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Novel application of geophysical measurements, lithium targets

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Abstract Three distinct geophysical methods were tested at the Kaustinen Leviäkangas site to investigate their potential for detecting a known lithium spodumene-pegmatite deposit within the surrounding gneiss. This task posed a challenge for most geophysical methods due to the nearly identical petrophysical parameters of the two rock types. The measurements were conducted using an electromagnetic GEM-2 equipment, employing various measurement frequencies. Due to the narrowness of the deposit, dense measurement lines and point separations were utilized. In addition, the self-potential method was employed to map voltage differences occurring naturally on the surfaces of different rock types. Both methods had limited previous application in lithium targets. Additionally, a dense magnetic measurement was carried out at the Leviäkangas site, which typically serves as a supportive measure for other methods. The maps illustrating the magnetic field distribution, self-potential and electric conductivity at the Leviäkangas site displayed noticeable structures that aligned with the anticipated locations. However, these anomalies did not exhibit a clear and definite correlation with the known pegmatite-spodumene deposit. The observed variations in the measurements were partially attributed to other factors, such as the presence of an approximately 8-meter thick overburden, which likely influenced the electric conductivity and self-potential readings. At the Kaustinen Syväjärvi site, a multi-frequency FrEM method was employed to map the gently dipping lithium-bearing pegmatite layer. However, the FrEM method, which detects variations in electric conductivity, was unsuccessful in accurately delineating the mineralization within the adjacent rock formations. Among the methods tested, the self-potential method appeared to be the most promising.	
Keywords Lithium, pegmatite, self-potential methods, electromagnetic methods, magnetic methods, multi-frequency FrEM method	
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1 INTRODUCTION

Lithium is one of the critical minerals in the transition to green technology. In the Kaustinen region, lithium has been found in several pegmatite deposits. Three different geophysical surveys, self-potential, EM and magnetic measurements, were carried out in Leviäkangas deposit (Figure 1) and described in Chapter 2. In addition, a multi-frequency FrEM method, which detects variations in electric conductivity, was employed in the nearby Syväjärvi deposit (Chapter 3). The aim was to test new methods and their applicability in improving lithium exploration.

Geophysical research methods cannot detect individual minerals or metals such as lithium in rock, but instead can distinguish between rock types. This is possible if the rock types have a sufficiently high contrast for some physical parameter. Parameters typically utilized in identifying rock types are density, magnetic susceptibility or electrical conductivity. This work presents test results in which the Geological Survey of Finland (GTK) has measured the spatial distribution of self-potential, magnetic field and electrical conductivity of rocks.

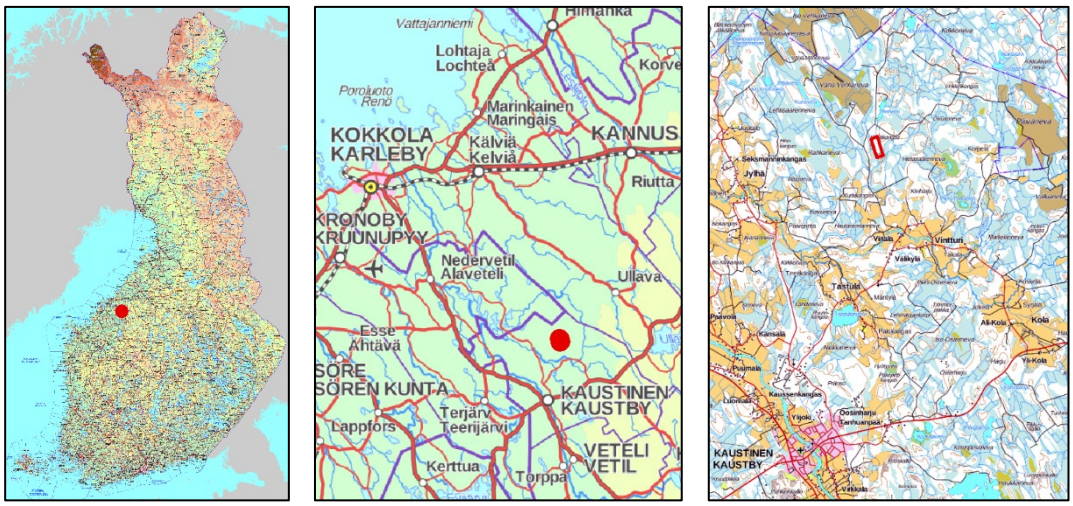


Figure 1. Leviäkangas deposit is located near Kokkola and Kaustinen. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

The objective of the test measurements was to successfully identify the pegmatite deposit within the biotite paragneiss. Leviäkangas test area, marked with a red rectangle on the geological map (Figure 2), is 200 meters wide and 600 meters long. The main lithological rock types are rare-element (RE) pegmatite, biotite paragneiss and graphite sulphide paraschist. As the map shows, the RE-pegmatite deposit is completely enclosed within the biotite paragneiss. 17 drill holes have been drilled in or near the test area. Drilling depth varies between 40 and 150 meters.

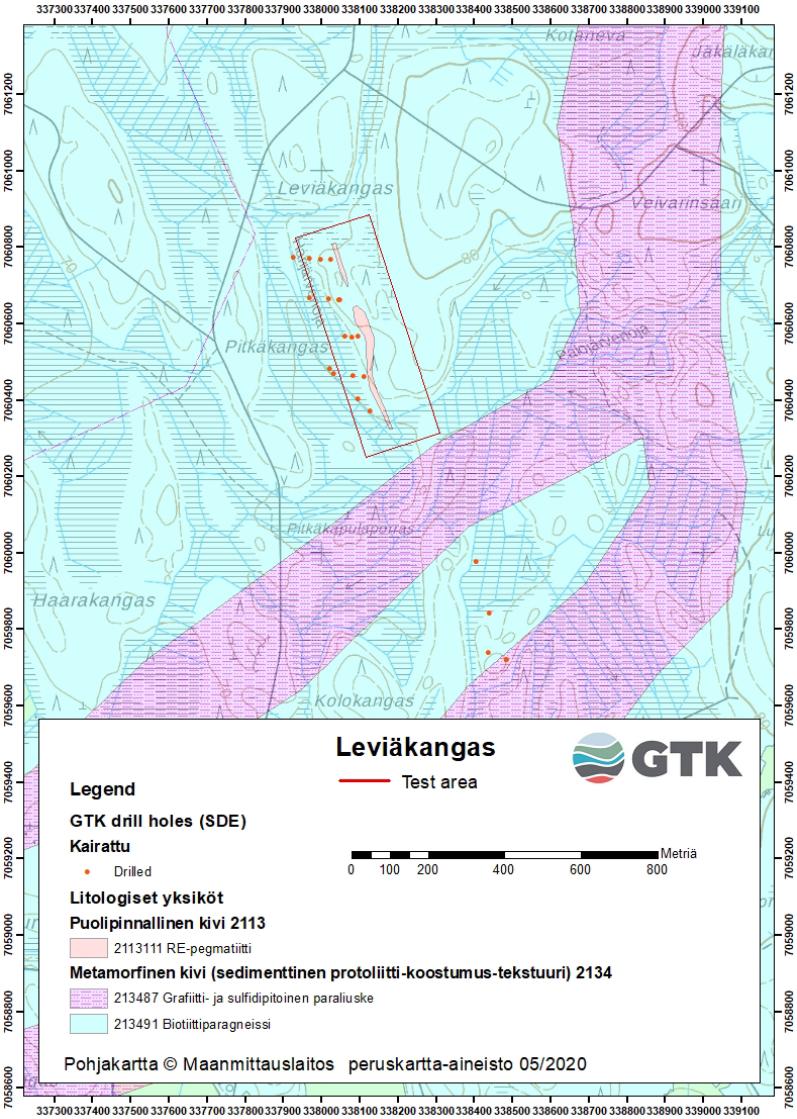
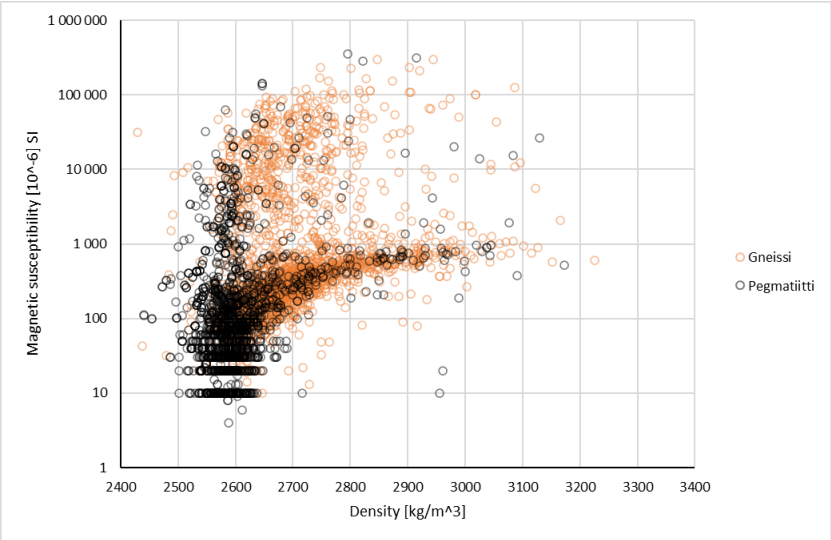


Figure 2. Leviäkangas test area, geology and bore hole locations.

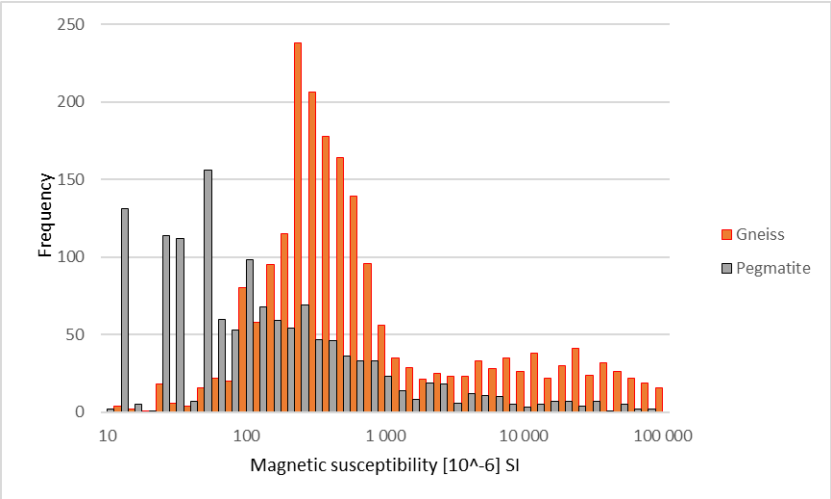
In GTK's petrophysical register (Airo & Säävuori 2013), there is an extensive dataset of physical properties of rock samples. This dataset enables estimating or predicting the exploration potential of various geophysical methods. GTK's petrophysics register contains petrophysical laboratory analysis of about 2 900 different pegmatite samples and about 30 000 different gneiss samples, such as amphibolite gneiss or granite gneiss. The register contains 2 100 gneiss samples without additional specifications in the name of the rock type. However, none of the samples are named exactly biotite paragneiss like the host rock on the geological map (Figure 2).

Petrophysical diagram for magnetic susceptibility versus density by 2 900 pegmatite and 2 100 gneiss samples is presented in Figure 3a. Rock types have similar distributions, but

pegmatite samples have populated mainly the weakly magnetic group (paramagnetic group) while gneiss samples have populated also the strongly magnetic group (ferrimagnetic group).



a)



b)

Figure 3. Petrophysical diagram of magnetic susceptibility versus density of gneiss and pegmatite samples in petrophysical register (3a) and histograms of magnetic susceptibility of gneiss and pegmatite samples (3b).

The histogram in Figure 3b shows that there are two different groups in the distribution of the magnetic susceptibility of gneiss. Gneiss is typically a non-magnetic rock type, but small percentage of gneiss contains ferrimagnetic minerals. Due to these types of pegmatite and gneiss distributions, it is not sure if pegmatite deposit can be detected within the gneissic host rocks by mapping the magnetic field. However, petrophysical data do not reveal how the magnetic field is spatially distributed in the study area. It is known that magnetic map can sometimes be flat, or contrary “noisy” due to detailed

geological variation. Also, the contact of rock types can stand out somehow on a magnetic map.

Unfortunately, no suitable petrophysical laboratory results for electrical conductivity were found. However, in-situ borehole logging data was found in GTK's registers where down-hole measurement had been conducted in gneiss, but not in pegmatite. Based on borehole logging data, the resistivity of granite pegmatite is approximately 4 700 Ohmm. Occasionally, the resistivity was much less, but without further study it is quite possible that these sections do not represent granite pegmatite. Resistivity of gneiss varies between 3 000 and 8 000 Ohmm. Both rock types have high resistivity and gneiss also has wide variation within the rock type. Additionally, reference from literature suggests that resistivity of pegmatite is about 5 000 Ohmm (Haase & Pohl 2022). Clearly, there would be a need for new petrophysics measurements.

Self-potential is a naturally generated target property, and it makes no sense to measure it in a laboratory. The method has previously been tested (but not published) also in other pegmatite targets, and it was believed beforehand that the method could provide new information in the pegmatite exploration.

2 LEVIÄKANGAS TARGET

Three different geophysical methods were tested in Leviäkangas deposit in Kaustinen: magnetic, electromagnetic and self-potential (SP) method.

The survey plan map is presented in Figure 4. The grey area on the map indicates the location of the lithium pegmatite deposit based on geological map. Green straight lines indicate the profile sites of magnetic and electromagnetic survey. Red lines show SP survey profiles.

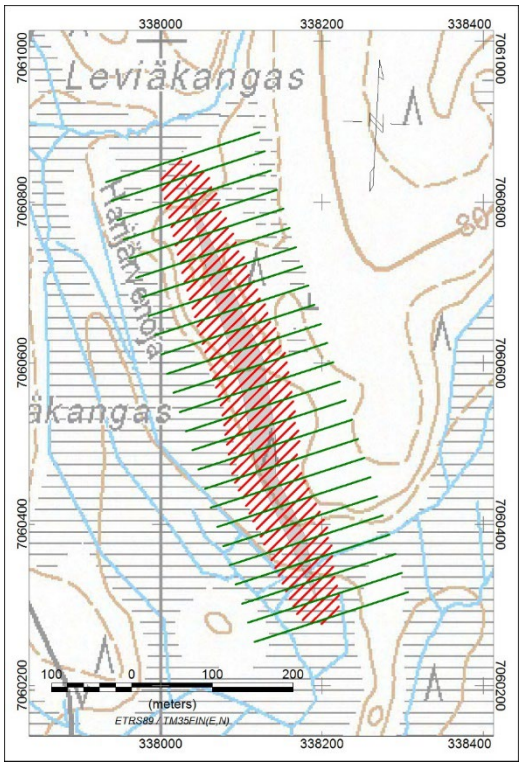


Figure 4. Survey plan including profiles for electrical conductivity and magnetic mapping (green lines) and profiles for self-potential measurements (red lines). The location of lithium-pegmatite deposit is marked by a grey polygon. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

A portable electromagnetic multi-frequency instrument Geophex's GEM-2 was used to measure distribution of electric conductivity. GEM-2 device has transmitter and receiver coils with coil separation of 1.66 m. Recorded EM data includes values of In-Phase and Quadrature components of four measured frequencies. Selected frequencies were 1475, 5825, 22225 and 75525 Hz. Survey was made by carrying the device at walking speed along lines. Device has a built-in GPS system for positioning the results. GPS location and electromagnetic data have been continuously measured and processed in real-time. Data is automatically stored in a data file at a constant sampling rate. The sampling distance along the profile is typically 7–8 cm. The measured frequency data are converted or interpreted as electrical conductivity values in the post-processing phase.

The magnetic survey was carried out by measuring the total magnetic field by proton magnetometer. The instrument used was GEM System's GSM-19 Overhouser magnetometer. The survey was conducted using the same profiles as the electromagnetic survey and one second sampling rate. Natural total field variation was removed according to the base station data. The base station was located outside the measuring area in a magnetically calm area.

2.1 SP detailed profile survey

Self-potential survey consists of 955 measured points of self-potential with 5 meters interval along lines and 10 m between lines. A non-polarized $PbCl_2$ electrode and a regular multimeter were used as equipment together with long cable connecting electrode on survey line to reference electrode at distance, see Figure 5. Minimum distance of 250 m from measurement point to reference electrode was maintained, usually distance being bigger. The idea is to have reference electrode in place far enough with constant grounding conditions, with no flowing water nearby.

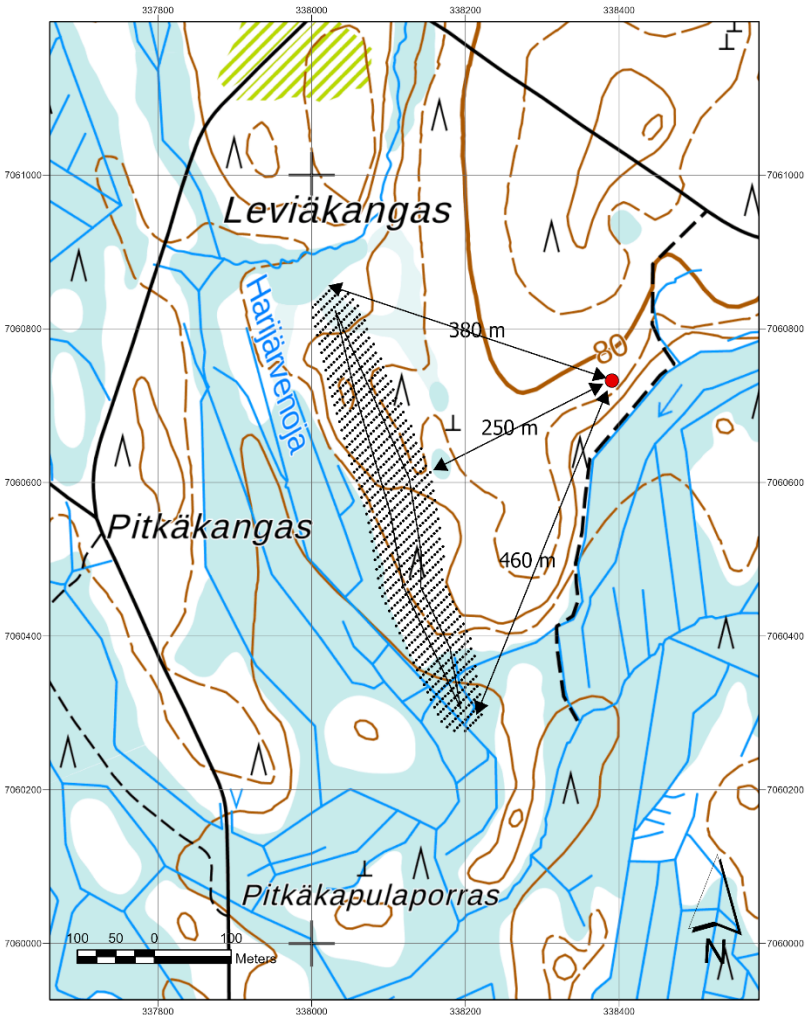


Figure 5. Setup of self-potential survey consisting of 955 measured potentials (black dots). Reference electrode is depicted by red circle. Distance from reference electrode to measurement points were at minimum 250 m. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

Self-potential measurement results are depicted in Figure 6. As measured self-potential polarity (+ or -) depends both on measurement area geology and on measurement configuration, there is no merit trying to attach meaning on polarity of self-potential but only on changes of potential in the whole measurement area. It is known that pegmatites should drag self-potential to opposite polarity than topography and electrically conducting minerals, but effect of groundwater might be to same or opposite direction (Reynolds 1997). Local elevation model in Figure 7 in decimeters (dm) suggests that topographic variation in measurement area is less than 1 m. This means that topographic effect can be considered small. Ground water system of area is unknown so its effect on self-potential cannot be estimated.

Taking into account these factors that influence self-potential, the measurement area is approximately divided into five units, progressing from South to North: 1) moderate to low potentials in the very South, 2) then peaking, 3) going low, 4) peaking again and 5) going moderate to low potentials in the very North. In the best scenario, these potential changes would correspond to variations in lithology and for that they should be crosschecked against geological data from drillholes and outcrops.

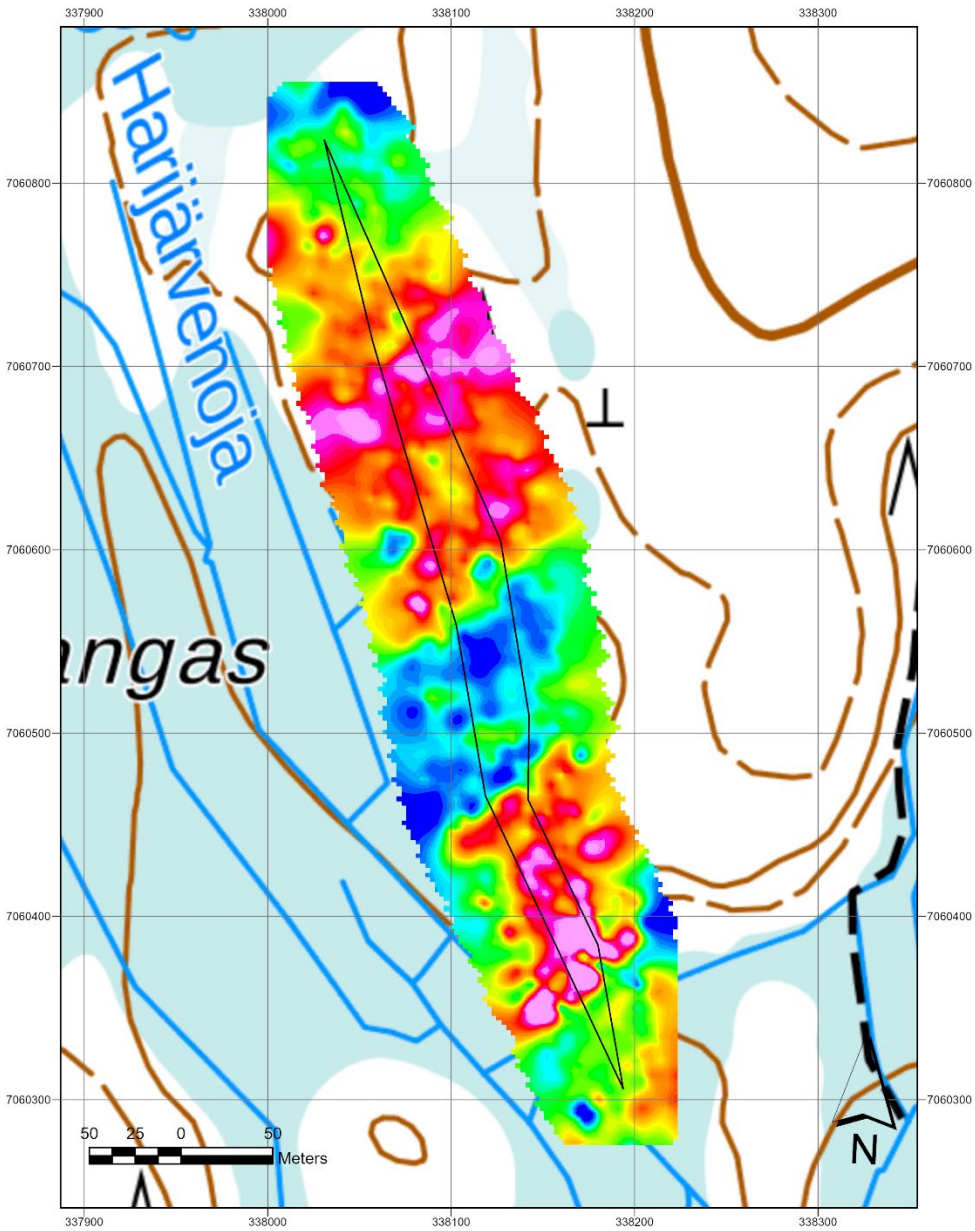


Figure 6. Self-potential measurements on topographic map. Area is divided roughly to five units from South to North based on self-potential: 1) moderate, 2) high, 3) low, 4) high, 5) moderate to low. It should be checked whether these changes reflect lithological changes. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

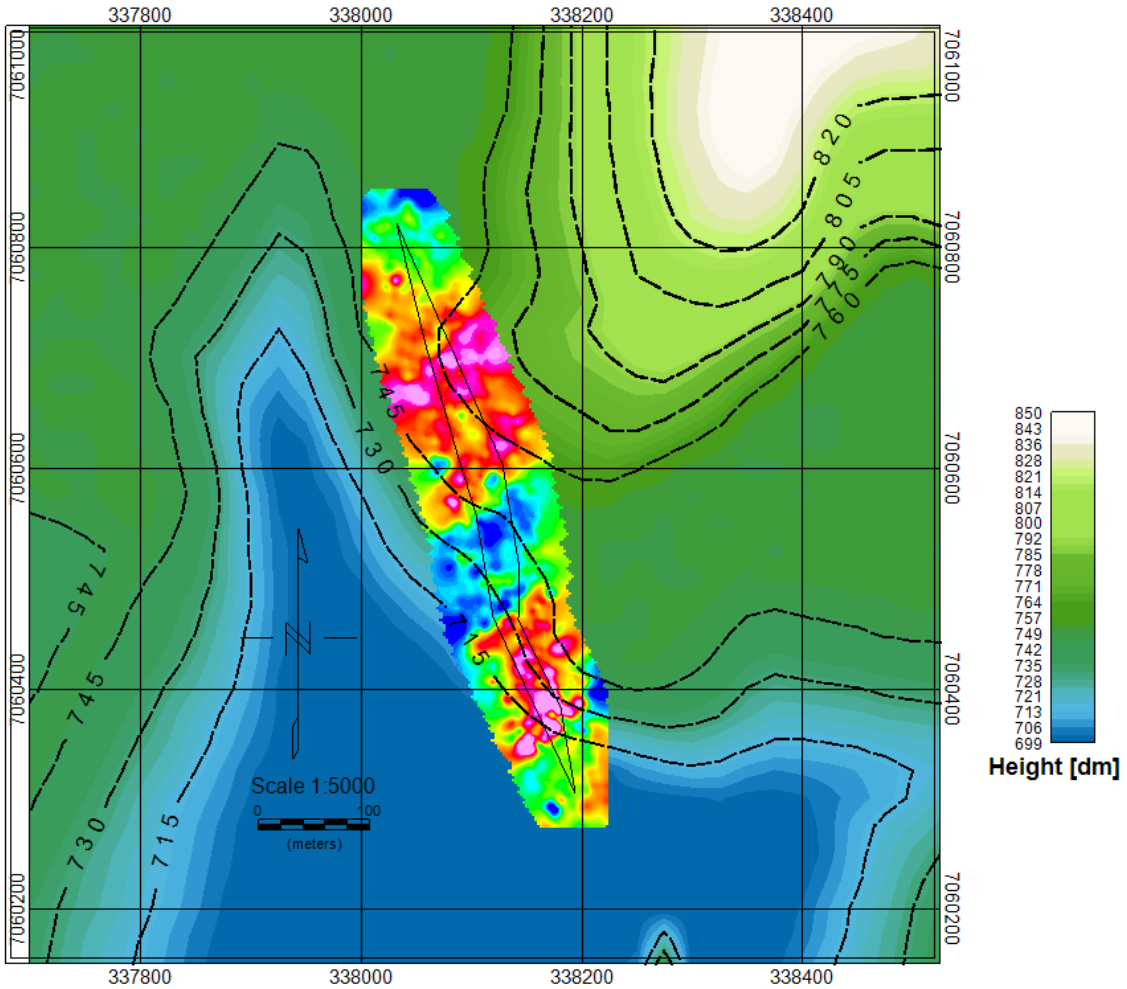


Figure 7. Results from self-potential measurements shown on elevation model using the decimeter (dm) scale. Topographic changes are small (within 1 m) which would suggest that self-potential is not topography driven but is more prone to reflect local geology.

2.2 EM profile soundings

Conductivity values have been calculated from the In-Phase and Quadrature components of electromagnetic GEM-2 results using the Invertor software (Geophex Ltd). Electrical conductivity values have been filtered to a sampling frequency of 1 m to reduce the noise level. The results have been converted to apparent resistivities (which are reciprocal values) and then interpolated into the resistivity map shown in Figure 8.

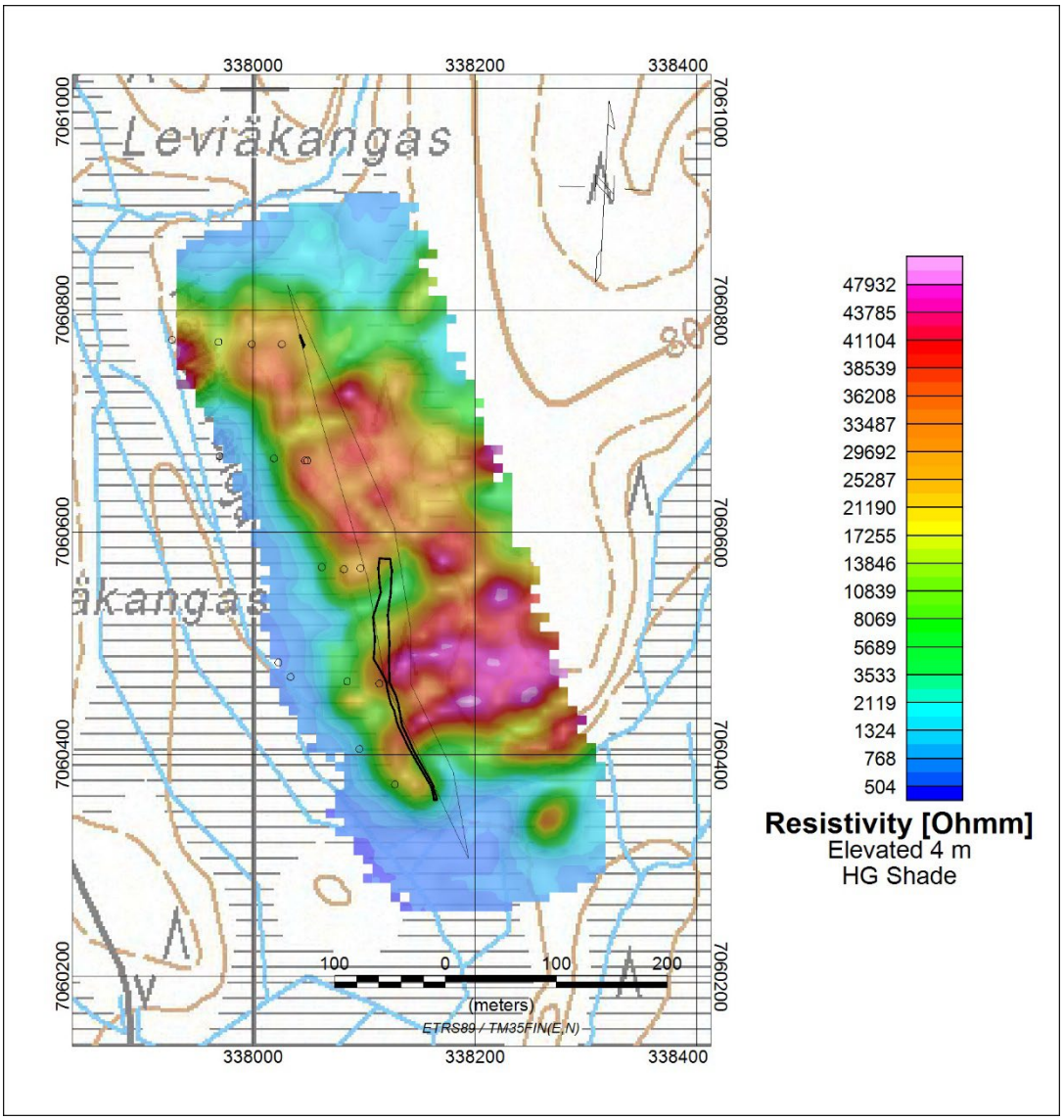


Figure 6. Apparent resistivity distribution in Leviäkangas test area. Red color indicates resistive and blue more conductive value. The map is smoothed with a vertical continuation filter 4 meters up. The shadows on the map depict the magnitude of the horizontal gradient. The boundaries of the pegmatite zone are represented by a thin black polygon. The boundaries of spodumene pegmatite on bedrock surface are represented by a thick black polygon. The locations of boreholes are marked by small black circles. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

The known spodumene pegmatite deposit does not stand out on the map. The greatest contrast on the resistivity map can be seen between wet and dry soils. The resistive area characterized by a low hill is very rocky with no marsh, and the results were noisy. The quality of the data is better in swamps and moist soils, where resistivity is low.

2.3 Magnetic profile survey

The magnetic field varies little in Leviäkangas test area, and therefore the magnetic map (Figure 9) highlights small changes in the bedrock. The locations of the bore holes are marked on the map. It appears that the ground tubes in the bore holes have not been affected by magnetic anomalies. Magnetic results are not affected by swamp or wet soil.

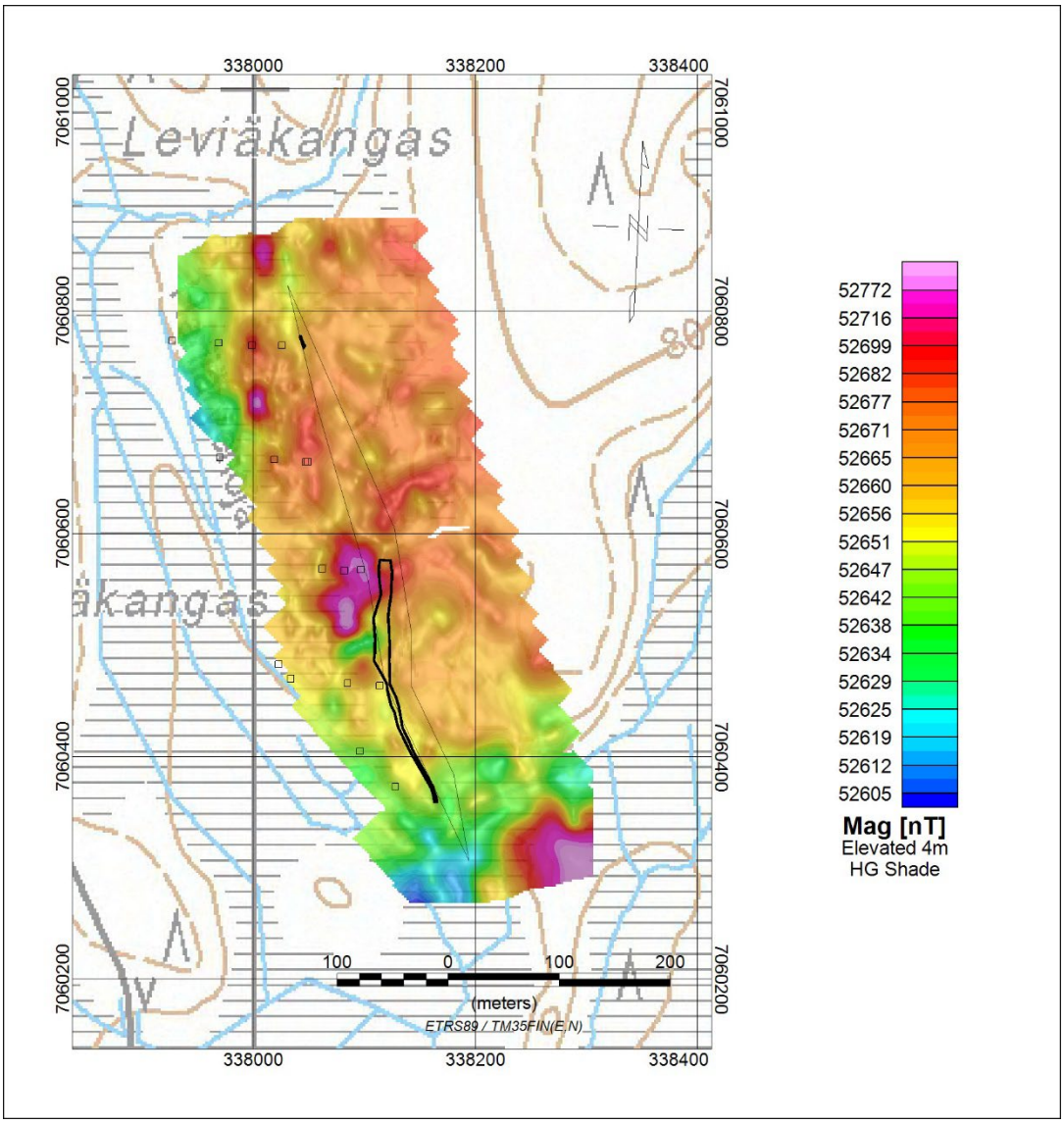


Figure 7. Magnetic field distribution in Leviäkangas test area. The borehole locations, the boundaries of the pegmatite zone and the boundaries of the spodumene pegmatite deposit are represented by black circles, thin and thick black polygons, respectively. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

There is an anomaly high in the southeast corner of the magnetic map indicating that the survey extends near the graphite sulphide paraschist. The maximum anomalies in

the center of the magnetic map are quite modest, although they are highlighted on this scale.

It is possible that pegmatite appears on the magnetic map as some sort of minimum or flatter area especially in the northern and southern part of the region. Although some variation can be found on the map, it would be impossible to distinguish these rock types based on magnetic data alone.

3 SYVÄJÄRVI TARGET

The FrEM method was tested in the Syväjärvi lithium pegmatite target. The research aimed to map the local spodumene pegmatite and adjacent lithologies based on their electromagnetic properties. The FrEM survey is a Frequency ElectroMagnetic method, which involves conducting measurements within specific frequency ranges. The device used in this study had 41 frequencies ranging from 100 to 10 000 Hz.

During ground survey arrangements, the transmitter consists of a conductive loop made of an insulated wire. It is typically laid out in a rectangular shape, with each side measuring between 50 and 1 000 m in length. The EM method relies on the phenomenon that electric current induces secondary magnetic fields, particularly in conductive structures. In the case of FrEM, the receiver is either moved along lines or measurements are taken at various locations within the research area. The receiver is equipped with three coils positioned in perpendicular directions, enabling simultaneous measurement of the total magnetic field.

The Syväjärvi lithium deposit is comprised of several north-northwest trending spodumene pegmatite dikes, with a plunge of 15−20 degrees to the north-northwest direction (Äijälä 2018). Additional rock types in the research area, as identified through Keliber's exploration, include mica schist, intermediate metatuffite and plagioclase porphyrite. Mica schists occasionally contain sulfides. The Syväjärvi spodumene pegmatite is situated in the municipality of Ullava, approximately 12 km northeast of the center of Kaustinen (Figure 10). The FrEM survey was conducted by Loop and Line Ltd., commissioned by the Geological Survey of Finland (GTK).

Figure 10. Location of the Syväjärvi target, indicated by the black rectangle. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

3.1 The measuring arrangement

The transmitting loop was positioned to the east of the research area. Ideally, it would have been more advantageous to place it to the south of the pegmatite. However, due to the presence of extensive water-filled ditches in that direction, it was not feasible to achieve this configuration within a reasonable timeframe. The length of the loop was approximately 1400 m, with dimensions of 500 m by 200 m. The distance from the target area was roughly 400 m, with the closest point being around 200 m away (Figure 11).

In the study area, a total of 6 measuring lines were established, covering an area of approximately 16 hectares (550 m x 300 m). Along these lines, measurements were conducted at 20 m intervals using 5 frequencies. Each measurement event on a stand lasted for 10 seconds. The applied frequencies were as follows: the lowest frequencies were 116 Hz, 330 Hz and 992 Hz, while the highest frequencies were 3189 Hz and 8929 Hz.

The second measuring arrangement involved using 41 multiple frequencies along 600 m long lines oriented in the northwest direction. One such line is shown as example in Figure 12. The frequencies were generated by the transmitter in repeated sets. Each measurement took approximately 5 minutes to complete. These measurements were conducted at intervals of 50 m, covering up to 12 sites within the area. The mapping of the entire area was carried out along several lines, over three periods spanning two days. The process of spreading the transmitter cable required one day.

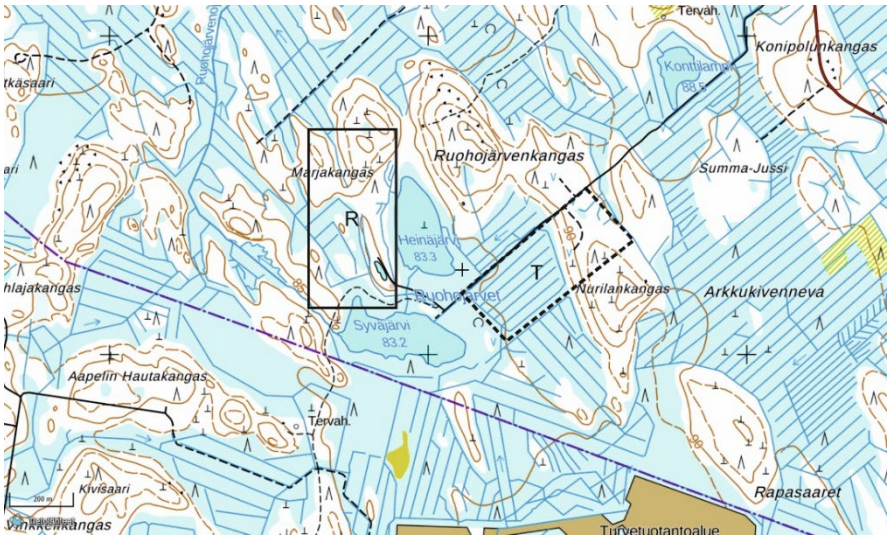


Figure 11. The Syväjärvi research area (R) enclosed within the solid line. The location of the transmitter loop (T) is indicated by the dashed line. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

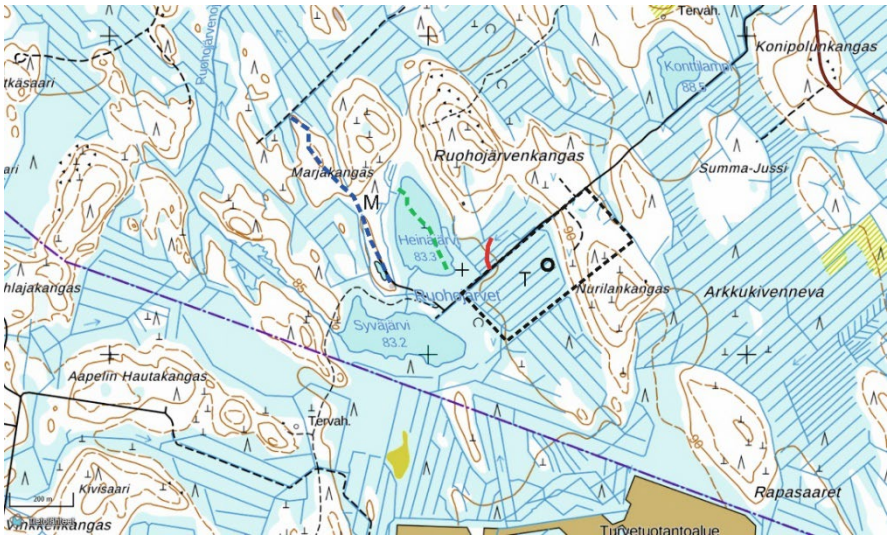


Figure 12. One of the multi-frequency sounding profiles is represented by the dark blue NW oriented dashed line on the map. When the receiver has followed the sounding profile, the measurement result is projected to the green line, halfway between the receiver and transmitter cables. The transmitter loop is depicted with the black dashed line (T), and the center of the loop is represented by the black circle. For calculations, the rectangular loop has been converted into an arch of a circle, shown as the red line. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

3.2 Results and discussion

On the eastern side of the research area (as shown in Figure 13), there existed a conductive lithological sequence consisting of a sulfide-bearing rock unit, mica schist. This presence of conductive rock between the measured area and the transmitter loop

caused significant noise interference and resulted in a considerable weakening of the signal, particularly at the lowest frequencies. Consequently, it was not feasible to identify the spodumene pegmatite or other lithological structures in the research area characterized by electrically resistive bedrock (Jokinen 2022).

It is likely that more favorable results could have been achieved if the transmitter had been located to the south of the study area, as initially planned. The conductive rock unit between the measured area and the transmitting loop also exhibits slight magnetic properties. It should be noted that on the geophysical map available on the GTK's Mineral Deposits and Exploration website, this conductive and slightly magnetic unit is inaccurately positioned further to the east compared to the original airborne magnetic anomaly map. Without this misleading magnetic information, it might have been possible to position the loop in a way that would have prevented such significant signal attenuation. Although signal weakening is anticipated in such situations, the rate of attenuation cannot be accurately predicted.

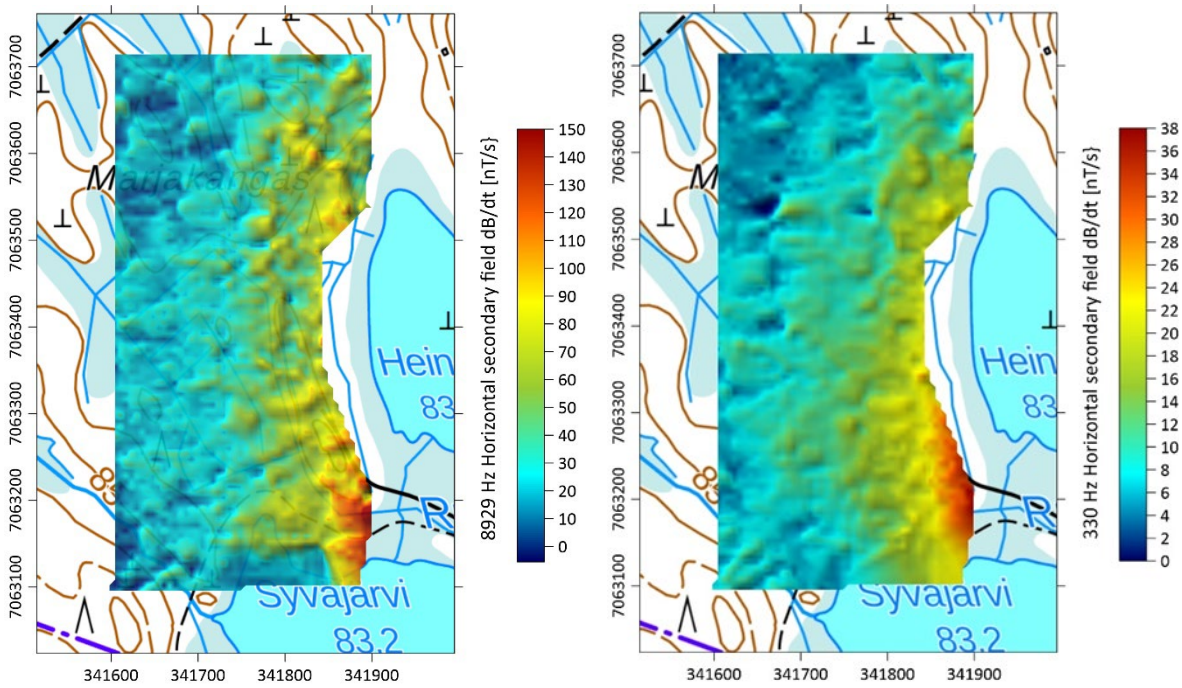


Figure 13. The maps derived from the Syväjärvi FrEM survey, which were interpolated from the horizontal component of the secondary field using 2 frequencies. On the left side, the map compiled from the highest frequency (8929 Hz) measurements displays conductive anomalies primarily at the upper levels of the bedrock. On the right side, the map compiled from the lowest frequency (330 Hz) measurements reveals deep-seated geological structures, with a particular emphasis on the largest conductive structures. It should be noted that sulfide-bearing conductive mica schist is present on the eastern side of the research area. Map copyright © Maanmittauslaitos (National Land Survey of Finland).

4 CONCLUSION

Self-potential, EM and magnetic measurements were carried out in Leviäkangas in Kaustinen. The purpose of the surveying was to delineate the lithium-pegmatite body known in the area.

Self-potential method divided the survey area into five domains ranging from low to moderate and high potentials. Geological interpretation of these domains remains to be established by comparing how they relate to available bore hole and rock sample data. In the best scenario, these domains reflect lithological changes of rock.

Very densely measured electromagnetic and magnetic profiles did not give a result in which the known location of spodumene pegmatite would have been clearly observed. The physical properties of the deposit (electrical conductivity and magnetic susceptibility) are not sufficiently different from those of the surrounding rock, and there are no factors at the deposit interface that would improve the detection of the contact between rock types.

At the Kaustinen Syväjärvi target, a multi-frequency FrEM method, which detects variations in electric conductivity, was unsuccessful in accurately delineating the mineralization within the adjacent rock formations.

The measured geophysical data has been processed by GTK standard systems and stored in GTK databases.

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