

Directional crystallization is not a mechanism of magmatic differentiation

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Current hypothetical mechanisms of magmatic evolution can be reduced to two main alternatives – directional crystallization and phase convection. The main difference between these two mechanisms is as follows. Hypotheses involving directional crystallization deny homogeneous nucleation of crystals and imply that crystallization takes place directly at a crystal-liquid interface as a result of a loss of heat through the roof. The heat transfer is supposed to occur by thermal convection of the main mass of homogeneous magma that is initiated by cooling at the roof solidification front. Convection-cumulative variant of phase convection is realized in a numerical model COMAGMAT [Frenkel, *et al.*, 1988]. In this model homogeneous nucleation and crystallization take place within a roof gradient zone. Crystals that form there settle through convecting magma and accumulate in the cumulate pile at the base of the intrusion. Convection has a chaotic, plume-like character. It emerges as a result of the inversion of density arising due to higher concentration of crystals at roof suspension layers.

Traditionally concepts of magmatic evolution are tested using ultramafic - mafic layered intrusions which represent the last bodies in terms of the depth that are accessible to direct examination. COMAGMAT allows reproducing quantitatively the distribution of major and trace elements in cross-section of differentiated dolerite sills as well as mafic-ultramafic layered intrusions (Fig. 1).

More than 20 years ago Frenkel [Frenkel *et al.*, 1988] came to conclusion that «all variants of model of the directional crystallization that ignore homogeneous nucleation of minerals and their transport by phase convection come into the contradiction with qualitative features of cross-sections of trap intrusions and dolerite sills». This conclusion was based on an analysis of still debatable heat and mass transfer processes of directional crystallization. This analysis was done by M.J.Frenkel at a physical and mathematical level that was difficult for the majority of igneous petrologists. In addition, the analysis was strictly applicable to dolerite sills, i.e. to differentiated intrusions of the "second" type. This result has been, however, practically ignored by the majority of experts in layered intrusions. Since that time we have studied a structure of many ultramafic-mafic layered intrusions and used these data to test a convection-cumulative model. In the present analysis of the directional crystallization we have decided to take an alternative approach. Let us assume that the directional crystallization is really realized in nature. What kind of compositional features should we expect in such layered intrusions on the basis of the fundamental principles of crystallization of silicate systems? How to accomplish this task? In fact, despite of greater popularity of a hypothesis of the directional crystallization, its quantitative model is not yet developed. However, we have thought that a variant of COMAGMAT with practically instant accumulation of crystallizing phases on the top of cumulative pile with almost crystal-free convecting melt may allows to simulate quantitatively the results of formation of intrusions by a mechanism of directional crystallization. Indeed, magma in the chamber is constantly maintained free of crystals and compositionally homogeneous and the solid phases, in the amount equivalent to heat lost through a roof, are accumulated on the top of growing cumulate pile. The realization of this scenario for Kivakka layered intrusion has revealed radical quantitative differences between the bodies modelled by directional crystallization (Fig. 2b) and convection-cumulative model. (Fig. 2A).

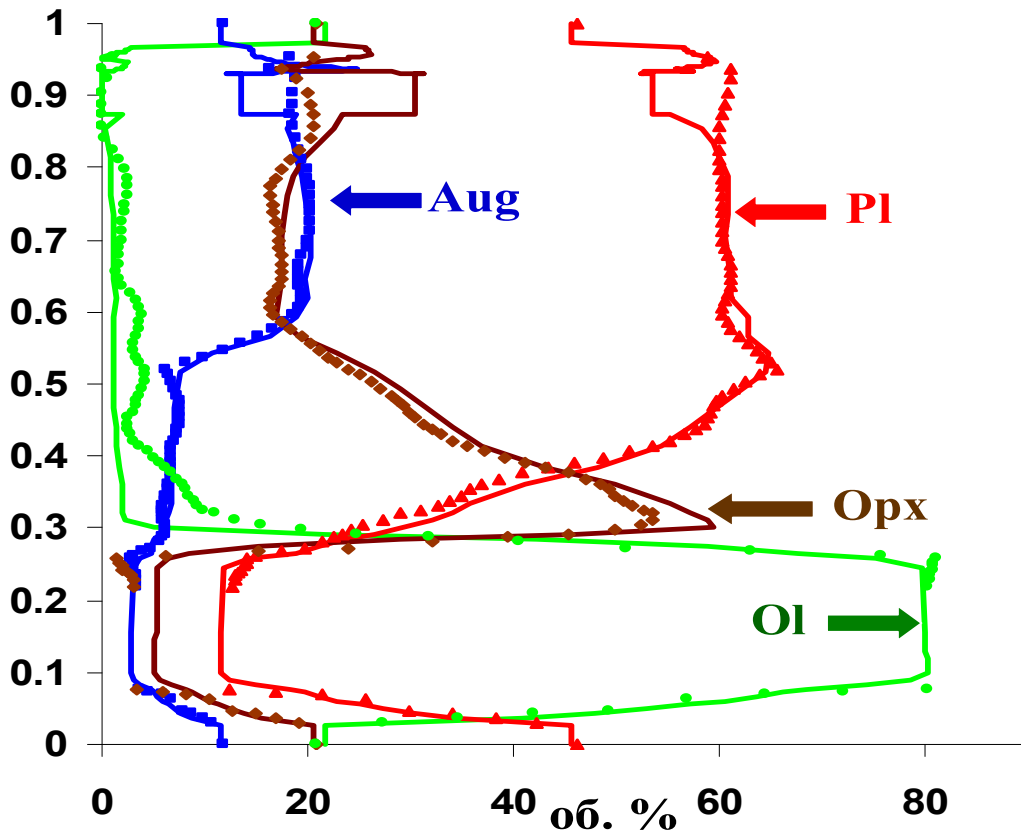


Fig. 1. The distribution of minerals in the section of the Kivakka layered intrusion (points) and modelled curves obtained in the frame of the convection-cumulative process.

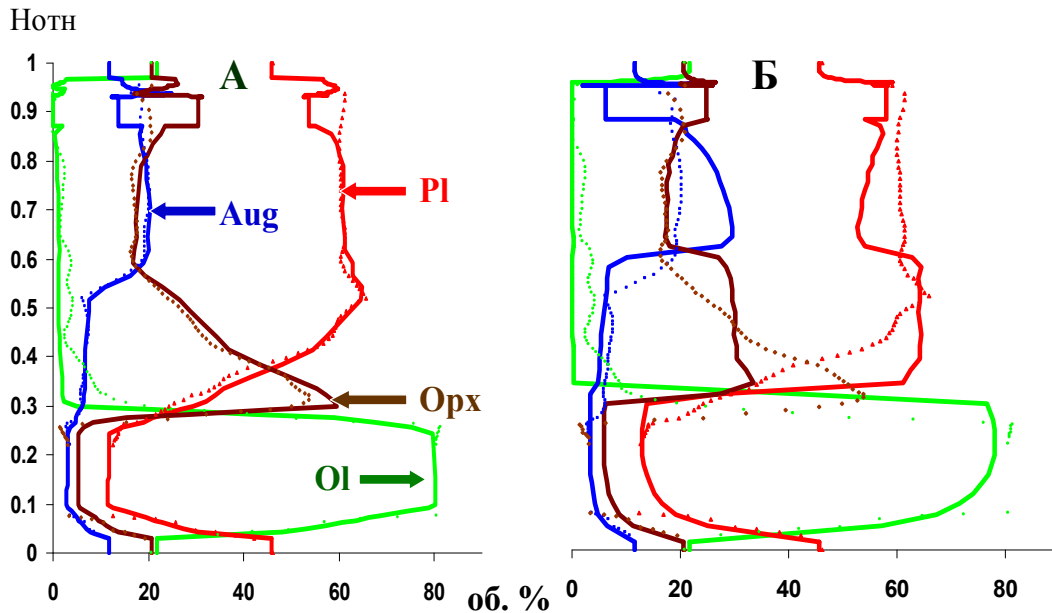


Fig. 2. The distribution of minerals in sections of the modelled intrusions: A - convection-cumulative model; B - directional crystallization model. Points – real data.

For the first of them, sharp boundaries between zones with various cumulative parageneses are observed and compositions of rocks in these zones are essentially different from natural data and convection-cumulative model. The fundamental reason for these differences is that the directional crystallization is a mechanism for fractionation of crystals from the melt, but not a mechanism of gravitational separation of minerals. In other words, on the surface of the crystallization front growing from below upwards the proportions of minerals should be consistent with cotectic proportions. This is not what is commonly observed in nature. It is proportions of minerals on the orthopyroxene-plagioclase and orthopyroxene-plagioclase-augite cotectics that are observed on the corresponding intervals in Fig. 2B. The differences are even more evident in terms of the distribution of incompatible elements such as Ni, Co, Cr and Sr (Fig. 3).

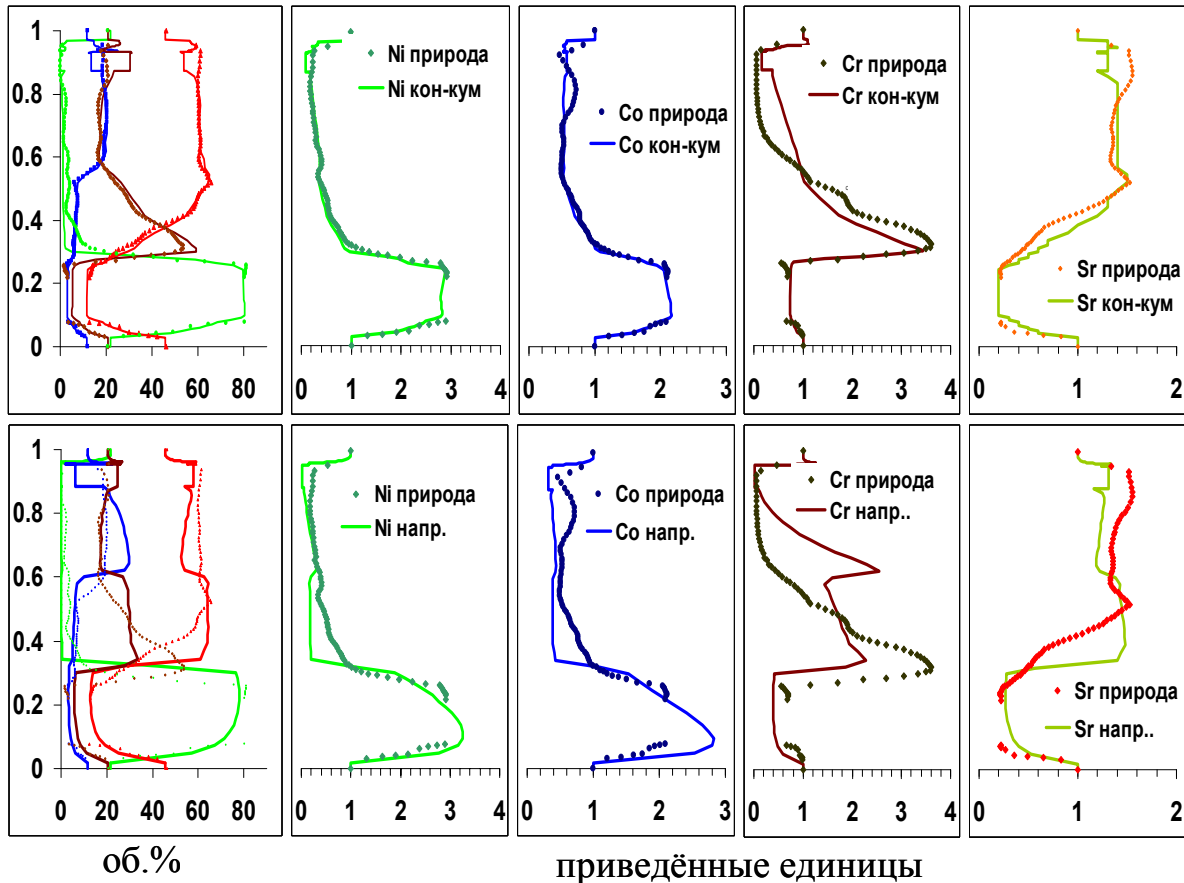


Fig. 3. Distribution of Ni, Co, Cr and Sr in the vertical sections of the Kivakka intrusion (points) and model objects (lines). The top series of plots corresponds to convection-cumulative model, the bottom series - the model of directional solidification.

To be fair, it is necessary to note that gradational change of composition of rocks in the basal part of the Noritic Zone is attained due to smoothing by a sliding window of the rhythmically layered package of rocks (Fig. 4A). Hypothetically, it is quite probable that rhythmic layering formed by directional crystallization will also result in gradual change in composition of rocks due to progressive change of thicknesses of alternating layers. me and Yana Bychkova have studied in details a rhythmically layered package of rocks of the Kivakka intrusion [Bychkova & Koptev-Dvornikov, 2004]. Fig. 4B shows variations in plagioclase content in alternating bronzitites and norites in this part of the section. Fig. 4B also shows the plagioclase contents in norites which should be expected if this package of rocks were formed by directional solidification. In other words, norites contain here plagioclase in proportions corresponding to crystallization on plagioclase-orthopyroxene cotectic. It is obvious that there is little in common between these two diagrams. This is an argument not only against an opportunity of formation of

rhythms in the frame of any version of the model of directional crystallization, but also against the directed crystallization itself.

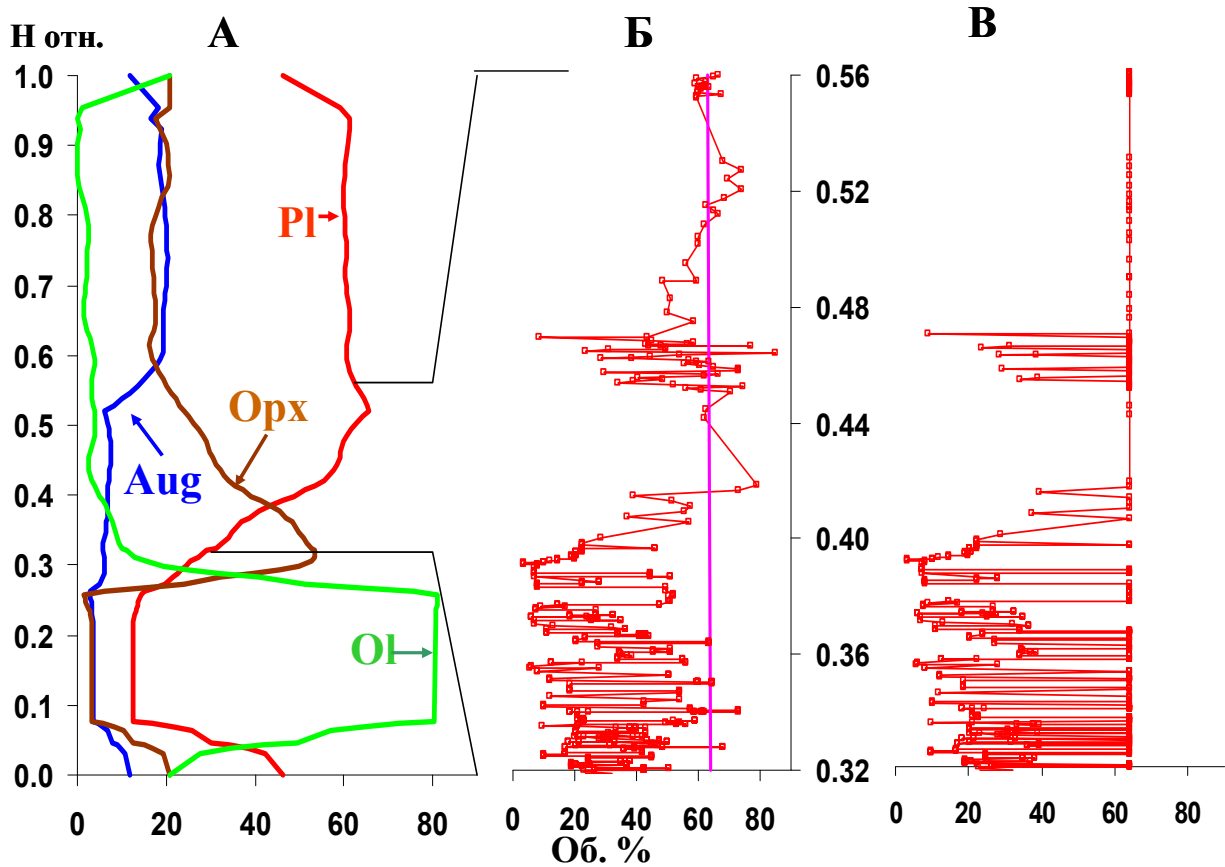


Fig. 4. Rhythmic structure of a layered series of the Kivakka intrusion in reality (B) and as predicted by directional crystallization (A)

We can thus now considerably strengthen our conclusion put forward in 1988 [Frenkel et al., 1988]. All variants of model of the directional crystallization that ignore homogeneous nucleation of minerals and their transport by phase convection come into the contradiction with qualitative features of cross-sections of mafic-ultramafic layered intrusions.

Thus, since the directional crystallization is not a mechanism of layered intrusion formation, it is not a mechanism of magmatic evolution.

Let us hope that this result will be more difficult to ignore since it is not based on an analysis of debatable heat and mass transfer mechanisms but on the fundamental laws of crystallization of mafic silicate systems.

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References

- Frenkel' M. Ya., A. A. Yaroshevskii, A. A. Ariskin, G.S. Barmina, E.V.Koptev-Dvornikov, B.S. Kireev (1988) *Dynamics of the in-situ Differentiation of Basic Magmas* Nauka, Moscow [in Russian].
 Ya.V. Bychkova, E.V. Koptev-Dvornikov Rhythmic Layering of the Kivakka Type: Geology, Petrography, Petrochemistry, and a Hypothesis for Its Formation *Petrology*. 2004. V. 12. №3. P.227-244.