GEOLOGICAL SURVEY OF FINLAND

Report of Investigation 220

2015

Overview of lithium pegmatite exploration in the Kaustinen area in 2003–2012

Timo Ahtola (ed.), Janne Kuusela, Asko Käpyaho and Olavi Kontoniemi

GEOLOGIAN TUTKIMUSKESKUS

Tutkimusraportti 220

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Front cover: A green spodumene lath in the Syväjärvi (DH R443 42.50 m)
spodumene pegmatite. Photo: J. Väätäinen, GTK.

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One of the main targets of the industrial mineral mapping projects by the Geological Survey of Finland (GTK) during 2003–2012 was to evaluate the Li (Ta, Nb, Be) potential in the Kaustinen Li province, western Finland. GTK carried out RC, percussion and diamond drilling, together with ground geophysical surveys in seven different exploration areas. Regional till samples from the 1970s were also re-analysed. The Li pegmatites in the Kaustinen region are texturally and mineralogically similar to each other and belong to the albite-spodumene subgroup of the LCT pegmatite family. Four new spodumene pegmatites (Matoneva, Päiväneva, Heikinkangas and Rapasaaret) were discovered. Additional mineral resources were found in the previously known Leviäkangas and Syväjärvi deposits. In total, Li potential mapping by GTK measurably increased the known Li pegmatite resources. According to the results from the re-assaying of old till samples, there are areas with good potential for new discoveries on the northwest and southeast sides of the known deposits. The Kaustinen region is the most potential area for Li mineralisation in Finland and also a significant Li province in the EU.

Keywords (GeoRef Thesaurus, AGI): pegmatite, mineral exploration, lithium ores, minerals, spodumene, resources, Kaustinen, Finland

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Geologian tutkimuskeskuksen (GTK) teollisuusmineraalivarojen kartoitushankkeen yksi tavoitteista oli kartoittaa Länsi-Suomessa sijaitsevan Kaustisen Li-provinssin Li (Nb, Ta, Be) -potentiaalia. Vuosien 2003–2010 aikana GTK suoritti alueella geofysikaalisia maastomittauksia, RC- ja timanttikairauksia sekä moreeninäytteenottoa seitsemällä eri tutkimuskohteella. Myös alueen vanhoja 1970-luvun linjamoreeninäytteitä analysoitiin uudelleen. Kaustisen alueen Li-pegmatiitit ovat tekstuuriltaan ja mineralogialtaan toistensa kaltaisia ja kuuluvat LCT-pegmatiittien albiitti-spodumeenialaryhmään. Neljän uuden pegmatiitin (Matoneva, Päiväneva, Heikinkangas ja Rapasaaret) löytymisen lisäksi jatkettiin 1960-luvulla paikallistettujen Leviäkankaan ja Syväjärven tutkimuksia. GTK:n Li-potentiaalin kartoitus kasvatti merkittävästi alueen tunnettuja mineraalivarantoja. Lisäksi uudelleen analysoitujen moreeninäytteiden perusteella on tunnettujen esiintymien luoteis- ja kaakkoispuolella hyvät mahdollisuudet löytää uusia Li-esiintymiä. Kaustisen provinssi on Li-potentiaalisin alue Suomessa mutta myös merkittävä koko EU:n alueella.

Asiasanat (Geosanasto, GTK): pegmatiitti, malminetsintä, litiummalmit, mineraalit, spodumeeni, varannot, Kaustinen, Suomi

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CONTENTS

1 INTRODUCTION

The lithium potential of the Palaeoproterozoic Pohjanmaa belt in western Finland has been known and explored since the 1960s. During 2003–2012, one of the main targets of the industrial mineral mapping projects by the Geological Survey of Finland (GTK) was to evaluate the Li (Ta, Nb, Be) potential and to discover new resources in the area. The focus was on the spodumene pegmatites in the Kaustinen (Kruunupyy-Ullava, Emmes) region.

The Li mineral spodumene was first identified from boulders in Kaustinen in 1959 (Boström 1988). Since then, several private enterprises have explored lithium-bearing pegmatites in the area. Suomen Mineraali Oy conducted the first exploration in the 1960s, which was continued in the 1980s by Paraisten Kalkki Oy, and from 1999 onwards by Keliber Oy. Of all the currently known Li pegmatites, Syväjärvi (previously called Ruohojärvet), Leviäkangas (Vintturi), Emmes, Jänislampi and Länttä were discovered by Suomen Mineraali Oy. The best known and fully permitted Li deposit is Länttä, for which Keliber Oy currently holds the mining concession. The deposit consists of two NW–SW-trending main dykes with some smaller parallel dykes. The length of the dyke swarm is 450 metres and the maximum width of individual dykes is 10 metres. The total mineral resource of the deposit is 1.3 Mt with 1.08 wt% Li_2O (Keliber Oy 2013). The company plans to commence lithium carbonate production at Länttä in the near future (Fig. 2).

Global lithium consumption has increased throughout the 2000s. The end-use markets of lithium and are estimated to be ceramics and glass (29%), batteries (27%), lubricating greases (12%), continuous casting (5%), air treatment (4%), polymers (3%), primary aluminium production (2%), pharmaceuticals (2%) and other uses (16%) (USGS 2012). Due to its physical properties, lithium is one of the most attractive materials in the battery industry, and the demand for lithium is predicted to grow most in this sector.

This report provides an overview of lithium pegmatite exploration in the Kaustinen area carried out by GTK between the years 2003 and 2012. As a result, four new spodumene pegmatites (Matoneva, Päiväneva, Heikinkangas and Rapasaaret) were discovered. In addition, the knowledge of the mineral resources of the previously known Leviäkangas and Syväjärvi deposits were improved. In total, Li potential mapping by GTK increased the known Li pegmatite resources by about 8 Mt.

By 2012, GTK had reported four deposits and occurences to the Ministry of Employment and the Economy (MEE). The investigation in the Matoneva claim area was reported in 2007 (Käpyaho et al. 2007b). Leviäkangas and Syväjärvi were reported in Ahtola et al. (2010a, b). The international tender notice of the MEE for these two deposits ended in the spring of 2011. As a result, the claims were transferred to Keliber Oy in late 2012. Kuusela et al. (2011) reported a new discovery the Rapasaaret Li deposit, which was handed to the Ministry in the summer of 2012. Additional information on the localities is available in Käpyaho et al. (2007a) and in Ahtola & Kuusela (2013). The Kaustinen Li province is also described in the GTK Special Paper Mineral deposits and metallogeny of Fennoscandia by Eilu (ed.) in 2012 under the title Emmes (Ahtola 2012).

2 GENERAL GEOLOGY OF THE KAUSTINEN LI PEGMATITE PROVINCE

The Kaustinen Li pegmatite province is located within the western Finland Palaeoproterozoic supracrustal rocks belonging to Pohjanmaa belt (Vaasjoki et al. 2005), sometimes referred to as the Ostrobothnia Schist Belt (Alviola et al. 2001). The Pohjanmaa belt is surrounded by the Central Finland Granitoid Complex in the east and Vaasa granitoid complex in the west (Figs 1 and 2).

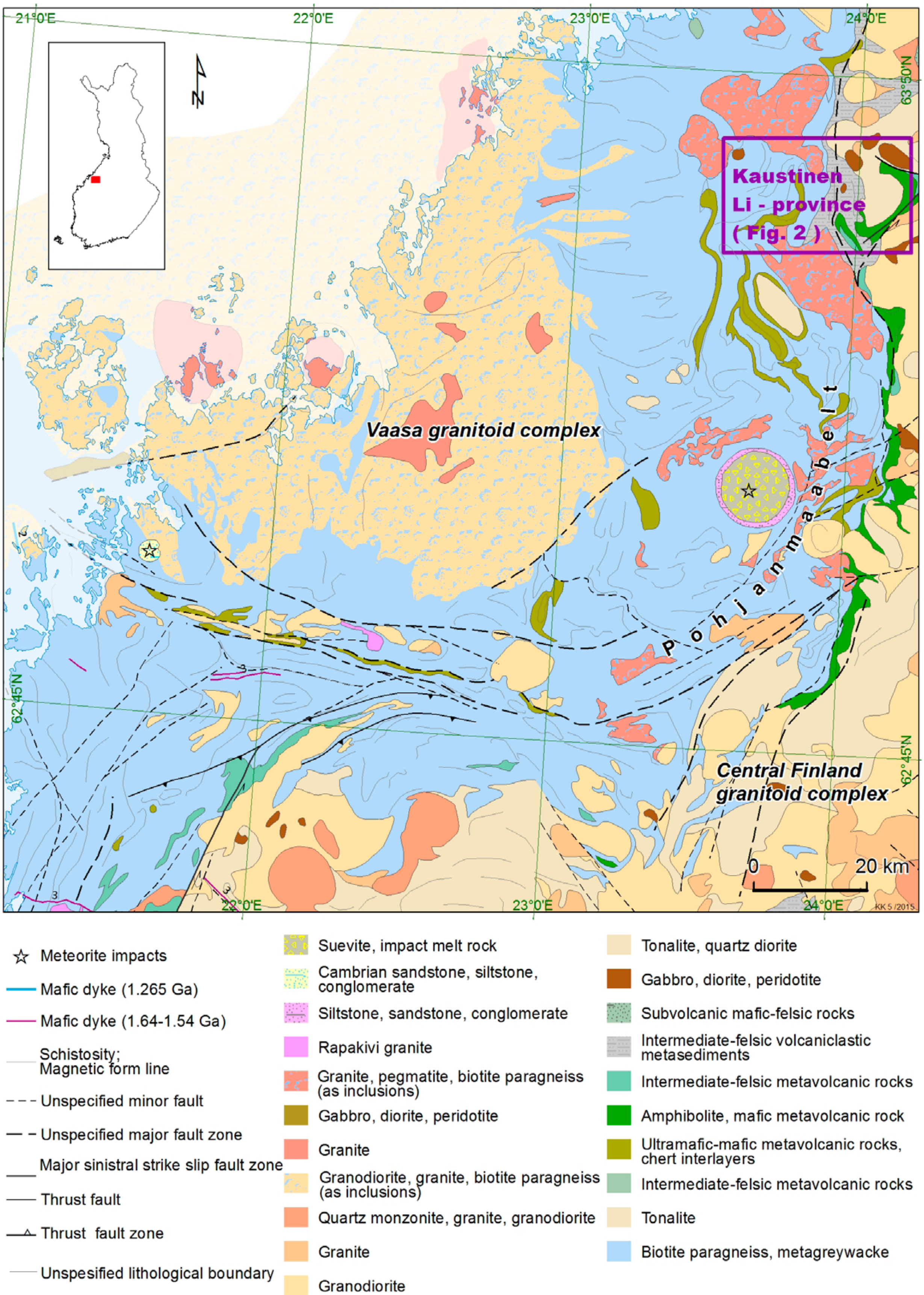


Fig. 1. Geological map showing the Pohjanmaa Belt after Nironen et al. (in prep.). The Kaustinen Li province is indicated by the rectangular upper right corner and described more detailed in Fig. 2.

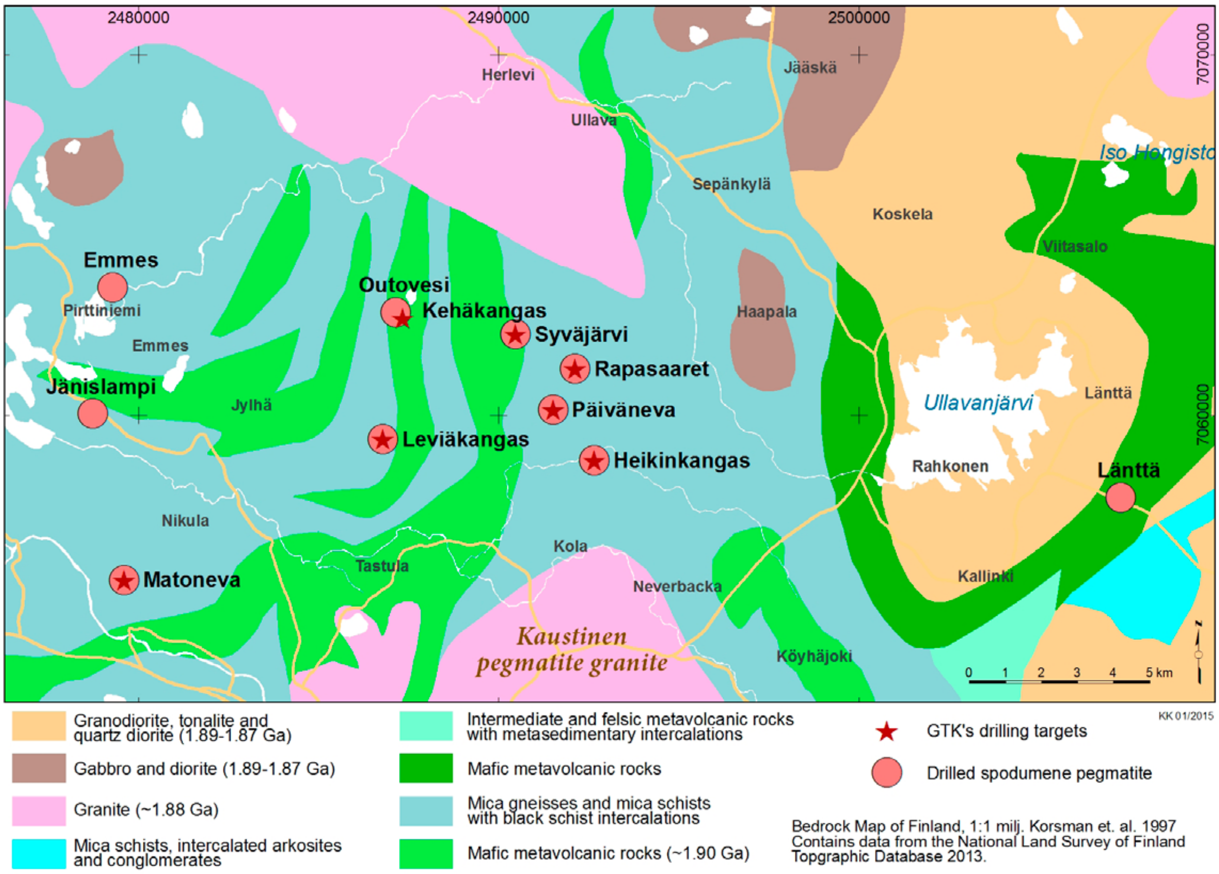


Fig. 2. The Kaustinen Li province, showing the locations of the drilling targets of GTK in 2004–2012, and other drilled spodumene pegmatites. The regional geological map is after Korsman et al. (1997).

The most common rock types within the Pohjanmaa belt are mica schists and mica gneisses, which are intercalated with metavolcanic rocks. The supracrustal rocks have been divided into two fields, the Evijärvi and Ylivieska fields (Kähkönen 2005), and the Kaustinen Li pegmatite area is located at the northern continuation of the Evijärvi field. Based on the studies by Williams et al. (2008), the metamorphic peak conditions took place at about 1.89–1.88 Ga in amphibolites facies conditions (Mäkitie et al. 2001).

The Pohjanmaa belt hosts several rare element pegmatites (Alviola et al. 2001), and the Li pegmatites of the Kaustinen province belong to the albite-spodumene type according to the classification of Černý & Ercit (2005). The Li pegmatites have intruded after the metamorphic peak conditions of the area. The U-Pb age on manganocolumbite for the Länttä albite-spodumene pegmatite is ca 1.79 Ga, which is considered as the crystallization age of the pegmatite (Alviola et al. 2001). Pegmatites crosscut the metavolcanic and metasedimentary rocks at the northern edge of the belt. At least 16 separate pegmatite occurrences are known in the area. The albite-spodumene pegmatites are covered by Quaternary sediments. The contact relationships can often only be seen in the erratic boulders and drill cores. Their geochemical characteristics are presented, for example, in Käpyaho et al. (2007a), Ahtola et al. (2010a, b), Kuusela et al. (2011) and Martikainen (2012). Pegmatite granites in the Kaustinen area have been speculated to be a candidate for the source of the albite-spodumene pegmatites (see Martikainen 2012), but confirmation of this would require the absolute age determination of these granites.

3 RESEARCH METHODS

3.1 Geological mapping

GTK commenced fieldwork in the Kaustinen area in 2004. Pegmatite exploration proved to be challenging, as none of the spodumene pegmatites are exposed. The petrophysical characteristics of spodumene pegmatites are also similar to mica schists, the most common host rock in the area. Pegmatites are covered by 3–18 m of Quaternary deposits. Therefore, the fieldwork mainly consisted of boulder prospecting. Spodumene pegmatite boulders are the only visible evidence of the lithium pegmatites in the field. The boulder fans at Leviäkangas, Syväjärvi and Rapasaaret are presented in Figures 4, 5 and 7. Due to the lack of outcrops, diamond drilling was the most useful method for sampling spodumene pegmatites in the Kaustinen district. Geological maps of the study areas are based on diamond drilling and ground geophysical surveys.

During 2004–2011, GTK carried out 15.5 line km of gravity and 4.4 km^2 of gravity and magnetic ground geophysical surveys in seven different exploration areas (Table 1). At Rapasaaret, a slingram survey was also conducted. Ground geophysics was surveyed to support geological mapping and to define the borders of the spodumene pegmatites. High-resolution, low-altitude airborne geophysics data for the year 2004 were also used.

In general terms, using geophysical surveys to locate or delimit contacts between pegmatites and host rocks in the Kaustinen area turned out to be very challenging. The petrophysical properties of the spodumene pegmatites are quite similar to mica schists, the most common host rock in the Kaustinen region. The electrical conductivity and susceptibility of spodumene pegmatites are low, and the density is 2.7–2.8 kg/cm^3. The spodumene pegmatites are weakly magnetic, but often appear to occur in contact with the intermediate volcanic rock horizons. The intermediate volcanic rocks often tend to show higher magnetic anomalies and are visible in the Syväjärvi (Fig. 3) and partly in the Rapasaaret deposits.

Gravimetric profiles were carried out in Rapasaaret, Leviäkangas and Syväjärvi in order to define the soil thickness and to outline whether the spodumene pegmatites can be seen as a change in elevation in the interpreted topography of the bedrock. While there were some changes in the gravity interpretation, there were no defined pegmatites. The soil thickness was approximately 10 metres in the area.

Table 1. Summary of the sampling and ground geophysics in Kaustinen Li area in 2004–2012.

Drilling target	Years of research	Diamond drilling Number of drill holes	Ground geophysics Total length (m)	Line km/km^2	Method	Till sampling (number of samples)	RC drilling (number of samples)
Kehäkangas	2004	6	469	1 km	gr		
Päiväneva	2004–2009	29	3375	8 km / 1+3 km^2	mg+gr	90	
Heikinkangas	2004–2009	34	3495			150	44
Matoneva	2004–2006	14	1503	4.5 km	gr		
Leviäkangas	2004–2008	22	2032	1 km^2	mg+ gr		60
Syväjärvi	2006–2010	24	2547	1 km^2	mg+ gr		56
Rapasaaret	2009–2012	26[1)]	3653[2)]	2.2 km^2	mg+sl+gr	508	
Total		155	17,074	13.5 km / 4.4 km^2		748	160

1) Incl. 8 drill holes from the ERDF Li project (KaLi)
2) Incl. 1117 m from the ERDF Li project (KaLi)

mg = magnetic
sl = slingram
gr = gravity

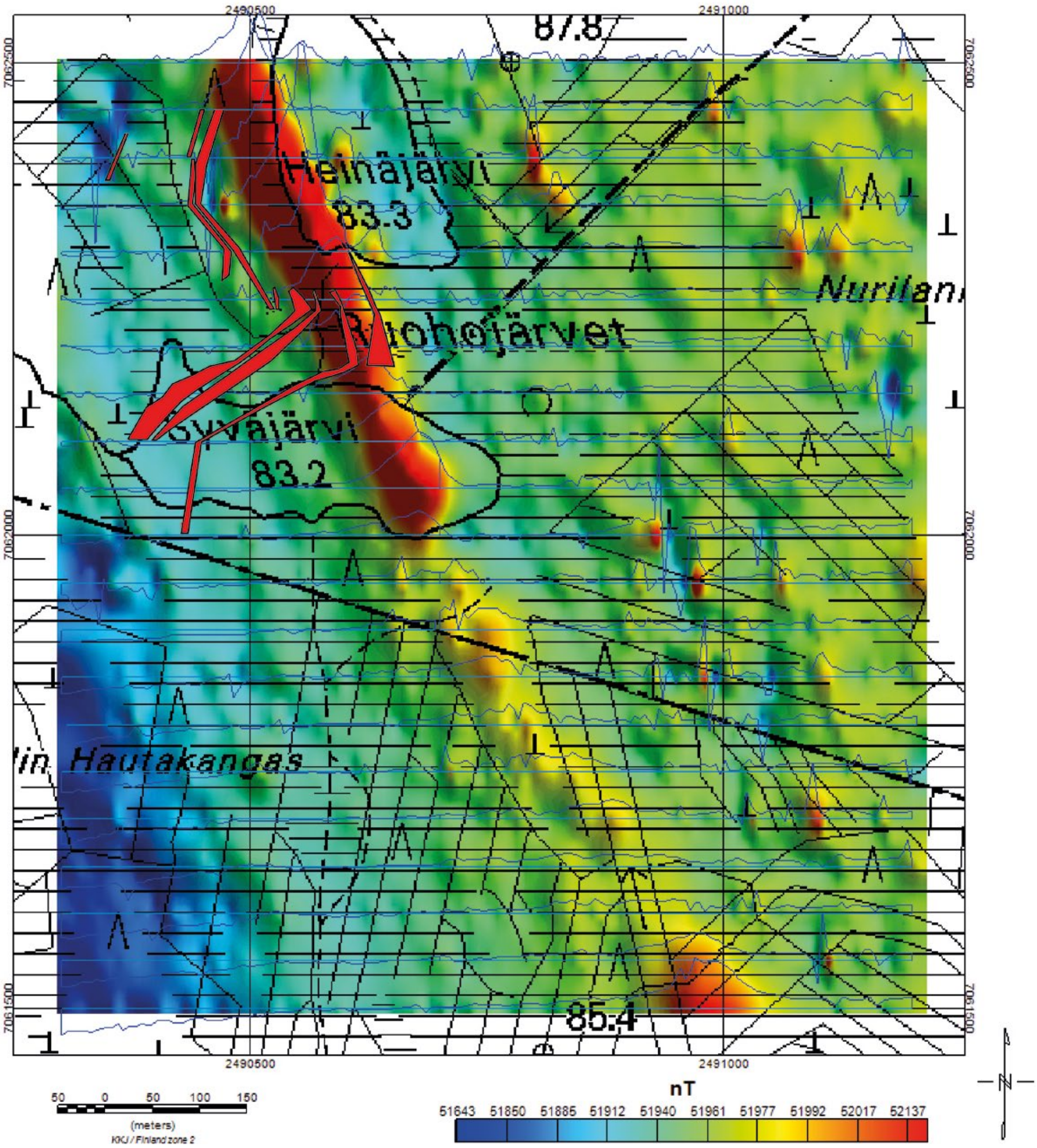


Fig. 3. Ground magnetic map of the Syväjärvi exploration area. The blue lines show the magnetic profiles and the red patterned line marks the spodumene pegmatite. The positive magnetic anomaly (red colour) is caused by intermediate volcanic rocks (Ahtola et al. 2010b). Basemap © National Land Survey of Finland, license number MML/VIR/TIPA/217/10.

In total, GTK drilled 155 drill holes (17 km) in seven prospect areas in 2004–2012 (Table 1). In Leviäkangas and Syväjärvi, older diamond drill cores were also available that had been drilled by Suomen Mineraali Oy in the 1960s and Paraisten Kalkki Oy in the 1980s.

In 2007–2008, GTK carried out a 60-sample RC drilling programme at Leviäkangas and a 56-sample RC drilling programme at Syväjärvi (Table 1). The objective was to locate the pegmatite dyke at the surface and to direct diamond drilling.

Till sampling was performed in Päiväneva, Heikinkangas and Rapasaaret during 2008–2010. In total, 748 percussion drilling samples were taken (Table 1). In Rapasaaret, grid sampling of 500 samples at a 50-m interval was successfully used to locate the spodumene pegmatite dyke swarm and to direct diamond drilling.

3.2 Analytical methods

All chemical analyses were performed by Labtium Oy. The drill cores of the spodumene pegmatites were systematically analysed using XRF for the major elements, ICP-AES for Li and ICP-MS for Ta, Nb and Be. In all other study areas, except Rapasaaret, the elemental determinations were performed from hydrofluoric acid – perchloric acid dissolution. In Rapasaaret, multielement analyses were carried out from sodium peroxide fusion. In total, 940 drill core samples were analysed, and 533 of these were spodumene pegmatites. A sample length of about two metres was typically used. The results of chemical analyses are summarised in Tables 3 and 4.

Till samples collected from Päiväneva, Heikinkangas and Rapasaaret during 2008–2010 were assayed using ICP-AES for Li. The results were used to direct diamond drilling.

During the latter half of the 1970s, the Geological Survey of Finland (GTK) collected more than ten thousand till samples in the Kaustinen area as part of a regional till sampling programme. Samples were collected along profiles with 500–2000 m separation and 100–400 m between sample sites (Fig. 13). Sampling profiles were planned to be perpendicular to the direction of the glacial ice drift. The average sample depth was about 2.4 m. At that time, no assays for Li were carried out. In 2010, GTK's KaLi-project (Li resources of the Kaustinen area), partly supported by the European Regional Development Fund (ERDF), re-analysed the till samples collected in 1970s. A total of 9658 samples from the Kaustinen area were assayed for ICP-AES, and these results were used for overall Li potential evaluation of the Kaustinen region. More detailed investigation results are published in Kontoniemi (2011, 2012 and 2013).

Mineralogical studies were conducted on 22 polished thin sections from the Matoneva, Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites. After identifying the main minerals with a polarizing microscope, their chemical compositions were determined using a microprobe analyser. Electron microprobe analyses of minerals were performed with the wavelength dispersive technique using a Cameca SX100 instrument at the Geological Survey of Finland (GTK) in Espoo. Natural minerals and synthetic metals were employed as standards. Analytical results were corrected using the PAP on-line correction program (Pouchou & Pichoir 1986).

4 RESULTS

4.1 General description of the studied spodumene pegmatites

The spodumene pegmatites of the Kaustinen Li pegmatite province resemble each other petrographically. Their main petrographical properties are summarized in Table 2. They all are typically coarse grained, light coloured, and they are mineralogically very similar, having albite, quartz, spodumene, muscovite and K-feldspar as the main minerals. They all show variation in the distribution of the main minerals, but well-developed internal zonation is often lacking in the dykes (Martikainen 2012), although as Figure 8 illustrates, geochemical zonation can sometimes be observed. Based on the drill core observations, the spodumene pegmatites sometimes show the preferred orientation of the main minerals.

4.1.1 Leviäkangas (Vintturi) deposit

The erratic boulder fan led to the discovery of the unexposed spodumene pegmatite dyke by Suomen Mineraali Oy and further by Paraisten Kalkki Oy in Leviäkangas in the 1960s and 1980s. GTK continued the research in 2006 and drilled 22 drill holes totalling 2032 m. Based on the available drilling data, the inferred length of the vein is 500 m and it strikes NW, dipping 40–60° to the west (Fig. 4). The pegmatite dyke is interpreted to be slightly discontinuous in its northern quarter, and its thickness varies from 1 to 20 metres. The host rocks of the dyke are mainly mica schists interlayered with metagreywacke and black schist layers. Locally, plagioclase porphyric rocks units are present. The Leviäkangas deposit is evaluated to

Table 2. Summary of the petrography of pegmatites in the Kaustinen area.

Deposit/ Occurrence	Petrography	Main minerals (in order of abundance)	Accessory minerals (in alphabetical order)
Leviäkangas	Coarse grained, light coloured with light grey to light green elongated, bladed 3–5 cm spodumene crystals rarely altered to muscovite. Creamy or grey alb often intergrown with smoky qtz. Perthitic micro-cline k-feldspar near wall rock contact	Albite, quartz, K-feldspar, spodumene, muscovite	Apatite, cassiterite, cookeite, garnet, graphite, Mn-Fe phos-phate, montebrasite, Nb-Ta oxides, sphalerite, tourmaline, zeolite
Syväjärvi	Coarse grained, light grey to light green elongated, bladed 3–5 cm spodumene crystals rarely altered to muscovite. Creamy or grey alb often intergrown with qtz. Perthitic microcline k-feldspar near wall rock contact	Albite, quartz, K-feldspar, spodumene, muscovite	Apatite, arsenopyrite, garnet, Nb-Ta oxides, sphalerite, tourmaline
Rapasaaret	Coarse grained, light green, sometimes light greyish lath shaped 2–10 cm spodu-mene crystals sometimes altered to flaky musc. White to grey coloured alb often intergrown with qtz. Perthitic microcline Kfsp present. Sporadic beryl crystals.	Albite, quartz, spodumene, K-feldspar, muscovite	Andalusite, apatite, arsenopyrite, beryl, calcite, chlorite, fluorite, garnet, Mn-Fe phospha-tes, Nb-Ta oxides, pyrite, pyrrhotite, tourmaline, zinnwaldite
Matoneva	Coarse grained, light green shaped spodumene 3–5 cm crystals sometimes altered to flaky muscovite and chlorite. White to grey coloured alb often inter-grown with qtz.	Albite, quartz, K-feldspar, spodumene, muscovite	Beryl, Nb-Ta-oxides, cassiterite
Heikinkangas	Coarse grained, light green spodumene 3–5 cm crystals sometimes altered to flaky muscovite and chlorite. White to grey coloured alb often intergrown with qtz.	Albite, quartz, K-feldspar, spodumene, muscovite	Apatite, biotite, garnet, tourmaline
Päiväneva	Medium to coarse grained, 1–3 cm light green spodumene, red coloured on weathered surface contact & alters to flaky muscovite	Albite, quartz, K-feldspar, spodumene, muscovite	Cassiterite, garnet, tourmaline

contain a 2.1 Mt mineral resource with 0.70 wt% Li_2O (Koistinen et al. 2010a).

4.1.2 Syväjärvi (Ruohojärvet) deposit

The Syväjärvi deposit was also discovered by Suomen Mineraali Oy via its boulder fan in the 1960s. Paraisten Kalkki Oy continued exploration in the 1980s and later GTK during 2006–2010 by drilling 24 drill holes totalling 2547 m. The deposit is composed of several dykes that have a varying strike from SW–NE to SE–NW, and occasionally also N–S. The length of the pegmatite swarm is about 500 m and it dips approximately 30–40° to a westerly direction. The thickness of pegmatites varies from 1 to 22 m (Fig. 5). The main host rocks of the Syväjärvi Li pegmatites are mica schists and intermediate volcanic rocks with associated agglomeratic layers. The mica schists are mostly greywackes and may sometimes contain staurolite. The majority of the solid modelling-based indicated tonnage of 2.6 Mt with 0.98 wt% Li_2O belongs to a flat-lying NW–SE striking spodumene pegmatite dyke.

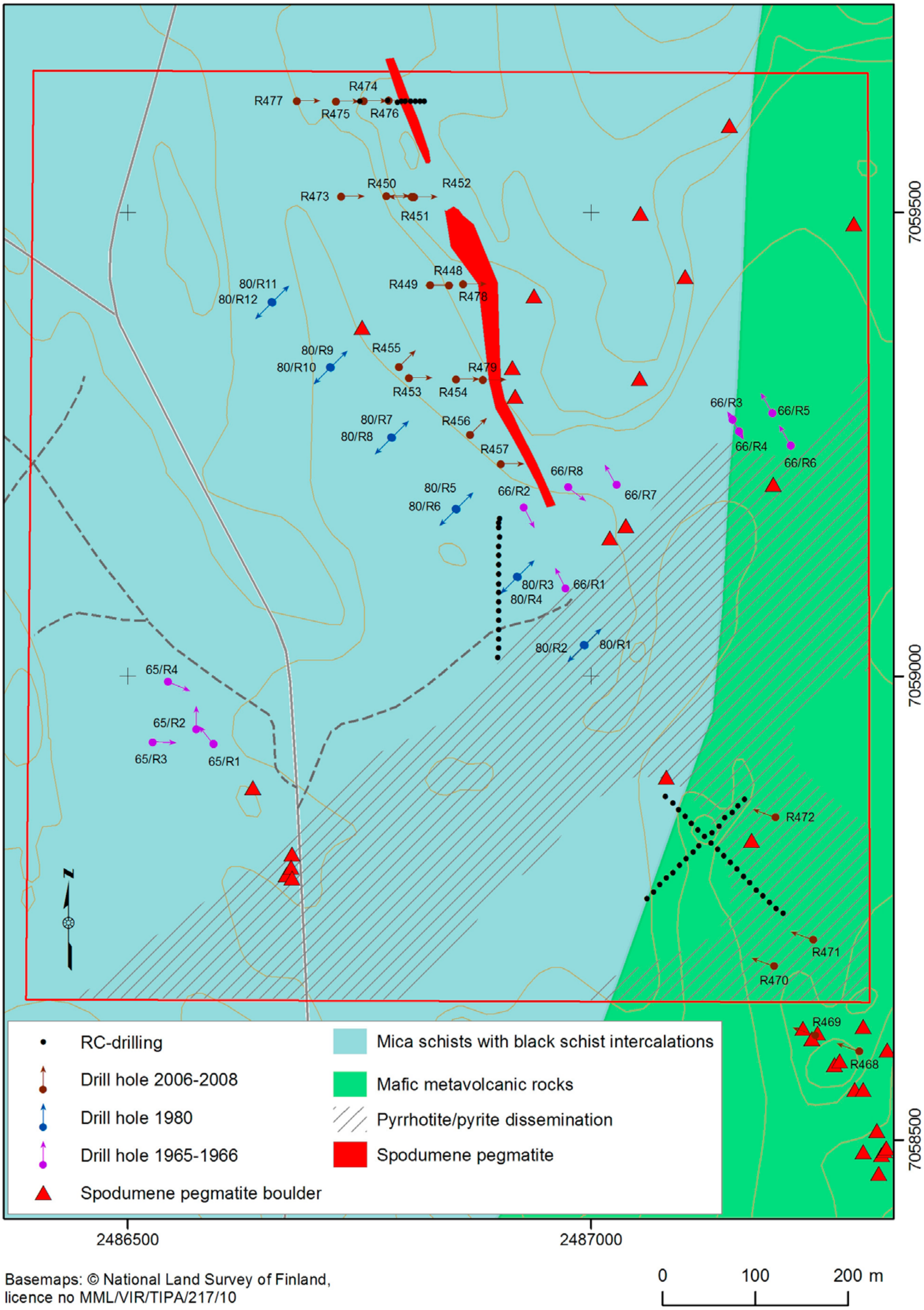


Fig. 4. A geological map of the Leviäkangas lithium pegmatite deposit. Plan projection of drill core and RC drilling sites and locations of spodumene pegmatite boulders (Ahtola et al. 2010a).

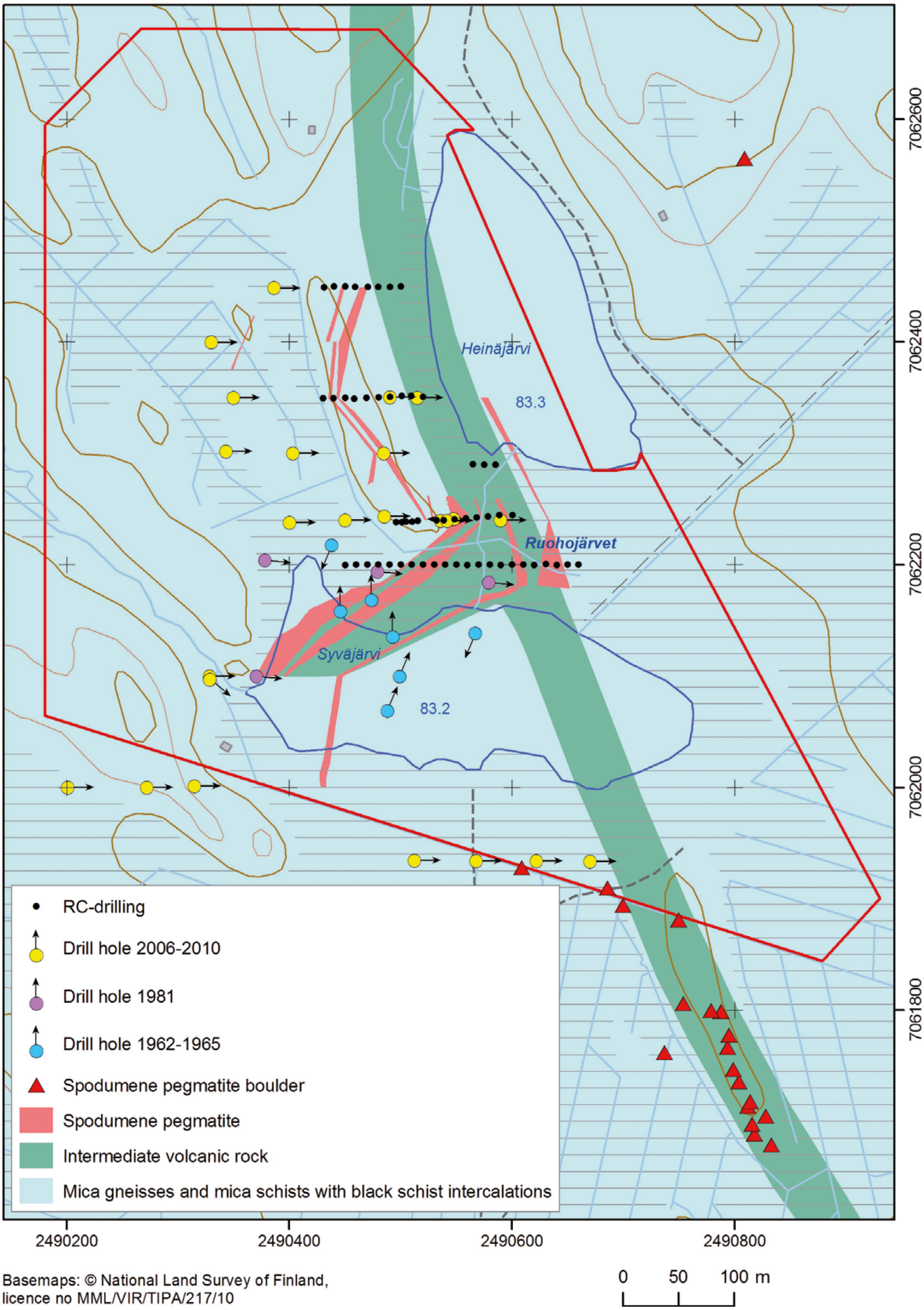


Fig. 5. A geological map of the Syväjärvi lithium pegmatite deposit. Plan projection of the drill core and RC drilling sites and the locations of spodumene pegmatite boulders (Ahtola et al. 2010b).

4.1.3 Rapasaaret deposit

The Rapasaaret deposit was discovered by GTK in 2009 close to a boulder fan. The Rapasaaret deposit (Fig. 7) has at least two dyke swarms, of which the eastern part appears to strike from to SE–NW, dipping SW 40–50°, and has a length of 700 m. The drillings suggest that the strike of the western dyke swarm bends from a northward direction to the NE, with a 60–75° dip to the NW, and has a length of 275 m. The dykes vary in thickness from 1 to 24 m. An extensive till sampling programme (Fig. 6) of 534 samples was carried out in 2009. The results of the programme were used to direct a drilling campaign of 26 drill holes totalling 3653 m. These resulted in a resource estimate of 3.7 Mt with 1.02 wt% Li_2O.

Typical host rocks for the Rapasaaret pegmatites are mica schists, greywackes and intermediate volcanic rocks. The mica schists locally contain staurolite, and in places tremolite and garnet are present. The intermediate volcanic rock has plagioclase phenocrysts, biotite aggregates and locally green amphibole. On the basis of available drilling and till sampling data, it cannot be confirmed whether the eastern and the western dykes are separate. The two dyke swarms could also possibly cross each other, one striking NE and the other NW.

4.1.4 Päiväneva occurence

The Päiväneva spodumene pegmatites were found by GTK in 2005. The Päiväneva area (Fig. 2) is a generally flat bog area with local hills consisting of till material that contain spodumene pegmatite boulders. Some of the boulders are tens of cubic metres in size. To locate the origin of the boulders, 21 holes totalling 2282 m were drilled in 2004 and 2005.

The predominant rocks observed are even-grained mica schists, locally showing primary sedimentary structures such as laminar fine-grained layering, graded bedding and occasionally being plagioclase porphyric. The schists are crosscut by albite-dominated pegmatite veins containing variable amounts of spodumene. Thickest observed drill core intersection of spodumene pegmatite vein is 4.9 m.

The length of the dyke swarm is unknown, but the distance between drilled sections where Li pegmatites have been observed is 200 m.

4.1.5 Heikinkangas occurence

Heikinkangas spodumene pegmatites were found by GTK in 2004. GTK carried out extensive research to localize the origin of the boulder fans in the Heikinkangas area between the years 2004 and 2009 (Fig 2).The area is poorly exposed and a drilling campaign consisting of 34 drill holes and covering a total of 3596 m was conducted in the area. Till sampling and RC drilling were also carried out in the region (Table 1).

The bedrock in the area is composed of folded fine-grained or medium-grained, layered mica schists with occasional staurolite porphyroblasts. Locally, graphite and sulphide-bearing schist horizons are present. A spodumene pegmatite dyke with a maximum drilled thickness of 10.5 m was located in the drilling. The length of the dyke (swarm) is unknown, but the distance between drilling profiles in which Li pegmatites have been observed is 100 m.

4.1.6 Matoneva occurence

Erratic boulders of Li pegmatite were found by Suomen Mineraali Oy in the 1960s in the Matoneva area (Fig 2). In 2004 onwards, GTK re-investigated the area by applying geophysical methods, including ground-penetrating radar, aerogeophysical methods and gravity measurements. On the basis of these investigations, GTK carried out a drilling programme covering 14 drill holes with a total length of 1503 m. As a result of this, a 7.60-m-thick spodumene-bearing pegmatite section was encountered, with an average Li_2O content of 0.22 wt% (n = 6).

The host rocks surrounding the pegmatite are composed of fine- to medium-grained mica schists locally having anhedral muscovite clusters, plagioclase, quartz and possibly very fine-grained andalusite. Locally, the schist has intercalations of graphite and sulphide-richer interlayers and the rock has skarn intercalations. GTK relinquished the claim and the investigation results have been reported by Käpyaho et al. (2007b).

4.1.7 Kehäkangas boulder fan

The spodumene pegmatite boulder fan located at Kehäkangas (Fig. 2) is 1 km long and irregular in shape. No outcrops can be found in the area. To localize the source of the boulders, 6 drill holes were

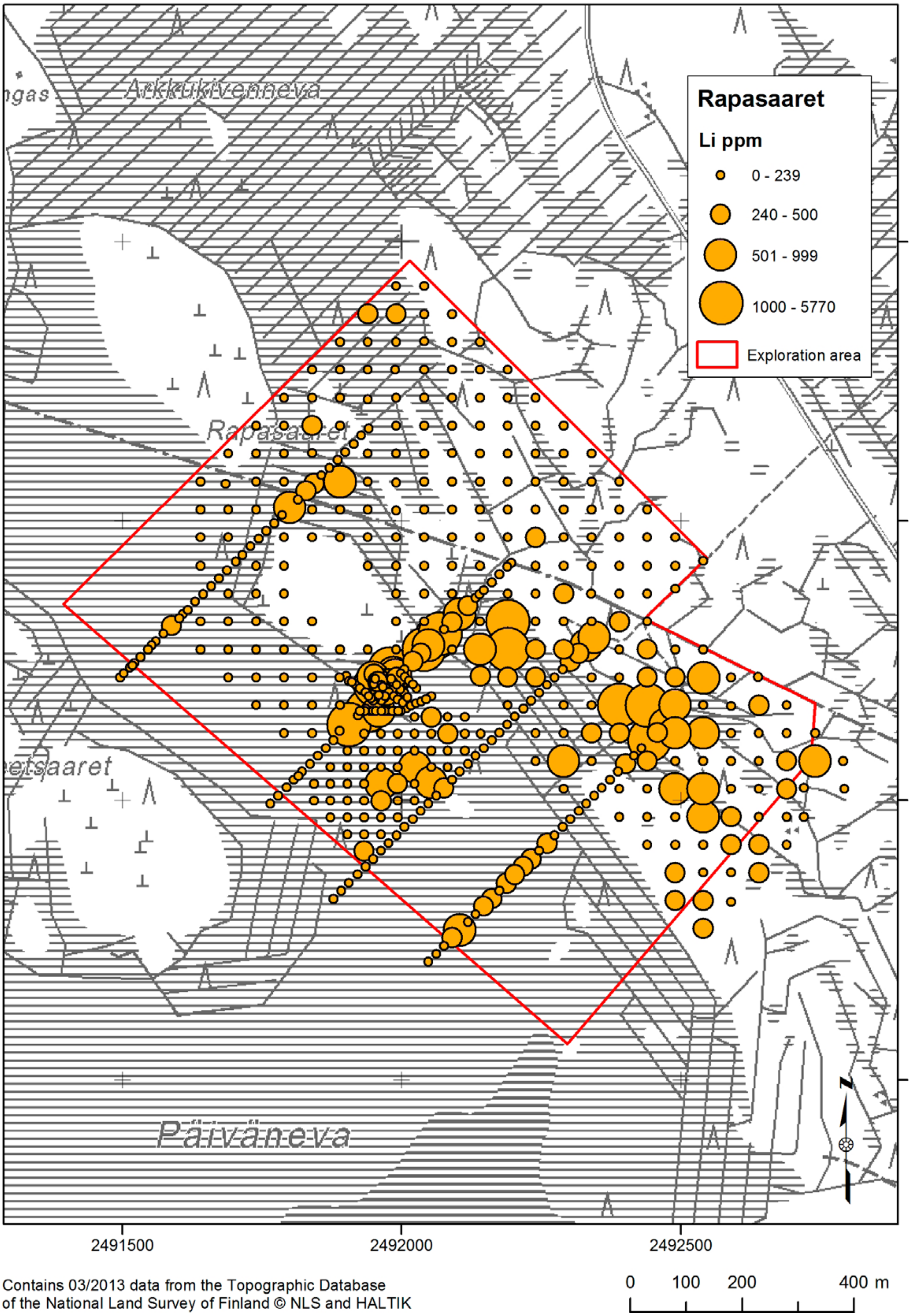


Fig. 6. A map of the till sampling grid with plotted Li anomalies (ppm) in Rapasaaret. The highest Li values (>1000 ppm) indicate the presence of Li pegmatite.

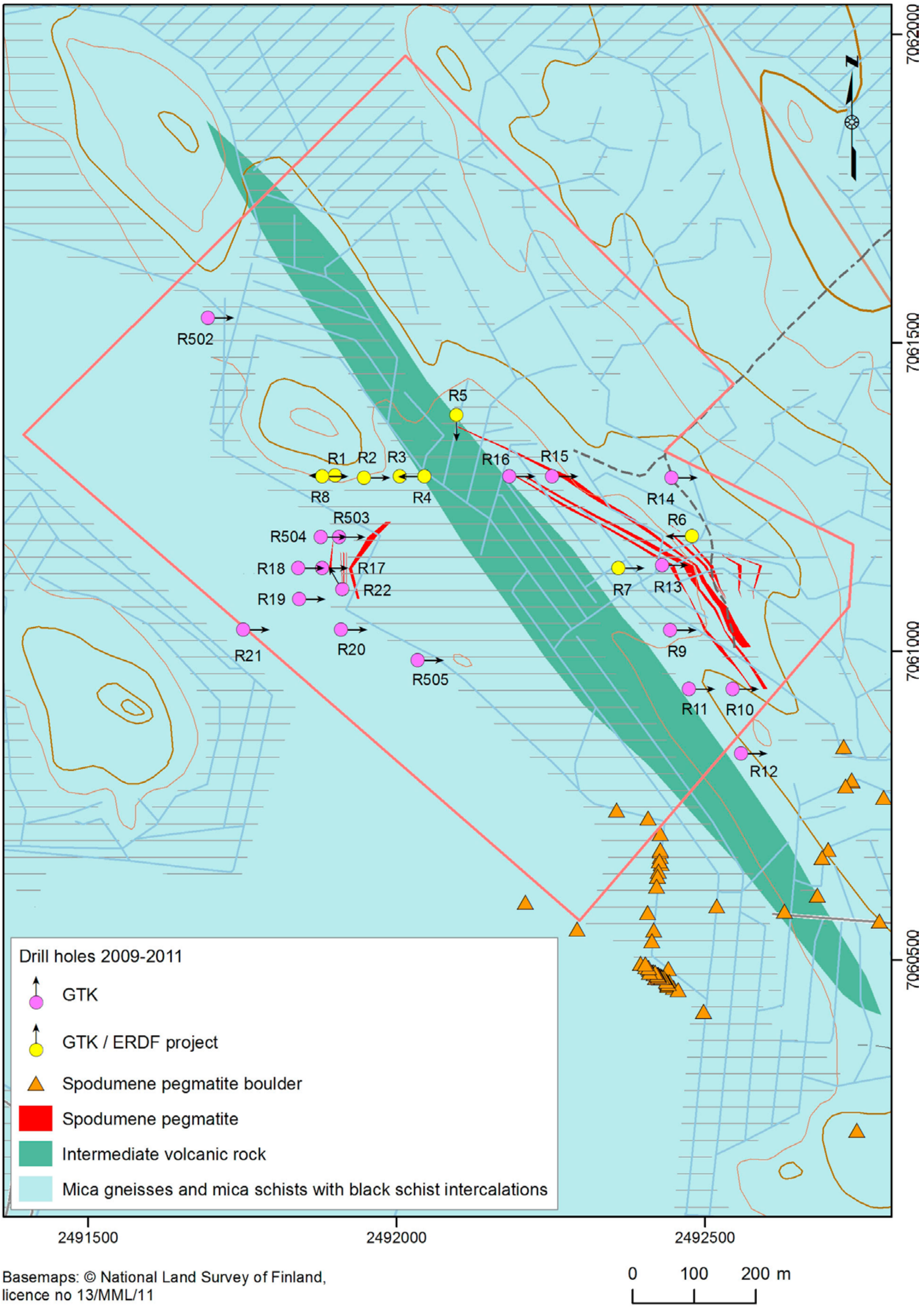


Fig. 7. A geological map of the Rapasaaret lithium pegmatite deposit with drilling sites and the locations of spodumene pegmatite boulders (Kuusela et al. 2011).

made with a total length of 468.70 m in 2004. The predominant rocks observed were mica schists and greywacke schists, locally having graphite- and sulphide-bearing interlayers. Albite pegmatites without spodumene were localized during the drillings.

4.2 Geochemistry and mineralogy of the studied spodumene pegmatites

4.2.1 Whole rock geochemistry

In total, 533 spodumene pegmatite samples from three deposits and three other drilling targets were analysed. A summary of these analyses is presented in Tables 3 and 4. The geochemistry of major elements is very similar in all studied spodumene pegmatites (Table 3). The highest average Li_2O (1.18 wt%) and BeO (502 ppm) contents are in the Rapasaaret deposit, while the highest average Nb-Ta oxides (Nb_2O_5 87 ppm and Ta_2O_5 72 ppm) are in the Leviäkangas deposit (Table 4).

Table 3. Average concentrations of major elements of spodumene pegmatites in the Kaustinen area.

	n	Na2O % XRF	MgO % XRF	Al2O3 % XRF	SiO2 % XRF	P2O5 % XRF	K2O % XRF	CaO % XRF	TiO2 % XRF	MnO % XRF	Fe2O3 % XRF
Matoneva	6	5.75	0.04	16.18	74.20	0.44	2.21	0.21	0.01	0.11	0.52
Heikinkangas	18	4.75	0.05	15.78	75.35	0.09	2.53	0.25	0.01	0.07	0.50
Päiväneva	49	4.36	0.39	15.89	73.91	0.32	2.84	0.59	0.10	0.09	1.13
Leviäkangas	101	4.79	0.09	16.21	74.63	0.31	2.60	0.24	*	0.08	0.38
Syväjärvi	200	4.42	0.11	16.00	74.96	0.35	2.64	0.35	*	0.10	0.60
Rapasaaret	159	4.44	0.16	16.08	74.73	0.30	2.81	0.31	*	0.10	0.65

* A significant part were below the detection limit

Table 4. Average, maximum and minimum concentrations of Li_2O and selected trace elements of spodumene pegmatites in the Kaustinen area

		Li_2O % ICP-AES			Ta_2O_5 ppm ICP-MS			Nb_2O_5 ppm ICP-MS			BeO ppm ICP-MS		
	n	avg.	max	min	avg.	max	min	avg.	max	min	avg.	max	min
Matoneva	6	0.18	0.27	0.03							170	366	82
Heikinkangas	18[1)]	0.76	2.06	0.02	16	43	6	24	68	9	134	249	55
Päiväneva	49[2)]	0.65	1.39	0.10	50	404	2	87	183	34	155	303	19
Leviäkangas	101[3)]	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

[1)] n: Be, Nb = 16
[2)] n: Be = 33, Nb = 10
[3)] n: Be = 96, Nb and Ta = 94

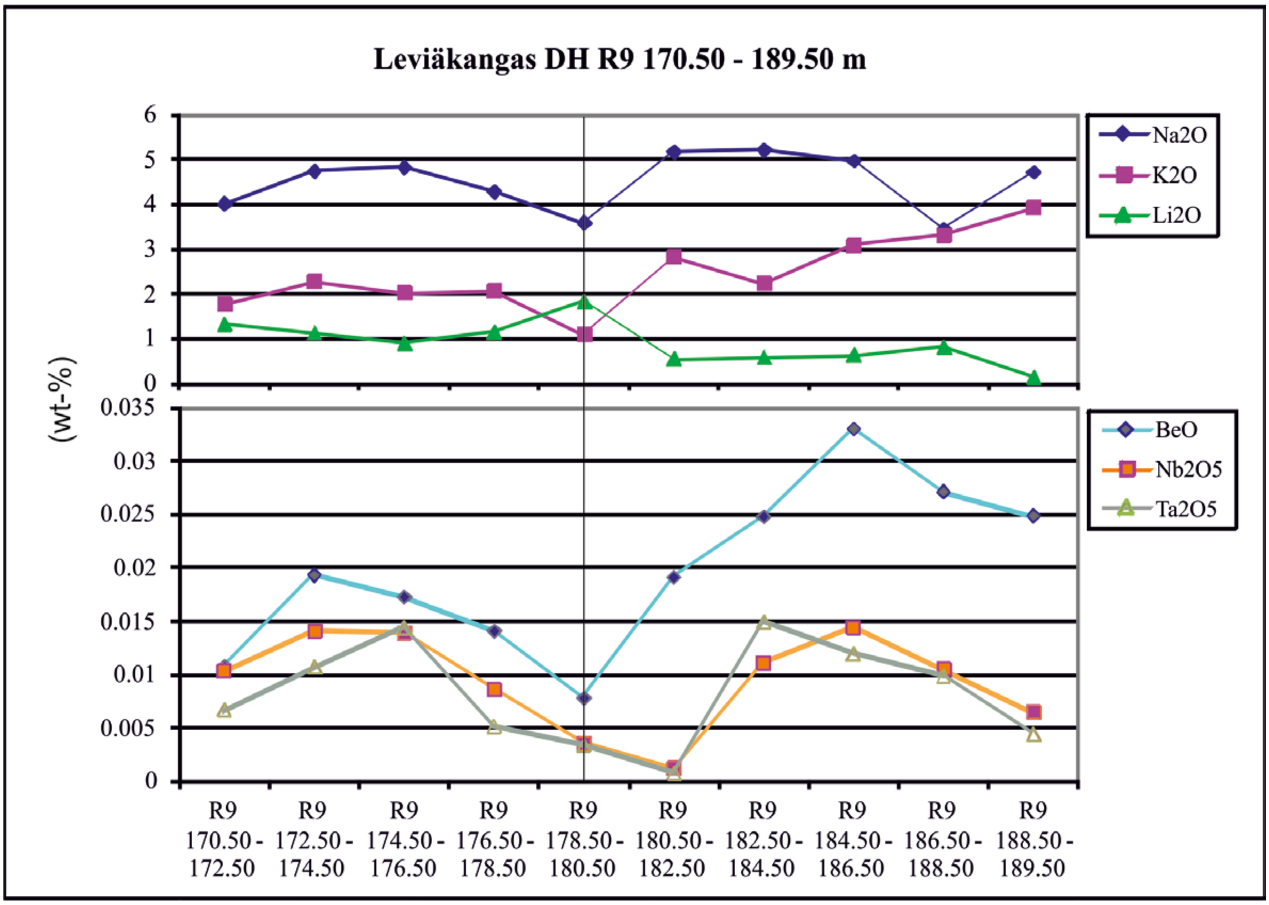


Fig. 8. Internal zonation in spodumene pegmatite of Leviäkangas (DH R9 170.50–189.50 m). The Li_2O content is highest in the core zone and lowest near the contacts.

The spodumene pegmatite veins in the Kaustinen area are sometimes weakly zoned. In these cases, the amount of Li_2O (spodumene) increases and the amounts of Na_2O (albite) and especially K_2O (potassium feldspar) decrease from the wall zone to the core. Similarly, a higher Na_2O content seems to correspond to a lower Li_2O content (Fig. 8). Higher Ta_2O_5, Nb_2O_5 and BeO contents especially occur in more albite-rich parts.

The geochemical characteristics of the Li pegmatites from the Kaustinen-Ullava region have also been discussed by Martikainen (2012). According to his study, Outovesi and Länttä pegmatites have the highest degree of fractionation of the studied pegmatites (Rapasaaret was not included).

4.2.2 Mineralogy

In total, 25 mineral species (Table 2) have been identified (polarising microscope, XRD, SEM-EDS, EPMA) in spodumene pegmatites of the Kaustinen area (Ahtola et al. 2010a, b, Kuusela et al. 2011, Al-Ani et al. 2008a, b). The five main minerals in all the spodumene pegmatites are albite, quartz, K-feldspar, spodumene and muscovite (Fig. 9). The accessory minerals are andalusite, apatite, arsenopyrite, beryl, calcite, cassiterite, chlorite, cookeite, fluorite, garnet, graphite, Mn-Fe phosphate, montebrasite, Nb-Ta oxides, pyrite, pyrrhotite, sphalerite, tourmaline, zeolite and zinnwaldite.

The chemical compositions of the minerals from Leviäkangas, Syväjärvi and Rapasaaret were determined from 19 polished thin sections using an electron microprobe. Some of the Nb-Ta oxides were studied by Al-Ani et al. (2008b) from separated grains.

Spodumene

Spodumene ($LiAlSi_2O_6$) is the only economic Li mineral in the Kaustinen pegmatites. Some cookeite (Li chlorite), montebrasite (Li phosphate) and zinnwaldite (Li silicate) have been identified with EMPA, but these are very rare. The

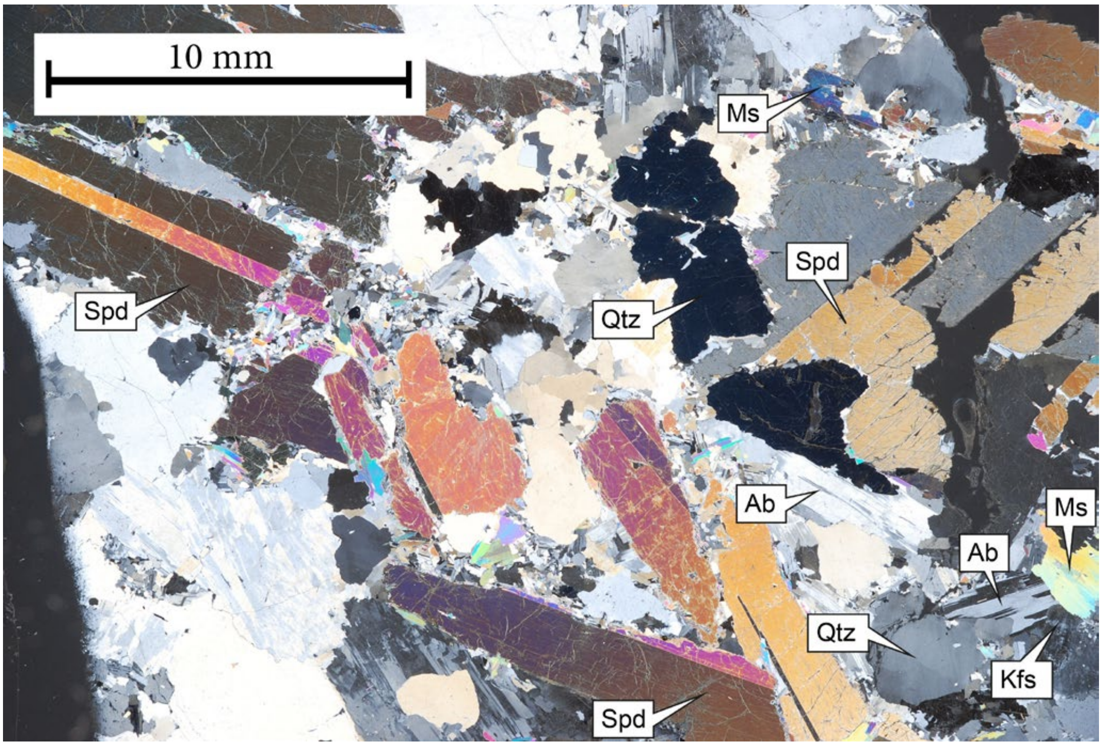


Fig. 9. Thin section of spodumene pegmatite from Leviäkangas (DH R1/66 31.90m). Spd = Spodumene, Qtz = Quartz, Kfs = Potassium feldspar, Ab =Albite, Ms = Muscovite.

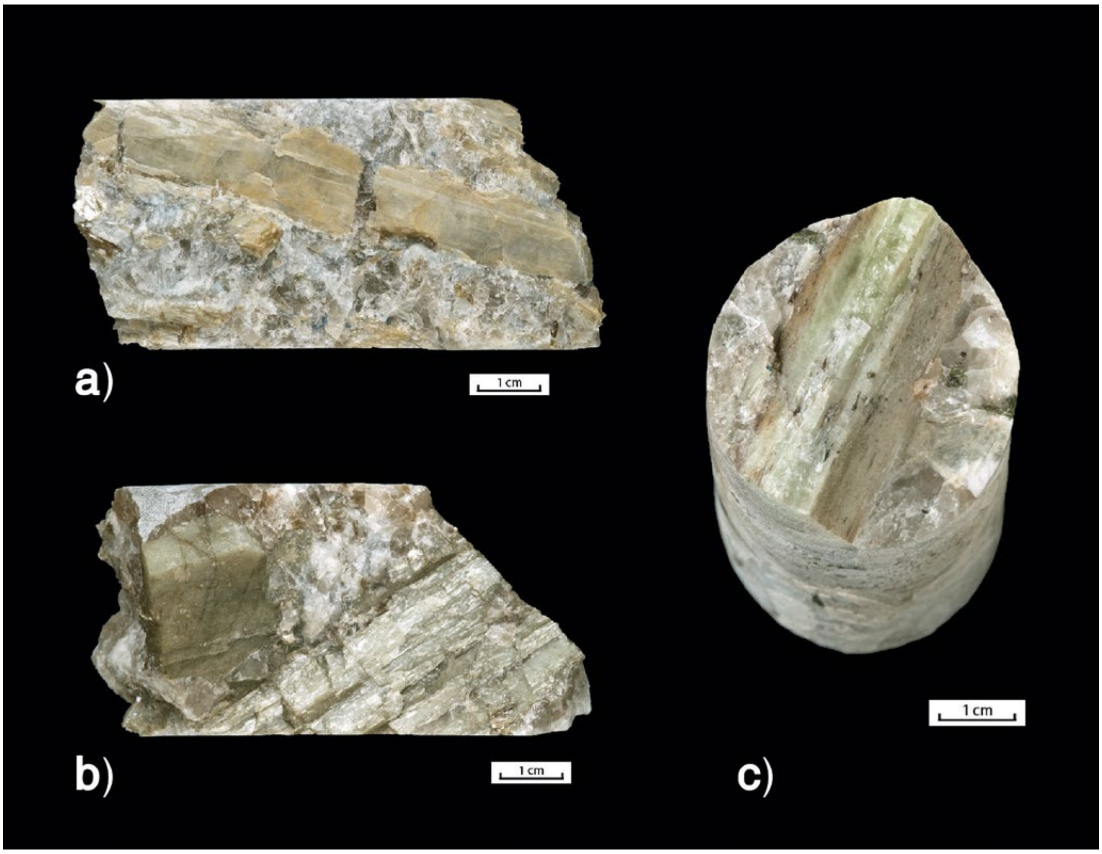


Fig. 10. Green spodumene laths in the Leviäkangas (a), Syväjärvi (b) and Rapasaaret (c) spodumene pegmatites. Photos: J. Väätäinen, GTK.

Table 5. The average chemical compositions (EMPA) of the spodumene grains from Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites.

Deposit /occurence	Leviäkangas	Syväjärvi	Rapasaaret
Number of analyses	83	85	94
Number of spodumene grains	16	9	25
SiO_2	65.17	65.07	64.78
TiO_2	0.01	0.01	0.01
Al_2O_3	26.98	27.01	26.88
Cr_2O_3	0.01		0.00
V_2O_3	0.01		0.01
FeO	0.29	0.48	0.55
MnO	0.09	0.13	0.11
MgO	0.01	0.01	0.03
CaO	0.01	0.02	0.01
Na_2O	0.09	0.09	0.17
K_2O	0.01	0.01	0.02
SrO	0.03	0.13	0.01
BaO	0.00	0.00	0.00
ZnO	0.02		0.17
Nb_2O_3	0.01		
P_2O_5	0.01		0.01
SO_2	0.01	0.01	0.01
NiO	0.01		0.01
F	0.02	0.02	0.02
F = O	-0.01		
Cl	0.00	0.00	0.01
Cl = O	-0.00		
Cs_2O		0.00	
Total	92.78	93.00	92.79
Max est. Li_2O*	7.22	7.00	7.21

*Maximum estimated Li2O = 100-total

spodumene of the studied pegmatites is coarse grained and typically occurs as elongated light green (Fig. 10), sometimes light greyish, lath-shaped crystals. These are usually 0.5–10 cm long. The pegmatites are occasionally zoned with higher spodumene concentrations in the core of the dyke, with the c-axes of spodumene grains pointing towards the wall rock contact point. The mean contents of spodumene (Li_2O % × 13.3 after Al-Ani et al. 2008a) in the Leviäkangas, Syväjärvi and Rapasaaret pegmatites are 10%, 13% and 15%, respectively, which in turn would correspond to 0.74%, 1% and 1.18% Li_2O (wt%). In total, 50 spodumene grains were analysed from 19 thin sections. Due to lightness of the Li, it cannot be determined with electron optical methods. Thus, the total maximum Li_2O content of the spodumene grains in Table 5 was estimated from microprobe analyses by assuming that the sum of all analysed elements, with Li_2O included, is 100%. Thus, the maximum Li_2O = 100 – total of the analysed elements.

The average estimated maximum concentrations of Li_2O in spodumene are 7.22%, 7.00% and 7.21% in Leviäkangas, Syväjärvi and Rapasaaret, respectively. The FeO content in spodumene in Kaustinen area is quite high, varying between 0.29% and 0.55%.

Plagioclase
The plagioclase is albite ($NaAlSi_3O_8$). It is the dominant mineral in the spodumene pegmatites in Kaustinen area, with an average normative content of 37–41 wt% (Ahtola et al. 2010a, b and Kuusela et al. 2011), and is sometimes present as cleavelandite. The albite laths are white to grey coloured and sometimes up to 10 cm in length. Albite from 38 grains from 19 separate thin sections was analysed. The CaO content in the albite of Leviäkangas, Syväjärvi and Rapasaaret varies between 0.00 and 1.26 (wt%), while the iron content is 0.0–0.28 wt% FeO.

K-feldspar
The average normative K-feldspar ($KAlSi_3O_8$) content of the Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites is 15, 16 and 9.5 (wt%), respectively. The potassium feldspar is usually perthitic and grey or slightly reddish, and sometimes up to 5 cm in length. The abundance of K-feldspar increases sometimes from the Li-rich core zone of the dyke to the wall rock contact point (Fig. 8). K-feldspar from 25 grains from 17 separate thin sections was analysed. The K_2O content was determined to vary between 14.52 and 16.53 (wt%), while the iron content varies from 0.01–0.58 wt% FeO.

Quartz
The average normative quartz (SiO_2) content in the Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites is 28, 27 and 26 (wt%), respectively. The quartz occurs as greyish, sometimes light brownish (smoky quartz) 0.5–1 cm crystals. The microprobe analyses revealed that quartz occurs as a geochemically pure mineral. The average iron content of quartz was 100 ppm in nine analysed quartz grains from Rapasaaret. In Leviäkangas and Syväjärvi, the iron content of quartz was below the detection limits, 176 ppm and 164 ppm.

Table 6. Selected microprobe analyses of the Nb-Ta oxide grains from Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites.

Deposit	Leviäkangas			Syväjärvi			Rapasaaret	
Hole ID	R9/80	R9/80	R9/80	R443	R443	R443	R2	R6
Depth	174.50 - 176.50	174.50 - 176.50	174.50 - 176.50	62.15-64.15	62.15-64.15	62.15-64.15	136.00	69.40
Index #	12072.08-12073.08	12082.08-12083.08	12106.08-12107.08	12036.08-12037.08	12056.08-12057.08	12070.08-12071.08	5300.11-5302.11	5298.11-5299.11
SiO_2							0.00	0.00
TiO	0.26	0.31	0.16	0.79	0.82	0.57	0.32	0.50
Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	7.59	6.69	6.33	8.11	7.26	7.36	4.01	12.32
MnO	11.77	10.69	12.34	7.73	8.57	8.53	15.20	7.56
MgO	0.02	0.00	0.00	0.02	0.02	0.02	0.00	0.06
CaO	0.02	0.01	0.02	0.00	0.04	0.01	0.01	0.00
SnO	0.01	0.11	0.00	0.03	0.09	0.20		
Na_2O							0.00	0.00
Nb	60.41	37.19	50.05	19.05	19.13	17.48	48.57	58.55
Ta	19.70	44.16	30.34	62.37	61.02	64.49	31.27	21.04
Ce_2O_3							0.05	0.08
WO_3							0.06	0.43
ThO_2							0.00	0.00
PbO							0.00	0.00
P_2O_5							0.01	0.04
F							0.01	0.05
Total	99.76	99.15	99.25	98.09	96.95	98.66	99.52	100.64

Muscovite
The average normative muscovite ($KAl_2AL-Si_3O_{10}(OH)_2$) content in Leviäkangas, Syväjärvi and Rapasaaret is 6–7 wt%. The muscovite of the studied pegmatites appears flaky, ranging from colourless to silvery-greenish aggregates, and is generally associated with or replaces spodumene.

Other minerals
The typical phases of the accessory minerals present in spodumene pegmatites in Leviäkangas, Syväjärvi and Rapasaaret are andalusite, apatite (fluorapatite), arsenopyrite, beryl, calcite, cassiterite, chlorite, cookeite (Li chlorite), fluorite, garnet (almandine and grossular), graphite, Mn-Fe phosphate, montebrasite (Li phosphate), Nb-Ta oxides, pyrite, pyrrhotite, sphalerite, tourmaline (schorl), zeolite and zinnwaldite (Li silicate).

Fluorapatite is the most abundant phosphate. Garnet is sometimes present and occurs as orange-red grains within albite-rich zones.

Nb-Ta-oxides
The average Nb and Ta content of the Leviäkangas, Syväjärvi and Rapasaaret spodumene pegmatites varies between 36–87 ppm Nb_2O_5 and 26–72 ppm Ta_2O_5. The range of Nb and Ta contents in whole-rock analyses varies between 11–312 ppm Nb_2O_5 and 3–547 ppm Ta_2O_5 in the studied pegmatites. In total, 45 Nb-Ta oxide grains were analysed with a microprobe (Table 6). Both Nb and Ta are mostly carried by Mn-columbite in Leviäkangas, Fe- and Mn-tantalite in Syväjärvi (Al-Ani et al. 2008b) and Fe- and Mn-columbite in Rapasaaret (Kuusela et al. 2011). The highest Nb and Ta contents occur within the most albite-rich zones. The grain sizes of Nb-Ta oxides in Kaustinen area are small, about 0.2–2 mm (Fig. 11).

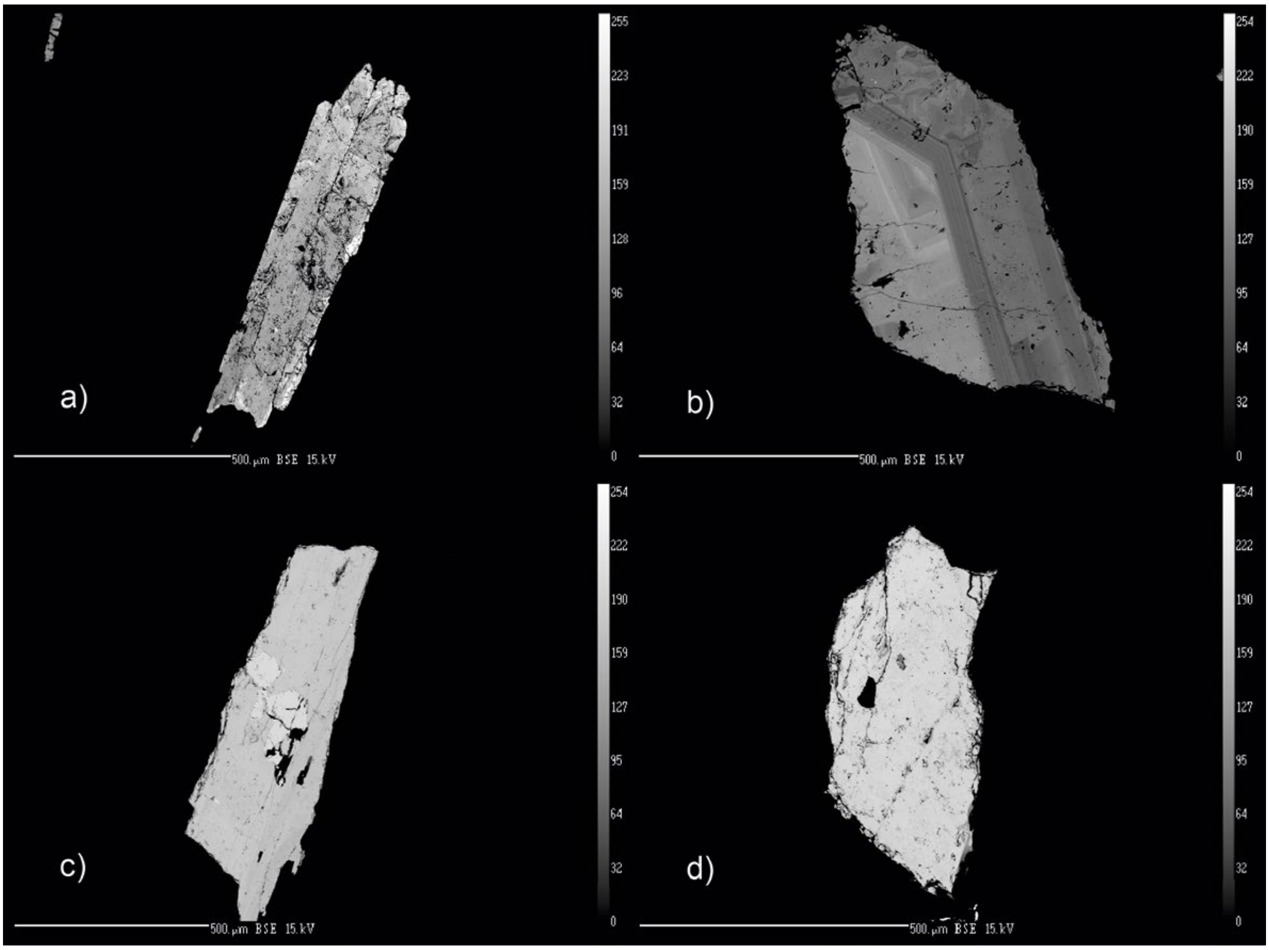


Fig. 11. BSE images of the Nb-Ta oxides of the Kaustinen area: a) a tabular crystal of Mn-columbite of Leviäkangas spodumene pegmatite; b) zoned Mn-columbite crystal of Leviäkangas. Darker rims are Nb-rich and lighter ones Ta-rich (Al-Ani et al. 2008b); c) Mn-tantalite and d) Fe-tantalite (Al-Ani et al. 2008b) of the Syväjärvi spodumene pegmatite (SEM images T. Al-Ani).

5 MINERAL RESOURCES

3D modelling and a preliminary mineral resource assessment were carried out for the Leviäkangas, Syväjärvi and Rapasaaret deposits (Fig. 12) by Koistinen et al. (2010a, b and 2011). Modelling was carried out in two stages for each deposit: first, by solid modelling using conventional sectional geological outlining of the mineralized bodies as 3D rings, and second, by block modelling inside the solid model.

The intersections of the mineralized rock in each section were first studied by compositing the assays to prepare the solid model of the mineralisation. The outlines of the mineral deposits were interpreted at each section and, consequently, the interpretations were connected to form the 3D solids.

For a more detailed mineral resource assessment using the block modelling method, the deposits and their surroundings were divided into 2 x 2 x 2 m^3 blocks. The average grades for each block were interpolated by the inverse distance method. The drill core assays were weighted using the inverse of the square of the distance (ID2).

Topographic and bedrock surfaces were modelled using diamond-drillhole survey data and a Laplace interpolation method (Gemcom GEMS). Elevations of the surfaces are less reliable farther from the positions of the drill collars.

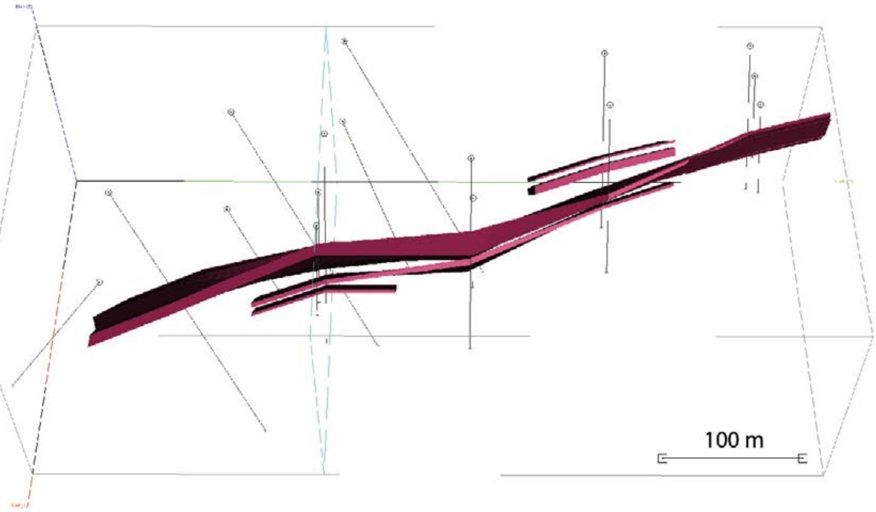
The tonnages for Leviäkangas, Syväjärvi and Rapasaaret deposits based on solid modelling and block modelling are summarized in Table 7. It is noteworthy that the resource (and reserve) assessments of the spodumene pegmatite dykes are currently under re-assessment by the current holder of the exploration and mining permits.

Based on the re-assaying of the previously collected till samples, the size of the Li province of the Kaustinen area might be even larger than previously thought. Confirmation of this needs further exploration activities in the area.

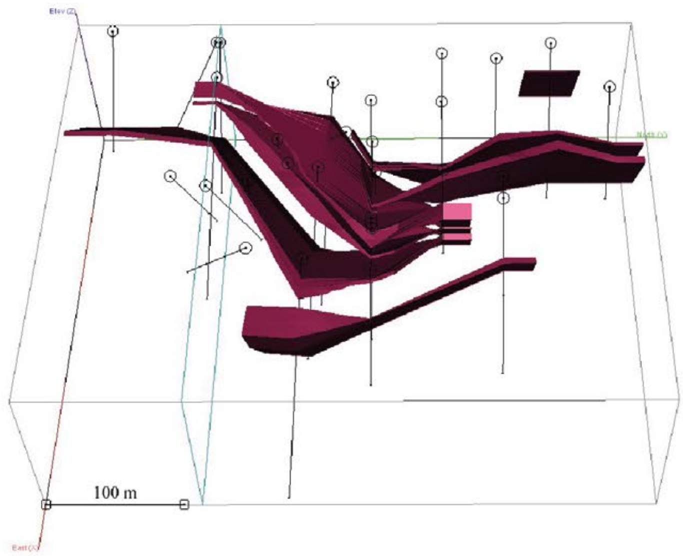
Table 7. Mineral resources of the Leviäkangas, Syväjärvi and Rapasaaret deposits based on solid and block modelling according to Koistinen et al. (2010a, b and 2011).

Deposit	Cut off	Solid model		Block model		Reference
	Li_2O wt%	Tonnage Mt	Li_2O wt%	Tonnage Mt	Li_2O wt%	
Leviäkangas	0.0	2.1	0.7	2.1	0.85	Koistinen et al. 2010a
Syväjärvi	0.0	2.6	0.98	2.6	0.78	Koistinen et al. 2010b
Rapasaaret	0.0	3.7	1.02			Koistinen et al. 2011
	0.2			3.0	1.17	
Total		8.4		7.7		

a)



b)



c)

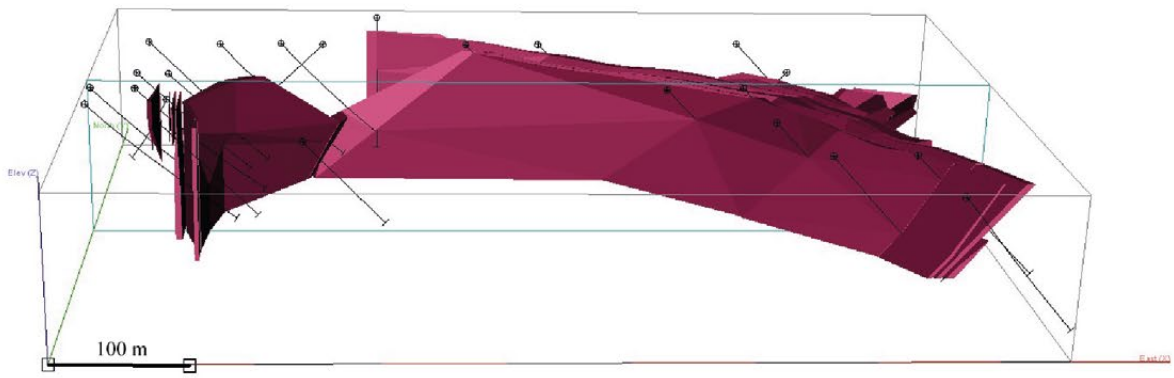


Fig. 12. 3D solid models of the Leviäkangas (a), Syväjärvi (b) and Rapasaaret deposits (c). Syväjärvi and Leviäkangas are viewed from the east and Rapasaaret from the south.

6 LITHIUM POTENTIAL IN THE KAUSTINEN AREA BASED ON REGIONAL TILL GEOCHEMISTRY

A regional distribution map of Li in till geochemistry is presented in Figure 13. A part of the known Li deposits and occurences (Leviäkangas, Rapasaaret, Jänislampi, Emmes) are well reflected in the till geochemistry, whereas Outovesi, Syväjärvi and Läntä deposits do not show as well. The results indicate that outside the lithium province (Läntä-Vintturi-Emmes area), there are many areas with high Li contents in till. The largest anomalous area locates NW of the Jänislampi-Emmes area. In particular, the Kaitfors-Rasmus region and the area around Rita village have high potential. The same areas also show some high Be contents in till. In the area of Alikylä-Emmes, Tunkkari-Kortjärvi and Liedes, there are Li anomalies that might relate to an unknown Li pegmatite.

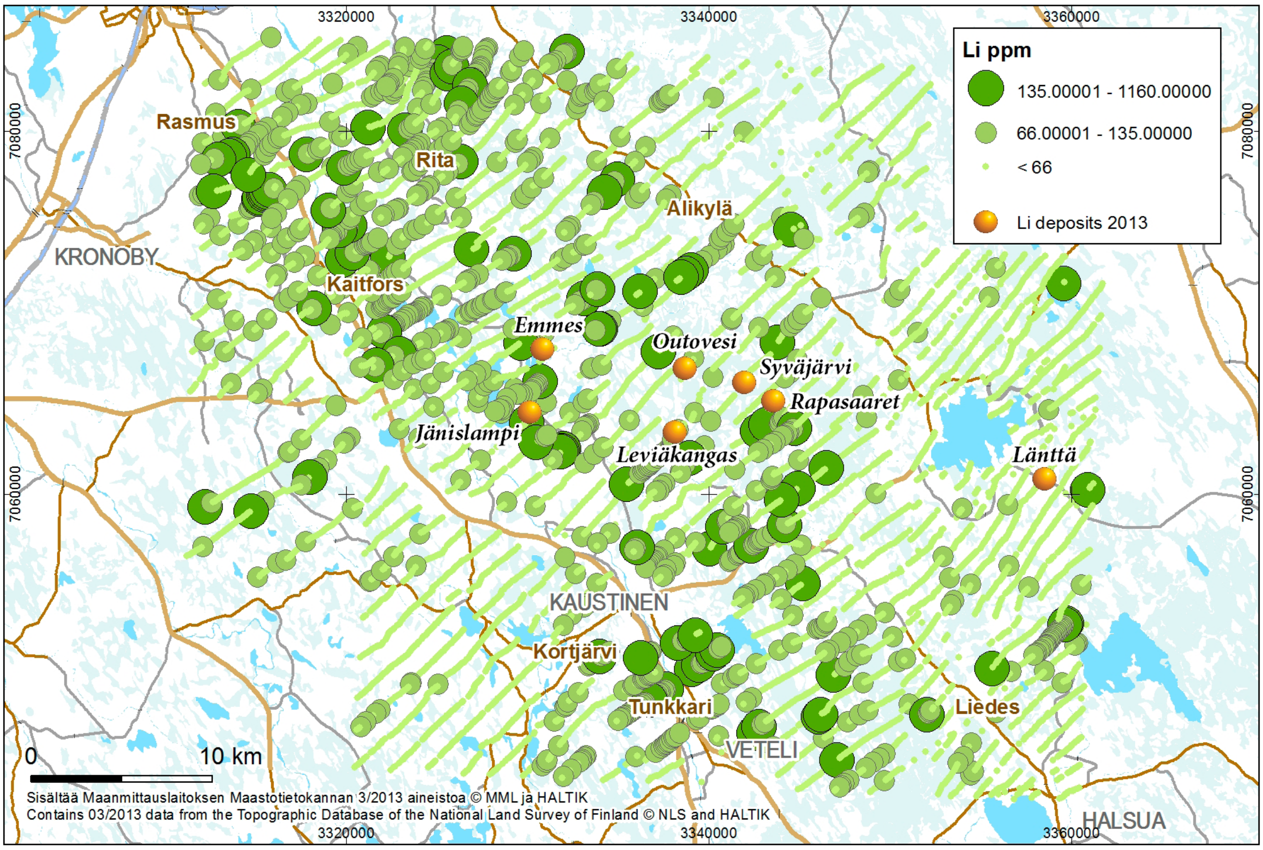


Fig. 13. Regional distribution of Li in till and the locations of known Li deposits. The glacial flow direction at Kaustinen is from NW to SE, about 150°–160°.

7 ENVIRONMENTAL ASPECTS

The study areas are located outside of settled areas. Päiväneva and Rapasaaret are partly located in peat production areas. The studied areas do not overlap with either conservation areas or valuable bedrock areas (Fig. 14). The closest conservation area is the Vionneva protected area (FI1000019), which belongs to the EU Natura 2000 network of protected areas. The Rapasaaret Li pegmatite is about 700 metres west of Vionneva. There are no documented important sand or gravel aquifers in the claim areas, which could have importance for the local water supply. The Quaternary deposits in the study areas and their surroundings mainly consist of peat and till. Detailed environmental statements on the Leviäkangas, Syväjärvi and Rapasaaret Li pegmatites are presented in Ahtola et al. (2010a, b) and Hatakka & Kuusela (2011), respectively.

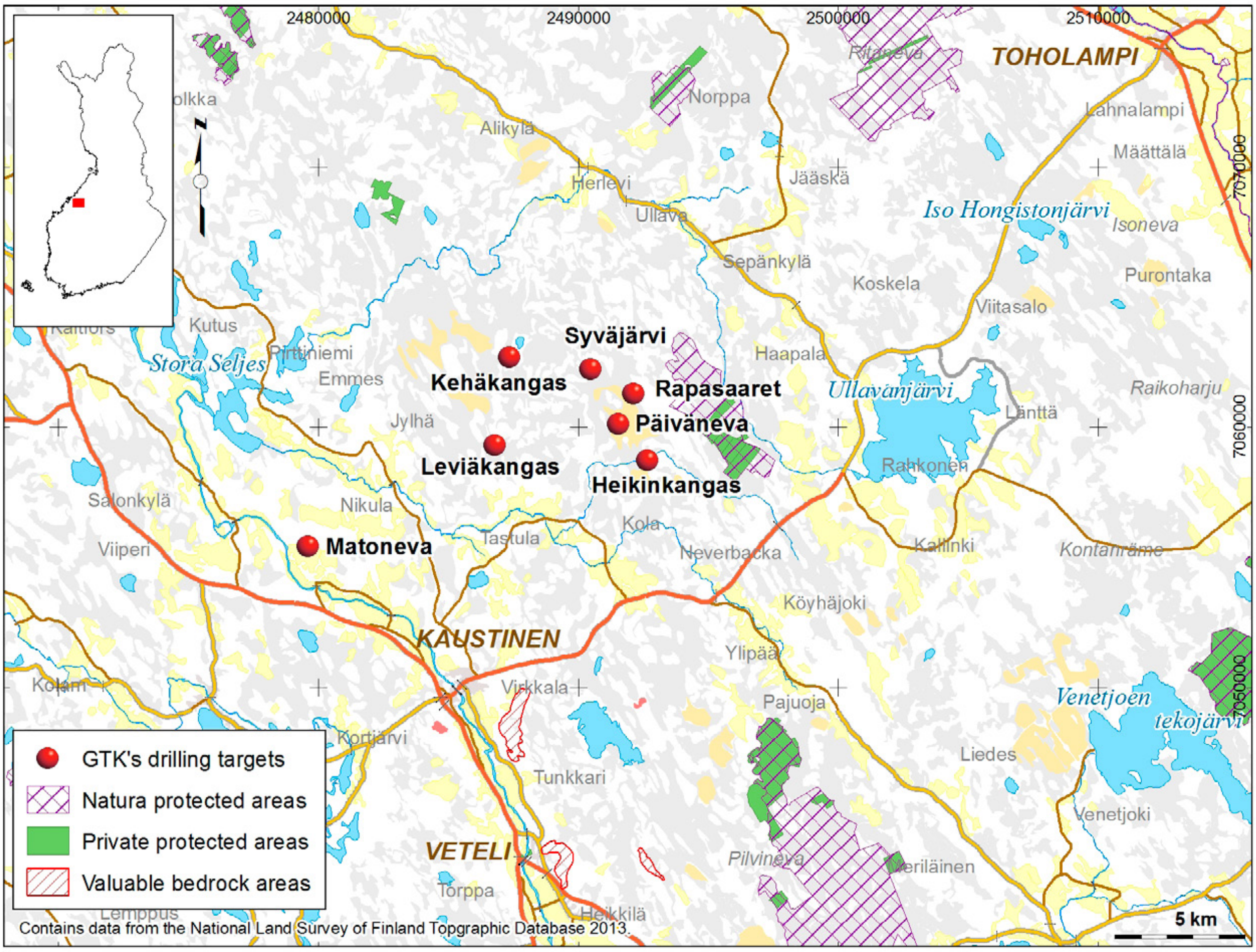


Fig. 14. The location of the drilling targets of GTK, protected areas and valuable bedrock areas in the Kaustinen region.

8 DISCUSSION AND CONCLUSIONS

The studied pegmatites in Leviäkangas, Syväjärvi, Rapasaaret, Päiväneva, Matoneva and Heikinkangas geochemically differ very little from each other. As noted earlier, the spodumene pegmatites are mineralogically and texturally similar. The studied pegmatites also resemble each other geochemically, but some minor differences exist. The only variation in the average major element concentration is in the Päiväneva pegmatites, with a higher MgO and Fe_2O_3 content (Table 3) that most probably originates from the surrounding host rock material within the pegmatite. The major trace element Li_2O has some variation in all six deposits. The average Li_2O concentration of the deposits varies from 0.65% to 1.18%, with the exception of 0.2% in Matoneva. In the average concentrations of selected trace elements, Ta_2O_5, Nb_2O_5 and BeO, there is no marked variation, except in the Rapasaaret BeO content, which is nearly three times higher (502 ppm BeO) than in the other deposits (Table 4). There is local variation in trace elements, but the increased amount of differentiation is mostly visible in the content of the trace elements Ta_2O_5, Nb_2O_5 and BeO that seems to decrease in the dykes core zone (with Na_2O and K_2O) where the Li_2O increases (Figure 8).

Despite not having the U-Pb age determinations to compare the ages between the dykes, we consider it likely that all the studied dykes are of the same age due to similarities in the mineralogy, geochemistry and geological environment of emplacement. Martikainen (2012) has proposed that based on the fertility of the granitoid plutons in the area, the Kaustinen pegmatite granite (Fig. 2) could be the most probable candidate for the source of the melts now forming the spodumene pegmatites. To confirm this hypothesis, new accurate age determinations would be needed from the dykes and potential source granitoids of the area.

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Global lithium consumption has increased throughout the 2000s. The demand for lithium is predicted to grow particularly in the battery industry. One of the main targets of the industrial mineral mapping projects by the Geological Survey of Finland (GTK) during 2003–2012 was to evaluate the Li (Ta, Nb, Be) potential and to discover new resources in the previously known Kaustinen spodumene pegmatite region. None of the studied spodumene pegmatites are exposed. Therefore, the fieldwork mainly consisted of tracing boulders, which are the only visible evidence of the lithium pegmatites in the field. In total, GTK carried out 15.5 line km and 4.4 km^2 of ground geophysical surveys, 17 km of diamond drilling, and collected 60 RC drilling samples and 748 percussion drilling samples in seven different exploration areas during 2004–2011. GTK also re-analysed 9,658 old regional till samples collected in the 1970s. Li pegmatites in the Kaustinen region are texturally and mineralogically similar and belong to the albite-spodumene subgroup of the LCT (Li, Cs, Ta) pegmatite family according to Černý et al. (2005). As a result of mapping of the Li potential in Kaustinen, four new spodumene pegmatites (Matoneva, Päiväneva, Heikinkangas and Rapasaaret) were discovered. In addition, the knowledge of the mineral resources of the previously known Leviäkangas and Syväjärvi deposits were improved. In total, Li potential mapping by GTK increased the known Li-pegmatite resources by about 8 Mt. According to the results from the re-assaying of old till samples, the size of the Li region in Kaustinen is even larger than previously thought. There are areas with a high Li content in till that have considerable potential for new discoveries on the northwest and southeast sides of the known deposits. The Kaustinen region is the most potential area for Li mineralisation in Finland, but also a significant Li province in the EU.

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