cumulus can be a reason for variations in the proportions of cumulus minerals in the alternating rocks of the layered series.

Ariskin et al. [75] attempted to evaluate the emplacement parameters and to justify the leading mechanism forming the phase layering (as it was referred to by the authors) of the Ioko-Dovyren intrusion. The values obtained for the temperature (1185°C), initial melt composition, which was, according to these researchers, cotectic and was in equilibrium with the olivine + plagioclase bimineralic assemblage, and the significant (40–50 vol %) content of the intratelluric phase (olivine and a certain amount of plagioclase) led the authors to the conclusion that the leading mechanism responsible for the formation of the olivine and olivine–plagioclase cumulus rocks (which account for approximately two-thirds of the vertical section of the layered series) was the sedimentation of intratelluric solid phases and the subsequent compaction of the cumulus. The authors did not explain as to how this part of the layered series underwent, in this situation, differentiation into olivine and olivine–plagioclase cumulus rocks that alternate with a sharp contact in the intrusion. This conclusion was based on the results of the geochemical thermometry of the possible compositions of the early cumulus rocks selected by the authors and, mostly, on interpretations of the plagioperidotites that compose the bottom of the intrusion as the solidification products of the initial (intrusive) magma. These researchers emphasized that the model underlain by this assumption is at variance with the weighted mean composition of the massif obtained in our earlier publications [66, 67] and presented some reasons for their doubts (the tapering of the ultramafic rocks in the southwestern part of the massif, a fact that was not taken into account in the course of our sampling).

The problem of the complete material balance for the Ioko-Dovyren intrusion and, particularly, the problem of the possible comagmatic character of the bottom plagioperidotites or their affiliation with the massif call for further research (the ambiguity of this situation was also stressed in the aforementioned paper by Ariskin et al. [75]. The principal criterion for the selection of representative chemical and modal composition of the emplaced magma was the need to make this composition consistent with the structure of the layered series. A crucial point there is the beginning of the development of the layered series with the accumulation of a thick dunite unit in the lower one-fourth of the intrusion, which proves the obvious absence of even insignificant amounts of intratelluric plagioclase (dunites contain only very insignificant concentrations of this mineral, which always occurs in them interstitially and has a more sodic composition than the obviously cumulus plagioclase in the overlying troctolites). These observations validate our conclusion that neither the composition of the melt phase of the intrusive magma nor its temperature corresponded to the olivine–plagioclase cotectic but occurred within the liquidus region of supracotectic olivine. Direct modeling confirms that no layering into dunite and troctolite zone can take place under the assumption of the cotectic nature of the parental melt.

CONCLUSIONS

As a principally important result of our research, we proved that the convection–accumulation model is able to quantitatively reproduce the main structural relations in the Ioko-Dovyren Massif as a typical layered magmatic complex of basic and ultrabasic rocks. This proof allowed us to formulate conclusions that can be of general character in application to petrological and geochemical problems of layered complexes.

First, an unambiguous solution is proposed for the alternative formulations of the main physical problem in the genesis of differentiated magmatic complexes: the sedimentation of the solid phase crystallizing near the roof of the magmatic chamber or directed upward solidification, including this process in the presence of free thermal convection in the main volume of the melt. The latter model is principally inconsistent with the scale of mass transfer needed for the quantitative interpretation of differentiation because only convective spatial separation of solid and liquid phases of various compositions (classical Bowen's mechanism) is an acceptable alternative for the only other currently justified mass transfer mechanism: diffusion, which is the process controlling the differentiation of chemical elements in any variant of the directed crystallization model.

Second, the following features were identified as typical of the genesis of layered magmatic complexes in compliance with the convection–accumulation mechanism:

* When emplaced, the parental magma should have normally contained (sometimes in significant amounts) intratelluric phases (or residual phases entrained from the magma generating region or crystallizing during the adiabatic ascent of the magma). In fact, this conclusion also returns us to Bowen's viewpoint that ultrabasic rocks in layered magmatic complexes are always composed of cumulus material. The same conclusion was drawn by Ariskin and Barmina [80] from the results of experiments on the modeling of a number of layered intrusive complexes of basic and ultrabasic rocks.

* It is very important that neither equilibrium crystallization nor ideal fractional crystallization can be quantitatively consistent with the distributions of chemical elements observed in the vertical sections of differentiated basic and ultrabasic complexes, which always show evidence of an intermediate variant with a variable and an *a priori* unknown content of solid phases suspended in the melt during all fractionation stages. This means that all numerical models displaying the quantitative consistency of these distributions with, for example, the Rayleigh fractionation are an illusion, which is underlain by the inaccurate application of the effective distribution coefficients of elements between the solid and melt phases [81].

Third, the convection–accumulation model developed for crystallization differentiation is necessary and sufficient for the quantitative reproduction of only principal relations and tendencies in the inner structures of layered complexes: the succession of cumulus mineral assemblages in the layered series, the ratios of the thicknesses of rock layers composed of various cumulus mineral assemblages, and the generalized (smoothed) evolutionary trend in the compositions of the rocks and minerals. The possibility of this reproduction means that the processes and mechanisms responsible for these relations and trends are adequately understood.

Fourth, the developed and verified (but still oversimplified) model of crystallization differentiation leaves unsettled numerous petrological and geochemical issues, first of all, the nature of the cyclic layering. This cannot, however, be regarded as a reason for rejecting the physically consistent scheme of processes in a magmatic chamber in favor of unjustified schemes, which often simply ignore even the principal relations observable in the inner structures of layered complexes. It seems to be much more fruitful to try to append the simple but physically coherent model with still unaccounted for phenomena and processes that could take place in a magmatic chamber, but only in the form of mechanisms complicating the major process but not invalidating it. It seems to be the most appealing to try to take into account phenomena and processes that were mentioned by several researchers but have not been systematically simulated as of yet, including the actual structure of convective motions in a magmatic chamber and phenomena accompanying the compaction and solidification of cumulus rocks and possibly occurring at the contact of the growing cumulus and convecting magma volume.

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