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Investigation of Dragbacken lithium pegmatite occurrences, Kruunupyy, Ostrobothnia, western Finland

Henrik Nygård, Helena Hulkki, Jarkko Jokinen, Janne Kuusela, Tuomas Leskelä and Noora Thurman

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

Front cover: Rock sample from Dragbacken with light green spodumenes.
Photo: Henrik Nygård, GTK.

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In 2019, the Geological Survey of Finland discovered previously unknown spodumene pegmatite dykes at Dragbacken, Kruunupyy, expanding the known occurrences in the Kaustinen lithium area westwards.

Bedrock mapping, till sampling and a ground geophysics programme were commenced to better understand the potential for lithium occurrences in the area. The extensions of the spodumene pegmatite dykes were drilled in a 1500 m drilling programme, together with exploratory drillholes at selected till anomalies. The northernmost spodumene pegmatite dyke was found to extend for a minimum of 350 m and vary in width between 0.5–5.8 m. The dyke is zoned and the lithium content varies, reaching at best the upper analytical limit of 10 000 ppm. An extensive halo effect in the wall rock of LCT pegmatite-related elements can be observed around the dyke.

The southern spodumene pegmatite dyke, with a width of 0.5–1 m, can be followed for approximately 100 m in a rock quarry wall at Dragbacken. Signs of other pegmatites were found in drillholes and in the till.

The host rock of the dykes mainly consists of mafic volcanic rocks, in places having layers of deformed black schist and sulphide-bearing schists. Fluid movement through the rock has locally resulted in elemental mobilization and the formation of sulphides as pyrrhotite and in places arsenopyrite.

An age-dating study on columbites from the southern pegmatite dyke yielded an emplacement age of 1796 ± 5.8 Ma. The only known possible exposed granitic magma source in the area is a 1801 ± 16 Ma old pegmatite granite intrusion located ca. 5 km northwards. The magmatic source may also lie at depth.

The boulder mapping located some highly evolved pegmatite boulders throughout the area. Considerable areas with pegmatite boulders indicate an abundance of various pegmatite dykes and intrusions in the bedrock covered by the glacial till.

In 2021, an exploration permit was applied for covering the spodumene dykes and the immediate area of Dragbacken.

Keywords: battery minerals, critical minerals, lithium, spodumene, pegmatite, Kruunupyy, Kaustinen, Pohjanmaa, Keski-Pohjanmaa

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Geologian tutkimuskeskus paikansi vuonna 2019 aiemmin tuntemattomia spodumeenipegmatiittijuonia Kruunupyyn Dragbackenissa, ja näin Kaustisen litiumalueen tunnetut esiintymät laajenivat länteen.

Alueen litiumpotentiaalin paremman ymmärryksen saavuttamiseksi tehtiin kallioperäkartoitusta, maaperänäytteenottoa sekä maastogeofysikaalisia mittauksia. Spodumeenipegmatiittijuonet ja niiden jatkeet kairattiin 1 500 m:n kairausohjelmalla. Osa moreeninäytteenotossa ilmaantuneista anomalioista selvitettiin tutkimuskairarei'illä. Pohjoisin spodumeenipegmatiittijuoni jatkuu vähintään 350 m, ja sen leveys vaihtelee 0,5 ja 5,8 m:n välillä. Juoni on vyöhykkeellinen, ja litiumin määrä vaihtelee saavuttaen parhaimmillaan analyysimetodin maksimiarvon 10 000 ppm. Pohjoista juonta ympäröi halo, jossa osa LCT-pegmatiitteihin liittyvistä alkuaineista havainnoidaan sivukivessä.

Eteläinen spodumeenipegmatiittijuoni on leveydeltään 0,5–1 m ja on seurattavissa noin 100 m Dragbackenin kiviaineslouhimon pystyseinällä. Merkkejä muista juonista on havaittavissa muissa kairasydämissä ja moreeniaineistossa.

Juonten sivukivi on usein emäksinen vulkaniitti, jossa esiintyy paikoin mustaliusketta tai sulfidipitoista liusketta. Paikoin fluidiliikunnan seurauksena kallioperään on muodostunut magneetti- ja arseenikiisuuntumaa.

Eteläisen juonen kolumbiiteista tehty ikämääritys osoitti juonen iäksi 1 796 ± 5,8 Ma. Noin 5 km pohjoisempana esiintyvä, lähialueen ainoa paljastunut mahdollinen lähdegraniittiintruusio, osoittautui 1 801 ± 16 Ma vanhaksi. On myös mahdollista, että juonten lähde sijaitsee syvyydessä.

Lohkarekartoitus paikallisti useampia pitkälle kehittyneitä pegmatiittilohkareita. Alueella esiintyy paikoin runsaasti monenlaisia pegmatiittilohkareita, ja se osoittaa, että alueen moreenipeitteen alla kallioperässä on runsaasti pegmatiittijuonia ja pegmatiitti-intruusioita.

Dragbackenin ympärille haettiin vuonna 2021 malminetsintälupaa kattamaan löydetyt juonet ja niiden välitön ympäristö.

Asiasanat: akkumineraalit, kriittiset mineraalit, litium, spodumeeni, pegmatiitti, Kruunupyy, Kaustinen, Pohjanmaa, Keski-Pohjanmaa

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CONTENTS

1 INTRODUCTION

The Raisjoki project formed part of GTK's battery mineral potential mapping project. The general investigated area was in the municipalities of Kruunupyy and Kaustinen. The aim of the project in this area was mainly to investigate the source of some historical layman boulder samples containing elevated cobalt. The sources of these boulders were deemed to be the generally north–south-running mafic volcanic and black schist belts in the area. At the same time, the potential for lithium-bearing LCT pegmatites was investigated, since very little historical work had previously been conducted in the area.

The potential for lithium pegmatites was estimated to be high because of the vicinity of the Li occurrences in the Kaustinen area. The area belongs to the Pohjanmaa schist belt, with the large, ca. 1800 Ma old post-tectonic pegmatite granite intrusions of Veteli and Alaveteli. These S-type granites are of the same age as the spodumene dykes in Kaustinen and are possible source granites for the spodumene occurrences (Mäkitie 2001).

At the start of the field mapping season of 2019, the GTK field team discovered previously unknown spodumene pegmatite dykes in the northern part of the Raisjoki investigation area at Dragbacken (Fig. 1). In the investigation, this area was named Honka, after a small village located to the east of the area.

An initial ground magnetometric survey and a percussion drilling campaign were conducted, together with complementary surface till sampling. After this, a decision was made to commence a 1500 m drilling programme. The aim was to investigate the extent of the spodumene dykes, as well as to check some lithium anomalies discovered during the till sampling, which could indicate possible additional pegmatite dykes.

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 when the reservation notification expired. This was to secure a possibility for further work in the area.

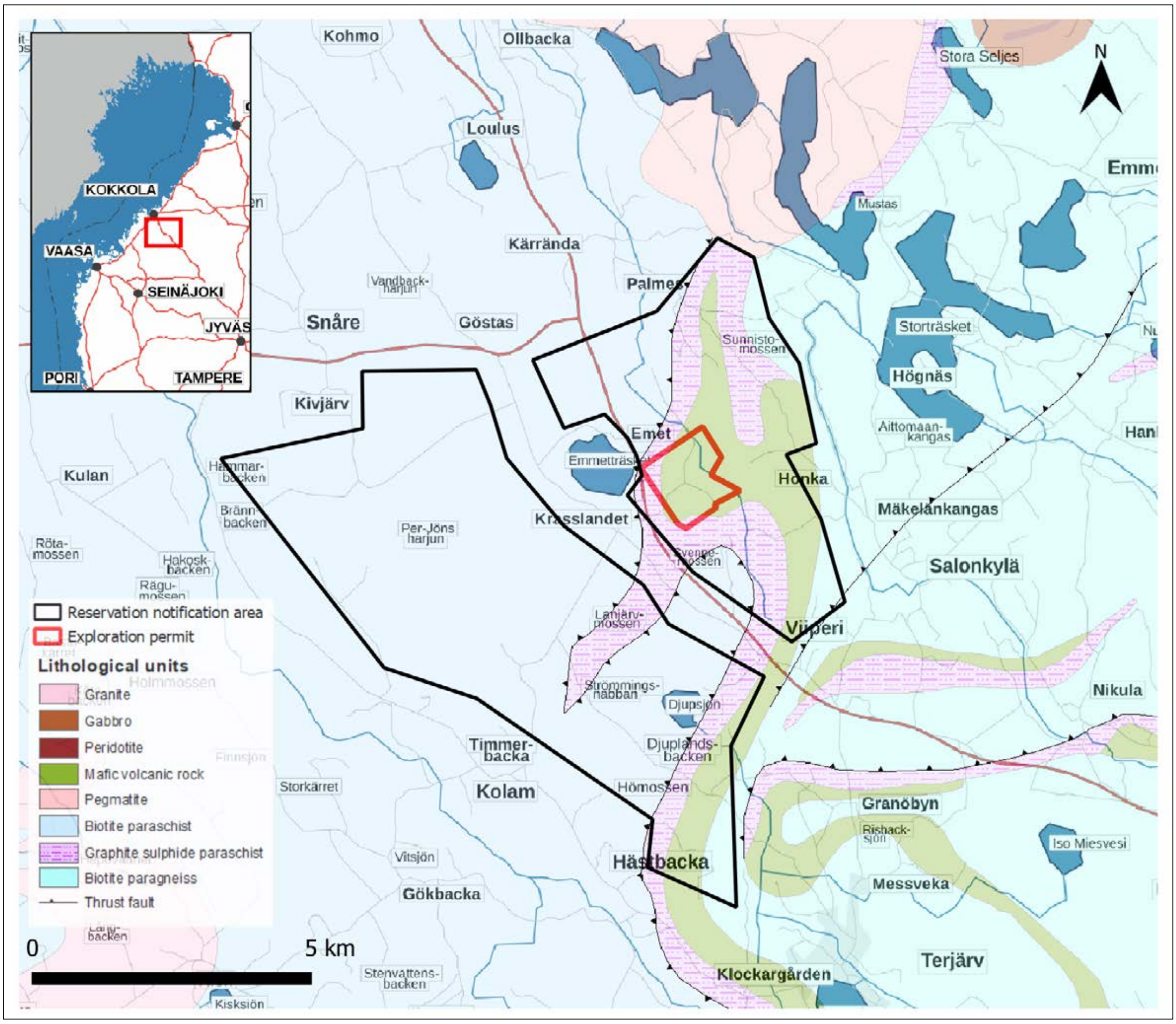

Fig. 1. A map showing the major lithological units. The location of the Honka reservation notification area is framed in black and the exploration permit in red around the immediate area of Dragbacken. Basemaps © National Land Survey of Finland.

1.1 General geology

The Dragbacken area is part of the Pohjanmaa schist belt, consisting of supracrustal metasediments (greywackes, pelites and black schists) and long-stretching belts of volcanic rocks (Fig. 1). Dragbacken is located in a north–south-extending volcanic belt that acted as an overthrust region during the 1900–1870 Ma Svecofennian orogeny, resulting in regional-scale folding of the bedrock. The Pohjanmaa schist belt is characterized by post-tectonic 1800–1790 Ma old S-type granite melts intruding into the metasediments (Mäkitie 2001).

The metamorphic grade has been interpreted as low amphibolite facies. This is the same grade as the Kaustinen spodumene pegmatite occurrence region, 10–20 km to the east. From Dragbacken, the metamorphic grade gradually starts to increase westwards towards the Vaasa Migmatite Complex, reaching granulite facies ca. 20 km to the west (Chopin et al. 2020). The low amphibolite facies favours the formation of fertile granites that generate rare-element pegmatites (Selway et al. 2005).

2 GROUND GEOPHYSICS

GTK's national aerogeophysical dataset covers the area. The new survey at Dragbacken consisted of a ground magnetic survey, with measurements conducted by GTK in 2020.

A total of 68 magnetic ground profile lines were measured, with a 50-m profile line spacing. The line directions were approximately at 100 degrees. Measurements were collected every 1 m with a GMS-19 Overhauser magnetometer. Multiple magnetic anomalies can be observed in the survey area (Fig. 2). The strongest anomalies relate to sulphide-bearing graphite paraschist and are probably caused by pyrrhotite.

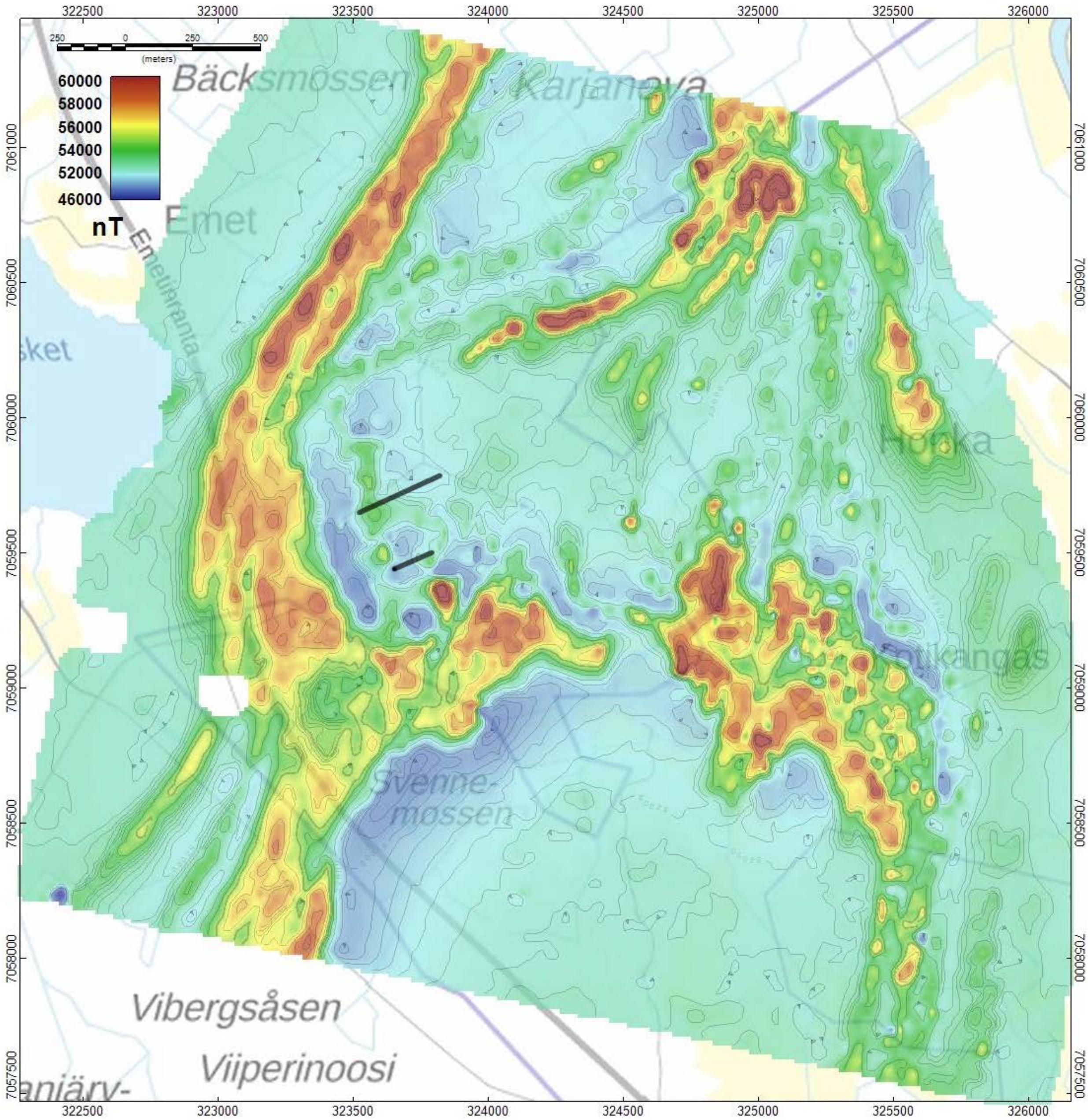

Fig. 2. Results of a magnetic ground survey presenting magnetic components over the survey area. The approximate locations of the spodumene pegmatite dykes are indicated with black lines.

3 TILL GEOCHEMICAL SURVEYS

Four separate geochemical surveys were performed in the Honka target area in 2020–2021 (Fig. 3). 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. Only significant results are treated in this report, while the results are described in more detail in Hulkki 2022 (*in prep.*).

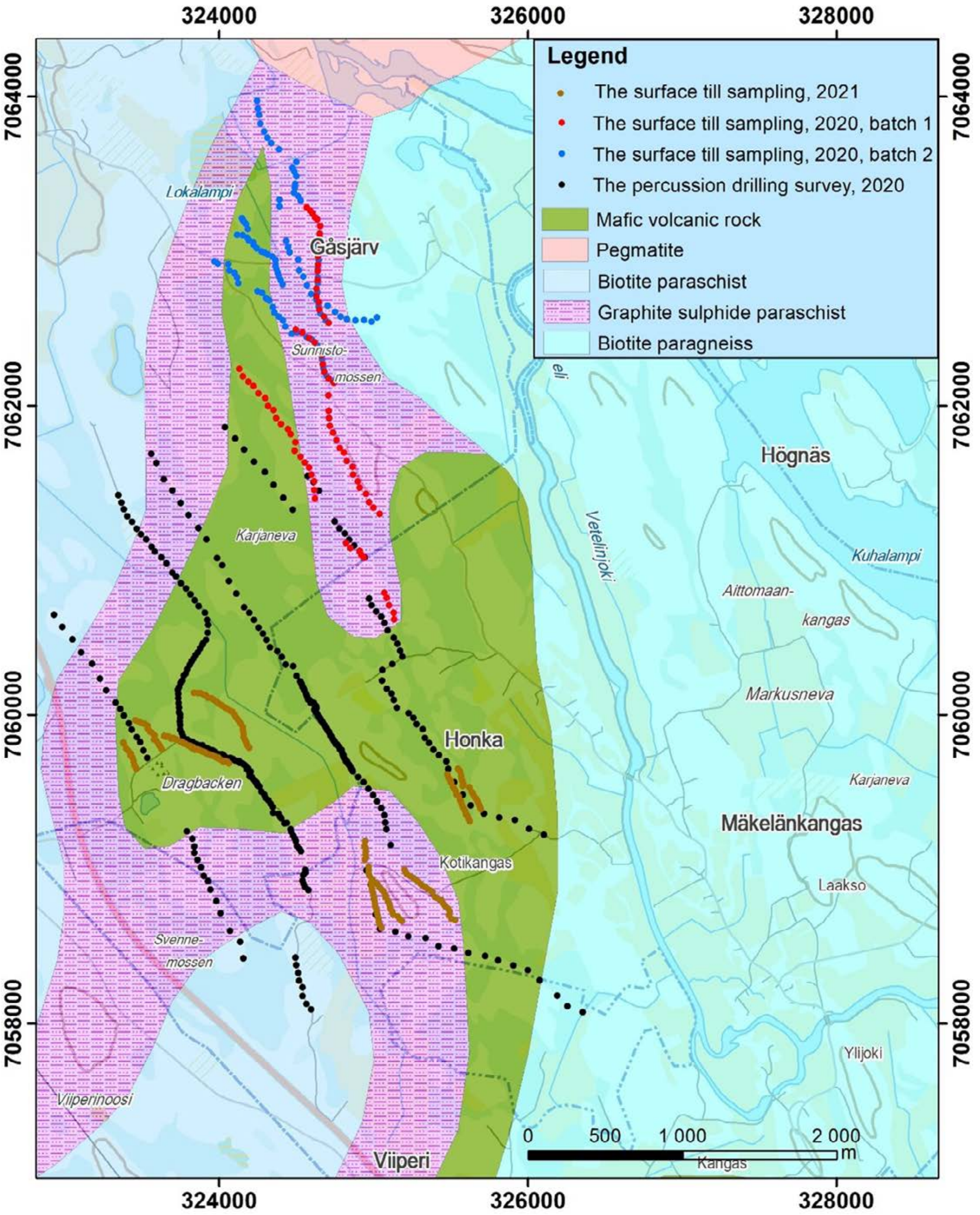

Fig. 3. The sample points of the geochemical till surveys on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Basemaps © National Land Survey of Finland.

3.1 Methodology

The geochemical surveys were carried out as line sampling with a sample spacing of 10–100 m. Deep-seated till samples were taken by percussion drilling from the base of the till. For the surface sampling, small pits were dug with a shovel (depth 30–40 cm) and the samples were taken from the B horizon.

The laboratories of ALS Finland Oy and Eurofins Labtium Oy provided the analyses. The till samples were analysed using different chemical methods: The surface till samples were analysed by modified aqua regia digestion (1:1 HNO_3:HCl) in combination with low-detection-limit ICP-MS (method ME-MS41W) or by ionic leach (a weak leach method) with ICP-MS (method ME-MS23). The samples collected with percussion drilling were analysed by aqua regia digestion and with ICP-OES-ICP-MS and GFAAS (methods 511P, 511M, 511U) and by 4-acid digestion with ICP-MS (method 306M). The base of till samples collected by percussion drilling was sieved to the fraction of <0.06 mm before analysis. Altogether, the concentrations of 59–65 elements were determined.

Data analysis was conducted as an anomaly assessment, in which element concentrations were classified into different categories and anomalous concentrations were separated from the background based on a threshold value. The threshold value was determined using a log-transformed Tukey boxplot, in which the threshold between the anomaly and the background was determined by the formula Q3 + (1.5 x IQR), where IQR = Q3-Q1 (Carranza 2009). In addition, another classification was used, in which response ratio (RR) values were determined for selected elements. The RR is the ratio of the sample element concentration to the element background value for all samples: RR = element concentration in a sample / median (Q1 of the element concentration). RR values > 5 are considered as anomalous. Elemental distributions of some elements were also presented as inverse distance weighted (IDW) interpolated maps. Only the elements related to possible Co mineralization (Co, As, Au, Cu, Ni) or Li pegmatite (Be, Ga, Li, Nb, Rb, Sn, Ta) occurrences are treated here.

3.2 Percussion drilling survey

According to the percussion drilling survey, there are several Li anomalies in the area (Fig. 4). The Li anomalies are sometimes associated with elevated contents of the pathfinder elements (Be, Nb, Rb, Sn, Ta, Tl). In general, the concentrations of Li and its pathfinder elements are elevated in the northern and southern parts of the area (Fig. 5). The site of the westernmost Li anomaly was examined by diamond drilling, and as a result, the drill core intersected a 5.8-m-wide Li-bearing pegmatite.

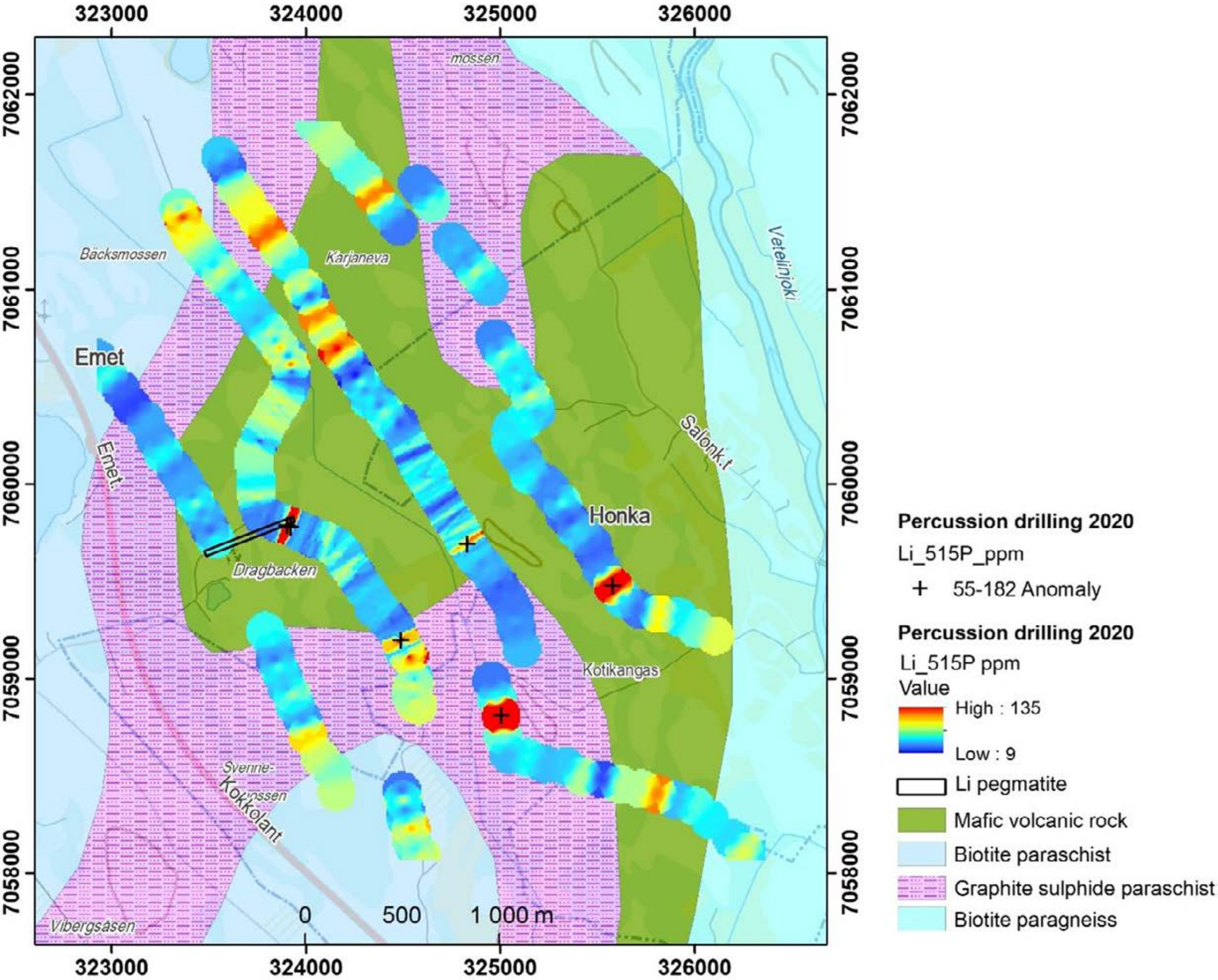

Fig. 4. Li anomalies determined using a log-transformed Tukey boxplot and the interpolated (IDW) concentration of Li presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Basemaps © National Land Survey of Finland.

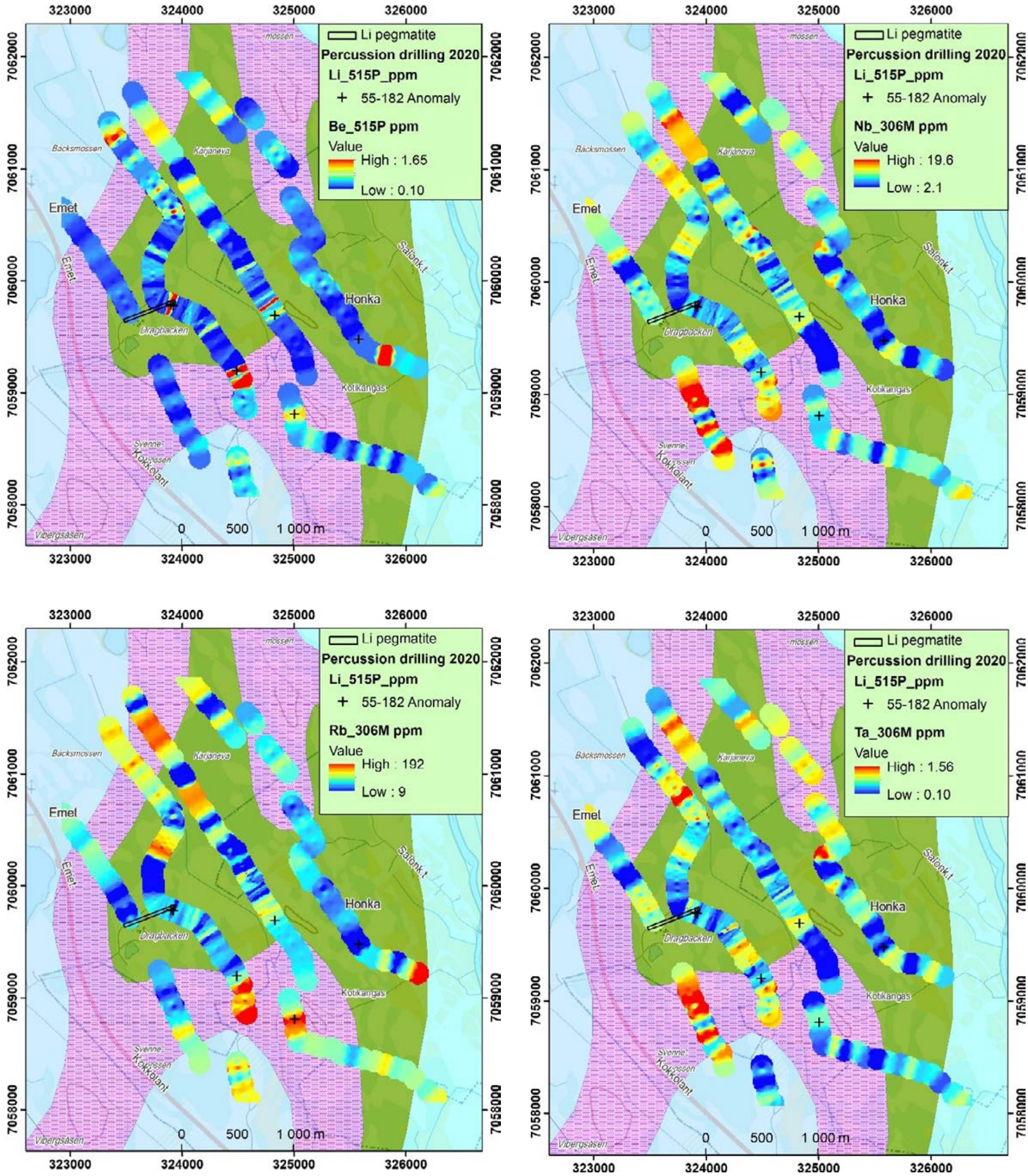

Fig. 5. Li anomalies determined using a log-transformed Tukey boxplot and the interpolated (IDW) concentration of Be, Nb, Rb and Ta presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Basemaps © National Land Survey of Finland.

The mafic volcanite unit in the area is widely Co anomalous (Fig. 6). Some of the Co anomalies are associated with elevated contents of As, Cu and Ni, especially in the western part of the area, concentrating on lithological contacts or close to them (Fig. 7). The anomalous values may simply indicate the existence of mafic or ultramafic rocks. In addition, the sulphide-bearing graphite schists observed intercalated with the mafic rocks can cause anomalous values of Co. On the other hand, the highest observed value of Co (474 ppm Co) could point to mineralization.

Some Au anomalies are present in the study area (Fig. 7), but these are usually of the "gold-only" type, signifying that they probably represent non-local anomalies. The exception is the site on the northern side of the recently discovered Li-bearing pegmatite. Here, the Au anomaly is associated with elevated concentrations of some of its pathfinder elements and with the Co anomaly (Fig. 7).

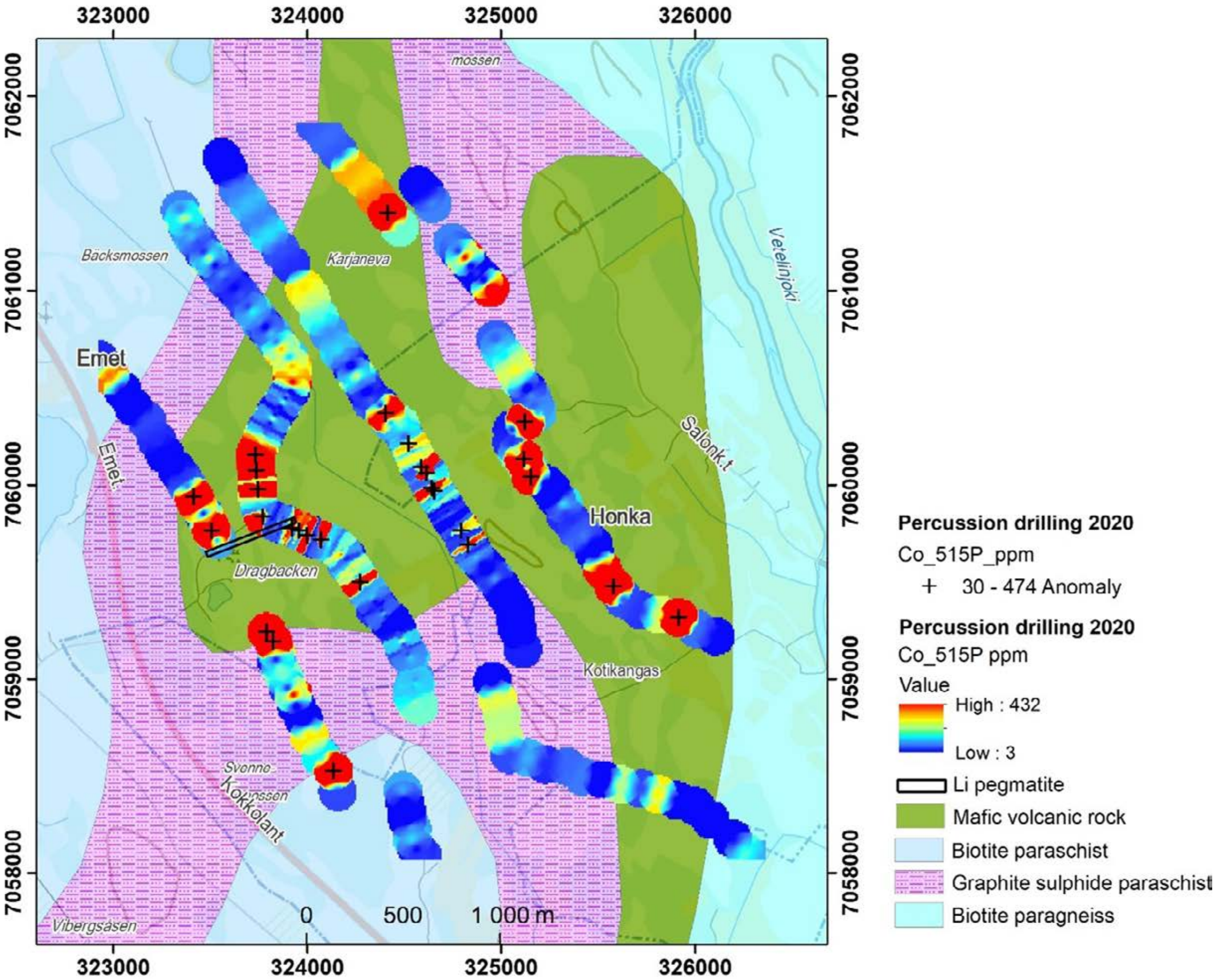

Fig. 6. Co anomalies determined using a log-transformed Tukey boxplot and the interpolated (IDW) concentration of Co presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Basemaps © National Land Survey of Finland.

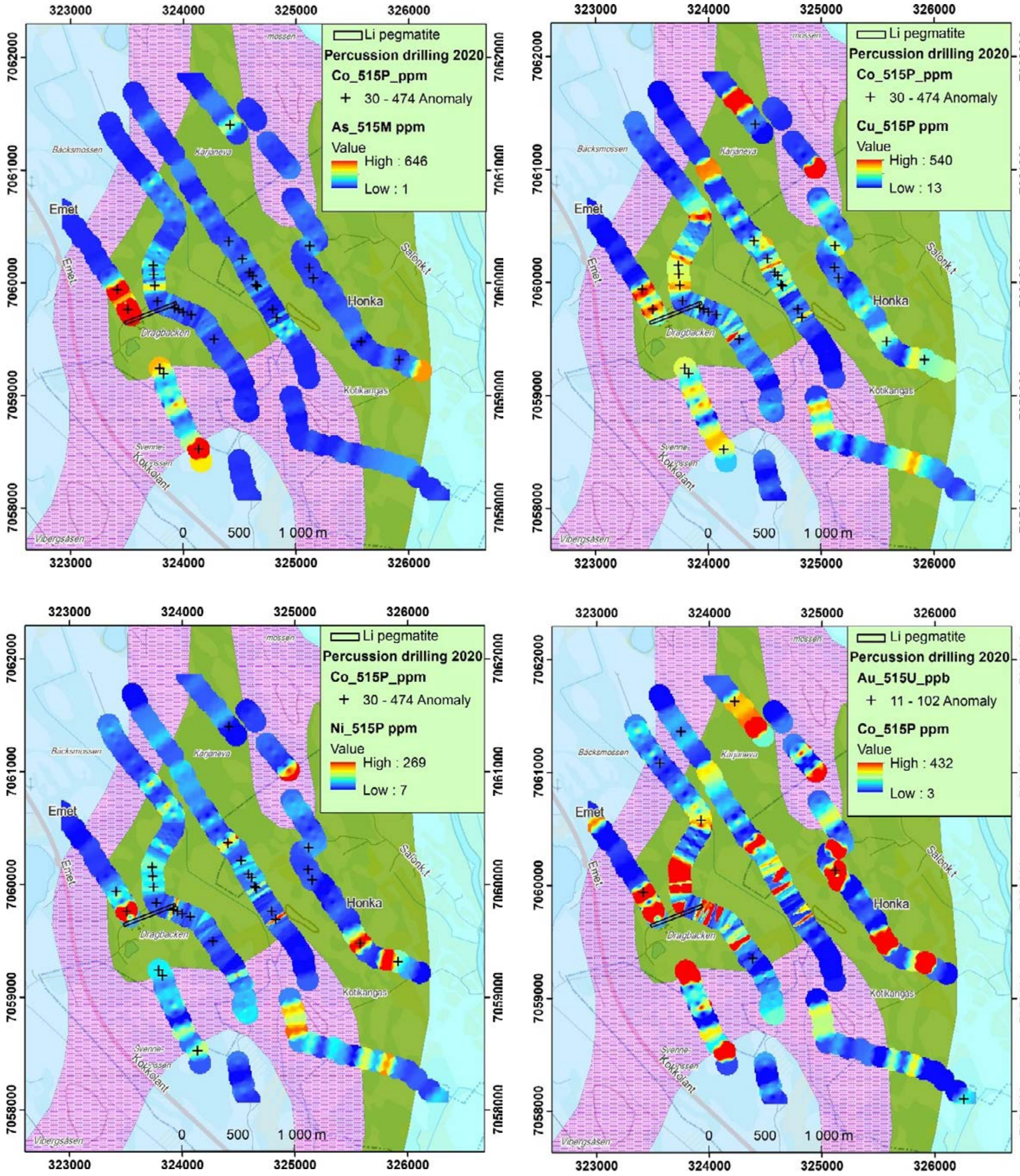

Fig. 7. Co and Au anomalies determined using a log-transformed Tukey boxplot and the interpolated (IDW) concentration of As, Cu, Ni and Co presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). Basemaps © National Land Survey of Finland.

3.3 Surface geochemical surveys

3.3.1 The 2020 survey of the Gåsjärv area

The northern part of the study area was investigated in 2020 in a surface geochemical survey consisting of two batches of analysis (Fig. 3). For the data analysis, the batches were classified separately due to differences in their elemental concentration levels.

According to the classification of the log-transformed Tukey boxplot, only a few Co anomalies (Fig. 8) or anomalies of its pathfinder elements (As, Cu, Ni) exist in the area. On the other hand, the central part of the area has elevated Co concentrations and represents a high background area. The same applies to the pathfinder elements of Co. It is noteworthy that the high background area appears to stretch in the direction of glacial transport. The modified aqua regia method of analysis to some extent digests grains of till, and the element signal is not therefore necessarily local, as it would be in the true weak leach method. If this is the case, the source of metals is located on the western or northwestern side of the high background area.

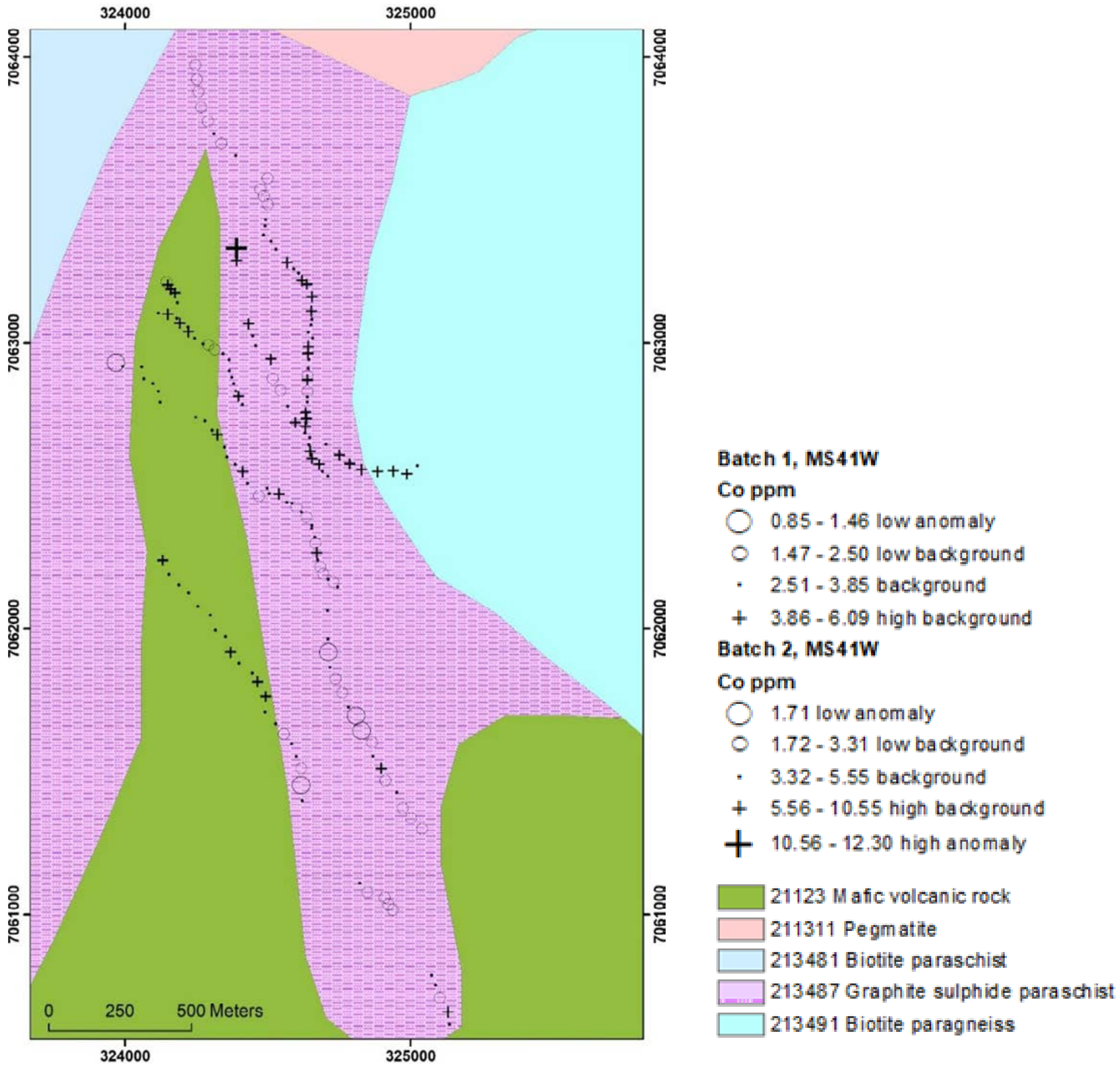

Fig. 8. The concentration of Co analysed using a modified aqua regia digestion method and classified using a log-transformed Tukey boxplot presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022).

The northernmost samples of the surface geochemical survey were also analysed using the ionic leach method (Batch 2; for location, see Fig. 3). According to the RR values, there is one Co–As–Cu-anomalous site at the contact of mafic volcanite and sulphide-bearing graphite schist (Fig. 9). The origin of this anomaly has not been examined, for instance, by diamond drilling.

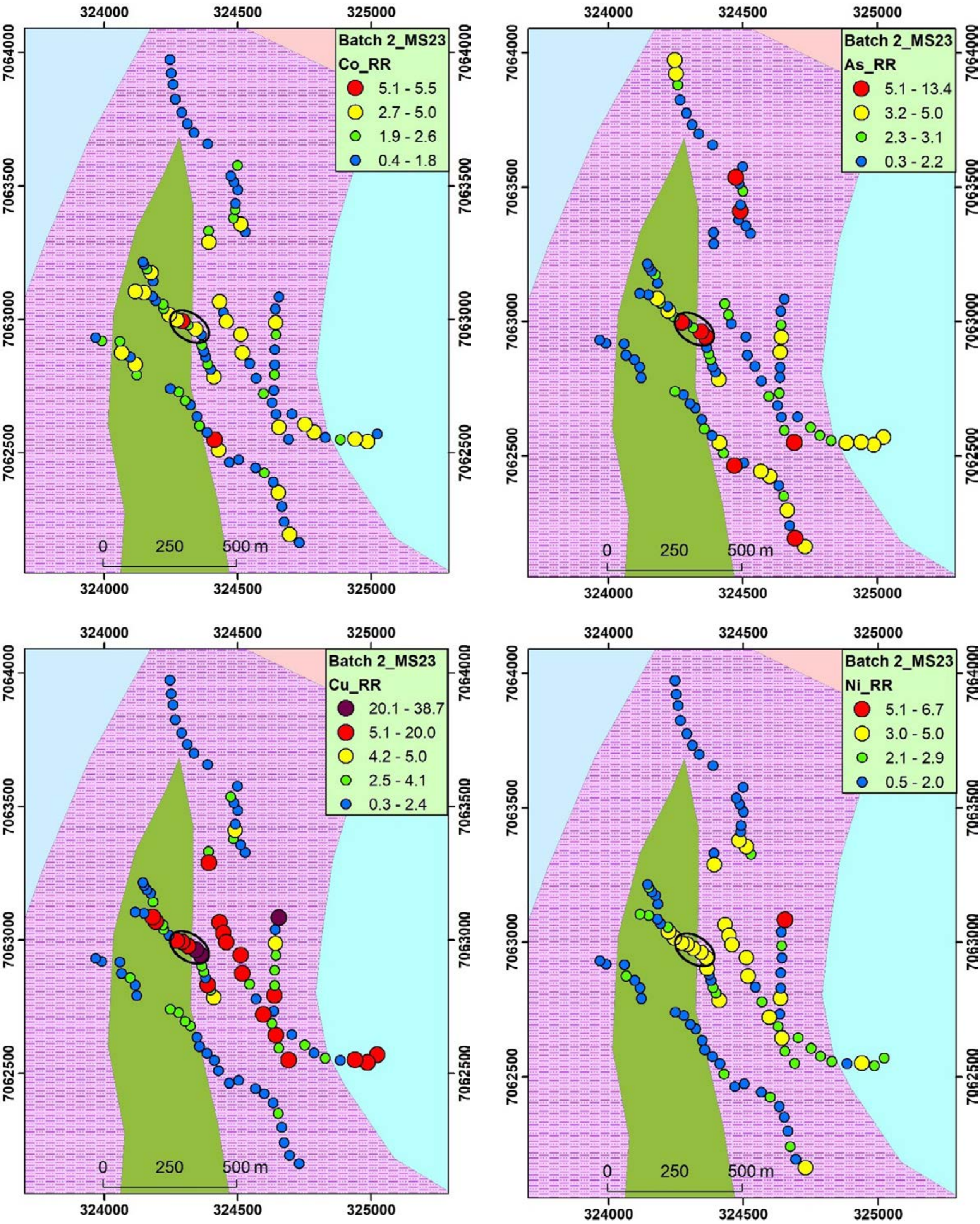

Fig. 9. Response ratio (RR) values of Co, As, Cu and Ni defined from ionic leach analysis presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). The Co–As–Cu-anomalous site is indicated with a black oval.

According to the classification of the log-transformed Tukey boxplot, no Li anomalies exist in the area based on the modified aqua regia digestion data, but the central part of the area has elevated Li concentrations and is seen as a high background area (Fig. 10). On the other hand, the RR values defined from the ionic leach analysis of batch 2 indicate several Li anomalies and/or anomalies of its pathfinder elements (Figs. 11 and 12). There are two Li–Ga–Nb–Sn–Ta and three Ga–Nb–Sn–Ta anomalies in the study area, forming an almost northwest-southeast-trending zone (Fig. 11). One Li–Ga–Nb–Sn–Ta anomaly, at the contact of mafic volcanite and sulphide-bearing graphite schist, coincides with the Co–As–Cu anomaly. The origin of the anomalies has not been examined, for instance, by diamond drilling.

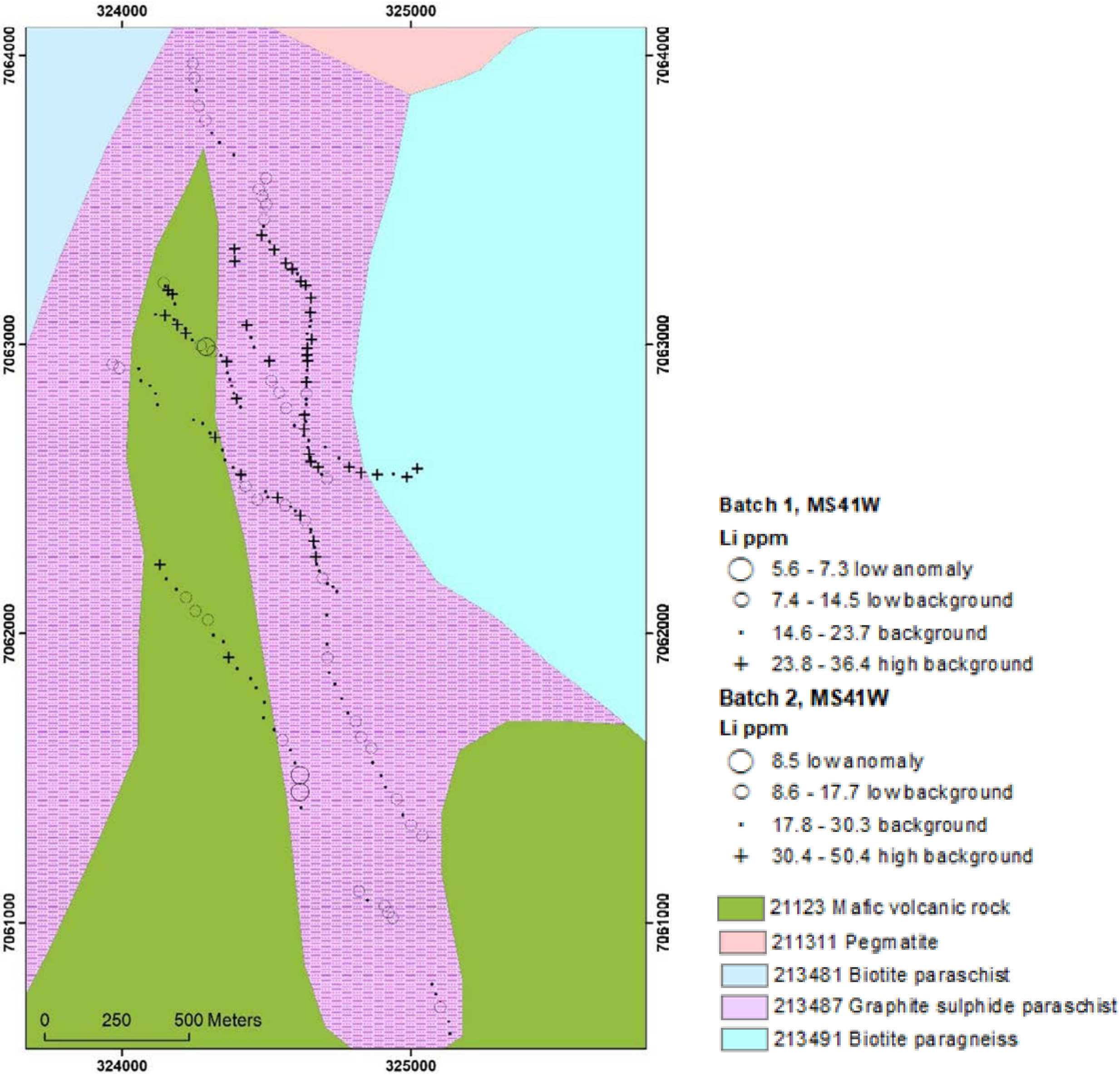

Fig. 10. The concentration of Li analysed using a modified aqua regia digestion method and classified using a log-transformed Tukey boxplot presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022).

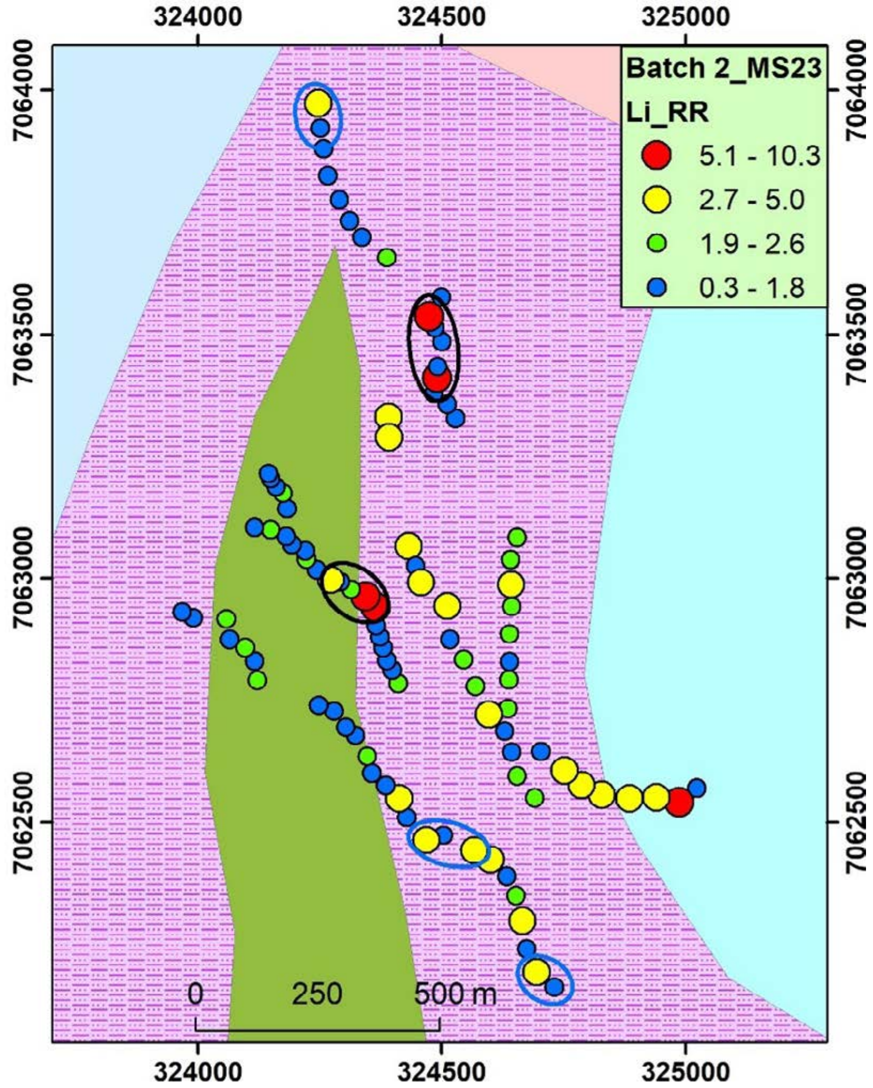

Fig. 11. Response ratio (RR) values of Li defined from ionic leach analysis presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). The Li–Ga–Nb–Sn–Ta-anomalous sites are outlined with black ovals and the Ga–Nb–Sn–Ta-anomalous sites with blue ovals.

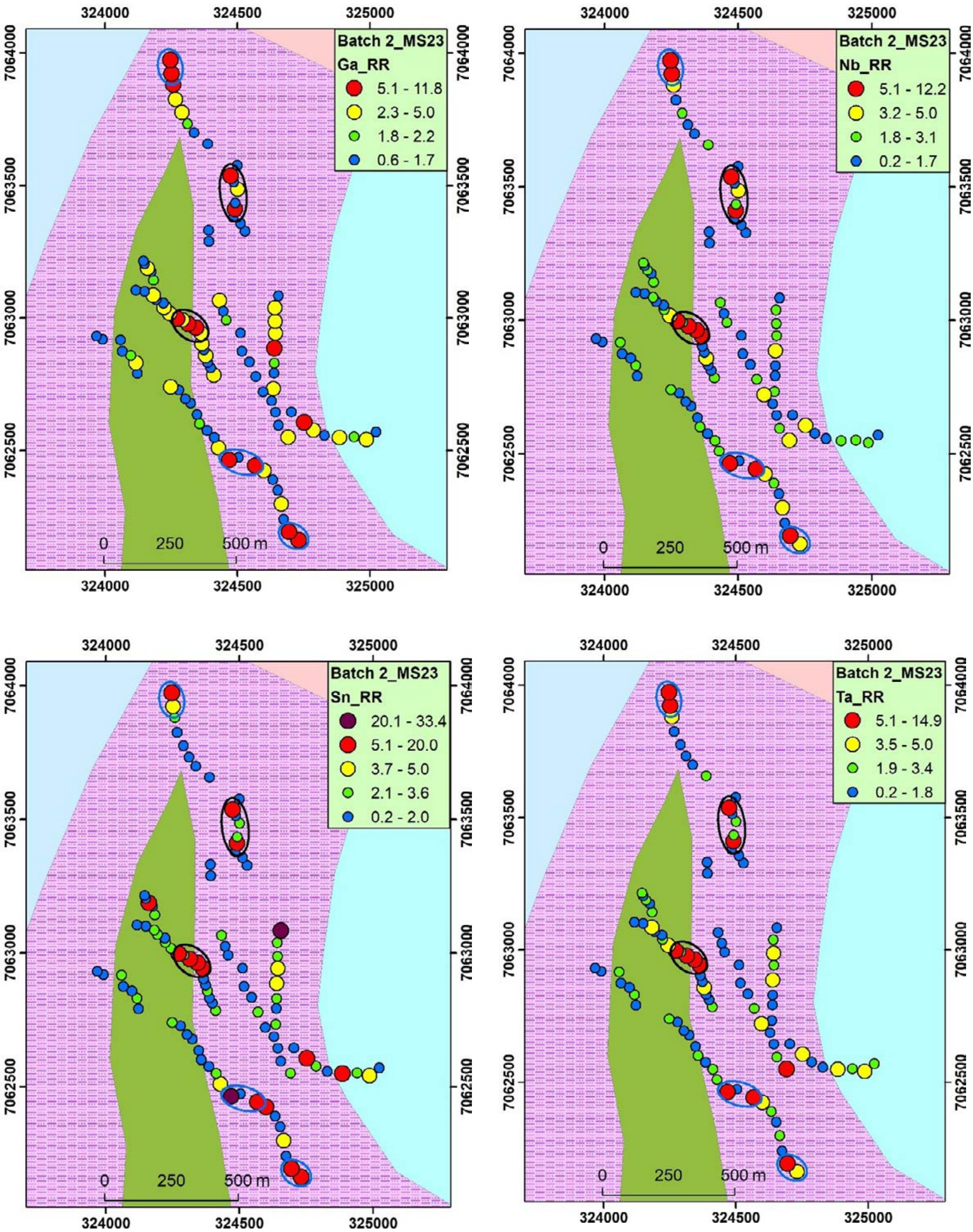

Fig. 12. Response ratio (RR) values of Ga, Nb, Sn and Ta defined from ionic leach analysis presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). The Li–Ga–Nb–Sn–Ta-anomalous sites are outlined with a black oval and the Ga–Nb–Sn–Ta-anomalous sites with blue ovals.

3.3.2 The 2021 survey in the Dragbacken area

In 2021, some of the Li anomalies detected in the percussion drilling survey in the Dragbacken area were examined by surface geochemical sampling (for location, see Fig. 3). The surface geochemical survey consisted of nine sampling lines and the samples were analysed using the ionic leach method. The strongest Li anomaly was observed around the southernmost Li anomaly of the percussion drilling survey (Fig. 13). Many clusters of Li anomalies were detected in the surroundings of the known Li pegmatite. This type of anomaly pattern could hint at the existence of a swarm of Li-bearing pegmatites instead of only one Li pegmatite. On the other hand, it is noteworthy that the sampling lines of the surface geochemical survey were too short to evaluate the exact extent and nature of the Li anomalies.

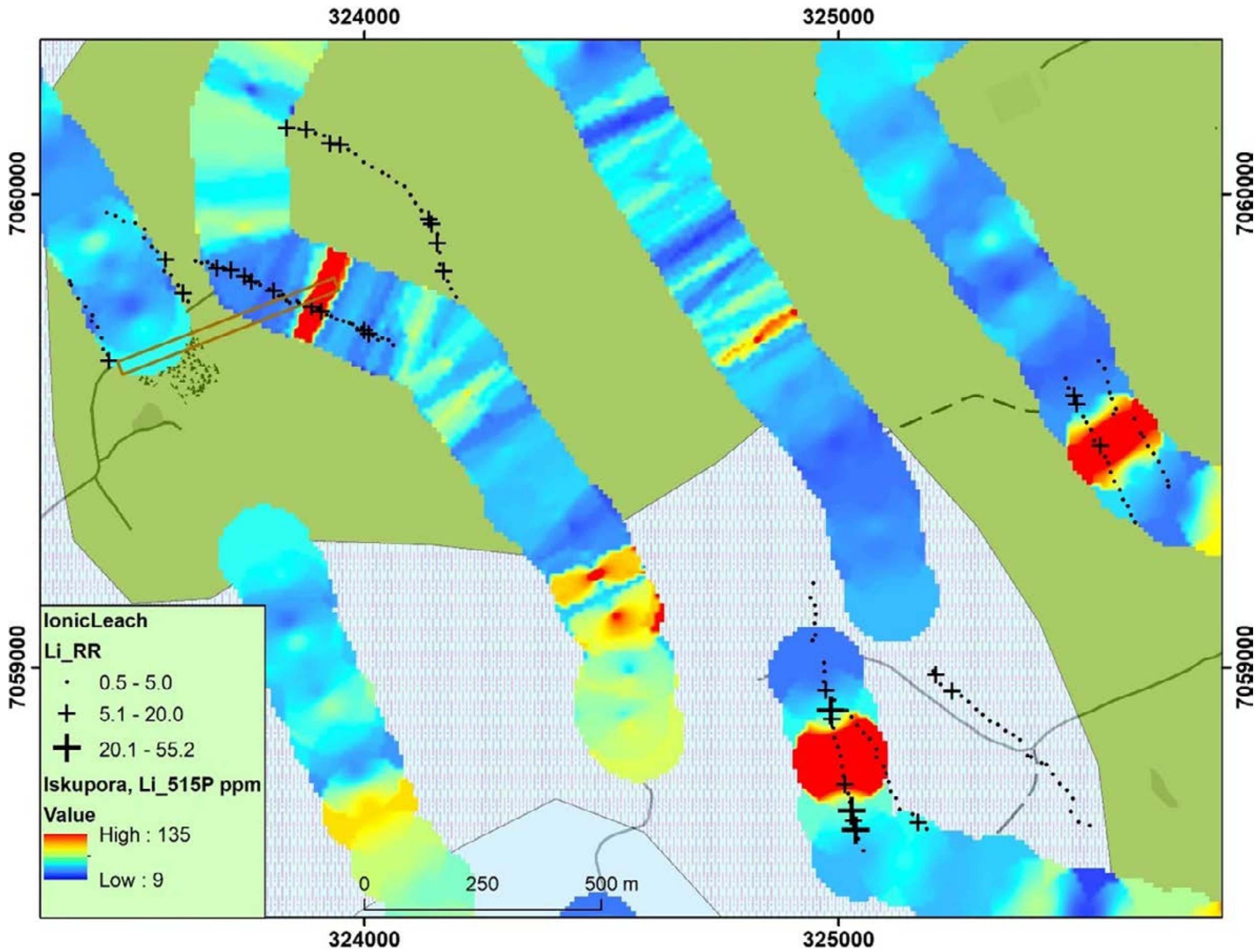

Fig. 13. Response ratio (RR) values of Li defined from ionic leach analysis and the interpolated (IDW) concentration of Li of the percussion drilling survey presented on the bedrock map (Bedrock of Finland scale-free © Geological Survey of Finland 2022). The discovered Li pegmatite is indicated by a brown rectangle. Basemaps © National Land Survey of Finland.

4 BOULDER MAPPING

4.1 Methods

There is a scarcity of bedrock outcropping in the reservation notification area. Most of the areas of exposed bedrock can be found around Dragbacken. Therefore, it was decided to focus on pegmatite boulder mapping during the field seasons of 2019 and 2020. Whole-rock assay of leucopegmatitic 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 glacial 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 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. 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 at Eurofins Labtium Oy using methods 306M and 306P. The digestion method was a strengthened four-acid solution.

In some cases, the field sampling technique may introduce possible 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, when possible.

Pegmatitic magma differentiation favours the enrichment of certain elements and depletion of others. A range of elements can be used to determine the differentiation grade of the pegmatite samples. The Mg/Li ratio is a common and established indicator and performs well, since Mg decreases and Li increases when the 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 indicate barren pegmatites, while values below 1 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 differentiated. Samples from the Dragbacken spodumene dykes displayed the lowest Li values of a few hundred ppm, depending on the sampled zone. Some zones can remain lithium poor. Certain LCT-related elements are, however, attracted to the major rock-forming mineral lattices during crystallization in different ratios and can therefore be used as a guide to the grade of pegmatite differentiation.

4.2 Results

Throughout the reservation notification area, some highly differentiated boulders were found during mapping. The locations of 60 boulders with Mg/Li values are presented in Figure 14. Some of the boulders, especially west of Lake Djupsjön, are moderately to highly differentiated. This indicates that at least some highly differentiated pegmatite dykes exist several kilometres 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 Vaasa Migmatite Complex (Chopin et al. 2020). The higher metamorphic grade does not favour the formation of LCT pegmatites.

No boulders with visible lithium minerals were found. A few evolved boulders were found down-range of the known spodumene dykes at Dragbacken, but none with spodumene.

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

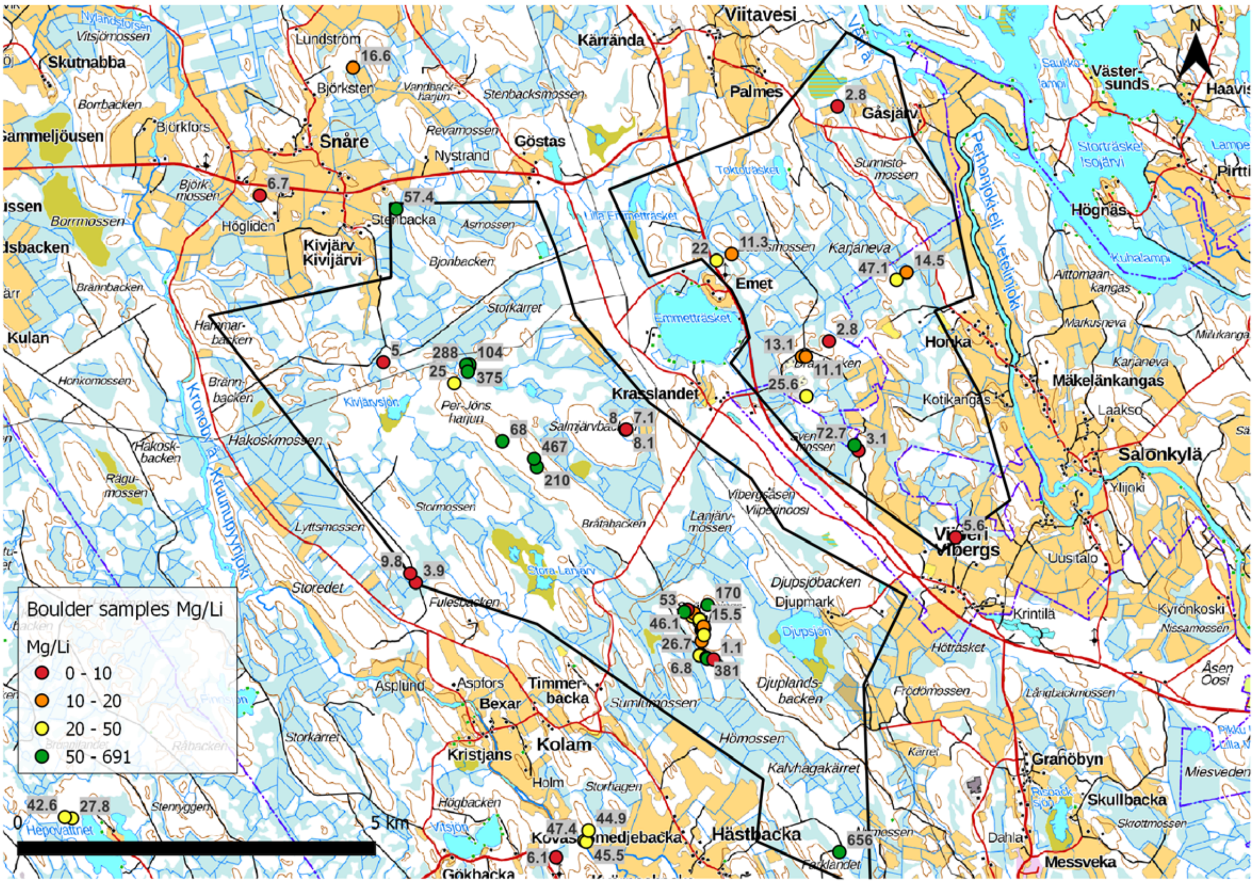

Fig. 14. Pegmatite boulders sampled during the field mapping. The Mg/Li value indicates the approximate differentiation grade of the boulders. The reservation notification areas are outlined in black.

5 LOCAL BEDROCK MAPPING

Bedrock and boulder mapping was performed during the field seasons of 2019 and 2020. A major discovery was the spodumene pegmatite dykes of Dragbacken. The area around Dragbacken and in the reservation notification in general has very sparse outcroppings. There are numerous glacial formations, mainly NW–SE-striking drumlins and wetlands in between. Most outcrops are located around the quarries at Dragbacken. The quarries are the best place to gain an insight into the bedrock. The main bedrock at this location consists of amphibolite or mafic volcanic rocks.

The host rock of the dykes is for the most part mafic volcanic rocks, in places having layers of deformed black schist. Localized fluid movement through the rock has resulted in elemental mobilization and the formation of sulphides as pyrrhotite and in places arsenopyrite and minor chalcopyrite.

The known dykes strike and dip in the same direction, which is approximately 340/50. This is possibly due to regional shearing forces acting on the north–south-running belt of volcanites and black schists during time of emplacement of the pegmatite dykes.

6 STRUCTURAL GEOLOGY OF THE DRAGBACKEN AREA

Dragbacken is located in the northern part of the N–S-trending Aho belt, in the immediate vicinity of the interpreted thrust between the sulphide graphite schists and Lappfors suite metasediments to the west and the Pirttikylä suite metasediments to the east. Deformation has occurred in several stages in southern and central Ostrobothnia, with the initial thrusting and possible thrust folding being re-worked in later events. The rocks at Dragbacken are mafic volcanics that are mostly massive and fine grained with graphite sulphide schist intercalations. Although regional-scale folding of the volcanic rocks is apparent in aerogeophysics, it is not readily apparent at the outcrop scale. Despite the excellent exposure of the volcanic rocks in the quarry walls at Dragbacken, foliations could only be measured from nine locations in the quarries (Figs. 15 and 16). Strain is not partitioned evenly throughout the volcanic rocks, as the measurements were taken from distinct zones of higher strain, as well as graphite sulphide schist intercalations within the volcanic rocks. Linear structures were not observed from the fine-grained Dragbacken volcanic rocks.

Aerogeophysics revealed that Dragbacken is situated near the hinge of a regional fold, although this could not be observed in the field. 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 plunging inclined antiform.

The pegmatite dykes at Dragbacken have not intruded in the orientation of the foliations measured from the volcanic rocks, nor have they intruded in the orientation of the axial plane or the orientation of the theoretical fold axis at Dragbacken. The pegmatite dykes are interpreted to have been emplaced later, in a brittle environment in a stress regime where the direction of σ3 was approximately NNW–SSE.

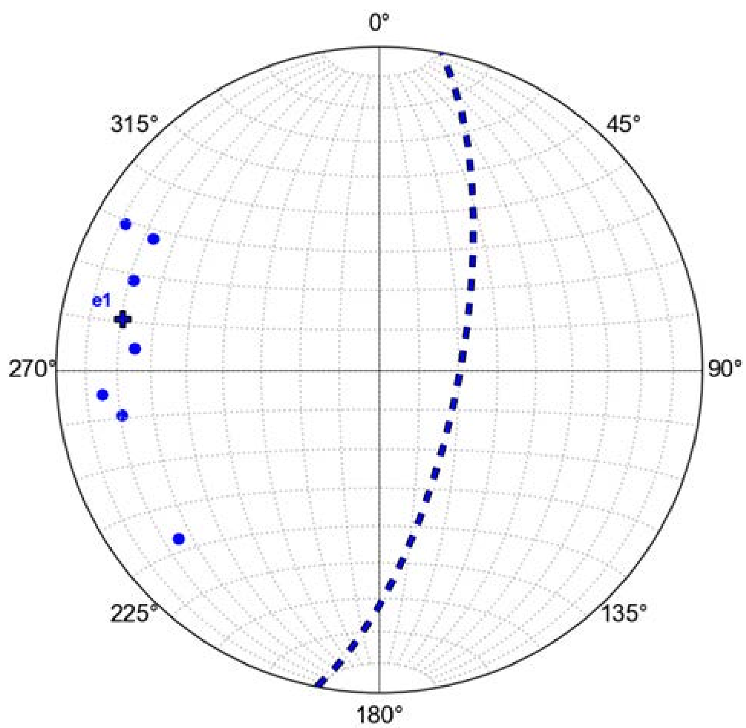

Fig. 15. Stereoplot of foliation measurements from the Dragbacken quarry. Individual foliation measurements as poles, the Fisher mean of all measurements as a dashed line.

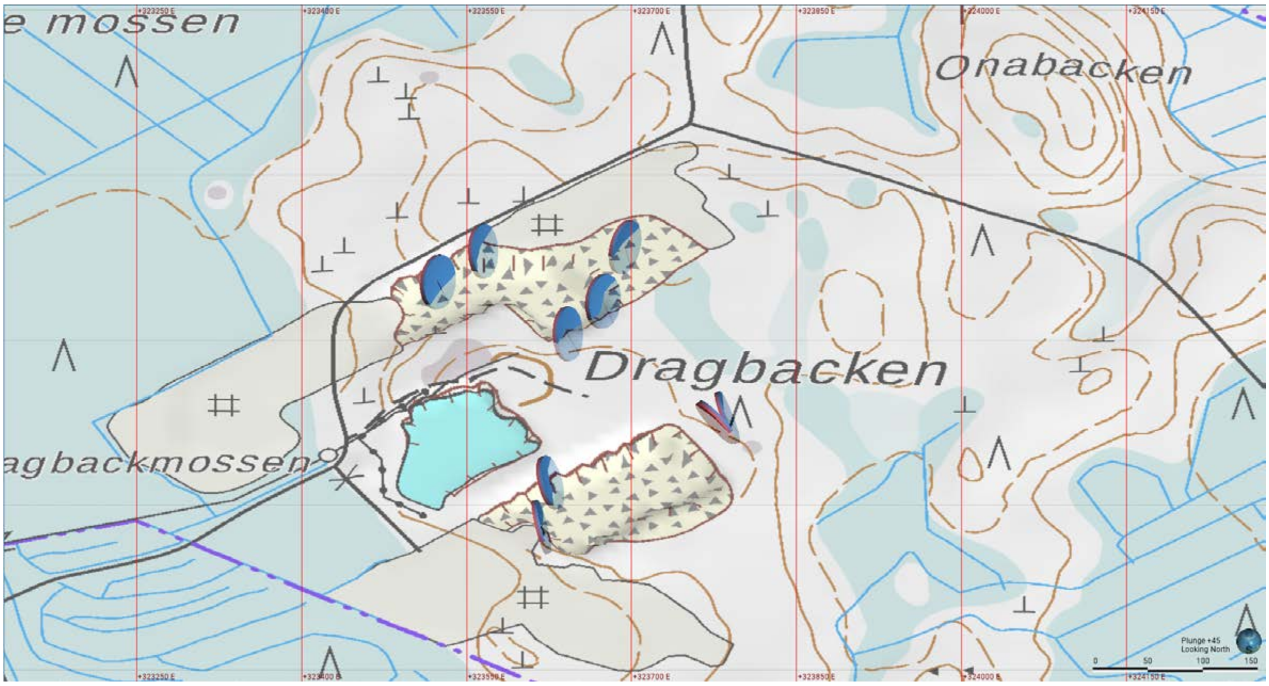

Fig. 16. Locations of the structural measurements taken from the Dragbacken quarry.

7 DIAMOND DRILLING RESULTS

A drilling campaign of approximately 1500 m was completed in 2020. Altogether, 16 drillholes of varying length between 55 m and 121 m were drilled. The drillholes are Q4112020R25 to Q4112020R40, and are hereafter referred to by the last three characters. The locations are indicated on the map in Figure 17. Detailed drill collar data are provided in Appendix 1, while Appendix 2 presents the lithological drill profiles of all the drillholes. The drilling was performed by Taratest Oy, with T-56 drill equipment and a core size of 41.7 mm. The northern spodumene dyke was the focus of the investigation. The aim was to determine the width and extent of the dyke and its chemical composition. Percussion drilling on the forest road to the NE in the direction of the dyke strike revealed elevated Li and Be. This was a prime drill target to test how well the anomaly targets of the percussion drilling can pinpoint spodumene dykes. Several exploratory drill holes were also drilled to determine the sources of other till anomalies.

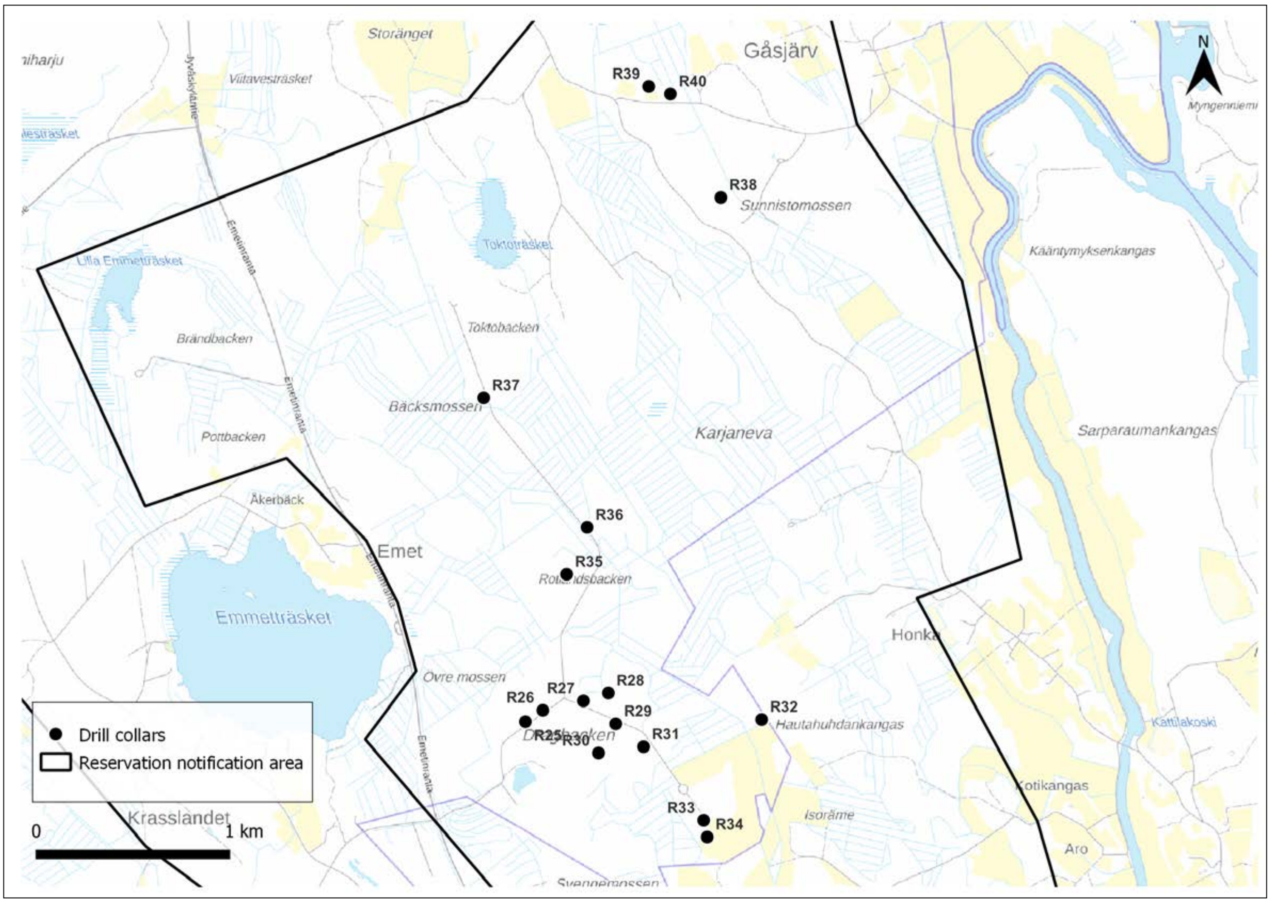

Fig. 17. The locations of drillholes R25 to R40.

7.1 Northern spodumene dyke

The northern spodumene dyke was intersected in drillholes R25, R26 and R27, the width increasing towards the northeast. The dyke width at the intersecting point was 0.5 m in R25, 2.55 m in R26 and 5.8 m in R27. The following drillhole, R28, located approximately 135 m northeast of drillhole R27, did not intersect the dyke. Either the dyke closed off or it changed direction so that the drillhole missed it. The strike length confirmed by drilling of the dyke is approximately 310 m. The dyke can, albeit with some difficulties, be observed striking a further 40 m westward on the ground level of the rock quarry. At the projected surface location of the intersect in drillhole R25, the dyke is wider, reaching approx. 2 m in width. This can be observed in an easterly bedrock wall of the rock quarry.

The northern dyke is 3D modelled in Figure 18 to a depth of 50 m. It is assumed to reach the surface and strike at least to the northeastern forest road, where elevated values of Li were detected in the percussion drilled till samples. The percussion drill samples were taken from the lower till bed, which has a transportation direction from the west (270°).

The widest 5.8 m intersection of the pegmatite dyke was in drillhole R27 at a depth of 37.90–43.70 m (Fig 19). The dyke sharply cuts the host rock amphibolite against the foliation. It is noteworthy that at the location of R27, percussion drilling and sampling from the base of the till revealed Li anomalies, which indicates that the dyke reaches the bedrock surface at this point.

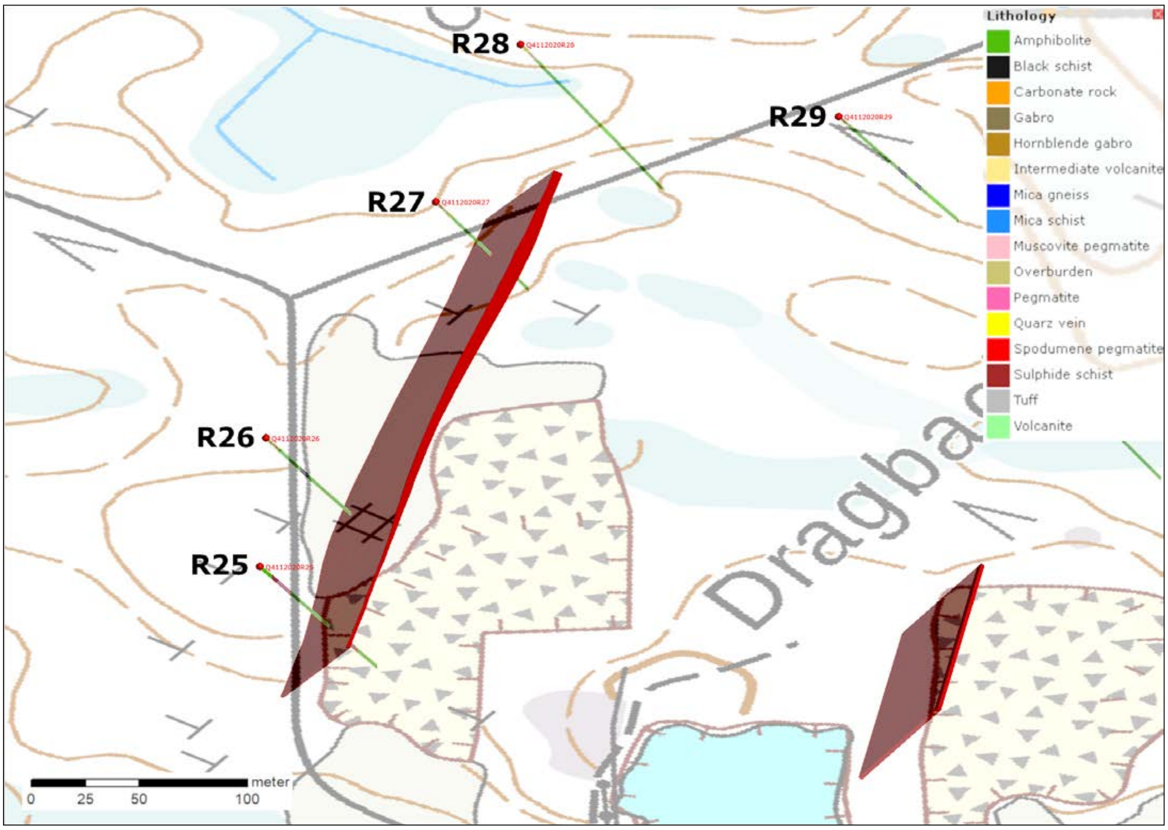

Fig. 18. A 3D model of Dragbacken. The semi-transparent 3D model shows the spodumene dykes plunging towards the northwest. The dykes are modelled down to a depth of approx. 50 m. The view is to the northeast, with a plunge of 40 degrees. Drillholes R25–R29 are presented together with lithologies.

Fig. 19. Wet core drill section from R27. The spodumene pegmatite dyke sharply cuts the downhole contact to the amphibolite at 43.70 m.

7.2 Southern spodumene dyke

The southern pegmatite dyke, or dykes, is included in the 3D model (Fig. 18), but was modelled from field observations alone. It is unclear whether the southern dyke originally consisted of two dykes, or one dyke that has been dislocated by later shearing of the bedrock. The dip and dip directions (50/335) are almost identical to the northern dyke. The host rock is mafic volcanic rock with occasional black schist and metasomatized sections with pyrrhotite. The rocks resemble those investigated at Kaitåsen (Nygård et al. 2021). The dyke cuts the foliation. Rock samples from the southern dyke appear for the most part indistinguishable in composition from the northern dyke. In places, elongated spodumene crystals reached up to 30 cm in length (Fig. 20).

Fig. 20. Left: Light green spodumenes in a rock sample. Right: the southern dyke shows up to 30-cm-long beige-coloured spodumenes (hammer head ca. 10 cm in size).

7.3 Petrophysics

Petrophysical *in situ* logging was carried out in eleven drillholes (Table 1). Measured data include magnetic susceptibility, resistivity, natural gamma radiation and gamma-gamma density. The sampling interval was 0.10 metres, and all measurements were carried out twice: first down (in) and then upwards (out). The data are stored in GTK databases, but processing is not complete. The recorded magnetic susceptibility and density parameters only have relative values until they are calibrated using petrophysical laboratory measurements.

The lithology and petrophysical *in situ* logging data for drillhole R27 are presented in Figure 21. The presented results of the drillhole measurements begin at a depth of 11.5 m, immediately below the ground casing tube. The penetrated spodumene pegmatite from 37.9 m to 43.7 m has an anomalous response in all measured parameters. The properties of spodumene pegmatite clearly contrast with those of the surrounding amphibolite. Spodumene pegmatite is a less magnetic (magnetic susceptibility diagram), electrically more conductive (resistivity diagram), more radioactive (natural gamma radiation diagram), and lighter rock type (density diagram) than amphibolite. Parameter changes along the drillhole due to spodumene pegmatite are sharp, except in resistivity data. Spodumene pegmatite causes clear anomalies in the *in situ* drillhole data, but more accurate conclusions can only be drawn after calibration of the results. A more thorough examination of the calibrated dataset of all 11 measured drillholes would also give the correct proportions for the results of drillhole R27.

Table 1. In situ logged drillholes. Locations are in the ETRS-TM35FIN coordinate system.

Num	East	North	Hole_ID	Depth	Susc	Res	NatG	Dens
1	323645	7059781	Q4112020R26	80.1	x	x	x	x
2	323855	7059829	Q4112020R27	63.6	x	x	x	x
3	323984	7059870	Q4112020R28	101.25	x	x	x	x
4	323933	7059560	Q4112020R30	120.25	x	x	x	x
5	324777	7059733	Q4112020R32	99.8	x	x	x	x
6	324477	7059211	Q4112020R33	55.7	x	x	x	x
7	324495	7059125	Q4112020R34	79.8	x	x	x	x
8	323768	7060484	Q4112020R35	100.3	x	x	x	x
9	323874	7060727	Q4112020R36	118.8	x	x	x	x
10	324566	7062434	Q4112020R38	120.45	x	x	x	x
11	324305	7062970	Q4112020R40	99.4	x	x	x	x

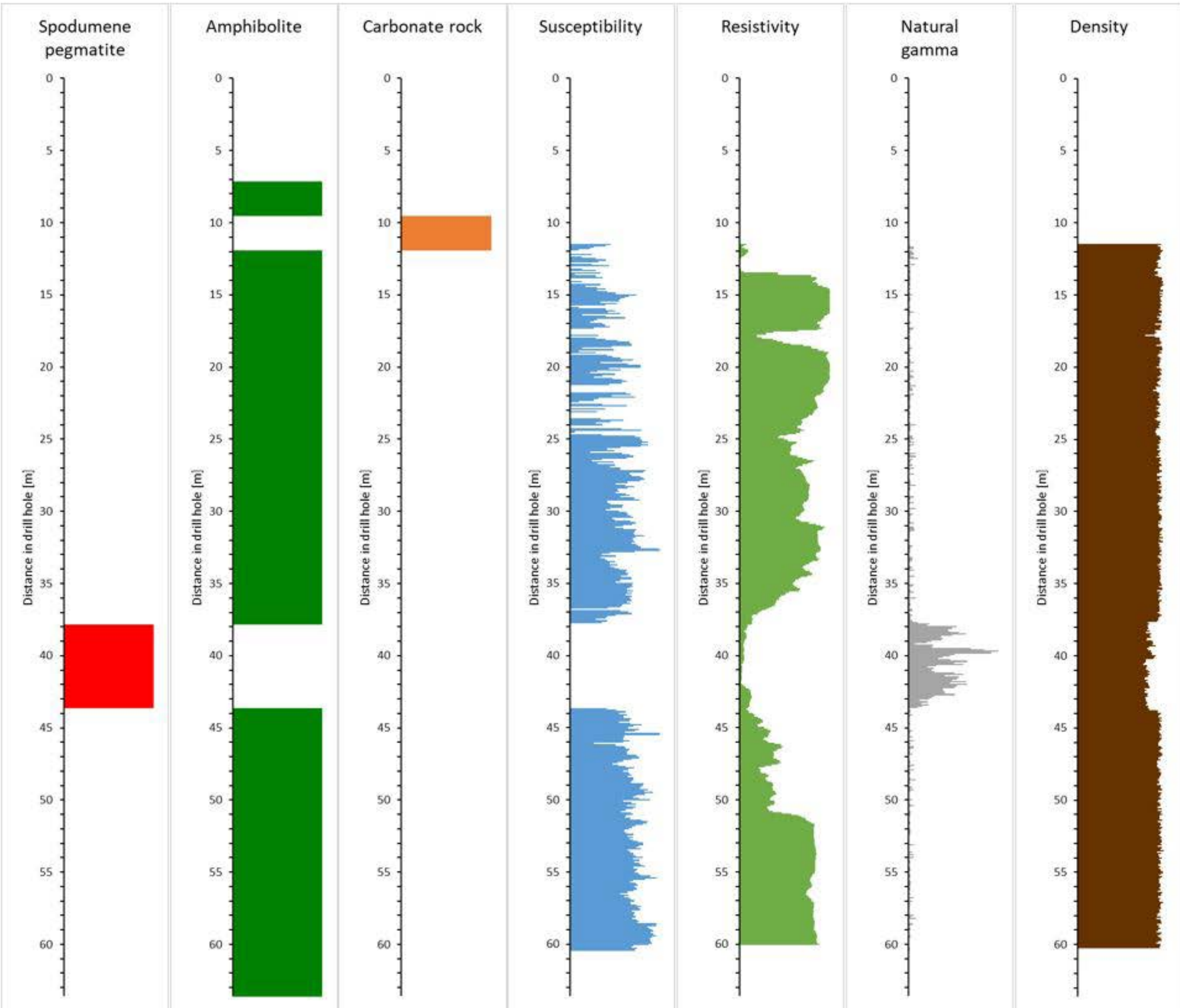

Fig. 21. Lithology and relative variation of four measured petrophysical in situ parameters in drillhole R27.

7.4 Chemical analyses

7.4.1 Methods

The chemical analyses of the drill cores were commenced by ALS as a CCP-PKG03 analysis package.

Analytical preparations were carried out with the package PREP-31 (crush to 70% less than 2 mm, riffle split off 250 g, pulverize split to better than 85% passing 75 microns). The major oxide elements were analysed with the method ME-XRF26, the trace elements and REEs, depending on the elements, with the method ME-MS81, ME-4ACD81 or ME-MS42, C was analysed with the method C-IR07 (total C) and S with S-IR08. Lithium was analysed using the method ME-4ACD81 with 4-acid digestion and ICP-AES finish. The upper analysis limit for Li was 10 000 ppm. Beryllium was added as an additional element.

The analysis of the drill core samples underwent an industry standard QAQC procedure (lithium CRM standards, blanks, duplicates). The CRMs results were within 2 or 3 standard deviations. All blanks were below the Li detection limit. The field duplicates displayed good reproducibility (r^2 = 0.98 for Li), as did the pulp duplicates. No corrective actions were needed.

Only the most geologically interesting sections of the lithologies where assayed. In practice, this means the lithological sections that were interesting from a lithium perspective. Some type examples from each of the different lithologies were also assayed. The full length of drillhole R27, with the widest intersection of spodumene pegmatites, was assayed to check for possible halo effects around the dyke in the wall rock. The assayed drill core sections were generally one metre in length, unless a change in lithology required alternative lengths, since the sections were required to not cut lithological contacts.

7.4.2 Results

7.4.2.1 Geochemistry of the spodumene pegmatites

Ten assayed drill core samples from the northern Dragbacken spodumene dyke are presented in Tables 2 and 3 as a combined average. For comparison, analyses of other spodumene pegmatite occurrences in the Kaustinen area are also presented. The localities are indicated on the map in Figure 22. The Dragbacken spodumene pegmatite displays very similar LCT elemental behaviour compared to the other occurrences. The small sample size of 10 drillhole assays should be considered, as the data may not represent the composition of the whole dyke.

Table 2. Average concentrations of major elements of spodumene pegmatites in the Kaustinen area (from Ahtola et al. 2015) compared with Dragbacken.

	n	Na_2O % XRF	MgO % XRF	Al_2O_3 % XRF	SiO_2 % XRF	P_2O_5 % XRF	K_2O % XRF	CaO % XRF	TiO_2 % XRF	MnO % XRF	Fe_2O_3 % 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
Dragbacken	10	5.20	0.29	15.45	72.83	0.71	2.01	0.90	0.01	0.08	1.02

*A significant part was below the detection limit.

Table 3. Average, maximum and minimum concentrations of Li2O and selected trace elements of spodumene pegmatites in the Kaustinen area (from Ahtola et al. 2015) compared with Dragbacken.

		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
Dragbacken	10	0.49[4)]	2.15[4)]	0.01	54	122	14	99	197	34	505	1091	300

1) n: Be, Nb = 16, 2) n: Be = 33, Nb = 10, 3) n: Be = 96, Nb and Ta = 94. 4) One sample with an analytical maximum level of 2.15% Li_2O used in determining the value.

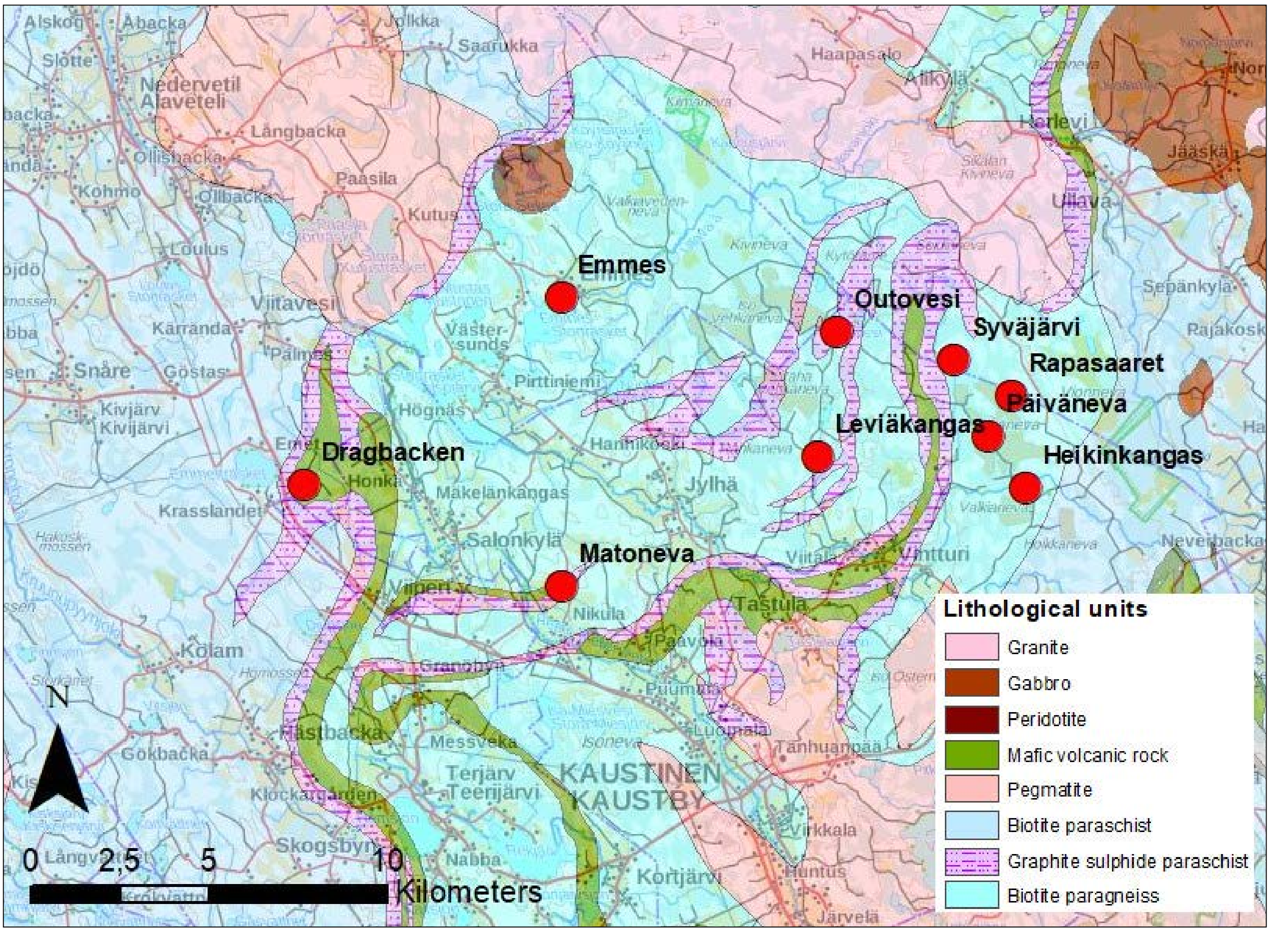

Fig. 22. The location of Dragbacken and the other lithium occurrences in the Kaustinen area.

Of the major elements, Dragbacken shows higher concentrations of P_2O_5 and CaO than any other occurrence. For MgO, Al_2O_3, SiO_2 and Fe_2O_3, Dragbacken is most similar to the Päiväneva occurrence.

For LiO_2, one sample included in the Dragbacken average calculations maxed out at 10 000 ppm Li or 2.15% LiO_2 due to restrictions in the analytical method. The LiO_2 average value of 0.49% LiO_2 therefore has to be considered as the minimum average, and the real value is possible slightly higher. Ta_2O_5 is similar to most of the occurrences, whereas Nb_2O_5 is the highest. BeO matches with Rapasaaret, but is otherwise much higher than in most of the occurrences.

The northern spodumene dyke is zoned. This can be observed in the widest section of the dyke in drillhole R27 at 37.9–43.7 m. In Figure 23, K_2O and SiO_2 display depletion in the core zone, whereas P_2O_5 behaves in the opposite way. Na_2O increases towards the downhole side. Li, Cs, Ta, Nb and Be all display enrichment in the core of the dyke in Figure 24.

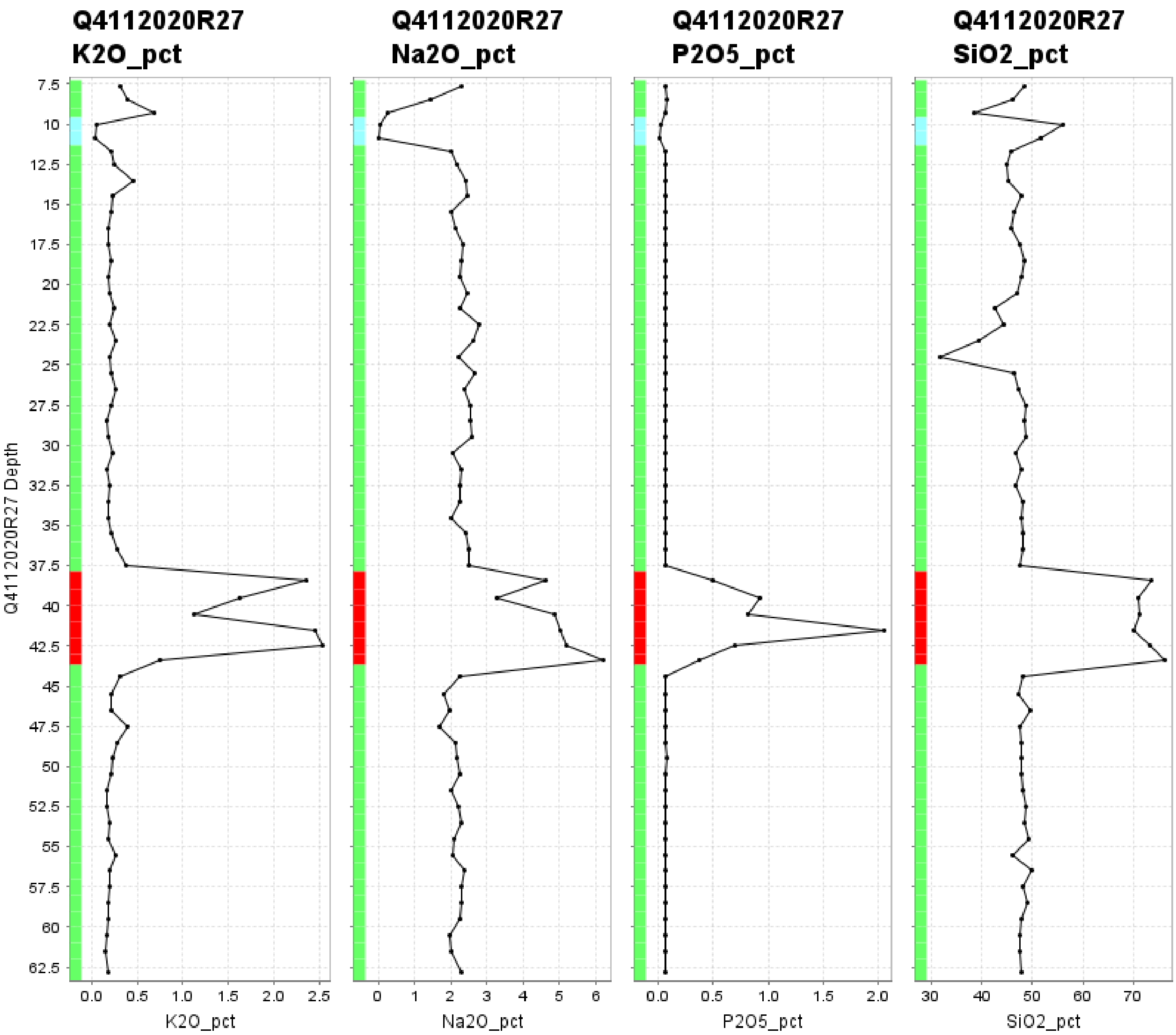

Fig. 23. Major elements from drillhole R27 as downhole plots.

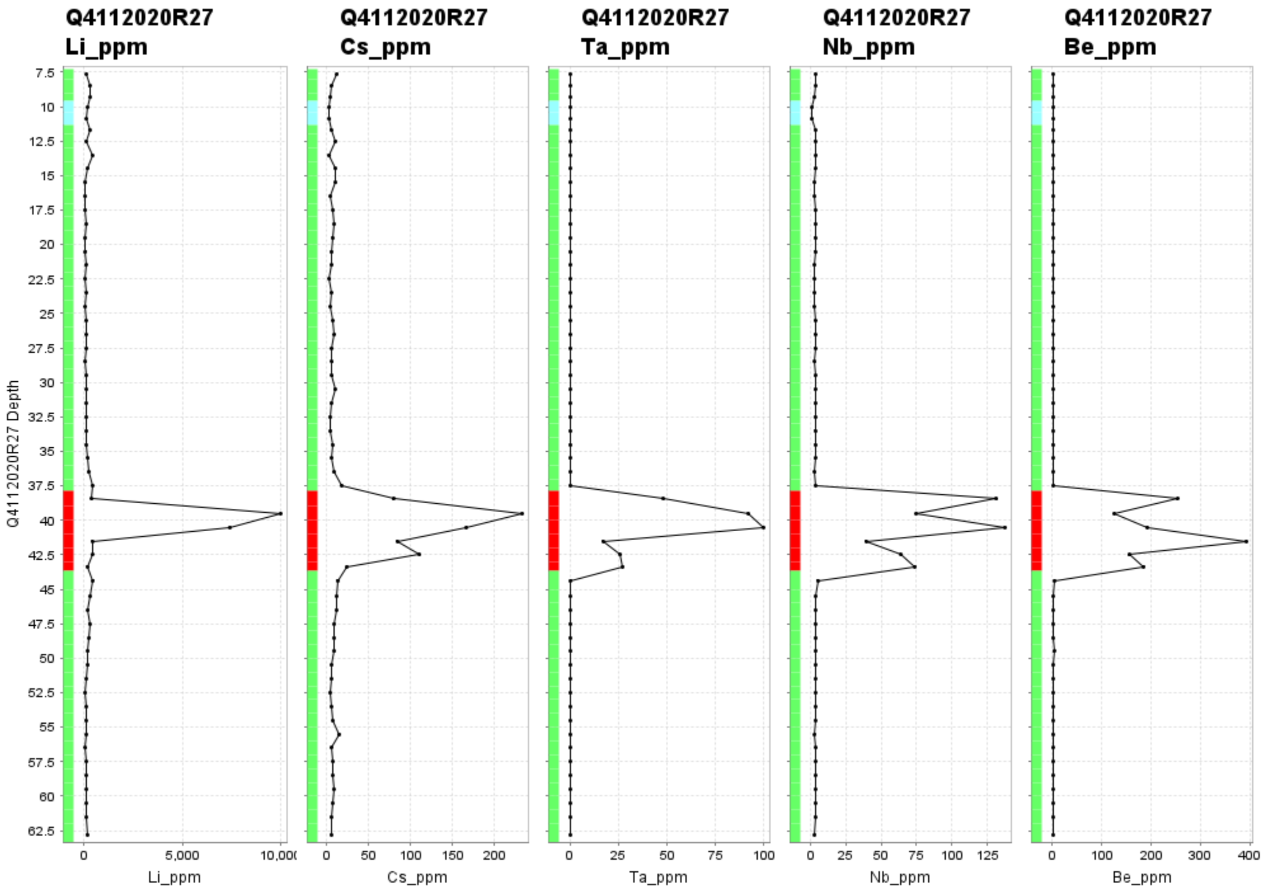

Fig. 24. LCT pegmatite-related elements from drillhole R27 as downhole plots.

7.4.2.2 Metasomatic aureole or the halo effect

Of the LCT-related highly mobile elements, lithium and caesium display the most distinct halo effect around the spodumene dyke in drillhole R27. Table 4 lists the highly mobile elements of the spodumene dyke for assayed samples approximately 15 m on either side.

Li increases from the background values of the amphibolite (median 115 ppm of 87 samples) to above 400 ppm adjacent to the dyke. A significant increase in Li can be detected 3 m uphole and 7 m downhole from the dyke. Cs behaves the same, but somewhat closer to the dyke, 2 m uphole and 6 m downhole. The background median value of 6.4 ppm Cs in the amphibolite increases to 17 ppm. The other mobile elements are mostly only slightly elevated in the closest metre to the dyke.

This behaviour is in line with the findings of Errandonea-Martin et al. (2022) of aplitic LCT pegmatite systems forming metasomatic haloes or aureoles in the host rock of psammitic and pelitic sediments. The most mobile elements were Li and Cs, followed by Rb and to a lesser extent Sn, F, B, Be and Tl. In their study, the first evidence of highly mobile elements was observed at a distance of 4–5 times the thickness of the dykes, and significant gains of >2 were observed at a distance of 1–2 times the thickness of the dyke.

In R27, the first evidence of Li and Cs can be observed at a distance of approximately 1x the thickness of the dyke, where it is double the background value. The type of host rock may, however, play a major role in halo creation caused by exsolution of metasomatizing fluids and volatiles from the pegmatitic melt. In R27 at Dragbacken, the host rock is amphibolite, whereas the study of Errandonea-Martin et al. (2022) was based on psammitic and pelitic host rocks.

The spodumene dyke at Dragbacken diplays a wider halo on the downhole or footwall side the dyke. This is possibly related to the dyke dipping at a 50-degree angle, which might have caused a disproportional dispersion of elements during displacement.

The assayed amphibolite at Dragbacken in the vicinity of the spodumene dykes appears to have generally high background values of lithium (median 115 ppm of 87 samples). This could indicate a more extensive halo effect or hidden dykes not penetrated by drilling. Nine amphibolite samples from drillholes R29, R33 and R35, located elsewhere, yielded a combined average of 31 ppm Li, which is more in line with the upper crust average of ca. 20 ppm (Selway et al. 2005).

Table. 4. Analytical samples from drillhole R27, with 5.8 m of spodumene pegmatite intersection. Assay results for chosen mobile elements ca. 15 m on either side of the dyke. For visualization, colour conditional formatting has been applied separately for each column. A shift towards red indicates more significant values.

DDH ID interval (m)	Lithology	Li ppm	Cs ppm	Nb ppm	Rb ppm	Ta ppm	Sn ppm	Be ppm	Tl ppm
Q4112020R27_23-24	Amphibolite	130	5.1	3.0	10	0.1	1	1	0.06
Q4112020R27_24-25	Amphibolite	70	3.9	2.3	12	0.1	1	1	0.03
Q4112020R27_25-26	Amphibolite	90	6.9	3.1	9	0.1	1	1	0.03
Q4112020R27_26-27	Amphibolite	110	9.1	3.1	13	0.1	1	1	0.03
Q4112020R27_27-28	Amphibolite	120	5.5	3.2	9	0.1	1	1	0.03
Q4112020R27_28-29	Amphibolite	70	6.1	2.9	7	0.1	1	1	0.02
Q4112020R27_29-30	Amphibolite	110	6.2	3.2	10	0.1	1	1	0.03
Q4112020R27_30-31	Amphibolite	130	9.3	3.1	12	0.1	1	1	0.03
Q4112020R27_31-32	Amphibolite	100	5.0	3.1	7	0.1	1	1	0.05
Q4112020R27_32-33	Amphibolite	110	3.7	3.2	9	0.1	1	1	0.03
Q4112020R27_33-34	Amphibolite	120	4.5	3.1	8	0.1	1	1	0.03
Q4112020R27_34-35	Amphibolite	110	6.6	3.3	8	0.1	1	1	0.03
Q4112020R27_35-36	Amphibolite	200	5.4	3.2	17	0.1	1	1	0.05
Q4112020R27_36-37	Amphibolite	220	8.4	3.0	23	0.1	1	1	0.07
Q4112020R27_37-37.9	Amphibolite	430	17.5	3.4	44	0.2	3	2	0.11
Q4112020R27_37.9-39	Spodumene peg	390	79.3	131.5	839	48.1	136	253	0.37
Q4112020R27_39-40	Spodumene peg	>10000	233.0	74.8	910	91.7	129	125	1.3
Q4112020R27_40-41	Spodumene peg	7420	166.5	137.5	638	99.7	209	192	0.68
Q4112020R27_41-42	Spodumene peg	410	83.8	39.1	727	16.9	171	393	0.33
Q4112020R27_42-43	Spodumene peg	410	110.5	63.9	854	25.8	61	155	0.43
Q4112020R27_43-43.7	Spodumene peg	160	23.9	73.9	289	27.2	62	185	0.15
Q4112020R27_43.7-45	Amphibolite	460	12.7	4.9	58	0.4	14	4	0.07
Q4112020R27_45-46	Amphibolite	310	11.5	3.3	28	0.1	2	1	0.06
Q4112020R27_46-47	Amphibolite	210	11.3	3.3	29	0.1	5	1	0.06
Q4112020R27_47-48	Amphibolite	280	8.7	3.2	32	0.1	4	1	0.08
Q4112020R27_48-49	Amphibolite	260	8.5	3.5	32	0.1	5	1	0.07
Q4112020R27_49-50	Amphibolite	190	8.7	3.4	24	0.3	9	3	0.06
Q4112020R27_50-51	Amphibolite	200	5.5	3.3	13	0.1	6	1	0.05
Q4112020R27_51-52	Amphibolite	110	5.4	3.2	10	0.1	1	1	0.02
Q4112020R27_52-53	Amphibolite	70	3.4	3.3	6	0.1	1	1	0.02
Q4112020R27_53-54	Amphibolite	110	5.2	3.3	9	0.1	3	1	0.02
Q4112020R27_54-55	Amphibolite	90	6.9	3.3	11	0.1	4	1	0.02
Q4112020R27_55-56	Amphibolite	120	14.8	3.0	26	0.1	1	1	0.06
Q4112020R27_56-57	Amphibolite	80	5.3	3.7	11	0.1	1	1	0.02
Q4112020R27_57-58	Amphibolite	120	7.5	3.4	11	0.1	2	1	0.03
Q4112020R27_58-59	Amphibolite	110	6.5	3.2	9	0.1	3	1	0.02

7.4.3 Other intersections

Drillhole R30, located 220 m to east of the southern dyke, intersected a 0.40 m pegmatite section in amphibolite (Fig. 25). Analytical results indicate no elevated lithium, but other LCT pegmatite-associated elements are elevated and of a similar distribution to the northern dyke, including Cs and Ta. Li appears to be elevated in amphibolite within the closest metre on both sides of the dyke, with values of 170 ppm and 130 ppm, respectively. This dyke is likely to be part of the same pegmatite dyke system as the other Dragbacken spodumene dykes.

Fig. 25. A 0.40 m pegmatite dyke in drillhole R30, 94.05–94.45 m, wet core.

The location of the exploration drillhole R36 was chosen based on till samples anomalous for Li. At 86.50 m to 99.50 m, the homogeneous amphibolite is intruded and/or metasomatized by possible pegmatite melt or pegmatite residual fluid. The flow direction is along the sub-core axis. Li is sporadically elevated up to 310 ppm. Cs is elevated up to 121 ppm, which is distinctly anomalous, the amphibolite median being 6.4 ppm. An image of the drill core is presented in Figure 26. Errandonea-Martin et al. (2022) found Li and Cs to be the most mobile elements in LCT-forming aplitic pegmatite systems. This lithology may represent a highly mobile part of residual volatiles originating from an LCT pegmatite system.

Fig. 26. Drill core of R36, showing the latter part of the possible pegmatite fluid-altered section 86.50–99.50 m. The host rock is amphibolite.

In some places at Dragbacken, metasomatism and alteration can be seen in the rock. This is most common in the amphibolite and sulphide/black schists, and usually results in the formation of pyrite and pyrrhotite. However, in some places, base metals are elevated together with arsenopyrite. One such section is in black schist section 57.2–62.85 m in drillhole R35, located north of the spodumene dykes at Dragbacken (Fig. 27). As an example, from 60–61 m, As reaches the analytical maximum of 250 ppm, Co 754 ppm and Ni 1180 ppm. 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.

Intersection of black schist or sulphide schist occurred in several drillholes and appears to be common in association with the volcanites at Dragbacken. In the lithologies interpreted as black schist (n = 33), the total carbon content was assayed as a median of 2.5% and maximum 7.3%. Lithologies interpreted as sulphide schist (n = 46) display a median of 2.3% C and maximum 5% C. Graphitic rocks were not a target of this study, and high-grade intersections were not aimed at.

Fig. 27. Sulphides in black schist in drillhole R35. Arsenopyrite is visible in veins between 60.90–61.00 m.

8 AGE STUDY

An age study was conducted on some selected magmatic rocks (GTK in-house study, unpublished at the time of writing) in Pohjanmaa, Keski-Pohjanmaa and Etelä-Pohjanmaa. Columbites from the southern spodumene dyke yielded an age of 1796 ± 5.8 Ma, belonging to the same age group as the Kaustinen dyke groups. The Alaveteli pegmatite granite intrusion, located 5 km to the north of Dragbacken and previously assumed to belong to the 1800 Ma post-orogenic S-type intrusions, was confirmed to be of this group. The age from zircons was determined to be 1801 ± 16 Ma.

The granite intrusion between Storbacka and Kisk, located approximately 12 km to the SW of Dragbacken, was determined from zircons as 1860 ± 23 Ma old, thus belonging to a different and older synkinematic group than the post-orogenic S-type intrusions forming the spodumene dykes.

9 CONCLUSIONS

The discovery of a new spodumene pegmatite occurrence at Dragbacken expanded the area of the Kaustinen lithium occurrence significantly westwards. The source of the spodumene-rich pegmatitic melts remains unknown. However, ca. 5 km to the north of Dragbacken is located the large, 10 km by 6 km Alaveteli pegmatite granite intrusion, which, according to Martikainen (2012), is probably large and fertile enough to have produced lithium-enriched melts originating from this intrusion. The ca. 5 km distance of the dykes from the granite intrusion places the dykes within the possible theoretical lithium zone 5–10 km from a source granite described by Černý (1991). The age study confirmed that the Dragbacken dykes and the Alaveteli pegmatite granite are of the same age.

The emplacement of pegmatitic melts in the bedrock is almost always structurally controlled. This is also the case at Dragbacken. The far-striking, parallel and sheetlike appearance of the two dykes located ca. 300 m apart hints at a large-scale strain, where a directional force has allowed the bedrock to open fractures for the intruding pegmatitic melts in the direction of minimum stress. This has happened in a brittle bedrock environment, since the dykes sharply cut the foliation. Therefore, it can be assumed that as yet undiscovered pegmatite dykes are likely to follow the same behaviour.

Pegmatite dykes seldom occur alone, but rather in swarms. This behaviour, accompanied by differentiated pegmatite boulders in the area, increases the potential for more occurrences. The 0.4 m highly differentiated pegmatite section in drillhole R30 and possible Li- and Cs-enriched pegmatite residual fluid in drillhole R36 points to additional pegmatite-forming activity in the area.

The Dragbacken occurrence has a similar elemental composition to the other lithium pegmatite occurrences in the Kaustinen area. The dykes display an internal zoned distribution of minerals and elements. The geochemical assay demonstrated that the distribution of lithium is concentrated towards the central core zone of the northern dyke. Spodumenes occur as coarse grains up to 5 cm in width and 30 cm in length.

The discovery of a halo in the host rock around the spodumene dykes has implications for exploration. Firstly, it confirms that haloes can form in amphibolite, and secondly, the existence of a halo greatly expands the detectable anomaly in the glacial till cover. Of the LCT-related elements, Li, Cs and Rb appear to create the most widespread halo. The abundance of these elements in the pegmatites also ensures that the element concentrations are well above assay detection limits in till samples.

Lithium background values in the amphibolite at the drill locations near the spodumene dyke appear to be high (median above 100 ppm). According to Selway et al. (2005), the average amount of Li in the upper crust is approximately 20 ppm. A few assayed amphibolite sections from drillholes at a distance from Dragbacken revealed lower Li values. This could indicate a more extensive halo effect around the dykes or the existence of more dykes in the area.

Petrophysical measurements of drillhole R27 demonstrated a high contrast between the spodumene pegmatite and the host rock of amphibolite. Pegmatites situated in amphibolites could therefore be detected by ground geophysics. The heterogeneous folded bedrock with variable amounts of magnetic minerals in, for example, black schist and the variable till cover levels at Dragbacken make detection very challenging.

There is a potential for other mineralizations in the volcanic belt that the Dragbacken study area forms a part of, namely cobalt, nickel, gold and graphite, as demonstrated in studies by Kuusela et al. (2022) and Nygård et al. (2021). These elements were not a focus in this report, but some hints of elevated levels could be found in the till survey and drill cores. The till survey revealed cobalt anomalies, some of which are 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 is associated with pathfinder elements. The As mineralization in drillhole R35 near this location also shows Au pathfinder elements together with Co and Ni. Black schist interlayers are common and associated with the volcanite rocks. The total carbon content reaches 7.3% at best.

The Kruunupyy and Kaustinen area is challenging for exploration because of the extensive glacial till cover and lack of outcrops. Geophysical data are challenging to use for the direct detection of pegmatite dykes because of bedrock folding and heterogeneous lithological units. Geophysics is better suited to indirect exploration, e.g., outlining lithological boundaries. Geochemical sampling of till is therefore key to finding LCT elemental anomalies.

The discovery of the Dragbacken lithium occurrence provides an additional insight into and adds to understanding of the mineral systems that formed the occurrences in the Kaustinen lithium area. The new Dragbacken occurrence also creates an opportunity for further research.

10 RECOMMENDATIONS FOR FURTHER WORK

A new second round of drilling was planned by GTK to be commenced in 2021. The drill locations were selected according to response ratio results from the newer ionic leach sampling. Due to the time limitations of the project and challenges in acquiring a suitable drilling rig, the drill campaign was never put into action. These anomalous till targets have therefore not been verified by drilling.

Previous studies (Kuusela et al. 2022 and Nygård et al. 2021) at other locations in the volcanic belt have demonstrated the potential for economic grades of crystalline graphite. A drillhole profile was planned to intersect the SW–NE-running strong magnetic anomaly north of Dragbacken. For the above reasons, this plan was also not realized. This anomaly is probably caused by pyrrhotite in the black schist. A separate graphite study is justified in this region.

Some anomalous till targets that were drilled during the 2020–21 campaign were chosen with azimuth and dip according to the known dykes at Dragbacken. It was assumed that most additional dykes in the region would have the same strike and dip. If this is not the case, some targets might have been missed by, for example, drilling parallel to a dyke.

A ground magnetic geophysics survey does not appear to be sufficiently accurate to distinguish the spodumene dykes from the host rock. However, it is a valuable tool to locate lithological boundaries and to determine the diamond drilling dip and azimuth direction in strongly folded bedrock.

Till sampling, whether it consists of traditional surface C horizon sampling, ionic leach sampling or percussion drilling, was found to be the best method to locate lithium anomalies in the area. The 5.8-m-wide spodumene dyke could only be seen in a 50-m-wide percussion drilling till section (in 5 samples taken 10 m apart). Therefore, sampling should be dense. Too large sample spacing could easily miss a target. The lower glacial till has a different glacial transport direction from the top layer, which needs to be considered when interpreting the till sampling results.

Gold and nickel–cobalt mineralisations are a possibility in the area, similar to the one found southwards at Emas, located in the same volcanic belt as Dragbacken. This investigation has been reported by Kuusela et al. (2022). The locations where gold pathfinder elements are elevated require additional attention.

There is a possibility for an in-depth mineralogical and petrographical study of the spodumene dykes and the surrounding halo effect. This could take into consideration a larger number of LCT-related elements and metasomatic mineral assemblages formed in the amphibolite, accompanied, for example, by a thin section study.

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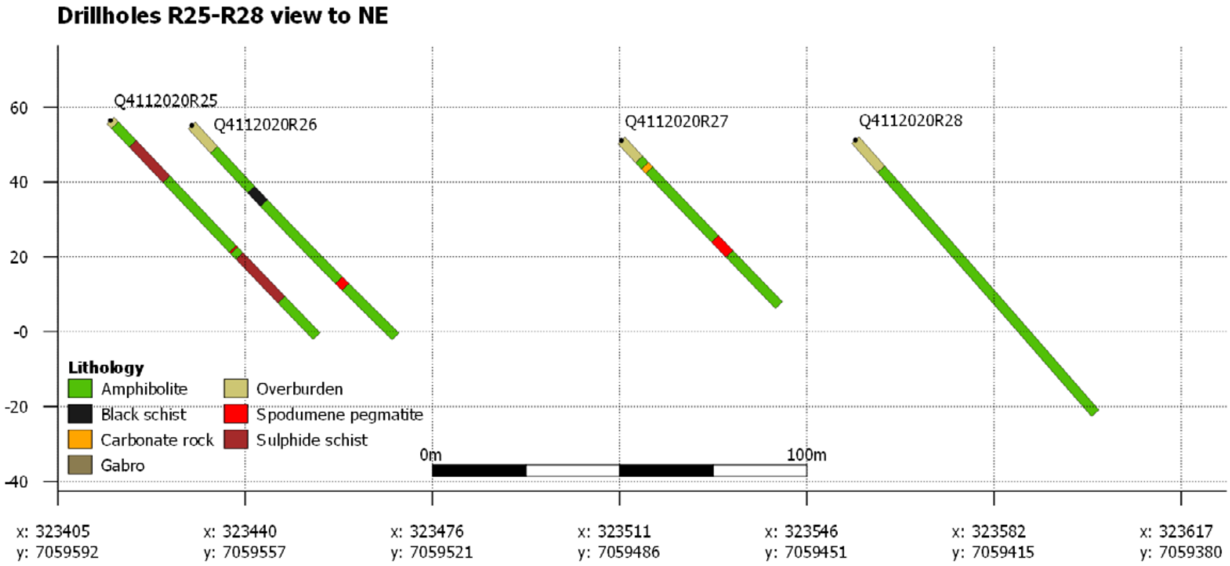
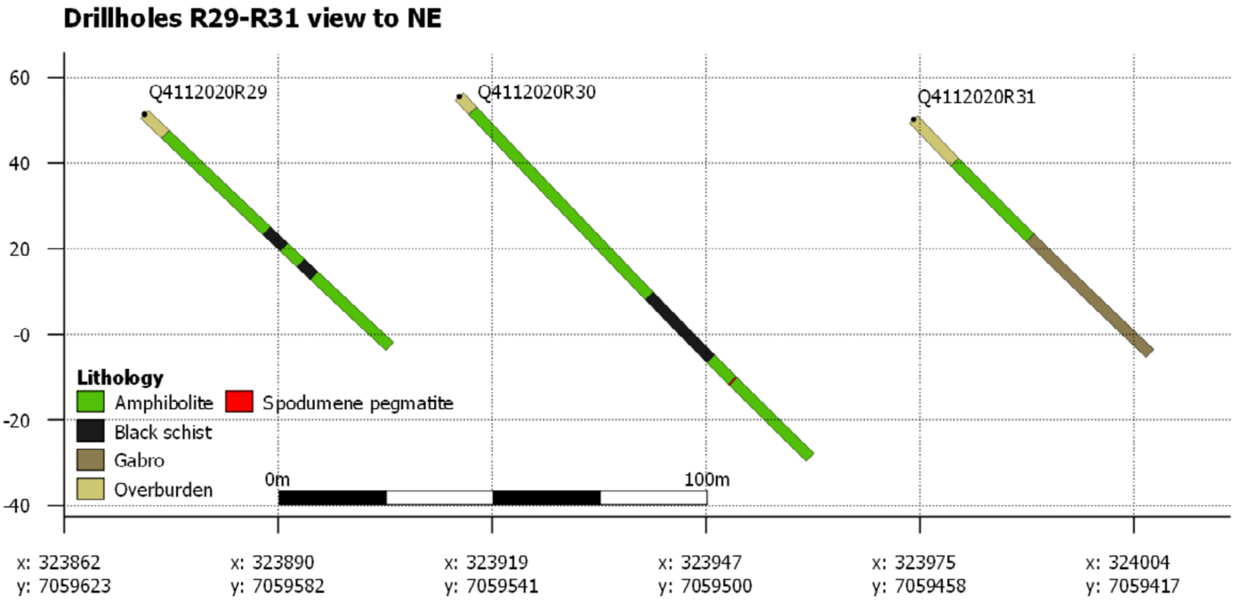
APPENDICES

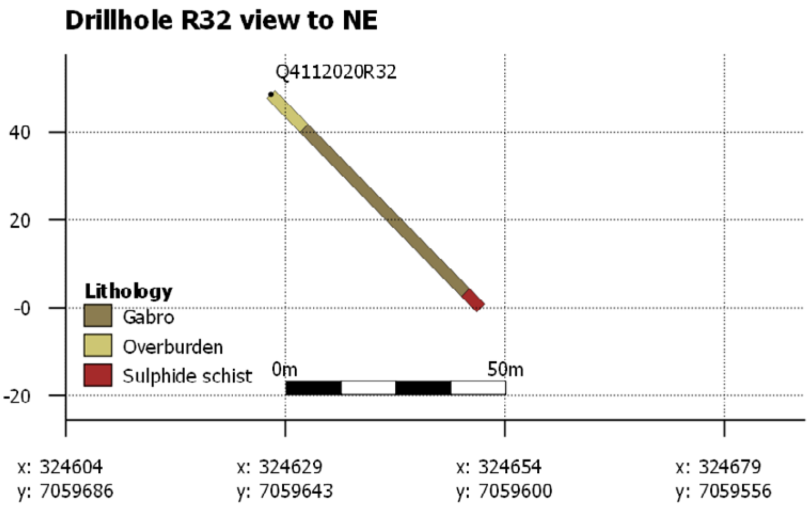
Appendix 1. Drill collar data.

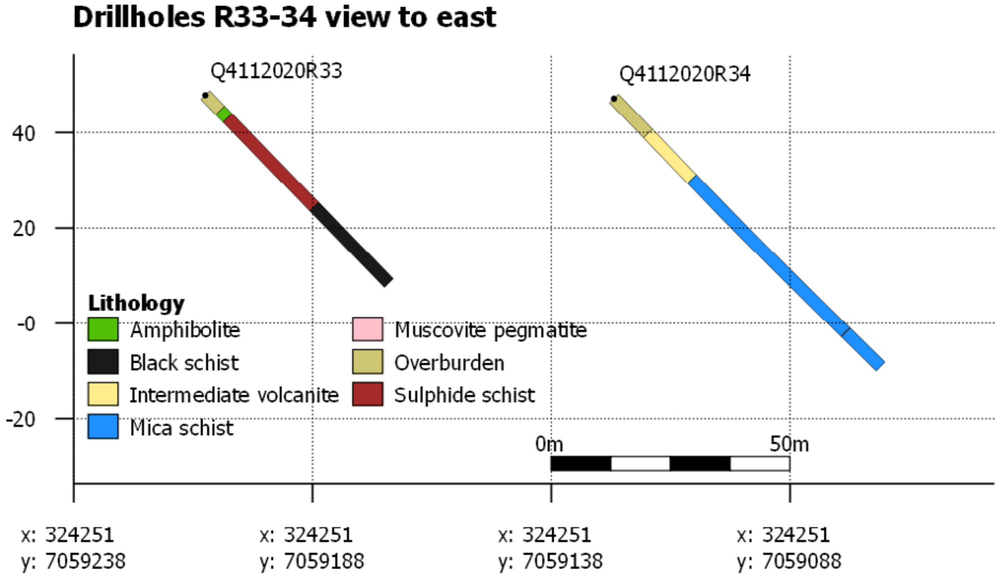
HOLE ID	N-TM35FIN	E-TM35FIN	Z-N2005N00	AZIMUTH	DIP	LENGTH (m)	OVERBURDEN (m)
Q4112020R25	7059722	323555	56.4	147.37	45.5	80.60	1.75
Q4112020R26	7059781	323645	55.1	151.86	46.2	80.10	8.90
Q4112020R27	7059829	323855	51.1	158.54	45.0	63.60	7.25
Q4112020R28	7059870	323984	51.2	159.09	45.8	101.25	10.85
Q4112020R29	7059711	324022	51.4	154.69	43.2	79.45	6.85
Q4112020R30	7059560	323933	55.6	162.42	46.0	120.25	4.70
Q4112020R31	7059592	324166	50.2	160.19	45.3	79.10	14.75
Q4112020R32	7059733	324777	48.6	136.70	44.8	99.80	10.95
Q4112020R33	7059211	324477	47.8	167.32	45.0	55.70	4.50
Q4112020R34	7059125	324495	47.1	169.99	45.5	79.80	10.30
Q4112020R35	7060484	323768	50.6	171.97	44.9	100.30	12.00
Q4112020R36	7060727	323874	44.8	170.13	45.9	118.80	10.10
Q4112020R37	7061397	323339	46.4	139.36	45.8	98.65	11.50
Q4112020R38	7062434	324566	48.4	44.27	45.6	120.45	14.50
Q4112020R39	7063009	324193	49.1	107.42	44.6	99.80	10.70
Q4112020R40	7062970	324305	45.3	109.56	44.3	99.40	9.00

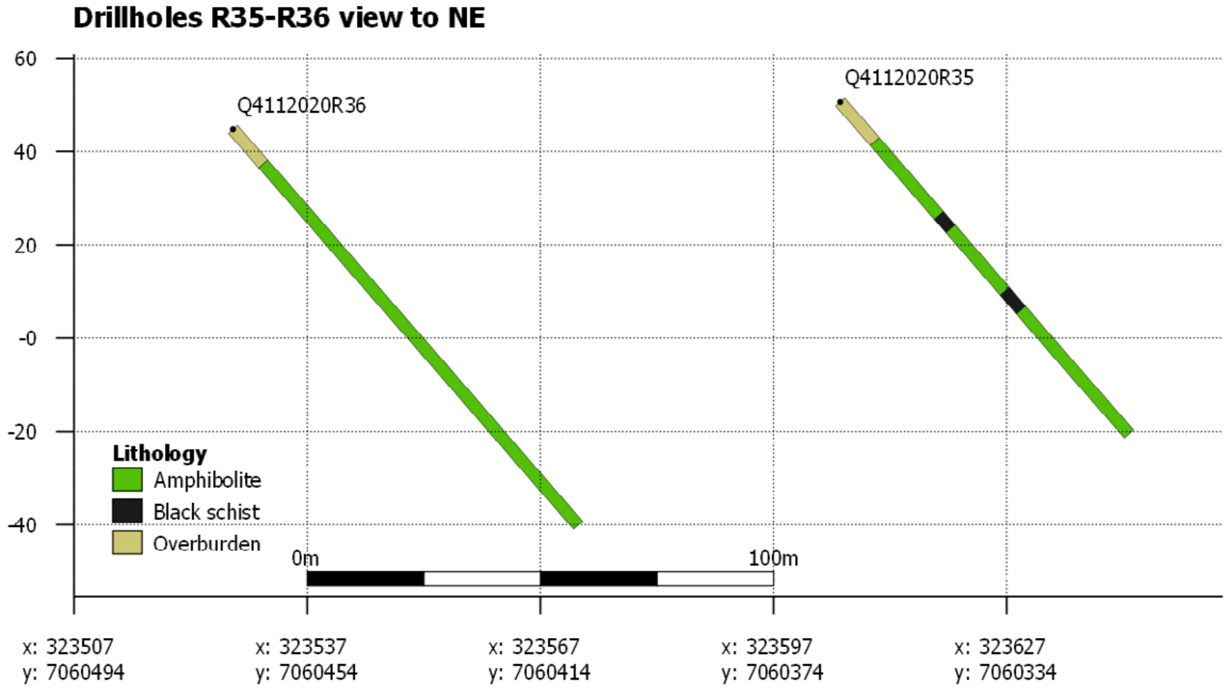
Appendix 2. Drillhole profiles R25–R40.

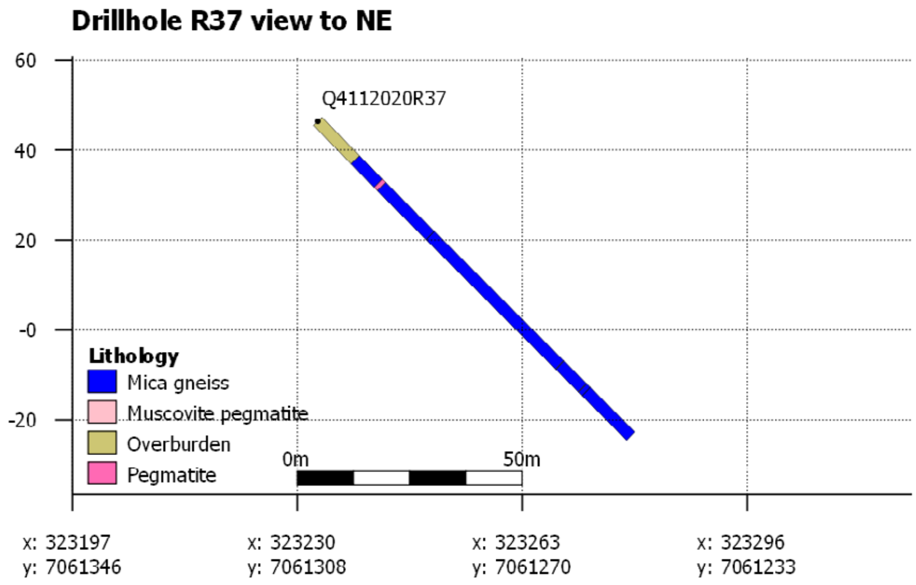


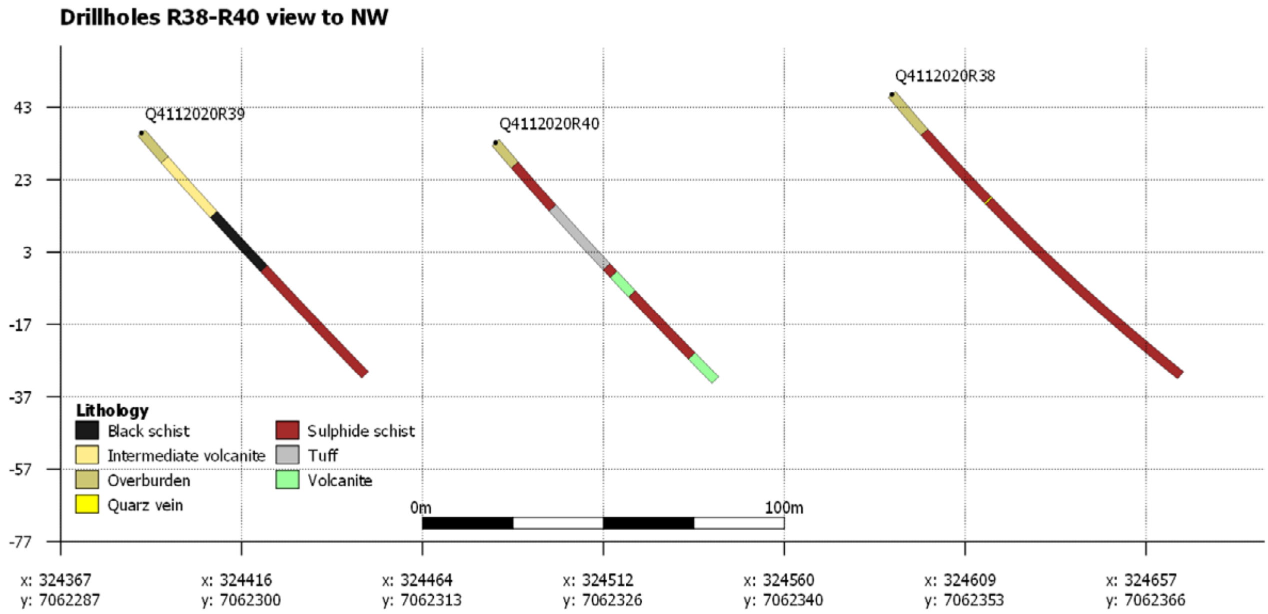





Drillholes R33-34 view to east
Q4112020R33
Q4112020R34
40
20
-0
-20
Lithology
Amphibolite
Black schist
Intermediate volcanite
Mica schist
Muscovite pegmatite
Overburden
Sulphide schist
0m
50m
x: 324251
y: 7059238
x: 324251
y: 7059188
x: 324251
y: 7059138
x: 324251
y: 7059088


Drillholes R35-R36 view to NE
Q4112020R36
Q4112020R35
60
40
20
-0
-20
-40
Lithology
Amphibolite
Black schist
Overburden
0m
100m
x: 323507
y: 7060494
x: 323537
y: 7060454
x: 323567
y: 7060414
x: 323597
y: 7060374
x: 323627
y: 7060334


Drillhole R37 view to NE
Q4112020R37
60
40
20
-0
-20
Lithology
Mica gneiss
Muscovite pegmatite
Overburden
Pegmatite
0m
50m
x: 323197
y: 7061346
x: 323230
y: 7061308
x: 323263
y: 7061270
x: 323296
y: 7061233


Drillholes R38-R40 view to NW
Q4112020R39
Q4112020R40
Q4112020R38
43
23
3
-17
-37
-57
-77
Lithology
Black schist
Intermediate volcanite
Overburden
Quarz vein
Sulphide schist
Tuff
Volcanite
0m
100m
x: 324367
y: 7062287
x: 324416
y: 7062300
x: 324464
y: 7062313
x: 324512
y: 7062326
x: 324560
y: 7062340
x: 324609
y: 7062353
x: 324657
y: 7062366

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