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Modeling of the Equilibrium Crystallization of Ultramafic Rocks with Application to the Problems of Formation of Phase Layering in the Dovyren Pluton, Northern Baikal Region, Russia

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Abstract—Phase equilibria and chemical characteristics of the initial magma of the Dovyren layered dunite–troctolite–gabbro pluton were modeled using the COMAGMAT-3.52 (2000) computer program. The chemical characteristics of marginal rocks and plagioperidotites of the basal zone and the weighted average composition of the intrusion were used for the calculations. Modeling was performed under thermodynamic parameters approaching natural solidification conditions (P = 0.5 kbar and WM buffer) with a crystallization increment of 1 mol %. The results of these calculations suggest an anchieutectic nature ($Ol + Pl \pm Cpx \pm Opx$) of the Dovyren magma. At the moment of emplacement, the magma had a temperature of 1180–1190°C and contained at least 40% intratelluric crystals. The liquid portion of this mixture was silica saturated (54–55 wt % SiO_2) and relatively high in MgO (~8 wt %). Owing to its high viscosity (~10^4–10^5 P) and the high degree of crystallization of the system, the melt could not fractionate via the convective cumulative mechanism. This inference is supported by minor variations in the compositions of rock-forming minerals in the section of the layered series and the occurrence of undisturbed xenoliths of magnesian skarn after carbonates. It is suggested that the main mechanism of formation of the layering included compaction of a primary crystalline precipitate, adcumulus growth, and residual melt infiltration toward the roof with its partial burial near the bottom of the magma reservoir.

INTRODUCTION

Layered mafic–ultramafic igneous complexes are spatial and temporal geochemical structures [1] formed under certain gradients of temperature, gravitational forces, and, probably, seismic influence [2]. The thermal aspect of the solidification of a magma reservoir is related to the heat transfer into the country rocks, which is the main factor controlling the formation and distribution of crystalline material within the magma chamber as a function of time. The comprehensive physical analysis of the thermal and phase evolution of these melt–crystal masses [3–5] is sometimes substituted for by discussing the constitution of intrusions as dissipative structures, which result from self-organization in magmatic systems in accordance with the principle of nonequilibrium thermodynamics [6]. The two methodological approaches do not contradict each other and can be combined for the construction of a general theory of solidification of intrusive bodies. However, the interrelations of physical and chemical parameters of chamber differentiation are currently better developed than the concept of structuring in magmatic systems in response to entropy production or energy dissipation. The analysis of the thermal and dynamic characteristics of magma solidification within a chamber allows the deciphering of the structure and formation sequence of layered complexes. This provides the possibility to approach the problems of formation of a wide spectrum of intrusive rocks genetically linked with a basaltic source. These problems involve questions concerning the direction of the phase and chemical evolution of magma (sequence and composition of differentiates) and the mechanisms of differentiation responsible for the relative volumes of various rock types and their position in the section of a massif.

Many mafic–ultramafic complexes show significant regular variations in the mineralogical composition of rocks in the vertical section (undisturbed position). The efficient separation of the melt and crystals in a magma chamber is a prerequisite for the large-scale occurrence of this phase or modal layering [7]. It is not by accident, therefore, that the current petrologic paradigm connects chamber differentiation with the fractional crystallization of magma accompanied by its global (convection) mixing (see [4, 8] for a review). Most petrologists agree that the fractionation was accompanied by the formation of a cumulus, which filled the magma chamber from bottom to top and evolved from high- to low-temperature mineral assemblages. However, the ideas on the mechanisms of matter separation in the chamber, influence of the thermal regime, role of volatiles, and formation of cumulus minerals are fundamentally different. During many years, the discussions focused on the hypotheses of “crystal settling” and directional (in situ) crystallization.

According to the former concept, most of the crystal material responsible for fractionation forms near the intrusion roof and moves into the lower part of the chamber under the influence of gravitational forces, producing layers of cumulus minerals [9–11]. The concept of directional solidification denies the significant role of gravitational separation and emphasizes the processes of crystallization near the bottom and walls of the chamber [12–14]. Note that both hypotheses emerged at the period when magma chambers were regarded as pools of essentially homogeneous melt, which was free of suspended crystals and was initially overheated relative to the liquidus. As a result, an opinion was formulated that mineral settling could occur only at homogeneous (volume) nucleation of crystal phases in the melt, which, in fact, is impossible because of the difference between the adiabatic gradient (controlling the onset of temperature convection [15]) and the real pressure dependence of the liquidus temperature of magma. These considerations formed a basis for the hypothesis on ubiquitous magma overheating in shallow levels and the possibility of efficient fractionation at the expense of prevalent crystallization near the lower solidification front [13, 16, 17]. According to this scheme, the mechanism of heterogeneous nucleation was realized in the lower part of an intrusion chamber and confined to the upper part of a thin heterophase zone separating the lower front of complete solidification from the magma layer above it. The chemical composition of magmatic liquid evolved progressively, because an exchange of components occurred between the boundary layer adjacent to the stagnant crystallization zone and the main volume of convective melt via the mechanism of concentration diffusion.

This model enclosed a problem, because the comparison of diffusion coefficients for silicate melts and solidification times of intrusive masses suggested that the mechanism of directional solidification could not cause significant differentiation [18]. This controversy stimulated a search for alternative and additional mechanisms that could provide a more efficient exchange with the crystallization zone and transport of components in magma. The progress of the past decades in this direction is related to the analysis of various convection phenomena occurring in crystallizing systems. Temperature convection in a homogeneous liquid was changed by more realistic models allowing crystal settling and sedimentation of suspensions enriched in solid phases in the main magma volume, as well as composition convection in the heterophase cumulus zone between the crystallization and solidification fronts [4, 8, 19–25].

The possibility of interaction and superposition of various convection motions [1] and predominance of a particular regime depending on the thickness and thermal condition of intrusion development [5] provide new insight into the problems of layering and the methods of the interpretation of layered rocks. The solution of current problems requires a combined analysis of thermal and dynamic situations near the roof, bottom, and walls of the chamber. This is connected with the search for indicators of the structure of intrusive bodies, which could be reliably interpreted as a result of the manifestation of a particular type of convection phenomena. This paper considers the structure of the Dovyren intrusion and the results of modeling of initial phase equilibria for its rocks from this standpoint. This intrusion can be considered as the best studied and, simultaneously, most puzzling layered complex in Russia. In addition to contrasting phase layering (from dunite to leucocratic gabbronorite), it is characterized by a narrow range of compositions of rock-forming minerals, which suggests the minor extent of the chamber fractionation, at least at the stage of formation of the lower and middle parts of its layered series. This contradiction can probably be resolved within the hypothesis of the essentially isothermal conditions of formation of the Dovyren massif, which promoted the compaction of initial cumulates, adcumulus growth, and filter-pressing of residual melt into upper levels. The argumentation of these conclusions invokes conceptions about the influence of magma convection on the character of layering and degree of differentiation of intrusive bodies. Because of this, the factual part of the work is preceded by a review of main results of the analysis of consequences of sedimentation and composition convection in an intrusive chamber.

CONVECTION REGIMES AND STRUCTURE OF INTRUSIONS

It is instructive to begin by pointing out the difference between situations corresponding to the intrusions of weakly crystallized magma (at temperature close to liquidus) and the input of magmatic material with an elevated degree of crystallinity. Reconstructions of the phase compositions of intrusive magmas by the methods of the modeling of melt–crystal equilibria have demonstrated that initial magmatic suspensions could bear from a few percent (differentiated traps of the Siberian plate) to 15–25% (Talnakh and Kiglapait massifs) and even 40–65% crystals (Kamenistyi sill and Partridge River intrusion) [26–28]. These differences could be related to the cooling of a basaltic magma during emplacement. Sharapov *et al.* [29] modeled the filling of a funnel-shaped chamber under nonisothermal conditions and estimated the concentration of suspended crystals as 10–15% at a high flow rate of magmatic material of 100–200 m^3/s; 25–30% at 10–100 m^3/s; and about 40% at a slow input of magma at a rate of 0.2–10 m^3/s. Thus, the concept of the instantaneous emplacement of overheated melt into the chamber is an oversimplification, which poses the problem of the efficiency of fractionation at early stages of magma solidification.

The second point concerns the conditions of nucleation and distribution of solid phases near the roof of an intrusion. Independent of the initial degree of crystallinity, the temperature difference between the basalt magma and its country rocks at the upper contact of the chamber is no less than 700–1000°C. This provides a high temperature gradient near the contact (four–five orders of magnitude higher than adiabatic gradient) and a heterogeneous nucleation of the solid phase, which is initially mechanically connected with the crystallization front coinciding with the surface of complete solidification. With decreasing heat flux from the intrusion, the transitional heterophase zone expands and envelop the temperature range from the solidus (complete solidification) to the liquidus of the igneous melt. As a result, an increasing amount of the solid phase precipitates at temperatures close to the liquidus (practically under the conditions of homogeneous nucleation) and begins to redistribute in the transitional layer, because the propagation rate of the upper front of the complete solidification becomes lower than Stokes' velocity of individual crystals [4, 30]. This is a selective process, which differently affects grains of different minerals, but it is important that the settling of solid phase oriented from the upper crystallization front generates or contributes to the inversion of magma density in the roof zone [24, 31–33]. Conditions are provided for the onset of sedimentation convection.

Mechanisms of Sedimentation Mass Transfer

It is convenient to distinguish two main mechanisms of solid phase transportation from the roof to the lower part of an intrusion chamber. The most obvious mechanism is the extensive settling of crystal individuals in melt. The sedimentation process must be accompanied by the formation of complementary ascending flows of igneous liquid, which provides the counter movements of solid phases and melt known as phase convection [1]. This type of "rain convection" may occur in a wide range of crystallinity of igneous suspensions and results in the formation of cumulus horizons with sharp phase boundaries [34], which correlate with differences in the densities (for anchieutectic systems) or crystallization sequences of minerals [35]. Such a scenario of sedimentation is probably also relevant for the lower transitional zone. However, the scale of movement and amount of crystals precipitating in situ in the lower zone are strongly limited by the movement of the lower solidification front and low (in comparison with the roof) heat flow [5].

The second mechanism of sedimentation mass transfer is directly related to the appearance and distribution of crystals in the roof zone. This fundamentally changes the stability conditions of the system with respect to convection. Such a situation was described by Hess at the analysis of the conditions of formation of magmatic currents in the Stillwater magma [36, p. 148]: "a layer of liquid might develop below the roof, which by loss of heat and impregnation by crystals become denser than the underlying liquid… One might expect that some inhomogeneity in the layer would cause it to get started at one point first. A downward bulge would form, the nose of which would accelerate rapidly. The velocity would be enormously greater than the settling of crystals. A single descending column of denser liquid might draw off the whole of the layer from below the roof. In would spread rapidly over the floor and come to rest."

The results of hydrodynamic calculations confirmed this foresight [25]. These authors carried out a series of numeric experiments on the modeling of convection in a two-phase system and established that, owing to the elevated density (crystallinity) of the boundary layer, a cloud of uniformly precipitating phase is rapidly deformed and degenerates into plumes of crystal mush, whose integral velocity at the chamber scale becomes higher than Stokes' velocity of individual crystal precipitation. Complementary flows of crystal-poor melt form simultaneously and ascend toward the intrusion roof. Thus, sedimentation convection forms in response to the origination of solid phase in the upper part of the chamber and becomes an important factor of global magma mixing, which smoothes the temperature distribution in the main volume and suppresses temperature convection. Because of this, this mechanism of heat and mass transfer is sometimes referred to as vigorous or "general convection" [1, 4]. An important feature of sedimentation or general convection is that it does not hinder the processes of Stokes' settling and floating of crystals, which occur in descending and ascending magma flows. This is supported by the results of laboratory experiments, which show that, even at active stirring, convection can sustain crystals in a suspended state only to a certain limit. The extensive precipitation of crystalline material begins above the critical concentration [20, 37], which results in a time dependency of periods of catastrophic sedimentation and repeated cycles of the complete overturn of the system [38, 39].

Evidence of General Convection in the Structure of Intrusions

It is evident from the above analysis that the net result of the superposition of general convection and phase convection is manifested in the movement of suspension enriched in solid phase to the bottom portions of the magma chamber and the sedimentation of crystals as cumulus minerals. The repeated spontaneous mixing promotes fractionation of the igneous melt. It is believed that such a type of process is characteristic of relatively thin shallow magma chambers losing heat primarily through the roof. In the 1980s, a semiempirical model was developed at the Vernadsky Institute of

Geochemistry and Analytical Chemistry combining the calculations of crystal–melt equilibria in crystallizing magmas with the cooling laws of intrusive masses and sedimentation dynamics at the movement of solidification and crystal accumulation fronts [4]. This convective–cumulative model was tested on the example of the differentiated sills of the Siberian craton and assisted in the construction of a combined petrologic and geochemical interpretation of the specific features of the structures of the Kuz'movskii (h = 85 m), Vavukan (h = 100 m), and Vilyui (h = 160 m) intrusions.

Here we pay attention to some results of that work that could be useful for the interpretation of the data on the structure of the Dovyren massif. Figure 1 compares the observed and calculated distributions of Ni, Cr, and V within a section of the Vavukan intrusion. These characteristics are compared with the model parameters of cumulus, which control the bulk mineral and chemical compositions of the rocks crystallizing in situ [26]. It is seen that the results of computer modeling adequately reproduce the S-shaped profile of Ni distribution, which is typical of the behavior of compatible elements in many differentiated intrusions [5, 30, 32]. All the inflections of the concentration lines for Ni are compatible with the regularities of the distribution of cumulus *Ol* and (to a smaller degree) *Aug* grains. The distribution of Cr and V is explained in a similar way. Their behavior is initially controlled by the amount of intercumulus melt and, then, clinopyroxene.

The smooth character of changes in the model contents of minor elements within the major portion of the section (rock-forming oxides show a similar behavior) is dictated by the condition of mixing, which is included by definition in the INTRUZIV model [26]. Thus, the absence of concentration and phase discontinuities in the trends is an important indicator of the dominant role of general convection [35]. The appearance of abrupt compositional changes should be regarded as evidence for the highly probable absence or suppression of general convection, when settling (floating) of crystalline individuals and/or migration of liquid become the main factors of mass transfer [1].

It is interesting to consider from this standpoint a small horizontal step in the geochemical and mineral distributions at the boundary of taxitophitic dolerite and gabbrodolerite (Fig. 1). Its reproduction within the model appeared to be possible only after introduction of "instantaneous" changes in the settling velocities of *Ol*, *Pl*, and *Aug*, which resulted in sharp changes in the proportions of minerals in the cumulus [4]. This fact did not initially receive any physical explanation, but it can be supposed that the stepwise changes in phase proportions were related to the cessation of general convection in the final stages of trap magma solidification. It is possible that such a change in the convection regime may also occur in larger intrusion chambers. In particular, a similar scenario was supposed for the interpretation of the mineralogical and textural characteristics of rocks from the upper part of the layered series of the Skaergaard intrusion [40].

On the Role of Compositional Convection

The ideas of concentrational or compositional convection have been developed since the 1970s and are based on the effect of different buoyancies of basic igneous melt and liquid resulting from crystallization in the basal layer. It is well known that olivine is usually the first phase crystallizing from basaltic melt and is the densest silicate phase. This results in the accumulation of components with high partial volumes (SiO_2, Al_2O_3, and alkalis) in the residual liquid. It is supposed that this feldspar-rich liquid forming at the boundary of the bottom zone of heterogeneous crystal nucleation can migrate upward owing to its lower density and mix with the overlying melt. This mechanism of melt mixing is more efficient than diffusion (see above). Many authors invoked this mechanism as a physical basement for the description of the thermal history and chemical evolution of homogeneous intrusive magma (e.g., [41, 42]). The theoretical analysis of the condition of occurrence of such convection flows was given in [19] and experimental evidence was reported in [43] on the example of the investigation of the crystallization of ammonium chloride aqueous solutions.

The experiments with salt systems revealed the interesting fact that, in addition to compositional convection, another type of convection flow forms at the boundary of the heterophase zone in the crystallizing system. This flow appears within the layer of partially crystallized solution. The subsequent analysis of this situation demonstrated that the nature of type II convection is also compositional and it is related to the ascent of less dense porous solution. It turned out that these movements have a structured character and develop somewhat later than type I convection. However, within a certain period of time (during the growth of the heterophase zone), jets of residual liquid impact the surface of the boundary layer, destroy the diffusion zone, and become the main factor of component exchange between the crystal mush and the overlying solution. The visualization of convection flows in experiments provided additional insights into the physical causes and characteristic features of redistribution of crystallization products, which allowed the development of a mathematical model of the initiation of compositional convection. The importance of these investigations goes far beyond the analysis of aqueous salt systems, because the character of relative motion of solutions and crystals in the heterophase zone shows an apparent similarity to processes occurring in igneous cumulus [5, 8], including the compaction of cumulates, migration of residual melts, and adcumulus growth.

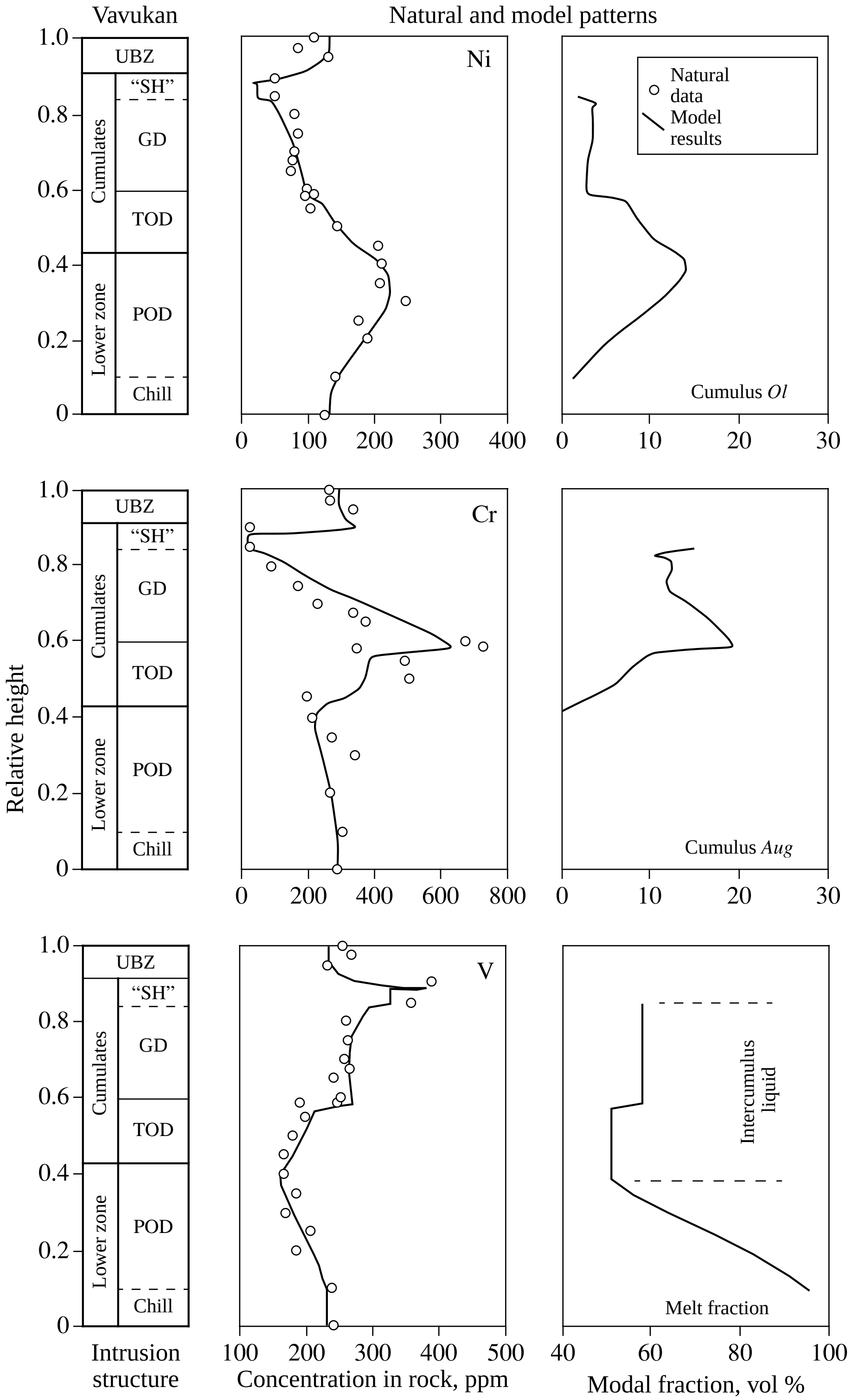

Fig. 1. Observed and model relationships of main types of rock, concentrations of trace elements, and initial proportions of crystals and melt for the Vavukan trap intrusion (100 m thick) [4].

The lower zone includes chilled rocks and poikilophitic dolerites (POD) formed through the entrapment of magmatic suspension by the solidification front. The zone of cumulates is defined by a critical melt fraction of 50–60% and is composed of taxitophitic dolerite (TOD) and gabbrodolerite (GD) grading into ferrogabbro of the "sandwich horizon" (SH). The upper border zone (UBZ) is formed by directional growth from the chamber roof. Smooth trends of changes in concentrations correspond to the high efficiency of the general sedimentation convection. The step on the TOD–GD boundary is interpreted as an indicator of the transition to crystal settling without the general stirring of the system.

Influence of Compaction and Adcumulus Growth

Irrespective of whether crystals precipitate from the main volume of magma or from a boundary layer near the lower crystallization front, the compaction of crystalline precipitate can occur in the accumulation zone [7]. This process develops as a result of the mechanical sorting and/or recrystallization accompanied by the filter-pressing of residual liquid [11, 44]. This is supported by recent experiments with mixtures of plagioclase and pyroxene crystals with diluted bromoform solutions. They demonstrated the formation of a self-sustaining crystal framework, which compacted with time, resulting in a decrease in porous space and the squeezing and migration of interstitial liquid [45]. It is suggested that such shrinkage convection flows [46] played an important role in the structural and chemical evolution of crystal mush and migrating melts in intrusion chambers at postcumulus stages [1, 44, 47, 48].

Possible changes in the chemical composition of the filtered liquid are related to the fact that it can move into the levels where the temperature, compositions of phases, and cotectic proportions of mineral grains differ from the conditions of initial crystal–melt equilibrium under which this liquid occurred in the moment of cumulus formation. If the velocity of the residual melt movement is lower than the rate of the attainment of equilibrium, the liquid becomes a thermal and reaction agent contributing to local temperature and compositional reequilibration. At the investigation of the Muskox intrusion, Irvine [47] referred to this process as magmatic infiltration metasomatism. He supposed that the directed migration of intercumulus (interstitial) liquid and the processes of recrystallization influenced by it could begin and occur within the layers of ultrabasic cumulates at depths of several hundred meters below the current level of crystal sedimentation. In the context of the dynamics of convection processes, melt infiltration is a kind of phase convection, because, similar to sedimentation, relative movements of crystals and liquid phase take place and can be described by a single system of differential equations [1, 49].

Compositional convection accompanied by compaction and melt migration in the cumulus fundamentally changes the heat balance at the boundary and within the heterophase zone, which could result in adcumulus overgrowth and crystal growth under near-isothermal conditions [5, 44]. The effect is that the input of “hot” undepleted magma into the crystallization zone is compensated by the ascending flow of heated porous residual melt. This contribution of the convection component of the heat transfer is manifested in that the total conductive heat flow through the lower solidification front decreases abruptly and the temperature at the front and within the heterophase zone can be kept constant over a prolonged period of time. This provides conditions for isothermal crystallization in accordance with the classic theory of adcumulus growth [50]. Kerr and Tait [51] calculated that the combined effect of the compositional convection and adcumulus growth results in a decrease in the porosity of the initial cumulates of up to 10–20%. As will be shown below, these estimates are consistent with the results of the reconstruction of phase relations for the marginal rocks and the weighted average composition of the Dovyren intrusion. The conclusion about the extreme depletion of the Dovyren cumulates in intercumulus melt is supported by geochemical evidence.

THE GEOLOGIC SETTING AND STRUCTURE OF THE DOVYREN MASSIF

The Dovyren (Ioko–Dovyren) dunite–troctolite–gabbro pluton is a spectacular and comprehensively studied example of the layered massifs of the northern Baikal region [52–55]. Although Late Precambrian in age (~700 Ma [55]), it did not experience metamorphic alterations and is therefore a convenient object for petrologic and geochemical investigations [56–60]. Despite rather contrasting phase layering, some characteristics of its structure suggest the absence of magma convection in the intrusion chamber at the stage of massif development. It has long been pointed out that this intrusion appears as if inserted into the host carbonate–terrigenous sequence. The carbonate layers of this sequence are the most resistant to the replacement by basaltic melt and are traced as xenoliths within the pluton. Their initial position remains undisturbed in the frame forming “transparent structures.” This suggests that there was no large-scale mingling, and the differentiation of the Dovyren magma could proceed via mechanisms including the “quiet” sedimentation of injected crystals and postcumulus melt infiltration.

Geologic Setting

The Dovyren intrusion (Fig. 2) occurs in the Late Proterozoic folded framing of the Siberian craton and is confined to a continental-margin rift structure known as the Synnyr trough in the literature. The enclosing Riphean deposits are represented by a regressive carbonate–quartz–mudstone sequence, which experienced complex dislocations and metamorphism of the greenschist facies. Volcanics of a basaltoid composition occur in the axial part of the rift. They are chemically similar to the rocks from the roof of the Dovyren massif [61] and are close to them in age (700 ± 20 Ma [62]). The pluton is expressed in the topography by the Ioko and Dovyren peaks separated by the valley of the Ondoko River (right tributary of the Tyya River). Geologically, it is a lenslike body $\sim 26 \times 3$ km^2 in size. Geophysical investigations traced it up to a depth of 4–5 km from the modern surface, and it pinches out gradually with depth. The massif lies conformably in the framing rocks both along the strike and the dip, which is near vertical owing to postintrusion fold deformations. Detailed mapping demonstrated that the contour of its bottom cuts the layered structure of the framing at an acute angle. This is

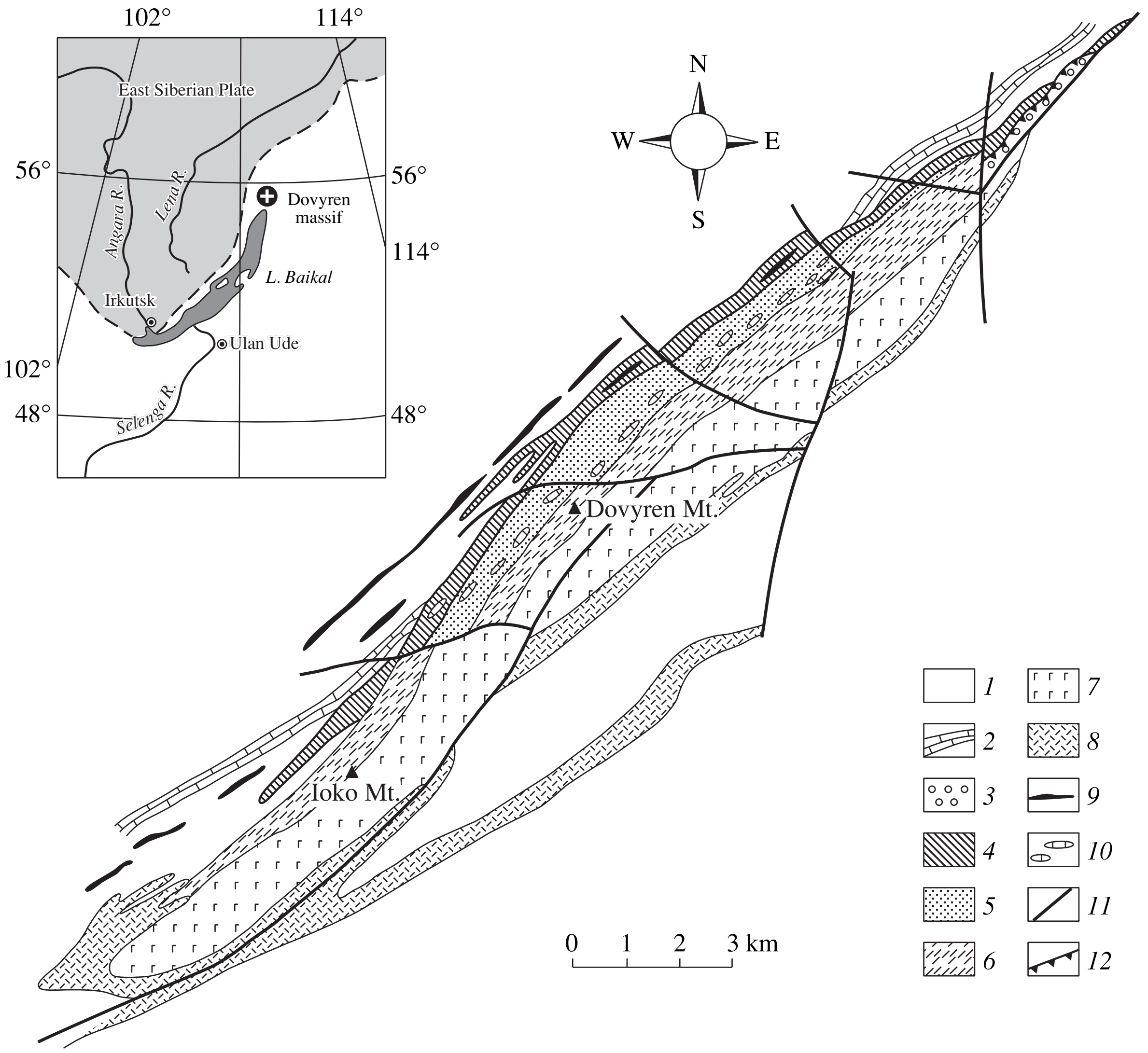

Fig. 2. Schematic structure of the Dovyren dunite–troctolite–gabbro (norite) pluton.

(*1*), (*2*) Rocks of the host Late Proterozoic sequence: (*1*) terrigenous and (*2*) carbonate; (*3*) conglomerate, sandstone, and mudstone of the Kholodninskaya Formation (Early Cambrian); (*4*)–(*9*) Dovyren layered pluton: (*4*) basal horizon of plagioclase lherzolite (plagioperidotite), (*5*) dunite zone *A*, (*6*) intercalation of melanocratic troctolite and plagioclase dunite of zone *B*, (*7*) olivine gabbro and gabbronorite of zones *C* and *D*, (*8*) olivine-free gabbronorite of zone *E*, and (*9*) sills and dikes of the same composition (comagmatic?); (*10*) xenoliths of magnesian skarn after carbonate in dunite; (*11*) fault; and (*12*) discontinuity. The inset shows the position of the massif in the structure of the folded framing (white background) of the Siberian craton.

illustrated by Fig. 2, where the northwestern contact of the pluton cuts a carbonate layer occurring near the bottom of the intrusion. The preintrusion position of the carbonate layer is clearly marked by xenoliths of magnesian skarn after dolomites.

Internal Structure of the Dovyren Massif

The structure of the pluton changes along strike: its center (Dovyren Mountain) includes a thick ultramafic sequence, while the southwestern margin (Ioko Mountain) is dominated by basic rocks. The phase layering is comprehensively studied in the ultramafic–mafic part of the intrusion. The main types and sequence of rocks in the sections are usually distinguished from the mineral assemblages of textural group I, which is identified as the combination of cumulus phases [53, 63]. On the basis of these data, a layer of basal plagioperidotite (*PP*) and five main zones are distinguished (Fig. 3). These zones correlate with changes in cumulus assemblages from bottom to top: $Ol + Chr$ (zone *A*) $\longrightarrow$ $Ol + Pl + Chr$ (zone *B*) $\longrightarrow$ $Pl + Ol + Cpx$ (zone *C*) $\longrightarrow$ $Pl + Ol + Cpx \pm Opx$ (zone *D*) $\longrightarrow$ $Pl + Opx + Cpx$ (zone *E*).[1] This general sequence was established from the

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[1] Abbreviations of mineral names: *Ol*, olivine; *Cpx*, clinopyroxene; *Opx*, orthopyroxene; *Phg*, phlogopite; *Chr*, chromite; *Fo*, forsterite; *E*n, enstatite; *An*, anorthite; *Mt*, magnetite; and *Qu*, quartz; *mg*# = Mg/(Mg + Fe).

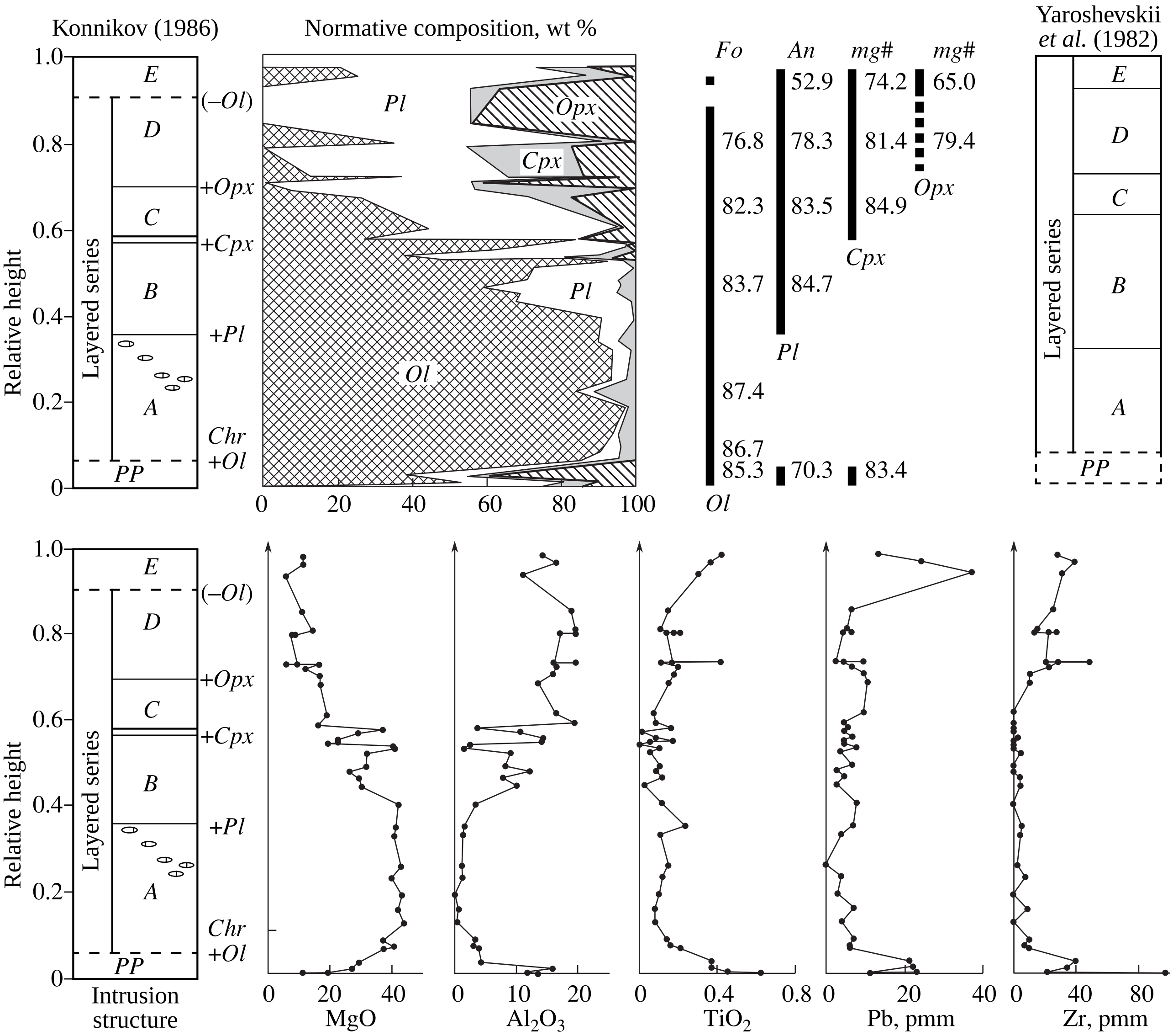

Fig. 3. Relationships of the main structural units of the Dovyren intrusion and their mineralogical and geochemical characteristics according to [53, 55, 56].

The black band in zone *C* shows a zone of "low-sulfide" PGE mineralization.

predominant mineral associations in textural group I. In reality, the interlayering and rhythmic intercalations of various rocks types are observed, and more "primitive" assemblages often return. The relative volumes of the main zones are similarly estimated by various authors; a more fundamental discrepancy concerns the geologic position of roof zone *E*. Yaroshevskii *et al.* [56] considered the most abundant olivine-free (granophyre) gabbronorite and quartz gabbro of this zone as an end-member of the layered series. According to another interpretation, the layered series of the Dovyren intrusion is crowned by olivine gabbro and gabbronorite (zones *C* and *D*), whereas the overlying rocks of zone *E* were formed by an independent injection of basic melt [53]. This discrepancy is reflected in the petrographic classification of the Dovyren intrusion, which is regarded as either a dunite–troctolite–gabbro–norite or a dunite–troctolite–gabbro pluton.

Basal plagioperidotites are represented by plagioclase lherzolites, which make up a layer from 160 to 270 m thick (~200 m on average). These rocks are composed of three cumulus minerals (*Ol* + *Pl* + *Cpx*). The interstices between them are filled with *Opx*, *Phg*, and pargasitic amphibole. Owing to variations in the proportions of cumulus minerals, the plagioperidotites are sometimes slightly differentiated and grade into olivine gabbronorite and gabbro. Quenching in the near-contact zone makes them similar to picrobasalt and picrodolerite (ophitic gabbro after [52]). The enstatite (*mg*# 79–85) and phlogopite (*mg*# 63–88) of the plagioperidotites form oikocrysts with poikilitic inclusions of cumulus minerals. Olivine is often corroded by orthopyroxene, which suggests their peritectic relationships. In addition to the basal zone, plagioperidotites occur as independent sills in the country rocks, which can be regarded as conduits of the Dovyren intrusion. The plagioperidotites are chemically similar to the weighted average composition of the massif.

Zone A (≤980 m thick) is the lowest in the layered series and is primarily represented by olivine mesocumulates and adcumulates. Olivine (80–97 vol %) forms euhedral grains, and the interstices are filled with chrome spinel, plagioclase, and minor clinopyroxene. The abundance of *Pl* in the dunite increases toward plagioperidotites, and the maximum of diopside content is confined to the upper part of zone *A*, where most xenoliths of magnesian skarn after carbonate occur (Fig. 3). According to Wenzel *et al.* [64], the appearance of intercumulus *Cpx* is related to the assimilation of CaO from the carbonate. The amount of diopside may reach 50 vol %, and the dunite grades into wehrlite with a poikilitic texture. Sometimes, clinopyroxene forms patches and irregular veins in dunite, which acquires a taxitic structure. Near the xenoliths, olivine is enriched in CaO (up to 0.9 wt %) and diopside is high in Al_2O_3 (up to 6.6 wt %) and wollastonite end-member.

Zone B (~700 m) overlies the dunite zone and is composed of intercalated melanocratic troctolite (30–50 vol % *Pl*) and plagioclase dunite (5–20 vol % *Pl*). The plagiodunite layers are thinner than troctolite ones (2–45 and 30–120 m, respectively). These rock types probably formed under the conditions of residual melt saturation in *Ol* and *Pl*, and both minerals can be considered as cumulus phases. The rocks show allotriomorphic textures, which are characterized by similarly anhedral habits of rock-forming minerals. The content of interstitial pyroxene is rarely higher than 2–3 vol % [63]. However, in the upper part of the zone, layers enriched in augite, poikilitic wehrlite, occur along with lenses of olivine gabbro similar in composition to the rocks of the following zone.

The thick overlying sequence (1100 m) of olivine gabbro and gabbronorite can be subdivided into two zones. *Zone C* is about 350–400 m thick and differs from the underlying rocks in the much lower content of olivine, appearance of augite, and predominance of plagioclase among cumulus minerals. Plagioclase laths often occur as inclusions in *Ol* and *Cpx*. The impregnation of uneven rims of augite grains into the interstices of *Ol* and *Pl* crystals is often observed. The rocks show gabbro to gabbroophitic textures. A characteristic feature of this olivine gabbro zone is the occurrence of numerous veins of gabbro pegmatite with taxitic structures in its lower part. They contain anorthositic aggregates with disseminated sulfides and high abundances of noble metals (PGE and Au). *Zone D* (≥600 m) is distinguished by the appearance of individual horizons of olivine norite and olivine gabbronorite. The rocks occur in a complex interlayering, and olivine gabbro is predominant. Its characteristic feature is the occurrence of large orthopyroxene oikocrysts. The olivine norites and olivine gabbronorites show gabbro textures. The cumulus assemblage includes rounded *Ol* grains, short tabular *Pl* crystals, prisms of *Cpx*, and orthopyroxene. Granophyres occur at the boundary between zones *D* and *E*.

Roof zone E is 250–350 m thick [52, 58, 63] and is characterized by the occurrence of olivine-free rocks, quartz gabbro and granophyric gabbronorite. In contrast to the underlying rocks, they do not bear accessory chrome spinel, which is substituted by ilmenite, Ti-magnetite, and apatite. The textures of the main rock types are characterized by the predominance of tabular grains of zoned labradorite–andesine, hypersthene, and augite. The interstices are filled with brown amphibole, biotite, and granophyre [55]. These rocks can be distinguished from the gabbroids of the lower zones by the composition of the interstitial material. In chemical and phase composition, zone *E* is similar to the sills and dikes cutting the basal plagioperidotites. It is also known that the bottom and roof granophyric gabbronorites meet at the southwestern pinching out of the massif (Fig. 2). This was used as an argument to discard the rocks of zone *E* as products of chamber differentiation of the Dovyren magma [53]. However, the geologic position of this zone allows alternative interpretations.

If the quartz gabbro and granophyric gabbronorite do not in fact belong to the layered series in the classic concept of the sequence of precipitation of cumulus minerals, it could be suggested that a significant portion of zone *E* is composed of the crystallization products of residual melts filtered from the underlying levels (see below). It is also possible that the “metasomatic” alteration of lower temperature crystallization products, which might form at the stage of sedimentational fractionation, could result from the influence of this ascending flow of relatively primitive pore melts. In any case, both hypotheses are consistent with the enrichment of zone *E* in incompatible elements and do not contradict the accumulation of Cu at late stages of the process [58–60]. The abundance of plagioclase crystals with contrast zoning [56] can be considered as evidence of such partial “autohybridization” of the roof rocks.

Evolution of Rock Compositions

Figure 3 displays some features of the chemical and mineralogical compositions of the Dovyren intrusion. In accordance with the phase composition of the cumulates, the MgO distribution is controlled by the content of *Ol* (in dunite, plagiodunite, and troctolite) and pyroxenes (gabbroids) and Al_2O_3, by plagioclase. Such a behavior of major rock-forming oxides is typical of many mafic–ultramafic layered complexes. It is unusual that the MgO content in the upper (probably, late) differentiation products decreases insignificantly and averages at about 10 wt % in zone *E* [63]. This suggests the absence of efficient fractionation of femic silicates at the final stages of solidification of the Dovyren magma or the influence of additional factors of component transport, which modified the primary (probably, more evolved) composition of the late differentiation products.

The behavior of incompatible elements provides some insight (Fig. 3). For example, Ti, Rb, and Zr show C-shaped distributions within the section with distinct maxima in the basal plagioperidotites and roof rocks. The concentrations of these elements decrease in the dunites and troctolites by a factor of 5–10. There are distinct Ti and Zr minima in the middle zone *B*. It is known that the concentrations of incompatible elements are indicators of the amount of mesostasis [65, 66], which allows the estimation of the fraction of interstitial liquid in the cumulus [67, 68]. Thus, the analysis of the behavior of Ti and Zr leads to the conclusion that the amount of intercumulus melt was the lowest in the troctolite zone and, in general, increased downward through the dunite zone toward the basal plagioperidotites (Rb is not considered because it occurs in part in *Pl* of troctolite). Incompatible elements (Ti, conventionally) are similarly distributed in the gabbroids and gabbronorites demonstrating a tendency of enrichment in zones *D* and *E*. The peaks of intercumulus liquid content mark anorthositic reefs with noble metal mineralization of the low-sulfide type [69]. Note that this level is also characterized by a sharp change in the mineral composition of rocks of the layered series.

Evolution of the Composition of Minerals

Figure 3 shows trends in the compositions of major cumulus minerals (*Ol*, *Pl*, and pyroxenes) through the section of the layered series of the Dovyren massif. These data are average values calculated for each zone after [53]. The standard deviations (1σ) of mineral compositions in zones *A*, *B*, *C*, and *D* for *Ol* and *Pl* are no higher than 1–2 mol %, and the *mg#* value of pyroxenes is estimated with an error of 2–4%. The compositions of minerals from zone *E* show a much larger scatter corresponding to 1σ of ~6–7% for all minerals. Note the relatively low *An* content of *Pl* from the bottom plagioperidotites (70.3 ± 14.5, $n = 6$). The main layered series ($A \longrightarrow B \longrightarrow C \longrightarrow D$) shows small variations in the compositions of *Ol* (10–12 mol % *Fo*) and *Pl* (~7 mol % *An*) and a systematic decrease in the concentrations of refractory components upward in the section. This is a typical evolutionary trend of intrusive magma. The distribution of *Fo* content in olivine from the lower part of the dunite layer and plagioperidotites is unusual. There is a certain tendency of enrichment in forsterite end-member from bottom to top at the transition from the plagioperidotites (85.3 ± 1.4 mol % *Fo*, $n = 11$) to the lower plagiodunites (86.7 ± 1.6, $n = 15$) and the main dunite volume (87.4 ± 1.5, $n = 60$). This is not consistent with the “normal” change of compositions in a crystallization process.

The geologic relationships suggest that the plagioperidotites could represent an independent injection of magma cogenetic with the parental magma from which the layered intrusion was formed. Another explanation is based on the supposition that the initial suspension included melt and solid phases, and its average composition did not correspond to the temperature and composition of the liquid but was enriched in higher temperature (refractory) components [28]. In such a case, the dunites can be interpreted as products of sedimentation and compaction of crystals of initially nonequilibrium high-magnesium olivine. Furthermore, there is reason to believe that such a character of the changes in the *Ol* composition in the lower part of the massif was related to higher rates of crystallization in the border zone in comparison with the inner parts of the intrusion chamber [70]. Finally, it can be supposed that the unusual trend of the *Fo* content is related to some specific features of recrystallization in the cumulus at early stages of the solidification of the Dovyren magma. Frenkel’ [1] demonstrated that an increase in *mg#* of cumulus minerals is possible at their partial melting, reequilibration, and filter-pressing of a part of the newly formed intergranular melt. This scheme requires additional heat supply and the occurrence of inflections in temperature profiles along the sections of the crystalline mush.

As of now, it is difficult to find conclusive arguments in support of or against these interpretations. We assume that the plagioperidotites and chilled marginal rocks were inherent parts of the Dovyren section, and the earliest (close to equilibrium) *Ol* crystals were $\sim Fo_{84-85}$, corresponding to olivine from the basal plagioperidotites and troctolites (Fig. 3). The composition of the earliest plagioclase crystals was probably within 80–85% *An*.

GEOCHEMICAL THERMOMETRY OF THE DOVYREN ULTRAMAFIC ROCKS

The problems of formation of the interior structure of the Dovyren massif cannot be solved without the estimation of the physicochemical parameters of the state of the initial magma. This task is connected with the determination of the thermodynamic and dynamic properties of the intruded material, including the temperature and composition of the initial liquid, degree of magma crystallization during the emplacement, proportions and compositions of mineral phases suspended in the melt, and rheological properties of the melt and magma. These parameters can be derived from the solution of an inverse geochemical problem on the basis of modeling primary melt–crystal equilibria for the marginal rocks (method of geochemical thermometry). This method relies on the use of the COMAGMAT computer model [71] and was initially developed for hypabyssal basic rocks. It provided information on the conditions of formation of differentiated sills, which is

Table 1. Compositions of rocks from the basal (marginal) zone and the average composition of the Ioko–Dovyren massif, wt %

Component	Rocks of border zone [52]			Rocks from lower and upper parts of plagioperidotite layer underlying plagiodunites and dunites of the main layered series [55]					Weighted average characteristics [63]	
	Gabbro ($n = 3$)	Olivine gabbronorite and plagioperidotite ($n = 19$)	Ophitic gabbro ($n = 3$)	Picrobasalt D476	Picrodolerite 245k	Olivine–phlogopite gabbronorites		Average composition of massif	Average composition ($n = 256$)	Chilled gabbronorite ($n = 2$)
						D59g	D476/k			
	1	2	3	4	5	6	7	8	9	10
SiO_2	48.46	44.69	48.48	52.32	48.53	50.79	48.50	46.52	44.54	47.71
TiO_2	0.43	0.25	0.49	0.63	0.57	0.42	0.46	0.37	0.09	0.36
Al_2O_3	10.07	5.93	10.58	13.72	9.84	14.06	11.93	7.83	10.64	9.11
FeO	10.23	11.53	10.70	9.61	10.31	8.28	10.19	10.44	10.05	10.37
MnO	0.20	0.16	0.18	0.16	0.18	0.11	0.16	0.19	0.14	0.15
MgO	20.47	32.56	18.57	11.08	22.53	15.59	19.45	27.17	26.57	24.75
CaO	8.50	4.27	9.26	9.89	6.47	8.08	7.25	6.43	7.35	6.03
Na_2O	0.79	0.35	1.06	1.96	0.92	2.04	1.34	0.66	0.54	0.94
K_2O	0.77	0.18	0.64	0.51	0.58	0.41	0.69	0.34	0.07	0.54
P_2O_5	0.07	0.07	0.04	0.11	0.07	0.22	0.03	0.06	0.01	0.04

Note: The compositions are normalized to totals of 100 wt %; all iron is given as FeO.

recorded in the bulk chemical compositions of dolerites from these bodies [72, 73].

The combined analysis of phase equilibrium calculations for the least fractionated (usually, border) samples and weighted average composition of a massif allows the reconstruction of the temperature, compositional, and phase characteristics of initial magma for larger intrusions [27, 28, 68, 74, 75]. These publications described in detail the thermodynamic principles, errors, and conditions of application of geochemical thermometry. In this paper, we only recall the sequence of steps at the practical application of this method. Thermometric investigations require (1) the selection of several samples from the rocks of a given intrusion, for which it is reasonable to suppose the most primitive composition of intercumulus or trapped liquid; (2) numeric experiments on the equilibrium crystallization of melts corresponding to the compositions of the selected samples; (3) the construction of temperature–concentration dependencies for model liquids; and (4) the determination of the point (domain) of intersection of evolution paths, which corresponds to the probable equilibrium of crystals and melt in the parental magma. This domain determines the temperature and composition of igneous melt at the moment of emplacement with an error of 10–15°C. Projection of the determined parameters onto the crystallization path of the weighted average composition of the intrusion allows the estimation of the phase composition (crystallinity) of the magma and of the initial compositions of intratelluric minerals [26].

Selection of Compositions

Table 1 presents the petrochemical characteristics of the rocks of the border and basal zones of the Dovyren intrusion [52, 55] and the weighted average composition of the massif [63]. The compositions representing the chilled facies and marginal material are potentially informative for the purposes of geochemical thermometry. The transition from particular samples to average contents in a given set does not affect the final result of thermodynamic calculations (the estimate of initial temperature), because any average composition can be presented as a mechanical mixture of several melt–crystal associations, from which the rocks crystallized. A more important problem concerns the possible modification of initial chemical characteristics by secondary oxidation, fluid influence, or assimilation processes near the contact of the intrusion. Strictly speaking, such investigations require a careful analysis of a representative collection of marginal rocks. For instance, such work was done for 80 samples of "chilled gabbro" from the Marginal Border Group of the Skaergaard intrusion [71, 76].

In the context of the problems of the Dovyren intrusion, we restrict our consideration to nine "near-contact materials" (compositions 1–9 in Table 1), relying on the remarkable property of geochemical thermometry to reject crystallization trends strongly deviating from the general population of cotectic lines. This provides the genetic informativity of the method [72], which is especially important taking into account a significant scatter in rock compositions from the chilled facies of the massif (cf. columns 3, 7, and 10 in Table 1). Moreover, there are discrepancies in the estimates of the weighted average compositions of the layered series of the massif, which, according to [53], is similar to the average composition of the basal plagioperidotite (except for K_2O and H_2O contents) and significantly lower in Al_2O_3 and CaO in comparison with the data of [63] (cf. columns 8 and 9 in Table 1). These discrepancies put some limitations on the interpretation of the results of modeling, which are described below.

Conditions of Modeling of Phase Equilibria

Calculations by the method of geochemical thermometry require the specification of pressure (total and water) and redox conditions of the initial magma intrusion. The geological data suggest that the Dovyren intrusion was formed at a depth of 1.5 km [52], which is equivalent to $P \sim 0.5$ kbar. This estimate is consistent with the determination of the pressure from the composition of magnesian skarns after carbonates [77]. The absence of hydrous minerals in the main rock assemblage of this intrusion and the occurrence of potassium feldspar antiperthite inclusions in plagioclase of the gabbroids suggest that the Dovyren magma was not saturated in H_2O. Kislov [55] estimated P_{H_2O} as no higher than 0.7 kbar, which is close to total pressure. The following calculations of phase equilibria were carried out for the conditions of a dry system.

The estimation of the oxygen fugacity is more controversial. It is usually based on the data on the bulk Fe_2O_3/FeO ratio in rocks, which, by analogy with melt, must depend on the T, f_{O_2}, and liquid composition [78]. Such an approach is impracticable for the Dovyren massif, because (as will be shown below) its initial magma contained considerable amounts of intratelluric crystals, mainly *Ol*. The assumption that the bulk composition of this mixture approximates the liquid phase would result in an unrealistically high emplacement temperature, and most of the ferrous iron from olivine would be stored in the melt. Because of this, the choice of redox conditions was based on well-known data on the degree of oxidation of natural magmas [79], taking into account the absence of magnetite among the cumulus minerals. Thus, the crystallization paths were modeled under relatively reduced conditions corresponding to the wüstite–magnetite (WM) buffer.

Results of Geochemical Thermometry

Equilibrium crystallization was modeled for every composition using the COMAGMAT-3.52 program at a pressure of $P = 0.5$ kbar and the WM redox buffer under the conditions of a sequential increase of melt crystallization with an increment of 1 mol %. In contrast to previous thermometric investigations, when the crystallization paths were calculated up to 40–30% of residual liquid, systems containing less than 10–15% melt were modeled for the Dovyren rocks. This was aimed at accounting for the possible compaction of cumulates. The idea of such calculations is based on the assumption that the Dovyren magma was not overheated (at an MgO content of about 27 wt %, this would require temperatures higher than 1500°C) and brought appreciable amounts of intratelluric phases ($Ol \pm Pl \pm Cpx$) into the chamber. In such a case, variations in rock composition near the lower contact and in the plagioperidotite layer can be considered as a result of the redistribution of crystals in the liquid that was produced by the crystallization of initial magma at the stage of emplacement [29]. The consistency of the model and observed compositions of rock-forming minerals, primarily *Ol*, can be used as a criterion for the feasibility of this assumption.

The main results of calculations are shown in Figs. 4–7. Note that these data concerning the selected marginal materials and the weighted average composition of the massif suggest a single trend of the temperature and compositional evolution of intercumulus melt, and significant differences in the cotectic compositions are observed only in the content of Na_2O in the melts and variations in the compositions of model plagioclase (Figs. 6, 7). This is an important preliminary conclusion indicating a common magmatic source of the chilled facies, basal plagioperidotites, and proposed model of the Dovyren magma.

The analysis of phase relationships was limited by the results for several representative compositions (ophitic gabbro, *Ol–Phg* gabbronorite, and average plagioperidotite) and the weighted average composition of the intrusion (compositions 3, 7, 8, and 9 in Table 1).

Evolution of the Phase Composition

According to calculations, the equilibrium crystallization of the melts of boundary rocks occurred in the sequence $Ol \longrightarrow Ol + Pl \longrightarrow Ol + Pl + Cpx \longrightarrow Ol + Pl + Cpx + Opx$ (Fig. 4). This sequence is determined by the strong oversaturation of all of the bulk compositions in the olivine components and may indicate that the chilled facies and plagioperidotites crystallized from mixtures containing from 37 to 58% *Ol* crystals (Fig. 5). At such a degree of crystallinity, plagioclase appears as a second (cotectic) phase, which is consistent with the structure of the Dovyren massif and the abundance of troctolite in its section (Figs. 2, 3). For all three compositions characterizing the plagioperidotite layer, the cotectic association $Ol + Pl$ appears at similar temperatures (~1200°C, Fig. 4) and the model compositions of olivine (84–86% *Fo*) and plagioclase (82–85% *An*) are similar to those observed in the layered series of the intrusion (Fig. 3).

The parameters of the *Ol–Pl* cotectic for the average Dovyren composition (Table 1) are somewhat different from the model characteristics of the plagioperidotites. The differences include the elevated initial temperature

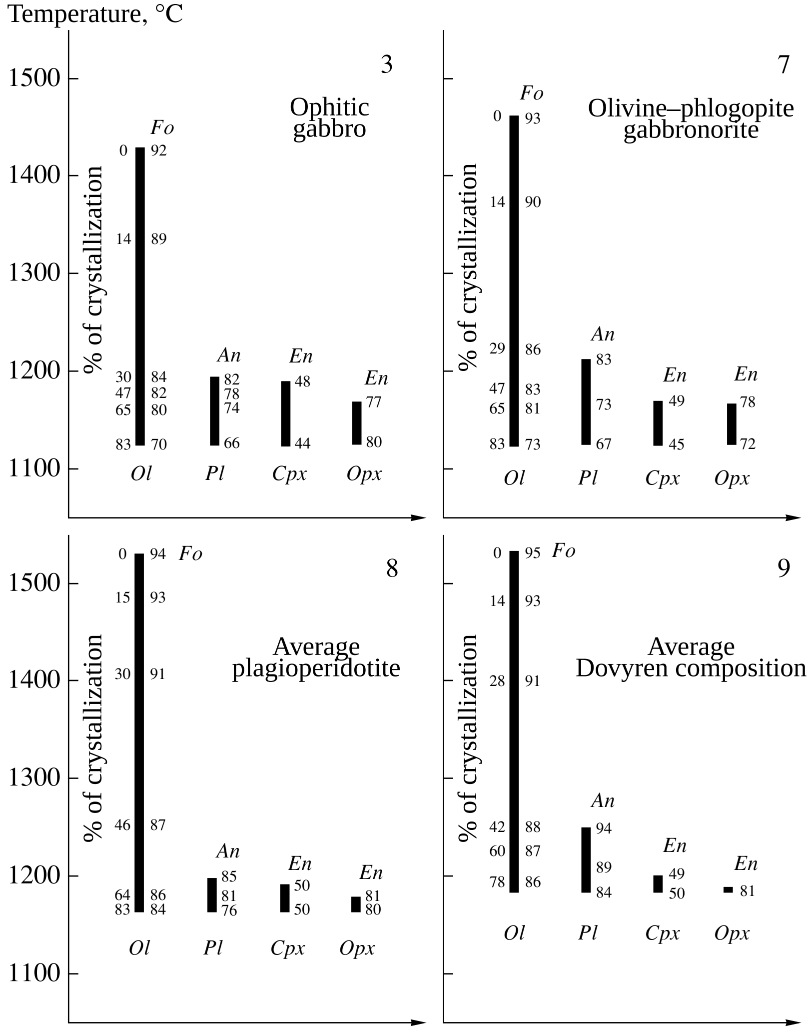

Fig. 4. Model crystallization sequences and compositions of minerals at the equilibrium crystallization of melts corresponding to the basal rocks and the weighted average composition of the Dovyren intrusion.

Chart numbers correspond to compositions in Table 1. The compositions were calculated by the COMAGMAT-3.52 program [26] at a pressure of 0.5 kbar, dry conditions, and f_{O_2} of the wüstite–magnetite (WM) buffer; the crystallization increment was 1 mol %. The degrees of crystallization of the system at given temperature are shown on the left of the *Ol* stability line.

of the simultaneous crystallization of *Ol* and *Pl* (~1250°C) and the more primitive compositions of the first cotectic crystals, 88% *Fo* and 94% *An* (Fig. 4). These differences are directly related to the estimate of the weighted average concentrations of rock-forming oxides, which were calculated in agreement with the accepted compositions and proportions of dunite, troctolite, and gabbroid in the massif [56, 63]. The highest temperature model parameters of the *Ol–Pl* assemblage mirror the considerable fraction of the "troctolite" component in the section (Fig. 3) and corresponding enrichment in alumina relative to the plagioperidotite (cf. columns 8 and 9 in Table 1). It is possible, therefore, that the average composition of the intrusion is, in fact, a biased estimate. However, it is important that the liquid line of descent for the average Dovyren composition enters precisely into the field of cotectic liquids calculated for the chilled facies and plagioperidotites (Fig. 6), although at unusually high crystal contents of about 85% (Fig. 5). These unusual "initial" phase characteristics will be interpreted in the following discussion.

Composition of Residual Liquid

Figure 6 demonstrates the convergence of the temperature–composition evolution lines of residual liquids for various initial compositions. It is clearly seen that the calculated trends approach each other for all components at the temperatures of the *Ol–Pl* cotectic and form rather compact clusters (intersection nodes) at 1190–1180°C. These intersections are most distinct on the diagrams of the temperature dependence of SiO_2, TiO_2, Al_2O_3, and CaO contents. We believe that the

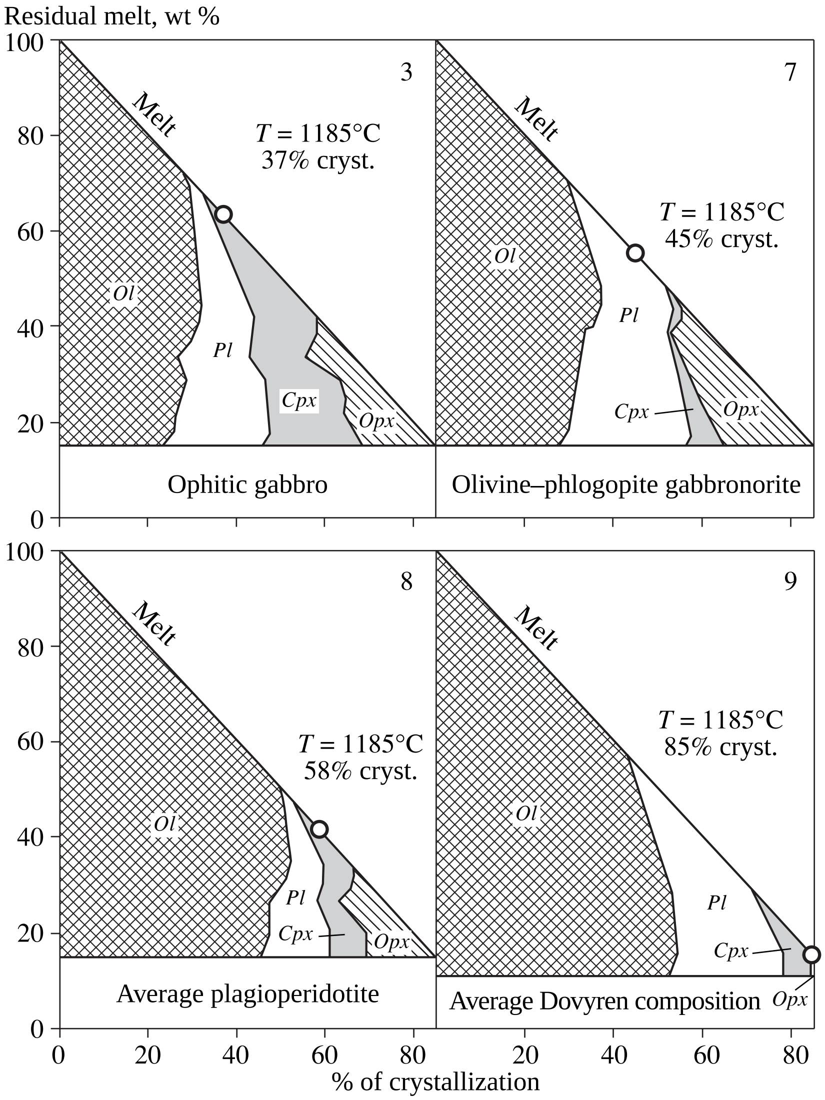

Fig. 5. Evolution of the phase composition of model systems at the equilibrium crystallization of melts corresponding to the basal rocks and weighted average composition of the Dovyren intrusion.

Chart numbers correspond to compositions in Table 1 and crystallization sequences in Fig. 4. For each composition, the degree of crystallization of the system corresponding to a temperature of initial magma of 1185°C is shown.

average value, 1185°C, can be regarded as the probable temperature of melt trapped in the intercumulus of the plagioperidotites and probably corresponds to the liquid portion of the parental magma.[2] The major-element composition of this liquid was calculated as an average of 10 model compositions at 1185°C (column 1 of Table 2). The chemical characteristics of the estimated melt correspond to silica-saturated and somewhat MgO-enriched (in comparison with typical tholeiitic basalt) basaltic andesite or boninite. Indirect evidence for the silica saturation of the initial melt is provided by the occurrence of gabbronorite and norite, which are characterized by the presence of orthopyroxene among cumulus minerals [56], in the upper part of the intrusion section and the replacement of olivine by enstatite in the plagioperidotite [53, 55]. Extensive experimental evidence on the melting of *Opx*-bearing intrusive and extrusive rocks suggests that this mineral usually crystallizes from basaltic andesite and andesite liquids.

Table 2 compares the average composition of the residual (presumably, initial) liquid with two model compositions corresponding to a temperature of 1185°C for particular trends: one of them characterizes the weighted average composition of the massif, and the other is a product of crystallization of the chilled gabbronorite (composition 10 in Table 1). Both compositions were included into the calculation of the average composition of the initial melt, but the comparison is

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[2] The term parental (initial) magma refers to the silicate melt mixed with crystals that filled the intrusive chamber of the Dovyren pluton.

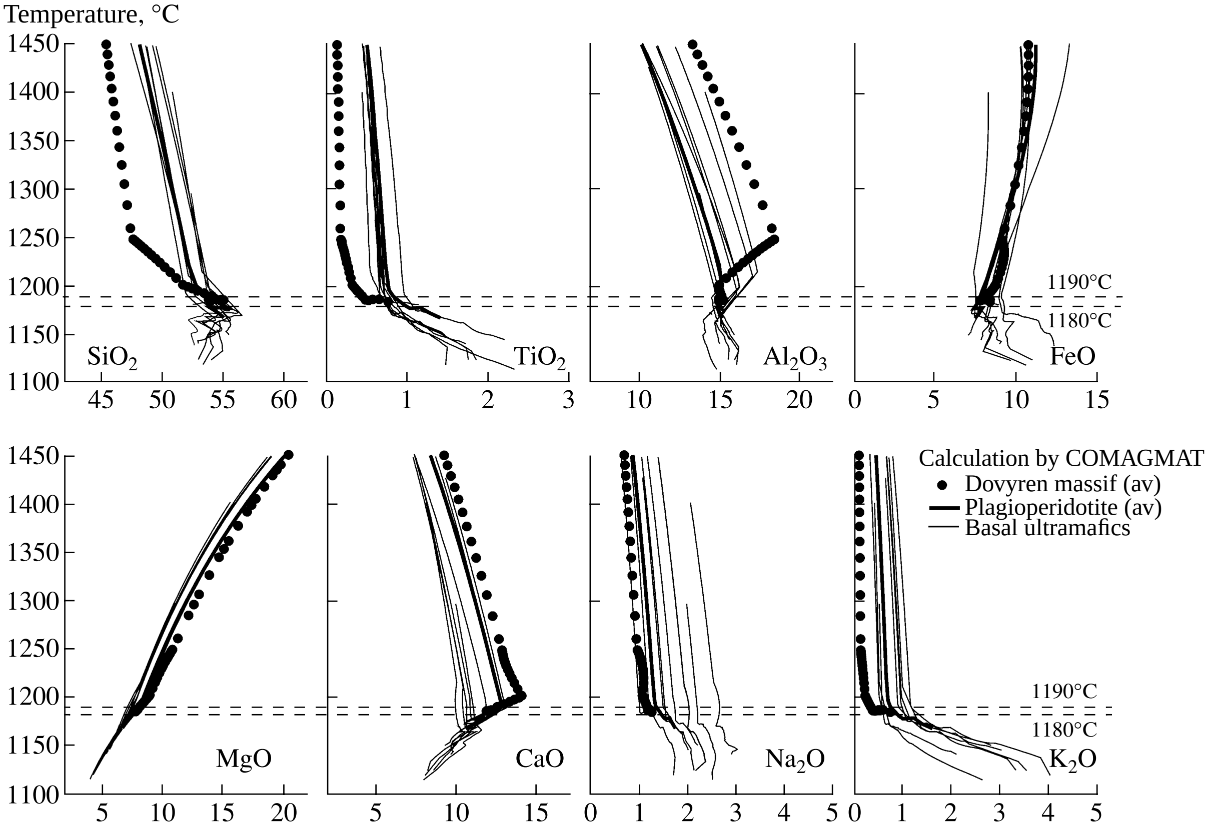

Fig. 6. Calculated liquid lines of descent for the equilibrium crystallization of melts corresponding to the basal rocks and weighted average composition of the Dovyren intrusion.

The convergence of evolution paths at temperatures of 1180–1190°C indicates the common composition of initial magmatic melts corresponding to silica-saturated magnesian basalt (Table 2). The calculation conditions are given in the caption of Fig. 4.

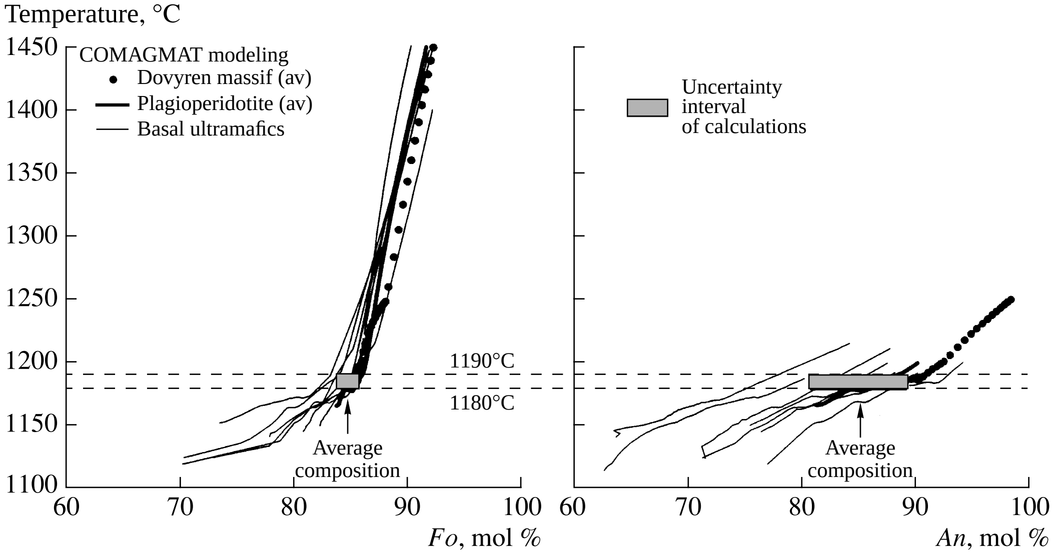

Fig. 7. Evolution of *Ol* and *Pl* compositions at equilibrium crystallization of melts corresponding to the basal rocks and the weighted average composition of the Dovyren intrusion.

The contents of *Fo* in model *Ol* at 1180–1190°C (84.5 ± 1.0 mol %) are similar to olivine compositions from the basal dunites and plagioperidotites [53, 55]. The considerable scatter in the calculated *An* contents of *Pl* (80.5 ± 4.5 mol %) reflects the uncertainty in the estimation of Na_2O content in the rocks and melts (Fig. 6).

Table 2. Chemical and phase characteristics of the possible "initial" magmas of the Ioko–Dovyren layered intrusion according to the results of computer modeling

Component	Initial melt (n = 10)	Average composition of massif (no. 9 in Table 1)	Chilled gabbronorite (no. 10, Table 1)
Melt composition at 1185°C, wt %			
SiO_2	54.13 (0.80)	55.19	55.00
TiO_2	0.78 (0.10)	0.48	0.74
Al_2O_3	15.24 (0.42)	15.22	15.52
FeO	8.19 (0.57)	7.78	7.58
MnO	0.15 (0.02)	0.15	0.14
MgO	7.51 (0.33)	7.83	7.33
CaO	11.33 (0.87)	11.72	10.80
Na_2O	1.65 (0.47)	1.18	1.72
K_2O	0.88 (0.25)	0.39	1.08
P_2O_5	0.14 (0.09)	0.06	0.08
Phase composition of initial magma, wt %			
Melt	100.0	14.5	48.9
Ol	$Fo_{84.6 \pm 1.0}$	54.3 ($Fo_{85.7}$)	46.5 ($Fo_{85.3}$)
Pl	$An_{80.5 \pm 4.5}$	23.6 ($An_{85.4}$)	4.6 ($An_{79.8}$)
Cpx	–	6.4 ($En_{50.9}Fs_{7.4}$)	–
Opx	–	0.1($En_{80.6}Fs_{12.5}$)	–
F	0.0	85.5	51.1

Note: The initial melt corresponds to the average of 10 compositions of model liquids at 1185°C (Fig. 6); standard deviations are shown in parentheses; and *F* is the percentage of crystals in the system (initial degree of crystallinity).

instructive, because it points out the above-discussed systematics of differences for the average compositions of the Dovyren massif [63]. Despite the identical temperature, this source yields a more refractory mineral assemblage, which, in addition to *Ol* and *Pl*, includes clinopyroxene and orthopyroxene at 1185°C (Figs. 4, 5).

Compositions and Proportions of Primary Cumulus Minerals

Taking into account that the method of geochemical thermometry is based on the assumption of the equilibrium partitioning of components between the minerals and the melt, the obtained data allow us to estimate the initial compositions of cotectic minerals occurring at the stage of initial magma emplacement into the intrusion chamber. Figure 7 shows the evolution of olivine and plagioclase compositions for all calculated compositions and the interval of uncertainty of model results at temperatures of 1190–1180°C. Similar to the composition of the residual liquid, the probable compositions of the primary cumulus crystals were calculated as averages of 10 model compositions at an emplacement temperature of 1185°C. These estimates are close to 85 ± 1 mol % *Fo* and 81 ± 5 mol % *An* (Table 1) and agree with the results of microprobe investigations of *Ol* and *Pl* from the rocks of the Dovyren pluton (Table 3). The great scatter of the anorthite mole fraction of plagioclase reflects the considerable variations in Na_2O content in model liquids (Fig. 6).

In addition to initial compositions, the results of phase equilibrium modeling allow the estimation of the initial proportions of crystals and melt for particular rocks and the initial magma (which is approximated by the weighted average composition of the intrusion). Figure 5 shows the degrees of crystallinity calculated at 1185°C for four systems. These data show that the boundary ophitic gabbro (composition 3) and *Ol–Phg* gabbronorite (composition 7) correspond to mixtures containing 37 and 45% of crystal phases, respectively. The plagioperidotite and the average composition of the intrusion yield much higher values, 58 and 85%, respectively. It is interesting that the system representing the chilled gabbronorite [63] contains 51% primary crystals (Table 2). Thus, the data obtained reveal characteristic differences between the phase compositions of the chilled marginal facies (~40–50% crystals) and systems of elevated crystallinity, *F*, including plagioperidotite (*F* ~ 60%) and the average composition of the intrusion (*F* ~ 85%). It is reasonable to suppose that the plagioperidotites could be enriched in cumulus minerals as rocks of the inner part of the massif. Applying the same reasoning to the weighted average composition [63], we must admit that the respective estimate contains some excess amount of ultramafic material.

Evidence for the Low Porosity of Dunites and Troctolites

The refractory character and elevated crystallinity of the model system corresponding to the average composition of the Dovyren massif can be interpreted as an indication of the high degree of compaction of crystalline material in the dunite and troctolite cumulates, which give the main contribution into the weighted average composition [63]. This implies the low fraction of the residual (interstitial) liquid, which is supported by the geochemical systematics of the Dovyren ultramafic rocks. The analysis of cumulus porosity is usually based on the behavior of incompatible elements, whose concentrations in rocks are proportional to the amount of trapped or intercumulus melt [65]. Of special value is the analysis of correlation relationships for several elements that distribute into the liquid phase [67]. An attempt to determine such correlations is illustrated in Fig. 8, which shows variations of V and Ti contents in the dunite, troctolite, and olivine gabbro from zones *A*, *B*, and *C* of the Dovyren intrusion (after [58]). Also shown are the compositions of two rocks representing the chilled facies.

It is clearly seen that the trend formed by the dunites and troctolites points toward the chilled rocks. How-

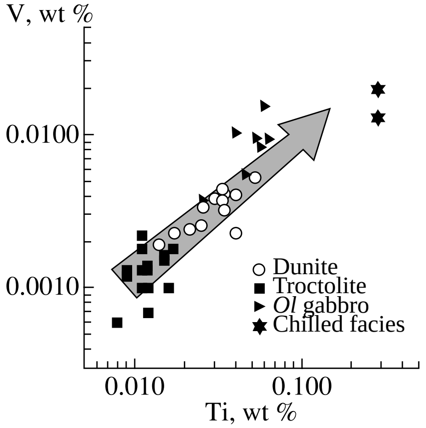

Fig. 8. Correlation of V and Ti contents in the dunites, troctolites, and olivine gabbros from zones *A*, *B*, and *C* of the Dovyren intrusion [55, 58].

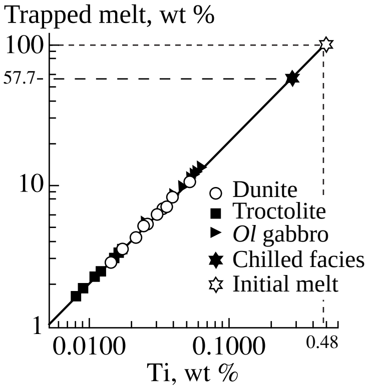

Fig. 9. Concentration of Ti in the Dovyren cumulates as a function of the amount of intercumulus (residual) melt.

The diagram is constructed assuming that titanium behaved as a perfect incompatible element. The point of weight Ti content at 100% liquid corresponds to 0.78 wt % TiO_2 in the initial magmatic melt according to the results of geochemical thermometry (Table 2).

ever, the compositions of gabbroids deviate from this trend. This is consistent with the well-known geochemical behavior of V and Ti, which can be regarded as incompatible components at the stage of *Ol* and *Pl* crystallization, but distribute into the solid phase after the onset of clinopyroxene crystallization. Two preliminary conclusions can be drawn from these data. First, the fraction of intercumulus liquid in the dunites and troctolites is lower than the amount of melt corresponding to the bulk composition of the chilled facies by a factor of 10–30. Second, it appears that the troctolites are characterized by the lowest porosity in the section of the massif even in comparison with the dunites (Fig. 8). These conclusions can be quantified on the basis of the results of geochemical thermometry.

For this may be used the average TiO_2 concentration in the initial melt (0.78 wt %, Table 2), which is equivalent to an element concentration of 4800 ppm (0.48 wt % of Ti) and is related to 100% of liquid phase. Considering titanium as "an ideal incompatible element," the value 0.48 wt % can be compared with the real Ti content in the dunites and troctolites and can estimate their porosity. This procedure is illustrated by Fig. 9. It is seen that the minimum amount of interstitial material lies in the troctolite layer, where the fraction of trapped liquid is 1.5–4.0%, rather than in the dunite zone as could have been anticipated. The estimate for the dunites shows from 3 to 10% of residual melt. Interestingly, such an approach yields about 58% melt for the chilled facies (Fig. 8). This is equivalent to 42% crystals and consistent with the results of phase equilibrium modeling for the marginal rocks (Fig. 5). A similar character of the distribution of interstitial melt is obtained from the data on Zr concentration in the section of the Dovyren layered series (Fig. 3).

DISCUSSION

The computer modeling of equilibrium crystallization of the marginal rocks of the Dovyren intrusion demonstrated that the liquid part of the initial magma was silica-saturated (~54 wt % SiO_2) and relatively rich in MgO (~7.5 wt %). At the moment of injection into the chamber, the magma was characterized by a high degree of crystallinity (more than 40%) and had a temperature of ~1185°C. The composition of the liquid corresponded to the *Ol*–*Pl* cotectic, but the proportions of introduced intratelluric crystals were strongly shifted toward olivine enrichment. The validity of these calculated primary characteristics of the Dovyren magma is supported by the similarity of the observed and model compositions of olivine and plagioclase, which are close to Fo_{85} and An_{80}.

Initial State of the Dovyren Magma

The modeling of phase equilibria suggested an unexpectedly high fraction of crystals in the magma entering the intrusion chamber. Proceeding from calculations for the rocks of the chilled facies and border zones, the initial crystallinity of the magmatic material was within 37–51 wt % at an emplacement temperature of 1185°C. If the average composition of the plagioperidotite is taken as the bulk composition of the initial magma, the fraction of crystals is estimated as 58%, whereas the weighted average composition of the intrusion after [63] yields 85% crystals. In the latter case, it is necessary to admit that the initial magma was represented by a subeutectic association containing ~54% *Ol*, 24% *Pl*, and about 7% pyroxene. We believe that the significant scatter in the possible degree of crystallization is related to the imbalance between the composition of the chilled facies and estimates of the bulk composition of the intrusion, which rely on overestimated fractions of adcumulates, which are represented by dunites and troctolites.

These considerations make us revise the geologic position of the Ioko gabbroid block, which was ignored in the previous estimates of the average composition of the Dovyren intrusion [53, 55, 56, 63]. It is probable that accounting for its relative volume and composition would result in better agreement between the calculated weighted average chemical characteristics of the Ioko-Dovyren intrusion and the compositions of the boundary facies. This mainly concerns the incompatible elements, including titanium, phosphorus, alkalis (Table 1), and zirconium. The distribution of these elements within the section (Fig. 3) can be interpreted as an indication of the existence of a more significant volume of complementary crystallization products enriched in incompatible components.

Independent of the balance of various rock types in the intrusion, the high crystallinity of the Dovyren magma at the final stage of emplacement raises the problem of estimation of the rheologic properties of the parental material and its constituents. At the accepted emplacement parameters of 0.5 kbar and 1185°C, the initial liquid had a density of 2.64 g/cm^3 [80] and a viscosity of ~900 P [81]. The Einstein–Roscoe equation $\eta = \eta_m(1.35 \times f_m - 0.35)^{-2.5}$, where η_m is the liquid viscosity and f_m is the fraction of the melt [82, 83], can be used to determine the bulk viscosity of a suspension. For a porosity of 40%, we obtain $\sim 6 \times 10^4$ P, and for lower degree of crystallization (f_m = 60%) ~ 6×10^3 P. The former estimate corresponds to the established phase composition of the plagioperidotite, and the latter approximates the border ophitic gabbro and gabbronorite (Fig. 5). Both values do not rule out the possibility of the movement and intrusion of magmatic masses, but the estimate obtained from the ophitic rocks directly near the contact seems to be more realistic.

On the Role of Cumulus Compaction and Pore Melt Migration

The problem of possible mechanisms of mineral and melt redistribution within the chamber of the Dovyren pluton can be tackled by comparing the geological and geochemical data with the results of modeling of initial phase equilibria in the ultramafic rocks. The occurrence of undisturbed xenoliths of carbonate rocks in the dunite zone and anomalously high CaO contents in olivine near these xenoliths (up to 1 wt % [64]) suggest the absence of large-scale stirring in the system, at least at the stage of dunite layer formation. This conclusion is consistent with the character of distribution of major and trace elements in the rocks of the Dovyren massif, which is characterized by stepwise, sometimes rather abrupt changes [56] rather than gradual compositional variations, which are expected during general convection [4]. The absence of efficient stirring restricts fractionation to the upper portion of the chamber, which is in agreement with small variations in the compositions of olivine and plagioclase in the dunites and troctolites (Fig. 3) [57]. We believe that the high crystallinity of the Dovyren magma at the moment of emplacement was the main factor that hindered the initiation of sedimentation plumes near the intrusion roof, which are necessary for general mixing [25]. After the filling of the magma reservoir, the processes of compaction and adcumulus overgrowth of supercotectic olivine crystals were probably predominant and resulted in the formation of the dunite zone. Part of interstitial liquid was buried in the basal layer beneath the olivine cumulus, whereas the major portion of intercumulus liquid was filter-pressed toward the roof, where it crystallized near the *Ol–Pl* cotectic.

The above-mentioned structural characteristics of rhythmic layering in the troctolite zone (lenticular banding, cross bedding, etc. [84]) suggest that the compaction of cumulus occurred concurrently with tectonic deformations of the intrusion chamber and viscous flow of magmatic suspension. The tectonic compression probably resulted in extensive filter-pressing of the magma with the almost complete elimination of the liquid phase from the cumulus. This is indicated by the very low contents of interstitial minerals (*Pl* and *Cpx*) in most dunites and troctolites (except for the hybrid wehrlite near altered carbonate xenoliths), corresponding SiO_2 deficit in the normative composition of the troctolite, and observed depletion of these rocks in incompatible elements (Ti and Zr). Relicts of residual melt were only occasionally found in the upper layers of *Ol–Pl* cumulates (troctolites) as lenslike bodies of olivine gabbro and gabbronorite. They occur locally in contrast to zone *D*, where the occurrence of *Cpx* and *Opx* reflects the subeutectic character of the residual magma and sequential crystallization of the gabbro and gabbronorite mineral assemblage.

Given the unusually low porosity of the troctolites (2–4%, Fig. 9), the composition of intercumulus melt buried in the mesostasis of these rocks can be estimated. Special calculations modeling equilibrium crystallization up to the maximum degree of crystallization of 99% were performed using the COMAGMAT program for the average composition of the troctolite zone [63]. These calculations revealed two surprising facts. First, the model solidus temperature of the troctolite system containing ~3% melt (1184°C) was identical to the emplacement temperature (1185°C). Second, the composition of the pore melt in the troctolite appeared to be close to saturation with *Ol, Pl*, and pyroxene and was essentially indistinguishable from the initial melt calculated from the data of geochemical thermometry (Table 2). It can be concluded, therefore, that the compaction of not only dunite but troctolite also occurred under isothermal conditions and was accompanied by the filter-pressing of subeutectic pore melts similar to the initial magmatic liquid. Obviously, simple mechanical compaction of the cumulus could not completely

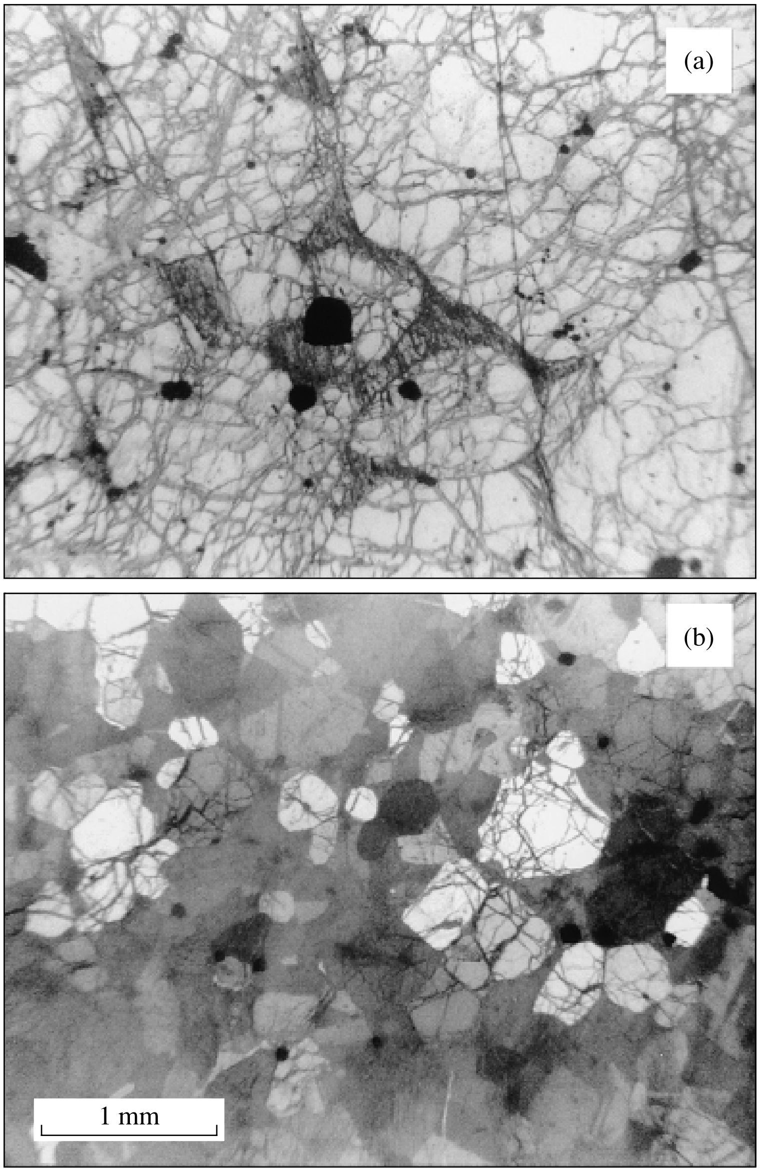

Fig. 10. Examples of typical adcumulates from the layered series of the Dovyren pluton.

Photomicrographs of thin sections: (a) Dunite in transmitted light; the interstitial material is clearly seen in the middle: it fills the space between large grains of *Ol* (white) and is represented by saussuritized *Pl* (gray). (b) Troctolite in cross-polarized light; *Ol* (mainly bright white) and *Pl* (gray) join without gaps and practically do not form interstices.

expel the melt. Thus, it can be stated that the more efficient extraction of residual liquid was promoted by the phenomena of isothermal overgrowth of initial cumulus minerals. This inference can be supported by the photomicrographs of thin sections of the dunite and troctolite illustrating typical equilibrium adcumulus textures (after nomenclature of [44]) and differing in the amount of interstitial material (Fig. 10).

The coeval processes of adcumulus growth and intergranular liquid migration were probably predominant at the early and middle stages of intrusion solidification and were the major factors of component redistribution on the chamber scale. This enables us to infer the dominant role of compositional convection, infiltration reequilibration, and isothermal overgrowth of initial crystals in the formation of layering in the Dovyren massif. Note that the term isothermal is used in the context of the results of geochemical thermometry, which suggest that the temperature of the local closure of cumulus systems (cessation of liquid movement) did not differ from the emplacement temperature of the initial magma (1185°C) within the accuracy of the method (±10–15°C). It is reasonable to suppose that this range corresponds to the real interval of the temperature of adcumulus growth and filter-pressing of residual liquid. Another important prerequisite for the formation of adcumulate concerns the relationships between the rates of crystallization and liquid movement in the lower boundary zone.

Simakin and Kislov [70] proposed an analytical model for the evolution of the porosity of crystalline sediment in a pseudobinary heterophase system (*Ol*–*Pl*–liquid) accounting for variable cooling rates in the lower border zone. The results of their calculations demonstrated that extremely low values of residual porosity (several percent) could be attained at high velocities of convection motion relative to the rate of melt crystallization ($V_{\text{con}}/V_{\text{cryst}} > 10$). This leads to the apparent conclusion about the impossibility of adcumulate formation near the contact and the occurrence of cumulates with the highest degrees of compaction in the interior parts of intrusive bodies. The application of these results to the problems of layering in the Dovyren massif provided a genetic interpretation for the rocks from the lower layers. According to this interpretation, the plagioperidotites are orthocumulates, plagiodunutes are mesocumulates, and dunites are typical adcumulates [55, 70]. This picture is qualitatively compatible with the results of geochemical thermometry, which suggested a persistent tendency of a porosity decrease at the transition from dunite to troctolite (Figs. 8, 9).

Relationships of Plagioperidotites and the Main Layered Series

Although the proposed evolution scheme of the phase composition of cumulates from the contact toward the interior of the intrusion is self-consistent and elegant, there remains the problem of the geologic relationship of the bottom zone plagioperidotites with the overlying dunite–troctolite–gabbro series. It was previously shown that the chemical composition of the basal rocks was similar to the weighted average composition of the layered series differing in elevated K_2O and H_2O contents [53]. According to [55], in the border zone of phlogopite-bearing plagioperidotite, the water pressure was no less than 1 kbar and the melt contained a few percent H_2O. Therefore, although the calculations of melt evolution for the compositions of plagioperidotite and dunite–gabbro–troctolite layered series of the massif supported their formation from a single parental magma, the differences in water and potassium contents permit the occurrence of alternative and additional petrologic and geochemical processes.

It can be supposed that the plagioperidotites and rocks of the main layered series resulted from (a) sequential (separated by a small time gap) injections of two peridotite melt portions of slightly different compositions; (b) modification of the boundary part of the Dovyren intrusion through interaction of basal rocks with interstitial melt buried at compaction; and (c) selective assimilation of H_2O and alkalis from the underlying terrigenous sediments (owing to high diffusion rates in comparison with other major components [53, 55]). The predominant development of serpentinization in the border zone of the Dovyren intrusion can be explained by water assimilation in this zone.

CONCLUSION

Characteristics of the parental magma and phase compositions of dunite and troctolite cumulates were estimated from phase equilibrium modeling by the method of geochemical thermometry [26] for the compositions of marginal rocks, plagioperidotites, and the weighted average composition of the Dovyren layered dunite–troctolite–gabbro (norite) pluton. The emplacement temperature of the initial magma of this intrusion (~1185°C) was calculated for the first time. It was shown that by the moment of chamber filling, the magma had experienced significant supercotectic crystallization and consisted of 40–50% solid phases (mainly, *Ol*) and boninite-like melt with ~54 wt % SiO_2. It was suggested that, owing to the high crystallinity of the initial magma, the general convection mixing of the system was improbable and the redistribution of crystals and liquid occurred through Stokes' settling and percolation of complementary liquid. The main mechanism of formation of the phase layering of the pluton was the compaction of the crystalline precipitate accompanied by the migration of pore liquid and (presumably) coeval tectonic deformations of the magma chamber. The dunites and troctolites had very low porosity (2–10%) and preserved geochemical evidence of adcumulus overgrowth and efficient filter-pressing of residual melt. The basal layer of plagioclase peridotite is interpreted as crystallizing from buried interstitial liquid with the possible additional input of water and alkalis from the enclosing sequence.

The proposed scenario of formation of phase layering in the Dovyren intrusion differs from the traditional schemes of chamber differentiation, which were developed for initial magmas with low contents of suspended (intratelluric) crystals and implied the prevalence of general convection over phase convection. This invites the construction and analysis of more sophisticated models of chamber processes accounting for the possibility of coupling of general and phase (compositional) convection with the suppression of sedimentation processes at final stages, when the transport of intercumulus liquid becomes the main process of separation accompanied by the compaction and recrystallization of primary cumulates. The formation of intrusions with high degrees of crystallization of the initial magma is probably not very rare in nature. We believe that the correct and systematic application of geochemical thermometry to such objects will supply a full set of information on the phase, chemical, and rheological characteristics of magmas, which is necessary for the construction and verification of modern computer models of chamber differentiation.

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