Ore Geology Reviews 72 (2016) 532–537

Contents lists available at ScienceDirect

Ore Geology Reviews

journal homepage: www.elsevier.com/locate/oregeorev

Short communication

Scandium of the Kovdor baddeleyite–apatite–magnetite deposit (Murmansk Region, Russia): Mineralogy, spatial distribution, and potential resource

A.O. Kalashnikov [a,*], V.N. Yakovenchuk [a,b], Ya.A. Pakhomovsky [a,b], A.V. Bazai [a,b], V.A. Sokharev [c], N.G. Konopleva [b], J.A. Mikhailova [a,b], P.M. Goryainov [a], G.Yu. Ivanyuk [a,b]

[a] *Geological Institute of the Kola Science Centre, Russian Academy of Sciences (GI KSC RAS), 14 Fersman Street, Apatity, Murmansk Region 184209, Russia*
[b] *Nanomaterials Research Centre of the Kola Science Centre, Russian Academy of Sciences (NRC KSC RAS), 14 Fersman Street, Apatity, Murmansk Region 184209 Russia*
[c] *JSC "Kovdorskiy GOK", 5 Sukhachova Street, Kovdor, Murmansk Region 184141 Russia*

ARTICLE INFO

Article history:
Received 13 April 2015
Received in revised form 18 August 2015
Accepted 19 August 2015
Available online 24 August 2015

Keywords:
Scandium
Baddeleyite
Carbonatite
Phoscorite
Kovdor
Murmansk Region Russia

ABSTRACT

Despite extensive industrial application, global scandium resources are uncertain. Although Sc is mainly supplied as a by-product of mining of rare earth metals, uranium or aluminum, it is also concentrated by carbonatite process, both magmatic and post-magmatic. In this paper, we report data on Sc distribution within the Kovdor baddeleyite–apatite–magnetite deposit (phoscorite–carbonatite pipe) in the Murmansk Region of Russia, which seems to be a significant reservoir of this "strategic" metal. We show that baddeleyite is the main Sc-concentrating mineral, and reveal the spatial distribution of Sc-bearing baddeleyite within the Kovdor phoscorite–carbonatite pipe. The scandium content in baddeleyite differs according to the petrographic zonation of the pipe culminating in the inner (axial) zone of the pipe and in dolomite carbonatites cutting the pipe. We have estimated the amount of Sc_2O_3 in the Kovdor deposit as amounting to 420 t at average content in baddeleyite of 0.078 wt.%, and revealed the economic potential for Sc recovery as a by-product. Other Sc-bearing minerals – pyrochlore and ilmenite groups, zirconolite, and juonniite – have been described and opportunity of Sc recovery was examined, too.

1. Introduction

Scandium is a minor metal consumed by high-tech industry such as optical, electronic, aeronautic, automotive, and other sectors. Scandium is primarily used in solid oxide fuel cells and aluminum–scandium alloys. According to various estimates, global production of scandium is about 2.5–4.5 t. The bulk of scandium oxide is supplied from former Soviet stockpiles, with primary production amounting to about 400 kg (Bell, 2015; Mineral Commodity, 2015; Wang et al., 2011). Scandium is rather an expensive metal whose variable price depends on chemical form and purity of a compound — in 2014, the average estimated price per gram ranged from $5 (99.99% purity oxide) to $221 (distilled dendritic metal) and $263 (99.9% purity fluoride) (Mineral Commodity, 2015). Scandium is considered a "strategic" metal in some countries, e.g. Russia and USA (Chakhmouradian et al., 2015).

Pursuant to recommendations of the International Union of Pure and Applied Chemistry, scandium belongs to the group of rare earth elements (REEs) that also includes yttrium and lanthanoids (Connelly et al., 2005). Similar to lanthanoids, scandium is a relatively widespread element in the Earth's crust — its abundance is 21.9 ppm, which is higher than that of "cheap" non-ferrous metals such as lead (11 ppm) and tungsten (1 ppm), and comparable with the abundance of copper and cobalt (about 27 ppm; Rudnick and Gao, 2003). However, scandium hardly ever concentrates in economic quantities because of its geochemical behavior — it readily substitutes for iron, aluminum, zirconium and other elements in minerals. Scandium rarely forms its own mineral phases — only 16 minerals incorporate Sc as a principal element (Mineralogical Database, 2015), with thortveitite being the most important.

There are a few deposits in the world where scandium is recovered: Zhovti Vody U–Fe deposit (Ukraine), Bayan Obo REE mines (China), and Iveland (Norway) (Wang et al., 2011; Liferovich et al., 1998). In addition, the Tomtor Sc–REE–Ta–Nb deposit (measured ore resources of 1.18 Mt at Sc_2O_3 grade of 0.048 wt.%; Tolstov and Gunin, 2001) in NW Yakutia, Russia is currently under exploration, and recovery of scandium from bauxite residue is regarded as rather a promising source (Ochsenku-Petropoulou et al., 2002; Zhou et al., 2008; Wang et al.,

* Corresponding author.
E-mail addresses: kalashnikov@geoksc.apatity.ru (A.O. Kalashnikov), yakovenchuk@geoksc.apatity.ru (V.N. Yakovenchuk), pakhom@geoksc.apatity.ru (Y.A. Pakhomovsky), bazai@geoksc.apatity.ru (A.V. Bazai), victor.sokharev@gmail.com (V.A. Sokharev), konoplyova55@mail.ru (N.G. Konopleva), ylya_korchak@mail.ru (J.A. Mikhailova), pgor@geoksc.apatity.ru (P.M. Goryainov), ivanyuk@geoksc.apatity.ru (G.Y. Ivanyuk).

http://dx.doi.org/10.1016/j.oregeorev.2015.08.017
0169-1368/

2013; Liu and Naidu, 2014). The unique Kumir Sc–U–REE deposit (metasomatites and hydrothermal bodies in rhyolite where thortveitite forms appreciable bunches) with Sc_2O_3 content of up to 0.1 wt.% and inferred + hypothetical resources exceeding 100 t lies in the Gorny Altai, Russia (Gusev, 2012). Scandium may also be recovered from uranium, titanium, zirconium, tungsten–tin, nickel, and tantalum–niobium ores (Wang et al., 2011).

As explained above, major deposits of scandium are confined to the Bayan Obo and Tomtor carbonatite-related deposits. However, other deposits in carbonatites and carbonatite residual soils are not recognized now as sources of scandium. One of thoroughly studied exploited deposits in carbonatite-bearing complexes is the Kovdor baddeleyite–apatite–magnetite deposit (NW Russia) (Ternovoy, 1977; Kharlomov, 1981; Epshteyn and Danil'chenko, 1988; Krasnova and Kopylova, 1988; Ivanyuk et al., 2002; Rimskaya-Korsakova and Krasnova, 2002; Krasnova et al., 2004, and others). Multicomponent ores of the Kovdor deposit contain REE and scandium mineralization that are not currently recognized as an economic product.

2. Geological settings

The Kovdor massif of peridotite, foidolites, phoscorites, carbonatites and related metasomatic rocks is situated in the SW part of the Murmansk Region, Russia (Ivanyuk et al., 2002; Krasnova et al., 2004). It intruded through Archean granite-gneiss 376–380 Ma (Rodionov et al., 2012). At the western contact of diopsidized peridotite with foidolite, a concentrically zoned pipe of phoscorites and carbonatites intrudes the massif (Fig. 1). The pipe generally coincides with the Kovdor baddeleyite–apatite–magnetite deposit. Phoscorite is a rare magmatic rock made up of forsterite, magnetite, apatite, and carbonates (predominantly calcite) in different proportions. Carbonatite is a magmatic rock with more than 50% of volume taken up by carbonates (Le Maitre, 2002). Within the Kovdor pipe, carbonatite gradually zones to phoscorite. Zonation of the phoscorite–carbonatite pipe is as follows: the marginal zone made up of forsterite-dominant and apatite–forsterite phoscorites (calcite < 10% of volume, magnetite < 10% of volume); the intermediate zone of low-calcite magnetite-rich phoscorites (calcite < 10% of volume, magnetite > 10% of volume); the inner (axial) zone of calcite-rich phoscorites (50% of volume > calcite > 10% of volume) and phoscorite-related carbonatites (non-vein bodies distinguished by transient contact with phoscorites and carbonate content of >50% of volume). A specific phoscorite-related rock is magnetite–dolomite–serpentine rock — a metasomatically altered peridotite or forsterite-rich phoscorite. This rock forms the minor ore body of the Eastern Satellite in host peridotite and some small parts within the main ore body. Veins of calcite carbonatite cut the entire volume of the pipe and surrounding silicate rocks. Zone of linear veins of dolomite carbonatite (the fault zone) extends from the central part of the pipe to the northeast (Ivanyuk et al., 2002, 2013; Mikhailova et al., 2015).

The Kovdor baddeleyite–apatite–magnetite deposit has been mined as an open pit since 1962 (Ivanyuk et al., 2002). Today, it is mined by the "Kovdorskiy GOK" company (Eurochem Holding). Measured ore resources of the deposit amount to 267,000 kt and indicated ore resources are 219,700 kt at grades of Fe_{total} — 27 wt.%, P_2O_5 — 6.8 wt.%, and ZrO_2 — 0.17 wt.% (Khramov, 2014). Average annual production of magnetite concentrate is 5700 kt, of apatite concentrate — 2700 kt, and of baddeleyite concentrate — 10 kt (Eurochem, 2014).

3. Materials and methods

In 2010–2012, we collected 550 borehole core samples taken at levels from −80 m to −450 m to cover the entire volume of the Kovdor phoscorite–carbonatite pipe and surroundings (Mikhailova et al., 2015). In addition, we used our previously collected mineral samples (Ivanyuk et al., 2002). Polished sections were investigated by optical and electron microscopy. BSE images, mineral diagnostics and preliminary analyses were carried out using an LEO-1450 scanning electron microscope equipped with a Röntek EDS microanalyzer. Chemical composition of

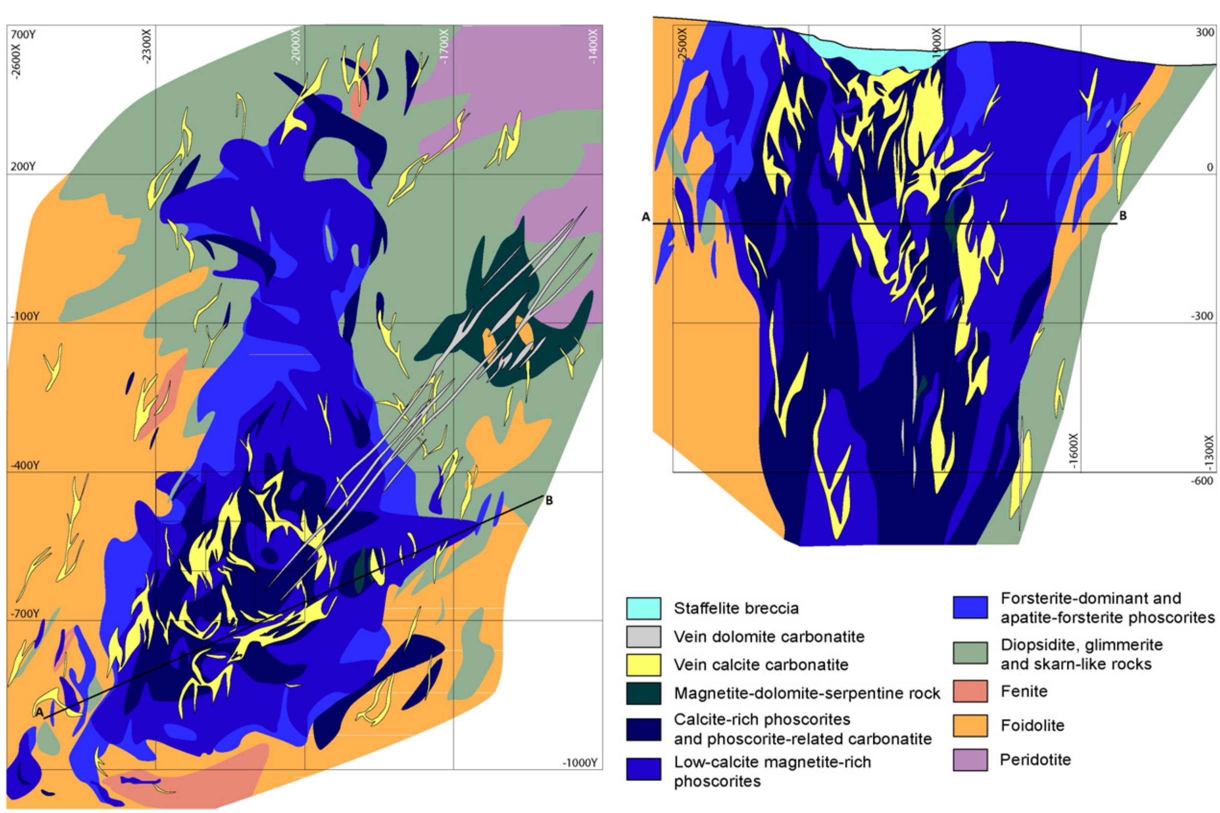

Fig. 1. Map (level −100 m) and cross-section of the Kovdor baddeleyite–apatite–magnetite deposit (Ivanyuk et al., 2013). Y axis shows the north.