Texture and Mineral Composition of Magmatic Apatite-Nepheline Ores: Technological Consequences (Exemplified by Khibiny)

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Abstract. The paper considers the relationship between textural and structural features and gross mineral and chemical composition of minerals and the physical properties of apatite-nepheline ores and their processing. It is noted that the change in the physical properties of ores involves primarily the change in their mineral composition due to apatite depletion. An increase in the content of nepheline and pyroxene to 35-55 % sharply increases the ore strength up to 47-104 MPa, which entails the growth of energy consumption for grinding. An important factor is that the ore contains high-strength poikilitic intergrowths of apatite with nepheline, pyroxene, and titanite, in which about 20 % of fine-grained apatite is concentrated, and the extraction of which is a complex technological problem. The authors attribute a change in the chemical composition of apatite to the main factors deteriorating the product quality. According to the studies, the chemical composition of apatite is unstable and varies in the content of P₂O₅ (37.20-42.6 %), SrO (2.29-5.36 %), and Tr₂O₃ (0.51-1.05 %). It is noted that a change in the composition may affect the flotation properties and quality of the concentrate.

1. Introduction
In recent years, insufficient attention has been paid to the issues of the Khibiny massif apatite-nepheline ore mineralogy, and the advanced technological studies have been reduced. However, as practice shows, the problems of apatite ore processing are increasing, associated with the deterioration of the apatite concentrate quality and the loss of apatite with tailings. In our opinion, in the apatite ore processing technology, there is now a gap between the modern process level and mineralogical research. In this regard, we have analyzed and additionally studied the material composition of one of the commercial ore types to explain the relationship between geological and mineralogical properties and technological ones.

The textures and structures of the Khibiny massif apatite-nepheline ores are most fully characterized from the standpoint of magmatic genesis [1, 2]. Spotted and spotty-striped ores take a particular place in the group of the natural types of the Khibiny deposit apatite-nepheline ores [3, 4]. They are common in all deposits and are the main high-grade ore type. They feature a relatively simple mineral composition: fluorapatite 60-95 %, nepheline 4-30 %, pyroxene 0-15 %, and titanite and feldspars less than 5 %, as well as distinct individual properties expressed in texture and structure and forming a basis for determining the ore and rock behavior in processes [5, 6].
2. Research methodology
Determining the apatite ore mineral composition is very difficult due to the non-uniform grain size and variability of texture, so we used several techniques. The composition of hand specimens ranging in size from 100 to 200 mm was assessed visually. In thin and polished sections, minerals were determined using polarizing microscopes in transmitted and reflected light by comparing optical and other physical properties with reference minerals [7]. In contrast to previous studies, we have used extensively reflected light techniques. Since in apatite-nepheline ores, all the main minerals are low-reflecting, we have developed a special technique to determine minerals by “color temperature” [8]. The average mineral composition of the powder samples was controlled by X-ray phase analysis. The chemical composition of minerals was determined using an electron microscope. The mineral composition inhomogeneity was studied using an X-ray energy dispersive spectrometer.

3. The study results
The textural and structural features of ores are the most important technological factor affecting the grinding [3, 5, 6]. The richest in apatite content spotted ores are products most difficult for processing. Spotted ores feature the development of poikilitic structures. These structures have been known for a long time; yet, they have not received due attention to date. The ore is composed of apatite and inclusions of nepheline, pyroxene, titanite, and biotite (Fig. 1).

![Figure 1. Spotted Apatite-Nepheline Ore with Fragments of Banded Texture.](image1)

![Figure 2. Panidiomorphic-Grained Structure of Monomineral Apatite. Photo in Transmitted Light.](image2)
Monomineral apatite has a full-crystalline panidiomorphic-grained structure (Fig. 2) typical of magmatic minerals such as olivine in dunites, chromite in chromitites, etc. Apatite grains are polyhedrons with even straight-line boundaries, up to 5 mm in size.

The inclusions of dark-colored minerals in monomineral apatite are composed of single crystals and polycrystalline aggregates of nepheline, pyroxene, biotite, and titanite. They are saturated with inclusions of apatite microcrystals, i.e., poikiloblasts [9]. The sizes of poikiloblasts are generally within 0.5-3 cm. The apatite grain shape in poikiloblasts is faceted crystals or roundish emulsion inclusions (Fig. 3).

![Figure 3. Poikilite Inclusions of Apatite in Nepheline. Electronic Image.](image)

The texture and structure of spotted ore allow attributing it to typical magmatic formations and considering monomineral apatite as an early magmatic phase, and poikiloblasts as a late magmatic melt crystallization phase [1]. Being a late crystallization phase, poikiloblasts played the role of cement, after curing of which the melt lost its fluidity; therefore, the spotted and lenticular-striped ore texture reflected the end of plastic deformations, and all subsequent deformations were rupturing ones. Spotted ore participated in the complex process of forming ore deposits as an independent melt; therefore, it occurs in the form of both cement of breccias and fragments cemented by other rocks [2]. From the technological point of view, two components in the ore composition are important: a matrix of monomineral apatite and poikiloblasts of various minerals with apatite. Poikiloblasts are in fact bimetallic rocks cementing the apatite matrix. This creates the ore strength anisotropy when ground due to the difference in the physical properties of minerals and aggregates.

From among all the ore components, free apatite-1 is most preferable for grinding: it is large, released, and has no obstacles to opening when ground. Since apatite is the softest of all the basic ore minerals [6], it has the best grindability [10].

The second textural ore element is the poikiloblasts of nepheline, pyroxene, and titanite. In the ore, they form “islands” with high strength and different resistance to grinding. Their finer grading is caused by the need for opening poikilitic apatite since it is 5 times finer than monomineral apatite. Due to the physical properties of the poikiloblasts of nepheline, pyroxene, and titanite, they are destroyed later than monomineral apatite and sequentially, according to a decrease in strength: nepheline, pyroxene, and finally, titanite. This sequence is well studied for apatite and nepheline [11, 3, 12].

3.1. Mineral composition of ore
Spotted ore is the main apatite concentrator in the Khibiny deposits. Its mineral composition is characterized by stable paragenesis. Apatite - 51.6-74.3 % and nepheline - 15.3-34.7 % components dominate in the composition, and aegirine - 4.0-5.2 %, feldspar -1.8-4.5 %, and titanite - 1.3-4.2 % are
the secondary ones. Apatite is represented in two genetic forms: a free monomineral phase and inclusions in poikiloblasts. Free apatite accounts for 78%, and poikilitic one about 22%, including about 9, 8, and 5% in nepheline, pyroxene, and titanite on average. Accessory impurities are represented by titanomagnetite, magnetite, ilmenite, pyrite, pyrrhotite, and chalcopyrite in the amount of 1-2%.

The predominance of apatite in ore determines its weak physical properties when ground [10, 3, 6, 13]. The ore strength decreases with growing apatite content and increases with growing nepheline and pyroxene content. By strength, ores with more than 35% nepheline and 15% pyroxene are classified as high-strength rocks [14]. The total nepheline and pyroxene content of 35% and 45-55%, respectively, is critical; at these values, a sharp increase in the ore strength and hardness occurs (up to 47-104 MPa and category 5-10, respectively).

3.2. Chemical composition of apatite
Apatite is the only carrier of P_2O_5 in the ore, therefore, its composition is of paramount importance for obtaining a stable high-quality phosphorus concentrate.

In terms of chemical composition, it belongs to fluorapatite in all the Khibiny rocks and ores. Studies have shown unstable composition of apatite [15, 16]. The P_2O_5 content deserves special attention. A change in composition is observed in both ore and accessory apatite. In ore apatite, the P_2O_5 content varies within 37.2-42.8%, on average 40.66%. In accessory apatite in rocks, its content varies within 29.69-43.30%, on average 40.17, 40.06, 39.82, and 39.96% in urtites, ijolites, malignites, and rischorrites, respectively.

Studying apatite in spotted ores has shown that free apatite contains from 39.42 to 41.99% of P_2O_5, on average 40.82%. In poikilitic apatite, the P_2O_5 content varies within 38.43-41.99%, on average 40.25%. The highest average content of 40.55% was found in apatite from titanite, the lowest in apatite from pyroxene - 39.10%. Thus, the apatite quality in poikilitic inclusions deteriorates since the average P_2O_5 content is 0.57% lower than in free apatite.

The apatite composition instability associated with crystallization zoning should be noted. Electronic studies have established the heterogeneity of early magmatic apatite crystals (Fig. 4).

**Figure 4.** Zoning in Free Fluorapatite Crystals: light zones contain more rare-earth elements. 1, 2 - composition analysis points. Electronic Image.

Apatite crystals contain up to 5 zones differing in the TR_2O_3 and SrO content. The SrO and TR_2O_3 contents vary within 2.29-5.36% and 0.51-1.05%, respectively. The crystal cores usually contain apatite enriched in TR_2O_3 and SrO. Zoning in crystals indicates a repeated change in composition in
the course of pulsing crystallization. It is of great importance for flotation. The zone widths reach 100 μm, therefore, in large crystals, when grinding apatite to a fraction of -0.04 μm, fragments of different composition zones are isolated, and free grains with a contrasting SrO and TR2O3 content emerge, which may affect the flotation properties.

4. Conclusion

The spotted ore study results allow distinguishing three features that should be considered when processing them: 1) textural-structural - spotted texture and poikilitic structure, 2) mineralogical - two apatite generations, 3) chemical - unstable composition of apatite.

1. The ore texture determines the presence of about 60 % free apatite and 40 % poikiloblast with apatite in the volume; i.e., 78 % of released apatite and 22 % of that enclosed in dark-colored minerals. Due to the difference in the physical properties of minerals and their aggregates, the ore is characterized by high heterogeneity. The opening of poikilitic apatite determines two aspects of the problem: the need to destroy the poikiloblast and the change in the grinding fineness with the apatite opening. Since poikiloblasts are dimineral aggregates and have a rock structure, the dependencies established for rocks can be used to analyze their destruction [3]. Considering the content of apatite in poikiloblasts, their properties can be roughly estimated by the mesh ore properties, which have higher physical strength than spotted ore. Judging by the physical properties, opening the pyroxene poikiloblasts requires the maximum costs since pyroxene has the highest hardness, almost 2 times that of apatite, and stress-strain characteristics. However, pyroxene has a higher cleavage degree, which promotes faster fracture, despite its high compressive and tensile strengths. The idiomorphism of grains may also affect grinding. Minerals with clear crystallographic boundaries – pyroxene and titanite are characterized by a weak bond between grains, which, along with increased fragility, can be the main cause of the fastest destruction during ore grinding.

2. Mineralogical features of spotted ores are associated with variations in the content of apatite, nepheline, pyroxene, and titanite, which lead to a change in the physical properties of the ore as a whole [3, 6, 17, 13, 14]. The regularities of changes in the spotted ore mineral composition are described by the equations: N=79,4 – 0,834A; P=8,0 – 0,056A; where N is nepheline, %, P is pyroxenes, %; A is apatite, %, and can be used for prompt assessment of stress-strain behavior [3]. The equations are valid when the apatite content in ores changes from 20 to 97 %, while the nepheline and pyroxene contents decrease from 63 to 0.4 % and 7 to 2.6 %, respectively. The apatite-nepheline ore density is promptly assessed by the apatite content in them: ρ = 3.88A + 2.74·10³. In the rich (60-95 % of apatite) and poor (up to 50 % of apatite) zones, the apatite-nepheline ore density may vary within 2.9-3.2103 and 2.8-3.0 kg/m³, respectively. A critical change in the mineral composition is the increase in the total content of nepheline and pyroxene in the ore - 35 and 45-55 %. At these values, a sharp increase in the ore strength and hardness occurs (up to 47-104 MPa and category 5-10, respectively). For all the mineral composition variations, it should be considered that soft mineral grinding is performed at the maximum mill productivity, i.e., free monomineral apatite requires a minimum grinding time [10]. In practice, this means the need to control the mill operation duration depending on the ore composition to prevent overgrinding of apatite to slime fractions, which float less effectively.

3. The chemical composition of apatite is unstable and should be controlled in technological sampling and mining of ores. The impact of the apatite chemical composition on the concentrate quality is most important since different P2O5 contents in apatite require different extraction into the concentrate. The study showed a particularly low phosphorus content in apatite from pyroxene poikiloblasts; therefore, an increase in their amount in the ore may be accompanied by the reduced P2O5 content in apatite. Thus, with an increase in the pyroxene content, both an increase in the ore strength and a decrease in the P2O5 content in apatite, i.e., deterioration in the concentrate quality can be expected. The chemical zoning of apatite requires a deeper study since zoning in apatite crystals causes an uneven distribution of strontium and rare-earth elements. The apatite grinding leads to the separation of zones with different contents of strontium and rare-earth elements and the occurrence of
apatite grains of different compositions in the pulp. Considering that the apatite floatability with the inclusions of strontium and rare-earth elements is theoretically higher [18, 15, 16], then conditions should be created for selective flotation of a part of apatite.

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