

Estimation of Chemical and Phase Characteristics for the Initial Magma of the Kiglapait Troctolite Intrusion, Labrador, Canada

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Abstract—The Kiglapait intrusion has an age of 1.4 Ga and is a funnel-shaped body, about 9 km thick in its central part. More than 90% of its volume is made up of the *Layered Group*, which includes boundary rocks, troctolites of the *Lower Zone* (~80% of section), and strongly differentiated rocks of the *Upper Zone* ranging from gabbroid to ferrosyenite. The formation of this sequence was related to the process of chamber differentiation of an initial magma in a closed system. In order to estimate the parameters of the injection and initial conditions of crystallization, phase equilibria were calculated for six rocks representing the lower third of the Layered Group and showing the most primitive compositions of olivine (Fo_{68-69}) and plagioclase (An_{64-67}). Crystallization paths were constructed by the COMAGMAT-3.65 program under the conditions of the *WM* buffer and a pressure of $P = 2.2$ kbar. It was inferred that the boundary rocks are subcotectic systems ($Ol + Pl$), and most of the troctolites were oversaturated in plagioclase. All the calculated paths showed convergence of the residual melt compositions at a temperature of about 1230°C, which was accepted as the emplacement temperature of initial magma. The average composition of the residual melt estimated for 1230°C characterizes the liquid portion of the magma at the moment of its inflow into the chamber and corresponds to the "high-alumina ferrobalt" ("Al-Fe troctolite liquid"). The initial magma contained about 75 wt % of melt, and its intratelluric phase was represented by olivine (~5%, Fo_{79}) and plagioclase (20%, An_{67}). The forsterite mole fraction of the model *Ol* is significantly higher than that of the most primitive crystals from the lower boundary zone, which is related to the reequilibration at the postcumulus stage.

INTRODUCTION

The investigation of the formation conditions of layered ultrabasic–basic massifs is among the major directions in igneous petrology. It is important both for the development of theoretical concepts of chamber differentiation mechanisms and in applied aspects related to the occurrence of iron-group element and noble metal ores in intrusive basic rocks. Among genetic problems, of particular importance is the estimation of the parameters of initial magmas, including the bulk chemical composition and the degree of crystallinity of magmatic suspension at the moment of injection and the proportions and compositions of initial intratelluric phases and liquid. The interpretation of magmas as multiphase polycomponent systems is complicated by possible disequilibrium of initial melt–mineral associations, which is suggested by the presence of compositional spectra for each intratelluric phase transported by a single melt. They could be represented by xenocrysts captured by magma in the course of segregation and movements or crystalline products of a more primitive parental melt, which bear imprints of the previous magmatic evolution of a common source. Thus, the typical state of a magmatic suspension is presumably a mixture of melt with a certain amount of solid phases with average compositions not necessarily corresponding to the

temperature and composition of the liquid but more likely shifted toward more refractory (high-temperature) components. The degree of this departure from equilibrium may vary, although it is not difficult to imagine an ideal situation when the crystals suspended in the magma had enough time to equilibrate with the melt before the injection of magmatic material into the chamber. This assumption provides a basis for the thermometry of mineral–melt equilibria by means of olivine, plagioclase, pyroxene, spinel, and other geothermometers (see [1, 2] for a review). In the middle 1980s, we proposed the method of geochemical thermometry for extrusive and intrusive rocks, which combined and extended the possibilities of traditional approaches based on the principles of equilibrium component partitioning between minerals and melt for magmatic systems of basic and intermediate compositions [3, 4].

The thermodynamic substantiation and pilot examples of geochemical thermometry for rocks of several differentiated sills from the Siberian craton were presented by Frenkel' *et al.* [5]. It is worth reminding, that this method relies on the application of computer models of phase equilibrium characterizing crystallization of natural melts in a closed system with decreasing temperature and sequential changes in the proportions of crystals and liquid. In principle, any algorithm model-

ing equilibrium crystallization at given pressure and oxygen fugacity can be used for this purpose. In our studies, we use the programs that have been collectively termed COMAGMAT since 1992 [6, 7].

Calculations by the method of geochemical thermometry yield, as the main output, estimates of temperature and composition of magmatic melt for the initial suspension that gave rise to the intrusive rock. This problem allows several variants of solution depending on the stage of chamber differentiation considered. For the initial stages of intrusive body solidification, of special interest is the approach that was first tested on the example of the plagioclase of the Kamenistyi sill [8] and further developed with application to the genetic problems of the Partridge River [9], Skaergaard [7], and Talnakh intrusions [10]. It uses the bulk chemical compositions of rocks representing the earliest stages of solidification with the participation of igneous melts near primary liquids. Such rocks are obviously confined to the near-contact zones (marginal series) or lower portions of layered units. The least fractionated character of these rocks is mirrored in the composition of their cumulus minerals, which usually show the highest enrichment in refractory components. It is reasonable to suggest that this early high-temperature assemblage must be close or identical to the association of crystals and liquid that composed the initial magma. Thus, the problem of the determination of the chemical compositions of the source is reduced to the choice of samples representing the early stages of intrusion solidification and the calculation of corresponding equilibrium crystallization trends in the temperature–composition coordinates. The processing of these data provides the compositions of initial melt and intratelluric phases [2], and the calculated temperature is regarded as an emplacement temperature, which enables one to estimate the proportions of melt and solid phases in the parent magma (see below).

GEOCHEMICAL THERMOMETRY OF THE KIGLAPAIT ROCKS

This paper deals with the results of phase equilibrium modeling for the rocks of the Kiglapait intrusion, which, owing to the detailed work by Morse [11–19], has long been one of the best studied complexes of basic composition. Interest in this object is stimulated not only by its size (total volume of the intrusion is about 3500 km³), but, more importantly, by its extensive differentiation. The latter is recorded in an extreme enrichment of late crystallization products in FeO and TiO₂ and evolution of olivine and pyroxene compositions up to pure ferroan varieties [11, 20]. In this respect, the Kiglapait bears resemblance to the Skaergaard intrusion, and it is not by accident that the two massifs are often mentioned together as typical examples of tholeiitic magma evolution toward extensive iron accumulation [21–23]. It is worth noting that the methods of estimating the compositions of differenti-

ated melts that had been first validated by the studies of Skaergaard layered series [24] were further developed with application to the Kiglapait rocks [16].

The difference lies in the fact that Morse rejected the graphical approach of Wager for the construction of liquid lines of descent and used the method of summation of the compositions of rocks corresponding to the sequential stages of intrusion solidification. Later, the feasibility of these calculations was questioned, because they turned out to be in conflict with the available data on the *Pl*–melt [25, 26] and *Ol*–melt equilibria and the results of crystal fractionation modeling for the initial magma of the Kiglapait intrusion [27]. The analysis of the causes of this discrepancy is an important moment in the general discussion of the problems of ferrobasic magma differentiation [7, 21–23, 27–31]. In this context, the correct estimation of the chemical and phase composition of the initial magma acquires a key role, and we hope that new data obtained by means of geochemical thermometry will shed new light on the problem of the evolution of the Kiglapait magma.

GEOLOGIC SETTING AND STRUCTURE OF THE INTRUSION

The Kiglapait intrusion is situated in the northern coast of the Labrador Peninsula (~57° N and 61°30' W) and is a funnel-shaped body made up of troctolite, gabbro, and ferrosyenite. It is about 9 km thick in the central part. The massif is slightly elongated in the NW–SE direction and is ~20 × 30 km in plan view. Its structural setting is defined by the confinement to the late units of the Early Riphean Nain anorthositic complex, which cuts the western margin of the Archean North Atlantic craton [11]. The geologic history of this region began at about 3.5 Ga, but the age of the oldest tonalite migmatites adjacent to the intrusion is estimated as 2.7 Ga. The massif is directly bounded on the northwest by the metamorphosed sediments and quartzites of the Snyder Group (Middle Proterozoic, ~1.8 Ga) [32], and its age is constrained by the timing of the younger Manvers granites, which occur as fragmentary stocks in the Kiglapait intrusion. These biotite-bearing granitoids were dated by Rb–Sr radiometry at 1.25 Ga. Taking into account these data and available estimates for the Nain anorthosite (1.388 ± 0.025 Ga), it is accepted that the Kiglapait intrusion was formed in the Late Proterozoic (Early–Late Riphean boundary), somewhat later than 1.4 Ga [11].

Structural Characteristics

The main units of the Kiglapait intrusion are the *Inner Border Zone* (IBZ), the *Layered Group* (LG), and the *Upper Border Zone* (UBZ) (Fig. 1). In addition, the Inner Border Zone is underlain by the *Outer Border Zone* (OBZ) of comparable thickness. The assignment of the OBZ to the intrusive is still disputable. Its rocks show a granular texture and, on the whole, correspond

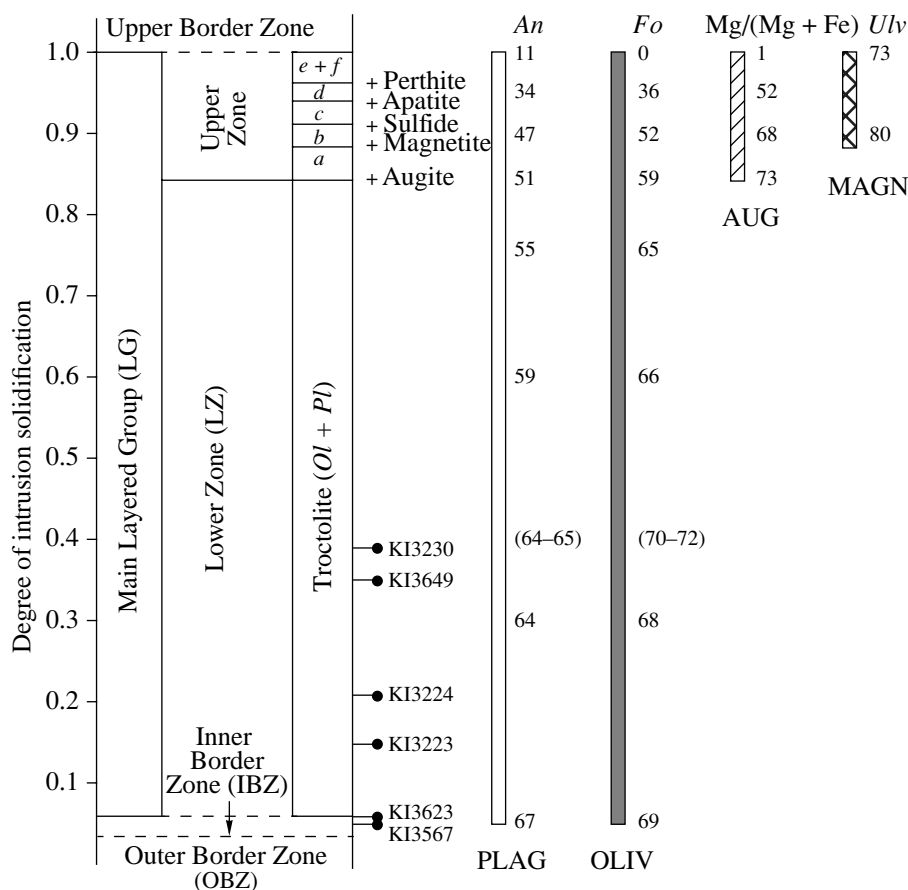


Fig. 1. Main structural units of the Kiglapait intrusion and corresponding degrees of solidification (constructed after [11]). The Lower (LZ) and Upper (UZ) zones of the Layered Group are separated by the appearance of cumulus clinopyroxene in the rocks. The evolution of mineral compositions is given in accordance with general trends derived from several sections of the intrusion (see text for explanation). Also shown are the positions of six samples that were used for geochemical thermometry.

to hornblende olivine ferrogabbro, which includes interlayers of sedimentary rocks (graywacke and quartzite) and, occasionally, ultrabasic rocks. There is an opinion that these gabbroids are products of the crystallization of basic melts of a supracrustal origin. However, their mineralogical and chemical resemblance to some rocks of the Layered Group allowed the interpretation of the Outer Border Zone as a bottom rock unit of the intrusion [11, 12].

The Inner Border Zone accounts for about 2% of the section and is composed of *Ol-Pl* orthocumulates, which contain ~70% of modal plagioclase, 11–12% of olivine, 11–12% of augite, about 3% of Fe–Ti oxides, and small amounts of minor minerals (hypersthene, apatite, biotite, and brown hornblende). They grade upward into the rocks of the *Lower Zone* (LZ) of the Layered Group, which account for 80% of the section (Fig. 1) and are represented by troctolite accumulates according to the nomenclature of [33]. This allows us to interpret the Kiglapait intrusion as a predominantly troctolitic massif, whose average modal composition is characterized by the strong predominance of plagioclase (67 wt %) and olivine (23%) [12].

Augite is a less abundant mineral (6.6% on average) and its appearance among cumulus phases marks the transition from the troctolite to the gabbroids of the *Upper Zone* (UZ). Despite the fact that this zone composes about 20% of the Layered Group, it shows the most significant variations in the compositions of rocks and minerals, which served as a basis for the inference on the extensive fractionation of the Kiglapait intrusion. The *Upper Zone* is subdivided into several sub-zones characterized by the appearance of new minerals: magnetite (UZb), sulfide (UZc), apatite (UZd), antiperthite (UZe), and mesoperthite (UZf) (Fig. 1). The sub-zones containing alkali feldspars display an extreme iron enrichment and are built up of ferrosyenites, which are overlain by the finer grained rocks of the *Upper Border Zone*. This structural unit shows inverted variations of mineral compositions in the same range as sub-zones UZf to UZa, which suggests the formation of the *UBZ* through directional roof growth in the intrusion chamber similar to the *Upper Border Series* of the Skaergaard intrusion [33, 34].

The boundaries of the distinguished structural units are manifested differently by various zones and hori-

zons. They are most clearly traced by the appearance of cumulus *Aug*. In addition, the Upper Zone of the LG contains an easily mapped layer enriched in titanomagnetite and (to a smaller extent) ilmenite. It is from 0.5 to 1.0 m thick, traced over a distance of up to 14 km, and referred to as the Main ore band (MOB) [12, 14]. The transition from the upper portion of the Lower Series to the Upper Border Zone is also distinct.

Compositions of Minerals

Morse evaluated the compositional variations of rock-forming minerals using a series of diagrams of the dependence of the *An* and *Fo* contents and the *En/(En + Fs)* ratio of augite on the degree of intrusion solidification. The latter parameter was calculated proportional to the position of a rock in the Layered Group and was plotted in logarithmic scale, from about 0.05 to 0.9999 [11, 14, 20]. This scheme was convenient for the presentation of the scales of Rayleigh fractionation in the Upper Zone of the LG, because in such a case, about 80% of the diagram displayed the characteristics of the upper 10% of the Layered Group. Variations of petrochemical and geochemical parameters were considered in the same way [11, 12, 17, 18]. Such a form of data presentation for the petrologic and geochemical information emphasizes the extent of the compositional variations in the late differentiation products, whereas the spatial coordinates of the lower half of the intrusion shrink to a small interval, and the compositions of troctolites and their minerals form compact clusters on such diagrams, slightly extending along the respective general trends. Since the problems formulated in the Introduction imply the analysis of information on the rocks of the low levels, a more traditional form of data presentation was invoked for the investigation of the chemical evolution of minerals (Fig. 1) and rocks (Fig. 2).

The compositional evolution of minerals as a function of the degree of intrusion solidification (Fig. 1) was constructed on the basis of published data [11, 14, 15, 17, 20]. In the earliest of these publications [11], Morse provided only graphical materials, including individual compositions for various sections and generalized trends approximating these data points. The trends were later tabulated for several values of the calculated percent solidified and these tables were given in the following publications. These values of *An*, *Fo*, and the *En/(En + Fs)* ratio of clinopyroxene are shown in Fig. 1.

Within the lower half of the LZ, these data show a small monotonous change in the composition of two major minerals, *Pl* ($An_{67} \rightarrow An_{63}$) and *Ol* ($Fo_{69} \rightarrow Fo_{67}$), whereas in the upper third of the Lower Zone, anorthite and forsterite mole fractions decrease more significantly, $An_{59} \rightarrow An_{51}$ and $Fo_{66} \rightarrow Fo_{59}$. The most considerable changes in mineral compositions occur in the Upper Zone of the Layered Group, where the *Fo* content falls to zero, and plagioclase is replaced by an alkali feldspar containing no more than

20–10 mol % of the anorthite component. The *En/(En + Fs)* ratio of augite also declines rapidly in the Upper Zone (Fig. 1). The change of the titanomagnetite composition appears to be not so dramatic ($Ulv_{80} \rightarrow Ulv_{73}$), but it should be kept in mind that these data are reconstructed primary compositions of oxides derived from the characteristics affected by subsolidus reequilibration [14].

In the context of the problem formulated in this study, we will focus on the compositions of olivine and plagioclase from the lower half of the Lower Zone of the Layered Group corresponding to a range of percent solidified of 4–40%. The fact is that the small decrease of the *An* and *Fo* contents in the troctolites shown in Fig. 1 does not reflect the real compositional variations but is tied to the “model trends” extrapolated into the lower part of the intrusion from the upper levels [11, Figs. 9–11]. This is related to the character of the genetic reconstruction by Morse, who tried to interpret the structure of the Kiglapait intrusion within the model of perfect crystal fractionation of an initially homogeneous magmatic melt. It is clear that within such a scheme, the compositions of minerals must evolve monotonously from the earliest stages of crystallization, and any departure from the model trends is most readily interpreted as a random variation or a result of the influence of superimposed factors. The analysis of the primary graphical material [11] suggests that such departures do occur in the lower part of the Kiglapait intrusion.

In particular, within the 30–40% solidification interval, the compositions of *Pl* (An_{64-65}) and *Ol* (Fo_{70-72}) are different from those deduced from the general trends, about An_{62} and Fo_{67} (Fig. 1). At first glance, these differences are not significant, but the fact of the presence of more primitive compositions is important as an indicator of possible troctolite formation from cumulates, whose crystals did not differ much from the compositions of early high-temperature minerals. This can be considered as evidence for insignificant changes in the composition and temperature of intercumulus melt within 4–40% of solidification. In such a case, the parameters of initial liquid could be estimated by the method of geochemical thermometry, if troctolite samples would be found whose bulk major-element compositions vary in accordance with the proportions of cumulus grains and melt. Fortunately, in published data there are several such contrast compositions for samples collected from the Inner Border Zone and the lower half of the Lower Zone of the Layered Group [16].

COMPOSITIONS OF ROCKS AND SELECTION OF SAMPLES FOR CALCULATIONS

Figure 2 shows the distribution of major elements in the rocks of the Layered Group of the Kiglapait intru-

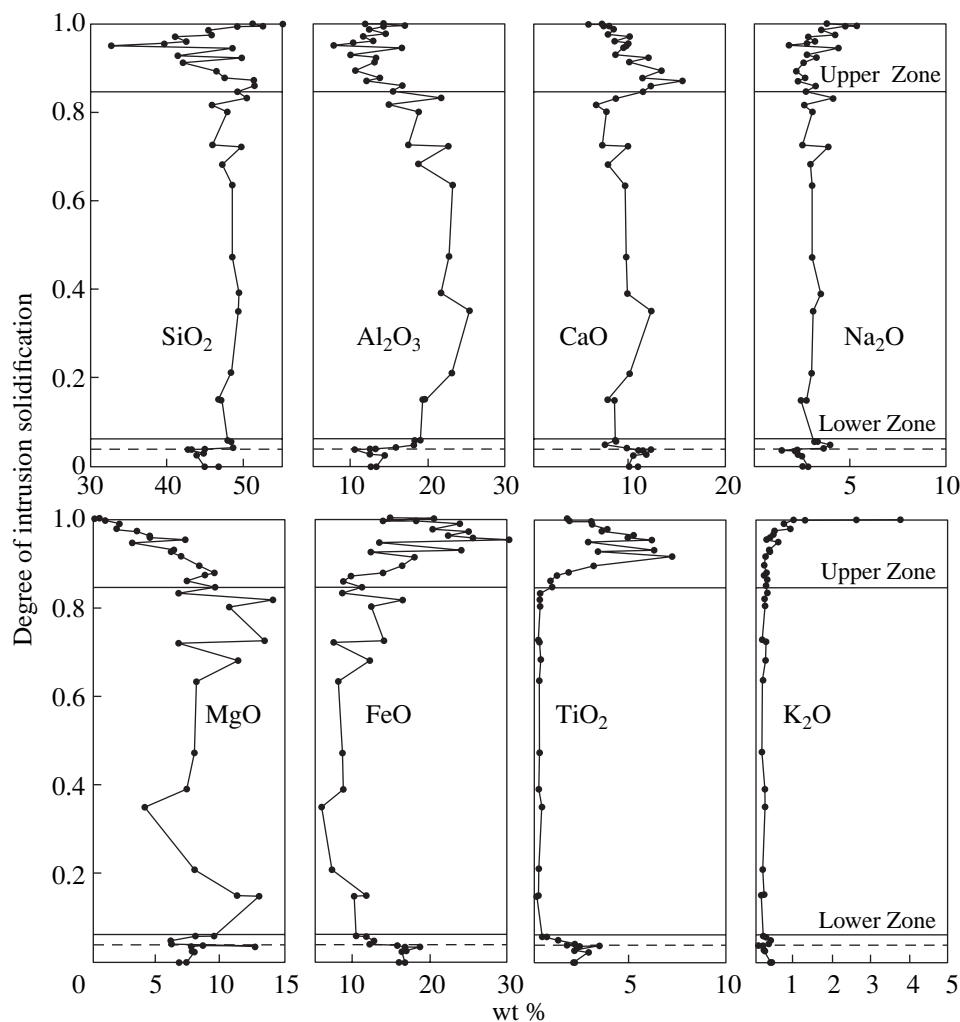


Fig. 2. Variations of the contents of major rock-forming components in the vertical section of the Layered Group of the Kiglapait intrusion (constructed after [16]).

sion as a function of the degree of solidification. The variations in the contents of rock-forming elements agree well with the established crystallization sequence (Fig. 1). The troctolite zone shows substantial variations in MgO, FeO, Al_2O_3 , and CaO in contrast to small changes in titanium and alkalis. Such patterns are typical of the systems having *Ol* and *Pl* as primary liquidus phases [2]. The appearance of *Aug* in the crystallization sequence is recorded by an increase in CaO content at the LZ/UZ boundary. An abrupt increase in FeO and TiO_2 contents, which is observed slightly higher, is related to the accumulation of these components in the melt and precipitation of Fe–Ti oxides.

More important for our purposes are variations in troctolite compositions in the lower third of the intrusion, where MgO and Al_2O_3 contents change within 4–13 and 18–25 wt %, respectively. The main reason of these changes in the bulk-rock composition at a small scatter in the compositions of rock-form-

ing minerals (see above) lies in the variations of the initial proportions of *Ol*, *Pl*, and melt, which crystallized later as an intercumulus material [9]. As was mentioned above, such a situation bears genetic information and meets the formulated conditions for the application of the method of geochemical thermometry.

For thermometric calculations, we used the compositions of two samples from the Inner Border Zone (KI3567 and 3623) and four troctolite samples corresponding to the solidification interval 15–39% (KI3223, 3224, 3649, and 3230) (Table 1). The position of these samples in the section is shown in Fig. 1. Additional calculations were performed for two compositions representing the weighted average composition of the Layered Group (composition *KIGLAP*, Table 1) and the average composition of the rocks of the marginal facies (*MAR*), which were considered as possible analogues of the initial magmatic melt that gave rise to the Kiglapait intrusion [19].

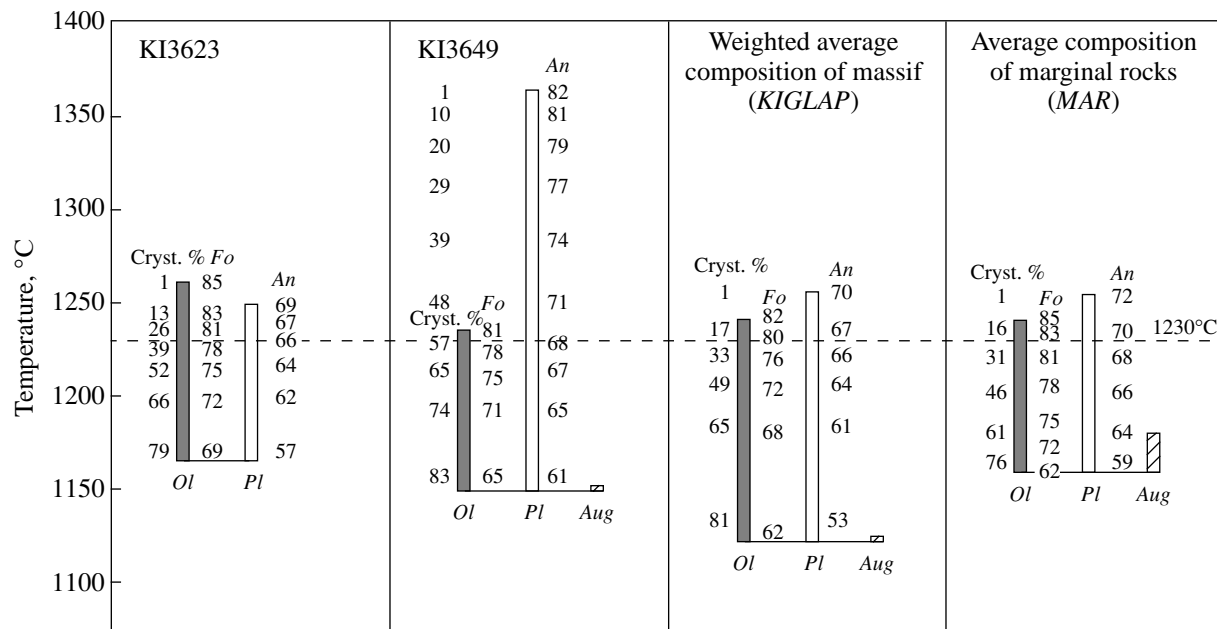


Fig. 3. Crystallization sequence and evolution of the compositions of minerals as a function of temperature for four compositions representing the rocks and weighted average characteristics of the Kiglapait intrusion. Calculations were carried out using the COMAGMAT-3.65 program (2000) for a pressure of 2.2 kbar and the redox conditions of the *WM* buffer. The indexes of rocks and average compositions are given in Table 1. The dashed line corresponds to the accepted temperature of the initial Kiglapait magma (Fig. 5).

Modeling of Phase Equilibria

Calculations were carried out using one of the latest versions of the COMAGMAT-3.65 (2000) program, which was calibrated for application to ferrobasic

melts and used for the thermometry of the rocks of the Skaergaard Layered Series [35]. Similar to the COMAGMAT-3.5 program [7], the new version is recommended for use in low to moderate alkalinity systems (olivine basalt, tholeiitic basalt, and ferroandes-

Table 1. Weighted average petrochemical characteristics of the Layered Group and boundary zones in comparison with the compositions of low-evolved troctolites from the Lower Zone of the Kiglapait intrusion

Parameter	Average composition			Inner Border Zone		Troctolites of the Lower Zone of the Layered Group			
	Layered Group	Outer Border Zone	marginal rocks	5.7	5.9	15.0	21.0	35.0	39.0
	<i>KIGLAP</i>	<i>OBZ</i> (<i>n</i> = 7)	<i>MAR</i> (<i>n</i> = 4)	KI3567	KI3623	KI3223	KI3224	KI3649	KI3230
SiO ₂	47.60	44.89	49.96	48.47	48.09	46.59	48.08	48.88	48.95
TiO ₂	0.81	2.40	0.30	0.67	0.40	0.12	0.22	0.36	0.20
Al ₂ O ₃	19.52	12.79	19.63	18.31	19.17	19.08	23.12	25.29	21.48
FeO	11.11	17.13	8.93	11.94	10.66	10.14	7.34	5.90	8.70
MnO	0.15	0.26	0.13	0.17	0.14	0.12	0.10	0.07	0.10
MgO	8.06	8.59	8.18	8.17	9.60	12.96	8.03	4.11	7.28
CaO	9.30	11.21	9.48	8.68	8.59	8.40	9.99	12.14	9.66
Na ₂ O	3.14	2.30	3.11	3.28	3.13	2.43	2.94	3.01	3.40
K ₂ O	0.22	0.24	0.25	0.27	0.20	0.14	0.17	0.23	0.21
P ₂ O ₅	0.09	0.19	0.04	0.05	0.02	0.01	0.01	0.01	0.01

Note: The average composition of marginal rocks, *MAR*, was calculated after [19], other compositions are after [16]. The positions in the section with respect to the degree of massif solidification (vol %) is shown for the rocks of the Inner Border Zone and troctolites of the Lower Zone (Fig. 1). All iron is given as FeO, and the compositions are normalized to totals of 100%.

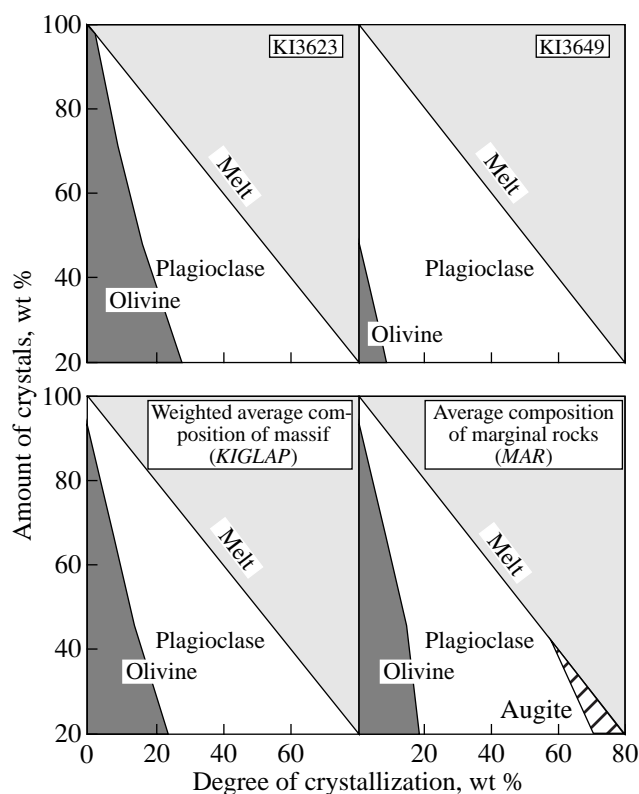


Fig. 4. The evolution of phase composition at the equilibrium crystallization of four compositions representing the rocks and weighted average characteristics of the Kiglapait intrusion. The results of calculations for the data shown in Fig. 3. Symbols are the same as in Fig. 3.

ite). The error of the temperature estimation is of an order of the accuracy of the geothermometers employed (10–15°C), and the accuracy of the major component contents calculation in melt is about 0.5 wt %. The departure of calculated mineral compositions from experimental values is rarely higher than 1 mol % (*Ol*) or 3 mol % (*Pl*), which allows the use of the compositions of natural minerals as an independent criterion for the control of calculations. Such a control is possible when two conditions are met.

First, natural compositions should not be significantly reequilibrated (recrystallized) under subsolidus conditions. However, there is no such assurance with respect to the Kiglapait troctolite. Olivine reequilibration is suggested by the comparison of the compositions of *Ol* and *Aug* at the boundary between the Lower and Upper zones (Fig. 1). The Mg-number of the earliest crystals of cumulus clinopyroxene is 73%, whereas the average composition of olivine is much richer in iron, Fo_{59} . The analysis of experimental data suggests that under subliquidus conditions, high-Ca pyroxene shows a higher Mg-number in comparison with olivine, but the difference is not great, usually no more than 10–15% rel. This leads us to the preliminary conclusion that the observed olivine compositions from the Kigla-

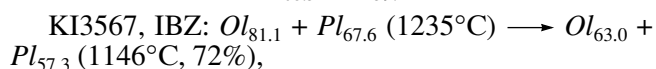
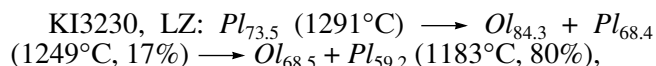
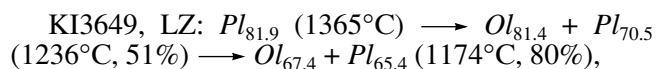
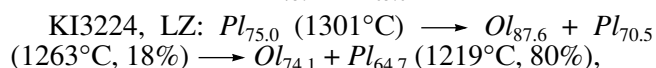
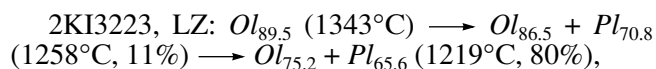
pait rocks are modified relative to the initial characteristics, at least by a few mole percent of *Fo*. On the other hand, it is reasonable to use the observed compositions of *Pl*, because the compositions of the cores of initial crystals remain practically unchanged at postcumulus stages owing to the low diffusivity of mineral-forming components [4].

The second limitation is related to the necessity in specifying the pressure and redox conditions of initial magma emplacement. This is especially important for intrusive bodies, where clinopyroxene and Fe–Ti oxides appear at early stages of solidification, for example, in Skaergaard [35]. Fortunately, this is not critical for the thermometry of *Ol–Pl* assemblages, because both minerals show approximately equal slopes of the pressure dependencies of the liquidus temperature (5–7°C/kbar), and the effect of oxygen fugacity on the composition of olivine corresponds to about 0.5 mol % *Fo* per one logarithmic unit of f_{O_2} within the accuracy of the geothermometers used [2]. The analysis of mineral assemblages in the contact aureole of the Kiglapait intrusion allows a reliable estimation of the pressure of initial magma emplacement as 2.2–2.3 kbar [21, 32], and the results of *Mt–Ilm* oxometry show that the conditions in the Lower zone were close to those of the wüstite–magnetite buffer [14].

Thus, the model paths of equilibrium crystallization were calculated assuming a pressure of 2.2 kbar and the redox conditions of the *WM* buffer. The calculations were carried out in sequence at an increasing degree of crystallization of melt of the given rock with a crystallization increment of 1 mol %. The maximum degree of crystallization of the model system was no higher than 70–80%, which implied the possible presence of 20–30% of intercumulus liquid.

CRYSTALLIZATION SEQUENCE

The calculated sequence of mineral appearance on the liquidus depends on the initial composition. A relatively wide *Ol* crystallization field is obtained for the most magnesian sample (KI3223), *Pl* is an early crystal phase in three aluminous compositions (KI3224, KI3649, and KI3230), and olivine and plagioclase show subcotectic relationships in samples from the Inner Border Zone:



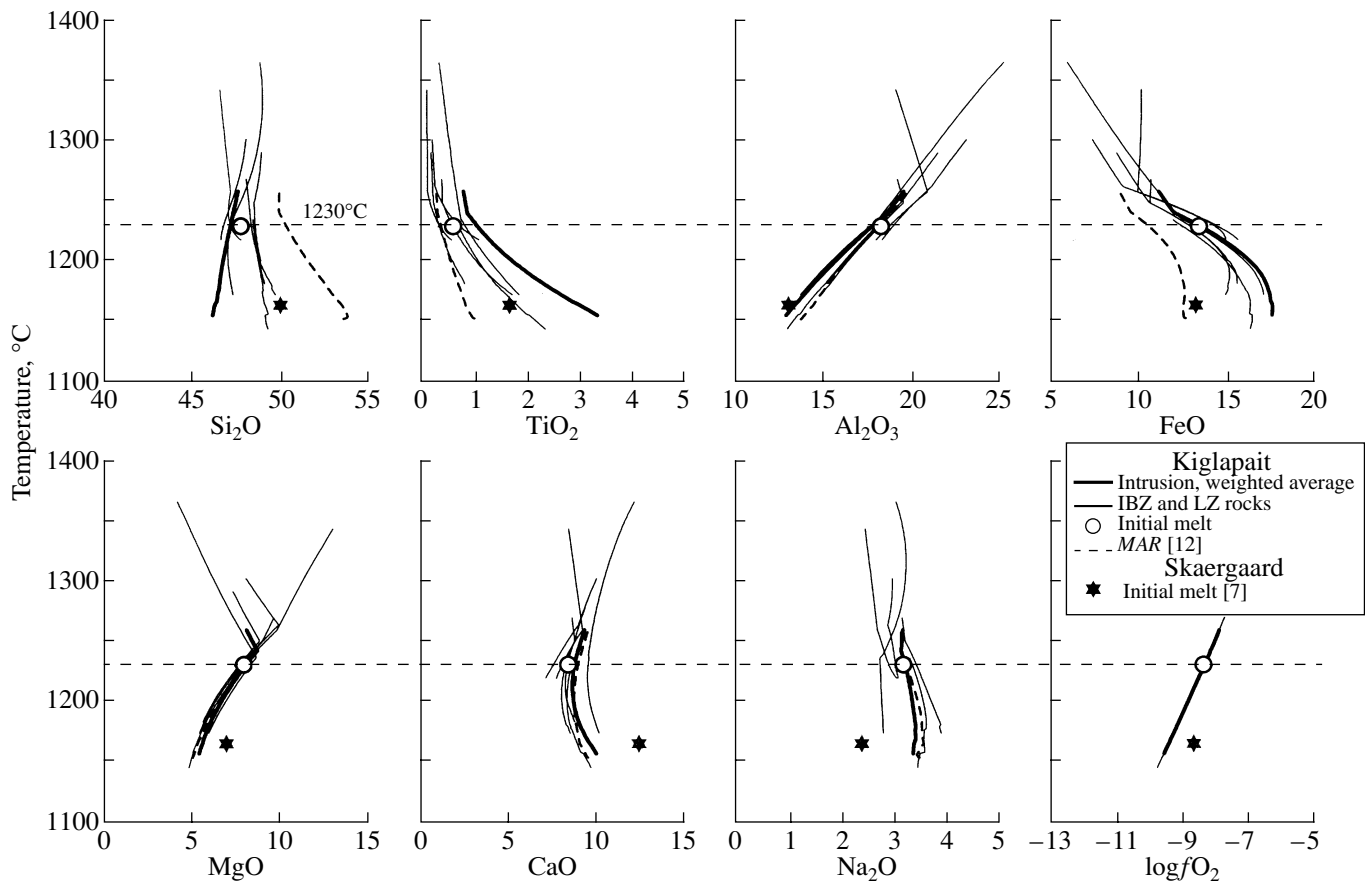


Fig. 5. Estimation of the temperature and composition of the magmatic melt (liquid portion of the Kiglapait magma at the time of its injection).

The accepted value of initial temperature, 1230°C, corresponds to the average of the interval of intersections (the most compact cluster) of the modeled liquid lines of descent for the compositions of six samples (Tables 1, 2). Bold and dashed lines show the evolution trends for the weighted average composition of the intrusion (*KIGLAP*) and the average composition of marginal rocks (*MAR*).

KI3623, IBZ: $Ol_{85.4}$ (1269°C) \rightarrow $Ol_{84.3} + Pl_{68.7}$ (1249°C, 3%) \rightarrow $Ol_{68.5} + Pl_{58.3}$ (1174°C, 77%).

The main characteristic feature of the model paths is the prolonged joint crystallization of *Ol* and *Pl*, which does not merely reflect the mineral compositions of samples from the Lower Zone, but also explains the predominant troctolite lithology of the Kiglapait on the whole, if the subcotectic relationships of the IBZ rocks are interpreted as an indicator of the proximity of their compositions to that of the initial magma. Figures 3 and 4 illustrate the examples of such relationships, including the evolution of phase proportions and *Ol* and *Pl* compositions for troctolite KI3649 (LZ) and sample KI3623 (IBZ). It is interesting, that even at 80% crystallization, troctolite melts do not precipitate clinopyroxene and are characterized by relatively high temperatures of 1174–1219°C. Comparing these values with a temperature of 1146°C at which augite still does not crystallize from the melt of sample KI3567, it can be suggested that the initial “troctolite” mixtures consisted of *Ol* and *Pl* crystals and melt, which was far from sat-

uration in *Aug* and Ti-magnetite. These suggestions are supported by the analysis of the model evolution paths for liquid and cotectic minerals.

RESULTS OF GEOCHEMICAL THERMOMETRY

Estimation of the Composition of Initial Melt

The thin lines in Fig. 5 are trends of changes in melt compositions calculated for the six samples as a function of temperature within 1365–1146°C. The thick and dashed lines are the evolution paths for the weighted average composition of the intrusion (*KIGLAP*) and the average composition of marginal rocks (*MAR*) (Table 1). It is clearly seen that the model paths of real samples approach each other and meet at a temperature of about 1240°C. This value can be regarded as an upper constraint for the possible temperature of the initial magma, which is similar to the value of 1250°C estimated by [11]. On the other hand, at temperatures of 1220°C and lower, the evolution paths diverge on the *T*-*X* diagrams, which is related to the principles of crys-

Table 2. Chemical and phase characteristics of the initial magma of the Kiglapait intrusion

Component	Data of geochemical thermometry for particular rocks	Calculation for the weighted average composition of the Kiglapait intrusion
Composition of initial melt at 1230°C, wt %		
SiO ₂	47.77 (0.74)	47.17
TiO ₂	0.61 (0.19)	1.08
Al ₂ O ₃	18.21 (0.45)	17.70
FeO	13.43 (0.76)	13.51
MnO	0.18 (0.02)	0.19
MgO	7.89 (0.20)	8.03
CaO	8.36 (0.61)	8.73
Na ₂ O	3.15 (0.31)	3.19
K ₂ O	0.38 (0.08)	0.28
P ₂ O ₅	0.03 (0.01)	0.12
Compositions of initial minerals, mol %		
<i>Pl</i>	<i>An</i> _{66.7 ± 1.6}	<i>An</i> _{66.7}
<i>Ol</i>	<i>Fo</i> _{78.8 ± 1.0}	<i>Fo</i> _{79.0}
Phase composition of magma, wt %		
Melt	100.0	75.2
<i>Pl</i>	–	20.0
<i>Ol</i>	–	4.8

Note: The data of thermometry are average estimates calculated on the basis of phase equilibrium modeling for the melts of six boundary rocks and troctolites (Table 1); standard deviations are shown in parentheses. For the initial magma (weighted average intrusion composition), the composition of its liquid portion and relative proportions of melt and crystals at the injection temperature are shown. Equilibrium crystallization was modeled under the redox conditions of the *WM* buffer and $P = 2.2$ kbar.

tallization of systems containing solid solution minerals [2]. Thus, 1220°C is accepted as a lower constraint for the initial temperature. The interval 1220–1240°C is determined with sufficient confidence, and we believe that an average value of $1230 \pm 10^\circ\text{C}$ is the most plausible estimate for the initial temperature of the Kiglapait magma. The relevance of this estimate is supported by its closeness to a liquidus temperature of 1235°C, which was calculated for cotectic sample KI3567 (see above). Then, knowing the temperature of injection, it is possible to calculate the composition of the liquid portion of the initial magma as an average of the six compositions of model liquids corresponding to the products of equilibrium melting of the rocks at 1230°C. This estimate is given in Table 2 and is depicted in Fig. 5 as an unfilled circle. This composition can be classed as the “high-alumina ferrobassalt” or “Al–Fe troctolite magma” taking into account the low contents of normative diopside in such melts [36].

Initial Compositions of Minerals

Since the method of geochemical thermometry relies on the assumption of equilibrium component partitioning between the minerals and melt, it can be expected that the mineral compositions calculated for the estimated composition and temperature of intercumulus liquid should be similar to natural initial crystals. Taking into account that all six paths shown in Fig. 5 produce the association *Ol* + *Pl* at 1230°C, the average compositions of these liquidus phases are accepted as initial characteristics of the Kiglapait magma. The calculated average values at this temperature are 66.7 ± 1.6 mol % *An* in *Pl* and 78.8 ± 1.0 mol % *Fo* in *Ol* (Table 2). The estimate of the composition of initial plagioclase crystals is consistent with the results of microprobe analysis, whereas the calculated olivine composition is significantly more magnesian than natural one (Fig. 1). This result is not unexpected and its main reason is the reequilibration of primary crystals at the post-cumulus stage (see the model *Ol* compositions for a degree of crystallization of about 80%).

Phase Composition of Troctolites

An important feature of calculation by the method of geochemical thermometry concerns the possibility to estimate the initial proportions of cumulus grains and melt, which are determined through the solution of the thermodynamic equilibrium problem for each sample at the established temperature of rock formation. Table 3 shows the phase characteristics of melt–crystal assemblages presenting the initial (at 1230°C) mixtures of crystals and melt that eventually produced the marginal rocks of the IBZ and troctolites of the lower portion of the Lower Zone. These data illustrate that the cotectic association *Ol* + *Pl* was established in all cases with the predominance of plagioclase, and the total fraction of cumulus material increases monotonously from 7.5% in the lower “cotectic” sample (KI3567) to 70% in sample KI3224, followed by a decrease to about 44% in troctolite sample KI3230.

Of particular interest is the comparison of the relative proportions of initial *Ol* and *Pl* crystals. Table 3 shows that, from bottom to top, the amount of cumulus olivine increases initially from 2 to ~26 wt % (sample KI3223) and, then, falls abruptly to 1.5 wt % in sample KI3649 (35% solidification). These variations are in an almost perfect correlation with MgO distribution along the section (Fig. 2). The amount of cumulus plagioclase in this interval increases gradually from 5.5 to 56 wt %, which is also consistent with variations in Al₂O₃ and CaO contents. It can be noticed that the very low *Ol*/*Pl* ratio in sample KI3649 (1.5/56.0) allows its formal classification as anorthosite (see composition in Table 1) despite the cotectic nature of the trapped melt. An abrupt increase in the amount of *Ol* and a complementary decrease in the amount of *Pl* at the transition from sample KI3649 to KI3230 (35–39% solidifica-

Table 3. Phase composition of initial mineral–melt assemblages for the marginal rocks and troctolites of the Lower Zone of the Kiglapait intrusion

Parameter	Inner Border Zone (IBZ)		Troctolites from the Lower Zone of the Layered Group			
	Percent solidified					
	5.7	5.9	15.0	21.0	35.0	39.0
	KI3567	KI3623	KI3223	KI3224	KI3649	KI3230
Melt, wt %	92.5	66.3	32.8	29.6	42.5	56.4
Crystals, wt %	7.5	33.7	67.2	70.4	57.5	42.6
<i>Ol</i>	2.0	10.7	25.9	14.3	1.5	7.2
<i>Pl</i>	5.5	23.0	41.3	56.1	56.0	36.4

Note: Equilibrium proportions were determined for a temperature of 1230°C from the results of the computer modeling of equilibrium crystallization of molten rocks at a pressure of 2.2 kbar and the redox conditions of the *WM* buffer.

tion) can be interpreted as a transition from the stage of redistribution of intratelluric material to the regime of magma fractionation owing to sedimentation of crystals forming in situ or near the roof of the intrusion [2, 5].

Phase Composition of Initial Magma

Thus, the established character of the evolution of initial olivine and plagioclase proportions in the rocks of the lower part of the intrusion has a bearing on the redistribution of intratelluric crystals at early stages of Kiglapait magma differentiation. It is obvious that this sorting strongly depends on the abundance of crystals in the initial magma at the moment of its injection. The methods of phase equilibrium modeling provide an opportunity to calculate these characteristics proceeding from the weighted average composition of an intrusion, which is usually regarded as the most reliable estimate for the chemical composition of initial magma. The average composition of the Layered Group of the Kiglapait intrusion (Table 1) was calculated proportionally to the abundance of various rock types taking into account the closed character of the magma chamber [16, 21]. Accepting this composition as a model for the initial magma, it is possible to derive the initial equilibrium proportions and compositions in the same manner as was done for the rocks of the lower horizons. Such an approach implies the construction of an equilibrium crystallization path for this composition and determination of the characteristics of the initial suspension at a known injection temperature of 1230°C.

The results of calculations by the COMAGMAT-3.65 program at a pressure of 2.2 kbar and the redox conditions of the *WM* buffer are shown in Table 2 (right column). It is reasonable to compare the calculated composition of the liquid portion of the initial magma with the average composition of intercumulus melt derived by geochemical thermometry. It is clearly seen that the difference between them is not considerable and is no higher than the accuracy of the method for

major components. On the other hand, the elevated contents of titanium and phosphorus in the liquid estimated from the weighted average composition draw attention. This difference is yet to be explained, but it should be noted that this situation resembles the problem of considerable TiO₂ and P₂O₅ imbalance between the marginal rocks (initial magma) and weighted average composition of the Skaergaard intrusion [35].

In both variants of calculation, the model compositions of *Ol* and *Pl* appeared to be identical, but the most important result lies in the estimation of the phase composition of initial magma as a mixture of melt and intratelluric material (Table 2). These data suggest that the magma that entered the Kiglapait chamber contained about 25% of the crystals, which were dominated by plagioclase (20 wt %) and subordinate olivine (about 5%). This value of the initial crystal content can be used to estimate the position of the boundary between the cumulus material dominated by intratelluric phases and the cumulus material containing mineral grains crystallizing within the chamber.

It is evident that the 100% precipitation of primary crystals (cumulate free of intercumulus liquid) would place this boundary at 25% of intrusion solidification according to the scheme of Morse [11]. Accepting an average crystal content of about 60% (40% melt) in the cumulus, the boundary of complete primary phase precipitation moves to the 40% solidified level, which approximately corresponds to the above-described region of the minimum contents of MgO and cumulus *Ol* in the rocks (Fig. 2; Table 3). Thus, this (though crude) estimate does not contradict the suggestion that the earliest fractionating crystals were introduced into the cumulus starting from the level corresponding to ~40% of intrusion solidification. This fact is probably responsible for the “accelerated” evolution of *Ol* and *Pl* compositions in the upper part of the Lower Zone (Fig. 1).

ON THE SIGNIFICANCE OF CHILLED MARGINAL ROCKS

In the 1980s, medium- to fine-grained gabbroids were discovered and described near the southern contact of the Kiglapait intrusion with the Nain anorthosites. These gabbroids are chemically similar to the weighted average composition of the Layered Group [19, 37]. This provided the basis for the consideration of these rocks as chilled marginal facies approximating the composition of the magma that gave rise to the intrusion [21]. One of the near-contact samples (KI3763) was used in equilibrium melting experiments aimed at the determination of phase relations and compositions of liquidus phases within a temperature interval of 1192–1250°C and a pressure of 1 atm [38]. It was found that the liquidus association included *Ol* and *Pl*, which, taking into account the extrapolation to pressures of about 2 kbar, must crystallize at a temperature of about 1240°C. This is consistent with our estimates obtained by geochemical thermometry. However, the compositions of the earliest olivine (FO_{82-85}) and plagioclase (AN_{72-74}) crystals appeared to be substantially more primitive than those observed in the rocks of the lower levels of the Kiglapait intrusion (Fig. 1). Thus, the validity of these fine-grained rocks as a model for the initial Kiglapait magma remains questionable.

We performed a series of equilibrium crystallization calculations for four compositions representing the near-contact gabbroids [19] and the average composition of these rocks (Table 1). The main characteristics of the averaged crystallization path of *MAR* at a pressure of 2.2 kbar and *WM* redox conditions are illustrated in Figs. 3–5. These data show several fundamental differences, which negate the interpretation of the rocks of the marginal facies as an initial liquid. First, in contrast to the determined “troctolite” melts (Table 2), the composition *MAR* is characterized by relatively early augite crystallization, which start to precipitate at a temperature of 1178°C (Fig. 3) and a degree of crystallization of about 60 wt % (Fig. 4). Second, at an estimated injection temperature of 1230°C, the average path yields about 15% of the troctolite assemblage ($FO_{83} + AN_{69}$), which is significantly different (more than the data of geochemical thermometry) from the observed natural compositions. Third, the liquid lines of descent of the *MAR* composition clearly indicate that these rocks represent a system oversaturated in SiO_2 and depleted in FeO relative to the source of Kiglapait rocks (Fig. 5).

CONCLUSIONS

Proceeding from the modeling of crystal–melt equilibria and the application of the method of geochemical thermometry for the rocks of the Kiglapait troctolite intrusion, the chemical and phase parameters of the initial cumulates and Kiglapait magma were estimated. Calculations performed by the revised version of the

COMAGMAT-3.65 model under the redox conditions of the *WM* buffer and a pressure of 2.2 kbar demonstrated that (1) initial magma intruded at a temperature of about 1230°C and contained about 25 wt % of intratelluric phases (*Ol* + *Pl*); (2) the average compositions of phenocrysts corresponded to FO_{79} and AN_{67} , and the composition of the liquid portion of the magma can be classified as a “high-alumina ferrobasalt” or an “Al–Fe troctolite liquid” according to the nomenclature of [36]; and (3) the phase composition of the melt–crystal source of the Inner Border Zone rocks corresponded to the presence of about 70–93% of melt, whereas the troctolites of the lower part of the Lower Zone contained 30–56% of intercumulus liquid.

The hypothesis is justified that the cumulus assemblage of troctolites from the lower 40% of the Layered Group was represented mainly by intratelluric crystals, and in higher levels, the cumulus was enriched in the material that crystallized within the chamber. This explains the more significant changes in the composition of *Ol* and *Pl* in the upper part of the troctolitic Lower Zone in comparison with its bottom. The high forsterite mole fraction of model olivine relative to the most primitive crystals from the lower boundary zone is interpreted as a result of reequilibration with intercumulus liquid at the postcumulus stage.

It was shown that the fine-grained gabbroids from the southern contact of the massif with the Nain anorthosites cannot be regarded as analogues of magmatic melt whose differentiation and solidification resulted in the formation of the observed structure of the Kiglapait intrusion.

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