CHAPTER

HIGH-TECH METALS IN FINLAND

9.2

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ABSTRACT

The demand for high-tech metals such as Li, Ti, Co, Ga, Ge, Nb, In, Sb, Ta, Pd, Pt, and rare earth elements (REE) has increased in recent years especially in green energy technology. In this chapter, we concentrate on REE, titanium, and lithium deposits, which are among the most important high-tech metal deposits in Finland.

The known REE deposits are associated with carbonatite dikes at Sokli, alkaline gneisses at Katajakangas, and monazite granites at Kovela. The Korsnäs Pb deposit contains rare earth elements in apatite and monazite, probably due to enrichment by hydrothermal and weathering processes. In the Sokli carbonatite complex, REEs are concentrated in late magmatic carbonatite veins in the surrounding fenite area. The Katajakangas Nb-Y deposit is enriched in heavy REE in zircon, bastnaesite, and columbite. At Kovela, late-orogenic S-type granite contains monazite with thorite inclusions.

The Otanmäki V-Ti-Fe, Koivusaarenneva Ti, Kauhajoki Ti-P-Fe, and Karhujupukka Fe-Ti-V deposits are associated with magmatic mafic layered intrusions. A common feature is that ilmenite and magnetite occur as individual grains and thus can be separated economically. Pure ilmenite and magnetite grains are primary magmatic minerals at Koivusaarenneva and Kauhajoki, but metamorphic at Otanmäki and Karhujupukka. In the future, these gabbro-hosted deposits could be important producers of Ti, Fe, V, and P with low environmental impact.

The Kaustinen Li province contains several economically interesting albite-spodumene pegmatite deposits such as at Länttä, Emmes, Outovesi, Syväjärvi, Leviäkangas, and Rapasaaret, and includes Li mineral resources for several decades. In the Somero-Tammela Li province with albite-petalite-spodumene pegmatites, exploration activity has been smaller, although the deposits contain high-quality petalite and spodumene in economic concentrations.

Keywords: high-tech metals; rare earth elements; spodumene; petalite; ilmenite; Finland.

INTRODUCTION

High-tech metals are essential for the production of high-tech devices such as computers, mobile phones, advanced weapons, solar panels, wind turbines, fuel cells, and batteries. Generally, high-tech metals include Li, Ti, Co, Ga, Ge, Nb, In, Sb, Ta, Pd, Pt, and rare earth elements (REEs), which are mostly produced as by-products of other metals. In this section, we focus on the rare earth elements, titanium and lithium. Cobalt and platinum-group metals are described in another part of this volume. Indium, gallium, and germanium are less common in the Finnish bedrock and are not discussed in this chapter. Magmatic REE deposits in carbonatite, alkaline intrusions and peralkaline granites, lithium deposits in LCT (Li, Cs, Ta) pegmatites, and Ti deposits in anorthosites and noritic gabbros occur in the Fennoscandian Shield (Eilu, 2012).

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A variety of techniques have been used in the exploration of REE, Ti, and Li deposits in Finland. Boulder fans (Li, REE), till- and lithogeochemistry (REE, Li), magnetic + gravity (Ti, REE), and radiation (REE) measurements have been the main exploration methods for these deposits.

RARE EARTH ELEMENT DEPOSITS

The REEs, comprising the lanthanide series from lanthanum to lutetium (atomic numbers 57 to 71) plus geochemically similar yttrium and scandium, occur in minor quantities in common rocks, with an average total abundance of 183 ppm in the upper crust (Rudnick and Gao, 2003), but economically mineable REE deposits are relatively rare. Carbonatites, ion-adsorption type deposits in weathered rocks, and heavy mineral placer deposits are the main sources for REE (Long et al., 2010). Primary magmatic or hydrothermal REE types of mineralization are mostly found with carbonatites and peralkaline igneous rock (Castor and Hedrick, 2006; Long et al., 2010).

Carbonatites are characterized by high abundances of light REE (LREE, La to Eu) while more valuable heavy REE (HREE, Gd to Lu) are concentrated in some alkaline rocks, fractionated granites and pegmatites, and ion-adsorption deposits. China currently produces at least 95% of the world's supply of rare earth elements. Examples of the tonnages and grades of exploited REE deposits are 48 Mt at 6 wt% RE_2O_3 in Bayan Obo Fe-REE-ore, China (Wu, 2008); 16.7 Mt at 7.98 wt% REO in Mountain Pass carbonatite, U.S.A. (Castor, 2008; Mariano and Mariano, 2012); and 0.05–0.3 wt% REO in ion-absorbed clays, 2.8 Mt (counted as REO) in Jiangxi, southern China (Chi and Tian, 2008). With current technology, only bastnaesite, monazite, loparite, and kaolinite with adsorbed REE have sufficient concentrations of REE, favorable lanthanide distribution, and processability for production. Other potentially exploitable minerals include xenotime, eudialyte, fergusonite, and apatite.

There are currently no known economic REE deposits in Finland. Nevertheless, REEs have been extracted in Finland: in the 1950s from apatite concentrate imported from the Kola Peninsula, and since 1963, from apatite concentrate mined as a by-product in the Korsnäs Pb mine in western Finland (Lounamaa, 1972). In addition to the Korsnäs Pb-REE deposit associated with a carbonate dike, the alkaline gneissic granite at Otanmäki, central Finland, hosts a small Nb-REE deposit (Hugg, 1985).

The Fennoscandian Shield hosts several REE deposits in the Devonian Kola alkaline province in Russia (Arzamastsev et al., 2008; Korsakova et al., 2012). The Sokli carbonatite complex (total area 20 km^2) is part of the province (Vartiainen, 1980; O'Brien et al., 2005) and recent studies have confirmed the high REE potential of the area. The Geological Survey of Finland (GTK) has focused on the fenite aureole and associated late-stage crosscutting carbonatite dikes that seem to have the highest potential for REE mineralization in the Sokli area (Sarapää et al. 2013).

Thorium and REE-rich mineralization of Kovela in southern Finland represents an REE ore type associated with late-orogenic granite.

KORSNÄS Pb-REE DEPOSIT

Galena-bearing boulders found by a layman initiated an exploration program by GTK in the Korsnäs area, and in 1955 extensive deep drilling led to the discovery of the ore in a gravity low (Isokangas, 1975). The Outokumpu Oy mining company operated the Korsnäs mine from 1961–1972 and produced 45,000 tons of lead and 36,000 tons of lanthanide concentrate (Himmi, 1975). The grade of the ore was 3.57%

Pb and 0.91% RE_2O_3 . The major ore minerals were galena, apatite, monazite, and allanite (Papunen and Lindsjö, 1972). The REEs were extracted from the apatite concentrate at Typpi Oy, Oulu.

The deposit comprises the Svartören Pb-REE-bearing carbonate dike which hosts the main ore body, measuring 5–30 m in width, up to 1.5 km in length, and extending down to a depth of around 350 m. The Svartören dike occurs in a north–south-trending fracture zone, dips to the east at an angle of 40–60°, and crosscuts ~1.9 Ga migmatitic mica gneiss (Isokangas, 1975; Lehtonen, et al., 2005) of the poorly exposed south Pohjanmaa schist belt, western Finland (Figs. 9.2.1 and 9.2.2). Thermal ionization mass spectrometry (TIMS) titanite U-Pb age of the Svartören dike is 1.825 Ga (Papunen, 1986a). It represents the largest dike in a network of narrow carbonate veins and dikes that occur in an area of

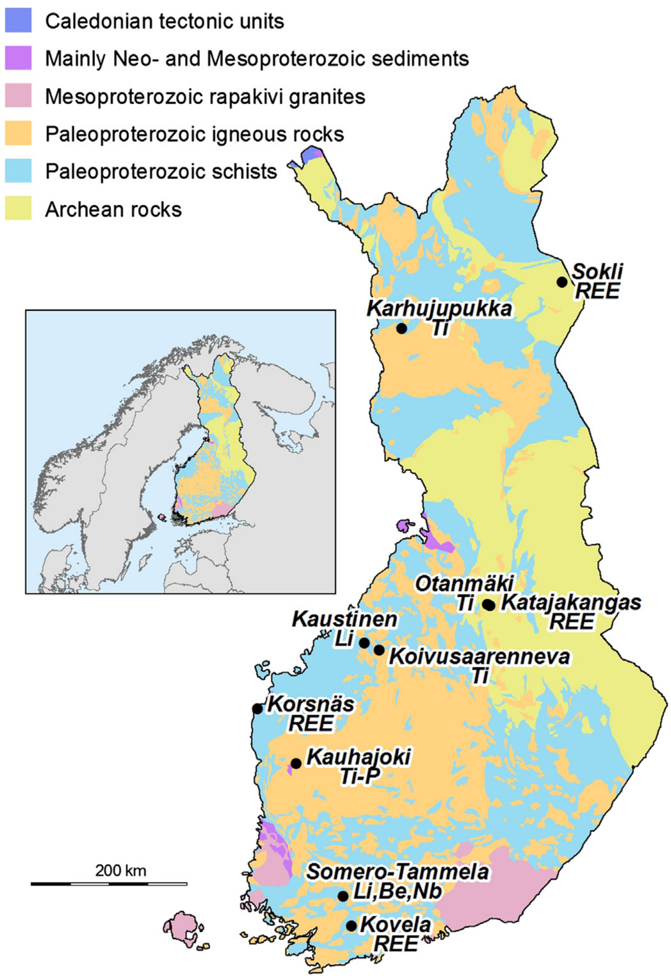

FIGURE 9.2.1 Simplified geological map of Finland showing the distribution of rare earth elements, titanium, and lithium deposits.

Source: *Bedrock according to GTK DigiKP.*

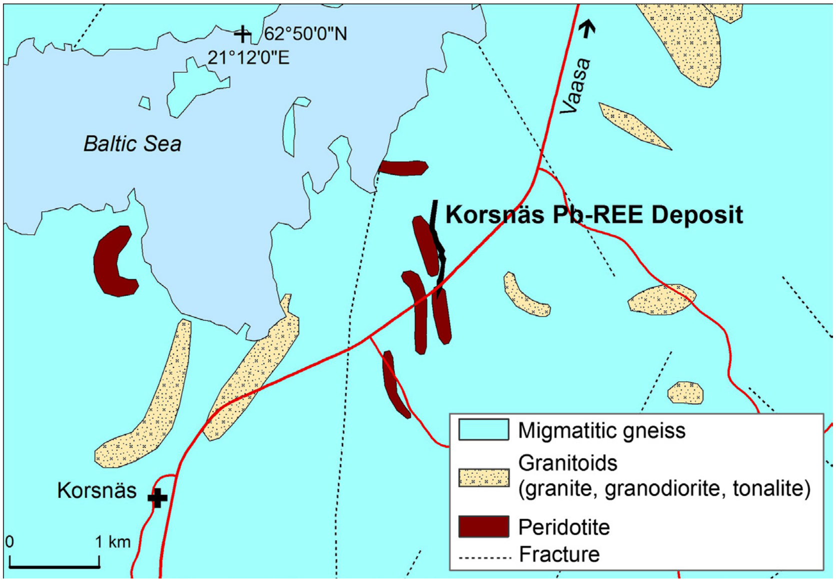

FIGURE 9.2.2 Geological map of the Korsnäs area showing the location of the Pb-REE ore.

Source: *Geology based on Bedrock of Finland–DigiKP.*

approximately 10 km^2. Some boulders appear to be derived from still-undiscovered sources, and testing gravity lows may be the best method to find new Pb-REE-bearing carbonate veins in the area. According to Torppa and Karhu (2013), the $\delta^{13}C$ isotopic values from −17 to −18‰ measured for Korsnäs rocks suggest a crustal source for carbon, and the positive δO^{18} values from +10 to +12‰ indicate probably a meteoritic origin for calcite. Pb isotopic compositions of the Korsnäs galena plot with the rest of the galena from Svecofennian supracrustal rocks studied by Vaasjoki (1981). Taken together, these data strongly suggest the carbonate is derived from crustal sources, probably hydrothermal in origin, and is not a carbonatite, sensu stricto (Mitchell, 2005).

The deposit consists of mineralized zones in pegmatite and the hydrothermal carbonate in calcareous scapolite-diopside-barite–bearing rocks. The ore zone is strongly sheared and weathered, and the wall rock of carbonate is kaolinized. Apatite and monazite are heterogeneously distributed in the ore but follow the occurrence of galena. Monazite occurs as small, discrete crystals or as fine-grained inclusions in apatite within the zones of the weathered rocks (Isokangas, 1975; Sarapää et al., 2013). The RE_2O_3 content in apatite is up to 6.16 wt% and contains more HREE than monazite and allanite (Papunen and Lindsjö, 1972). However, the chondrite-normalized REE patterns for drill-core samples from the Korsnäs Pb-REE deposit are very similar in shape to those of the Sokli carbonatite due to the concentration of LREE in monazite and allanite. The weathered ore is clearly more enriched in REEs than unweathered carbonate rock (Fig. 9.2.3).

KATAJAKANGAS Nb-REE DEPOSIT

The Katajakangas Nb-REE deposit is located within alkaline gneissic granite in the Otanmäki area, central Finland (Fig. 9.2.1 and Fig. 9.2.4). Similar small mineralizations have also been discovered

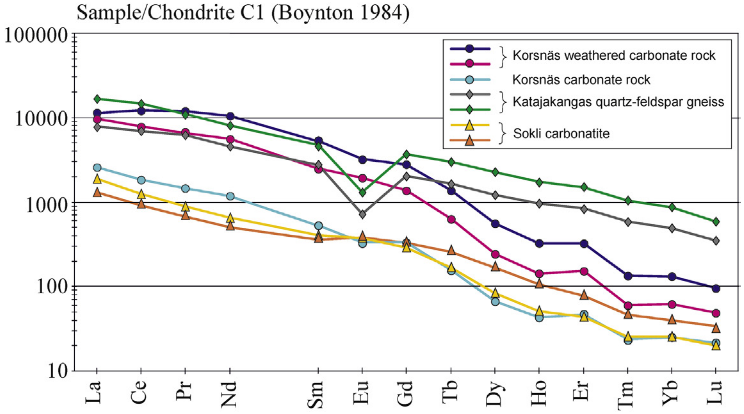

FIGURE 9.2.3 Chondrite-normalized REE abundances for selected carbonatites of Sokli, the carbonate dike at Korsnäs, and alkaline gneiss of Katajakangas.

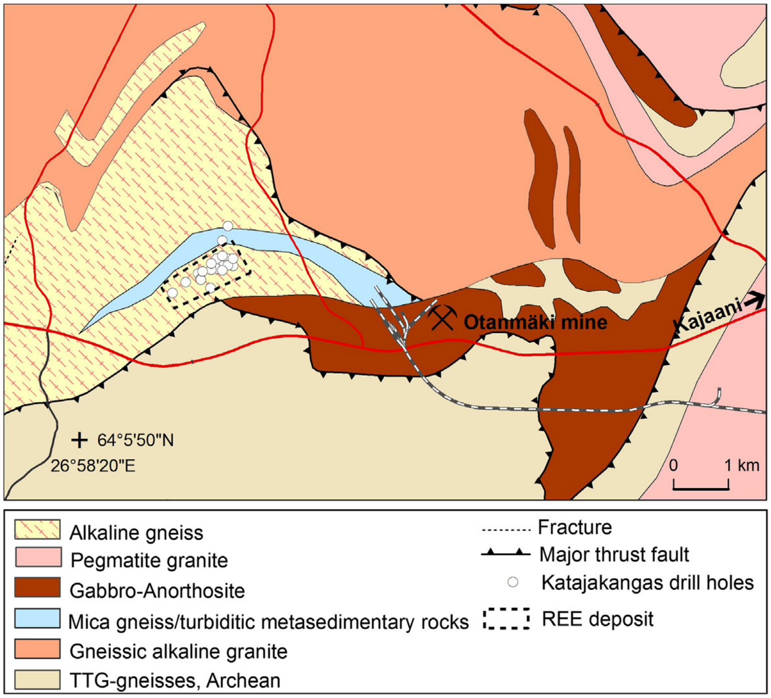

FIGURE 9.2.4 Geological map of the Otanmäki area, showing locations of the closed Fe-Ti-V mine and Katajakangas REE deposit.

Source: *Geology based on Bedrock of Finland–DigiKP.*

elsewhere in the area (Hugg, 1985), which is dominantly composed of Archean granitic gneisses and alkali-granites and ~2.05 Ga gabbro-anorthosites with Fe-Ti-V mineralizations (Lindholm and Anttonen, 1980; Talvitie and Paarma, 1980; Kontinen et al., 2013). The Nb-REE mineralization occurs in the contact zone between turbiditic metasediments and gneisses (Marmo et al., 1966; Puumalainen, 1986). The mineralization consists of a few-meters-wide lenses or layers in sheared Katajakangas quartz-feldspar gneiss with riebeckite and alkaline pyroxene. The main ore minerals are zircon, bastnaesite, columbite, and thorite (Hugg and Heiskanen, 1986; Äikäs, 1990). The narrow mineralized zone contains high concentrations of Nb, Zr, Y, Th, and REE, with an estimated Nb-YREE resource of 0.46 Mt at 2.4% RE_2O_3, 0.31% Y_2O_3, and 0.76% NbO. The mineralization also contains 0.7–1.5% Zr and 0.1–0.2% Th (Hugg and Heiskanen, 1986).

Drill-core samples have relatively high HREE contents compared with samples from carbonatites (Sarapää et al., 2013; Fig. 9.2.3). At Katajakangas, the La/Yb ratio is between 16 and 20 and the maximum Dy content is up to >700 ppm. A metasomatic origin is obvious for the Katajakangas mineralization. The alkaline gneisses from the Otanmäki area have the same kind of mineral and chemical compositions as peralkaline granites of an Ocean Island Basalt (OIB) affinity (Kontinen et al., 2013).

SOKLI CARBONATITE VEINS

The Sokli carbonatite (~360–380 Ma) in northeastern Finland is part of the Kola alkaline province and hosts an unexploited phosphate deposit enriched in Nb, Ta, Zr, REE, and U (Fig. 9.2.1; Vartiainen, 1980; Kramm et al., 1993; Korsakova et al., 2012).

The carbonatite intrusion consists of a magmatic carbonatite core, which is surrounded by metacarbonatite and a wide fenite aureole, altogether about 9 km in diameter (Fig. 9.2.5). The late-stage carbonatite veins and dikes in the central fracture zone and in the fenite zone have a high potential for REE mineralization (Vartiainen, 2001; Al-Ani and Sarapää, 2013).

Recent chemical analyses from drill cores show that the 0.5–1 m wide carbonatite dikes in fenites are enriched in P_2O_5 (19.9 wt%), Sr (1.9 wt%), Ba (6.8 wt%), and Zn (0.3wt%) and also have a high total REE content of 0.5–1.83 wt%, including 0.11–1.81 wt% LREE and 0.01–0.041 wt% HREE (Sarapää et al., 2013). Dominant REE-bearing minerals in the Jammi carbonatite dikes are REE carbonates ancylite-(Ce) and bastnaesite-(Ce), Sr-apatite, monazite, strontianite, barite, and brabantite, which are enriched in LREE, P, F, Sr, and Ba (Al-Ani and Sarapää, 2013). Secondary alteration of monazite is probably of a hydrothermal origin. Mineralogical and chemical evidence demonstrates that late-stage magmatic processes were responsible for the hydrothermal REE mineralization in the Jammi carbonatite veins, where igneous apatite and carbonate minerals were partially replaced by various assemblages of REE-Sr-Ba minerals.

KOVELA MONAZITE GRANITE

The late-orogenic Kovela monazite-bearing granite, which shows a strong positive aeroradiometric gamma-radiation anomaly, penetrates migmatitic gneisses in the Svecofennian Uusimaa belt, which is, according to Kähkönen (2005), 1.91–1.88 Ga in age (Fig. 9.2.1). Two very strong positive thorium anomalies were drilled by GTK in 2011 and 2012, and the holes penetrated two northwest–southeast-trending zones of REE mineralization in monazite- and garnet-bearing, coarse-grained microcline granite.

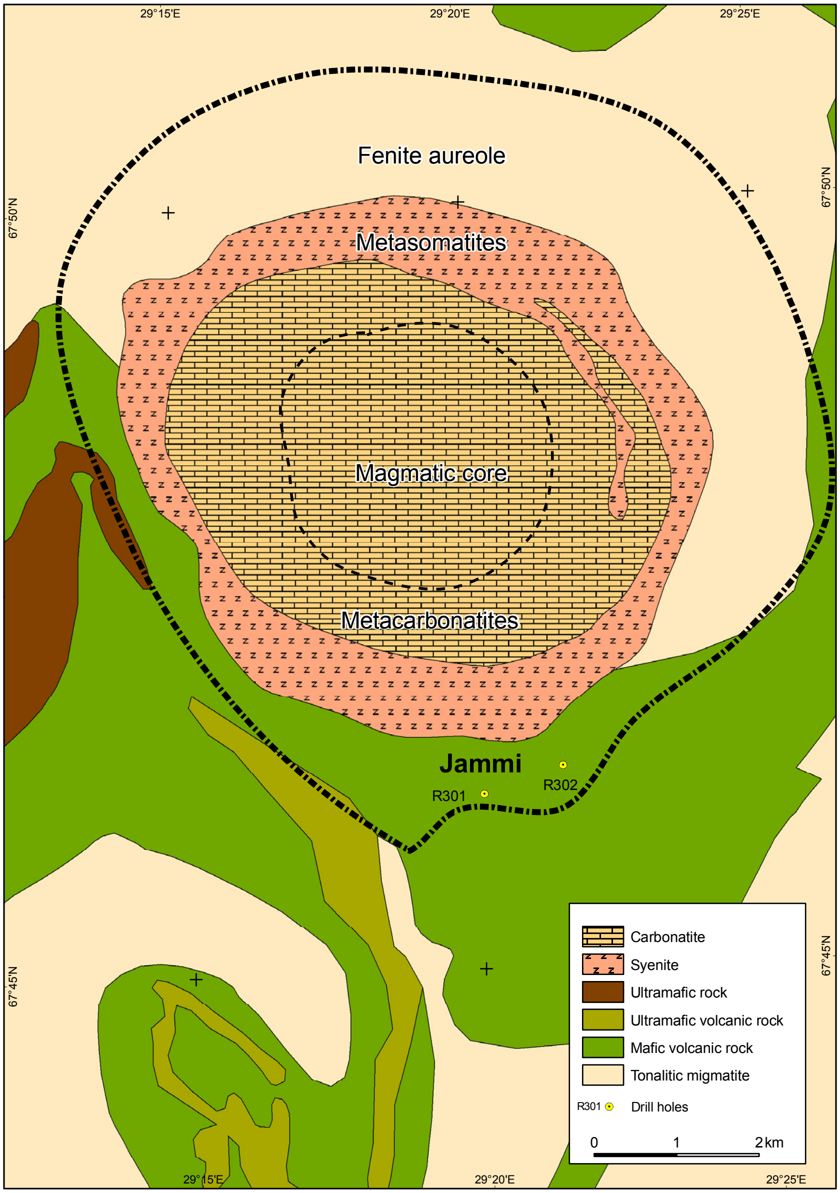

FIGURE 9.2.5 Geological map of the Sokli complex showing rocks from the oldest to the youngest: fenite aureole, metasomatic silicate rocks, metasomatic carbonatites, and magmatic carbonatite core.

The surrounding rocks are Archean tonalitic migmatites and mafic and ultramafic volcanic rocks.

Source: *Modified from Vartiainen (1980) and Bedrock of Finland–DigiKP.*

The Kovela monazite granite is a peraluminous, S-type granite according to the definition of Shand (1943), with molecular (Al_2O_3/CaO + Na_2O + K_2O) ratios (A/CNK) greater than 1.2. The wall rock, K-rich calc-alkaline granite, has a lower REE content than the REE- and Ca-rich pegmatitic monazite granite. Monazite is the dominant REE-mineral, and accessory minerals include zircon, xenotime, and thorite (Al-Ani and Grönholm, 2011). Anhedral to subhedral crystals of monazite are evenly disseminated throughout the rock. The size of the monazite crystals is usually 100–1000 µm, with the largest being up to 0.3 mm long. The crystals are zoned and inclusions of thorite are common. The monazite crystals contain Ce, La, Nd, Pr, and Sm averaging around 26.6, 9.6, 9.5, 2.5, and 1.5 wt%, respectively, and significant amounts of ThO_2 (14.9–22.1 wt%).

The chemical analysis of four monazite granite samples show 1800–17,700 ppm Ce, 786–8100 ppm La, 739–7000 Nd, 211–2000 ppm Pr, 120–1180 ppm Sm, and 87.6–620 ppm Gd. The thorium content varies between 1110 and 10,100 ppm and the uranium content between 3 and 320 ppm. Whole-rock REE contents in 2-m drill-core sections vary from 0.6–4.3 %.

TITANIUM DEPOSITS

The major titanium minerals are anatase, brookite, ilmenite, leucoxene, perovskite, rutile, and sphene, but only ilmenite, leucoxene, and rutile have economic importance (USGS, 2013). Titanium is a light metal compared to iron, has a high strength-to-weight ratio, and high corrosion resistance. Most titanium (95%) is consumed as titanium dioxide (TiO_2) pigment for a white material in paints, paper, and plastics. High refractive index and light-scattering ability impart excellent hiding power and brightness. Titanium dioxide also has a possible use in solar cells.

The most important titanium mineral is ilmenite, as well as Rutile. Most of the commercial ilmenite and rutile deposits are sedimentary heavy mineral concentrates in coastal environments, ocean beaches, or shoreline eolian dunes; only a few are located in an alluvial environment such as riverbeds and deltas (Murphy and Frick, 2006).

Primary, magmatic ilmenite deposits are found in gabbroic rocks related to mid-Proterozoic massif-type anorthosites in Lac Tio, Canada, and Tellnes, Norway. Ilmenite is also enriched in large mafic layered intrusions (e.g., Bushveld and Koillismaa), but true ilmenite deposits are rare because Ti usually occurs as an ulvöspinel component or fine-grained ilmenite lamellas in magnetite, and the separation of ilmenite from magnetite grains makes the recovery of ilmenite presently uneconomic.

OTANMÄKI V-Ti-FE DEPOSIT

The first Fe-Ti-V ore boulders from the area were found in 1937 at Sukeva, 60 km south of Otanmäki. The following year, the source of the boulders was traced by GTK geologists to a magnetic anomaly found while mapping the Otanmäki area (Papunen, 1986a,b). The Otanmäki Fe-Ti-V deposit, composed mainly of magnetite and ilmenite, was mined from 1953 to 1985, and produced 31 Mt ore with 32–34 wt% Fe, 5.5–7.6 wt% Ti, 0.26 wt% V, and some pyrite as a by-product. The deposit contains two ore bodies, Otanmäki and Vuorokas, with the remaining reserves being estimated at 16 Mt with additional resources of 3 Mt (Puustinen, 2003; Vuorokas Oy, 2013).

The Otanmäki magnetite-ilmenite deposit is hosted by Paleoproterozoic (2.06 Ga) layered gabbro-anorthosite (Fig. 9.2.3) that intruded between the Archean Pudasjärvi and Iisalmi blocks (Talvitie and Paarma, 1980; Kuivasaari et al., 2012). The ore deposit consists of hundreds of lenses up to 200 m in length and 3–50 m in width (Illi, 1985). Massive ore lenses are situated in a heterogeneous contact zone between amphibolite and anorthosite. Fractional crystallization and accumulation of Ti-magnetite formed the proto-ore while regional metamorphism at amphibolite facies caused recrystallization of igneous ulvöspinel or Ti magnetite with fine ilmenite exsolution lamellae forming independent grains of ilmenite and magnetite (Pääkkönen, 1956). Consequently the main ore minerals are ilmenite and vanadium-rich magnetite (0.62 wt% V). High-grade ore contains 30–40% magnetite and 28–30% ilmenite. Chlorite, hornblende, some plagioclase, and pyrite (up to 1–2%) make up the gangue. Two main components for TiO_2-pigment production, ilmenite ore from Otanmäki and sulfuric acid, were the domestic raw materials for the then active titanium pigment factory founded in Pori in 1957.

KOIVUSAARENNEVA TI DEPOSITS

The small ilmenite-magnetite-gabbros (1881 Ma) at Koivusaarenneva, Kaireneva, Peräneva, Lylyneva, and Riutta make up a chain of igneous bodies in tonalite in the northwestern part of the Central Finland Granitoid Complex (Fig. 9.2.6) (Kärkkäinen and Bornhorst, 2003; Sarapää et al., 2001). Gravity and magnetic highs, and anomalies in Electromagnetic (EM) measurements indicate the locations of these buried deposits, composed mainly of ilmenite and lesser magnetite in gabbronorite and pyroxenite of

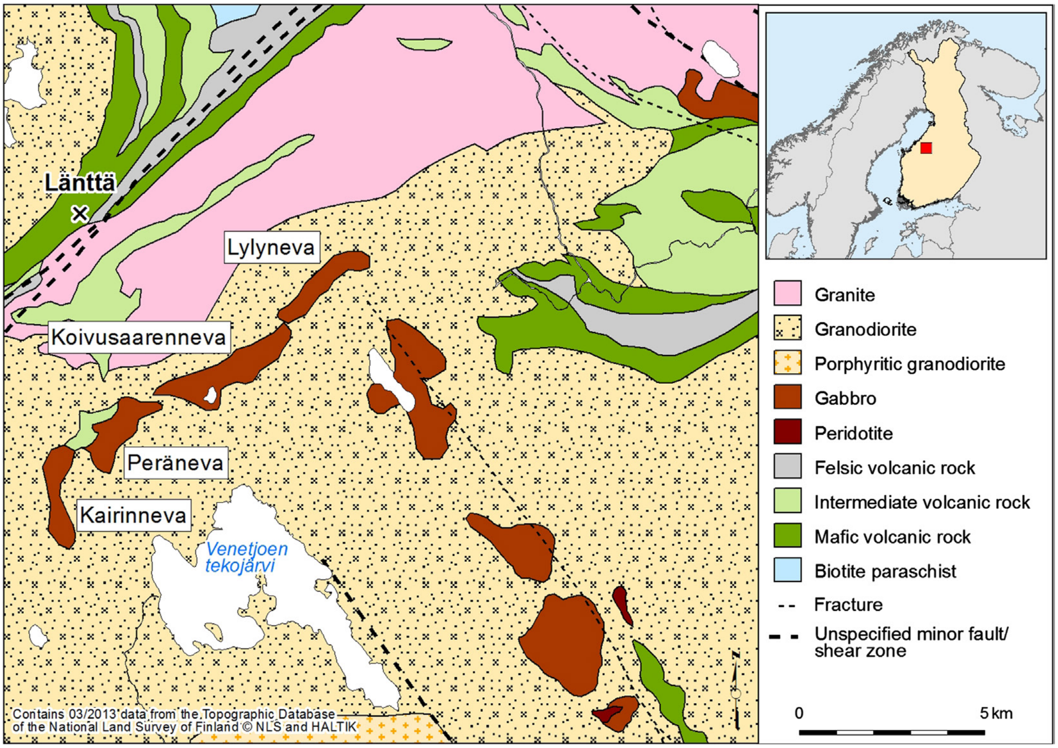

FIGURE 9.2.6 Location of Koivusaarenneva Ti deposits and Länttä Li deposit.

Source: *Geology based on Bedrock of Finland–DigiKP.*

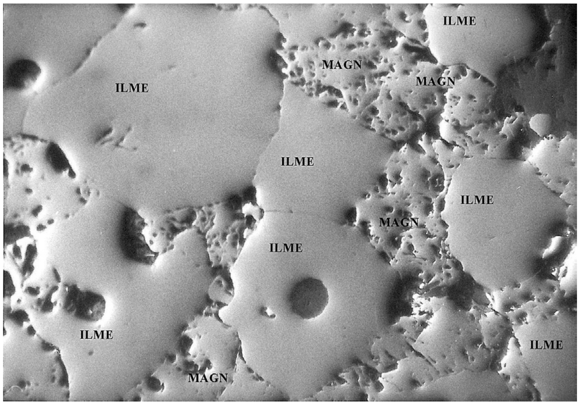

FIGURE 9.2.7 Photomicrograph of Koivusaarenneva ilmenite ore (grains 0.5–3 mm).

Source: *Photo by Niilo Kärkkäinen.*

the layered mafic intrusions. The resource estimate is 74 Mt ore with 8 wt% TiO_2 (or 16% ilmenite) and 5.2 wt% magnetite (Kärkkäinen, 2012a; Endomines, 2015).

The most important of the intrusions is the Koivusaarenneva gabbro, a 3-km-long and 0.5–1-km-thick, sill-like intrusion. It is divided into lower, middle, and upper zones, in which the typical minerals are ilmenomagnetite, ilmenite, and apatite, respectively. The middle zone contains a 2-km-long ilmenite ore body that grades between 8 and 48% ilmenite. Ilmenite and magnetite occur mainly as discrete grains in the middle zone and in the upper zone. Regional metamorphism has had only a small role in the textural development of ilmenite. Based on the clear stratigraphic control in textural types of the Ti-Fe oxides within the intrusion, ilmenite in the middle and upper zone is magmatic in origin (Fig. 9.2.7).

The middle zone has been interpreted to represent a channel for magma flow where the large mass of oxides were trapped and accumulated in favorable localities within the channelways from multiple magma pulses (Kärkkäinen and Bornhorst, 2003). The parent magma was fractionated in a deep crustal reservoir under dry and low-oxygen fugacity conditions, which enabled generation of the Ti-enriched mafic magma. Subsequent low pressure magmatic processes in an open system initiated crystallization of ilmenite from Ti-enriched magmas.

The type of bedrock is critical for the existence of these ilmenite gabbros. Rather homogenous felsic and intermediate intrusive rocks or high-grade metamorphic environments with relatively small amounts of OH-bearing minerals favor the occurrence of ilmenite in a mafic intrusion. A low-f_{O2} environment enables enrichment of Ti in the magma, due to delayed titanomagnetite crystallization (Fenner-type crystallization series). The abundance of iron sulfides shows a strong positive correlation with the abundance of ilmenite in this type of Fe-Ti oxide-rich rocks.

KAUHAJOKI Ti-P-FE

The Ti-P-Fe deposits in the Perämaa (or Peräkorpi), Kauhajärvi, and Lumikangas layered mafic intrusions were discovered by drilling gravity and magnetic highs in the western part of the Central Finland Granitoid Complex (CFGC) (Kärkkäinen and Appelqvist, 1999; Sarapää et al., 2005). The CFGC represents a primitive Paleoproterozoic arc complex and is composed mainly of collision-related felsic intrusive rocks (Korsman et. al., 1997). Mafic intrusions of the Kauhajoki area intrude granitoids of the CFGC and are closely associated with the K-rich Lauhanvuori granite that implies a mature postorogenic magmatism (Rämö et al., 2001; Peltonen, 2005). Ti-P-Fe gabbros form an enormous low-grade mineral resource of more than 500 Mt mineralized rock with a total amount of apatite, ilmenite, and ilmenomagnetite ~20 wt% (Kärkkäinen, 2012b). The Perämaa deposit contains maximum values of 8–9 wt% TiO_2, 2.5–4.0 wt% P_2O_5, and 20–27 wt% Fe; the Kauhajärvi deposit contains 4–8 w% TiO_2, 1–3.6 wt% P_2O_5, and 13–28 wt% Fe; and the Lumikangas deposit contains 8.7 wt% ilmenite (maximum 21 wt%), 5.4 wt% apatite (maximum 17 wt%), and 4.8 wt% magnetite (maximum 17 wt%). Perämaa and Kauhajärvi show a complete differentiation series from peridotite to anorthosite. The main zone of the Kauhajärvi gabbro crystallized under rather high f_{O2} conditions, from a fractioned P-Ti-Fe–rich mafic magma, which enabled apatite to crystallize at the same time as ilmenite and Ti magnetite in the earliest olivine- and pyroxene-rich cumulates (Kärkkäinen and Appelqvist, 1999). Lumikangas is composed of homogenous layered gabbro and monzogabbro with a high normative alkali feldspar content and shows coeval crystallization of apatite, ilmenite, magnetite, and mafic minerals (Sarapää et al. 2005).

KARHUJUPUKKA FE-TI-V DEPOSIT

In 1988, GTK discovered the Karhujupukka deposit by drilling into a positive magnetic anomaly, which was completely covered by till and weathered bedrock (Karvinen et al., 1989). The Karhujupukka area belongs to the western part of the Central Lapland Greenstone Belt composed of tholeiitic and komatiitic volcanic rocks, mica gneisses, gabbros, and granitoids (Fig. 9.2.1). The host rock of the deposit is amphibolite occurring between hanging wall anorthosite-gabbro and footwall metasediments. The Ti-V-Fe ore body has a thickness of 10–50 m and a total length of 550 m.

The ore contains 40 wt% Fe, 5.5 wt% Ti, 0.3 wt% V. Ilmenite occurs as anhedral grains (0.5–2.0 mm) with minute inclusions of hematite. Granoblastic magnetite contains minor ilmenite exsolution lamellae. Sulfides between ilmenite and magnetite grains include pyrrhotite, chalcopyrite, pentlandite, violarite-polydymite, pyrite, and marcasite. The gabbroic rocks were enriched in Fe, Ti, and V during magmatic differentiation and a granoblastic texture was developed during recrystallization under amphibolite facies metamorphic conditions. Due to the granoblastic texture of the ore and the large grain size of ore minerals, concentration tests on the ore gave high-quality magnetite and ilmenite concentrates. The magnetite concentrate contained 92–94 wt% Fe_3O_4 tot, 0.84 wt% V_2O_3, and the ilmenite concentrate 47.6 wt% TiO_2, 46.5 wt% FeO tot.

LITHIUM DEPOSITS

Global lithium consumption has increased throughout the 2000s. The main uses of lithium are ceramics and glass 30%, batteries 22%, lubricating greases 11%, metallurgical 5%, air treatment 4%, polymers 3%, pharmaceuticals 2%, primary aluminum production 1%, and other uses 23% (USGS, 2013). The growth rate is highest for batteries, because the properties of lithium make it the most suitable of all the elements for battery materials. Lithium is produced from brine deposits in Chile, Argentina, and China; granites in China; and pegmatites in Australia, China, Brazil, Portugal, and Zimbabwe (Linnen et al., 2012, USGS, 2013). It occurs in 145 minerals, but only spodumene, petalite, amblygonite, lepidolite, and eucrytite have been commercial Li sources.

According to the classification of Černŷ and Ercit (2005), lithium-bearing pegmatites belong to the LCT (Li, Cs, Ta) family of pegmatites, and generally occur in fault zones in areas in which the metamorphic grade corresponds to greenschist or amphibolites facies. According to Selway et al. (2005), LCT pegmatites are associated with late-tectonic S-type, peraluminous (A/CNK <1.0) quartz- and feldspar-rich granites. Fertile granites have Mg/Li <10 and Nb/Ta <8. S-type granites and are derived from a magma produced by partial melting of sedimentary rocks; extreme fractional crystallization of these magmas concentrates rare elements in residual melts that form the pegmatites (Linnen et al., 2012). In Finland, LCT pegmatites are common in many places in southern Ostrobothnia, including Kaustinen, Somero-Tammela, Kitee-Tohmajärvi, Haapaluoma-Kaatiala, Eräjärvi, Seinäjoki, Heinola, Kisko, Kemiö, and Kalajoki (Alviola, 2012). The most prospective Li provinces are Kaustinen and Somero-Tammela (see Fig. 9.2.1), which have been the main focus of exploration in recent years.

KAUSTINEN Li PROVINCE

In the Kaustinen Li province, spodumene boulders were first discovered in 1959. Since then, several companies have carried out Li exploration in the area. Suomen Mineraali Oy started the first studies in the early 1960s, continued by Paraisten Kalkki Oy in the 1980s, while Keliber Oy started in 1999 and GTK in 2003. These studies have led to the discovery of dozens of spodumene pegmatite dikes and hundreds of ore boulders. Keliber Oy is planning to begin lithium carbonate production at Länttä within the next few years (Fig. 9.2.8).

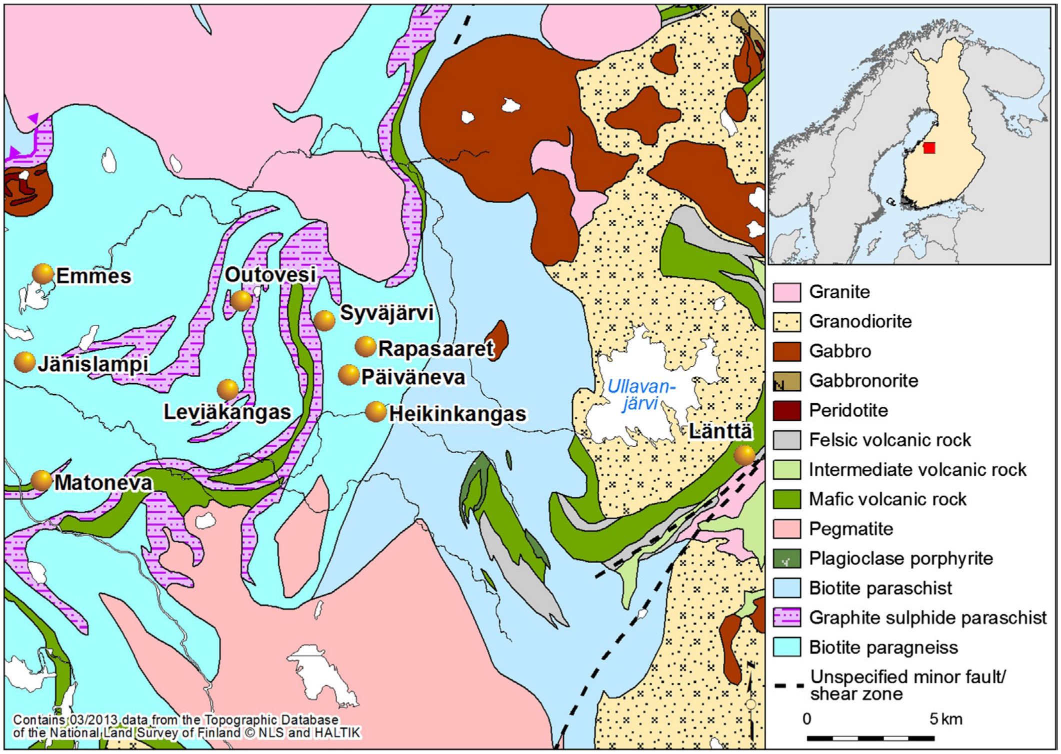

FIGURE 9.2.8 Geological map of Kaustinen Li province showing the most important Li deposits of Kaustinen.

Source: *Geology based on Bedrock of Finland–DigiKP*

The Kaustinen Li province in the Pohjanmaa schist belt is part of the Paleoproterozoic Svecofennian accretionary arc complex in central and western Finland (Kähkönen, 2005). The Pohjanmaa belt is bordered by the Central Finland Granitoid Complex in the east and the Vaasa migmatite complex in the west. The Kaustinen Li province covers 500 km^2, or even more according to new Li analyses on regional till samples (Kontoniemi, 2013).

The most common rock types within the Kaustinen province are mica schists and mica gneisses, intercalated with metavolcanic rocks. Sedimentation, which took place after 1.92 Ga, was followed by amphibolite facies metamorphism ~1.9 Ga (Williams et al., 2008) with peak metamorphism 1.89–1.88 Ga. U–Pb dating of columbite from the Ullava albite-spodumene pegmatite gave an age of 1.79 Ga, significantly post peak metamorphism (Alviola et al., 2001).

The Li pegmatites of the Kaustinen province belong to the albite-spodumene type and intrude both pyroclastic metavolcanic and metasedimentary rocks, mostly conformably. At least 16 separate Li pegmatite occurrences are known. They are not exposed, and the contact relationship can be seen only in erratic boulders and drill cores. According to Martikainen (2012), the Kaustinen pegmatite granite is the most probable source of the spodumene pegmatites, but to confirm this, age determinations of the granitic pegmatites are still required.

The Läntta Li deposit is an example of a homogenous albite-spodumene pegmatite. It consists of two main boudinized dikes at the contact between metavolcanic rock and graywacke schist. The vertical dikes, with a thickness of up to 10 m, trend northeast and dip 70° to the southeast. The total mineral resource is 1.3 Mt, 1.08 wt% Li_2O with a cutoff value at 0.5 wt% Li_2O (Keliber, 2013).

GTK investigations from 2003–2012 led to the discovery of the Rapasaaret deposit and new resources for the previously known Leviäkangas and Syväjärvi deposits, which are all located in a geologically similar area (Ahtola et al., 2010a,b; Käpyaho et al., 2007; Kuusela et al., 2011). The only visible evidence of the Li pegmatites are glacially transported boulder fans down-ice (to the southeast) of all of the discovered occurrences.

The pegmatites have intruded into mica and graywacke schists and plagioclase-phyric rocks or intermediate volcanic rocks. Locally scheelite-garnet-tremolite skarns and quartz veins are present in the wall rocks. The presence of pyrite and pyrrhotite in fracture zones and disseminations in mica schist cause magnetic and electromagnetic anomalies. With the influx of graphite and sulfides, the schists were transformed into black schists.

Spodumene, albite, quartz, K-feldspar, and muscovite are the main minerals in the Li pegmatites (Ahtola et al., 2010b; Al-Ani and Ahtola, 2008). Spodumene contains 6.5–7.4 wt% Li_2O and 0.1–0.6 wt% FeO and is often altered to muscovite. The accessory minerals are apatite, beryl, tourmaline, Li- and Mn-Fe phosphates, graphite, garnet, Nb-Ta oxides, arsenopyrite, cassiterite, sphalerite, zinnwaldite, zeolite, and cookeite. The spodumene content increases toward the center of the dike and the c-axes of spodumene crystals are generally oriented perpendicular to the wall rock contact.

The Leviäkangas spodumene pegmatite dike has a length of 500 m and a thickness of 1–20 m, with a northwest–southeast strike, dipping 40–60° to the west (Ahtola et al., 2010a). The deposit contains 2.1 Mt at 0.70 wt% Li_2O. The Syväjärvi northwest–southeast striking dikes dip 30-40° west, have a thickness of 1–22 m, and resources of 2.6 Mt at 0.98 wt% Li_2O (Ahtola et al., 2010b). The Rapasaaret deposit consists of at least two dike swarms with dike thicknesses ranging from 1 to 24 m. After an extensive till-sampling program, drilling resulted in a resource estimate of 3.7 Mt at 1.02 wt% Li_2O (Kuusela et al., 2011). Also, tantalium, beryllium, and niobium contents are relatively high (Table 9.2.1).

Table 9.2.1 Lithium, tantalium, niobium, and beryllium contents in the Kaustinen spodumene deposits studied by GTK; analyses by ICP-AES

			Li_2O %			Ta_2O_5 ppm			Nb_2O_5 ppm			BeO ppm	
	n	**avg.**	**max**	**min**	**avg.**	**max**	**min**	**avg.**	**max**	**min**	**avg.**	**max**	**min**
Leviäkangas	101	0.74	2.13	0.02	72	337	8	87	312	12	185	494	77
Syväjärvi	200	1.00	2.09	0.03	26	119	4	36	149	11	148	497	67
Rapasaaret	159	1.18	3.36	0.05	53	547	3	58	209	13	502	1912	141

Spodumene pegmatites have also been drilled at the Matoneva, Heikinkangas, and Päiväneva targets (Ahtola et al., 2012). Uninvestigated spodumene pegmatite boulder fans and recent till geochemistry from the region further indicate that there is a great potential for new discoveries (Kontoniemi, 2013; Wik et al., 2013).
Source: *Ahtola et al. (2010a,b)* and *Kuusela et al. (2011).*

SOMERO-TAMMELA RE PEGMATITES

The Somero-Tammela RE pegmatite area in the Häme belt, southern Finland, is 400 km^2 in total size and comprises at least 56 complex pegmatites enriched in Li, Nb, Ta, Be, Sn, Cs, P, and B. The Häme belt is composed of mafic volcanic rocks and mica schists into which syntectonic gabbro, diorite, granodiorite, late-tectonic microline granite, and finally LCT pegmatites dikes have intruded (Alviola, 2003; Ahtola, 2012). RE pegmatites include lithium silicates and phosphates such as cookeite, elbaite, heterosite-siclerite, lepidolite, lithiophilite, petalite, spodumene, triphylite, and Li-Fe-micas (Vesasalo, 1959; Alviola, 1993).

The largest and best-known Li pegmatites are the Hirvikallio petalite pegmatite and the Kietyömäki spodumene pegmatite. Hirvikallio was drilled by GTK in 1958 and later studied by Lohja Oy/Partek Oy in 1974–1996. The dike is 170 m long, 5–25 m wide, and contains 0.2 Mt with 1.8 wt% LiO_2 to the depth of 50 m. The Hirvikallio petalite pegmatite occurs in a weakness zone along the contact between mica schists and amphibolites (Vesasalo, 1959). Petalite contains 4.74 wt% Li_2O and a very low iron content of 0.01 wt% Fe_2O_3. The Kietyönmäki dike swarms were drilled by GTK in 1987–1988. Petalite occurs only in one dike; elsewhere it has completely been converted to spodumene and quartz by hydrothermal alteration (Alviola, 1993). The main dike contains 0.4 Mt with 1.5% Li_2O, 0.016% Sn, 0.003% Ta. It is highly likely that several undiscovered RE pegmatites still occur in the Somero-Tammela area.

DISCUSSION

The world-class REE deposits, such as Bayan Obo, Mountain Pass, and Mount Weld, are associated with carbonatite complexes. However, the most promising HREE- deposits are closely associated with alkaline and peralkaline rocks such as Norra Kärr in Sweden and Kvanefjeld in Greenland. In Finland, the Korsnäs Pb-REE–bearing dike has similar REE patterns to those in carbonatites, but isotopic evidence proves that it is derived from crustal sources. Late-magmatic, hydrothermal, and weathering processes may have caused the enrichment of REEs in apatite. The Katajakangas Nb-YREE deposit occurs in alkaline gneisses and shows clear enrichment of HREE contained in the minerals zircon, bastnaesite, and columbite.

The mineralogical and chemical studies of the Sokli carbonatite veins indicated that the REE minerals rarely form during the primary crystallization of carbonatite. Postcrystallization hydrothermal solutions, metasomatism, metamorphism, and weathering can all result in remobilization of REEs and changes in the original mineralogy. REE-bearing minerals concentrated especially in late carbonatite veins are ancylite, bastnaesite, monazite, allanite, and REE-apatite. During late-stage processes, apatite and carbonate minerals were partially replaced by various assemblages of REE-Sr-Ba minerals. In the Kovela late-orogenic, S-type granite, monazite is the dominant REE mineral and the accessory minerals are zircon, xenotime, and thorite. Monazite granites of southern Finland, such as the Kovela pluton, may be potential Th and REE sources in the future.

The texture of Fe-Ti oxides is an important factor in evaluating the utilization potential of ilmenite deposits as ilmenite should occur as discrete grains instead of lamellae in magnetite; the latter cannot be separated economically. In the Otanmäki massive Fe-Ti oxide ore, there are almost equal amounts of magnetite and ilmenite, whereas in the Koivusaarenneva deposit, ilmenite is clearly more abundant than magnetite.

Ilmenite is a primary igneous mineral at Koivusaarenneva and Kauhajoki, whereas at Otanmäki and Karhujupukka, discrete ilmenite, and magnetite grains developed by breakdown of the ulvöspinel-magnetite solid solution during regional metamorphism. A typical feature of Otanmäki, Karhujupukka, and Kälviä is that magnetite has a high vanadium concentration (averaging 0.4–0.6 wt% V), whereas at Kauhajoki there is a large amount of apatite (up to 8 wt%) along with Ti-Fe oxides and Fe-Mg-silicates. The low-grade Ti-Fe-P deposits at Kauhajoki may also be potential phosphorus sources for fertilizer industries in the future.

All the Finnish magmatic ilmenite deposits are hosted by Paleoproterozoic mafic intrusive rocks, but the internal structure of deposits is as diverse as their geotectonic setting and age. Karhujupukka (~1.9 Ga) is closely related to a greenstone belt, the Otanmäki (2.05 Ga) gabbro was intruded into an Archean granite-gneiss complex, the Koivusaarenneva (1.88 Ga) igneous body occurs in an intermediate igneous environment below arc-type volcanic rocks, and the host rocks of the Kauhajärvi (1.87 Ga) deposits were emplaced in an environment containing diverse granitoids. However, a common feature of these intrusions is a relatively dry crustal emplacement environment that seems to favor enrichment of Ti and crystallization of ilmenite at the expense of Ti magnetite. This contrasts with Ni-enriched Svecofennian mafic–ultramafic intrusions that were intruded into supracrustal belts and are often closely associated with graphite- and sulfide-rich schists.

The Kaustinen spodumene pegmatites and Somero-Tammela petalite-spodumene pegmatites contain potential Li resources for the battery industry of the European Union countries. At Kaustinen, current known mineral resources are sufficient for several decades. The quality of spodumene and petalite is good owing to high lithium and low iron contents.

The Li pegmatites belong to the LCT family. They are characterized by a significant enrichment in Li, Cs, and Ta, as well as Rb, Be, Sn, B, and F and are fractionation products of S-type, peraluminous granites (Černŷ and Ercit, 2005). The P and T conditions during mineral formation controlled the Li mineralogy in the deposits. At Kaustinen, spodumene crystallized as the first Li mineral during a late magmatic stage. However, the Somero-Tammela Li pegmatites occur in a weakness zone where the pressure was probably lower, and primary magmatic petalite was later converted to spodumene and quartz by hydrothermal processes, except at Hirvikallio.

SUMMARY

Finland has several different potential sources of rare earth elements, namely in the carbonate veins at Korsnäs (0.9 wt% REE) and the alkaline gneiss at Katajakangas, central Finland (2.4 wt% REE); in the fenite zone of the Sokli carbonatite complex (1–2 wt% REE), northern Finland; and in the Kovela monazite-granite in southern Finland (0.5–4.3 wt% REE). The LREE minerals dominate, including ancylite, bastnaesite, monazite, allanite, and apatite.

The Ti potential of small mafic intrusions of Finland is prominent in various geotectonic settings, based on large ilmenite deposits (50 to more than 100 Mt) at Otanmäki and Koivusaarenneva. One economic benefit of the gabbro-hosted deposits is that they also have potential for Fe and V, or P in addition to Ti. The Otanmäki mine was a globally important producer of vanadium and nationally important source of iron for the steel industry. In the future, the Kauhajärvi-type large, low-grade Ti-P-Fe deposits may be important producers of phosphorous in addition to iron and titanium. Gabbro-hosted ilmenite deposits have a low environmental impact because they show low abundances of harmful elements (U, Th, and S) and the wall rocks usually serve as good construction materials.

Recently, the lithium resources of several Li-bearing spodumene pegmatite occurrences at Kaustinen have been estimated by GTK and Keliber Oy. The high potential of the area is supported by areas with boulder fans without known sources and recent Li analyses of regional till samples.

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