Secondary resources directive

Characterisation of mining waste in Northern Lapland, Sweden

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Cover picture: View of the tailing ponds and the lake Aisjaur seen from the Laisvall mine.
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CONTENTS

ABSTRACT

In 2021, the Geological Survey of Sweden (Sveriges geologiska undersökning, SGU) together with the Swedish Environmental Protection Agency received a governmental directive to work to increase the possibilities for sustainable extraction of metals and minerals from secondary resources (N2021/01038). The work is intended to contribute to the transition to a more circular and resource-efficient economy. The directive in its entirety was reported to the government in February 2023 (SGU RR 2023:01).

As part of the directive, SGU has documented, sampled, and characterised mining waste (waste rock and tailings) at closed Swedish mines to estimate the quantities of metals and minerals. Metallurgical slag and burnt alum shale were also investigated. Secondary resources from mining waste can possibly contribute to the supply of the critical raw materials needed in the ongoing energy transition.

A total of 70 locations was sampled by SGU during 2021 and 2022, with altogether 1,067 samples. A series of reports present background information and available data for each of these locations, as well as the results from the new investigations.

This report covers a subset of the investigated locations within the directive, from the northern parts of Lapland in Sweden. Sampling was conducted at three locations at the mine sites of Viscaria, Laisvall and Pahtohavare. At these mines, copper, zinc, and lead have been enriched, but also some gold.

Sampling was carried out using proven methods, where all samples consisted of 5 subsamples/sample and weighed about 5 kg. At the investigated sites, 16–18 samples of waste rock and tailings were sampled. A majority of the samples were sampled from the surface (depth 0.5 m) with a shovel, however, sampling tailings in the Viscaria mine was conducted with a screw sampler at depths of 0.5–19 m. Samples were submitted to an accredited laboratory and analysed for a large number of metals such as rare earth elements (REEs), base metals (e.g., copper, zinc, and lead), bismuth, cobalt, germanium etc. with an analytical package consisting of ICP-AES, ICP-MS and LECO.

The results from the analysed mining waste show high levels of copper, zinc and lead. Based on the results of analyses of these wastes as well as historical information on quantities and tonnage at each mine, a resource estimate was conducted. Given that sampling is representative of these waste facilities, the quantities of copper, zinc and lead were estimated at 45,000, 100,000 and 240,000 tons in waste rock and tailings from Viscaria and Laisvall. For Pahtohavare, no resource estimate could be performed, as the quantities of waste rock are unknown.

SAMMANFATTNING

År 2021 fick Sveriges geologiska undersökning (SGU) tillsammans med Naturvårdsverket i regeringsuppdrag att arbeta för ökade möjligheter till hållbar utvinning av metaller och mineral ur sekundära resurser (N2021/01038). Arbetet är tänkt att bidra till omställningen till en mer cirkulär och resurseffektiv ekonomi. Uppdraget i sin helhet redovisades till regeringen i februari 2023 (SGU RR 2023:01).

Som en del av uppdraget har SGU dokumenterat, provtagit och karakteriserat gruvavfall (varphögar och sandmagasin) vid nedlagda svenska gruvor för att bedöma mängden metaller och mineral. Även metallurgiskt slagg samt rödfyr, som är en rest av bränd alunskiffer, har undersökts. Sekundära resurser från gruvavfall kan möjligen bidra till försörjningen av de kritiska råvaror som behövs i den pågående energiomställningen.

Inom uppdraget har totalt 70 platser provtagits under 2021 och 2022, med sammanlagt 1 067 prover. I en serie rapporter presenteras förutom resultaten från de nya undersökningarna även bakgrundsinformation och tillgängliga data för respektive undersökt plats.

Denna rapport tar upp en delmängd av de undersökta platserna inom uppdraget, från Norra Lappland. Provtagningen utfördes på tre platser vid gruvorna Laisvall, Pahtohavare och Viscaria. Vid dessa gruvor har framför allt koppar-, zink- och blymalm anrikats, men även en del guld.

Vid Laisvalls gruva togs 18 ytliga prover av anrikningssand med spade. För provtagning av gruvavfall vid Viscariagruvan togs 18 prover av anrikningssand med skruvprovtagare på ett djup av 0,5–19 m, samt 16 ytliga prover av gråberg med spade. Vid Pahtohavaregruvan togs 18 ytliga prover gråberg med spade. Provtagningen utfördes med metoder som tagits fram enligt vetenskaplig standard. Samtliga prover bestod av 5 delprov/prov och vägde ca 5 kg.

Proverna skickades in till ett ackrediterat laboratorium och analyserades med ett analyspaket bestående av Inductively coupled plasma atomic emission spectroscopy (ICP-AES), Inductively coupled plasma mass spectrometry (ICP-MS) och LECO. Ett urval av proverna har också analyserats med röntgendiffraktometrisk analys, s.k. XRD (eng. *X-ray diffraction*). Utvärdering och tolkning av diffraktometerrådata gjordes manuellt medelst Bruker AXS programvarupaket DIFFRAC*plus* och programmet EVA med Powder Diffraction File-databasen (ver. 1994, 2013).

De geofysiska data som presenteras i rapporten är en redovisning av det material som finns i SGU:s databaser för Laisvall, Pahtohavare och Viscaria. Materialet omfattar flyg- och markgeofysiska data samt analyserade petrofysikprov. Datamängderna har samlats in under flera mätkampanjer och kartläggningsprojekt vid eller i närheten av respektive gruva. Även tidigare utförda geofysiska mätningar av prospekteringsbolag, och vars data nu finns i SGU:s databaser, finns redovisade i rapporten.

Gruvavfallen har analyserats med avseende på ett stort antal metaller såsom exempelvis sällsynta jordartsmetaller (REE, eng. *rare earth elements*) och basmetaller som till exempel koppar, zink och bly, men även andra metaller varav somliga betraktas som kritiska för den gröna omställningen. I det provtagna gruvavfallet återfanns höga halter av koppar, zink och bly (ca 2,4 viktprocent koppar, 8 000 mg/kg bly samt 4 000 mg/kg zink).

Utifrån analysresultaten tillsammans med historisk information om mängder och tonnage vid respektive gruva har en resursuppskattning utförts. Givet att provtagningen är representativ för dessa avfallsanläggningar har mängden koppar, zink och bly uppskattats till 45 000, 100 000 och 240 000 ton i gråberg och anrikningssand från Viscaria och Laisvall. För Pahtohavare kunde ingen resursuppskattning utföras då mängden gråberg var okänd.

INTRODUCTION

In 2021, the Geological Survey of Sweden (Sveriges geologiska undersökning, SGU) together with the Swedish Environmental Protection Agency received a governmental directive to work to increase the possibilities for sustainable extraction of metals and minerals from secondary resources (N2021/01038). The work is intended to contribute to the transition to a more circular and resource-efficient economy. The directive in its entirety was reported to the government in February 2023 (SGU RR 2023:01).

As part of the directive, SGU has documented, sampled, and characterised mining waste (waste rock and tailings) at closed Swedish mines to estimate the quantities of metals and minerals. Metallurgical slag and burnt alum shale were also investigated. Secondary resources from mining waste can possibly contribute to the supply of the critical raw materials needed in the ongoing energy transition.

The European Commission has classified 34 raw materials as critical and strategic for our society and industry, and the demand for these materials will increase in the future. A large part of the production of these materials occurs outside the EU where China is the largest producer of many critical raw materials such as the rare earth elements. The EU's intention is to increase the degree of self-sufficiency of the materials. There is a significant number of known deposits of critical material within the EU, in particular Sweden.

Sweden has a long mining history and holds many abandoned mines with remaining waste rock and tailings. Waste rock is the uneconomical fraction removed from a mine to access ore, as well as mineralised rock of lower grade that were uneconomical to process during the life of the mine. Tailings are a fine sand that is the residual product of ore after crushing, milling, and separating the economic fraction from the uneconomic fraction. As no recovery method is 100% effective, a fraction of the targeted minerals will remain in the tailings.

Whitin the directive, a total of 70 locations was sampled by SGU during 2021 and 2022, with altogether 1,067 samples. A series of reports present background information and available data for each of these locations, as well as the results from the new investigations.

This report covers a subset of the investigated locations within the directive, from the northern parts of Lapland in Sweden. Sampling was conducted at three locations at the mine sites of Viscaria, Laisvall and Pahtohavare. At these mines, copper, zinc, and lead have been enriched, but also some gold.

Regional geology

The Viscaria and Pahtohavare mines (Fig. 1) are located in the Northern Norrbotten ore province, which consists of a wide range of deposits, the most important types being stratiform copper deposits, iron formations, Kiruna-type iron oxide–apatite deposits and epigenetic copper-gold deposits (Bergman 2018).

In the Laisvall mine (Fig. 1), lead and zinc were mined from a sandstone-hosted lead-zinc deposit located in the southwestern parts of Norrbotten, situated at the Caledonian border of Sweden (Bergman & Kathol 2018).

Figure 1. Overview map over northwestern Sweden that shows the location of the sampled mine sites in this report.

METHODS

Sampling

Tailings and waste rock were sampled following the method developed by Sädbom & Bäckström (2018). For tailings, 18 samples á 5 kg of tailings (5 subsamples/sample) were collected at Laisvall with a shovel at a depth of approx. 50 cm. At the Viscaria mine, samples were sampled with a screw sampler at depths of 0.5–19 m. For waste rock, 16–18 samples á 5 kg of waste rock (5 subsamples/sample) were collected at each site with a shovel at a depth of approx. 50 cm.

Samples of waste rock and tailings were analysed by the accredited ALS Analytical laboratory in Piteå.

X-ray diffraction (XRD)

Powder X-ray analyses were conducted in Uppsala at the office of the Geological Survey of Sweden on a Siemens D5000 teta-teta-diffractometer using a Cu Kα radiation source (40 kV and 40 mA) over the range $2\vartheta = 2–65°$. Samples were grounded in a pestle and packed into a plastic container before analysis. Results were evaluated and interpretated manually using the Bruker AXS program DIFFRACplus, EVA with a Powder Diffraction File-database (ver. 1994, 2013).

Geochemical analyses

Geochemical analysis of all samples was conducted by ALS laboratories. Sample preparation including weighing and crushing took place at ALS Piteå, Sweden. Samples were initially crushed to approximately 2 mm, and the samples were subsequently split and pulverised to <75 µm fractions for analysis at ALS Galway, Ireland. Three SGU internal standards were analysed with each batch of samples to ensure the accuracy of the results. A total of 61 major and trace elements were analysed. Major elements were analysed using ICP-AES after acid digestion. Trace elements were analysed using lithium borate fusion prior to acid digestion and ICP-MS. Aqua regia and 4 acid digestion with ICP-MS analysis was used for trace elements with low concentrations. Samples that contained high concentrations of an analysed metal exceeding the limit of standard analyses (typically 10,000 ppm) were analysed again using methods designed for higher concentrations. Many elements were analysed multiple times using several analysis methodologies, and data in this report are presented using SGU's preferred analysis methodology. For a complete list of elements analysed and their preferred analytical methodology, see Appendix 1: Sample Digestion and Analytical Methods.

LAISVALL MINE

Background

The Laisvall mine (Fig. 2) was a lead-zinc mine situated 35 km west of the city of Arjeplog (SWEREF99 TM 7338329/597640). Laisvall mine was one of the largest lead mines in Europe at the time of operation. The Laisvall mine was a sandstone-hosted lead-zinc deposit found in 1938 and operated by Boliden 1943–2001. Galena, sphalerite and pyrite were the principal sulphides, with native silver occasionally occurring in association with galena. In total, approx. 64 million tonnes of ore were extracted containing approx. 63 605 t of lead, 13 010 t of zinc and 13.1 t of silver. During the lifetime of the mine, 60 million tonnes of tailings were generated and deposited in tailings dams. Waste rock was backfilled into the underground mine – the quantity is unknown (Holmqvist 2001).

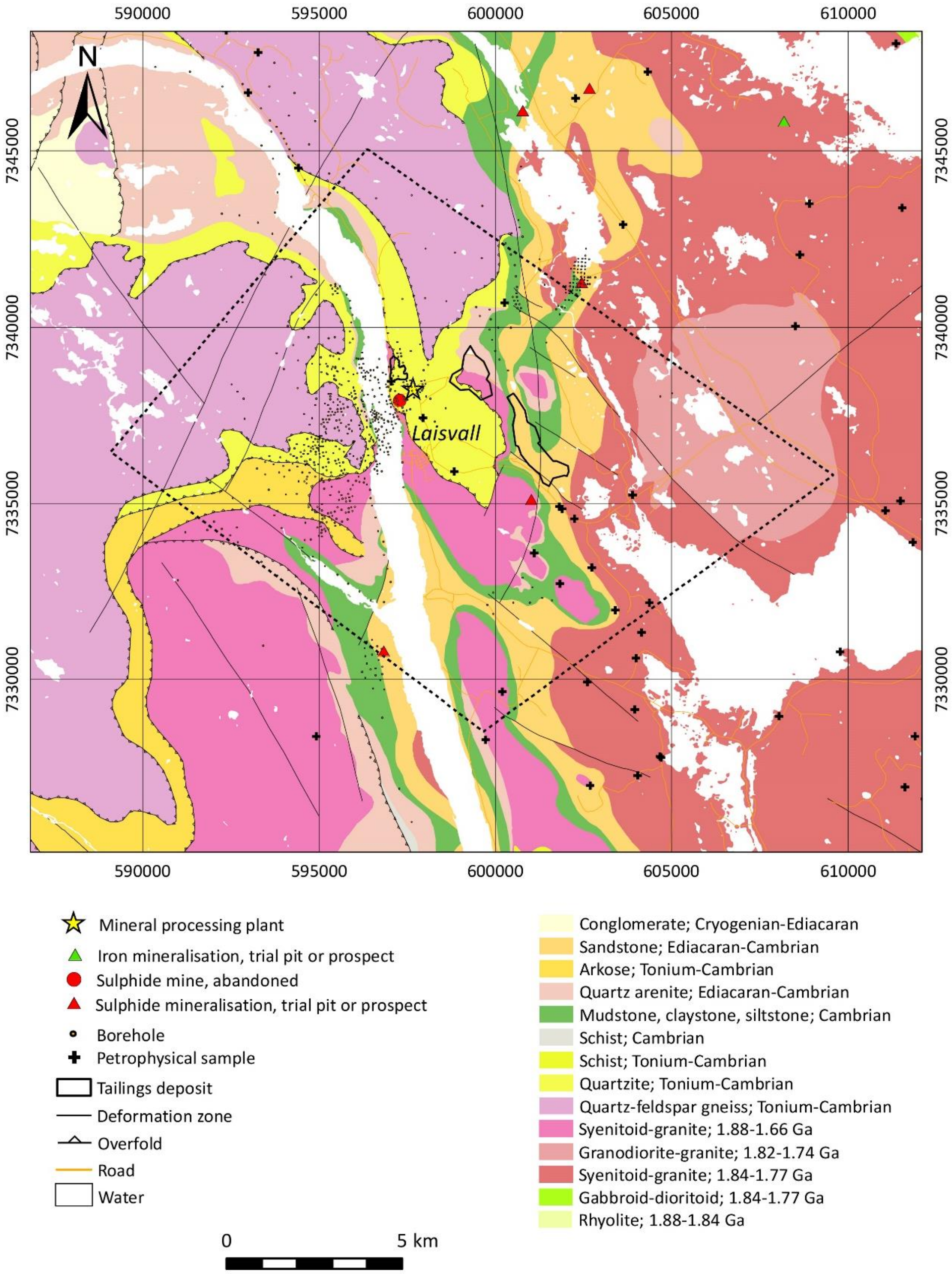

Figure 2. Simplified bedrock map over Laisvall and in its neighbouring areas (SGU 2022). The Laisvall area is shown as a polygon with dashed black line.

Existing data

Airborne geophysics

Two airborne geophysical surveys have been conducted by SGU over the Laisvall area. A compilation over these can be found in Table 1. The VLF (*Very Low Frequency*) measurements from two transmitters that SGU did in 2013 can be used to derive apparent resistivity and current density maps of the ground. Also, the electrical conductors in the ground can be identified independently of their direction with respect to the VLF transmitters. The geophysical data presented in Figures 3 and 4 are derived from SGU's airborne survey in 2013.

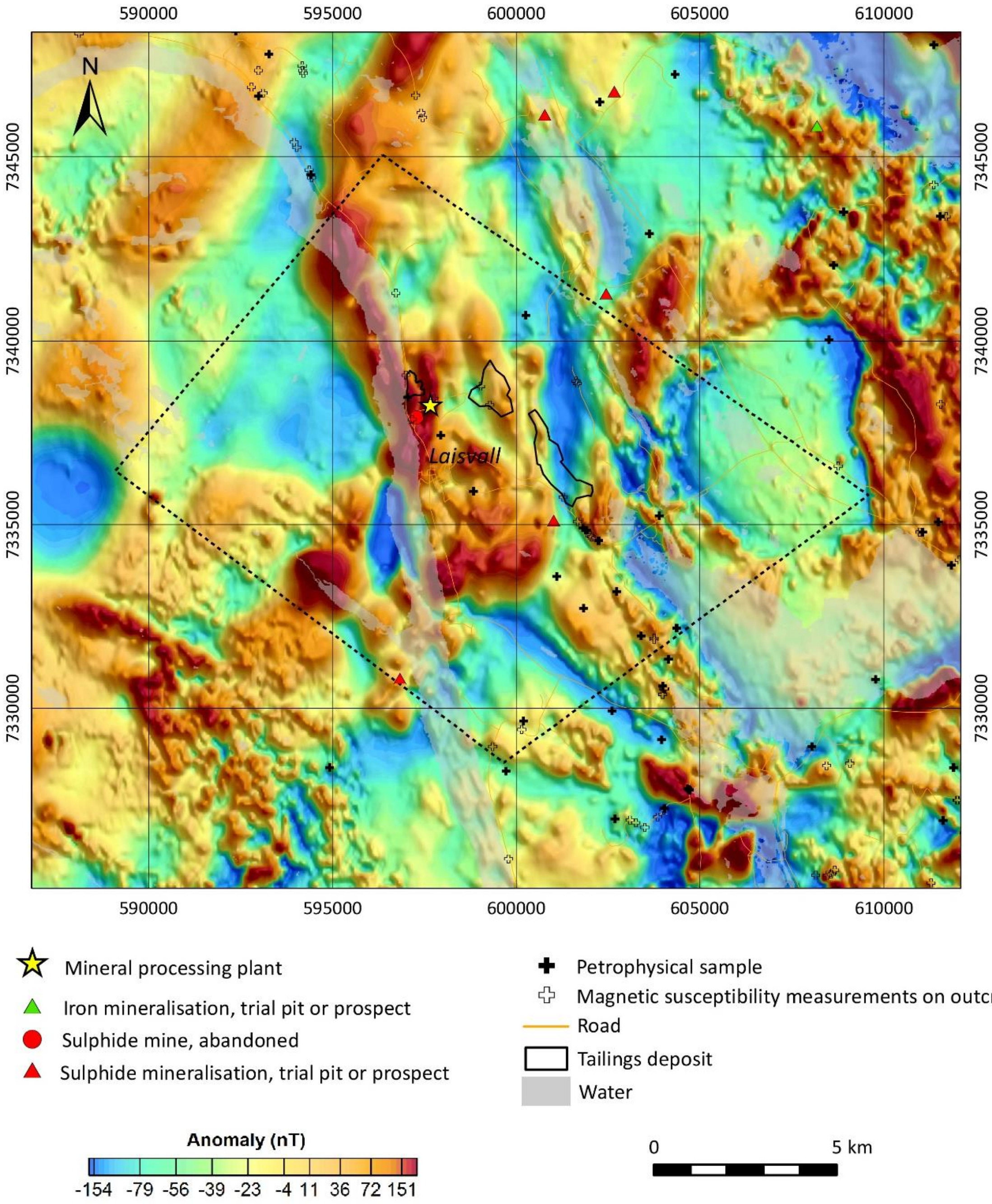

Figure 3. Map showing the magnetic anomalies at Laisvall and in its neighbouring areas. The magnetic anomaly is expressed as the difference between the pole-reduced total magnetic field and an analytical continuation upwards to 1 km. The Laisvall area is shown as a polygon with dashed black line.

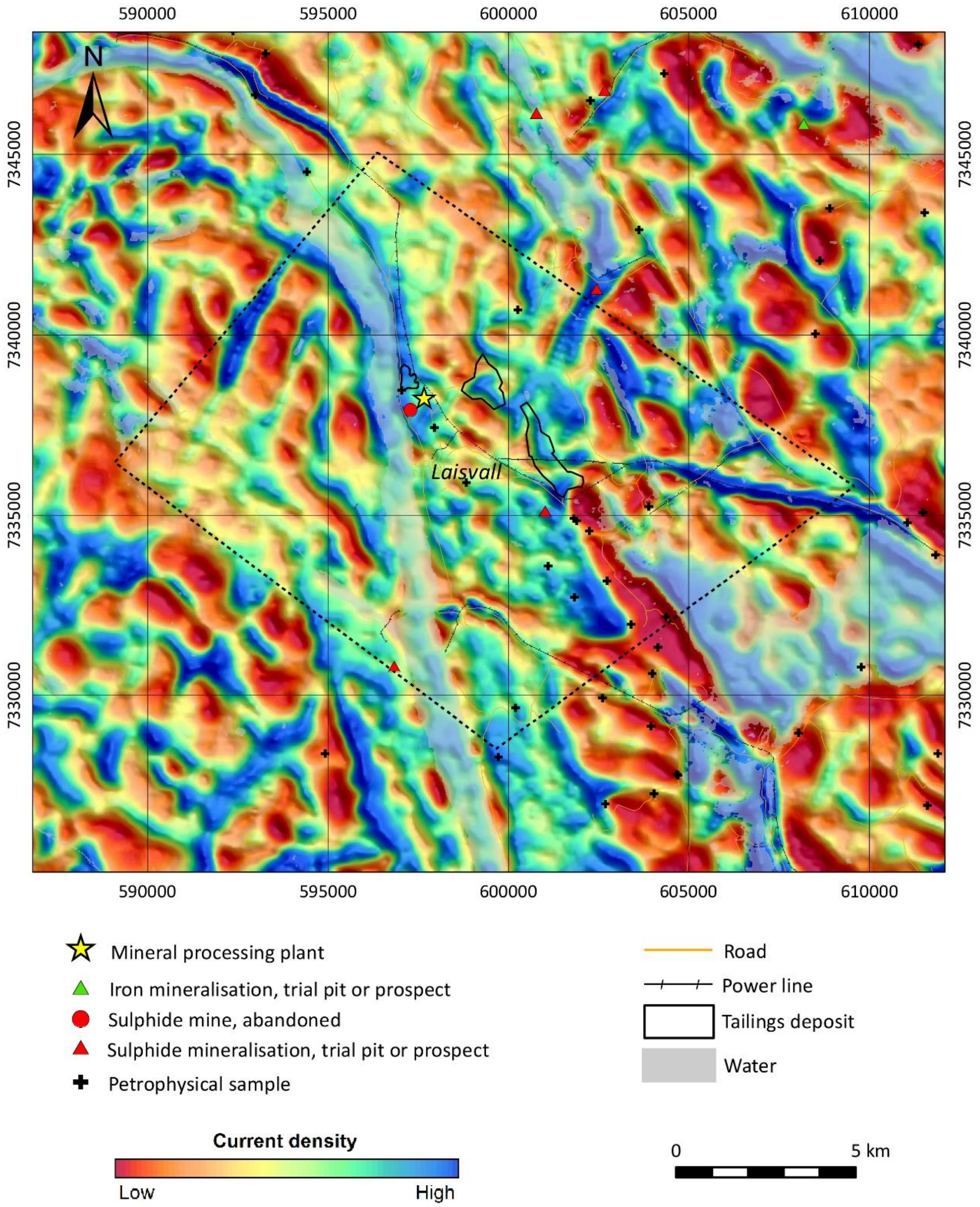

Figure 4. Map showing the current density in the ground at Laisvall and in its neighbouring areas. The Laisvall area is shown as a polygon with dashed black line.

Table 1. Previous geophysical airborne surveys by SGU over Laisvall and in its neighbouring areas.

Year	Geophysical methods used	Flight direction	Flight line separation (m)	Flight altitude (m)
1969	Magnetics, gamma spectrometry	East–west	200	30
2013	Magnetics, gamma spectrometry, VLF (2-transmitters)	East–west	200	60

Ground geophysics

SGU has previously conducted four gravity surveys at Laisvall and in the surrounding areas. These surveys were carried out in 1978, 2009, 2012, and 2013 when measurements were made in the area as part of larger campaigns. In total, 265 gravity measurements have been made during these years at Laisvall and in its neighbouring areas, corresponding to the geographical extent in Figures 2–5. The distance between the measurement stations ranges from 200 m to 3.5 km.

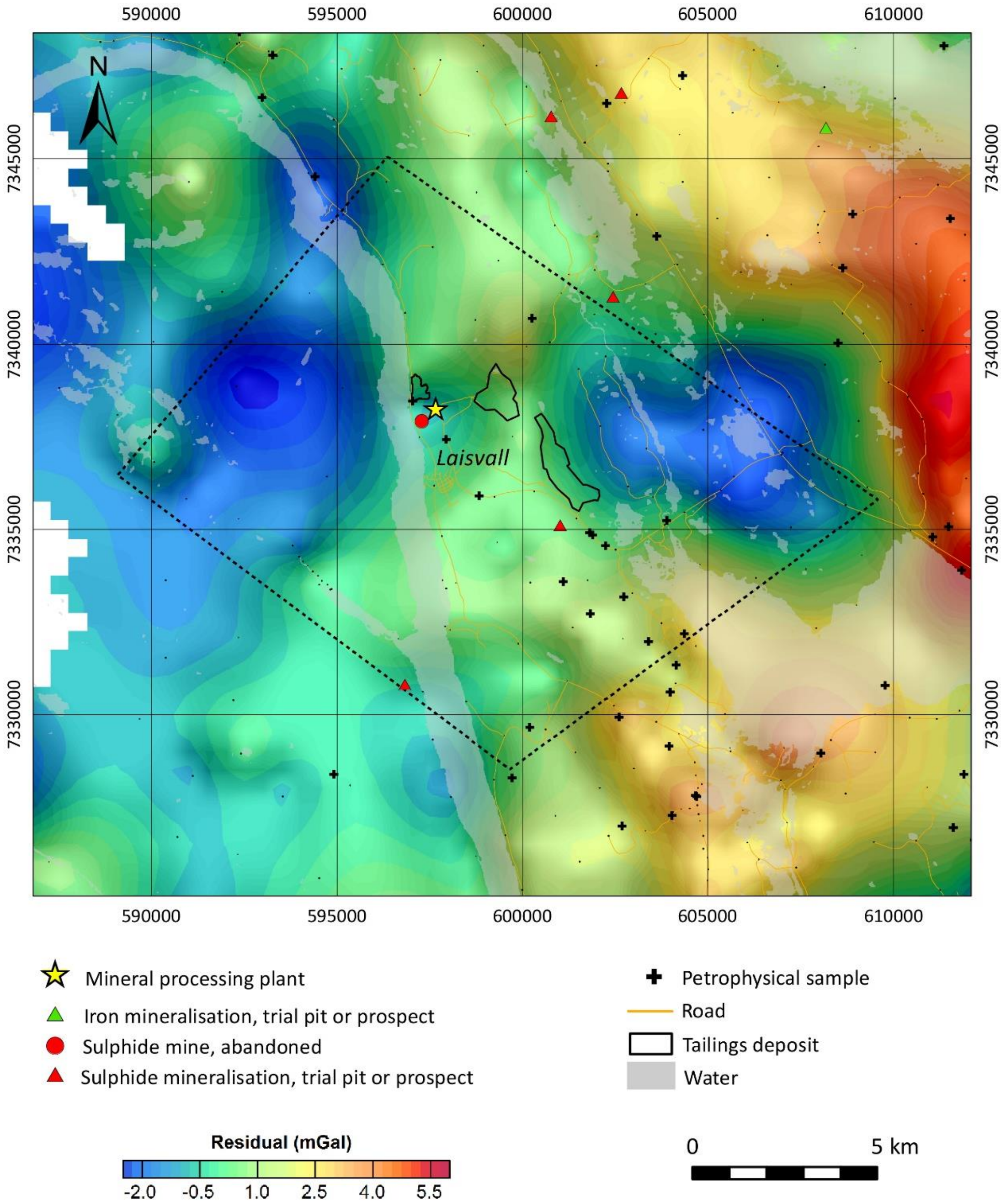

Figure 5. Map showing the residual gravity anomalies at Laisvall and in its neighbouring areas. The residual gravity is expressed as the difference between the Bouguer anomaly and an analytical continuation upwards to 3 km. The small black dots represent localities for gravity measurements. The Laisvall area is shown as a polygon with dashed black line.

Petrophysics

From previous mapping activities in the area around Laisvall, 43 petrophysical samples have been acquired and analysed for their densities and magnetic properties. The location of these samples is presented in Figures 2–5.

Surface sampling of tailings

Samples from the tailings dams constructed in the 1940's, 1950's and 1960's were fine-grained, overgrown by vegetation and exhibited a yellowish colour (Fig. 6). Samples from tailings generated more recently (1980's and onwards) were greyish, more coarse-grained (than presumed older tailings) and not overgrown by vegetation. Results from the analysis shows high concentrations of zinc and lead (0.1 – 0.4 wt. %) (Table 2).

Figure 6. Sampling tailings at the Laisvall mine. Photo: Roger Hamberg.

Table 2. Results from ICP-AES, LECO and ICP-MS analyses of tailings from Laisvall, n = 18.

Element	Unit	Average	Max	Min	Std.dev
Be	ppm	0.2	0.6	0.1	0.1
Bi	ppm	0.0	0.1	0.0	0.0
Co	ppm	1.1	1.9	0.5	0.4
Ga	ppm	1.1	2.8	0.7	0.6
Ge	ppm	0.1	0.1	0.1	0.0
Hf	ppm	0.4	1.0	0.2	0.2
In	ppm	0.1	0.2	0.0	0.1
Li	ppm	4.3	11	1.7	2.6
Nb	ppm	0.2	0.5	0.1	0.1
P	ppm	132	310	70	61
PGM	ppm	0	0	0	0
REE	ppm	61	129	35	22
Sb	ppm	1.3	2.9	0.7	0.6
Sc	ppm	0.9	1.9	0.5	0.4
Sr	ppm	79	116	34	22
Ta	ppm	0	0	0	0
Ti	ppm	88	120	50	33
V	ppm	4.9	11	3	2
W	ppm	0.2	0.6	0.1	0.1
Fe	ppm	6844	8500	5400	732
Ni	ppm	3.9	6	1	1
Cu	ppm	5.9	20	3	4
Pb	ppm	3847	8130	2280	1654
Zn	ppm	1034	3710	137	1230
Ag	ppm	0	0	0	0
Au	ppm	0	0	0	0

REE: Sum of Rare earth elements, PGM: Platinum group metals

According to the XRD-analyses, the major tailings mineral assemblage in the Laisvall tailings consisted of quartz (SiO_2), microcline ($KAlSi_3O_8$) and small quantities (less than 1 wt. %) of tennantite ($Cu_{12}As_4S_{13}$, tetrahedrite ($Cu_{12}Sb_4S_{13}$) and sphalerite (ZnS).

Secondary resource potential at Laisvall mine

Based on the above information, and under assumption that our calculated average metal concentrations are representative for the entire volume of tailings, the tailings dams at the Laisvall mine may in total contain approx. 240 000 tonnes of lead and 60 000 tonnes of zinc.

PAHTOHAVARE MINE

Background

The Pahtohavare mine (Fig. 7) is situated approx. 10 km southwest of Kiruna (SWEREF99 TM 7527789/714460). The deposit was a copper oxide/sulphide – gold mine where chalcopyrite and gold were mined. The mine was operated by Outokumpu 1989–1996 and produced 1.7 million tonnes of ore with a content of 4 wt. % Cu and 0.9 g Au/ton. The ore was concentrated at the Viscaria mine (also operated by Outokumpu), and waste rock was deposited at the Pahtohavare site. The quantity of tailings is approx. 1.5 million tonnes, while the quantity of waste rock is unknown (Lovisagruvan AB 2022).

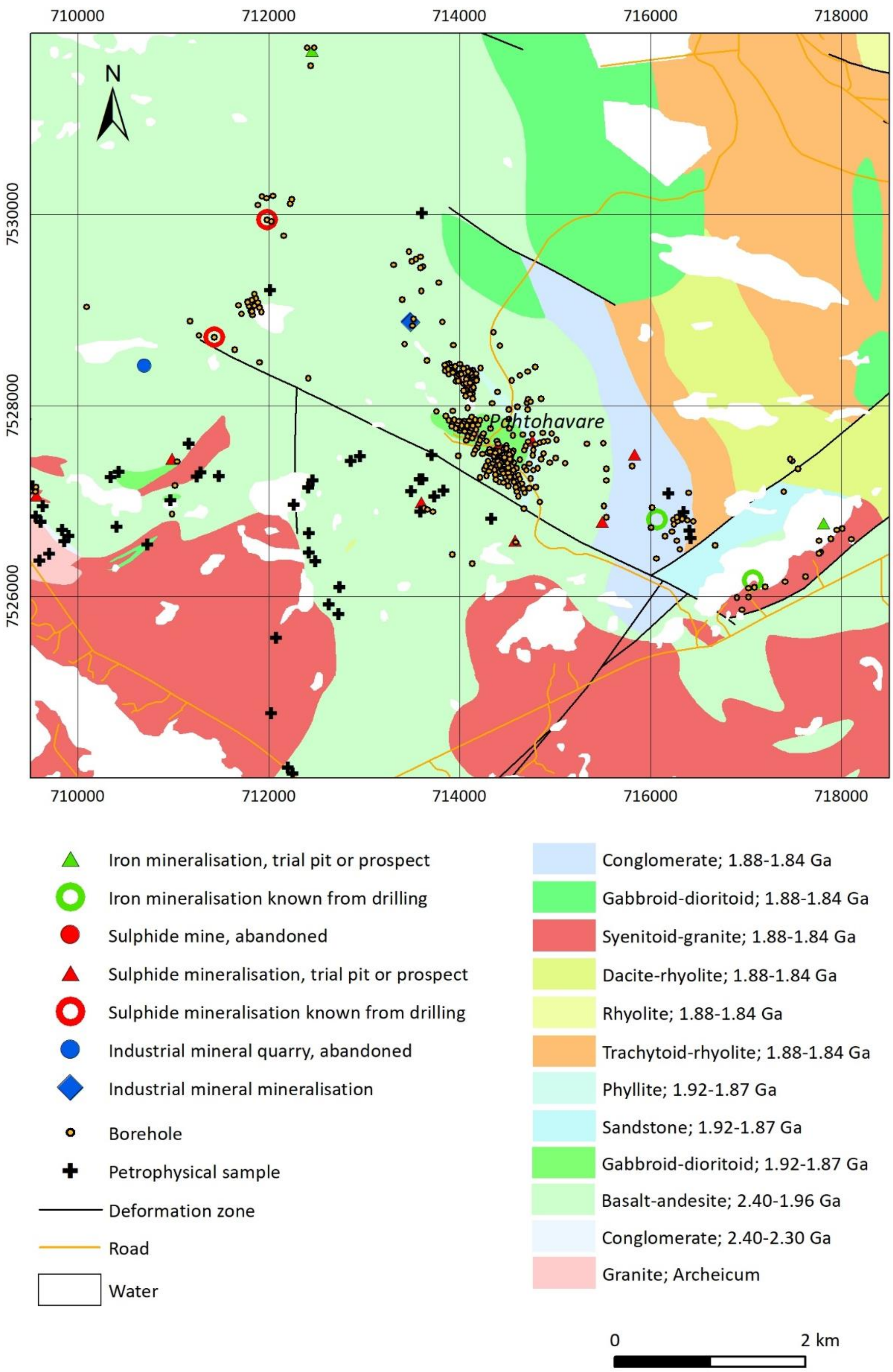

Figure 7. Simplified bedrock map over the Pahtohavare area and its closest surroundings (SGU 2022).

Existing data

Airborne geophysics

Several airborne geophysical surveys have been carried out by SGU/NSG or LKAB over Pahtohavare and in its neighbouring areas (Fig. 8). A compilation of these can be found in Table 3. Maps showing the magnetic anomalies and slingram data over the Pahtohavare area can be found in Figures 9–14, 16, and 17.

Table 3. Previous airborne geophysical surveys by SGU/NSG or LKAB over Pahtohavare and in its neighbouring areas.

Year	Organisation	Geophysical methods used	Flight direction	Flight line separation (m)	Flight altitude (m)
1960	NSG	Magnetics	East–west	200	30
1973	LKAB	Gamma spectrometry, VLF (1-transmitter)	East–west	200	30
1975	NSG	Magnetics, gamma spectrometry, VLF (1-transmitter)	East–west	200	30
1981	LKAB	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	45–225 degrees (northeast–southwest)	200	30
1983	LKAB	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	East–west	200	30
1985	LKAB	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	East–west	100	30
1986	NSG	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	25–205 degrees (north-northeast–south-southwest)	100	30

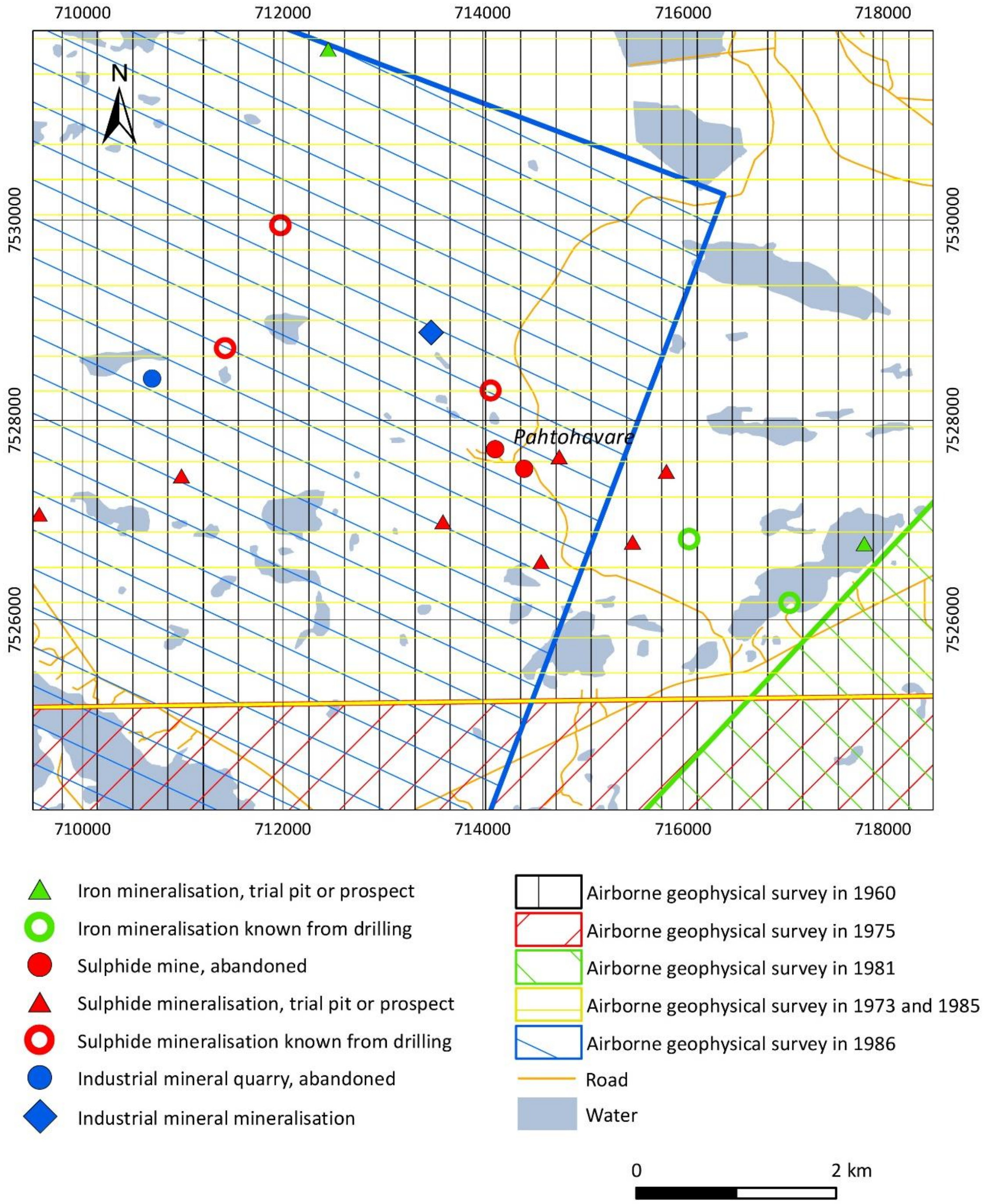

Figure 8. Map showing the coverage of previously made airborne geophysical surveys over Pahtohavare and in its neighbouring areas. In addition to those presented in here, LKAB made an airborne survey in 1983 which covered the entire geographical extent.

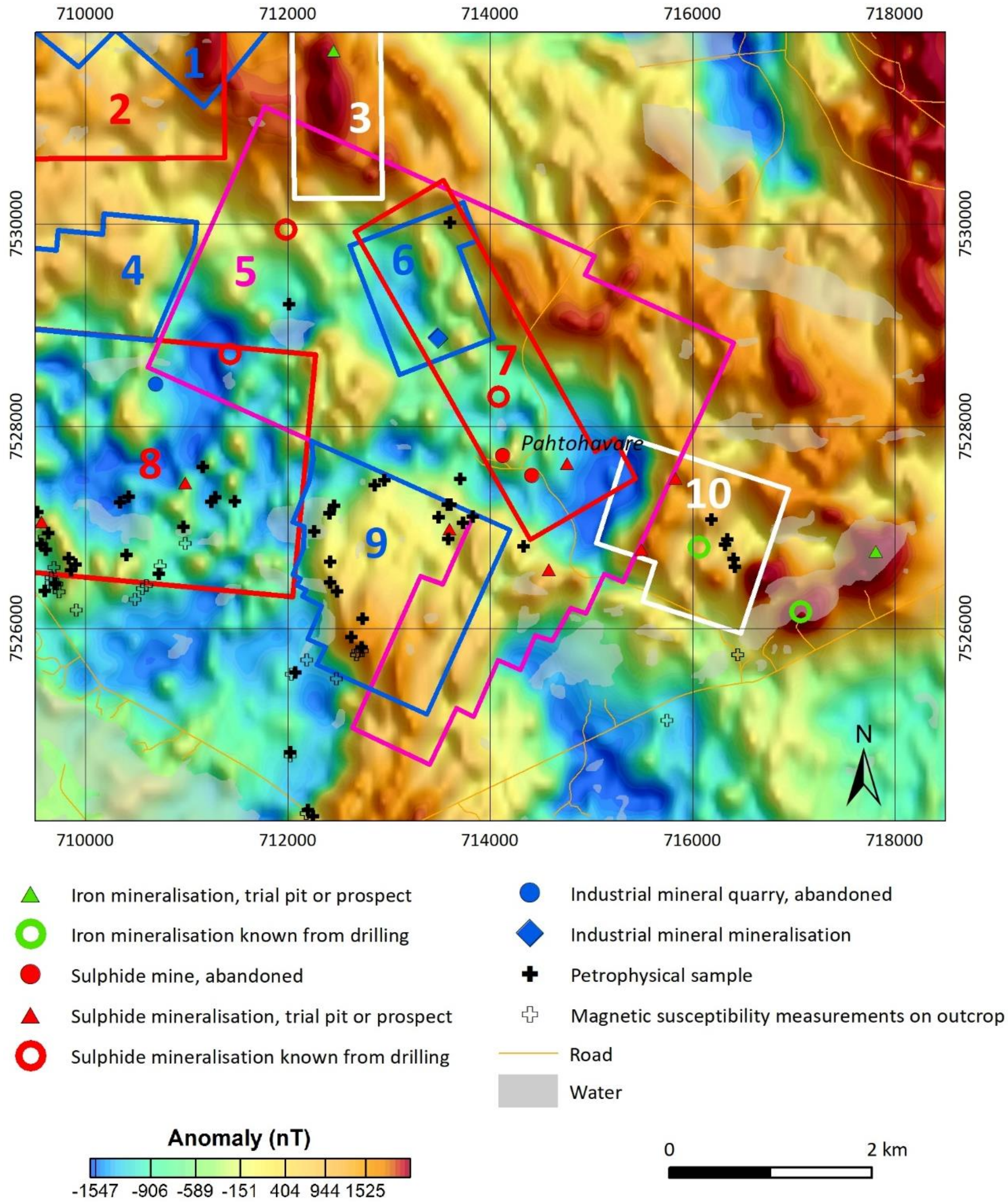

Figure 9. Map showing the magnetic anomalies, derived from airborne measurements, at Pahtohavare and in its neighbouring areas. The magnetic anomaly is expressed as the difference between the pole-reduced total magnetic field and an analytical continuation upwards to 1 km. The coloured and numbered polygons correspond to areas where ground magnetic surveys previously have been made (Table 4).

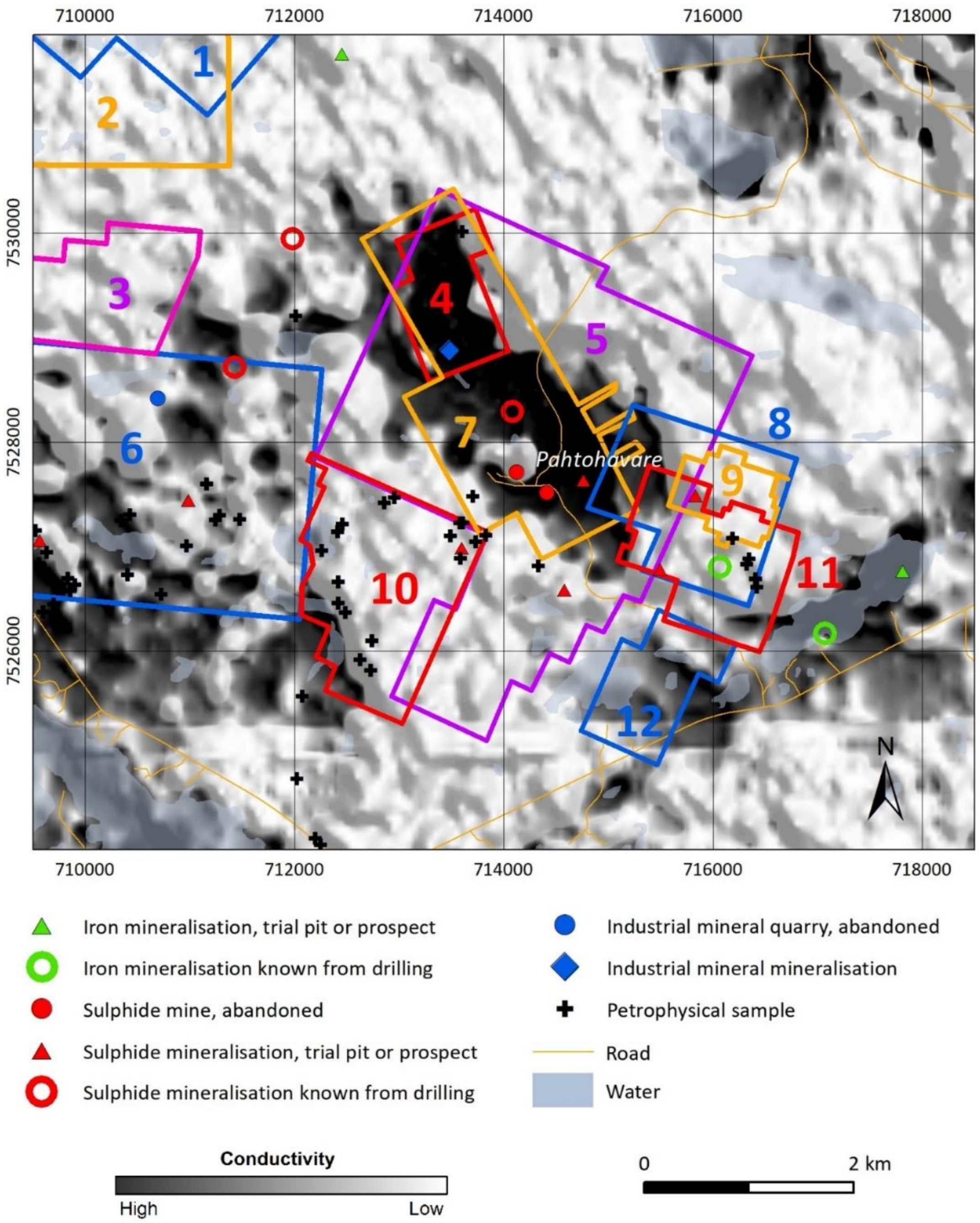

Figure 10. Map showing the real-part of the slingram data, derived from airborne measurements, at Pahtohavare and in its neighbouring areas. Darker colours correspond to areas with higher electrical conductivity. The coloured and numbered polygons correspond to areas where ground electric or electromagnetic surveys previously have been made (Table 5).

Ground geophysics

Several ground-based surveys measuring the magnetic field have been conducted at Pahtohavare and in its neighbouring areas. Figure 9 shows the magnetic anomalies over the Pahtohavare area, derived from airborne measurements, along with the geographical extent of these ground-based surveys. A compilation over these surveys is found in Table 4 and data from the surveys are presented in Figures 11 and 12.

Table 4. Previous ground magnetic measurements at Pahtohavare and in its neighbouring areas. The polygon numbers in the table correspond to those in Figure 9.

Polygon nr	Name of investigated area	Geophysical data	Responsible	Year acquired
1	Viscaria	Magnetics	Outokumpu (classified)	1970s
2	Suolojaure	Magnetic anomaly	SGAB	1989
3	Suolojåkk	Magnetic anomaly	SGU	1963–1965, 1968
4	Ajlatisvaara	Magnetic total field	SGAB	1990
5	Pahtohavare	Magnetics	SGAB	1984–1988
6	Väst-Pahto	Magnetics	SGAB	1988
7	Pahtohavare	Magnetics	LKAB	1977
8	Saarijärvi	Magnetic total field	SGAB	1986
9	Pahtohajåkk	Magnetics	SGAB	1990
10	Rakkurijärvi	Magnetic anomaly	SGU	1972

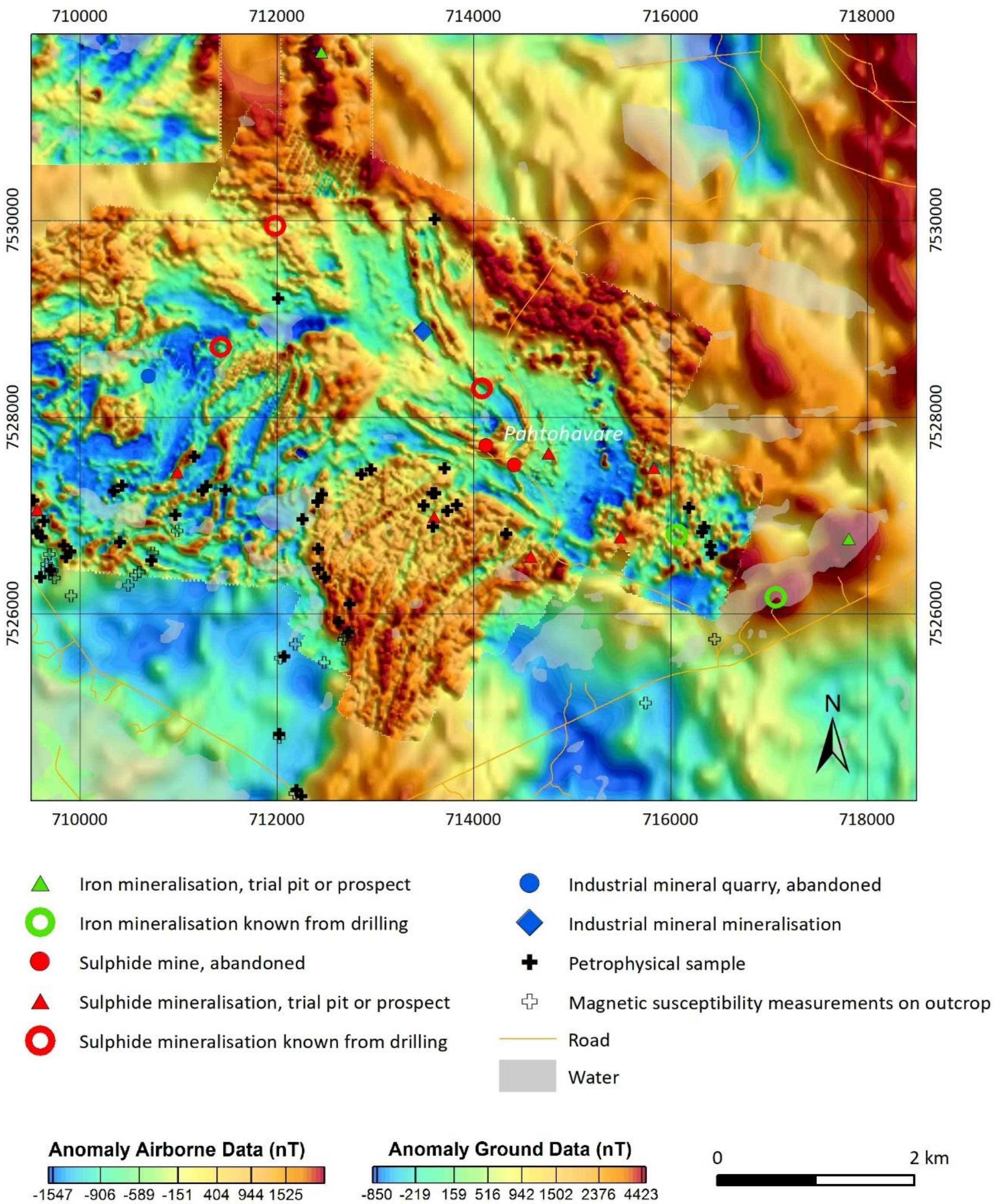

Figure 11. Map showing the magnetic anomalies from previously acquired ground magnetic measurements at Pahtohavare and in its neighbouring areas, listed in Table 4. The backdrop image shows the magnetic anomalies, derived from airborne measurements.

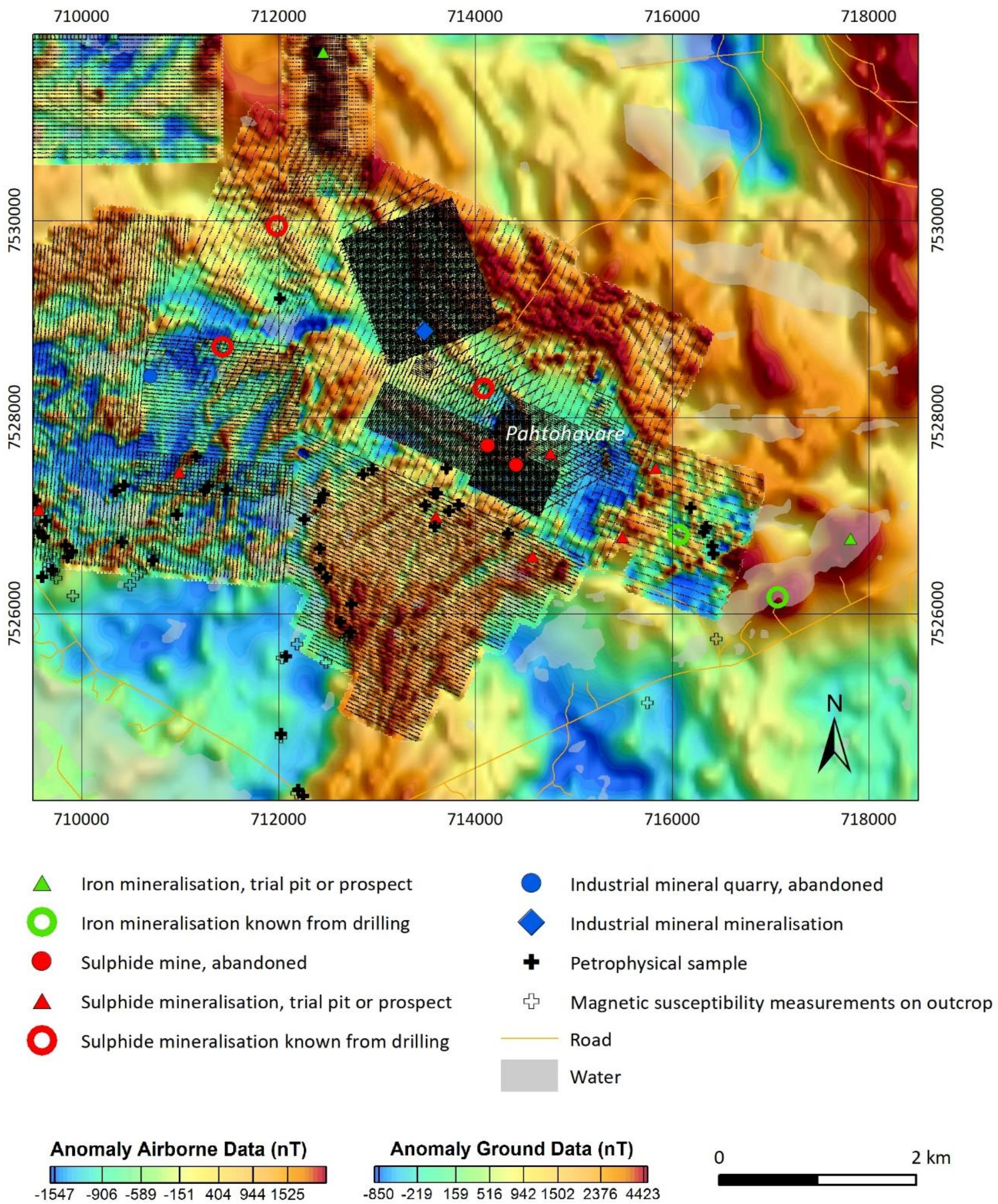

Figure 12. Map showing the measurement stations (black dots) from the previously made ground magnetic surveys at Pahtohavare and in its neighbouring areas, listed in Table 4. The backdrop image shows the magnetic anomalies, derived from airborne measurements.

Several ground-based surveys acquiring SP, IP, resistivity, Mise a la masse and slingram data have been conducted at Pahtohavare and in its neighbouring areas. Figure 10 shows the real-part of the slingram data, derived from airborne measurements, at Pahtohavare and in its neighbouring areas together with the geographical extent of these ground-based surveys. A compilation over these surveys is found in Table 5 and data from the slingram surveys are presented in Figures 13 and 14.

Five gravity surveys were previously made by SGU or LKAB at Pahtohavare and in its neighbouring areas. These surveys were carried out in 1964, 1965, 1968, 1988, and 1989. In total, 3 900 gravity measurements have been made during these years at Pahtohavare and in its neighbouring areas, corresponding to the geographical extent in Figures 7–18. In Figure 15, the residual gravity anomalies are shown together with the measurement stations. As seen in the figure, there is a big difference in the distance between the measurements over the area. In the eastern part, dense gravity measurements along parallel profiles were acquired by LKAB in the 1960's for their exploration activities. The profiles have a distance of 100–400 m between themselves, along which measurements were made every 40–80 m. In the northern part of the area, densified gravity measurements were made in 1968 by SGU around the iron mineralisation Suolojåkk, which also was a target for ground magnetic measurements (Fig. 9, Table 4).

SGU has also made denser gravity measurements along profiles in the western part of the area. These measurements were made in 1989, every 20 m along profiles with 100 m line spacing. This area corresponds to the Saarijärvi area, within which also ground magnetic and slingram measurements were made (Figs. 9 and 10, Table 4 and 5). In the central part of the area, at Pahtohavare, several measurement profiles were made in 1988 by SGU (Fig. 15) along which gravity measurements were made every 20 m. Throughout the area shown in Figure 10, SGU has carried out regional gravity measurements with a station spacing of approximately 300 m to 1.3 km.

Table 5. Previous ground electric and electromagnetic surveys at Pahtohavare and in its neighbouring areas. The polygon numbers in the table correspond to those in Figure 10.

Polygon nr	Name of investigated area	Geophysical data	Responsible	Year acquired
1	Viscaria	Slingram	Outokumpu (classified)	1970s
2	Suolojaure	Slingram	SGAB	1989
3	Ajlatisvaara	Slingram	SGAB	1990
4	Väst-Pahto	Slingram	SGU	1985
5	Pahtohavare	Slingram	SGAB	1984–1990
6	Saarijärvi	Slingram	SGAB	1986
7	Pahtohavaara	Slingram, SP, Mise a la masse	LKAB, SGAB	1974, 1987–1988
8	Rakkurijärvi	Slingram	SGU	1968, 1972
9	Rakkurijärvi	Slingram, SP, IP, Mise a la masse	SGAB	1967, 1969–1970
10	Pahtohajokk	Slingram	SGU	1972
11	Rakkurijärvi	SP, IP, resistivity	SGU	1968–1971
12	Öst-Pahto	Slingram	SGU	1985

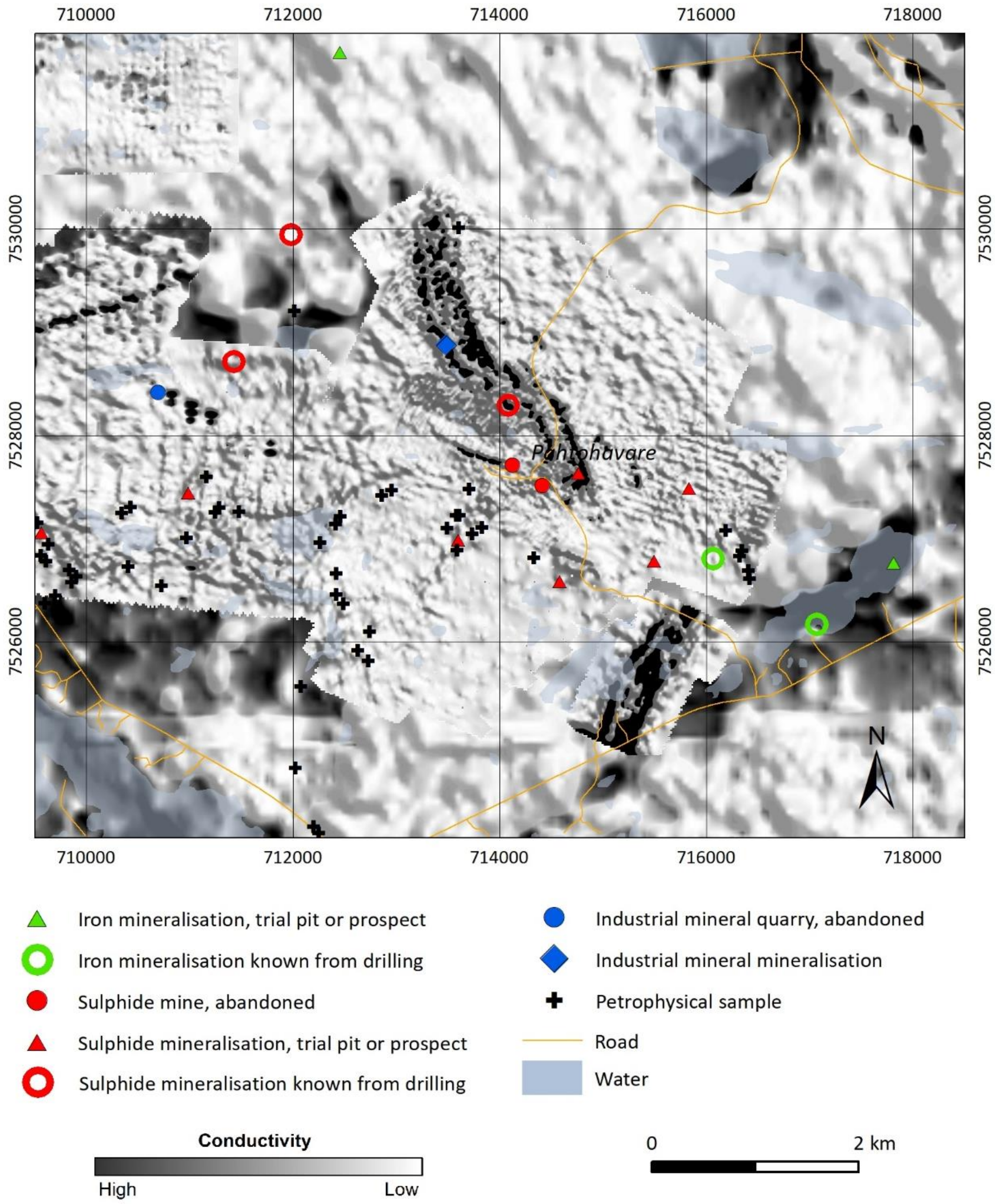

Figure 13. Map showing the real-part of the slingram data from previously acquired ground slingram measurements at Pahtohavare and in its neighbouring areas, listed in Table 5. The backdrop image shows the real-part of the slingram data, derived from airborne measurements.

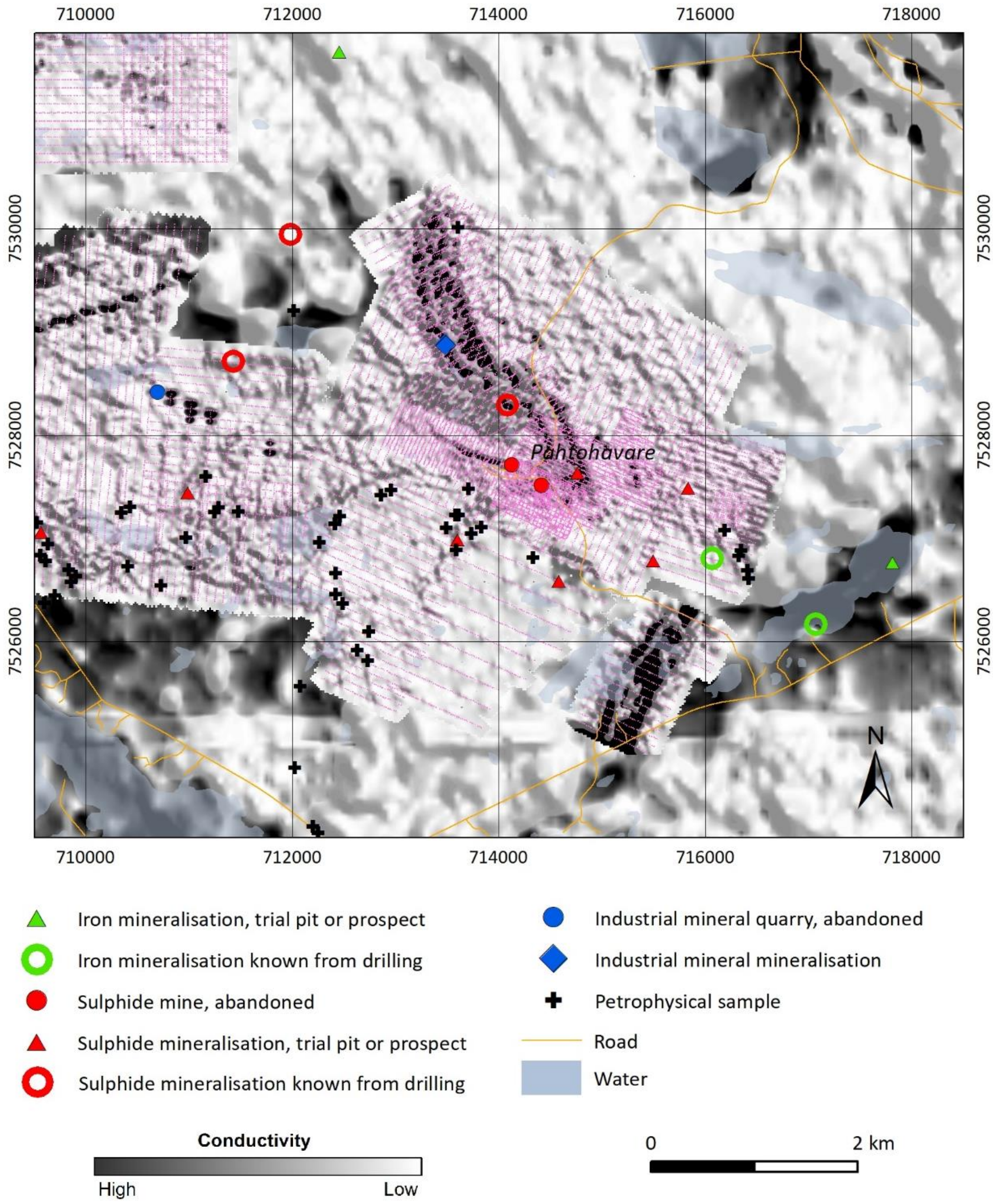

Figure 14. Map showing the measurement stations (pink dots) from the previously made ground slingram surveys at Pahtohavare and in its neighbouring areas, listed in Table 5. The backdrop image shows the real-part of the slingram data, derived from airborne measurements.

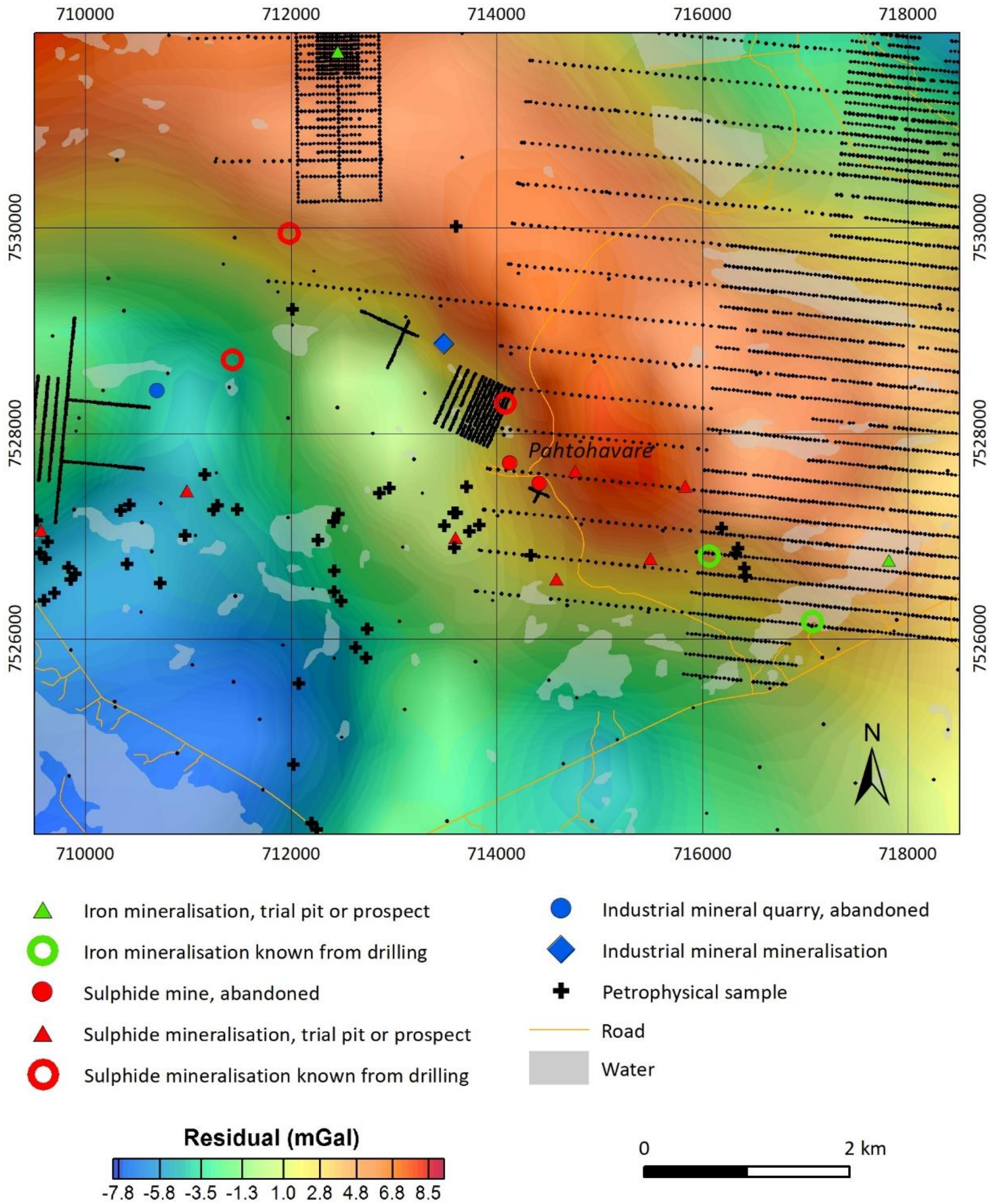

Figure 15. Map showing the residual gravity anomalies at Pahtohavare and in its neighbouring areas. The residual anomaly is expressed as the difference between the Bouguer anomaly and an analytical continuation upwards to 3 km. Black dots represent gravity measurements.

Petrophysics

From previous mapping activities in the area around Pahtohavare, 55 petrophysical samples have been acquired and analysed for their densities and magnetic properties. The location of these samples is presented in Figures 7 and 9–18.

Exploration geophysics

Several geophysical surveys have been made by exploration companies in the area around Pahtohavare, from which data now are present and available in SGU's databases. These datasets consist of magnetic, electric, electromagnetic, and gravity data. The extent of these exploration permits is shown in Figures 16 (magnetics), 17 (electric and electromagnetics), and 18 (gravity), within which geophysical exploration surveys were made. More information regarding these surveys can be found in Table 6–8.

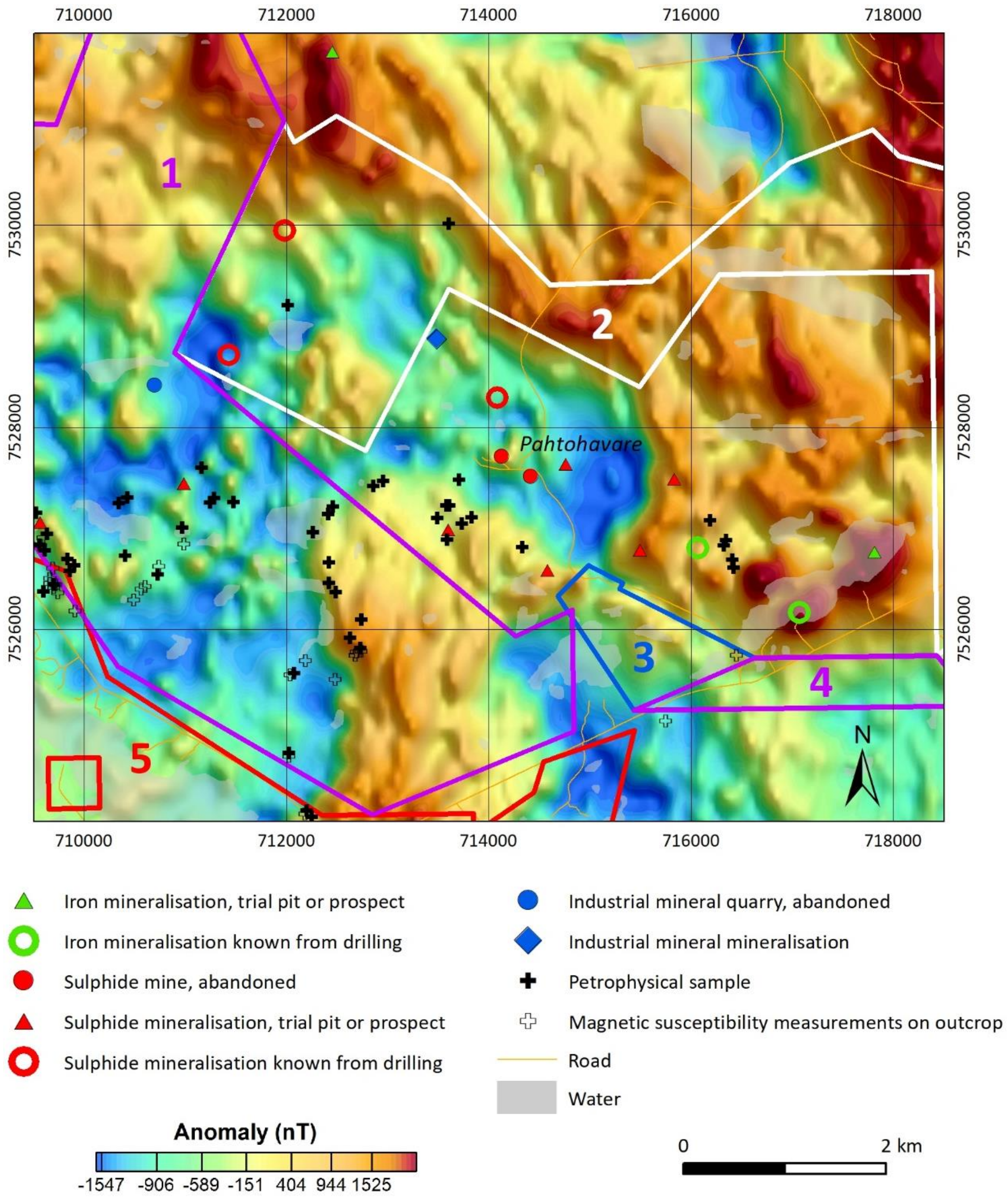

Figure 16. Map showing the magnetic anomalies, derived from airborne measurements, at Pahtohavare and in its neighbouring areas. The coloured and numbered polygons correspond to areas within which geophysical exploration surveys previously have been made. Data from these surveys are now available in SGU's databases (Table 6).

Table 6. Previous geophysical exploration surveys at Pahtohavare and in its neighbouring areas, from which data now are available in SGU's databases. The polygon numbers correspond to those found in Figure 16.

Polygon nr	Name of exploration area	Geophysical methods used	Responsible	Year of permit
1	Puoltsa nr 10	Magnetics, electromagnetics	Eurasian Minerals Sweden AB	2010–2016
2	Luossajoki nr 1	Magnetics, IP	Equinox Resources NL Australia	2006
3	Rakkurijärvi Södra nr 1	Magnetics	Anglo American Exploration B.V.	2001–2008
4	Norrbotten nr 106	Magnetics	Lundin Mining Exploration AB	2002–2008
5	Norrbotten nr 105	Magnetics, IP, electromagnetics	Lundin Mining Exploration AB	2006

Table 7. Previous geophysical exploration surveys at Pahtohavare and in its neighbouring areas, from which data now are available in SGU's databases. The polygon numbers correspond to those found in Figure 17.

Polygon nr	Name of exploration area	Geophysical methods used	Responsible	Year of permit
1	Puoltsa nr 10	Magnetics, electromagnetics	Eurasian Minerals Sweden AB	2010–2016
2	Luossajoki nr 1	Magnetics, IP	Equinox Resources NL Australia	2006
3	Puoltsa nr 1	Electromagnetics	Anglo American Exploration B.V.	2002–2010
4	Norrbotten nr 120	IP	Lundin Mining Exploration AB	2003–2009
5	Norrbotten nr 105	Magnetics, IP, electromagnetics	Lundin Mining Exploration AB	2006

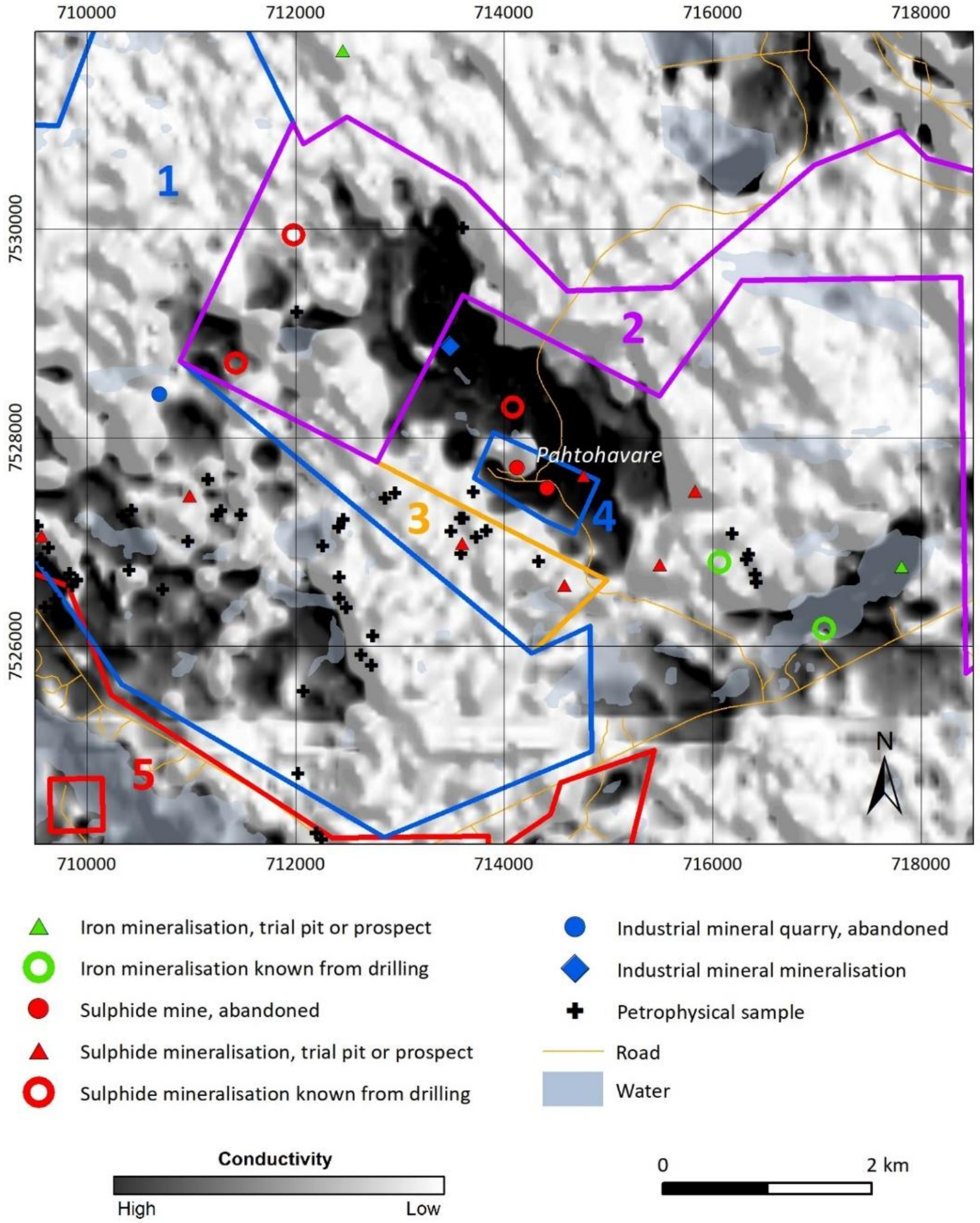

Figure 17. Map showing the real-part of the slingram data, derived from airborne measurements, at Pahtohavare and in its neighbouring areas. The coloured and numbered polygons correspond to areas within which geophysical exploration surveys previously have been made. Data from these surveys are now available in SGU's databases (Table 7).

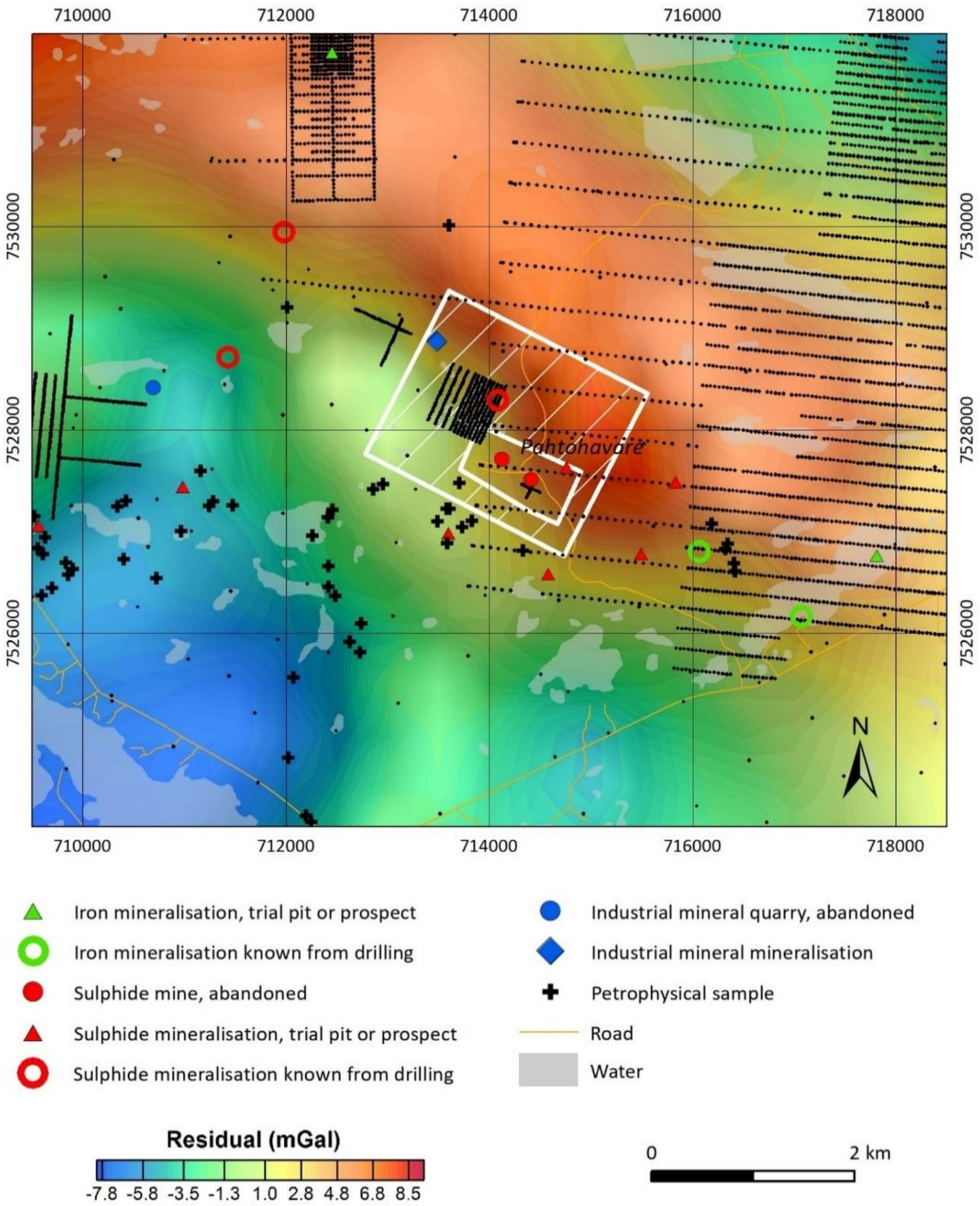

Figure 18. Map showing the residual gravity anomalies at Pahtohavare and in its neighbouring areas. Black dots represent gravity measurements. The white polygon with hatches corresponds to the area within which an exploration gravity survey previously has been made. Data from this survey are now available in SGU's databases (Table 8).

Table 8. Previous exploration gravity survey at Pahtohavare, from which data now are available in SGU's databases. The measurement area is found in Figure 18.

Name of exploration area	Geophysical method used	Responsible	Year of permit
Pahtohavare nr 1	Gravity	Anglo American Exploration B.V.	2002–2008

Sampling of waste rock

In total, 18 samples á 5 kg of waste rock (5 subsamples/sample) were collected at Pahtohavare with a shovel at a depth of approx. 0–50 cm. The waste rock exhibited an oxidised, rusty surface and the particle size was < 70 mm (Fig. 19). Results from the analysis shows high concentrations of copper (0.5 wt. %) (Table 9).

Figure 19. Sampling waste rock at the Pahtohavare mine. Photo: Roger Hamberg.

Table 9. Results from ICP-AES, LECO and ICP-MS analyses of waste rock from Pahtohavare, n = 18.

Element	Unit	Average	Max	Min	St.dev
Be	ppm	0.6	0.2	0.1	0.2
Bi	ppm	0.0	0.1	0.0	0.0
Co	ppm	105	244	41	58
Ga	ppm	13	21	8	3
Ge	ppm	0.2	0.3	0.2	0.0
Hf	ppm	0.2	0.4	0.1	0.1
In	ppm	0.1	0.3	0.0	0.0
Li	ppm	25	41	16	8
Nb	ppm	0.1	0.2	0.1	0.0
P	ppm	625	1740	310	383
PGM	ppm	0.0	0.0	0.0	0.0
REE	ppm	135	516	58	80
Sb	ppm	0.1	0.2	0.1	0.0
Sc	ppm	21	37	7	8
Sr	ppm	18	35	5	9
Ta	ppm	0.0	0.0	0.0	0.0
Ti	ppm	2569	4250	1810	632
V	ppm	243	324	162	46
W	ppm	0.4	0.9	0.1	0.2
Fe	ppm	100973	136000	78000	15005
Ni	ppm	119	159	88	21
Cu	ppm	5150	24400	318	5928
Pb	ppm	12	36	2	10
Zn	ppm	32	68	13	12
Ag	ppm	0.8	0.5	0.8	0.3
Au	ppm	0.2	0.0	0.2	0.2

REE: Sum of Rare earth elements, PGM: Platinum group metals

According to the XRD-analyses, the major mineral assemblage in the Pahtohavare waste rock consisted of quartz, biotite, albite and chalcopyrite.

Secondary resource potential at Pahtohavare mine

Considering that the quantity of waste rock is unknown, it is not possible to estimate the secondary resource potential for the Pahtohavare waste rock deposit.

VISCARIA MINE

Background

The Viscaria mine (Fig. 20) is situated (SWEREF99 TM: 7538179/715769) approx. 5 km northeast from the city of Kiruna in the county of Norrbotten. The deposit consists of a number of volcanogenic massive sulphide mineralisations with chalcopyrite as the main ore mineral. Viscaria was mined from 1983–1996 by a partnership between LKAB and Outokumpu.

In total, approx. 12.5 million tonnes of ore were extracted containing approx. 2.3 wt. % Cu. During the lifetime of the mine, 12 million tonnes of tailings were generated and deposited in tailings dams. Waste rock was backfilled into the underground mine and the quantity was approx. 4.5 million tonnes (Copperstone 2022).

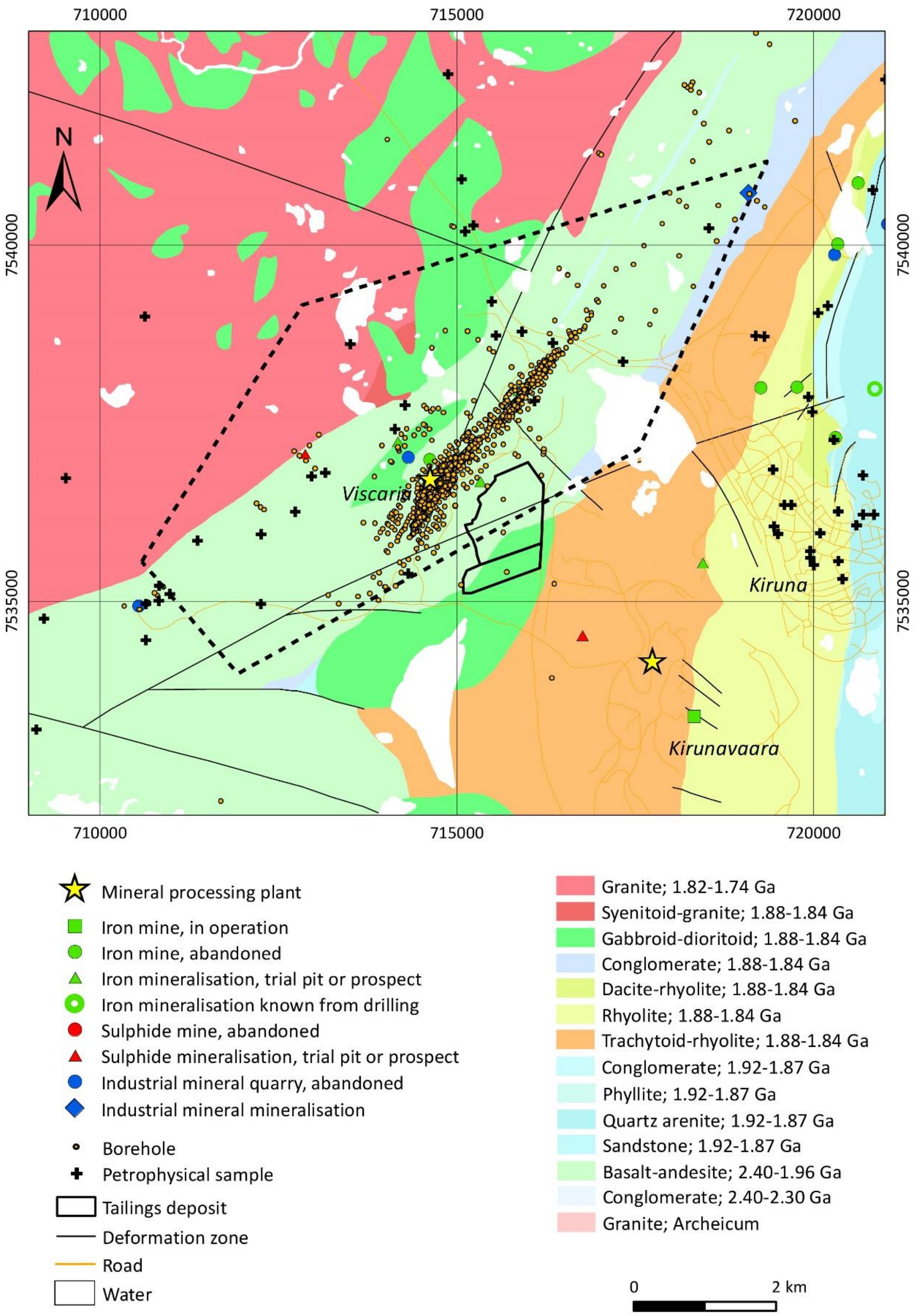

Figure 20. Simplified bedrock map over Viscaria and in its neighbouring areas (SGU 2022). The Viscaria area is shown as a polygon with black dashed line.

Existing data

Airborne geophysics

Several airborne geophysical surveys have been carried out over Viscaria and in its neighbouring areas. A compilation of these can be found in Table 10 and their geographical extent in Figure 21. Maps showing the magnetic anomalies and the real-part of the slingram data, derived from airborne measurements, at Viscaria and in its neighbouring areas can be found in Figures 22, 23, 25, and 26.

Table 10. Previous airborne geophysical surveys by SGU or LKAB over Viscaria and in its neighbouring areas.

Year	Organisation	Geophysical methods used	Flight direction	Flight line separation (m)	Flight altitude (m)
1960	NSG	Magnetics	East–west	200	30
1973	LKAB	Gamma spectrometry, VLF (1-transmitter)	East–west	200	30
1983	LKAB	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	East–west	200	30
1985	LKAB	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	East–west	100	30
1986	NSG	Magnetics, gamma spectrometry, slingram, VLF (2-transmitters)	25–205 degrees (north-northeast–south-southwest)	100	30

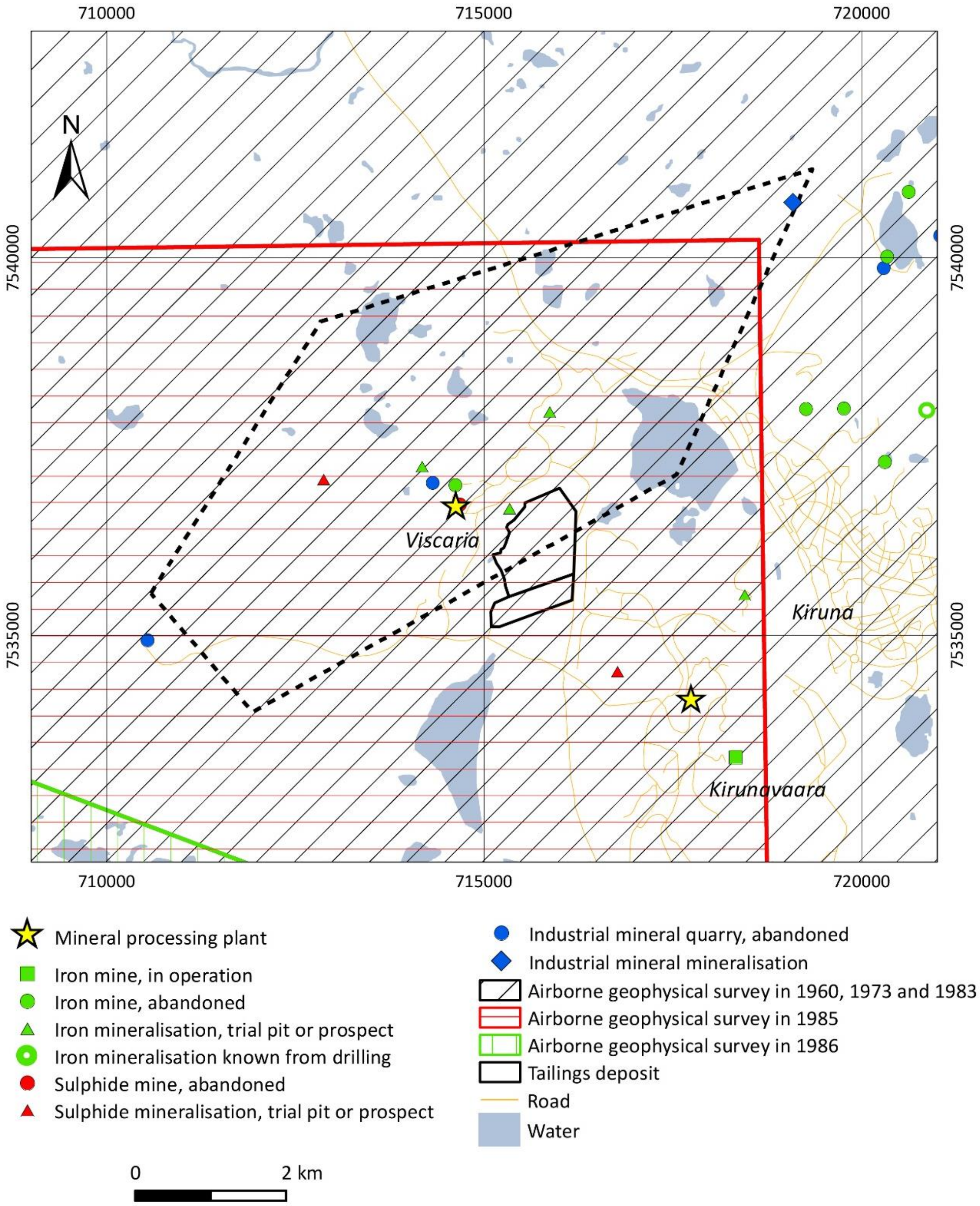

Figure 21. Map showing the coverage of previously made airborne geophysical surveys over Viscaria and in its neighbouring areas. The Viscaria area is shown as a polygon with black dashed line.

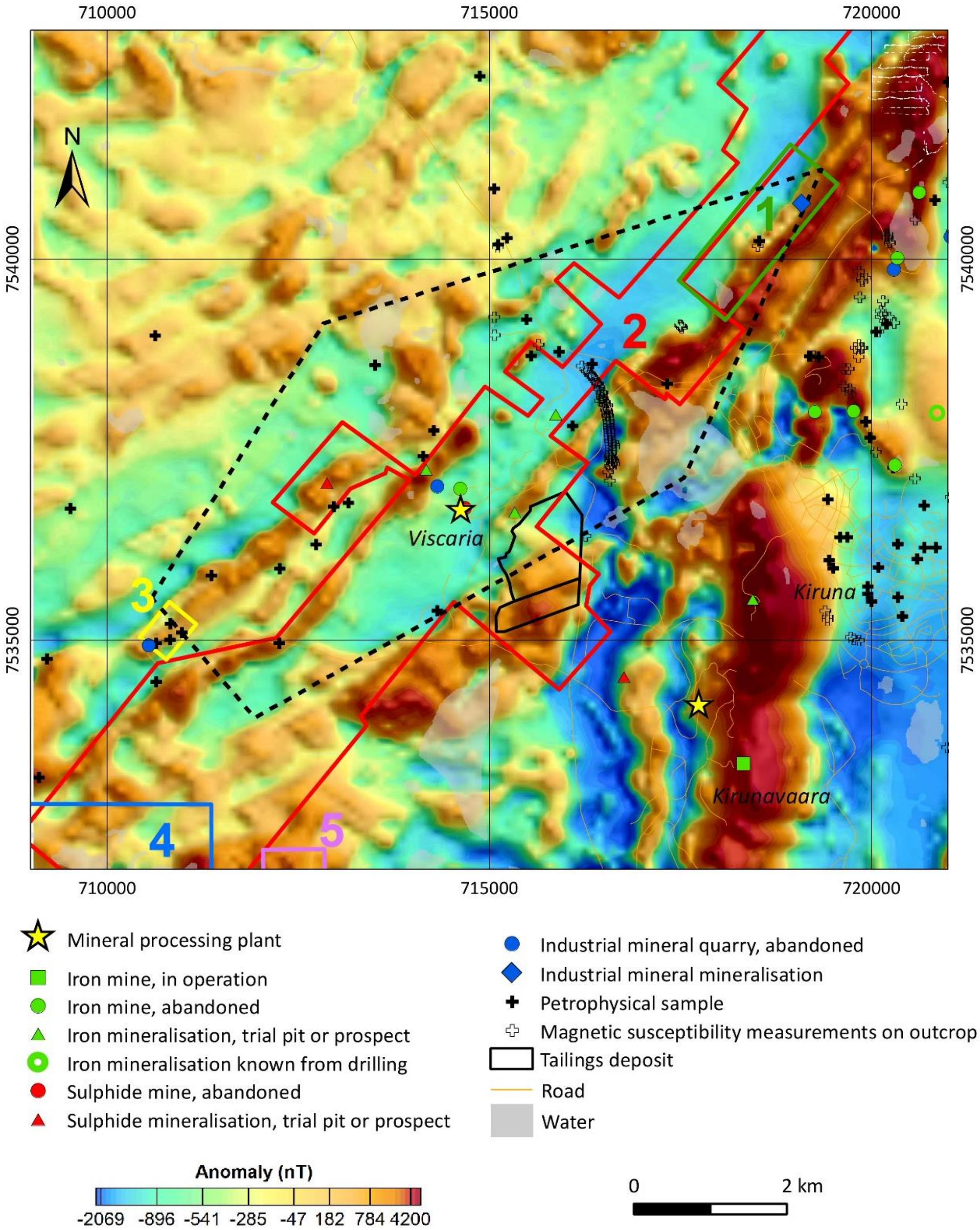

Figure 22. Map showing the magnetic anomalies, derived from airborne measurements, at Viscaria and in its neighbouring areas. The magnetic anomaly is expressed as the difference between the pole-reduced total magnetic field and an analytical continuation upwards to 1 km. The coloured and numbered polygons correspond to the extent of previously made ground magnetic surveys (Table 11). White lines in the upper right part of the map represent previously made ground magnetic measurements. The Viscaria area is shown as a polygon with black dashed line.

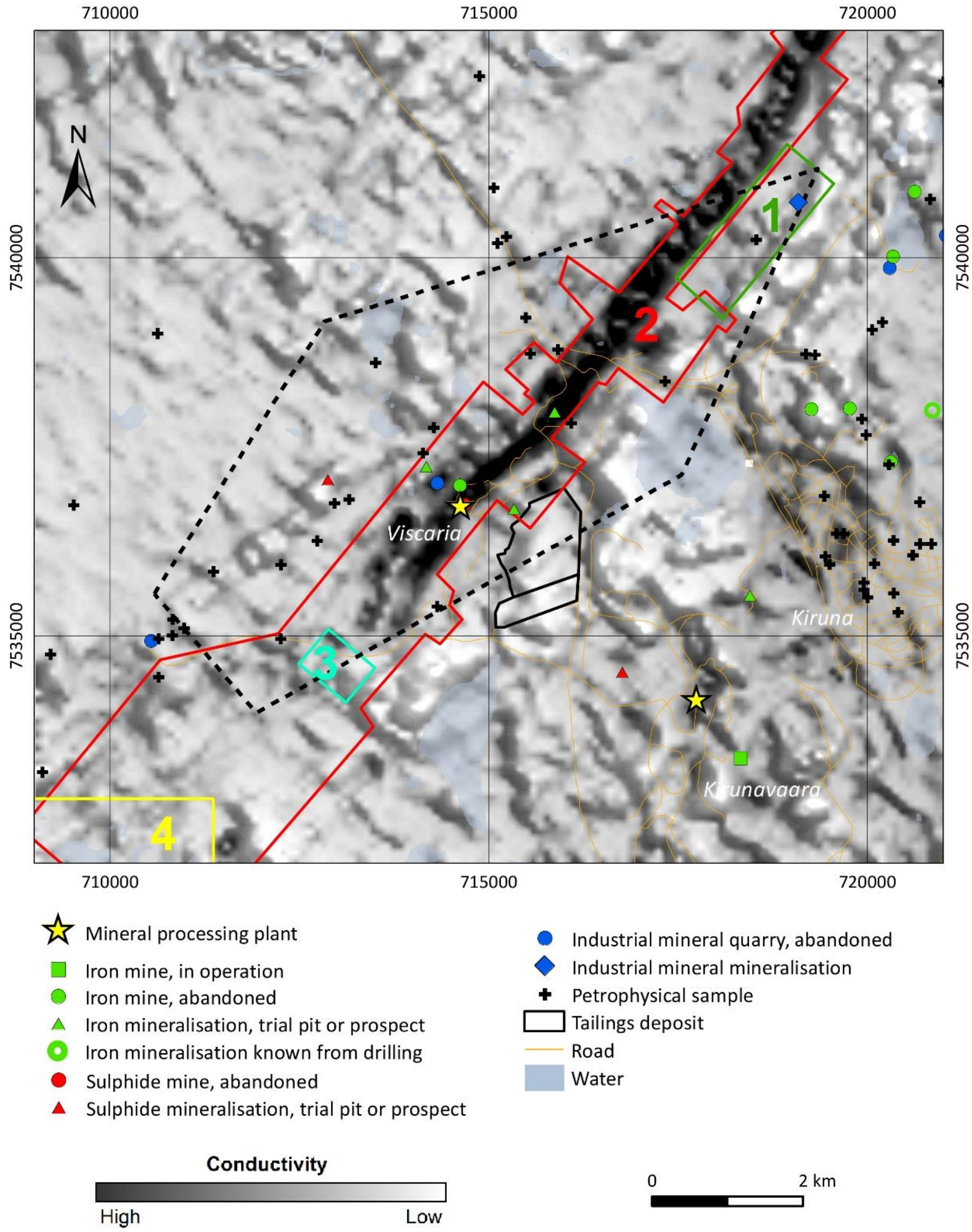

Figure 23. Map showing the real-part of the slingram data, derived from airborne measurements, at Viscaria and in its neighbouring areas. Darker colours in the map correspond to areas with higher electrical conductivity. The coloured and numbered polygons correspond to the extent of previously made ground electromagnetic surveys (Table 12). The Viscaria area is shown as a polygon with black dashed line.

Ground geophysics

Several ground-based geophysical surveys acquiring magnetic or electromagnetic data have been conducted at Viscaria. A compilation over these magnetic surveys can be found in Table 11, while Figure 22 shows the geographical extent of these ground-based surveys. The extent of the previously made ground-based electromagnetic surveys is presented in Figure 23 and they are compiled in Table 12.

Three gravity surveys were previously made by SGU or LKAB at Viscaria and in its neighbouring areas. These surveys were carried out in 1964, 1965, and 1968. In total during these years, 4 690 gravity measurements were made within the area, which corresponds to the geographical extent in Figures 20–26. In Figure 24, the residual gravity anomalies are shown together with the measurement stations. As seen in the figure, there is a big difference in the distance between the measurements when comparing the western part to the eastern. In the eastern part, LKAB made quite dense gravity measurements during their exploration activities in the 1960's. This densified measurement area continues both farther north, south, and east of Figure 24. These gravity measurements were made along semi-parallel profiles, which have a distance of 200–400 m between themselves. Along these profiles, most of the measurements were made every 40–80 m. In the western part of Figure 24, SGU has made regional gravity measurements with a measurement distance of mostly 500 m–2 km.

Table 11. Previous ground magnetic surveys at Viscaria and in its neighbouring areas. The polygon numbers in the table correspond to those in Figure 22.

Polygon nr	Name of investigated area	Geophysical data	Responsible	Year acquired
1	Nukutus	Magnetic total field	SGU	1985
2	Viscaria	Magnetics	Outokumpu (classified)	1970s
3	Adnamvare	Magnetic total field	LKAB	1985
4	Suolojaure	Magnetic anomaly	SGAB	1989
5	Suolojåkk	Magnetic anomaly	SGU	1963–1965, 1968

Table 12. Previous ground electromagnetic surveys at Viscaria and in its neighbouring areas. The polygon numbers in the table correspond to those in Figure 23.

Polygon nr	Name of investigated area	Geophysical data	Responsible	Year acquired
1	Nukutus	VLF	SGU	1985
2	Viscaria	Slingram	Outokumpu (classified)	1970s
3	Kartek	Slingram	Unknown	1984
4	Suolojaure	Slingram	SGAB	1989

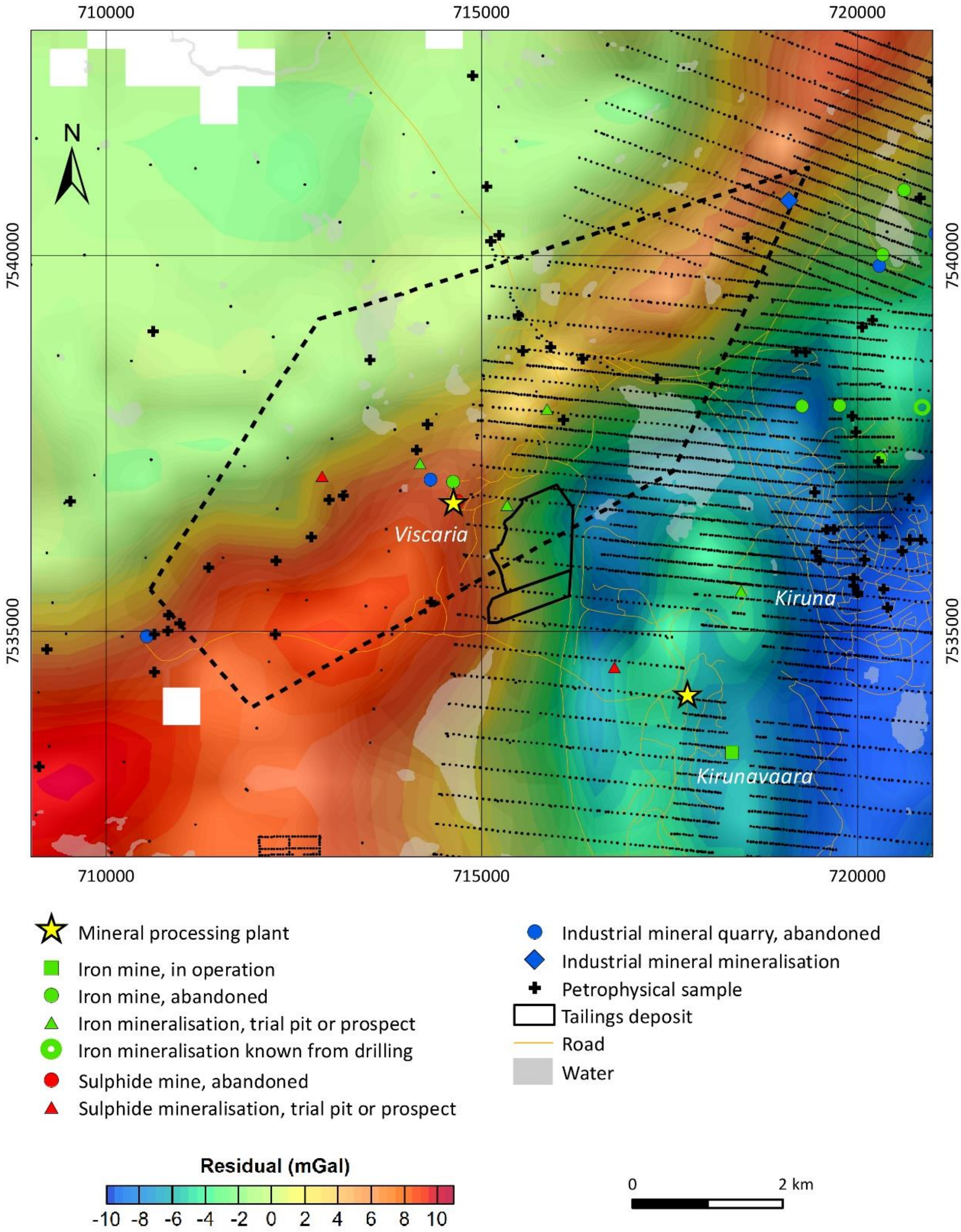

Figure 24. Map showing the residual gravity anomalies at Viscaria and in its neighbouring areas. The residual gravity anomaly is expressed as the difference between the Bouguer anomaly and an analytical continuation upwards to 3 km. Black dots represent gravity measurements. The Viscaria area is shown as a polygon with black dashed line.

Petrophysics

From previous mapping activities in the area around Viscaria, 92 petrophysical samples have been acquired and analysed for their densities and magnetic properties. The location of these samples is presented in Figures 20 and 22–26.

Exploration data

Several geophysical surveys have been made by exploration companies in the area around Viscaria, from which data now are present and available in SGU's databases. These datasets consist of magnetic or electromagnetic information. The extent of these exploration permits, within which geophysical surveys were made are presented in Figure 25 and Table 13 (magnetics), and in Figure 26 and Table 14 (electromagnetics).

Table 13. Previous geophysical exploration surveys (magnetics) at Viscaria and in its neighbouring areas, from which data now are available in SGU's databases. The names of the surveys correspond to those found in Figure 25.

Name of exploration area	Geophysical method used	Responsible	Year of permit
Norrbotten nr 104 B	Magnetics	Lundin Mining Exploration AB	2002–2007
Puoltsa nr 2	Magnetics	Anglo American Exploration B.V.	2002–2009
Puoltsa nr 3	Magnetics	Anglo American Exploration B.V.	2002–2009
Puoltsa nr 10	Magnetics	Eurasian Minerals Sweden AB	2010–2016

Table 14. Previous geophysical exploration surveys (electromagnetics) at Viscaria and in its neighbouring areas, from which data now are available in SGU's databases. The names of the surveys correspond to those found in Figure 26.

Name of exploration area	Geophysical method used	Responsible	Year of permit
Norrbotten nr 104 B	Electromagnetics	Lundin Mining Exploration AB	2002–2007
Puoltsa nr 2	Electromagnetics	Anglo American Exploration B.V.	2002–2009
Puoltsa nr 3	Electromagnetics	Anglo American Exploration B.V.	2002–2009
Puoltsa nr 10	Electromagnetics	Eurasian Minerals Sweden AB	2010–2016

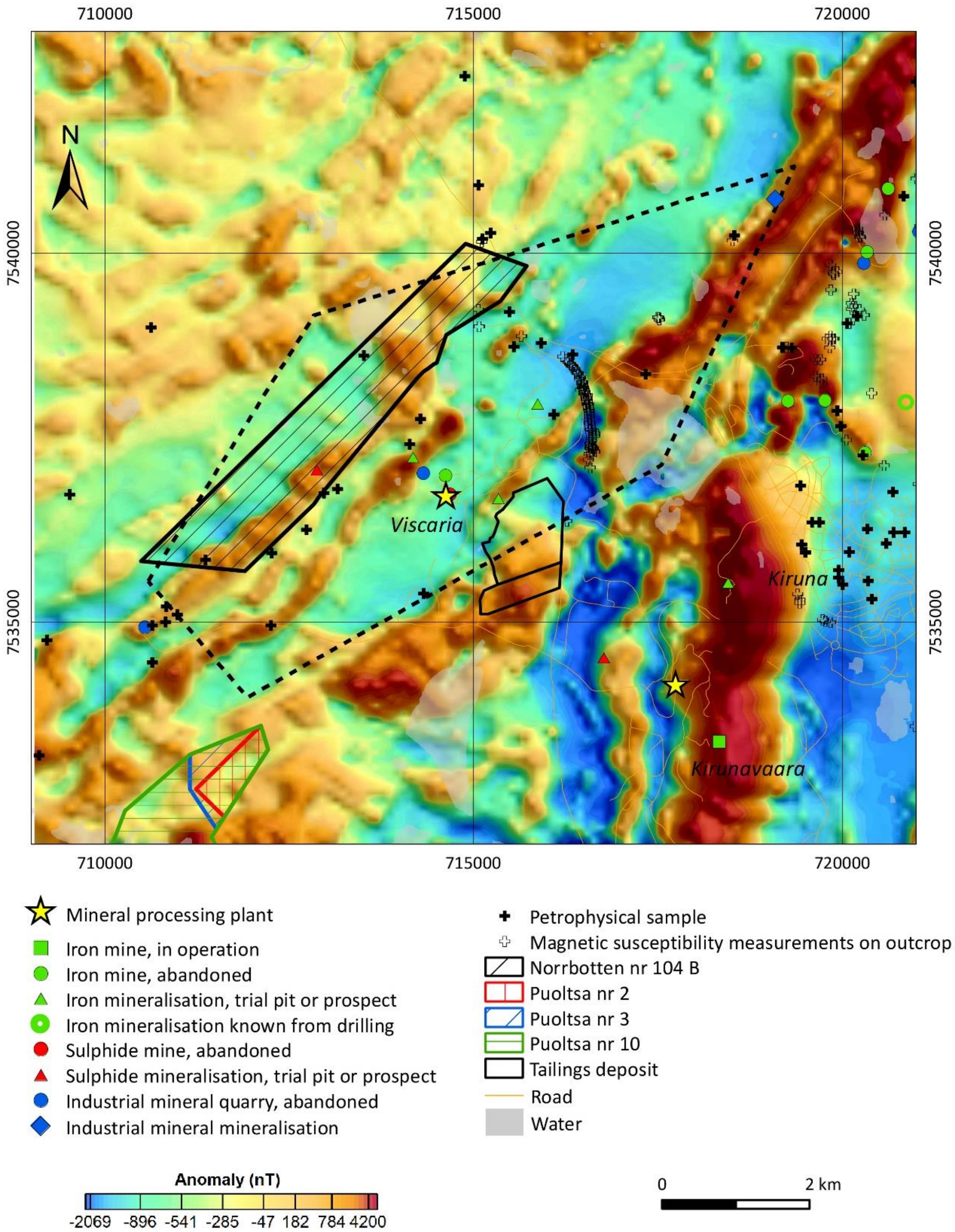

Figure 25. Map showing the magnetic anomalies, derived from airborne measurements, at Viscaria and in its neighbouring areas. The coloured polygons correspond to areas within which geophysical exploration surveys (magnetics) previously have been made. Data from these surveys are now available in SGU's databases (Table 13). The Viscaria area is shown as a polygon with black dashed line.

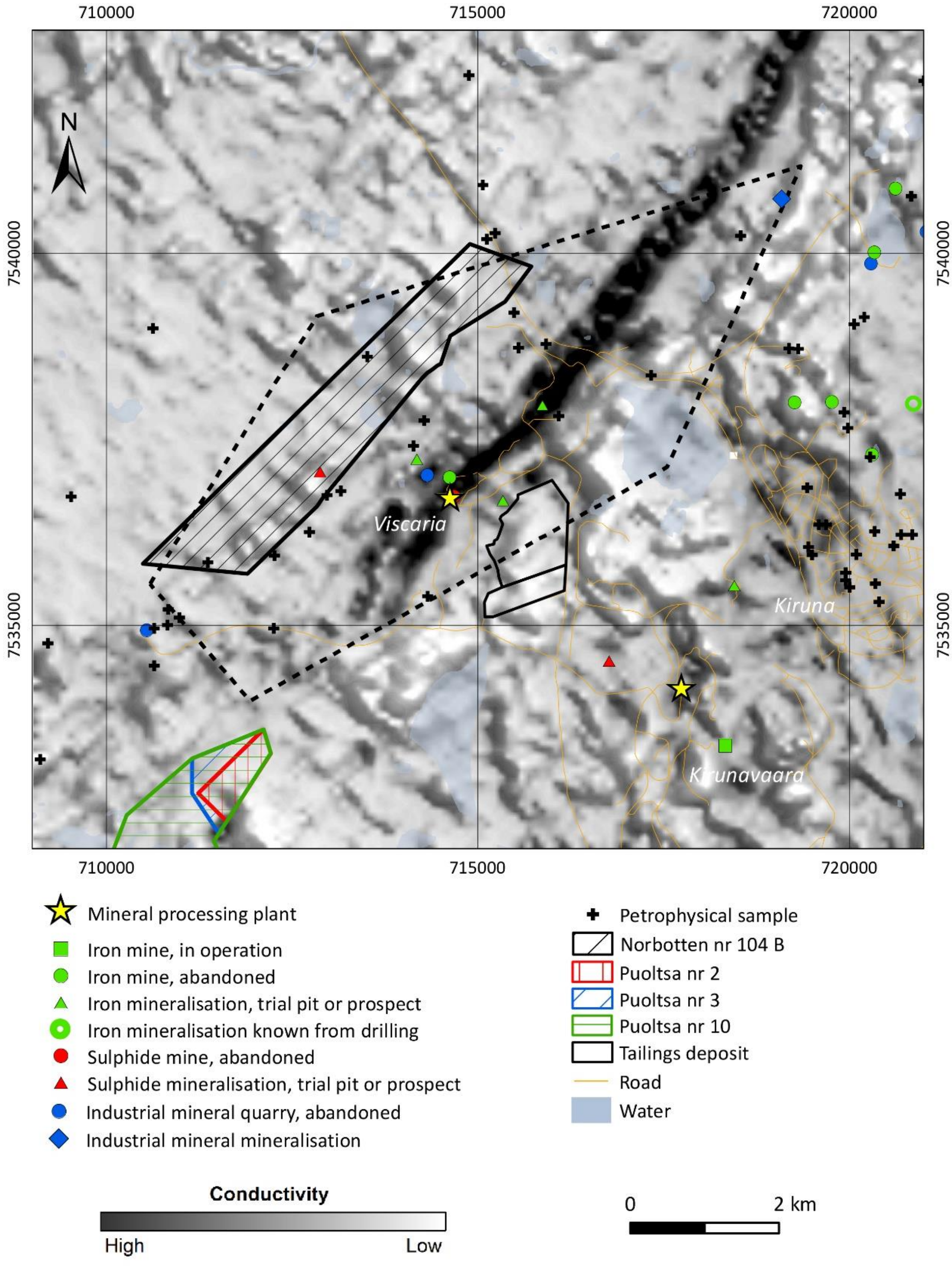

Figure 26. Map showing the real-part of the slingram data, derived from airborne measurements, at Viscaria and in its neighbouring areas. The coloured polygons correspond to areas within which geophysical exploration surveys (electro-magnetics) previously have been made. Data from these surveys are now available in SGU's databases (Table 14). The Viscaria area is shown as a polygon with black dashed line.

Sampling of waste rock

In total, 16 samples á 5 kg of waste rock (5 subsamples/sample) were collected at Viscaria with a shovel at a depth of approx. 0–50 cm. The waste rock exhibited an unoxidized, fresh surface and the particle size was < 70 mm (Fig. 27). Results from the analysis shows high concentrations of copper (0.2 wt. %) and zinc (0.1 wt. %) (Table 15).

Figure 27. Sampling of waste rock at the Viscaria mine. Photo: Roger Hamberg.

Table 15. Results from ICP-AES, LECO and ICP-MS analyses of waste rock from Viscaria, n = 16.

Element	Unit	Average	Max	Min	St.dev
Be	ppm	0.3	0.5	0.1	0.1
Bi	ppm	0.5	3.4	0.1	0.7
Co	ppm	57	145	39	28
Ga	ppm	18	20	17	2
Ge	ppm	0.0	0.0	0.0	0.0
Hf	ppm	2.3	3.4	1.8	0.2
In	ppm	0.2	0.7	0.0	0.1
Li	ppm	39	45	31	9
Nb	ppm	0.1	0.2	0.1	0.3
P	ppm	628	1010	390	247
PGM	ppm	0.0	0.0	0.0	0.0
REE	ppm	104	157	65	25
Sb	ppm	0.3	0.5	0.2	0.1
Sc	ppm	34	41	30	1.5
Sr	ppm	0.7	1.6	0.3	17
Ta	ppm	0.2	0.4	0.1	0.0
Ti	ppm	2340	2590	2100	530
V	ppm	290	332	265	25
W	ppm	1.0	1.0	1.0	0.1
Fe	ppm	98746	104567	93376	12432
Ni	ppm	110	126	94	28
Cu	ppm	1775	8570	173	1777
Pb	ppm	105	425	12	105
Zn	ppm	1015	1730	366	429
Ag	ppm	0.9	1.6	0.5	0.3
Au	ppm	0.0	0.0	0.0	0.0

REE: Sum of Rare earth elements, PGM: Platinum group metals

Sampling of tailings

In total, 18 samples á 2–3 kg of tailings (5 subsamples/sample) were collected at the tailings dam at Viscaria with a screw sampler at depths of approx. 0–19 m (Fig. 28). Tailings exhibited an unoxidised surface. Samples were analysed by the accredited ALS Analytical laboratory in Piteå. Results from the analysis shows high concentrations of copper (0.3 wt. %) and zinc (0.3 wt. %) (Table 16).

Figure 28. Tailings pond at the closed Viscaria mine. Photo: Roger Hamberg.

Table 16. Results from ICP-AES, LECO and ICP-MS analyses of tailings from Viscaria mine, n = 18.

Element	Unit	Average	Max	Min	St.dev
Be	ppm	0.5	1.1	0.3	0.1
Bi	ppm	5.2	9.3	1.8	1.7
Co	ppm	141	256	102	36
Ga	ppm	9.8	13	7.2	1.8
Ge	ppm	0.3	0.6	0.1	0.1
Hf	ppm	0.6	0.7	0.4	0.0
In	ppm	0.7	0.9	0.2	0.2
Li	ppm	26	45	14	9
Nb	ppm	0.1	0.2	0.1	0.0
P	ppm	1534	2290	840	360
PGM	ppm	0.0	0.0	0.0	0.0
REE	ppm	360	500	242	67
Sb	ppm	0.6	1.1	0.3	0.2
Sc	ppm	9	14	6	2
Sr	ppm	49	72	23	14
Ta	ppm	0.01	0.01	0.01	0.0
Ti	ppm	2010	3310	1280	620
V	ppm	154	187	120	19
W	ppm	0.7	1	0.4	0.2
Fe	ppm	103978	181500	72900	30224
Ni	ppm	124	150	103	14
Cu	ppm	2999	7980	1075	1462
Pb	ppm	142	329	26	68
Zn	ppm	2731	5260	609	1180
Ag	ppm	0.9	1.8	0.6	0.4
Au	ppm	0.1	0.1	0.0	0.0

REE: Sum of Rare earth elements, PGM: Platinum group metals

Secondary resource potential at Viscaria mine

Based on the above information, and under assumption that our calculated average metal concentrations are representative for the entire volume of tailings, the tailings dams at the Viscaria mine may in total contain approx. 36 000 tonnes of lead and 36 000 tonnes of zinc.

SUMMARY OF SECONDARY RESOURCE POTENTIAL

The results from analysing mine waste show high levels of copper, zinc and lead. Based on the assumption that our calculated average metal concentrations are representative for the entire volume of tailings and waste rock at the Viscaria and Laisvall mines, a resource estimate was conducted. Quantities of copper, zinc and lead were estimated to 45.000; 100.000 and 240.000 tons in waste rock and tailings from these waste facilities. For Pahtohavare, no resource estimate could be performed, as the quantities of waste rock are unknown.

REFERENCES

Bergman, S., 2018: Geology of the Northern Norrbotten ore province, northern Sweden. *Rapporter och meddelanden 141*, Sveriges geologiska undersökning, 40 s. ISBN 978-91-7403-393-9

Bergman, S. & Kathol, B., 2018: Synthesis of the bedrock geology in southern Norrbotten County, northern Sweden. *Rapporter och Meddelanden 144*, Sveriges geologiska undersökning, 246 s. ISBN 978-91-7403-410-3

Copperstone, 2022: Avfallshanteringsplan, *Viscaria Bilaga E,* 91 s.

Holmqvist, B., 2001: *Karta över Laisvallgruvan belägen i Arjeplogs kommun inom Norrbottens län*. Tillägg till Gruvkarta 807, Sveriges geologiska undersökning, 41 s.

Lovisagruvan AB, 2022: *Pahtohavare Joint venture*. <https://www.lovisagruvan.se/lovisagruvan-utveckling-ab/pahtohavare/> Åtkommen 7 september 2022.

SGU, 2022: Bedrock 1:50 000–1:250 000 – database. 2022-10-25.