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Battery mineral investigations in the Ostrobothnian Schist Belt, Western Finland, 2019–2022

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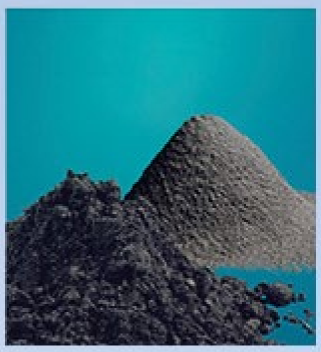
GTK Open File Research Report 11/2024



GTK

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Unless otherwise indicated, the figures have been prepared by the authors of the report.

Front cover: New battery mineral discoveries from Central and Southern Ostrobothnia 2019–2022: Clockvise starting from upper left: Semimassive Ni–Co–Au mineralisation, Outcropping spodumene pegmatite (Li), Flake graphite and Montebrasite–Amblygonite (Li).
Photo: Janne Kuusela and Thair Al-Ani, GTK.

Layout: Elvi Turtiainen Oy

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A four-year battery mineral project executed by GTK in the Raisjoki research area in Western Finland resulted in the discovery of several new battery mineral occurrences. Additional investigations for lithium were executed in the Saarala and Lapua–Kuortane areas. The key geological components linking the discoveries of lithium–graphite–nickel–cobalt mineralizations are the metavolcanic sequences that crosscut the central and southern Ostrobothnian region. Additionally, several indications from the entire Raisjoki research area display potential for Au.

Two new spodumene pegmatite dykes were discovered in the Dragbacken area, with the main dyke having a strike length of 310 m and a maximum width of 5.8 m, with a 4.7-m intersection of 0.84% Li_2O due to the upper detection limit of the assay method. In Lapua–Kuortane, an LCT pegmatite containing montebrasite–amblygonite was discovered. The length and width of this new outcropping pegmatite is open. The graphite-rich black schists have anomalously high Ni and Co concentrations in all the investigated targets in the Raisjoki area, which may be due to the structural trapping of concentrate in semi-massive bodies, such as in the Emas target, reaching local concentrations of 10.5 m at 0.11% Co and 0.8% Ni. Other indications of such mineralisations include layman boulder data, with several high-content Ni–Co boulders in the research area. Cobalt is distributed in cobaltite, gersdorffite, cobalt pentlandite, Co-rich arsenopyrite, pyrrhotite, and pyrite. The sulfide mineralization zone is located within a 15-m-wide alteration zone, where the Co content varies between 100–200 ppm. The graphite beds in Raisjoki and Emas had several 10–15-m sections with average graphite concentrations of >7%. In Kaitåsen, the graphite content in a 20-m section reached a median of 4.4% graphitic carbon. In a first-stage quality assessment, the Emas and Raisjoki graphite had a measured flake size of 30–200 µm.

Due to the high flaky graphite content, samples from Emas and Raisjoki were sent for bench-scale testing at Mintec Outokumpu. The tests involved crushing, grinding, flotation, and purification by alkaline roasting and acid leaching. Using ultrafine grinding before three flotation stages proved the most efficient, giving a concentrate with 89% purity and 66.2% recovery. After the purification process, a Cg grade of >99% was achieved.

In the Raisjoki investigation area, six targets were chosen for closer study, including Emas, Dragbacken, Kaitåsen, Raisjoki, Kedonkangas, and Sammaloja in Kruunupyy, Evijärvi, and Veteli. In Lapua–Kuortane, investigations were delimited to the Kurjenneva and Pikkalantausta targets. All areas except Sammaloja, Kedonkangas, and Kurjenneva underwent geophysical ground measurements, including magnetic and multi-frequency electromagnetic (EM) methods, and in Emas, gravity measurements were additionally undertaken. Before geophysical ground measurements in the Raisjoki area, airborne geophysical data on EM, magnetic and radiometric maps were combined using a fuzzy logic method as an aid to target selection.

Percussion drill sampling, totaling 478 samples, was undertaken in the Sammaloja and Dragbacken targets, and various surface geochemistry sampling techniques were applied in Dragbacken and Emas on a total of 635 samples to direct diamond drilling. Geological mapping with a special focus on LCT pegmatites was performed in the Raisjoki study area and Lapua–Kuortane. Diamond drilling was executed in all targets except Sammaloja, Lapua–Kuortane, and Saarala, comprising a total of 39 drill holes and 4180 m.

Keywords: battery minerals, potential deposits, bedrock, mapping, mineral exploration, geochemistry, geophysics, beneficiation, drilling, pegmatite, graphite, lithium, cobalt, nickel, gold

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GTK on tutkinut Pohjanmaan liuskevyöhykkellä sijaitsevien Ahon ja Raisjoen vulkaanisia jaksoja vuonna 2019 alkaneessa nelivuotisessa akkumineraaliprojektissa. Tutkimusten päätavoitteena oli arvioida koboltin, nikkelin, litiumin sekä luonnongrafiitin potentiaalia noin 900 km^2:n kokoisella alueella, ns. Raisjoen tutkimusalueella. Tämän lisäksi GTK suoritti litiumtutkimuksia myös Kokkolan Saaralassa sekä Lapuan ja Kuortaneen alueilla. Raisjoen tutkimusalueen pohjoispäässä GTK löysi Dragbackenin kohteessa uuden spodumeenipegmatiittiesiintymän, joka lävistettiin timanttikairauksin kolmella lävistyksellä. Spodumeenipegmatiittijuonen pituus on noin 310 m ja lävistyksien paksuudet ovat 1–6 m. Paras lävistys on noin 5,8 m leveä ja sen Li_2O-pitoisuus 4,7 m:n matkalta on 0,84 %. Lapua-Kuortaneella löydettiin uusi montebrasiitti-amblygoniittia sisältävä pegmatiittijuoni, jonka pituus ja leveys on vielä avoin. Tämän lisäksi GTK löysi mineralogisten laatuselvitysten sekä rikastuskoetuloksien vahvistamana kaksi uutta suomugrafiittiesiintymää Emaksen ja Raisjoen kohteissa. Emaksen sekä Raisjoen kohteissa on paikoin 10–15 m:n grafiittiosueita, joiden grafiittipitoisuudet ovat > 7 %. Kaitåsenin kohteessa grafiittipitoisuus on 20 m:n matkalla keskimäärin 4,4 %. Emaksen kahden grafiittipitoisen vyöhykkeen välistä löytyi paikallinen Ni–Co–Au-mineralisaatio, jossa 10,5 m:n matkalla on 0,11 % Co ja 0,8 % Ni sekä 2 m:n matkalla 0,34 ppm Au. Kiisumineralisaation päämineraalit tunnistettiin gersdorfiitiksi, Co-arsenopyriitiksi, cobaltiitiksi sekä pentlandiitiksi. Kiisumineralisaatio sijaitsee n. 15 m leveässä muuttumisvyöhykkeessä, jonka selvästi anomaalinen Co-pitoisuus vaihtelee 100 ja 200 ppm välillä.

Mineralogisessa laatuselvityksessä todettiin sekä Emaksen että Raisjoen grafiitin suomukoon olevan 30–200 µm, minkä vuoksi näytteitä lähetettiin rikastuskokeisiin GTK:n Mintec Outokumpuun. Rikastusprosessi sisälsi murskauksen, jauhatuksen, vaahdotuksen sekä rikasteen puhdistamisen pasutuksella ja happoliuotuksella. Ultrahienolla jauhatuksella ennen kolmea vaahdotusvaihetta saatiin (Cg) 89 %:n puhtausasteen rikaste 66,2 %:n saannilla Emaksen näytteistä. Raisjoen näytteissä vastaava tulos oli 87,5 %:n puhtaus sekä 48,2 %:n saanti. Pasutuksen ja liuotuksen jälkeen rikasteen puhtausaste ylitti 99 % molemmissa näytekannoissa.

Raisjoen tutkimusalueeseen valittiin kuusi kohdetta lisätutkimuksia varten. Nämä kohteet ovat Emas, Dragbacken, Kaitåsen, Raisjoki, Kedonkangas ja Sammaloja, jotka sijaitseva Evijärven ja Vetelin ja Kruunupyyn kunnissa. Lapua-Kuortaneen alueella lisätutkimuksia varten seuloutuivat Kurjennevan ja Pikkalantaustan alueet. Kaikissa kohteissa paitsi Kedonkankaalla, Sammalojalla sekä Kurjennevalla tehtiin geofysikaalisia mittauksia, johon sisältyi sähkönjohtavuus- ja magneettisuusmittauksia. Emaksessa tehtiin löydetyn kiisumineralisaation vuoksi myös painovoimamittauksia. Ennen geofysikaalisia maastomittauksia Raisjoen tutkimusalueen lentogeofysikaalista aineistoa mallinnettiin sumealla logiikalla tavoitteena tunnistaa potentiaalisia alueita Ni–Co-esiintymien suhteen. Kohdevalinnoissa hyödynnettiin myös vanhaa GTK:n linjamoreeniaineistoa.

Koneellisia iskuporanäytteitä otettiin sekä Sammalojan että Dragbackenin kohteissa yhteensä 478 kpl. Tulevien timanttikairausten kohdistamiseen otettiin pintanäytteitä pääosin B-horisontista eri menetelmin Dragbackenin ja Emaksen kohteissa yhteensä 635 kpl. Geologista kartoitusta tehtiin Raisjoen sekä Lapua-Kuortaneen sekä Saaralan tutkimusalueilla, ja palanäytteitä pääosin lohkarehavainnoista analysoitiin Raisjoen alueelta yhteensä 310 kpl. Timanttikairausta tehtiin kaikissa muissa kohteissa paitsi Sammalojassa, Saaralassa sekä Lapua-Kuortaneella yhteensä 39 reikää ja 4 180 m.

Asiasanat: akkumineraalit, potentiaaliset esiintymät, kallioperä, kartoitus, malminetsintä, geokemia, geofysiikka, rikastus, kairaus, pegmatiitti, grafiitti, litium, koboltti, nikkeli, kulta

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CONTENTS

1 INTRODUCTION

The Ostrobothnian schist belt (OSB) in Western Finland is known for its LCT pegmatites. The region can be divided into two main pegmatite areas, the Kaustinen and Seinäjoki areas, which have received the attention of many authors (Mäkitie 2001, Alviola et al. 2001, Vaarma & Pipping 1997), as well as exploration and mining companies. The Raisjoki area is a part of N–S-trending volcanic sequences best known for their relation to the spodumene-bearing LCT pegmatites in the Kaustinen, Veteli, and Seinäjoki regions (Mäkitie 2001, Ahtola et al. 2015).

The Raisjoki study area is located in the region of Ostrobothnia, Central Ostrobothnia and South Ostrobothnia in the municipalities of Kruunupyy, Evijärvi, Kaustinen, and Veteli. (Fig. 1). The closest town, Kokkola, is 40 km to the NW and has a port and railway connection. A restoration project in the River Raisjoki revealed sulfide-rich boulders and became a popular site for layman sampling in the 1960s. Some of the samples have displayed an exceptionally high content of Cu, Ni, and Co, which led to the execution of several later geophysical and geological investigation programs in the 1970s and 1980s (Lindmark 1978, Ruskeeniemi 1988, Sipilä 1989).

Within the framework of a new four-year battery mineral project starting in 2019, the Geological Survey of Finland reactivated investigations at the site (Kuusela et al. 2020, Al-Ani et al. 2020). The Raisjoki belt was also investigated in Sammaloja (Hulkki 2022) and the Aho Belt in Emas (Kuusela et al. 2022), Kaitåsen (Nygård & Kuusela 2021), Dragbacken (Nygård et al. 2023), and Kedonkangas (Kuusela et al. 2023). Additional lithium investigations were performed in Saarala (Wik et al. 2020) and during the latter half of the project in Lapua–Kuortane (Nygård et al. 2024). During the active investigations, GTK was granted reservation notifications covering all the targets. This report summarizes the investigations performed in the Raisjoki, Saarala, and Lapua–Kuortane investigation areas.

2 REGIONAL GEOLOGY

The study area is a part of the OSB, composed of supracrustal rocks. Based on an analysis of detrital zircons, Lahtinen et al. (2017) have proposed a maximum deposition age of 1.92–1.91 Ga for this stratigraphic unit. The region is a part of the Svecofennian accretionary arc complex (Nironen 1997) and underwent at least four deformation phases (Vaarma & Pipping 1997) during the Svecofennian orogeny, which took place from 1.92–1.77 Ga. The gneissose Pohjanmaa greywacke and mica schists belonging to the Lappfors and Pirttikylä suits are separated by a N–S-trending metavolcanic sequence, the Aho belt, which has a neighboring similar trending volcanic sequence, the Raisjoki belt, 5 km towards the east in the Pirttikylä Suite (Fig. 1). Along with the volcanic rocks are horizons of black schists and skarn-altered rock sequences with thin mafic and intermediate tuffite layers (Vaarma & Kähkönen 1994). Towards the NE is the oval-shaped Veteli granodiorite, and further to the NE, bordering the Central Finland Granite Complex (CFGC), are stocks of pegmatitic granites belonging to the Seinäjoki granitic pegmatites. West of the OSB is the Vaasa migmatite complex (VMC). The grade of metamorphism in the OSB rises from east to west/southwest. The bedrock in the OSB was strongly deformed during the 1860 Ma orogeneses of the Svecofennian bedrock, being thrusted into the CFGC. The north–south-trending volcanic belt, together with the black schists, acted as a regional overthrust and slip/fault zone (Vaarma & Pipping 1997). The black schists are fine-grained pelitic sulfidic graphite schists, and the graphite content varies between 3–12%. In some places, the black schist sequences may contain tremolite skarn pods and volcanic tuff interlayers a few meters wide (Vaarma & Pipping 1997).

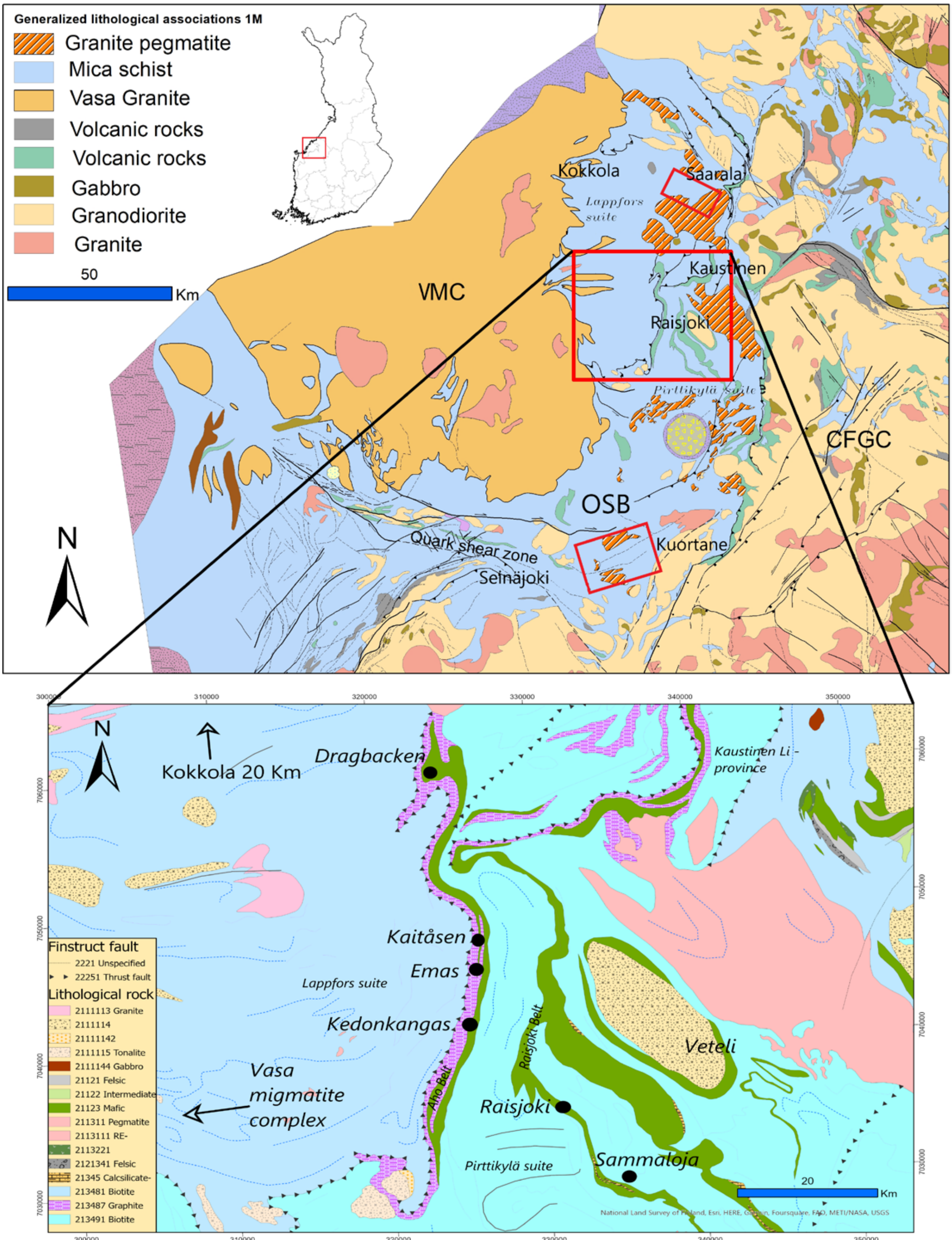

Fig. 1. A regional geological map of the research areas denoted by red squares (above) and a camp-scale geological map with investigation target locations in the Raisjoki area marked with black dots. (Bedrock of Finland scale-free © Geological Survey of Finland 2022).

3 RESEARCH METHODS

Data from GTK databases was gathered for the Raisjoki, Saarala, and Lapua–Kuortane investigations, covering airborne geophysics and line moraine data for target generation purposes. The Raisjoki target, with a multitude of layman samples displaying anomalous Ni–Co contents (Lindmark 1978), was used as a geophysical reference point from which radiometric, conductive, and magnetic airborne geophysical data were projected in a fuzzy logic-based model, aiming to locate similar areas along the metavolcanic sequences in the study area (Kuusela et al. 2019). The combination of boulder data and structural interpretation in the Raisjoki area with this prospectivity model resulted in four chosen targets, Emas, Kaitåsen, Haltas, and Kedonkangas, where ground geophysical measurements would be directed. The Sammaloja target was delimited from a combination of structural and boulder data interpretation. The re-analyzed targeting till geochemistry sample data (Kontoniemi 2012) were reviewed, pointing out anomalous areas for Li and Co to the NE of the Dragbacken area and in Veteli (Li). The location of the Dragbacken aggregate rock quarry in the middle of the metavolcanic rock sequence, relatively close to the Co anomalous line moraine datapoint, made it an obvious sampling site, which eventually led to the discoveries of new spodumene pegmatite dykes (Nygård et al. 2023) and to Dragbacken becoming a new investigation site and one of the major till sampling sites for percussion drilling and surficial sampling. Due to the new Dragbacken discovery, boulder mapping became more focused on LCT pegmatites. The other major percussion drilling site was in Sammaloja. An extensive summary of all till sampling during the project is presented in Hulkki (2022). In the Haltas target, only geophysical ground measurements were performed, and the target was left uninvestigated due to the difficult terrain and the discoveries in Dragbacken and Emas. The sampling methods used for each target are summarized in Table 1, which also cites reports that provide a more detailed description of the investigations at each target. The drill core samples from the entire project are stored in the GTK drill core archive in Loppi.

Table 1. Research methods listed by target in the Raisjoki, Saarala, and Lapua–Kuortane research areas.

Target	Diamond drilling		Ground geophysics			Till sampling		Boulder sampling	Benefi-ciation tests	Report
	Drill holes	Total length (m)	Magnetic	Maxmin	Gravity	Percussion drill	Surface			
Dragbacken	16	1477	X			360	491	310		Nygård et al. 2023
Emas	10	1152	X	X	X		144		X	Kuusela et al. 2022
Raisjoki	4	472	X	X					X	Kuusela et al. 2021
Kaitåsen	5	618	X	X						Nygård et al. 2021
Kedon–kangas	4	460	*	*						Kuusela et al. 2023
Haltas			X	X						Kuusela et al. 2019
Sammaloja						118				Hulkki 2022
Lapua-Kuortane			X	X		X	X	X		Nygård et al. 2024
Saarala										Wik et al. 2020
Total	39	4179				478	635	310		
			* Previously done							

3.1 Assay methodology

After the first year (2019) of the project, GTK changed the supplier of laboratory services from Eurofinns Labtium to ALS Chemex, resulting in drill hole samples and till samples from different time periods in the project being analyzed with different method coding. Basically, all drill core, percussion drilling, and boulder sample analytics were performed in Eurofinns Labtium, except for the Dragbacken drill core and Lapua–Kuortane percussion drilling, surficial sampling, and boulder sampling (Nygård et al. 2023), which were carried out in the ALS Chemex laboratory. All the surficial till sample analyses, including ionic leach and modified aqua regia solution, were analyzed by ALS Chemex. A summary of the assay method coding is provided in Table 2. More detailed descriptions of the analysis methods used in each target can be found in the reports cited in Table 1.

Table 2. Assay methodology listed by sampling technique in the Raisjoki area.

Sampling method	Samples analyzed	Assay methodology	LAB	Sampling sites
Diamond drilling 2019	569	306PM	Eurofinns Labtium	Emas, Raisjoki, Kaitåsen, Kedonkangas
Diamond drilling 2021	234	CCP-PKG03 package	ALS Chemex	Dragbacken
Till sampling percussion drilling	576	515M, 515P, 515U	Eurofinns Labtium	Dragbacken, Sammaloja
Till sampling ionic leach	409	ME-MS23	ALS Chemex	Dragbacken
Till sampling modified aqua regia	226	ME-MS41W	ALS Chemex	Dragbacken, Emas
Boulder samples	310	306PM	Eurofinns Labtium	All targets
C analyses	255	811L	Eurofinns Labtium	Emas, Raisjoki, Kaitåsen, Kedonkangas

4 GEOPHYSICAL DATA

Airbourne geophysical data (Hautaniemi et al. 2005) were a vital parameter in the target generation procedure. The dataset consists of magnetic, frequency-domain electromagnetic (EM), and radiometric measurements. As most of the Co-rich boulders found in the Raisjoki study area originate from sulfide and graphite-rich schists, which are conductive and magnetic rocks, the fuzzy logic prospectivity modeling method was used to distinguish new potential areas. The previously investigated Raisjoki target (Lindmark 1979) was used as a reference for the fuzzy logic classification.

After combining the outcome of fuzzy logic modeling with existing boulder and targeting till geochemistry data, the Emas, Kaitåsen, Kedonkangas, Raisjoki, and Haltas targets were chosen for further investigations. The Dragbacken LCT pegmatite target was discovered later during the project. The geophysical ground measurements in Dragbacken, although not showing the pegmatites themselves, revealed the structural control of emplacement described in chapter 10.

The new ground surveys applied several geophysical methods, including gravity, magnetic, and electromagnetic (EM) ground profiles. Petrophysical drillhole logging was also conducted in intact drill holes, comprising magnetic, electrical conductivity, density, and the natural gamma ratio measurements (Kuusela et al. 2022, Nygård et al. 2023).

In Raisjoki, Kaitåsen, and Dragbacken, only magnetic and conductive ground measurements were performed. In Kedonkangas, preexisting ground measurement data from the 1980s were used. Area-wise, the greatest ground measurement efforts were focused on Dragbacken and Emas, in the latter of which gravity measurements were also performed.

Multiple magnetic anomalies can be observed in the survey area (Figs. 2, 3 and 4). The strongest anomalies relate to sulfide-bearing graphite paraschist and are probably caused by pyrrhotite. Magnetic susceptibility and the magnetic anomalies are related to the pyrrhotite, which may also carry remanent magnetization (not determined). The conductivity response is probably due to a combination of the graphite and sulfide minerals.

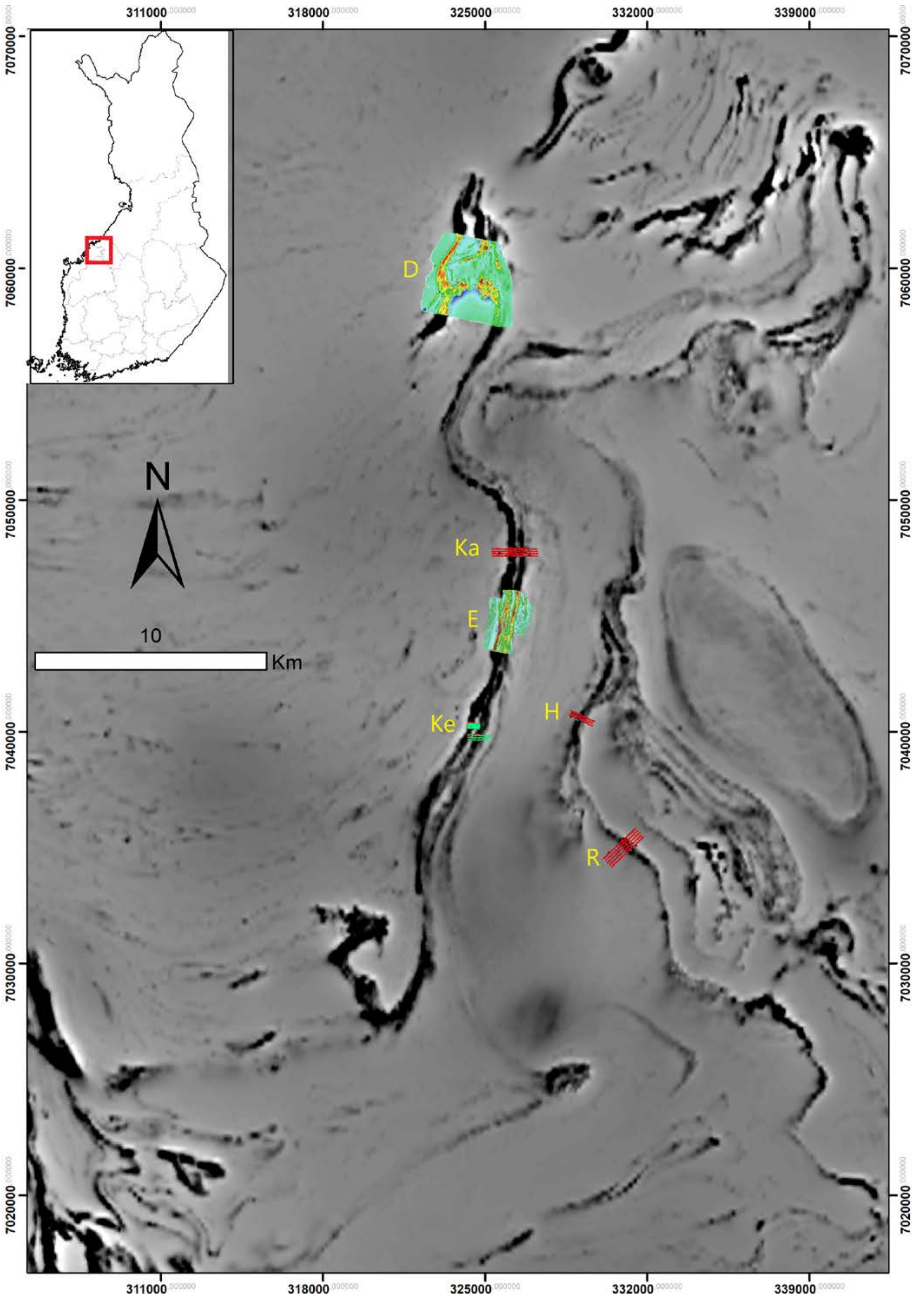

Fig. 2. Overview of the geophysical ground measurements performed in the Raisjoki study area. D = Dragbacken, Ka = Kaitåsen, E = Emas, Ke = Kedonkangas, H = Haltas, R = Raisjoki. An aeromagnetic map is used as background.

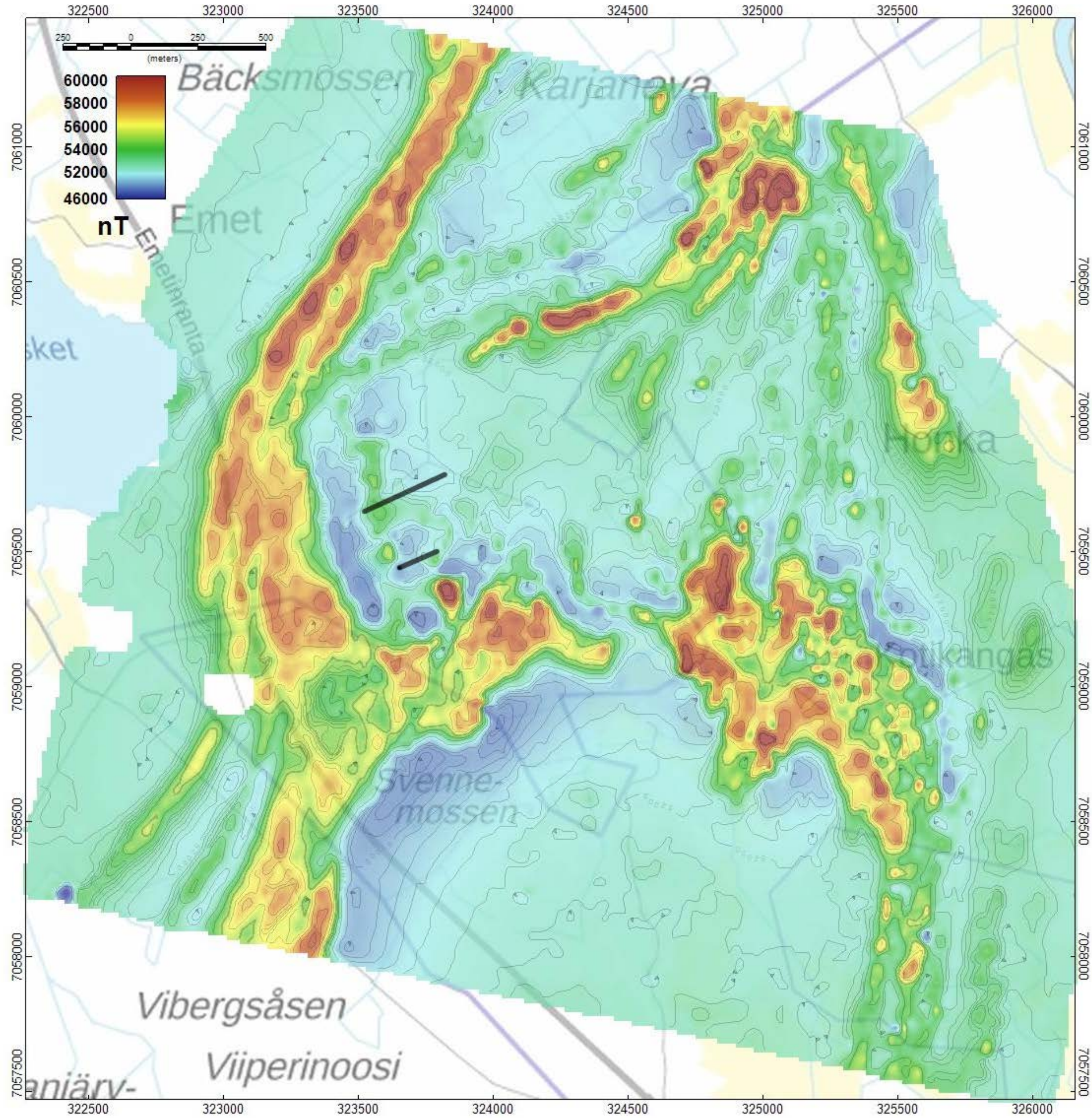

Fig. 3. Results of a magnetic ground survey, presenting magnetic components over the Dragbacken survey area. The approximate locations of the spodumene pegmatite dykes are indicated with black lines (Nygård et al. 2023).

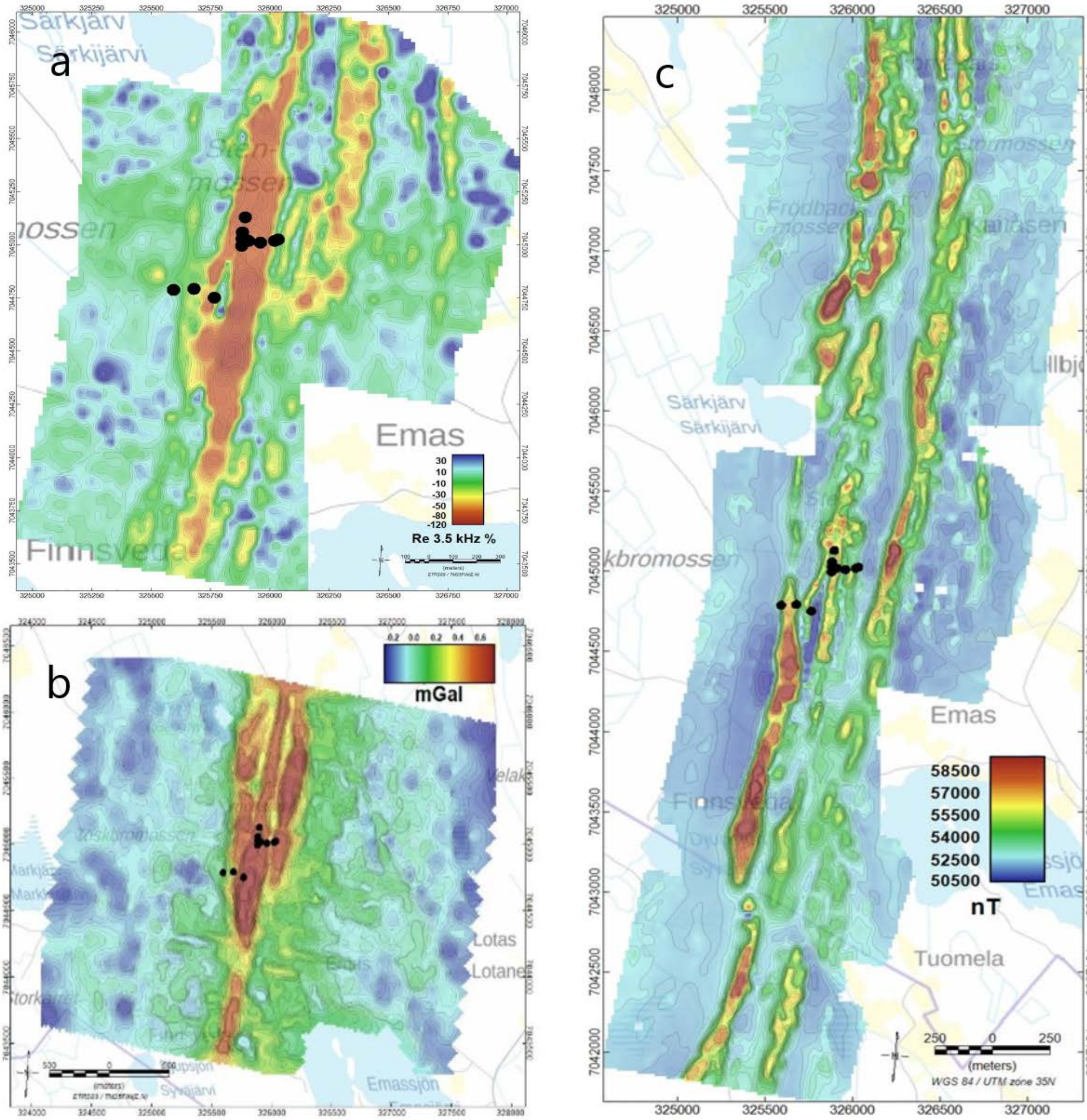

Fig. 4. Geophysical ground measurements performed with a) electromagnetic, b) gravimetric, and c) magnetic methods in Emas during 2019–2021. The black dots are diamond drill holes (Kuusela et al. 2022).

5 PEGMATITE BOULDER MAPPING

5.1 Methods

Few bedrock outcrops exist in the Raisjoki project area. Therefore, it was decided to focus on pegmatite boulder mapping during the field seasons of 2019 and 2020. The whole-rock assay of leuco pegmatitic boulders provides a good insight into the grade and amount of evolved pegmatites in the region. As a result, the LCT-pegmatite prospectivity potential of the area can be established.

The glaciated drumlin formations and the extensive peatlands make boulder tracing challenging. The drumlins usually consist of many surface boulders, but their origin may easily become uncertain, because the glacial movements have been quite large. In many cases, the boulders are quite rounded due to transportation and deposition in the elongated drumlins. The drumlins have an average axis trend of 324°. The Kruunupyy–Kaustinen area has two different glacial transportation directions (see chapter 6). The lower till bed has a direction from the west (270°), whereas the top layer has been transported from the northwest (330°). The boundary between the layers is usually sharp and lies at a depth of 2.0–3.3 m at several test sites (Iisalo 1992).

Altogether, 120 pegmatite boulder samples were collected and assayed for whole-rock geochemistry. The samples were assayed at Eurofins Labtium Oy with the methods 306M and 306P. The digestion method used was a strengthened four acid solution.

In some cases, the field sampling technique may introduce some data quality errors. Coarse-grained pegmatites require a large sample size for a representative bulk composition assay. For logistical reasons, the typical sample size was kept at approximately 20 x 20 cm.

A range of elements can be used to determine the differentiation grade of pegmatite samples. The Mg/Li ratio is a common and established indicator and performs well, since Mg decreases and Li increases as a magmatic system evolves. Whole-rock Mg/Li ratios of 0–10 are considered to indicate high, 10–20 medium, and 20–50 low differentiation. Values above 50 are barren pegmatites, while values below 1 would indicate extreme differentiation and a possible spodumene pegmatite (Selway et al. 2005).

Other indicators to consider are K/Rb, Al/Ga, K/Ba, Rb/Sr, and many of the lithophilic elements. The lithium value itself does not necessarily need to be high for a pegmatite to be highly fractionated. Samples from Dragbacken spodumene dykes display the lowest Li values of a few hundred ppm, depending on the sampled zone.

5.2 Results

The map in Figure 5 displays the locations of pegmatite samples collected throughout the Raisjoki project area. The label provides the Mg/Li value of the samples. Many localities besides the sample locations on the map were also visited where no samples were collected due to several reasons, the most common being the lack of representative leuco pegmatitic boulders to sample.

Most pegmatite boulders in the area are barren pegmatites. However, some boulders clearly originated from evolved or highly differentiated pegmatites. This could be determined visibly in the field, these being leuco pegmatites, usually with yellowish colored muscovite micas. The differentiation was further confirmed by whole rock chemical assay. The assay results from boulders with Mg/Li values of less than 10 are listed in Table 3.

During the Raisjoki mapping project, two spodumene dykes were discovered at Dragbacken, southeast of Lake Emetträsket. Samples from these dykes provided an opportunity to compare the elemental composition with the most evolved pegmatite boulders. The median values of 10 spodumene dyke samples assayed with the same analytical method as for the boulders are also presented in Table 3. For further comparison, the median values of each Mg/Li range for the boulder samples have also been calculated. More sample data are available in GTK's national database.

Noteworthy discoveries include a boulder from Skogsbyn with a similar elemental composition to that of the Dragbacken spodumene dykes. The boulder is located ca. 10 km southwest of Dragbacken and does not fit with the glacial transportation direction from this site. Other boulders, especially west of Lake Djupsjön, are also highly differentiated. This indicates that at least some highly differentiated pegmatite dykes exist several

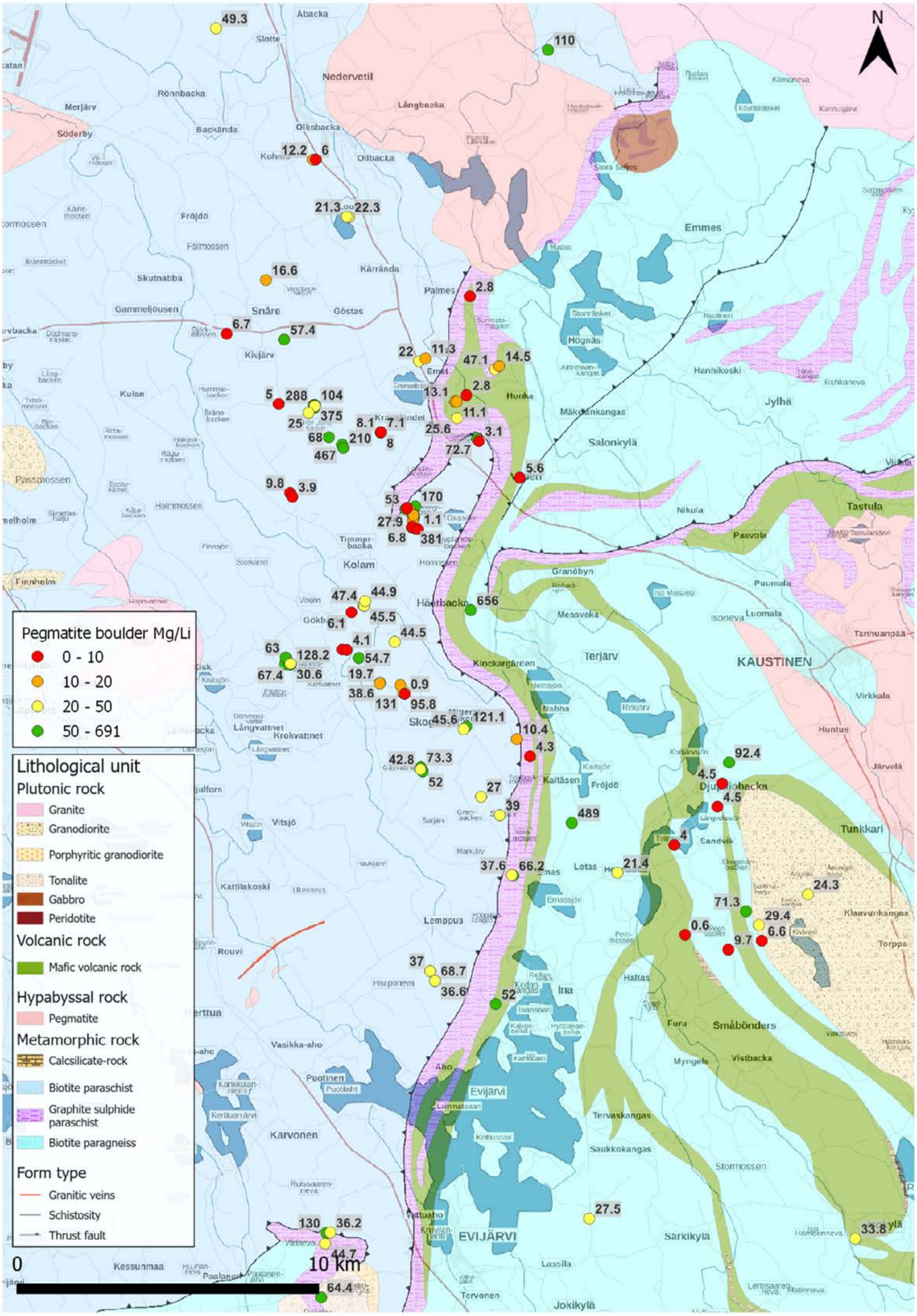

Fig. 5. Boulder map of the Raisjoki area with Mg/Li values that indicate the pegmatite boulder fertility grade. (Bedrock of Finland scale-free © Geological Survey of Finland 2022)

kilometers westwards from the northern part of the N–S-striking volcanic belt at Lake Emetträsket and Lake Djupsjön.

Further westward from these locations, the metamorphic grade gradually increases from low amphibolite facies to granulite facies going west towards the Vasa migmatite complex (Chopin et al. 2020). A higher metamorphic grade does not favor the formation of LCT pegmatites. To the west of Lake Emassjön and Lake Evijärvi, no highly differentiated boulders were found.

The area between Djupsjöbacka and Småbönders hosts a few highly differentiated boulders and appears prospective for LCT pegmatites. This area lies 5 km from the extensive Veteli pegmatite granite intrusion, which belongs to the 1.8 Ga post-tectonic S-type pegmatites considered to potentially be part of the spodumene dyke-creating system (Martikainen 2012). The area also has favorable fold structures and lithological contacts that may favor pathways for pegmatitic magma.

The eastern Terjärvi area around Rekjärv, Iso Miesvesi, Granöbyn, and Salonkylä does not favor boulder mapping due to extensive esker and peatlands and was therefore omitted from the mapped areas.

No boulders with visible lithium minerals were found. A couple of evolved boulders were found down-range of the known spodumene dykes at Dragbacken, but none with spodumene. This illustrates the difficulties of boulder mapping in glaciated drumlin terrain with extensive peatlands.

The mapping also determined that the bedrock of the area probably has an extensive number of pegmatite dykes. Beside the north–south-striking volcanic belt, the bedrock is generally composed of mica schist and different metapelites. There are, however, many forest clearings throughout the area with abundant pegmatitic boulders. This indicates pegmatite dykes and intrusions, which are not exposed due to the extensive glacial till cover.

Table 3. A list of the most differentiated samples according to the Mg/Li ratio of less than 10. As a reference, the median values for samples from the Dragbacken spodumene dykes are included, as well as the median values for different Mg/Li intervals. Conditional formatting coloring has been individually applied for each column, where a gradient towards red represents more significant values.

Sample	X	Y	Location	Mg/Li	K/Rb	Al/Ga	K/Ba	Rb/Sr	Li (ppm)	Ga (ppm)	Nb (ppm)	Ta (ppm)	Rb (ppm)
HJNY-2019-64,1	322053	7050015	Skogsbyn	0.4	62	1832	1630	27	323	33	76	27	263
AOJO-2019-3,1	331358	7042016	Småbönders	0.6	94	2786	2385	54	40	17	8	2	329
TJLE-2019-51,1	322486	7055489	Kolam	1.1	64	2954	988	8	173	18	5	3	92
AOJO-2019-31,1	324102	7059936	Honka	2.8	91	2148	1458	17	84	24	11	1	64
AOJO-2019-39,1	324220	7063219	Gåsjärv	2.8	76	1772	2591	44	30	20	6	1	376
HJNY-2019-37,1	324514	7058409	Honka	3.1	53	No data	1682	14	108	No data	35	4	349
AOJO-2020-17,1	318324	7056562	Kolam	3.9	125	2160	1080	27	32	25	14	2	173
HGW-2020-12,1	331000	7045000	Djupsjöbacka	4.0	125	3182	1650	38	29	19	14	4	342
HJNY-2020-10,1	320129	7051478	Gökbacka	4.1	52	1512	533	37	25	34	39	7	491
HJNY-2019-7,1	326211	7047943	Kaitåsen	4.3	114	4910	9133	96	27	14	5	2	479
TJLE-2019-8,1	332435	7046272	Djupsjöbacka	4.5	191	1678	1486	9	89	32	21	2	109
HJNY-2019-6,1	332592	7047039	Djupsjöbacka	4.5	173	2057	1757	14	31	24	12	2	71
HJNY-2020-6,1	322124	7056183	Kolam	4.7	116	2091	1071	17	39	33	37	11	221
HJNY-2020-8,1	317869	7059644	Kivijärvi	5.0	114	2624	2617	74	11	25	11	3	414
TJLE-2020-61,1	325871	7057195	Honka	5.6	31	1538	3783	135	9	26	45	7	728
TJLE-2020-59,1	319101	7067761	Alaveteli	6.0	73	1821	1116	31	18	30	118	32	477
AOJO-2020-14,1	320285	7052723	Gökbacka	6.1	82	2480	1107	57	58	20	18	2	188
TJLE-2019-12,1	333905	7041820	Småbönders	6.6	186	2220	1286	16	18	19	8	2	145
AOJO-2020-1,1	316142	7061973	Kivijärvi	6.7	106	2693	3042	65	46	22	11	2	344
AOJO-2019-40,1	322296	7055556	Kolam	6.8	103	1876	2333	56	34	32	26	4	203
AOJO-2020-30,1	321266	7058706	Krasslandet	7.1	57	1544	5050	142	27	36	39	9	356
TJLE-2020-37,1	319981	7051490	Gökbacka	7.9	91	1983	3667	61	14	29	137	38	121
AOJO-2020-28,1	321254	7058699	Krasslandet	8.0	57	2095	3700	38	51	36	46	5	391
AOJO-2020-29,1	321258	7058701	Krasslandet	8.1	56	2460	1243	22	36	32	33	10	462
HJNY-2019-54,1	332794	7041524	Småbönders	9.7	31	2334	835	16	11	32	58	26	455
HJNY-2020-11,1	318246	7056692	Kolam	9.8	129	3247	1383	23	18	24	11	7	257
Mg/Li < 10 (median) n = 26				4.6	93	2121	1666	33	35	26	18	3	279
Mg/Li 10-20 (median) n = 13				15	106	2797	919	25	18	23	22	6	469
Mg/Li 20-50 (median) n = 40				36	138	3125	922	12	11	21	14	3	216
Mg/Li > 50 (median) n = 38				100	181	3348	646	10	5	21	11	2	207
Spodumene peg. (median) n= 10	323545	7059656	Dragbacken	0.2	25	1754	608	43	2170	41	58	20	747

6 SURFICIAL GEOLOGY OF RAISJOKI RESEARCH AREA

Diverse geological research was carried out in the study area in 2019–2021, the purpose of which was to determine the mineral potential of the area (Au–Cu–Li–Ni–Co). Battery minerals were the focus of research. The purpose of till sampling in the area was to map or locate potential Co or Li mineralizations. The target areas were Honka, Emas, and Sammaloja (Fig. 6).

Glaciologically, the Raisjoki study area is in the proximal part of the Näsijärvi–Jyväskylä and Lake Finland ice lobes, in the vicinity of the interlobate zone between them. The surficial deposits in the area mainly consist of basal till and hummocky moraines covering the higher areas, as well as silt, clay, and peat deposits in the lower valleys and riverbanks. The northern part of the area is crossed by an esker running from southeast to northwest according to the direction of retreat of the continental ice sheet. The southern part of the area is characterized by extensive lowland marshes (Fig. 7).

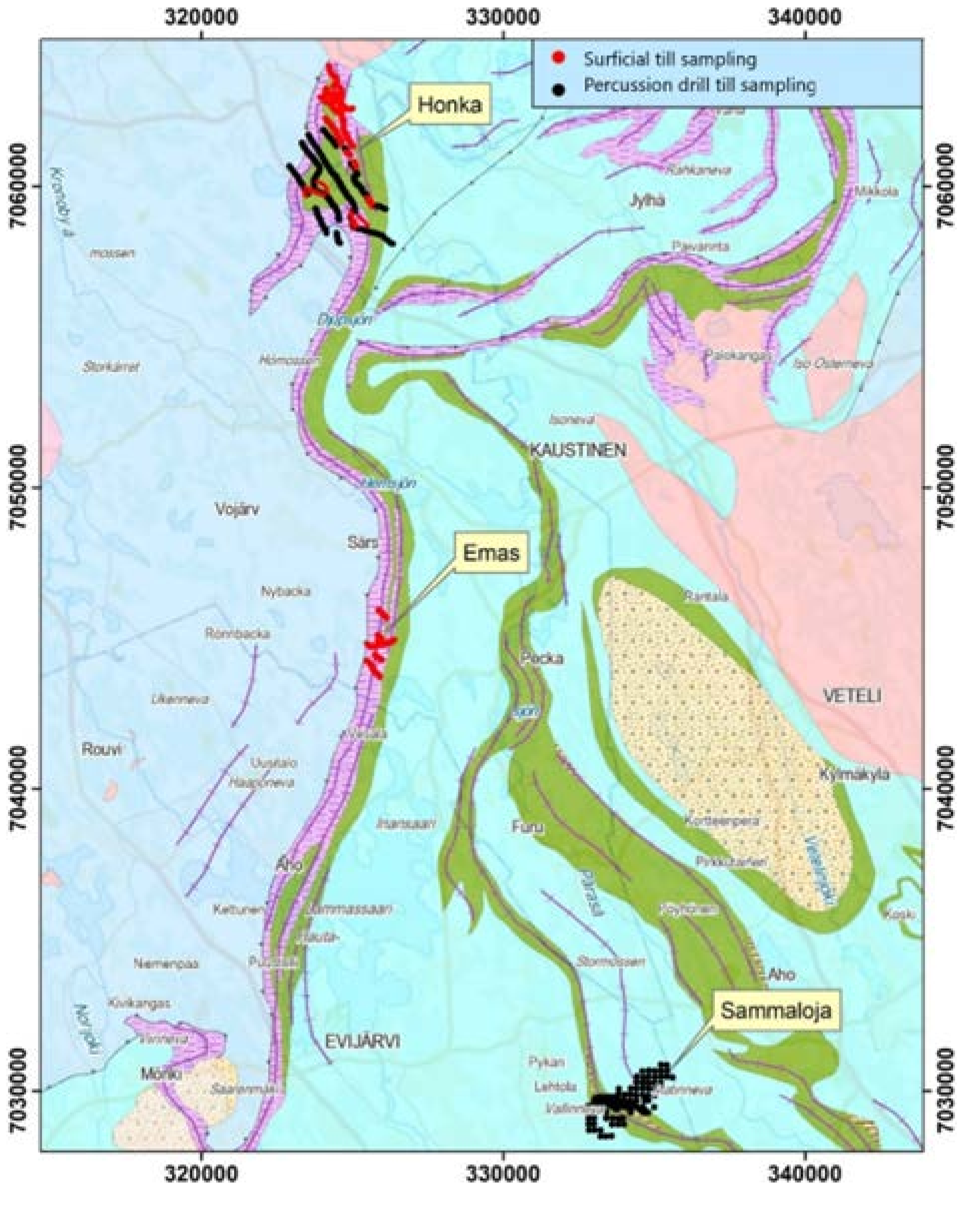

Fig. 6. Till sampling sites in the Raisjoki study area in 2019–2021 on a bedrock map (Hulkki et al. 2022) (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Base map © National Land Survey of Finland

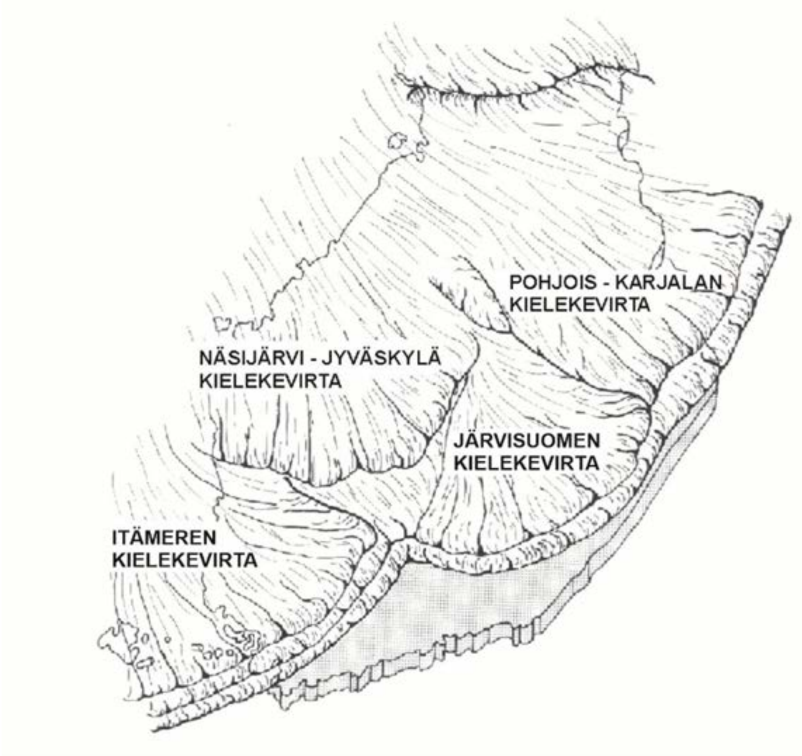

Fig. 7. Ice lobes of the Scandinavian ice sheet in southern Finland during deglaciation (Iisalo 1992).

The moraine forms typical of the entire study area are the oriented moraine formations representing the latest flow direction of the glacier, the northwest–southeast drumlin ridges. The average orientation of the longitudinal axes of the ridges in the whole study area and target areas is 324° (Iisalo 1992). According to previous till stratigraphic studies, two till beds of different ages have been found in the area. The topmost basal till bed consists of grayish sandy till. Based on the till fabric analysis, the direction of deposition of the till bed is 330° from the northwest. The lower, finer basal till is blue-gray in color and less stony. According to the till fabric analysis, the deposition direction of the till bed is 270° west. The interface between the upper and lower till beds is in the range of 2.0–3.3 meters. The contact is clear and sharp, or the beds are separated by a thin, approximately 10-cm layer of sand, with iron deposits in places. In glacial till stratigraphy, the upper till bed probably represents the Late Weichselian glaciation and the lower the Early Weichselian (Iisalo 1992).

Based on the above-mentioned studies, the basal till beds of the Raisjoki study area were deposited first because of the western ice flow (lower till) and then as a result of the northwestern ice flow (upper till bed). In the field of mineral exploration, there is a possibility of complex transport, where boulder transport and moraine anomalies have been affected first by the western glacier transport and then by the northwest (Hirvas & Nenonen 1984) (Figs. 8 and 9). This possibility applies to all separate sampling sites in the study area, in Honka, Emas, and Sammaloja. In the case of complex transport, the most difficult problem is caused by the transport distance of the material, i.e., how far the till material or boulders have been transported with the glacial flow in different directions. In complex transport, the trace element content of the till is also diluted, so that the mineralization is not clearly reflected in the geochemistry of the younger till bed. For this reason, sampling should extend to the oldest till bed (Hirvas 1977, 36–37).

In drumlinized areas, transport distances are usually quite long, from several hundred meters to several kilometers. In Central Ostrobothnia, in the study area and its surroundings, the length of boulder fans is most often 1–5 km (Salonen 1985).

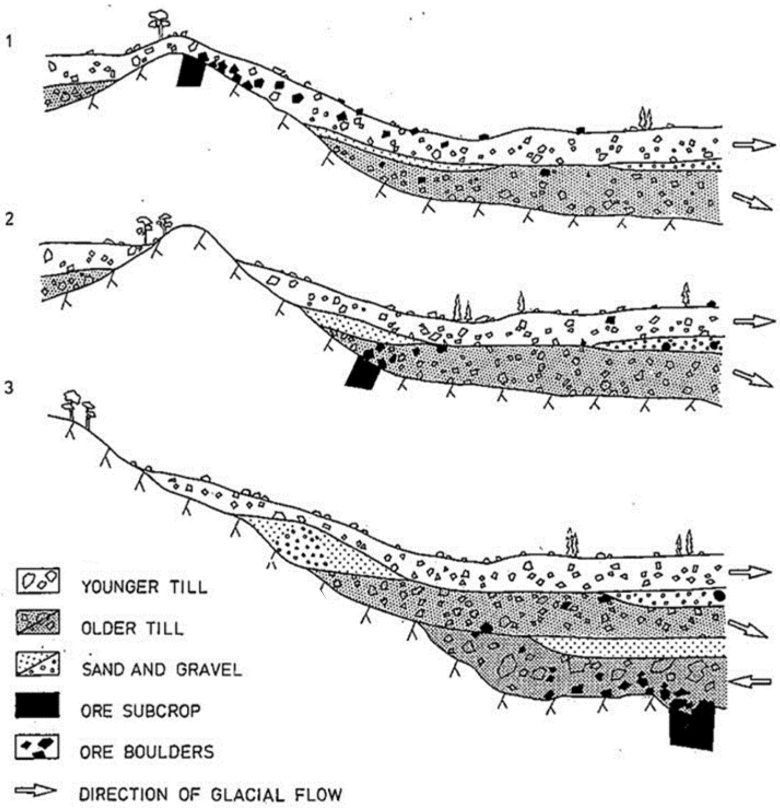

Fig. 8. Schematic diagram of the influence of glacial stratigraphy on the transport of ore indicators. Model 2 describes a complex transport situation in which ore indicators are transported by two different ice flows and by glacier meltwater. (Hirvas & Nenonen 1984)

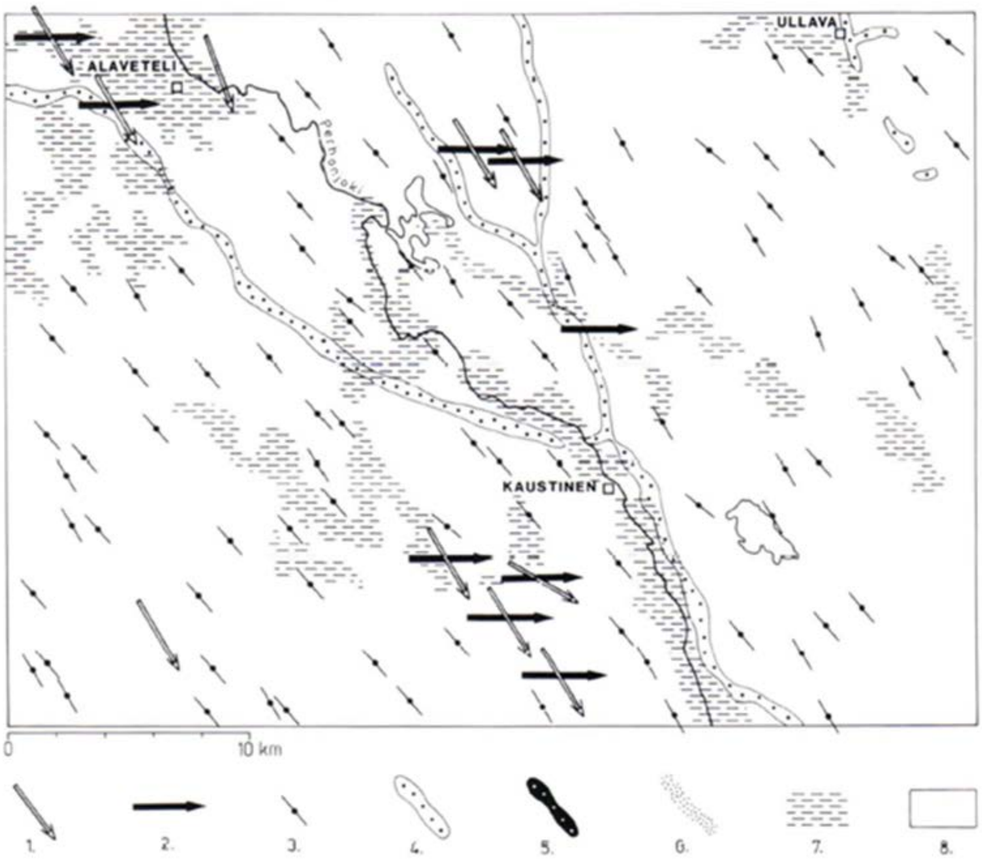

Fig. 9. Quaternary deposits in the Kaustinen–Alavetelin–Ullava area and ice-flow directions of the continental glacier (Iisalo 1992).

6.1 Sammaloja

The Sammaloja area, which is located SE of the Raisjoki target, was originally chosen for investigation due to its sulfide layman (Ni–Co–Au) boulders combined with a bended structure visible in the aeromagnetic map (Figs. 17 and 29). GTK executed a combined till and base of till grid sampling program, which delimited a potential area for further investigations (Hulkki 2022).

Based on the till samples from Sammaloja, Au is only anomalous at one sample point (Au = 9.2ppb). At this point, the elements normally associated with gold are not anomalous, indicating that the source of the anomaly is not local. The Au and Au indicator element and base metal contents are low, although slightly anomalous. The Sammaloja area has one sample point with an S content of 1.4% (and 5.3 ppb Au), and according to the Tukey boxplot, the threshold value is slightly anomalous.

According to the base of the till geochemistry, locations where the skarn sequences cross are clearly anomalous from the base metal perspective, especially Zn, with the highest value of 0.19%. The Tukey box plot threshold value shows higher S background values of 5–8%, which indicates a sulfide mineralization in the bedrock (Fig. 10c). As the higher Zn values from deep-seated samples are not displayed in the till samples, it is probable that the till material is not local.

6.2 Dragbacken

Four different surficial methods were used in Dragbacken to trace more LCT pegmatites dykes around the quarry area. A till sampling survey using percussion drilling consisted of 360 samples from 347 sampling sites, and during three surface till sampling surveys, 491 samples were collected from 369 sampling sites. All sampling programs were carried out as line sampling. The percussion drilling sampling program (Fig. 10a) revealed several new potential areas.

6.3 Emas

In Emas, the sampling was carried out as line sampling consisting of six lines with a sample spacing of 10–50 m. The lines were planned to crosscut and chart possible N–S extensions of the mineralization encountered in drill hole P4222919R7. The Ca/Cr ratio in the sampling program revealed that the possible southern continuation of drillhole R7 may have sinistrally faulted apart 120 m to the east (Fig. 10b) and that new anomalous areas are located 1 km to the south of drillhole R7.

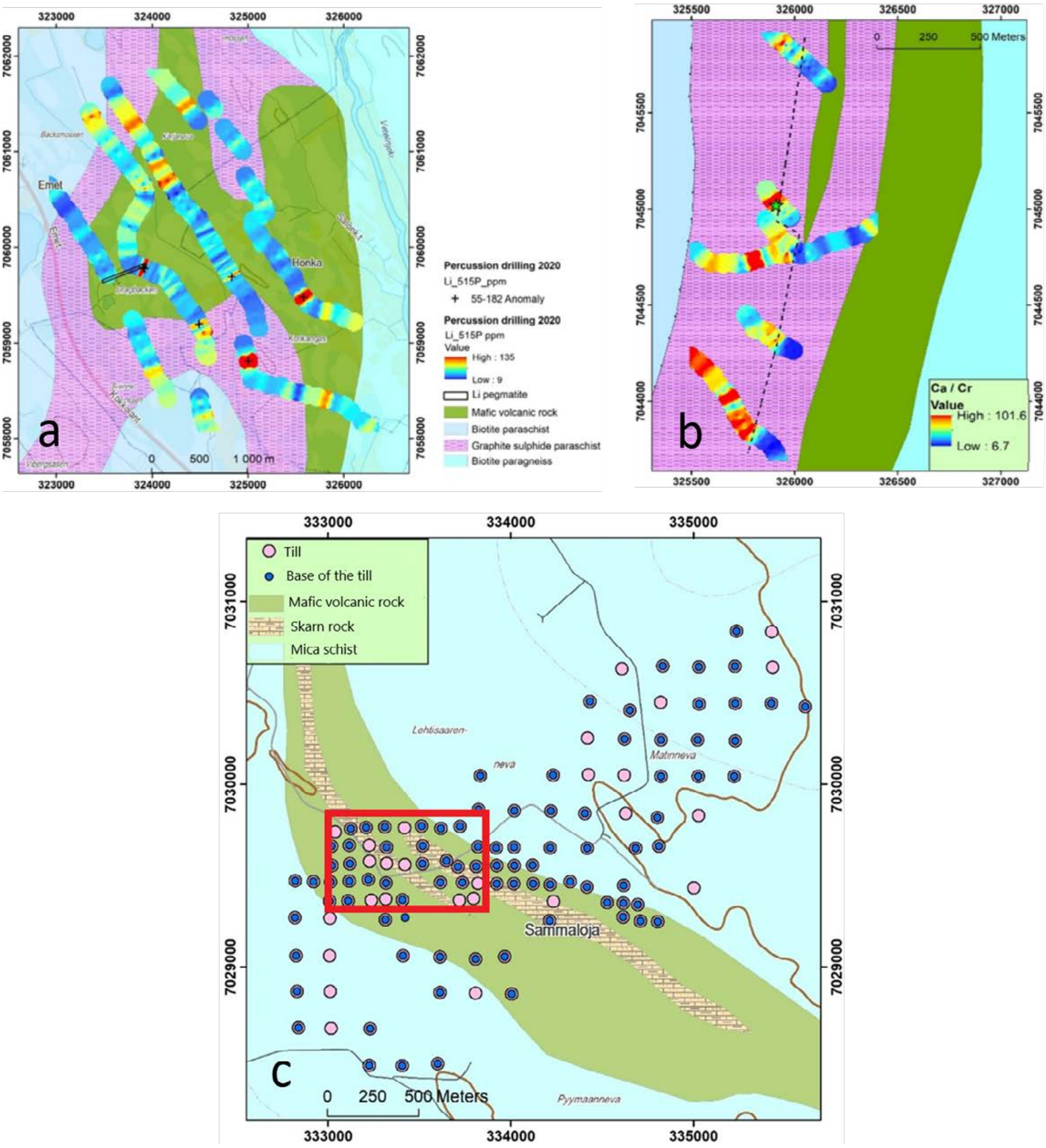

Fig 10. a) Percussion drill sampling in Dragbacken with lithium values highlighted. b) Surficial till sampling results with Ca/Cr ratio values displayed, revealing possible sinistral slip movement of the mineralized horizon. c) Percussion drilling samples from Sammaloja with till and base of till samples, indicating a potential sulfide mineralization area in the red square. (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Floor map © National Land Survey of Finland.

7 LITHIUM INVESTIGATIONS

Besides Dragbacken, lithium investigations took place also in Saarala, as well as in the Lapua–Kuortane areas (Fig. 11). The lithium investigations in Lapua–Kuortane were executed in the latter half of the four-year battery mineral project. The Dragbacken, Saarala, and Lapua–Kuortane investigations are fully covered in separate open-file reports by GTK (Wik et al. 2020, Nygård et al. 2023, Nygård et al. 2024).

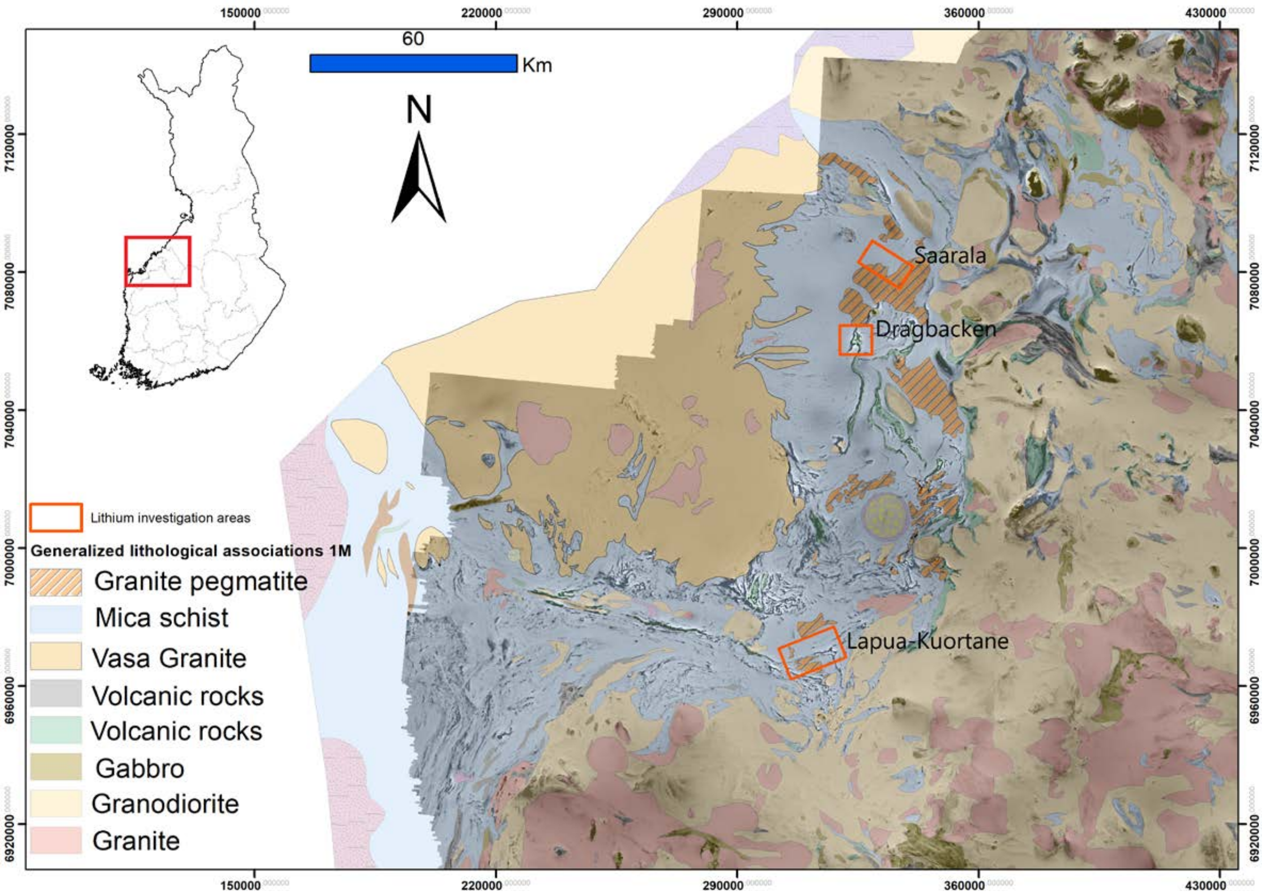

Fig. 11. Geological map with the locations of lithium investigation areas in Saarala, Dragbacken, and Lapua–Kuortane (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Base map © National Land Survey of Finland.

7.1 Saarala

Saarala is a village in Kälviä and a part of the domicile of Kokkola. The Saarala investigation area is located on the northern side of the Ullava granite, which is considered to relate to the presence of Kaustinen spodumene pegmatites (Martikainen 2012). GTK re-assayed 295 targeting till geochemistry samples in the Saarala area in 2019 to outline new potential areas for LCT pegmatites. GTK had received a reservation notification in September 2018 for an area of 32.46 km^2. The assay results displayed a few anomalous clusters with elevated Li in the till (Fig. 12). After receiving the assay results, one geologist carried out in total 12 days of boulder tracing and mapping of outcrops. Most boulders encountered were not considered potential. The reservation notification expired on September 24th, 2020. Based on the results, GTK decided not to continue the investigations.

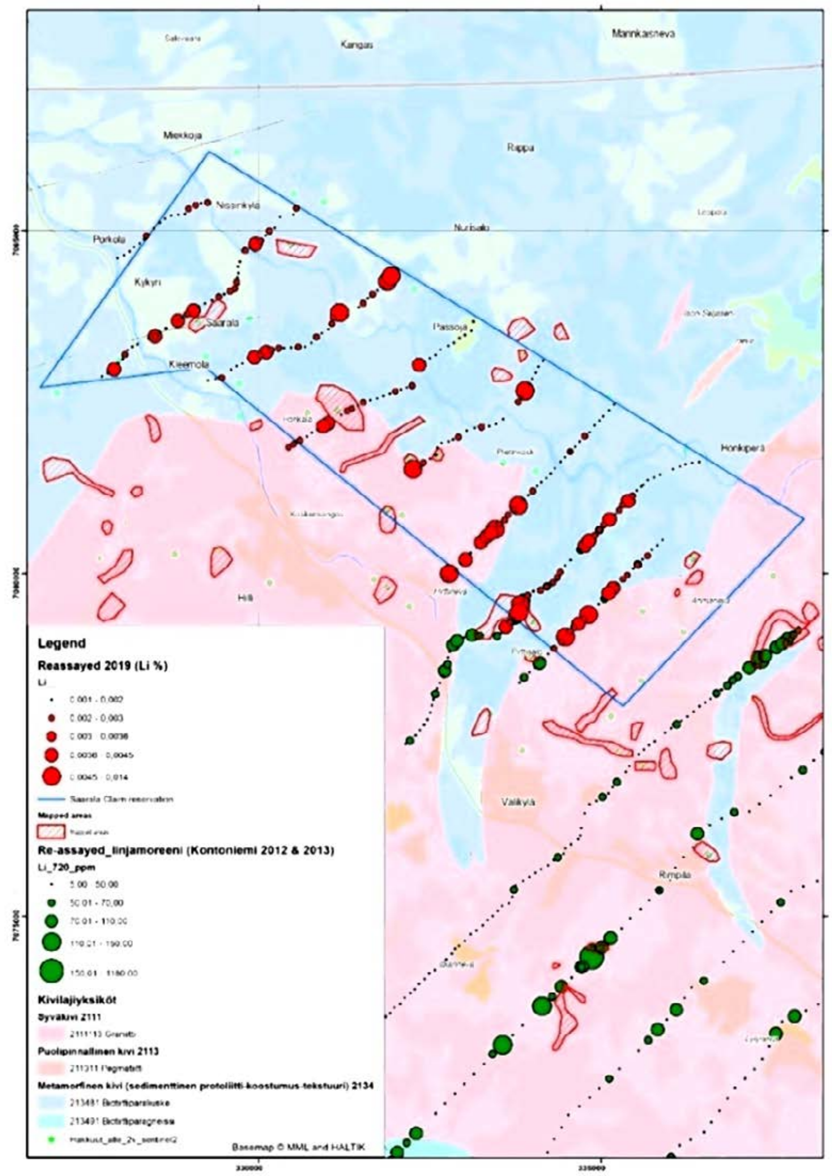

Fig. 12. The study area in Saarala, which was also outlined as the reservation area from September 2018 to September 2020 (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Floor map © National Land Survey of Finland.

7.2 Dragbacken

In 2019, the Geological Survey of Finland discovered a previously unknown lithium occurrence at Dragbacken, located in the municipality of Kruunupyy. The smaller southern dyke was initially discovered in the southern quarry wall (Fig. 14c), which led to a more thorough investigation of the area and eventually to the discovery of the northern dyke, striking in a parallel direction. The dykes are located approximately 300 m apart. In the following mineral potential mapping stage, several exploration methods were used. These methods were bedrock and boulder mapping, several different till sampling programs, a ground geophysics magnetometry survey, and finally a 1500 m diamond drilling program (Nygård et al. 2023).

A reservation notification called Honka was applied for and granted in 2019. A smaller exploration permit around the Dragbacken area was applied for in 2021 (Fig. 13).

The northern dyke sharply cuts the host rock amphibolite against the foliation. The northern spodumene dyke was intersected in three drillholes (Q4112020R25, Q4112020R26, Q4112020R27) (Fig. 14b). The northern dyke reaches a thickness of 5.8 m and has high lithium content in the intervals 39–40 m (>10 000 ppm) (Fig. 14a) and at 40–41 m (7420 ppm).

Lithium reaches ca. 3000 ppm in the interval 59–60 m in Q4112020R26. The lithium occurs in coarse-grained, light green elongated spodumene crystals. The dykes are coarse grained with white to gray albite and quartz. Muscovite occurs as medium to coarse grained yellowish colored flakes.

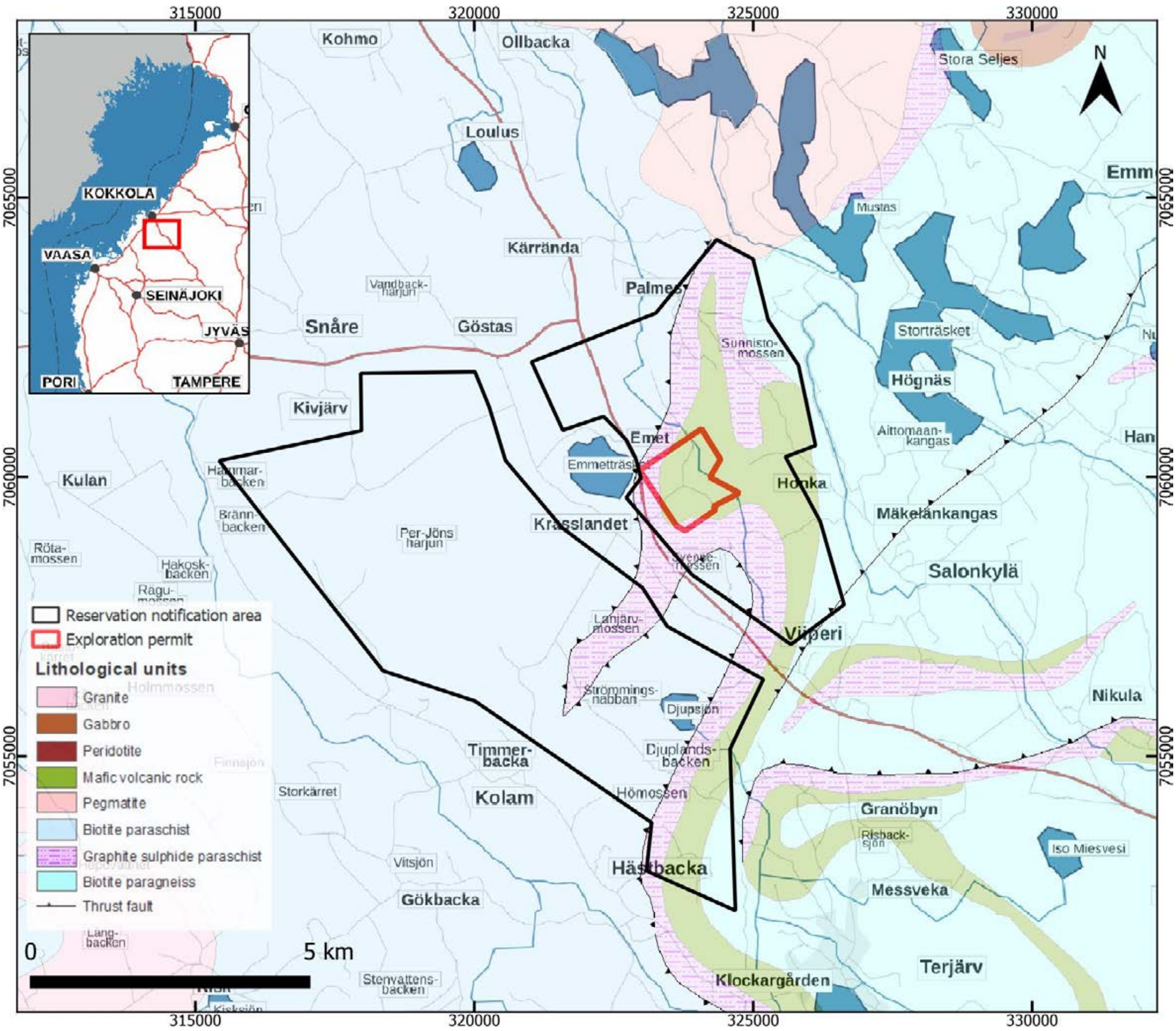

Fig. 13. A map showing the major lithological units. The location of the Honka reservation notification area is framed in black and the exploration permit in red around the immediate area of Dragbacken (Basemaps © National Land Survey of Finland).

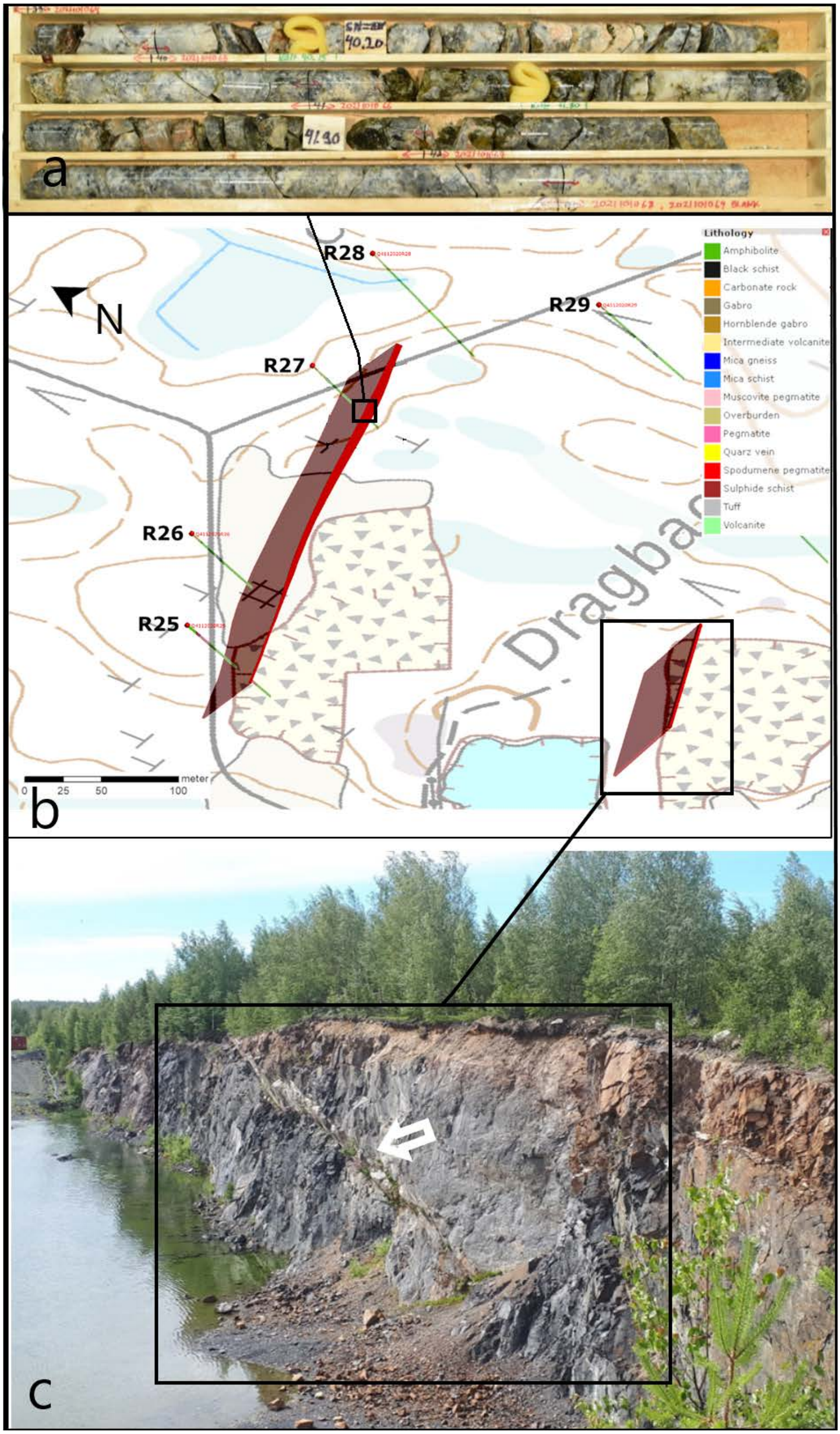

Fig 14. Drill core image a) of a part of the best intersection from the northern dyke in the Dragbacken aggregate rock quarries in which two spodumene pegmatite dykes were located 300 m apart b). The southern dyke b, c) was the first-discovered spodumene pegmatite (Basemaps © National Land Survey of Finland).

7.3 Lapua–Kuortane

GTK decided to expand LCT pegmatite investigations to the Lapua–Kuortane area, located in the southern part of the OSB. The need of material for the ceramics and glass industry has brough forth several historical LCT pegmatite occurrences in the area, such as at Kaatiala, Pajuluoma, Haapaluoma, Hunnakko, and Tarikko (Haapala 1966, Mäkitie 2001, Alviola 2001). A more detailed description of the investigations is provided in Nygård et al. (2024).

The geology is similar to the Kruunupyy and Kaustinen areas (Fig. 15). Compositionally, the LCT pegmatites in southern Ostrobothnia are more complex when compared to Kruunupyy–Kaustinen (Mäkitie 2001). Geochemically, this means higher Rb, Cs, Be, Ta, Nb contents than in the albite–spodumene type that dominates in the Kaustinen area, which generally contains higher amounts of Li (Martikainen 2012).

The terrain in Lapua–Kuortane has, in contrast to Kruunupyy–Kaustinen, less ground cover with better exposed rocks, allowing more thorough rock sample-based field research methods such as the estimation of the differentiation grade of pegmatitic rocks via the element ratios Li/Mg and K/Rb, which are considered the best indicators to delimit pegmatite rocks that are favorable to carry Li minerals (Černý 1991) .

7.3.1 Initial investigations

Initial work included geochemical sampling of the granitic pegmatitic stocks, which are also referred to as the Seinäjoki granites in Lapua–Kuortane (Alviola 2001). Any area of metasediments that is encircled or has proximal range with Seinäjoki pegmatite granites within the OSB can be considered potential for LCT pegmatites. The differentiation degree based on the geochemical ratios of Mg/Li and K/Rb can further determine how favorable the geological environment is for the existence of LCT pegmatites. If a granitic pegmatite stock or batholite is considered favorable, it is likely that LCT pegmatites can be found within a range of 2–10 km radius from the stock (Černý 1991). These measures were the initial steps in Lapua–Kuortane stocks A–C (Fig. 15) to assess the Li potential of the surrounding area.

The Lapua–Kuortane area is known to contain radioactive coltan minerals that are closely associated with LCT pegmatites (von Volborth 1952, Kinnunen 2012). The first field work executed was based on aerogeophysical radiometric maps showing a multitude of anomalous spots that were considered potential sites for LCT pegmatites. Another task was to re-analyze older till samples taken in the Kurjenneva area. After these stages, new percussion drilling lines were planned and boulder mapping executed to delimit the potential areas. The outcome of the mineral potential mapping resulted in subdividing the investigations between two potential areas, the Kurjenneva and Pikkalantausta areas. In Pikkalantausta, additional surficial sampling was performed after locating fertile boulders and a mineralized outcrop.

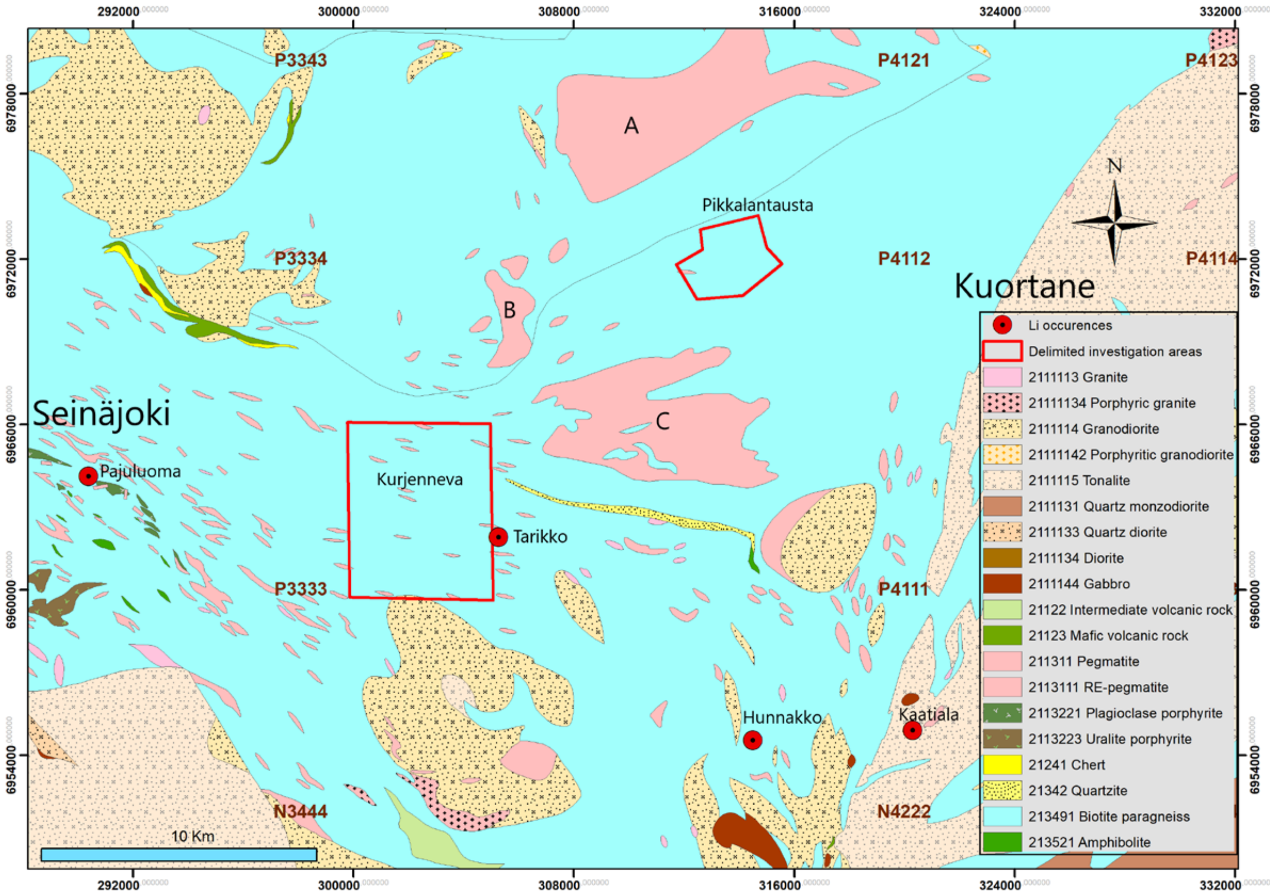

Fig. 15. Geological map of the Lapua–Kuortane study area with previously known lithium occurrences indicated on the map. (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Floor map © National Land Survey of Finland.

7.4 Results

7.4.1 Kurjenneva

In the early stages of the boulder mapping, a pegmatite boulder containing spodumene was found in an area (Fig. 16a) delimited by the re-assayed till samples in the Kurjenneva area. New percussion drilling was directed to locations with elevated values of Li in combination with other indicator elements such as Nb and Ta.

7.4.2 Pikkalantausta

In Pikkalantausta, a pegmatite outcrop containing the lithium phosphate mineral montebrasite–amblygonite was located via a boulder found in the vicinity (Fig. 16b). The analyzed boulder contained >25 000 ppm Li, which was the assay detection limit, and also had a highly elevated 2000 ppm of Sn. In the Pikkalantausta area, other boulders and outcrops indicating a high fertility grade and the presence of several LCT dykes in the area were found. Due to the good investigation results, GTK applied for an exploration permit in the area in early 2023.

Fig. 16. LCT pegmatites found from the study area in Lapua–Kuortane. a) A spodumene-bearing boulder from Kurjenneva. b) Montebrasite–amblygonite (encircled) from Pikkalantausta.

8 NI–CO–AU–W INVESTIGATIONS

8.1 Previous work

The original aim of the battery mineral project in 2019 was to locate new Co-bearing occurrences. At several locations, sulfidic boulders and bedrock have been found and investigated (Järnefelt 1936) (Fig. 17). The Raisjoki target was under intense layman activity when the Raisjoki river underwent a restoration program in the 1960s, and some boulders had exceptionally high Cu, Ni, and Co contents, which resulted in later re-occurring research activity in the area (Lindmark 1978, Lonka 1981, Ruskeeniemi 1988, Sipilä 1989).

In an investigation by Sipilä in 1989, the Ni–Co–Cu mineralization was related to sulfide veins and lenses that crosscut the black schists. The metavolcanic belts have previously been associated with an elevated content of arsenopyrite and associated mineralizations. According to a GTK report (Kärkkäinen 2001), a 1 x 2 m sulfide-rich boulder was found in Köyrinen, NE of the Aho belt (Fig. 17). The results of the whole rock analysis from the boulder were reported: 160–480 ppm Ag, 4–22 ppm Au, 2–4% Cu, 0.4–0.9% Co, <1% Pb, <1% Zn, and 32 ppm – 0.33% Sb. The source of the boulder has not been found. The area where the volcanic belts occur has also been investigated for tungsten-bearing scheelite at the Fröidömossen and Kirkkoharju targets in a 6-km range from Kaitåsen (Lindmark 1979). In the village of Ina, scheelite investigations were also planned (Västi 1988). In Kellokallio in Veteli, which was originally an Outkokumpu gold exploration target (Sandberg 1985), a 30-m section in a metavolcanic layer contained abundant arsenopyrite, reaching 0.5% As at best in an analyzed section (Kuusela et al. 2020).

8.2 Diamond drilling results

In Emas, a lens containing semi-massive As-rich sulfides was penetrated in a small drilling campaign (Fig. 18). The mineralized section contained the minerals gerssdorfite, cobaltite pentlandite, and Ni-rich pyrite, with 3 m @ 0.5% Co with 2% Ni or 10.5 m @ 0.8% Ni with 0.11% Co (Table 4). The semi-massive section also contained 0.32 ppm Au in a 2.15-m section. The Kaitåsen target, which is the northern continuation of Emas, had elevated As in drillhole P4222019R13, especially in the section 172–173 m, where the As content was 1250 ppm (Table 4). In the same drillhole, the section 170–174 m contained 150 ppm Co and 0.08% Ni. In Dragbacken, one arsenopyrite-rich section was found in the black schists, section 57.2–62.85 m in drillhole R35, located north of the spodumene dykes at Dragbacken. In R35, from 60–61 m, As reaches the analytical maximum of 250 ppm, Co 754 ppm and Ni 1180 ppm (Table 4). Gold mineralization-related Te (10.5 ppm), Sb (13.5 ppm), Bi (1.08 ppm), and Se (7.5 ppm) are highly elevated. The assay did not include Au or PGE-group elements. Despite promising layman boulder data, the Co content in target Raisjoki drillholes remained feeble, with the best section in drillhole R4, from 42.9–46 m, containing 126 ppm Co. In Kedonkangas, two scheelite sections were penetrated, with the better one in drillhole R19, from 59–60 m, containing 1970 ppm W, while in drillhole R16, section 64–65 m contained 0.126 ppm Au (Table 4).

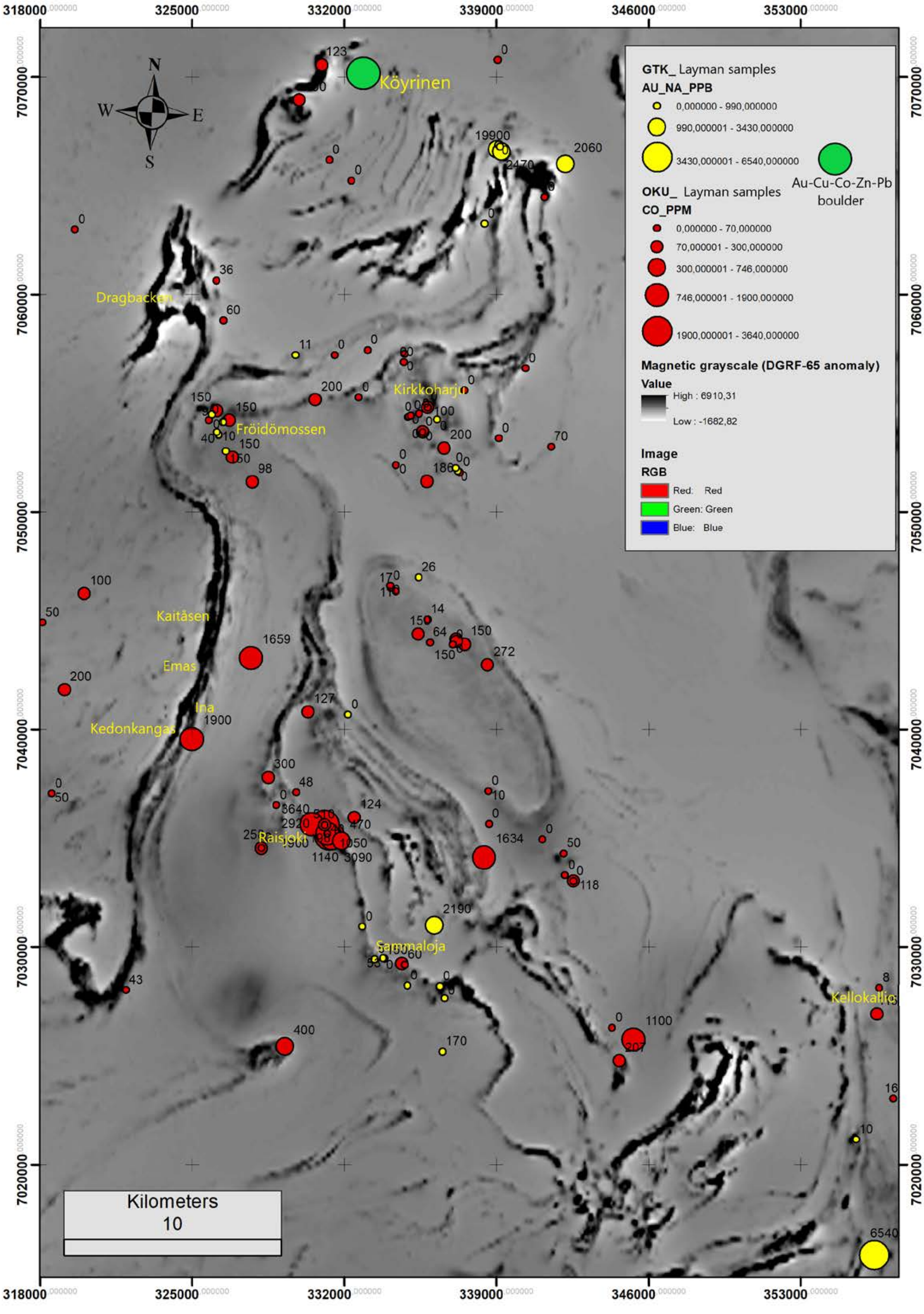

Fig. 17. Analyzed layman samples from GTK and Outokumpu samples with Co and Au contents displayed. Also highlighted is the "Sirén" polymetallic boulder located in Köyrinen. The background map is an aeromagnetic map.

Table 4. Summary table of best drill intersections of Ni, Co, Au, and W in the Raisjoki area.

Target	Drill hole	From (m)	To (m)	Intersection (m)	Element	Content
Emas	P4222019R7	32,5	43	10,5	Co	0,11%
Emas	P4222019R7	32,5	43	10,5	Ni	0,80%
Emas	P4222019R7	33,7	35,85	2,15	Au	0.32 ppm
Emas	P4222019R21	98	114	16	Co	102 ppm
Emas	P4222019R21	98	114	16	Ni	0,10%
Emas	P4222019R22	66	84	18	Co	176 ppm
Emas	P4222019R22	66	84	18	Ni	0,18%
Kaitåsen	P4222019R13	170	174	4	Co	150 ppm
Kaitåsen	P4222019R13	170	174	4	Ni	0,08%
Dragbacken	Q4112020R35	60	62	2	Co	471.5 ppm
Dragbacken	Q4112020R35	60	62	2	Ni	0,09%
Raisjoki	P4222019R4	42,9	46	3,1	Co	129 ppm
Kedonkangas	P4222019R19	64	65	1	W	0,20%
Kedonkangas	P4222019R19	43	45	2	W	137 ppm
Kedonkangas	P4222019R16	64	65	1	Au	0.126 ppm

8.3 Metasomatic alteration

The rocks in Emas and Kaitåsen are hydrothermally altered and in places silicified with white-grayish quartz veins (Fig. 19a). In places, they contain a brownish biotite mass or alteration. The rock is brecciated with a flow texture and is folded in places. Disseminated and patchy pyrite and pyrrhotite may occur, in some places with fuchsite-bearing veining (Cr). Elevated Cr and high As values in Dragbacken drillhole Q4112020R35 suggest that the alteration may be similar (Fig. 19b). The protolith of the metasomatic rock is possibly a mix of meta-sediment, mixed with black schist layers where hydrothermal fluids flowed through the rock. The analysis revealed in places a few percent graphite. In Kedonkangas, the rock appears strongly silicified with local enrichment of scheelite (Fig. 19c). In some sections in Kedonkangas, Co is anomalous at 100 ppm but does not involve elevated Cr.

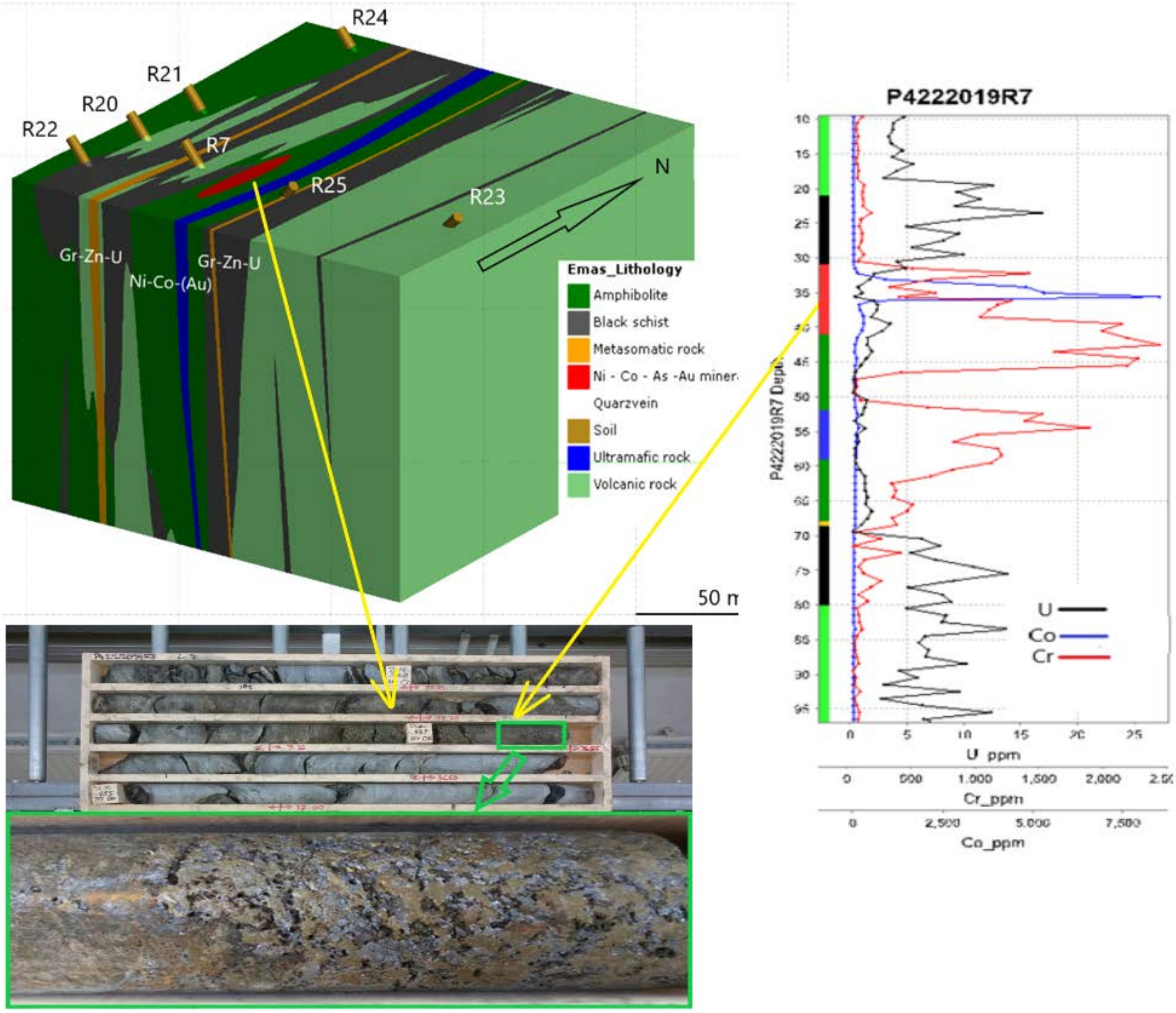

Fig. 18. The Emas sulfide mineralization within the metasomatized alteration zone with elevated Cr.

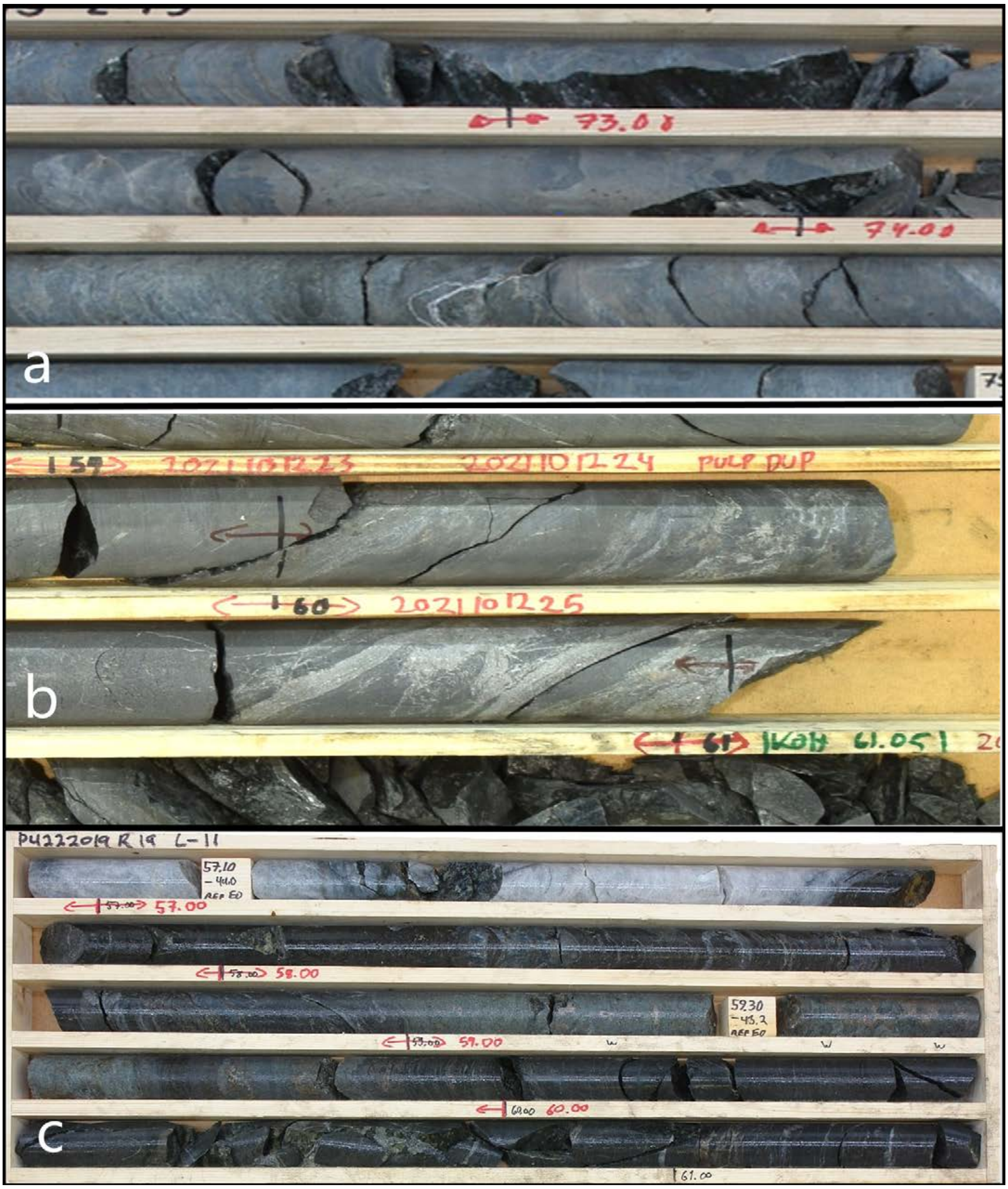

Fig. 19. a) Metasomatic alteration volcanic rock from Kaitåsen. b) Potential Au-bearing rock from Dragbacken with grayish As-rich stripes. c) Silicified scheelite-bearing rock from Kedonkangas.

8.4 Mineralogy

The sulfide rock samples were analyzed with optical microscopy and SEM from 35 polished thin sections in the GTK mineral laboratory. Other equipment used for the microanalysis of Ni–Co–As–Zn–Cu-bearing phases included a CAMECA SX100 electron microprobe equipped with five wavelength-dispersion spectrometers (TAP, 2 LLIF, PET, and LPET) and one EDS detector. Natural minerals were used as reference standards.

8.4.1 Identified sulfides

The main sulfide minerals identified in the Raisjoki area were pyrite (FeS_2), pyrrhotite ($Fe_{1-x}S$), sphalerite (ZnS), and chalcopyrite ($CuFeS_2$). Cobalt is distributed in cobaltite, gersdorffite, cobalt pentlandite, Co-rich arsenopyrite, pyrrhotite, and pyrite. As is present in many mineral phases, including nickeline (NiAs), and sulpharsenides of nickel and cobalt, such as cobalt gersdorffite (NiAsS), cobalt pentlandite ($(Fe,Ni)_9S_8$), and cobaltite (CoAsS) (Fig. 21a–f).

8.4.2 Geochemical Characteristics of Sulfides

Figure 20 summarizes the results of chemical composition analysis obtained from 560 samples collected from 13 drill holes, which were taken at an interval of 1–2 m/sample. The Al–(Fe + Ti)–Mg classification diagram (Jensen 1976) indicates that most of the studied samples cluster on the border of high-Fe (HFT) and high-Mg (HMT) tholeiitic basalt. Some of the samples are Mg-rich and plot in the basaltic komatiitic (BK) field (Fig. 20a). In the plot for selected samples with a high content of sulfides (Fig. 20b), the tholeiitic basalts fall into the field of high-Mg or, more rarely, high-Fe tholeiites, and other samples are plotted on the komatiitic basalts (Fig. 20b). TC content varies from 5% to 12.6% (avg. 8.5% C) and the TS content from 2.9% to 12.3% (avg. 7.2% S). The maximum values for metals in the Raisjoki mineralized intervals are 0.85 wt% Co, >4 wt% Ni, 4.5 wt% As, 0.35% Cu, 0.3 wt% Zn, and 36 ppm U (Kuusela et al. 2022).

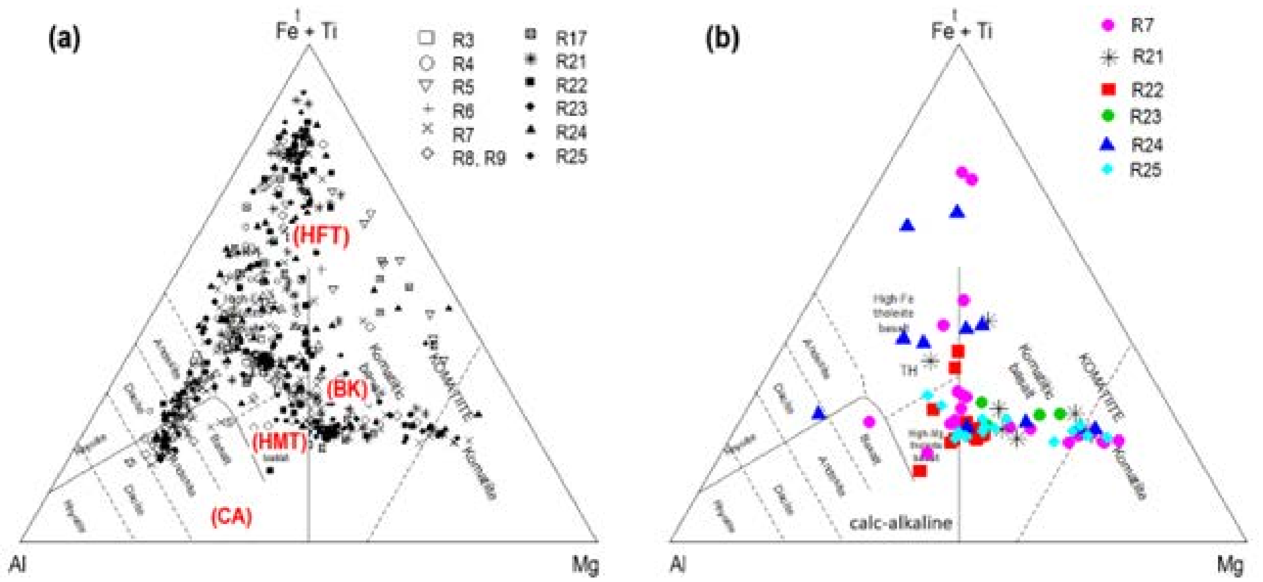

Fig. 20. Jensen's cation plot for all studied samples a) and sulfide-rich samples b) in the Raisjoki (Emas) area (after Jensen 1976).

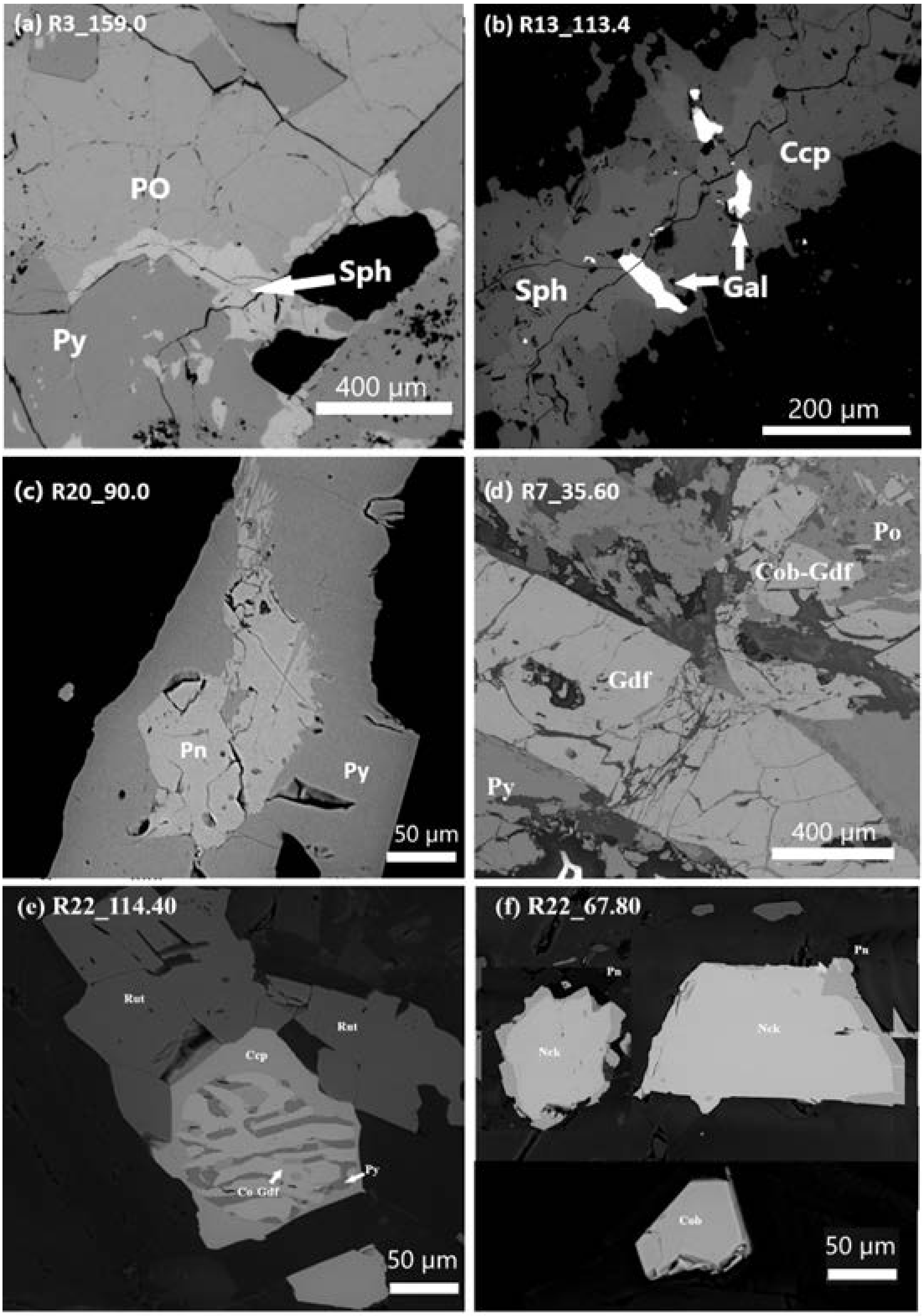

Fig. 21. Selection of electron microscopy backscattered images from the Raisjoki sulfide phases. a) Intergrowth of pyrite (Py) and pyrrhotite (Po) with cracks filled by sphalerite (Sph). b) Chalcopyrite (Ccp) and sphalerite usually occur as subhedral to anhedral disseminated grains and contain inclusions of galena (Gal). c) Cobalt pentlandite (Pn) with pyrite. d) Cobaltite (Cob) and gersdorffite (Gdf) are present as large crystals. e) Gersdorffite belongs to a solid solution series with cobaltite. f) Nickeline (Nck) occurs as small subhedral small grains enclosed by pentlandite.

Table. 5 Selected samples with a high content of metal sulfides from the Raisjoki (Emas) area.

Sample	Interval	Rock type	Co ppm	As ppm	Ni ppm	Cu ppm	Zn ppm	S wt%	C wt%
P222019R7	32.50-33.70	Ni-Co-As-Au min.	910	3800	8800	519	162	7.57	1.01
P222019R7	33.70-34.70	Ni-Co-As-Au min.	4820	18400	29700	611	103	22.9	1.03
P222019R7	34.70-35.35	Ni-Co-As-Au min.	5310	18700	15700	3470	147	14.1	0.32
P222019R7	35.35-35.85	Ni-Co-As-Au min.	8510	44900	40100	431	121	26.5	0.27
P222019R7	35.85-36.50	Ni-Co-As-Au min.	515	2520	5240	257	189	4.5	0.11
P222019R7	36.50-37.0	Ni-Co-As-Au min.	173	332	2540	199	200	2.39	0.61
P222019R7	37.00-38.0	Ni-Co-As-Au min.	202	61	3480	170	235	3.63	0.19
P222019R7	38.00-39.0	Ni-Co-As-Au min.	298	21	6340	371	277	6.49	0.13
P222019R7	39.00-40.0	Ni-Co-As-Au min.	301	66	4030	178	313	2.58	0.07
P222019R7	40.00-41.0	Ni-Co-As-Au min.	259	31	3310	383	208	3.57	0.09
P222019R22	67.00-68.0	Amphibolite	297	1630	2410	188	134	1.4	
P222019R22	68.00-69.0	Amphibolite	173	110	2320	159	188	1.07	
P222019R22	69.00-70.0	Amphibolite	357	1200	2550	382	157	1.31	
P222019R22	77.00-78.0	Amphibolite	440	31.4	7510	287	148	6.77	
P222019R22	78.00-79.0	Amphibolite	205	75.4	2090	258	195	1.24	
P222019R23	99.0-100.0	Amphibolite	134	62.7	1950	134	163	0.801	
P222019R23	100.0-101.0	Amphibolite	152	250	2480	163	162	1.23	
P222019R24	85.0-86.0	Amphibolite	249	10.2	4830	320	178	6.67	
P222019R24	86.0-87.0	Amphibolite	105	5.75	1680	218	231	3.85	
P222019R25	36.0-37.0	Amphibolite	188	166	2090	131	177	1.11	
P222019R25	37.0-38.0	Amphibolite	186	95	1770	191	159	0.703	
P222019R22	69.0-70.0	Amphibolite	357	1200	2550	382	157	1.31	
P222019R22	77.0-78.0	Amphibolite	440	31.4	7510	287	148	0.587	
P222019R24	78.0-79.0	Amphibolite	298	52.5	1570	287	104	0.59	

The components Ni, Co, As, Cu, and Zn of the observed minerals gersdorffite (NiAsS), pentlandite ($(Fe,Ni)_9S_8$), nickeline (NiAs), and cobaltite (CoAsS), and base metals Ni, Co, As, Cu, and Zn correlate well with S and C, which demonstrates that the elements are incorporated into sulfide phases (Fig. 22a,b). The results indicate a good correlation between Ni–As and Co and a poor correlation with Zn (Fig. 22c,d,e). Pb correlates moderately with U (Fig. 22f) (Table 6).

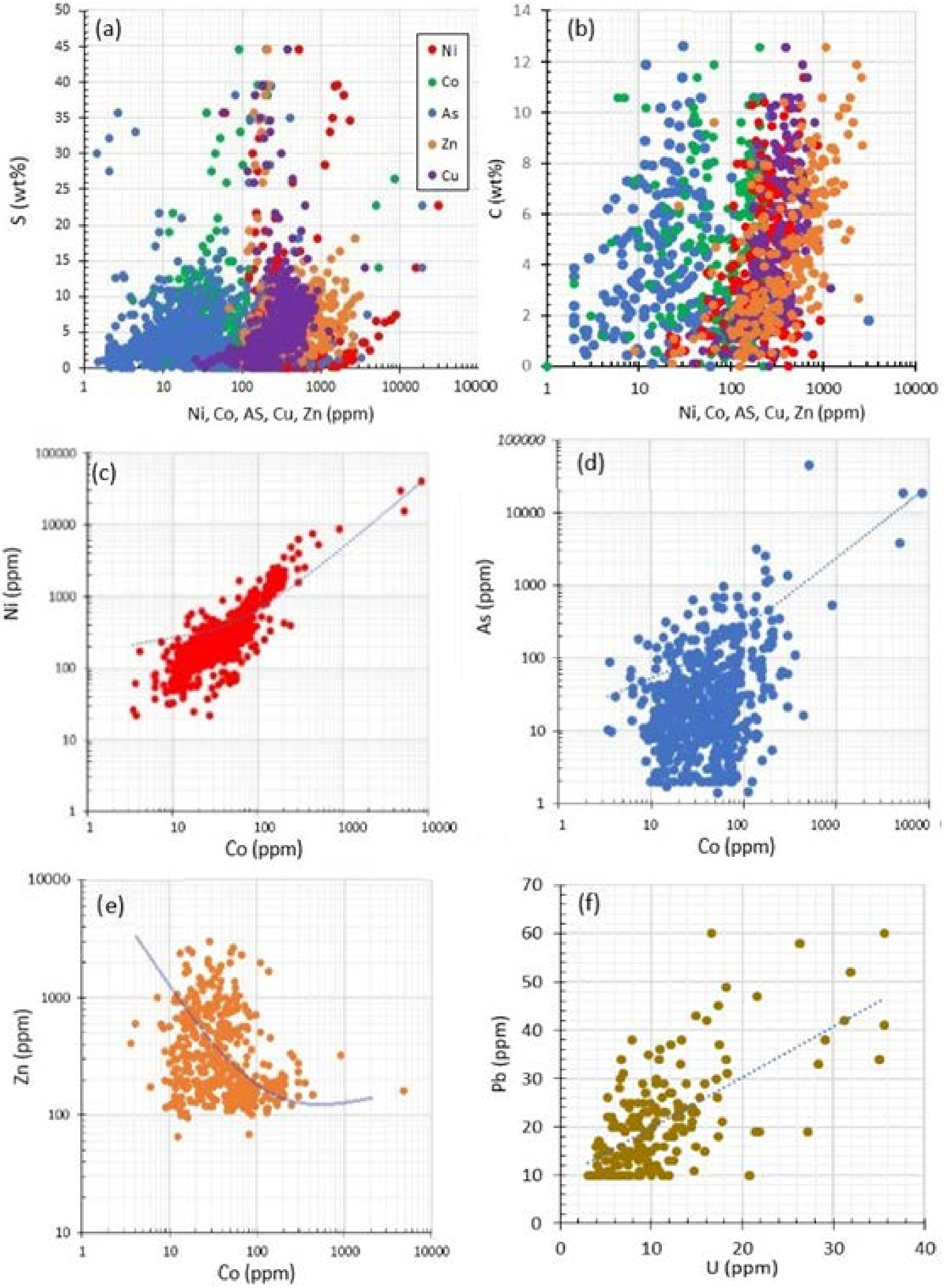

Fig. 22. Results of geochemical characterization of the sulfides in the Raisjoki area.

9 NATURAL GRAPHITE INVESTIGATIONS

Natural graphite is included in the 2023 critical raw materials list of the EU and is widely used as an anode material in batteries. The presence of abundant graphite in the metavolcanic sequences in the Kaustinen–Kruunupyy–Evijärvi area has been known for some time (Lindmark 1978, Lonka 1981). According to geophysical data and diamond drilling, graphite-bearing rocks extend in a N–S direction for several tens of kilometers, with a width ranging from a few to a hundred meters. Diamond drilling in Raisjoki, Emas, and Kaitåsen resulted in intersections of several graphite-rich layers, of which the thickest, reaching a width of approximately 40 m, was penetrated in the Raisjoki target. The graphite content in Raisjoki–Emas sections varies from 5% to 12.6% (Tables 6 and 7). Graphitic carbon (Cg) in the black schists of Kaitåsen has a maximum value of 11.4%, with a median of 4.4% (Nygård & Kuusela 2021). The high graphite content correlates generally well with U and also Zn in samples from Emas and Raisjoki (Table 6). In Emas samples, a graphite content of >4% correlates well with U, but the correlation is poor if Cg > 4% (Fig. 24, Table 6).

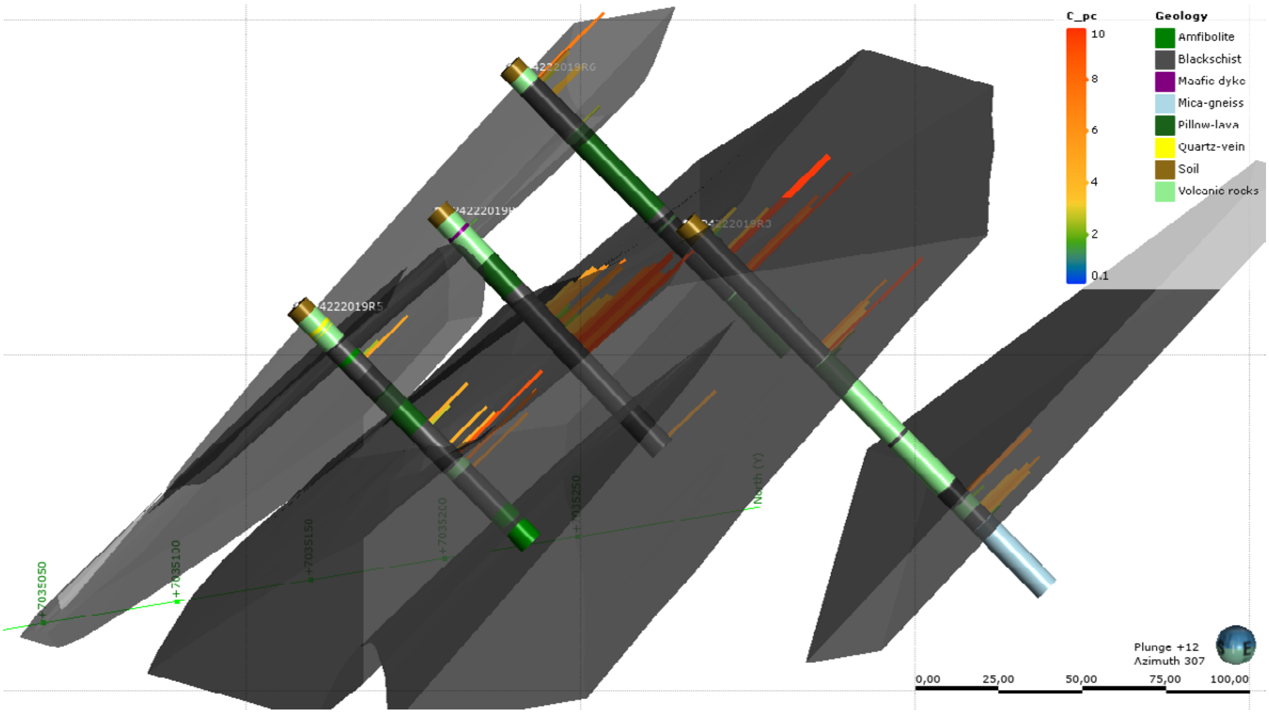

Fig. 23. Simple 3D model of graphite-rich beds in Raisjoki looking NW.

Table. 6 Selected graphite-rich samples with a high content of U and metal sulfides from the Raisjoki area.

Sample	Section	C %	U ppm	As ppm	Co ppm	Cu ppm	Ni ppm	Zn ppm	S %
P222019R3	15.00-16.00	10.6	29.1	216	43.5	552	426	1970	11.2
P222019R3	16.00-17.00	10.6	31.2	180	49.4	448	433	1960	12.1
P222019R4	57.00-58.00	10.2	31.9	442	53.6	272	536	1680	16.4
P222019R4	58.00-59.00	9.89	21.6	266	36.3	288	376	1510	12.3
P222019R4	61.00-62.00	11.4	26.3	29.4	22	674	613	2590	9.93
P222019R5	65.00-66.00	9.14	21.9	44.2	46	402	545	1900	7.69
P222019R6	27.00-27.75	2.55	20.8	5.37	42.5	453	329	218	4.15
P222019R7	113.0-114.0		27.2	1.84	24.2	295	316	1180	4.29
P222019R22	38.0-39.0	1.11	35.1	5.33	72.9	120	490	450	4.22
P222019R24	66.0-67.0	9.46	28.4	27.8	19.8	379	280	591	3.96
P222019R24	67.0-68.0	12.6	35.6	30.7	37.2	397	400	1090	5.7

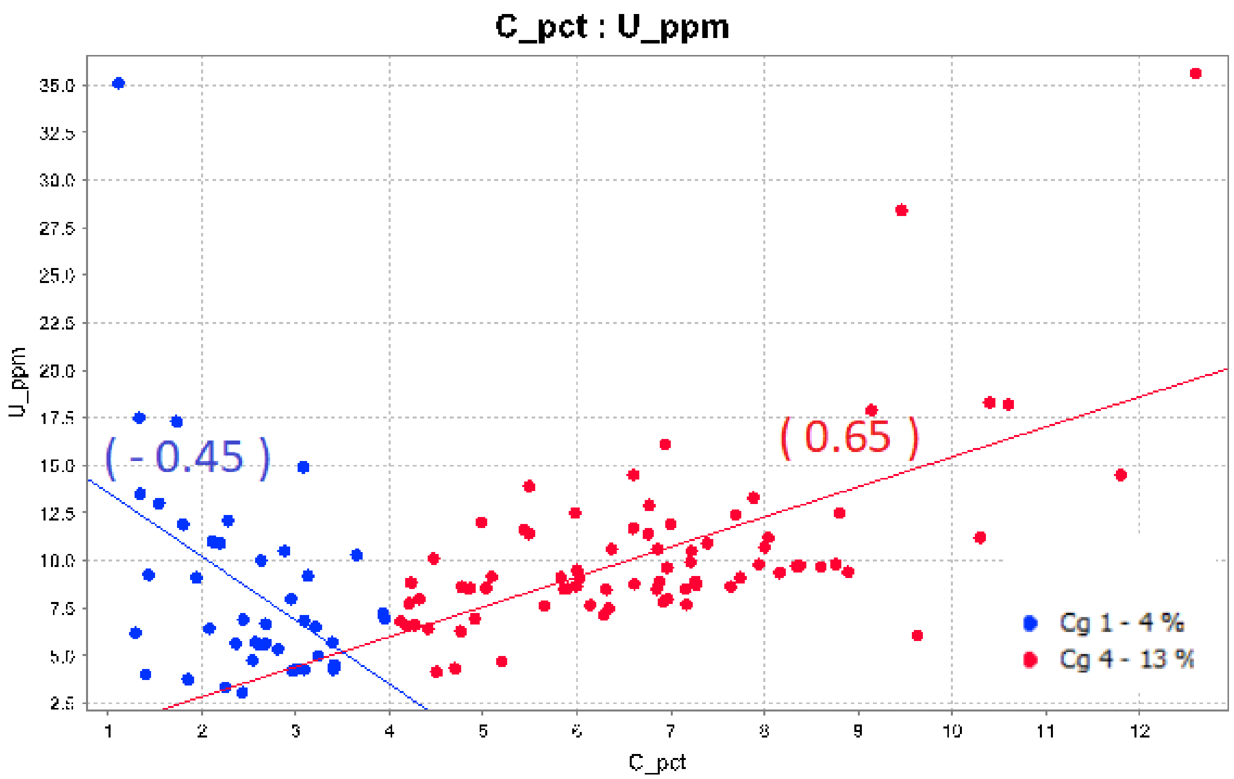

Fig. 24. Two sample populations, with the blue population consisting of 42 samples with graphite Cg > 4% and the red population of 78 samples with Cg > 4%. The correlation between C and U is good if Cg > 4% and poor if Cg is < 4%. High U values are not excluded if Cg < 4%.

Table 7. Intersections from Raisjoki and Emas of black schists with the graphitic carbon content (Cg).

Target	Drill hole	From(m)	To (m)	Intersection (m)	Cg %
Raisjoki	P4222019R4	48	62	14	6.9
Raisjoki	P4222019R4	55	62.65	7.65	9.3
Raisjoki	P4222019R3	15	17	2	10.15
Raisjoki	P4222019R5	92	95	3	8.8
Emas	P4222019R20	32	39	7	7.30
Emas	P4222019R21	35	43	8	7
Emas	P4222019R22	16	31	15	7.20
Emas	P4222019R24	20	28	8	7.10

9.1 Mineralogical outlook

A mineralogical examination under an optical microscope (Al-Ani 2020) indicated that the samples primarily consist of quartz, alkaline feldspar, biotite with subordinate graphite, pyrite, carbonate, and chlorite. Most of the graphite flakes occurred as small, flat, plate-like crystals with lengths of 30 to 200 µm (Fig. 25). Since the graphite occurred in a crystalline (not microcrystalline) form, GTK decided to run quality assessment of test samples of graphite-rich sections from Raisjoki and Emas.

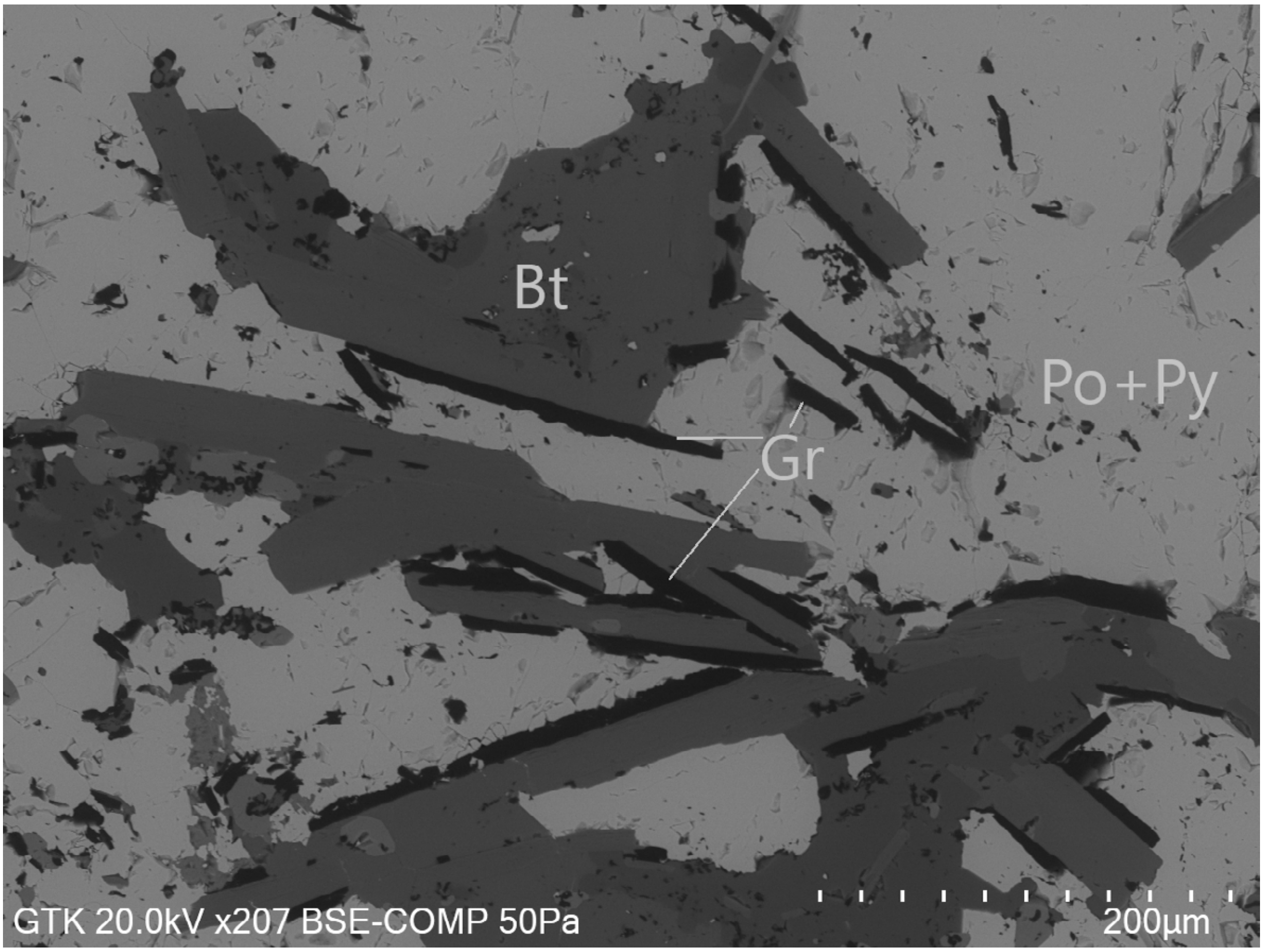

Fig. 25. SEM image of sample R22_95.55m from Emas. Graphite flakes up to 200 µm bordering biotite embedded in pyrrhotite and pyrite.

9.2 Graphite Beneficiation

From Emas and Raisjoki, samples of 16 kg from each target were sent for beneficiation testing. The procedure is described in detail in Salvador (2021). The C feed grade of the samples was 10.1% for the Raisjoki and 7.8% for the Emas sample. The samples were tested with two major flowsheets, in which the later more successful one included an attritor mill (Fig. 26).

After the samples were crushed and grinded with a rod mill, they underwent a rough flotation stage with Kerosen and an MIBC (methyl isobutyl carbinol) compound. Before the cleaning stage, the concentrate was once more milled with an attritor mill (ultrafine grinding).

The ultrafine grinding stage proved to be extremely vital to raise the C grade and recoveries. After two to three cleaning stages, the Emas sample reached a grade of 89% with 66.2% recovery and the Raisjoki sample a grade of 87.5% with 48.2% recovery. For the Raisjoki sample, the C grade after 2–3 cleaning stages improved 2.5x from 35% to 87.5%. After the multistage flotation, the concentrate underwent an alkaline roasting purification process, which raised the purity grade above 99% (Figs. 27 and 28).

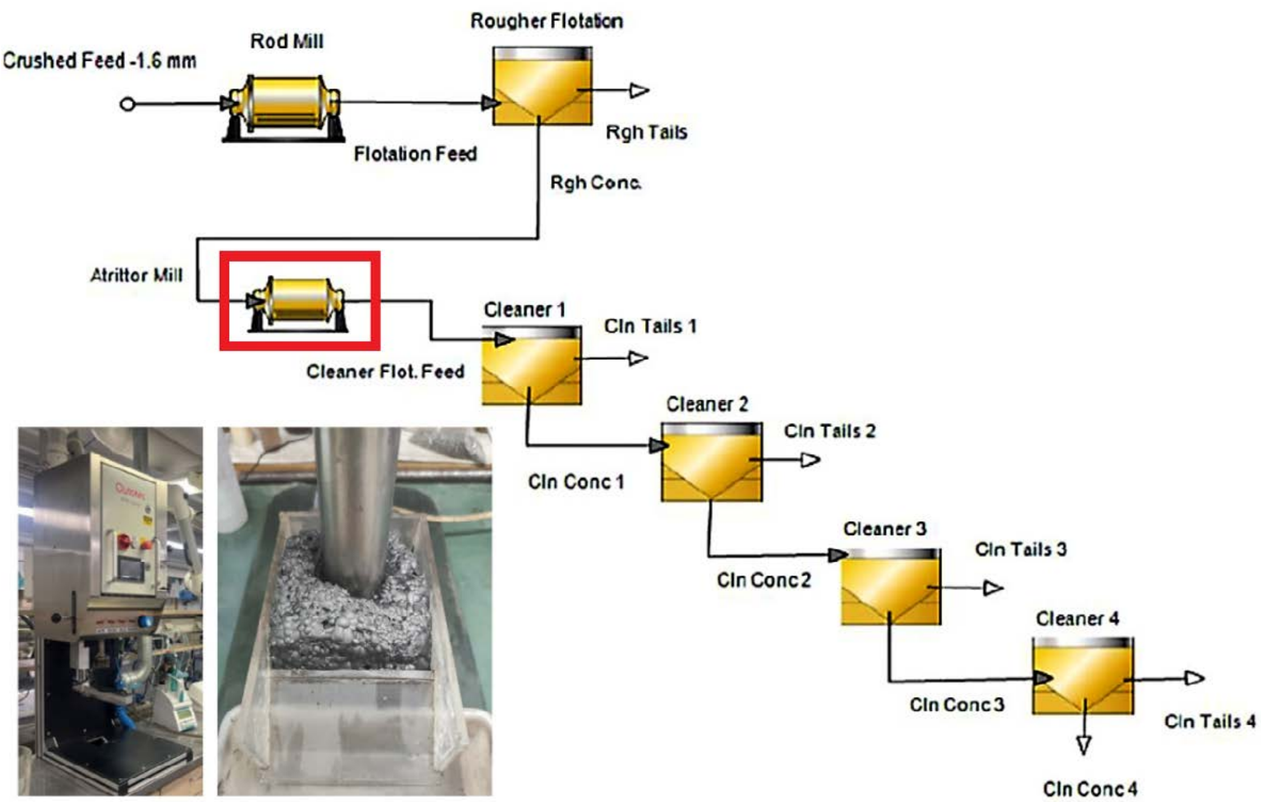

Fig. 26. The beneficiation flow sheet with the ultrafine grinding stage highlighted with a red box.

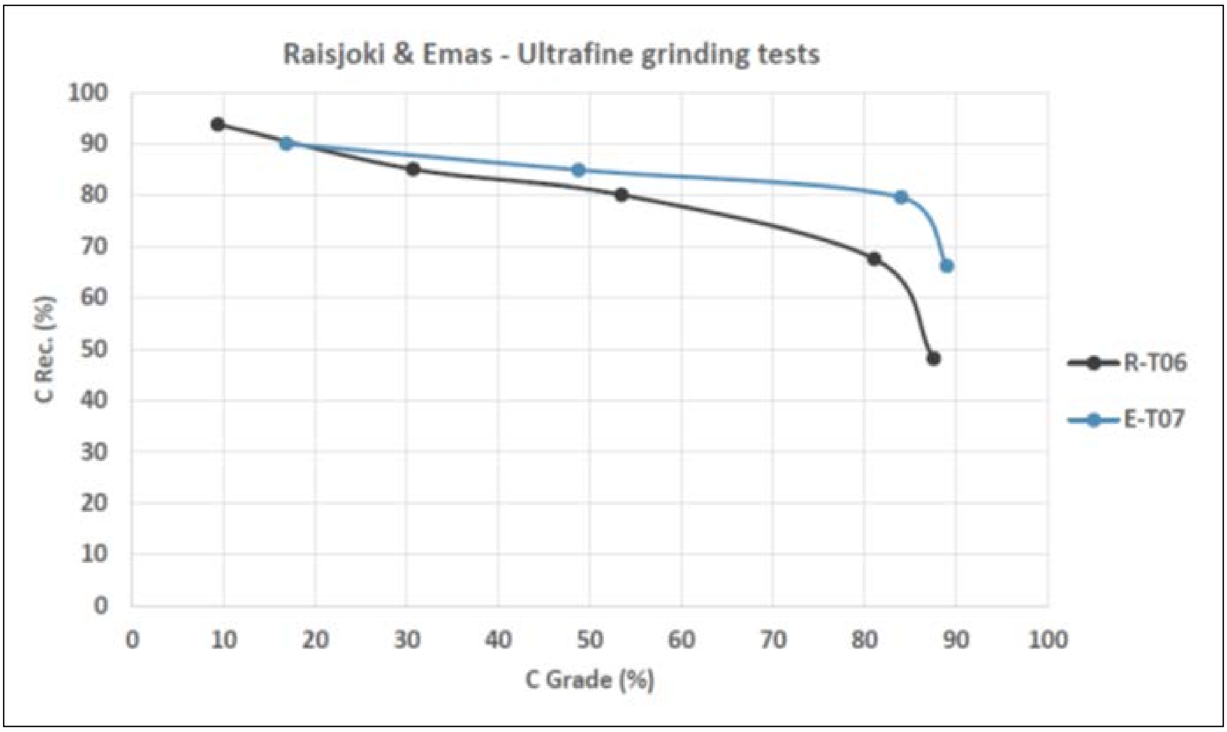

Fig. 27. Adding ultrafine grinding to the flowsheet of Emas and Raisjoki significantly improved the graphite grade after the flotation stage.

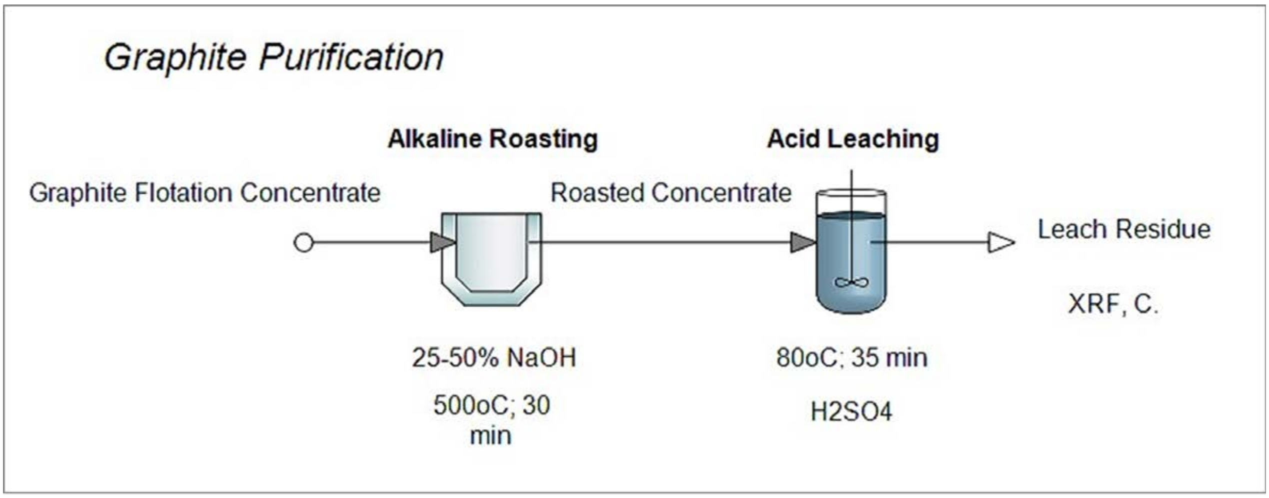

Fig. 28. The graphite purification scheme.

10 STRUCTURAL GEOLOGICAL OVERVIEW OF THE RAISJOKI INVESTIGATION AREA

At least four deformation stages have been recognized in the Ostrobothnian schist belt (Mäkitie 2001). Features from the two first deformation stages, D1 and D2, are the ones best recognized at the map scale and outcrop scale. The accretion of Karelia and Norrbotten continental blocks was recognized by Nironen (1997) and Lahtinen et al. (2005) to be the D1 event, which caused eastward thrusting and the formation of the S1 foliation (Vaarma & Pipping 1997, Chopin et al. 2020). The primary bedding (S0) is often parallel to the S1 direction, which follows the main strike trend of the D1 thrust fault (Fig. 29). The Aho Belt, acting as the thrust fault zone, is also the border zone between the Lappfors and Pirttikylä suites (Fig. 30). The D2 event is associated with the collision of the Bergslagen and Keitele microcontinents, producing N–S compression and the development of F2 folds. The S2 foliation formed in D2 is best visible in the area (Vaarma & Pipping 1997). However, the S2 foliation was not noticed in the Aho and Raisjoki belts, which may be due to the recrystallisation of biotite and hornblende (Vaarma & Pipping 1997). The S2 foliation has an E–W trend similar to the F2 folds that can be observed on the macroscopical scale from the aeromagnetic map in Figure 29. Recumbent F2 folding can interpretably be seen in a transect of a deep seismic reflection profile (FIRE 3a) combined with a conductivity profile in the areas numbered 1 to 4 (Korja & Heikkinen 2008, Vaittinen et al. 2012) (Fig. 29).

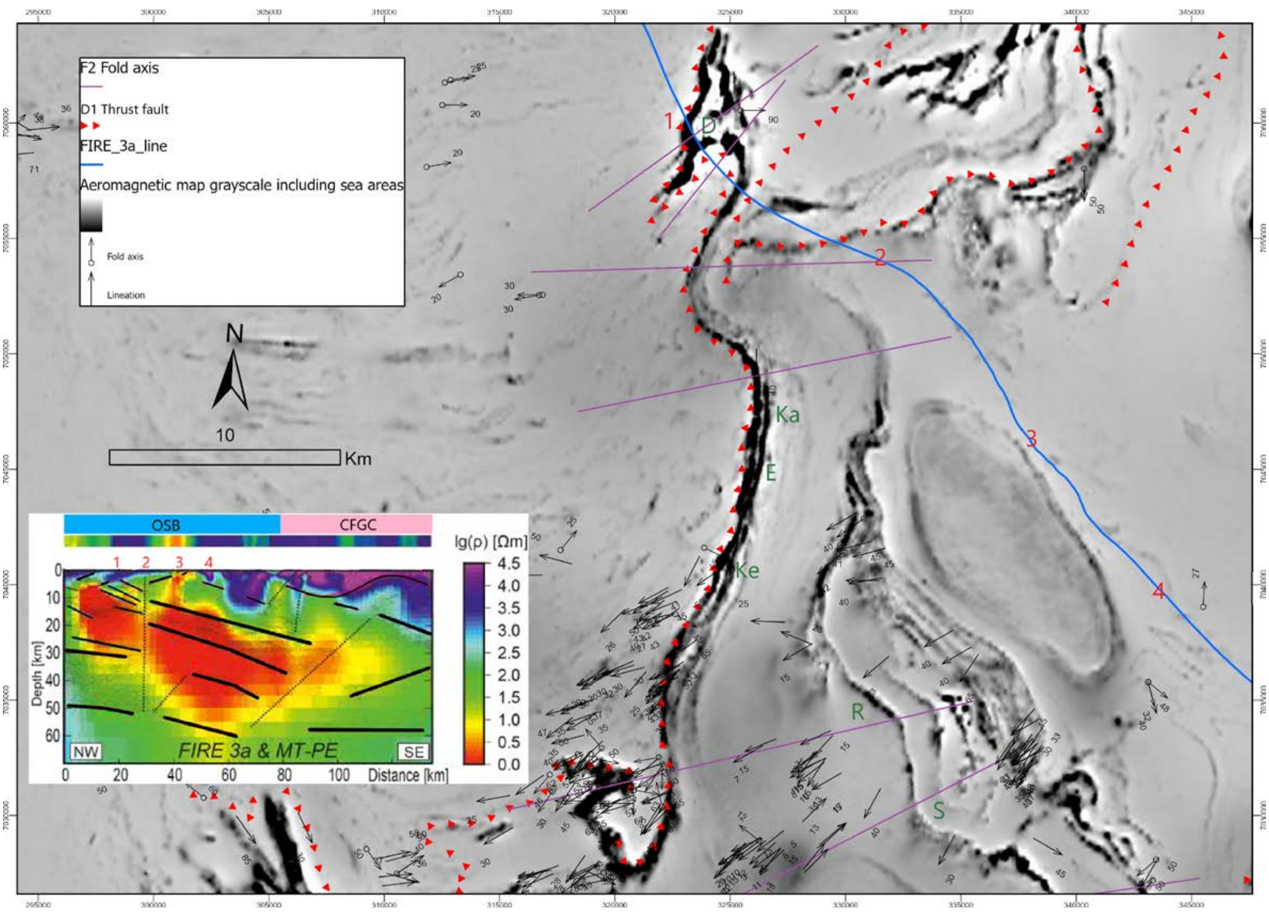

Fig. 29. Aeromagnetic map with macroscopic structural features visualized and investigation targets. D = Dragbacken, Ka = Kaitåsen, E = Emas, Ke = Kedonkangas, R = Raisjoki, S = Sammaloja. The deep seismic reflection profile FIRE 3a transects the area and is sectioned by numbers 1–4. The inset map displays the seismic profile combined with a conductivity map (MT-PE) and deep-seated interpretation by Korja and Heikkinen (2008) and Vaittinen et al. (2012).

10.1 Structural measurements from drill core and outcrops

Structural geological measurements were taken from the drill core wherever possible after each drill run of 3 meters. The measurements represent the best visible foliation in the metavolcanic rock that is interpreted to be S1, which in the thrusted metavolcanics is mostly parallel to the primary bedding S0 (Fig. 30). It is worth noting that local folds might remain unnoticed, since the measurements are not continuous along the core. Bedrock folds, especially in the black schist, often coincide with brittle shear zones. The measured S1 (S0) foliation was visualized in stereo plots from all drilling targets in the Raisjoki study area (Fig. 30).

Outcropping rocks are a rarity around most drilling sites, except in the Dragbacken area, which has an active aggregate rock quarry. Dragbacken is located in the northern part of the N–S-trending Aho belt, in the immediate vicinity of the interpreted thrust between the sulfide graphite schists and Lappfors suite metasediments to the west and the Pirttikylä suite metasediments to the east. The rocks at Dragbacken are mafic volcanics that are mostly massive and fine-grained with graphite sulfide schist intercalations. Although regional scale folding (F2) of the volcanics is apparent in aerogeophysics (Fig. 29), it is not readily apparent at the outcrop scale. Despite the excellent exposure of the volcanics in the quarry walls at Dragbacken, foliations could only be measured from nine locations in the quarries (Fig. 30). Strain is not partitioned evenly throughout the volcanics, as the measurements were taken from distinct zones of higher strain, as well as graphite sulfide schist intercalations within the volcanics. Linear structures were not observed from the fine-grained Dragbacken volcanics.

Aerogeophysics suggest that Dragbacken is situated near the hinge of a regional fold; this could not be observed in the field, however. Since the planar structures are subvertical, it is possible that the area is isoclinally folded, and the hinge of the fold has been removed at the current erosional level. It is also possible that the entire quarry is situated on the same limb of a large fold structure. Linear structures observed to the south of Dragbacken in the central and southern parts of the Aho belt dip at a moderate angle (ca. 45 degrees) to the south. Based on structural measurements, the aerogeophysical data, and regional structural data, the Dragbacken quarry is situated near the hinge or on one limb of a horizontally inclined or a plunging inclined antiform. Geophysical ground magnetic maps suggest emplacement of the spodumene pegmatites in Dragbacken in a fold hinge axial plane according to Ramsay (1967) (Fig. 30a,b,c).

Mansikka-aho is located on the southern edge of the Aho Belt and was chosen for closer study due to the better exposed rocks (Lehto 2021). In this study area, three visible recognizable foliation trends were recognized. In Mansikka-aho, pegmatitic dykes and quartz veins appear to have two dominating directional trends, NNE–SSW and W–E, of which the latter is close with the strike direction of the Dragbacken spodumene pegmatites. According to Chopin et al. (2020), the W–E foliation trend is the S2 foliation that is a remanence of D2 folding. The S2 foliation is more clearly visible in the metatexites in the internal part of the VMC.

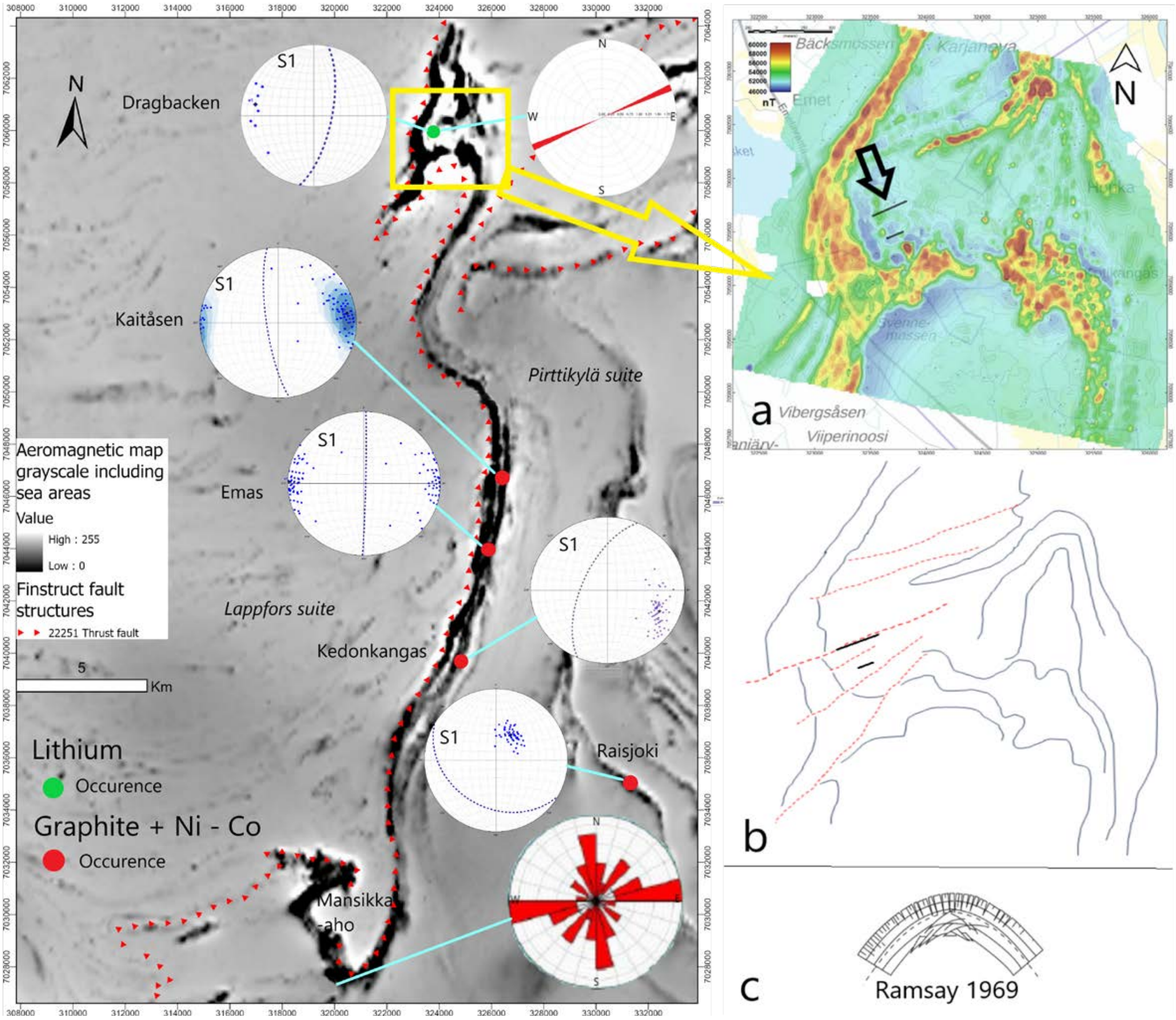

Fig. 30. Left image: Aeromagnetic map with stereo plots of the main foliation trend, interpreted to be S1. The rose diagrams display the measured strike directions of pegmatite dykes in Mansikka-aho and Dragbacken. The dominant W–E strike direction is coeval with the S2 foliation according to Chopin et al. (2020). Right images: a) Geophysical ground magnetic map of the Dragbacken area, with an arrow pointing to spodumene pegmatites (black lines). b) Interpretation of the magnetic data displays an axial plane fracture pattern similar to that described by Ramsay 1967, which appears to be aligned with spodumene pegmatite emplacement.

11 CONCLUSION

GTK investigated the Aho and Raisjoki metavolcanic sequences in central and southern Ostrobothnia in a four-year battery mineral project starting in 2019, with the focus on evaluating the battery mineral potential of Li, Co, and natural graphite in a 900 km^2 area, the so-called Raisjoki investigation area. Additional lithium investigations were executed in the Lapua–Kuortane and Saarala (Kokkola) areas.

On the northern edge of the Aho belt, GTK discovered a new spodumene pegmatite occurrence in the Dragbacken target that was intersected with three drillholes, giving the dyke a strike length of 310 m, with intersections ranging from 1–6 m in width. The best intersection was 4.7 m @ 0.78% Li_2O. Another new lithium occurrence discovery was made at the Pikkalantausta target in Lapua–Kuortane, where an outcropping LCT pegmatite contained the lithium phosphate amblygonite–montebrasite.

Supported by mineralogical quality assessments and beneficiation testing by Mintec Outokumpu, two new discoveries of flake graphite occurrences in the Emas and Raisjoki targets can be confirmed. Before the beneficiation process, selected graphite samples were investigated with the Raman spectrometry technique to assess the graphitization temperature and degree of crystallinity. The results of drill core assays on Emas samples verified a flake graphite content of >7% in several black schist sections of up to 15 m in length. In the previously known Raisjoki target, a 20-m layer with Cg > 6% Cg was intersected. In the Kaitåsen target, a 20-m section contained 4.4% graphite, locally reaching up to 9% Cg. In a mineralogical overview, the graphite flake sizes in Emas and Raisjoki varied from 30 µm to 200 µm, and samples were therefore sent for beneficiation tests at Mintec Outokumpu. The tests involved crushing, grinding, flotation, and purification by alkaline roasting and acid leaching. Using ultrafine grinding before three flotation stages proved most efficient, giving a concentrate in Emas samples of 89% purity and 66.2% recovery and in Raisjoki samples of 87.5% purity and 48.2% recovery. After the purification process, a Cg grade of >99% was achieved in Emas and Raisjoki samples.

Between the graphite layers in Emas, in partly metasomatically altered volcanic rocks, a local Ni–Co–Au sulfide mineralization reached grades as high as 3 m @ 0.5% Co and 2% Ni, with a 2-m section of 0.34 ppm Au or 10.5 m of 0.11% Co and 0.8% Ni. A total of 35 thin sections from 10 drill holes were selected for mineralogical studies. Selected samples underwent mineralogical and micro-textural characterization by optical microscopy and scanning electron microscopy (SEM), while quantitative and qualitative microanalyses of sulfides were performed using a CAMECA SX100 electron microprobe (EPMA) and scanning electron microscopy with EDS system model SU3900 at the GTK mineral laboratory. The main ore-forming minerals containing Ni–Co–Au were identified in a mineralogical examination as gersdorffite, Co–arsenopyrite, cobaltite, and pentlandite. A significant rise in Ni–Co concentrations in sections of 15 m or greater could be followed to the north and south, with an average Co content of 100–200 ppm and a Ni content varying from 0.1–0.2%. An elevated Co content was observed along the metavolcanic sequence 3 km further north in Kaitåsen. Elevated levels of the elements Ni, Co, As, Cu, and Au were found in the Dragbacken area in till survey and drill cores. The till survey revealed cobalt anomalies, some of which were associated with As, Cu, and Ni. Gold is anomalous at a few sampling locations. North of the spodumene pegmatite dykes is a location where Au potential is associated with pathfinder elements. The As mineralization in drillhole R35 near this location also shows Au pathfinder elements, together with Co and Ni. In Kedonkangas, indications of scheelite (W) were confirmed, at best reaching 1970 ppm in one intersection. Additionally, in Kedonkangas, silicified rocks, although not systematically analyzed for Au, contained 0.126 ppm Au in one drill intersection.

In Sammaloja, till and base of the till sampling indicated a potential sulfide mineralization in a delimited area. Due to the discoveries of spodumene pegmatite, Dragbacken was a major site for surficial and percussion drill till sampling. LCT pegmatites can display elevated concentrations of elements in the form of a reaction halo in contact rocks around the pegmatite body. The most mobile elements are Li, Cs, and Rb, which seem to create the most widespread halo in the amphibolite contact in Dragbacken. Surficial till sampling was also executed in Emas, displaying well-elevated Co and Cr anomalies in the continuation one kilometer further south. The till sampling result emphasized a lateral fault slip movement in the area, demonstrating sharp contact horizons with a high contrast in interpolated Ca/Cr values.

The black schists have high conductivity and higher magnetic susceptibility. The black schists also tend to have higher gamma radiation than neighboring rocks. In Emas, the elevated U content in black schists correlates well with high Cg values. The volcanic (volcanic rock, amphibolite, basalt) lithologies can clearly be distinguished from the other lithologies based on geophysical downhole data in Emas and Kaitåsen. These have low electrical conductivity, low gamma radiation, and a high density. The graphite-rich black schists are the least competent rock units, and have acted as a thrust slip movement surface (Vaarma & Pipping 1997), and as indicated in these investigations, they could have acted as intrusion channels for rocks of a mafic and ultramafic nature. Elevated values of Co, Ni, As, Cr, P, and REE elements in metasomatized rocks within black schists could be the result of an interaction of these processes in Emas, Kaitåsen, Raisjoki, and Kedonkangas, but this requires further geochronological verification work.

Brittle deformation in mafic competent rocks has, in contrast, acted as intrusion channels for a spodumene pegmatite in Dragbacken. The emplacement of pegmatitic melts in the bedrock is almost always structurally controlled, which is also the case at Dragbacken. The Dragbacken spodumene pegmatites have intruded in a lineament visible in ground geophysical maps. The lineament is interpretably an axial plane of a fold structure that bends the volcanic sequences in Dragbacken. Similar structural locations of emplacement for spodumene pegmatites are common in the Kaustinen region. The W–E strike directions of pegmatites, in accordance with the direction of S2, have been mapped in the southern part of the Aho belt by Lehto (2021).

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