Crystallization and Cooling of the Noril’sk Intrusions According to the Pyroxen’s Geothermometry Data

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Abstract. Composition of clinopyroxenes in vertical sections of some ore-bearing basic intrusions in the Noril’sk area has been studied by EPMA. These data formed the basis for the calculation of the pyroxene crystallization temperatures using the El Negro monopyroxene geothermometer (Fe-Mg exchange between M1-M2 positions). The results of the calculations allowed estimating the variations of temperature crystallization within the magmatic chambers from early to the late stages. The temperature varies from 1200 for idiomorphic crystals in equilibrium to liquid and up to 400 degrees (in solid intrachamber exchange) for xenomorphic grains and marginal zones of pyroxenes. We reconstructed the regimes of crystallization of the magmatic chamber by this data. The vertical distribution of paleotemperatures of the intrusive chamber there is the evidence of absence vertical move crystals into such magmatic chambers.

1. Introduction
One of the key problems of intra-chamber differentiation and magmatic layering origin is a thermal regime of melt crystallization with a heat loss of the intrusive chamber. This problem is quite relevant for Cu-Ni sulfide deposits related to basic-ultrabasic intrusions. There are different points of view on the rate of cooling for intrusions in the Siberian trap province [1-4]. The numerical models of A. A. Ariskin and others [5, 6] describe intra-chamber differentiation based on theoretical and experimental concepts of phase equilibrium in parent melts. The basic principle of such a model is the relative free moving of crystals of different mineral phases in the melt inside the magmatic chamber as a direct result of the free transportation crystals in large volume liquid's space. However, these models consider the inner structure of formation of intrusions only at the stage of a sufficiently large volume of melt in the chamber, when crystals move freely, according to the difference between densities of the minerals crystals and melt and the hydrodynamics of the fluid movement. The task of this work is to estimate the crystallization temperatures of pyroxenes in the magma chamber from the beginning of crystallization to its complete solidification. If we can calculate the gradient of paleotemperatures in the section of real intrusions that we take the possibilities to evaluate the real picture of the cooling of intrusions, compare ore and barren intrusions, estimate the mode of crystallization in different parts of the magmatic chamber.

2. Methods and input geological data.
A list of intrusive bodies whose pyroxenes were analyzed and used in this work is given in table 1. These intrusions comprise sulfide mineralization graduated in economic value, from the extra-large deposit (the Kharaelakh intrusion) to sub-economic (the Bolshaya Bariernaya intrusion) and barren...
(Maslovsky sill). We used core material from boreholes penetrated intrusions from top to bottom. Figure 1 demonstrates the example of cross-section I-I for the South Maslovsky intrusion.

![Cross-section I-I](image)

**Table 1.** Mineralized intrusions of the Noril’sk region

| N  | Intrusion       | Hole, N | Depth (top-bottom), m | Points from set | Temperature maximum | Temperature minimum |
|----|-----------------|---------|-----------------------|-----------------|---------------------|---------------------|
| 1  | Kharaelakh      | TG-21   | 1228-1346             | 218             | 1110                | 411                 |
| 2  | Kharaelakh      | KC-56   | 1360-1550             | 348             | 986                 | 413                 |
| 3  | North Maslovsky | OM-4    | 815-999               | 217             | 1120                | 430                 |
| 4  | South Maslovsky | OM-24   | 506-803               | 619             | 1240                | 616                 |
| 5  | Maslovsky sill  | OM-25   | 428-711               | 113             | 1110                | 438                 |
| 6  | Noril’sk-2      | MP-18   | 139-312               | 426             | 1172                | 412                 |
| 7  | Bolshaya Bariernaya | MP-38 | 82-136                | 185             | 1025                | 436                 |

Clinopyroxenes were analyzed at a microprobe with a sufficiently large frequency to evaluate variations in their compositions throughout the section. The number of analyzes within each hypsometric level ranged from 5 to 30 points. The idiomorphic grains of pyroxene, the central and marginal zones of the crystals, and the xenomorphic interstitial pyroxene were analyzed (figure 2). This allowed us to obtain the entire range of temperatures occurred during the crystallization of the intrusion.

We used a mono-mineral pyroxene geothermometer based on the intracrystalline redistribution of Mg-Fe between the M1-M2 positions [8-12]. This approach allows estimating the crystallization temperatures of pyroxenes at an early stage and during late recrystallization of pyroxene upon interaction with an interstitial melt. We divided the obtained set of analyzes into two groups: (i) early
idiomorphic crystals and (ii) xenomorphic grains. Unfortunately, the division into these two groups is not always correct, since a number of analyzes in idiomorphic crystals were made at the edge of the grains and their composition corresponded to the later stages of the development of the magmatic system. On the contrary, a number of analyzes of xenomorphic grains turned out to be high-temperature.

![Image](image_url)

**Figure 2.** Micro photos of zonal clinopyroxene crystals (type 1) - A; Late xenomorphic clinopyroxene (type 2, B), in the interstitial zone between clinopyroxene crystals (type 1). Image in BSM

The possible reason for this situation that gabbro structure does not always allow to determine which generation of pyroxene relates with a specific grain. The calculated temperatures were subdivided into two conditional subgroups corresponding to high temperature stage with \( T > 800^\circ C \) and late magmatic stage with \( T < 800^\circ C \) (Figure 3). The points of these subgroups are marked with different markers on the graphs, the depth along the well versus the equilibrium temperature (Figures 3, 5).

### 3. Results of calculation

The results of the calculations are presented in the figures in the form of two data series (figure 3). A rather unexpected fact is a sharp predominance of low-temperature interstitial pyroxenes in the samples of South Maslovsky and Kharaelakh intrusions (boreholes OM-24 and KC-56) and other. We suggest that either the most part of analyzes reflect the composition of marginal zones in idiomorphic crystals or they indicate the composition of crystals formed at high-temperature and then re-equilibrated with the interstitial melt at a low temperature. However, the cooling kinetics could hardly support such a secondary composition change. The fact of occurrence of analysis corresponding to liquidus of early pyroxenes indicates this. Therefore, we adhere to the point of view that the main stage of pyroxene crystallization began late.

Calculations revealed at least two types of intrusions with different temperature distributions over the vertical section. Figure 3 shows the most interesting results of calculations for two intrusive sections. There is a common observation that the temperature trends in both sections have a complex shape. In general, it can be said that in the upper parts of intrusions there are more high-temperature pyroxenes than in the lower ones. But the main difference between the South Maslovsky and Kharaelakh intrusions is in the distinct trends of change temperature equilibrium pyroxene-liquid for the first intrusive body (figure 3A) and the more chaotic distribution of points for the second one.
The South Maslovsky intrusions (about 300 m thick) demonstrates a strong gradient (about 150 degrees) of the temperatures for early pyroxenes over the vertical section. The trend paleotemperature demonstrates abrupt changes in the upper and lower contacts and a smooth decrease in temperature from top to bottom. The trend of interstitial pyroxenes almost completely repeats the trend of high-temperature idiomorphic crystals. The lowest temperatures are typical of the lower parts of the intrusion, while the pyroxenes from the upper contact zone are characterized by a recrystallization temperature about 500-600 (100-150 degrees higher). In contrary, the Kharaelakh intrusion (about 200 m thick) is characterized by the absence of noticeable gradients. The trend of equilibrium temperature for idiomorphic early clinopyroxenes in the upper part is similar to the trend in the upper part Maslovsky section, but lower part values of temperatures do not depend on the depth over the intrusion section, and we can only note a decrease in the equilibrium temperatures for low-temperature pyroxenes in the lower parts of the section.

Figure 3. The pyroxene paleotemperatures distribution in vertical section of the intrusions: A - Maslovsky (borehole OM-24) and B - Kharaelakh (borehole KC-56). Non-filled circles - calculated early equilibrium temperatures, flooded points - late temperatures of xenomorphic grains and edge zones of crystals. The vertical axis is the depth m.
Figure 4 shows a comparison of paleotemperature distribution with the rock compositions in the vertical section of the South Maslovsky intrusion. The chemical composition of rocks changes from the bottom to top: MgO decreases while alkali and silica increase in this direction. The decrease in liquiduspyroxene temperatures in the magma chamber with a simultaneous increase in the magnesium content in the rocks along the sections from top to bottom is an unexpected fact. It is usually assumed that early cumulus minerals (especially olivine) are concentrated in the lower parts of the intrusions (by gravitational force), thereby increasing of the rocks magnesium there. Our calculations show that this scenario is not realized in the South Maslovsky intrusion. For the KC-56 section and a number of other sections with absent such clear trends, there is no decrease in temperature in the lower part. But for them, there is no inverse tendency to increase liquidus temperatures along the top-down section.

Figure 4. Paleotemperature crystallizations pyroxene (A) and composition of rocks (B) in the South Maslovsky intrusion. The MgO and FeO contents are in wt.%

That is, the paradox stays between the trend of increase of rocks magnesium downwards and the decrease or persistence of crystallization temperatures in the lower section of the intrusion. In the future, we plan to calculate temperatures for olivine, and then we can consider this paradox with great reason. Unexpected facts are a sharp change of iron content and a corresponding peak of nickel...
concentrations in the middle part of OM-24 section of the Maslovsky intrusion. In addition, there is a trend to reduce the nickel concentration to the lower contact from the nickel maximum (figure 5). The reason for the jump in the iron content in the area of the nickel maximum is not clear (figure 5). This trend coincides with the trend to reduce early liquidus temperatures. The position of the maximum concentration of nickel in the section coincides with the level where the trends of crystallization temperatures of xenomorphic and idiomorphic crystals are connected. It is not yet clear how far this regularity is repeated in other intrusions and from other chalcophile elements. Additional research is requested.

![Figure 5](image_url)

**Figure 5.** Calculated temperature gradients for early pyroxenes (A) and the composition of rocks (MgO, FeO wt.%, Ni ppm) (B) in the South Maslovsky intrusion

4. **Results and discussion.**

A wide range of temperatures at each hypsometric level of the intrusion implies a gradual cooling of the considered sub-plate intrusions. Attention is drawn to the temperature gap between early and late igneous pyroxenes associations. In the upper parts of the intrusion (especially Maslovsky), the gap between the crystallization temperatures of early and late pyroxenes is significant. In the middle and at
the bottom of the section, the gap is practically absent, and pyroxenes of the entire liquidus temperature range are noted. Figure 6 shows a result of calculations for the Kharaelakh intrusion in the borehole TG-21. On figure showed generalized data (figure 6 A) and total set of data (figure 6 B).

Figure 6. Temperatures of crystallization for the pyroxenes from the Kharaelakh massif: only average temperatures for early and late pyroxenes (A) and the full entire temperature range (B)

The reason for this phenomenon needs more detailed consideration, but as a preliminary hypothesis, it can be assumed that the width of this gap is related to the degree of crystallization of the intrusion. At the initial moment of time when the proportion of liquid in the chamber prevails, early crystals can move freely over the chamber intrusion, vertically from their initial crystallization centers. Later this possibility disappears due to the decrease in the amount of residual melt in the chamber and an increase in its viscosity. Crystals of primary magmatic associations remain at the point of crystallization and converge with the pyroxene grains crystallizing with a consequent decrease in liquidus temperatures. It is interesting to discuss the presence of two trends of change paleotemperatures for early idiomorphic pyroxene crystals in the vertical section of the South Maslovsky intrusion (figure 1A). We suggest that these two trends reflect two stages of crystallization of early pyroxenes. The much lower temperature trend corresponds to the mainstage.
trend is associated with the possible participation of convection currents. These data indicate a limited manifestation of the displacement of early crystals in the chamber along the vertical line and, therefore, the absence of convection process in the reservoir of several hundred meters in the thickness. Figure 5 shows the temperature equilibrium for the Kharaelakh intrusion (TG-21 section). On figure 6 (B), it can be seen that the changes in liquids temperatures are almost continuous for each level of the section. Gaps in the temperature ranges are observed only for high-temperature pyroxenes. There is a gradual, without any interruption, a decrease in the re-crystallization temperatures of pyroxenes below 800°C. It means that these low temperatures reflect the mode of gradual cooling of the magmatic chamber without moving the crystals within the magmatic chamber.

5. Conclusions.
Distribution of paleotemperatures in seven sill-like intrusions of the Noril’sk region has been carried out based on the chemical compositions of the clinopyroxenes. Similar crystallization-cooling modes were established for all intrusions.

Firstly, there is a wide temperature range from high-temperature idiomorphic pyroxene crystals to low-temperature xenomorphic grains and edge zones of crystals.

Secondly, the large obtained interval of the temperatures indicates that the cooling and crystallization of the intrusion occurred without significant movement of the pyroxene crystals in space. Consequently, the bulk of pyroxene crystallized in the absence of convective displacements or gravitational sedimentation of crystals.

An unexpected consequence of the calculations was the conclusion that the most differentiated low-temperature portions of the melt are crystallized to the lower parts of the section.

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