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Economic minerals of the Kovdor baddeleyite-apatite-magnetite deposit, Russia: mineralogy, spatial distribution and ore processing optimization

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ABSTRACT

The comprehensive petrographical, petrochemical and mineralogical study of the Kovdor magnetite-apatite-baddeleyite deposit in the phoscorite–carbonatite complex (Murmansk Region, Russia) revealed a spatial distribution of grain size and chemical composition of three economically extractable minerals — magnetite, apatite, and baddeleyite, showing that zonal distribution of mineral properties mimics both concentric and vertical zonation of the carbonatite-phoscorite pipe.

The marginal zone of the pipe consists of (apatite)-forsterite phoscorite carrying fine grains of Ti–Mn–Si–rich magnetite with ilmenite exsolution lamellae, fine grains of Fe–Mg-rich apatite and finest grains of baddeleyite, enriched in Mg, Fe, Si and Mn. The intermediate zone accommodates carbonate-free magnetite-rich phoscorites that carry medium to coarse grains of Mg–Al-rich magnetite with exsolution inclusions of spinel, medium-grained pure apatite and baddeleyite. The axial zone hosts carbonate-rich phoscorites and phoscorite-related carbonatites bearing medium-grained Ti–V–Ca-rich magnetite with exsolution inclusions of geikielite–ilmenite, fine grains of Ba–Sr–Ln-rich apatite and comparatively large grains of baddeleyite, enriched in Hf, Ta, Nb and Sc. The collected data enable us to predict such important mineralogical characteristics of the multicomponent ore as chemical composition and grain size of economic and associated minerals, presence of contaminating inclusions, etc. We have identified potential areas of maximum concentration of such by-products as scandium, niobium and hafnium in baddeleyite and REEs in apatite.

1. Introduction

Phoscorites belong to a rare type of igneous rocks in relation to carbonatite magmatism. They predominantly consist of forsterite, magnetite, apatite and carbonates. Phoscorite and carbonatite igneous complexes may host important deposits of Fe, Cu, Nb, PGE, REE, P and Zr (Wall and Zaitsev, 2004): Phalaborwa (South Africa), Sokli (Finland), Catalão (Brasil), Mt. Weld (Australia). The Kovdor phoscorite–carbonatite pipe hosting the Kovdor magnetite-apatite-baddeleyite deposit is a typical example of such deposits. Currently the open pit mine "Zhelezniy" located at the Kovdor deposit produces about 5.7 Mt/year of magnetite concentrate, 2.7 Mt/year of apatite concentrate and 10,000 t/year of baddeleyite concentrate (Eurochem, 2014; Khramov, 2014). The deposit has been mined as an open pit since 1962. Today it is owned by JSC "Kovdorskiy GOK", part of Eurochem Corporation. Resources of Russian A + B + C1 categories (approximately corresponding to measured resources in JORC classification) amount to 267 Mt, while the resources of C2 category (approximate equivalent of indicated resources) are 219.7 Mt at grades (average for all categories) of 27 wt.% Fe_{total}, 6.8 wt.% P_2O_5 and 0.17 wt.% ZrO_2 (Khramov, 2014).

The Kovdor deposit is mineralogically diverse. This, on the one hand, gives a long-term outlook, but exploration becomes more complicated, on the other hand. This required a detailed and systematic 3D mineralogical mapping (Kalashnikov et al., 2012; Ivanyuk et al., 2013; Mikhailova et al., 2015), as modern economic conditions call for an advanced and more precise extraction technology for different elements. Development of the Kovdor deposit is an example of the most efficient use of complex mineral resources. But the modern economy requires an advanced and more precise elements recovery technology. One of significant concentration problems is the irregular distribution of Mg and Mn in magnetite. Other problems are variation of magnetite grain size, different gauge microinclusions (spinel or/and ilmenite group minerals, quintinite). In addition, characterization of the spatial distribution of

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other potentially economic components (e.g., scandium in baddeleyite, Kalashnikov et al., 2016) could improve efficiency of the mine. There are no fast and inexpensive methods for real-time assaying of chemical composition, grain-size distribution and inclusions of the ore minerals in each exploration block. The necessity for rather accurate forecast of the ore minerals properties became another reason for mineralogical mapping. An idea about geological, mineralogical and metallurgical mapping of the Kovdor deposit was suggested by Riko et al. (1987) and Krasnova and Kopylova (1988), who compiled a geological model and designed a mapping program for complex ores with different processing and metallurgical properties. This resembles a concept of geometallurgical units (Lotter et al., 2003). However, the political and economic crisis in the late USSR put those plans on shelf. Our study is the further development of this idea.

We have introduced the 3D mineralogical mapping approach in our previous papers. Mikhailova et al. (2015) presented new petrographic and geological data and compiled all previous borehole data. The authors proposed a new classification of rocks for the phoscorite–carbonatite series. Based on these data, zonation and rock relationships were identified at the Kovdor deposit. Here we present a model of spatial distribution of properties of recoverable minerals — magnetite, apatite and baddeleyite. These minerals have been thoroughly described in numerous articles (Rimskaya-Korsakova, 1950, 1963; Rimskaya-Korsakova and Dinaburg, 1964; Rimskaya-Korsakova et al., 1968, 1979; Kurbatova, 1974; Kopylova et al., 1980, 1985) and summary monographs (Kukharenko et al., 1965; Ternovoy et al., 1969; Kapustin, 1980; Rimskaya-Korsakova and Krasnova, 2002; Wall and Zaitsev, 2004; Afanasyev, 2011). However, all these works are based on the data obtained from optical microscopic observations and conventional wet chemical or emission spectrometry assays. Ivanyuk et al. (2002) published representative electron-microprobe data on most Kovdor minerals, yet those remained unstructured and rather few for every mineral. Therefore, this study is devoted to results of modern systematic investigation of the deposit. About 60 microprobe analyses of XYZ-coordinated baddeleyite samples from deep levels of the Kovdor phoscorite–carbonatite pipe were published by Polyakov and Polezhaeva (1991), and we used some of them in this work.

2. Geological setting

The Kovdor alkaline ultramafic massif is situated in the southwest of the Murmansk Region, Russia (Fig. 1). It consists of peridotite, foidolite, phoscorite, carbonatite and the related metasomatic rocks (Kukharenko et al., 1965; Ivanyuk et al., 2002; Krasnova et al., 2004; Afanasyev, 2011). The Kovdor massif is a central-type multiphase volcano–plutonic complex that intruded into the Archean granite-gneiss at 376–380 Ma (U–Pb and Th–Pb data on zircon, baddeleyite, apatite and calcite) (Bayanova et al., 1997; Amelin and Zaitsev, 2002; Rodionov et al., 2012). At the western contact of the diopsidized peridotite with foidolite, a concentrically zoned phoscorite–carbonatite pipe intrudes the massif (Fig. 1) and is a host to the Kovdor baddeleyite-apatite-magnetite deposit (Fig. 2). Carbonatite is a magmatic rock, where more than 50% of the volume is represented by carbonates; and phoscorite is a magnetite-olivine-apatite-carbonate (predominantly calcite) rock associated with carbonatites (Le Maitre, 2002). The classification of phoscorites, based on the schemes by Streckeisen (1974) and Yegorov (1993) and the International Union of Geological Sciences recommendation (Le Maitre, 2002), is introduced in Mikhailova et al. (2015). Modal compositions of the studied phoscorite–carbonatite series are shown in Fig. 3.

The rocks of the Kovdor phoscorite–carbonatite complex form natural series with the significant content of apatite and magnetite, which first gradually increases due to the earlier forsterite and then decreases due to development of carbonates (Rimskaya-Korsakova, 1963; Ternovoy, 1977; Dunaev, 1982; Ivanyuk et al., 2013; Mikhailova et al., 2015). As a result, the phoscorite–carbonatite pipe has a clear concentric zonation (from margins to the center, Fig. 2): the marginal zone consists of forsterite-dominant and apatite-forsterite phoscorites (F and AF fields in Fig. 3); the intermediate zone comprises low-calcite magnetite-rich phoscorites (M, MF, MA and MAF fields in Fig. 3); the inner (axial) zone includes calcite-rich phoscorites (CA, CM, CMA, CMF, CAF and CMAF fields in Fig. 3) and phoscorite-related carbonatites (red points in the carbonatite half of the Fo-Ap-Mag-Cb tetrahedron in Fig. 3). Logical calculation of the phoscorite name, based on percentage of carbonates, magnetite, apatite and forsterite is presented in Supplementary Material 1. Magnetite–dolomite-(phlogopite)-serpentine rock is a metasomatic rock after peridotite or forsterite-rich phoscorite. The magnetite–dolomite-(phlogopite)-serpentine rock constitutes a small ore body (so called "Eastern Satellite") in the east of the Kovdor phoscorite–carbonatite pipe and several clusters within the main ore body (Fig. 2). Veins of calcite carbonatite (blue points in the carbonatite half of Fo-Ap-Mag-Cb tetrahedron in Fig. 3) intersect the entire pipe and host rocks. The northeast-trending linear zone of dolomite carbonatite veins (Fig. 2) extends from the central part of the pipe to the Eastern Satellite (Ivanyuk et al., 2013; Mikhailova et al., 2015).

3. Samples and methods

For this study we have collected 546 samples of phoscorites (mainly), carbonatites and host rocks from 108 holes drilled within the Kovdor phoscorite–carbonatite complex (Mikhailova et al., 2015). Thin polished sections of these samples were petrographically analyzed under a microscope to estimate texture, mineral relations and grain size, and to determine the scope of electron microscopic study. Grain size of the minerals was estimated with Image Tool 3.0 as a mean equivalent circle diameter.

We have conducted our studies with the LEO-1450 scanning electron microscope featuring the Röntek energy-dispersive microanalyzer (at Geological Institute of the Kola Science Center, Russian Academy of Sciences (GI KSC RAS), Apatity) to obtain BSE-images of the key regions and fulfill the preliminary analysis of all minerals found (including fluorine in apatite). Chemical composition of minerals was measured in the MS-46 Cameca electron microprobe (GI KSC RAS) operating in WDS-mode at 20 kV and 20–30 nA. Beam diameter varied from 1 to 10 μm (depending on mineral stability). The used standards and limits of accuracy for each measured elements are shown in Table 1. For statistical investigation, values of analyses below the limit of accuracy are recognized as ten times less than the limit.

Chemical analyses of rocks used for mineralogical prognosis were performed in analytical laboratory of JSC "Kola Geological Informational Laboratory Center"(Apatity, Murmansk Region, Russia) using conventional wet chemical method for SiO_2, TiO_2, MgO, CaO, K_2O, Na_2O, Al_2O_3, Fe_{total}, $Fe_{magnetic}$, P_2O_5, ZrO_2, S_{total} and CO_2. In total, we analyzed 1846 drillcore intervals, averaging 16 m length, from 180 exploration drill holes, totaling 30,213 m and representing the entire deposit.

Statistical studies were carried out using STATISTICA 8.0 (StatSoft). For statistics, values of analyses below the limit of accuracy (Table 1) are recognized as values ten times less than the limit. Geostatisical studies were conducted by GEOMIX (JSC "VIOGEM", Belgorod, Russia). Interpolation was performed by ordinary Kriging. Phoscorite types were named according to the main minerals: A — apatite, C — carbonate, F — forsterite and M — magnetite. The respective abbreviation for names of rock-forming minerals is included in denomination of a rock if the content of such mineral exceeds 10 mod %. Within the phoscorite–carbonatite series, the rocks with carbonate content exceeding 50 mod % received the denomination of "phoscorite-related carbonatites", while the remaining rocks are named "phoscorites" (Mikhailova et al., 2015). The automatic naming of rocks of phoscorite–carbonatite series were carried out by logical evaluation in Microsoft Excel spreadsheet (Supplementary Data 1).