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High-tech metal potential in Finland with emphasis on rare earth elements (REE), titanium and lithium

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This article evaluates the known rare earth elements (REE), Ti and Li occurrences and exploration potential in Finland, based on existing data combined with new geochemistry and mineralogy, heavy mineral studies, geophysical measurements, geologic mapping and recent drilling of new targets.

The potential rock types for REE include carbonatite (Sokli, Korsnäs), alkaline rocks (Otanmäki, Lamujärvi, and Iivaara), rapakivi granite and pegmatite (Kovela), and kaolin-bearing weathering crusts in eastern and northern Finland. The highest REE concentrations occur in late magmatic carbonatite veins in the fenite area of the Sokli carbonatite complex. Detailed mineralogical investigations have revealed three distinct types of REE mineralization as phosphates, carbonates and silicates in the studied areas. Mineralogical and mineral chemical evidence demonstrates that hydrothermal processes are responsible for the REE mineralization in the studied rocks and confirms that such processes are predominant in the formation of REE minerals in carbonatite, calc-silicate rocks and albitite. Titanium occurs as ilmenite in hard rock deposits in Paleoproterozoic subalkaline mafic intrusions. The Otanmäki ilmenite was mined together with vanadium-rich magnetite from 1953 to 1985 from a small gabbro–anorthosite complex, which still contains potential for Ti resources. Other major ilmenite deposits are within the Koivusaarenneva ilmenite gabbro intrusion and Kauhajärvi apatite–ilmenite–magnetite gabbro complex. Possible Ti resources are included in Ti-magnetite gabbro of the large layered mafic intrusions in northern Finland, such as at the former Mustavaara vanadium mine. For several years, Rare Element (RE)-pegmatite of the Kaustinen and Somero–Tammela areas has been the objective of Li exploration by the Geological Survey of Finland (GTK). At Kaustinen, Li-pegmatite occurs as subparallel dyke swarms in an area of 500 km^2 within Paleoproterozoic mica schists and metavolcanic rocks. Li pegmatite contains more than 10% spodumene as megacrysts (1–10 cm), albite, quartz, K-feldspar, muscovite and accessory minerals such as columbite-group minerals, apatite, tourmaline, beryl, Fe-oxide minerals and garnet. The Kaustinen spodumene pegmatite and Somero–Tammela petalite–spodumene pegmatite contain potential Li resources for the battery industry in EU countries.

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

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Introduction

The demand for high-tech metals and critical minerals has rapidly increased in green energy technologies such as solar panels, wind turbines and batteries, and they are also essential for the production of high-tech devices such as computer circuit boards, mobile phones and advanced weapons. The critical raw materials in the EU are as follows: antimony, beryllium, borates, chromium, cobalt, coking coal, fluorspar, gallium, germanium, indium, magnesite, magnesium, natural graphite, niobium, PGMs, phosphate rock, REEs (Heavy), REEs (Light), silicon, and tungsten (European Commission 2014). Table 1 presents the critical commodities of the EU combined with Li, Ta, Ti and an estimate of their availability potential in Finland. In this article we review deposits of the rare earth elements (REEs), titanium and lithium, which have good exploration potential in Finnish bedrock, based on the investigations by the Geological Survey of Finland (Geologian Tutkimuskeskus – GTK) and private companies during the past few years (Fig. 1). The EU is highly dependent on imports of "high-tech" metals, including REE, Ti and Li.

Table 1
Critical raw materials in EU and in Finland (Cr, Co, P, Si, Li, Nb, PGM, REE, Ta, Ti, W)

Class	Raw materials	Exploration potential	Mine/Deposit
2	Antimony	Moderate	Kalliosalo, Törnävä
3	Beryllium	Moderate	Länttä, Rapasaari, Kymi, Väkkärä
4	Borates	Low	
4	Coking coal	Low	
1	Chromium	Good	Kemi/Koitelainen, Akanvaara
1	Cobalt	Good	Talvivaara, Hitura, Kevitsa, Kylynlahti
4	Fluorspar	Low	
4	Gallium	Low	
4	Germanium	Low	
3	Indium	Low	Sarvlax
2	Lithium	Good	Länttä, Rapasaari, Somero
3	Magnesite	Moderate	Lahnaslampi talc etc.

Table 1 (continued)

Class	Raw materials	Exploration potential	Mine/Deposit
4	Magnesium	Low	
3	Natural graphite	Moderate	Kiihtelysvaara, Juuka
2	Niobium	Good	Sokli, Katajakangas
2	PGMs	Good	Suhanko, Kevitsa
1	Phosphate rock	Good	Siilinjärvi/Sokli, Iivaara, Kortejärvi, Kauhajoki
3	REEs (Heavy)	Moderate	Sokli, Katajakangas
3	REEs (Light)	Good	Sokli, Korsnäs
2	Silica	Good	Nilsiä/Siiselkä, Virtasalmi
3	Tantalum	Good	Kemiö, Sokli
2	Titanium	Good	Koivusaari, Otanmäki
3	Tungsten	Good	Ahvenlammi, Hieronmäki

Class: 1: Active mines – the material is produced as the main or accessory product from operating mine(s) in Finland (Eilu 2012)

2: Mine projects – promising deposits

3: Known deposits

4: No known deposits

Exploration potential: good, moderate, low

REE deposits occur in carbonatite, alkaline intrusions and peralkaline granite. Lithium or spodumene deposits occur in LCT-pegmatite, enriched in Li, Cs and Ta, whereas titanium or ilmenite deposits mostly occur in anorthosite and noritic gabbro. Exploration techniques that have traditionally been used for such prospective rocks include boulder fans, till- and lithogeochemistry data, high-resolution airborne and surface gamma-ray spectrometric (to detect Th and U contents), magnetic (presence of magnetite), and gravity (dense lithologies) surveys, and heavy-mineral studies and radiometric surveys. These techniques are applied shortly before trenching and drilling programs.

The tonnages and grades of the currently exploited giant deposits of REE, Li and Ti across the globe are shown in Table 2.

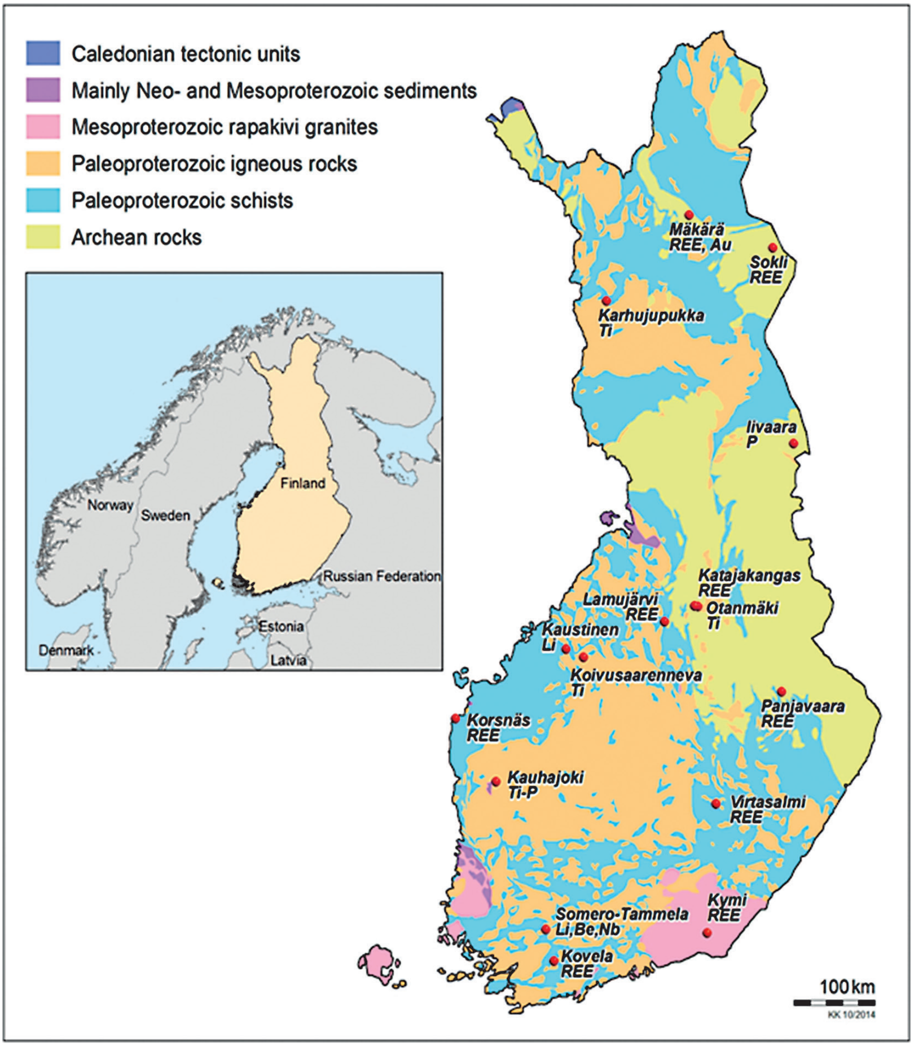

Fig. 1
The distribution of rare earths, titanium and lithium deposits on the geologic map of Finland; geology based on Bedrock of Finland

Deposits of Rare Earth Elements (REE)

Finland is situated in the central part of the Fennoscandian shield, which is the largest outcropping Precambrian domain in Europe, and has high potential for REE and other metals (Eilu 2012). The known examples of REE mineralization in Finland occur in car-

Table 2
Deposit type, reserves and grades of world class REE, Li and Ti mines

Mines	**Deposit type**	**Reserve**	**Grade**	**Reference**
Bayan Obo, China	Carbonatite: Fe-REE-ore	48 Mt	6 wt % RE_2O_3	Wu 2008
Mountain Pass, USA	Carbonatite	16.7 Mt	7.98 wt % REO	Castor 2008
Southern China	Ion-adsorption clays	nx100 Mt	0.05–0.3 wt % REO	Chi and Tian 2008
Greenbushes, Australia	LCT-pegmatite	70.4 Mt	2.6 wt % Li_2O	Bradley and McCauley 2013
Bikita, Zimbabwe	LCT-pegmatite	12 Mt	1.4 wt % Li_2O	Bradley and McCauley 2013
Tellness, Norway	Anorthosite Hemo-ilmenite	300 Mt	18 wt % TiO_2	Gross et al. 1997
Lac Tio, Canada	Anorthosite Hemo-ilmenite	125 Mt	32 wt % TiO2 36 wt % FeO	Gross et al. 1997

bonatitic and alkaline intrusives, granite, hydrothermal alteration zones in various types of rocks and kaolinitic saprolite (Sarapää et al. 2013). The currently most promising REE deposit, however, is the Sokli carbonatite complex in northeastern Finland.

REE in carbonatite

The Sokli carbonatite (approximately 360–380 Ma) in northeastern Finland, a part of the Devonian Kola alkaline province, hosts an unexploited and deeply weathered phosphate deposit enriched in niobium (Nb), tantalum (Ta), zirconium (Zr), REE and uranium (U). The carbonatite intrusion consists of a magmatic carbonatite core, surrounded by metacarbonatite and a wide fenite aureole, altogether about 9 km in diameter (Fig. 1). Late-stage carbonatite veins in the magmatic core and in the fenite zone have high potential for REE mineralization (Vartiainen 1980; Al-Ani and Sarapää 2013). Chemical analyses from drill cores indicate that the carbonatite veins are enriched in phosphorus pentoxide (P_2O_5) up to 19.9%, strontium (Sr) up to 1.9%, barium (Ba) up to 6.8%, Zn up to 0.3%, and also have a high total REE content of 0.5–1.8% (Sarapää et al. 2013, 2014); they are locally very rich in REE, with over 10%. REE-bearing mineral phases including ancylite-(Ce) and bastnäsite-(Ce), Sr-apatite, monazite, strontianite, baryte and brabantite; and these minerals are strongly enriched in LREE, P, F, Sr and Ba. During late-stage processes, apatite and carbonate minerals were partly replaced by various assemblages of REE–Sr–Ba minerals.

The Korsnäs Pb–REE-bearing carbonate dyke intrudes Paleoproterozoic mica-gneisses of the South Pohjanmaa Schist Belt (Torppa and Karhu 2013; Fig. 1). The Outokumpu CO mining company operated the Korsnäs mine from 1961 to 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% total rare earth oxides (RE_2O_3). The major ore minerals are galena, apatite, monazite and allanite. The deposit consists of mineralized zones in pegmatite and carbonate dyke or calcareous scapolite–diopside–barite-bearing skarn rock. The wall rock of the dyke is characterized by a strongly kaolinized sheared ore zone. Apatite and monazite are heterogeneously distributed in the ore but follow galena (Papunen and Lindsjö 1972).

A swarm of REE-enriched carbonatite dykes and associated alkaline veins is found within an extensive area covering over 100 km^2, centered on Panjavaara–Juuka, eastern Finland (Fig. 1).

The dykes and veins are highly enriched in REE, measuring 5–10% (Torppa and Karhu 2007), and the smallest veinlets show levels of 1–2% total REE. The studied rocks display elevated LREE to HREE ratios, with bastnäsite, ancylite and monazite as the most important REE carriers.

REE in alkaline intrusive rocks

The Katajakangas Nb-REE deposit is located within alkaline gneissic granite at Otanmäki, central Finland (Fig. 1), dominated by Archean granitic gneiss, alkali-granite and ca. 2.05 Ga gabbro–anorthosite with Fe–Ti–V deposits (Kontinen et al. 2013). The Nb–REE mineralization consists of narrow lenses or layers a few meters wide in sheared quartz-feldspar gneiss with riebeckite and alkaline pyroxene. The main ore minerals are zircon, bastnäsite, columbite and thorite. These narrow mineralized zones contain high concentrations of Nb, Zr, Y, Th and lanthanides, with an estimated Nb-YREE resource of 0.46 Mt with 2.4% RE_2O_3, 0.31% Y_2O_3, 0.76% Nb_2O_5 0.7–1.5% Zr and 0.1–0.2% Th (Hugg and Heiskanen 1986). At Katajakangas, the La/Yb ratio is between 16 and 20 and the maximum Dy content is up to > 700 ppm (Sarapää et al. 2013). A metasomatic origin is proposed for the Katajakangas mineralization.

The Lamujärvi syenite (Fig. 1) south of Otanmäki displays strong enrichment in Zr (1587 ppm), Nb (up to 685 ppm), Ta (up to 82 ppm) and REE (up to 5350 ppm), but the grades and volumes of these rocks appear too small to be currently of economic potential. The major REE-bearing minerals in the enriched rocks are allanite and monazite.

Iivaara is the type locality of ijolite (Fig. 1), which is a common rock type in carbonatite-bearing alkaline complexes. The phosphorus potential of the Iivaara intrusion is very high. The REE potential is still under study. The Iivaara intrusion has close similarities with the Lovozero REE-rich alkaline massif. Geophysical interpretations have revealed ring structures around Iivaara, which could be interpreted as an indicator of REE targets (Sarapää et al. 2014; Turunen et al. 2014).

REE in granitic pegmatite and granite

The late-orogenic peraluminous Kovela (Fig. 1) monazite–granite shows up as a strong positive aeroradiometric gamma radiation anomaly in the Svecofennian Uusimaa Belt, in southern Finland. Monazite is the dominant REE mineral, whereas accessory minerals include zircon, xenotime and thorite (Al-Ani and Grönholm 2011). The REE content is high, ranging from 0.6 to 4.3%. Th contents are mostly high, varying between 110 and 10,100 ppm, and the U content between 3 and 320 ppm. Some miarolitic pegmatite with topaz and fluorite occur within the Wiborg Rapakivi batholith, southeastern Finland. The largest and mineralogically most interesting REE pegmatite surrounds the Kymi topaz granite stock (Fig. 1) and contains REE minerals (monazite, xenotime), Nb–Ta minerals, beryl, phenacite, bertrandite and tourmaline.

REE in kaolinitic saprolite

The kaolin deposits at Virtasalmi in southeastern Finland (Fig. 1) have thicknesses of 30–40 m, and more than 100 m in places. The deposits are lenticular in shape, generally less than a few hundred meters wide and a half to two kilometers long, covered by a 20–30 m-thick till bed. The kaolin contains 40 to 75 weight % kaolinite, 20–30% quartz, and some potassium (K)-feldspar and muscovite (Sarapää 1996). The total REE content of kaolin in the basal part of the weathering profile reaches a maximum of 0.1–0.2% REE (Al-Ani and Sarapää 2011).

The 200 km-long Tana Belt on the southern side of the Lapland Granulite Belt includes HREE and LREE anomalies in regional till geochemistry and kaolinitic saprolite (Sarapää and Sarala 2013). The REE content in the Mäkärä (Fig. 1) Au-bearing saprolite is 0.05%, but local concentrations are as high as 0.4 wt % REE. Typical REE-rich minerals are monazite, rhabdophane and xenotime.

Titanium deposits

The most important titanium mineral is ilmenite, and another important one is rutile. Most of the commercial ilmenite and rutile deposits are sedimentary heavy mineral concentrates in a coastal environment, ocean beaches or shoreline eolian dunes (Murphy and Frick 2006).

Primary magmatic ilmenite deposits are mined from gabbroic rocks related to mid-Proterozoic massif-type anorthosite in Lac Tio, Canada, and Tellnes, Norway (Gross et al. 1997; Murphy and Frick 2006).

Otanmäki V–Ti–FE deposit

The Otanmäki magnetite–ilmenite deposit (Fig. 1) consists of massive ore lenses up to 200 m in length and 3–50 m in width between amphibolite and anorthosite in Paleoproterozoic (2.06 Ga) layered gabbro (Kuivasaari et al. 2012). Magmatic segregation–fractionation processes produced the primary ore, and regional metamorphism at amphibolite facies was the possible mechanism for the recrystallization of ilmenite and magnetite (Pääkkönen 1956). The main ore minerals are ilmenite and vanadium-rich magnetite (0.62 wt % V). High-grade ore contains 30–40 wt % magnetite and 28–30 wt % ilmenite. Chlorite, hornblende, some plagioclase and pyrite (up to 1–2 wt %) make up the gangue.

The Otanmäki Fe–Ti–V deposit produced 31 Mt of ore in 1953–1985, mainly composed of magnetite and ilmenite, and 32–34 wt % Fe, 5.5–7.6 wt % Ti, 0.26 wt % V and some pyrite as a by-product (Puustinen 2003). In 1957, ilmenite ore and sulphuric acid from pyrite were the two main raw materials for TiO_2 pigment production at the new Pori factory.

Koivusaarenneva Ti deposits

The Koivusaarenneva, Kaireneva, Peräneva, Lylyneva and Riutta ilmenite–magnetite gabbro (1881 Ma) form lens-like bodies in a tonalite intrusion in the northwestern part of the Central Finland Granitoid Complex (Sarapää et al. 2001; Kärkkäinen and Bornhorst 2003; Figs 1, 2). The resource estimate is 74 Mt of ore with 7.9 wt % TiO_2 (Endomines 2014).

The Koivusaarenneva gabbro, which is a 3 km-long and 0.5–1 km-thick sill-like intrusion, typically contains Ti–Fe minerals including ilmenomagnetite, ilmenite and apatite (Kärkkäinen 2012a). Ilmenite and magnetite occur as separate grains in the middle and upper zones, and the ilmenite grains are magmatic in origin. The parent magma was fractionated in a deep crustal reservoir under dry and low oxygen fugacity conditions. Magmatic processes close to the surface in an open system concentrated ilmenite from this Ti-enriched magma. A low fO^2 environment enables enrichment of Ti in the magma.

Kauhajoki Ti–P–FE

The Kauhajoki Ti–P–Fe deposits (Fig. 1) in the Central Finland Granitoid Complex were discovered in layered mafic intrusions by drilling high gravity and magnetic anomalies at Perämaa (or Peräkorpi), Kauhajärvi and Lumikangas (Kärkkäinen and Appelqvist 1999; Sarapää et al. 2005). Ti–P–Fe gabbro forms a low-grade mineral resource of over 500 Mt, containing apatite (4–6 wt %), ilmenite (8–10 wt %) and ilmenomagnetite (5–6 wt %), with a total mineral content of 20% (Kärkkäinen 2012b). Perämaa and Kauhajärvi have a complete differentiation series from peridotite to anorthosite. The main zone of the Kauhajärvi gabbro crystallized under rather high fO^2 conditions from a fractionated P–Ti–Fe-rich mafic magma. Apatite, ilmenite and Ti-magnetite crystallized at the same time as ilmenite and Ti magnetite in the earliest olivine- and pyroxene-rich cumulates (Kärkkäinen and Appelqvist 1999). The mafic intrusion at Lumikangas consists of homogeneous layered gabbro and monzogabbro with a high normative alkali feldspar content and coeval crystallization of apatite, ilmenite, magnetite and mafic minerals (Sarapää et al. 2005).

Karhujupukka Fe–Ti–V-deposit

GTK discovered the Karhujupukka deposit (Fig. 1) in 1988 by drilling into a high magnetic anomaly, which was completely covered by till in the western part of the Central Lapland Greenstone Belt (Karvinen et al. 1989). The host rock of the deposit is amphibolite between 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, 40 wt % Fe, 5.5 wt % Ti and 0.3 wt % V. Magmatic differentiation enriched the gabbroic rocks in Fe, Ti and V. Superimposing amphibolite facies metamorphism upgraded the quality of the ore. Due to the coarse and granoblastic texture, the ore provided high-quality ilmenite and vanadiferous magnetite concentrates.

Lithium deposits

Lithium occurs in ca. 145 minerals, but only spodumene, petalite, amblygonite, lepidolite and eucryptite have commercial value. Lithium-bearing pegmatite belongs to the LCT (Li, Cs, and Ta) family (Černý and Ercit 2005). Rare-element pegmatite occurs in fault zones in areas where the metamorphic grade corresponds to greenschist or amphibolite facies. According to Selway et al. (2005), LCT pegmatite is associated with late-tectonic S-type, peraluminous (A/CNK > 1.0) quartz- and feldspar-rich granite. Fertile granites have Mg/Li < 10 and Nb/Ta < 8. S-type granite is derived from a magma produced by partial melting of sedimentary rocks; extreme fractional crystallization concentrates rare elements in residual melts (Linnen et al. 2012). In Finland, LCT pegmatite is common in many places in southern Ostrobothnia, including Kaustinen (Fig. 1), Somero–Tammela, Kitee–Tohmajärvi, Haapaluoma–Kaatiala, Eräjärvi, Seinäjoki, Heinola, Kisko, Kemiö and Kalajoki (Alviola 2003, 2012). The most prospectable Li provinces are Kaustinen and Somero–Tammela (Fig. 2), which have been GTK's main focus of exploration in recent years.

Kaustinen Li province

In 1959, the first spodumene pegmatite boulders were found in Kaustinen (Figs 1 and 2). Since then, dozens of spodumene pegmatite dykes and several hundreds of ore boulders have been discovered and the mining company Keliber Oy is planning lithium carbonate production in the area (Fig. 2).

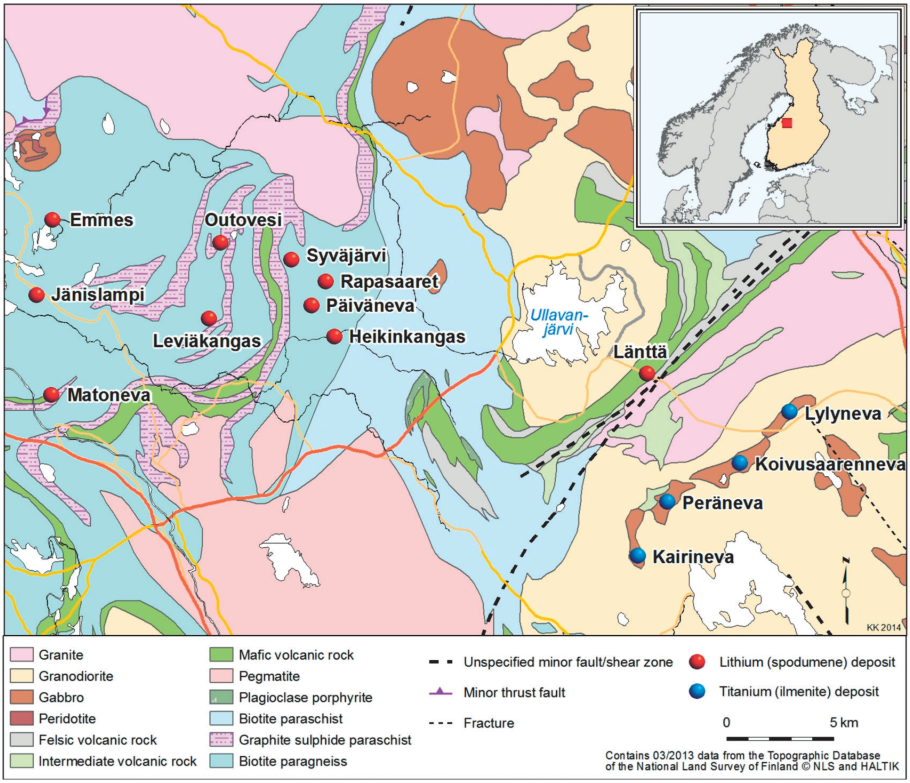

Fig. 2
Location of Koivusaarenneva Ti-deposits and Kaustinen Li-deposits; geology based on Bedrock of Finland

The Kaustinen Li province covers roughly 500 km^2 in the Paleoproterozoic Pohjanmaa schist belt (1.92 Ga), and at least 16 separate albite–spodumene–pegmatite occurrences are known. Länttä is the best-known deposit and is composed of two boudinized dykes, with a thickness of up to ten meters. These NE-trending dykes dip 70° to SE, between a metavolcanic rock unit and a greywacke schist formation. The resources are 1.3 Mt, 1.08 wt % Li_2O with a cut-off value at 0.5 wt % Li_2O (Keliber Oy 2013).

Between 2009 and 2012, GTK investigated the Rapasaaret deposit and estimated resources of 3.7 Mt at 1.02 wt % Li_2O (Kuusela et al. 2011). New resources were discovered in the Levikängas (2.1 Mt~1.02 wt % Li_2O) and Syväjärvi (2.6 Mt at 0.98% Li_2O) deposits (Käpyaho et al. 2007; Ahtola et al. 2010a, b). In these deposits spodumene contains 6.7–7.4 wt % Li_2O and 0.5 wt % Fe_2O_3. The other main minerals are albite, quartz, K-feldspar and muscovite (Al-Ani and Ahtola 2008). The accessory minerals are apatite, beryl, tourmaline, Li- and Mn–Fe phosphates, graphite, garnet, Nb–Ta oxides, arsenopyrite, cassiterite, sphalerite, zinnwaldite, zeolite and cookeite. Spodumene pegmatite boulder trains and till geochemistry from the region indicate that there is great potential for new discoveries (Wik et al. 2013; Laxström et al. 2014).

Somero–Tammela rare element (RE) pegmatite

The Somero–Tammela RE-pegmatite area is 400 km^2 in size, located in the Häme Belt, southern Finland (Fig. 1). The area includes 56 RE-pegmatite dykes enriched in Li, Nb, Ta, Be, Sn, Cs, P and B (Alviola 2003; Ahtola 2012). At least nine of these RE-pegmatite dykes contain lithium silicates and phosphates such as cookeite, elbaite, heterosite–siclerite, lepidolite, lithiophilite, petalite, spodumene, triphylite and Li–Fe-micas (Vesasalo 1959; Alviola 1993).

The best-known Li pegmatites are the petalite pegmatite located at Hirvikallio and the spodumene pegmatite located at Kietyönmäki. The Hirvikallio petalite pegmatite dyke is 170 m long, 5–25 m wide, and contains 0.2 Mt with 1.8 wt % Li_2O to the depth of 50 m. Petalite contains 4.74 wt % Li_2O and the iron content is very low, at 0.01 wt % Fe_2O_3. The Kietyönmäki spodumene (SQI) dyke contains 0.4 Mt with 1.5 wt % Li_2O, 0.016 wt % Sn and 0.003 wt % Ta. The bedrock is poorly outcropped and it appears obvious that several unknown RE-pegmatite dykes 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. The HREE deposits are closely associated with alkaline and peralkaline rocks such as Norra Kärr in Sweden and Kvanefjeld in Greenland.

Mineralogical and chemical studies on the Sokli carbonatite veins indicated that few of the REE minerals were formed during the primary crystallization of carbonatite (Al-Ani and Sarapää 2013). Post-magmatic hydrothermal solutions, metasomatism, metamorphism and weathering all resulted in the remobilization of REEs and modification of the original mineralogy. REE concentrations occur as ancylite, bastnäsite, monazite, allanite and REE–apatite in late carbonatite veins. During late-stage processes, apatite and carbonate minerals were replaced by various assemblages of REE–Sr–Ba minerals. In Korsnäs, in a Pb–REE-bearing carbonatite dyke, late-magmatic, hydrothermal and weathering processes may have caused the enrichment of REEs in apatite. The Katajakangas Nb–YREE deposit occurs in alkaline gneiss and the clear enrichment of HREE is carried by zircon, bastnäsite and columbite.

In the Kovela late-orogenic S-type granite, monazite is the dominant REE mineral and the accessory minerals are zircon, xenotime and thorite. Monazite granite of

Southern Finland, such as the Kovela pluton, is a potential Th and REE resource to supply future needs.

The texture of Fe–Ti oxides is an important factor, since ilmenite should occur as individual grains so that it can be economically separated. Ilmenite is a primary igneous mineral in the Koivusaarenneva and Kauhajoki deposits, whereas at Otanmäki and Karhujupukka, regional metamorphism upgraded the primary magmatic ore by development of coarse-grained, porphyroblastic ilmenite and magnetite. In the Otanmäki, Karhuhupukka and Kälviä deposits, magnetite has a high vanadium concentration (averaging 0.4–0.6 wt % V). At Kauhajoki, there is a large amount of apatite (up to 8%) along with Ti–Fe oxides and Fe–Mg-silicates; this may be a potential phosphorus source for fertilizer industries. Important mineral resources remained in the Otamäki deposits when mining ceased in 1985, and now a new start is under development (Otanmäki Mine Oy 2014).

Another potential Ti resource is included in the titanomagnetite of the Mustavaara Fe–V deposit. The future Fe–V mine would produce titanium slag as a by-product for the raw material of TiO_2 pigment (Mustavaaran Kaivos Oy 2014).

All the Finnish magmatic ilmenite deposits are in Paleoproterozoic mafic intrusive rocks. Karhujupukka (ca. 1.9 Ga) is closely related to a greenstone belt, the Otanmäki (2.05 Ga) gabbro was intruded in an Archaean 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 was emplaced in an environment containing diverse granitoids. A common feature of these intrusions is a relatively dry crustal emplacement environment that appears to favor the enrichment of Ti and crystallization of ilmenite at the expense of Ti magnetite.

The Kaustinen spodumene pegmatite and Somero–Tammela petalite–spodumene pegmatite contain potential Li resources for the battery industry in the EU. At Kaustinen, current known mineral resources are sufficient for several decades. The quality of the Li ore is good due to the high spodumene and petalite contents of this pegmatite.

Kaustinen and Somero-Tammela Li-pegmatites belong to the LCT family, are characterized by a prominent accumulation of Li, Cs and Ta, in addition to Rb, Be, Sn, B and F, and is the fractionation product of S-type, peraluminous granite (Černý and Ercit 2005). The pressure–temperature conditions of pegmatite formation control the Li mineralogy of the deposits. At Kaustinen, spodumene precipitated as the first Li mineral during a late magmatic stage. However, the Li-pegmatite occurrences in the Somero–Tammela area are confined to a low-strain zone, where the pressure was probably lower and petalite formed first and was later converted to spodumene and quartz, except at the Hirvikallio deposit.

Conclusions

The potential sources of rare earths are associated with carbonate dykes at the Korsnäs deposit (average grade of 0.9 wt % RE_2O_3) and alkaline gneiss at the Katajakangas deposit (average grade of 2.4 wt % RE_2O_3), late carbonatite dykes in the Sokli carbonatite complex (between 1–10 wt % RE_2O_3), and in the Kovela monazite–granite (between 0.5–4.3 wt % RE_2O_3). The titanium potential is based on large ilmenite deposits (50 to over 100 Mt) at the Otanmäki and Koivusaarenneva deposits. These gabbro-hosted deposits also have potential for Fe and V. The Kauhajärvi-type large, low-grade Ti–P–Fe deposits may be important producers of phosphorous in addition to iron and titanium. The gabbro-hosted ilmenite deposits are environmentally friendly for producing TiO_2 pigment because they have much lower U, Th, and S contents than sedimentary ilmenite-rich heavy mineral concentrations. Resources of several spodumene pegmatites have recently been estimated by GTK and Keliber Co. The great potential of the area is supported by spodumene pegmatite boulder trains and recent re-assays of old till samples in relatively unexplored regions.

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