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Review

Characterization of apatite resources in Norway and their REE potential — A review

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ABSTRACT

Apatite is a necessity for the production of phosphorus fertilizers and presents a potential raw material for the extraction of REE and Y. A wide spectrum of apatite deposits is found in Norway including sedimentary, igneous, and vein type deposits. The igneous deposits which appear to have the greatest potential for exploitation occur associated with alkaline complexes, massif-type anorthosite complexes and monzonitic complexes. One of the most promising is found in the monzonoritic Bjerkreim–Sokndal Layered Intrusion of the early Neoproterozoic Rogaland Anorthosite Province in southwest Norway. The intrusion hosts three cumulate units with high-grade ore zones. The most promising resource is confined to MCU IV which is 50–170 m thick and nearly 10 km long with average normative contents of 10.2% apatite, 12.4% ilmenite and 7.3% vanadium-rich magnetite. The late Neoproterozoic–Cambrian carbonatite-bearing alkaline complexes are generally of low grade to represent potential resources of apatite as the sole commodity. However, apatite may represent a byproduct of potential Nb and REE + Y mineralisation in the Fen Complex in southern Norway. The late Ordovician–Silurian Misværdal complex comprising multiple alkali clinopyroxenite intrusions in the Uppermost Allochthon of the Caledonides in northern Norway contains 1–1.5 km long and 100–200 m wide ultrapotassic clinopyroxenite dykes with average contents of 7–10 wt.% apatite and with intermediate levels of TREY (~0.5 wt.%). However, high levels of Th in the apatite make it less suitable as a raw material for fertilizer production. Apatite–Fe–Ti oxide ores being characteristic for the monzonitic complexes are especially well developed in the Permian Oslo Igneous Province where apatite-rich magnetite clinopyroxenite cumulates are found in the Larvik Plutonic Complex. The Kodal body has an inferred open-pit ore reserve calculated to 70 Mt with approximately 11.6 wt.% apatite, 3.0 wt.% ilmenite and 26.5 wt.% ilmenomagnetite. The apatite contains about 1 wt.% REE. Comparable types of deposits of Palaeoproterozoic age have recently been recognized in the alkali-calcic mangeritic to syenitic intrusions in the Lofoten–Vesterålen Mangerite Complex in northern Norway, whereas complexes with variable proportions of anorthosites (s.s.), jotunites and mangerites occurring in the Middle Allochthon of the Caledonides in South Norway also are known to host apatite-bearing Fe–Ti oxide deposits, some high in apatite. These complexes represent potential areas for green-field exploration. The TREY (TREE + Y) contents of the apatite in the igneous deposits are discussed and comprise very low levels in the Bjerkreim–Sokndal Layered Intrusion, intermediate levels in the carbonatites and pyroxenites of the alkaline complexes as well as nelsonite dykes and mangerite-associated deposits to high levels in the monzonite-associated deposits.

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1. Introduction

Apatite [$Ca_5(PO_4, CO_3)_3(OH, F, Cl)$] is the most abundant crystalline phosphate mineral which is found as an accessory mineral in most rock types on the earth surface. However, exploitable deposits of apatite are mainly found in sedimentary and igneous rocks. The former comprises stratiform phosphorite deposits in shelf-type shale-carbonate sequences that contain high-phosphorous ores of microcrystalline CO_2-rich fluorapatite (francolite) and cryptocrystalline collophane. The igneous deposits comprise fluorapatite ores which are mostly hosted by carbonatites and other types of alkaline intrusions. The magmatic ores are generally of lower grade, but give higher quality beneficiation products with low contents of unwanted contaminants (Cd, As, U, Th, Mg, and Al).

Beneficiation products of apatite ores as a commodity are traded as phosphate rock. It is the only significant global resource of phosphorus used dominantly in the manufacturing of nitrogen–phosphorus–potassium (NPK) fertilizers for food-crop nutrition and the production of animal feed supplements. Only 10–15% of the world production of phosphate rock has other applications (e.g. pharmaceuticals, ceramics, textiles and explosives). Sedimentary apatite rock makes the largest contribution to the world production of about 210 Mt (2012) whereas igneous apatite rock accounts for only 10–15% of this total (Jasinski, 2011, 2013). Although present resources of phosphate rock are large, the general high demand has over the years lead to a progressive depletion of high-grade ores and ores of good quality with few contaminants. In general, the phosphate content of economic ore appears to have decreased by about 0.45 wt.% P_2O_5 per decade. The economic grade of a sizeable igneous apatite deposit is now 4–5 wt.% P_2O_5.

Presently, there is no production of phosphate rock in Norway and has in the past been of minor importance. Today, Yara International ASA which operates two NPK-fertilizer plants in Norway imports large volumes of phosphate rock. In spite of a long standing production of NPK-fertilizers by the company and its forerunner Norsk Hydro few efforts have been made to explore potential apatite provinces in Norway. However, renewed interest for potential apatite resources in Norway occurred when China, the dominant producer of REE in the world, implemented export restrictions for REE products in 2008. In the rest of the world, this lead to intensified search for alternative sources of REE, including deposits of LREE-enriched apatite [$(Ca, LREE)_5(PO_4, SiO_4)_3(F)$] normally found in igneous deposits. Magmatic apatite contains commonly more than 0.35 wt.% REE or 0.4 wt.% REO (see Tables 3 and 4). According to the mineral production statistics given by Brown et al. (2013) and Jasinski (2013) the world production of apatite from igneous deposits in 2011 was 20–30 Mt. If 25 Mt is estimated to contain apatite with an average content of 0.5 wt.% REO, the total amount of REO residing in the world production of igneous apatite would be approximately125,000 tonnes with predominance of LREO. This is roughly equal to the world production of REO in 2011 which suggests that extraction of REE from apatite as a byproduct of NPK-fertilizer production represents an important alternative source of REE.

In Norway a number of geological provinces with a wide variety of apatite deposits are currently investigated by Norges geologiske undersøkelse (NGU; Geological Survey of Norway) including the REE contents of apatite. The present paper is based on unpublished results of on-going NGU projects and from data given in published papers, NGU reports, Norsk Hydro internal prospecting reports archived at NGU, NGU Ore Database and NGU Industrial Mineral Database. Most of these data are stored in NGU archives and reports are given in Norwegian like most of previously published accounts on the occurrence of apatite in Norway, e.g., Neumann (1985). Thus, the aim of the present paper is to present for the first time an up to date overview in English of phosphate deposits in Norway and their resources.

2. Geological setting

Norway is situated on the western margin of the Fennoscandian Shield which comprises an Archaean cratonic nucleus with Palaeoproterozoic greenstone belts in the northwest being fringed by successively younger mobile belts towards the southwest (Fig. 1). These include the Palaeoproterozoic Svecofennian mobile belt in the central part and the Late Mesoproterozoic–Early Neoproterozoic Sveconorwegian mobile belt (SMB) in the southwest. These two mobile belts are separated by the Transscandinavian Igneous Belt (TIB) which developed episodically over the period 1860–1650 Ma in a convergent continental-margin setting (Andersson et al., 2004, and references therein). The Archaean and Proterozoic mega-units are to a large part covered by nappe complexes of the Norwegian Caledonides and younger rocks of the Late Carboniferous–Early Triassic Oslo Paleorift including the Oslo Igneous Province (OIP) along the centre of the rift grabens.

The Fennoscandian Shield contains a large diversity of ore deposits and represents a major producer of metals and industrial-mineral raw materials in Europe. In 2013, the three sole producers in Europe of high-grade igneous phosphate rock are found at Siillinjärvi in Finland (Fig. 1) and at Kirovsk and Kovdor in Russia where an Archean carbonatite and Devonian alkaline complexes with nepheline syenite and phoscorite are being worked, repectively (Ilyin, 1989; Puustinen and Kauppinen, 1989). The apatite deposits in the Norwegian part of the Shield comprise sedimentary, igneous and vein type deposits (Table 1). The first two are largely syngenetic whereas the latter is epigenetic. Potential apatite resources are only found associated with the igneous deposits which occur mainly in the SMB, in the plutonic rocks of the OIP, in the TIB intrusions, and in the Caledonides in order of potential economic importance.

The TIB comprises dominantly batholithic massifs of monzonitic to granitic composition intruding comagmatic volcanites. The majority of the plutonic rocks in the belt have sub-alkaline and alkali-calcic chemistry with I-type signature that in some areas may comprise A-type and rarely S-type varieties (Andersson et al., 2004). The batholiths of alkali-calcic mangerites (opx. monzonites) and monzonites (Malm and Ormaasen, 1978) of the Lofoten–Vesterålen Mangerite Complex (Fig. 1, LVMC) in the northern extension of the TIB contain abundant