KARTERING BARENTS 2013

Summary report on the geological and geophysical characteristics of the Harrijärvet–Vittangivaara key areas

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cover picture: View on Mount Vittangivaara from the west. Photo: Stefan Luth, SGU.

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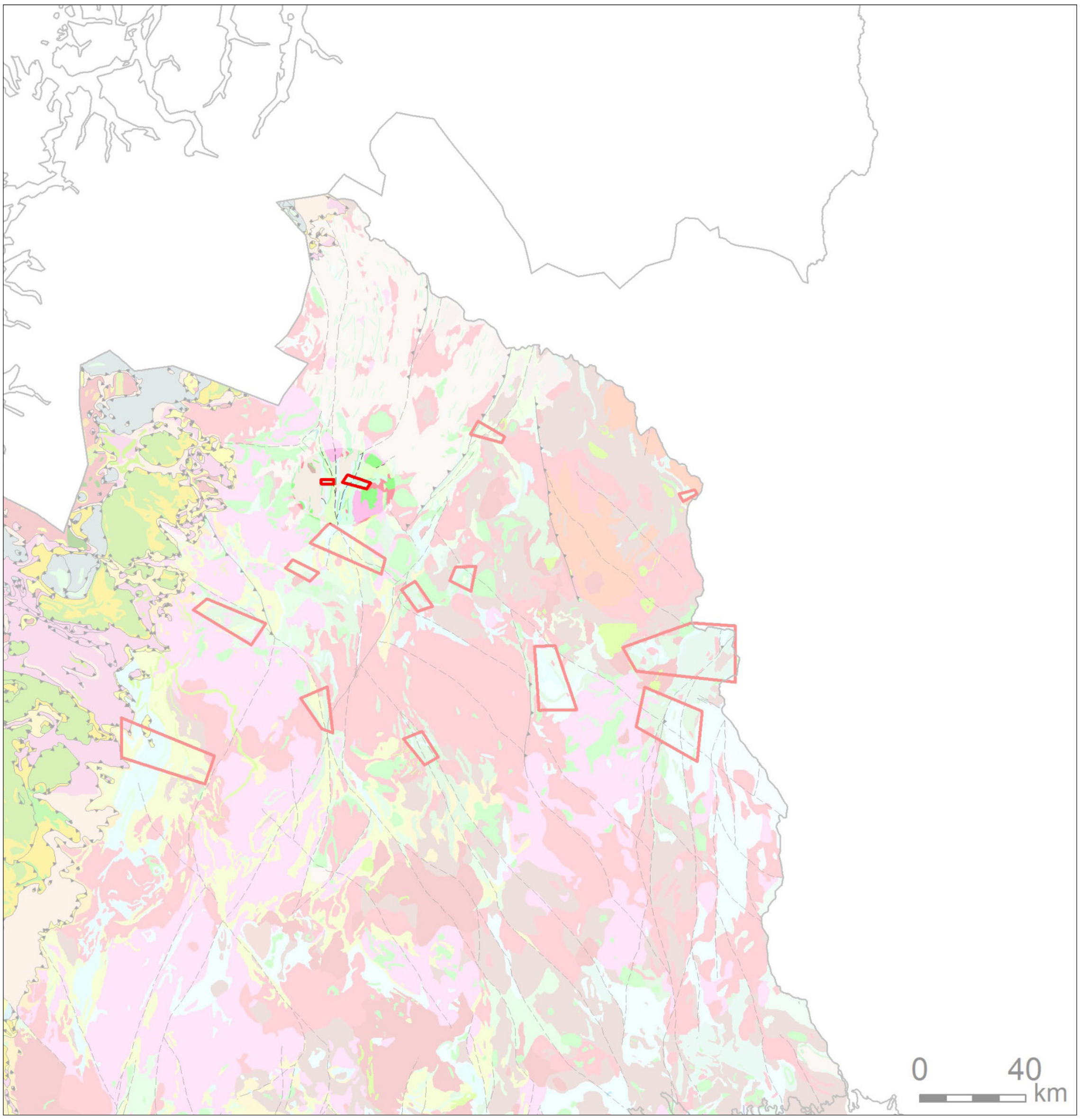


Figure A. The Harrijärvet and Vittangivaara areas are located in northernmost Sweden (bright red). These areas are two out of 12 key areas in the Kartering Barents project. Basemap is the bedrock map (1:1.000.000)

INTRODUCTION

The rocks of the northern Fennoscandian shield are the bearers of Europe's largest mineral resources. The region Norrbotten in northern Sweden is particularly important for it hosts large deposits of apatite iron ores, copper and gold deposits. Despite its economical impor¬tance, the development of the Fennoscandian crust and subsequent geological history is still poorly understood. Geological and geophysical field studies are few and are often too scattered to allow for correlation between stratigraphic units or to constrain the tectonic history of the Norrbotten area.

The Barents project targets 15 key areas distributed over Norrbotten county to resolve regional-scale issues by answering key area-specific questions. This report briefly summarizes the existing data within the Vittangivaara and Harrijärvet areas, and concludes with a list of remaining questions that will be addressed in the upcoming field studies. The questions primarily relate to the following topics:

Regional stratigraphy
- geological and geochemical characterization
- geophysical characterization
- dating of metavolcanic rocks
- dating of detrital zircons on sediments
- depositional environment

Regional tectonics
- detailed mapping of deformation zones and folding patterns
- relative and absolute time constraints on deformation
- construction of a tectonic model

Mineralization and alteration
- chemical characterization
- relation to lithology
- relation to structures and deformation processes

AVAILABLE DATA FOR THE HARRIJÄRVET–VITTANGIVAARA REGION

Published material

Table 1. SGU reports relevant to the Vittangivaara and Harrijärvet key areas:

Code	Title	Year	Author	Location	Most relevant
C 697	Urbergsstratigrafisk studie över Vittangivaara, Norrbottens län	1974	G. Folcker	Vittangivaara	Stratigraphy, Abstract (English)
Ba 56	Regional geological and geophysical maps of Northern Norrbotten (1:250.000)	2001	S. Bergman	Northern Norrbotten	Regional geology, stratigraphy, deformation history
Ca 41	Berggrundskara över urberget i Norrbottens län	1957	O. Ödman	Norrbotten	Regional geology, and zoom in map Vakko-Kovo zones
C 366	Berggrunden inom malmtrakten Kiruna–Gällivare–Pajala	1931	P. Geijer	Kiruna–Gällivare–Pajala	Regional geology and stratigraphy

Table 2. SGU map sheets relevant to the Vittangivaara and Harrijärvet key areas.

Code	Title	Year	Author	Relevant to key area	Descriptions	GIS
Ai 133	30J Rensjön SO (1:50.000)	1999	O. Martinsson	Harrijärvet and western Vittangivaara	Stratigraphy	yes
Af 33	30K Soppero SV (1:50.000)	1967–1970	U. Hallgren	Vittangivaara	No	yes
Af 2	29J Kiruna NO (1:50.000)	1967	J. Offerberg	South of Harrijärvet–Vittangivaara	Stratigraphy	yes
Ba 56	Regional geological and geophysical maps of Northern Norrbotten (1:250.000)	2001	S. Bergman	Harrijärvet–Vittangivaara	Regional geology, stratigraphy, deformation history	yes
Ca 41	Berggrundskara över urberget i Norrbottens län	1957	O. Ödman	Harrijärvet and western Vittangivaara	Regional geology, and zoom in map Vakko-Kovo zones	no

Table 3. Prospecting reports relevant to the Vittangivaara and Harrijärvet key areas.

Title	Author	Year	Company	Location	Type	Relevant part
NSG93003, The Swedish Norrbotten Greenstone Belt	Bosse Gustafsson	1993	Sveriges Geologiska AB	Norrbotten	Stratigraphy, lithogeochemistry	Stratigraphic variations in the Greenstone belt
Brap95013, Interimsrapport över prospekteringsundersökningar utförda av Sveriges geologiska undersökning på uppdrag av Luossavaara-Kiirunavaara AB 1975	SGU	1975	SGU	30 J Rensjön SO, 30 K Soppero. Detailed maps on mineralization in the Vittangivaara region	Bedrock mapping incl. mineralization geochemistry, and geophysics.	Good alternative for missing map sheet descriptions in 30K Soppero
Mink0753, VIP-projektet Slutrapport	Lisbeth Godin	1989	Viscaria	Laanijärvi and Harrekutjaure	Drilling and geochemistry	Introduction, well logs
Ki578	Lisbeth Godin	1978	LKAB	Linkaluoppal, Linkatjåkko Vittangivaara, Ussalahti, Supasnimi, Vittangijoki	Summarized ongoing work: Copper mineralization and geophysics	pp. 27–38: pp. 50–68:
Pro8037, Geokemiska undersökningar 1975–1980. Slutrapport	J.-O. Larsson	1980	LKAB	Ussalahti, 30 K Soppero	Geochemistry	–

Table 4. Scientific publications relevant to the Vittangivaara and Harrijärvet key areas.

Title	Author	Year	Journal	Relevance
Geology and metallogeny of the Northern Norrbotten Fe–Cu–Au province	O. Martinsson	2004	Society of economic geologists, Guide-book series, Volume 33, p 131–148	Review on regional geology, stratigraphy, mineralization and tectonics
Precambrian geodynamics and ore formation: The Fennoscandian Shield	P. Weihed et al.	2005	Ore geology reviews, Volume 27, p 273–322	Review on geodynamic of Fennoscandian. Cartoons on deformation history and depositional environments.
Tectonic setting and metallogeny of the Kiruna Greenstones	O. Martinsson	1997	PhD-thesis, LTU. ISSN: 1402–1544	Regional geology and stratigraphy
Early deformation in the Svecokarelian greenstone belt of the Kiruna iron district, Northern Sweden	F. Vollmer	1984	GFF, Vol. 106 p 109–118	Field study on the deformation patterns in the Kiruna district
On the age of the Kiruna Greenstones, Northern Sweden	T. Skiöld	1986	Precambrian Research	Minimum age constrain of the Kovo group, south of Vittangivaara

Table 5. Scanned maps from reports and publications relevant to the Vittangivaara and Harrijärvet key areas.

Map title	Author	Report	Location	Relevance	Scale	Digital
Selected areas for stratigraphic profiles	Bosse Gustafsson	NSG93003 (p. 7)	Norrbotten	Stratigraphy	1:250.000	No
Berggrunden i Vittangivaara	G. Folcker	1956	Vittangivaara	Bedrock and Stratigraphy	–	No
Vittangivaara regional	SGU 1975	Brap95013 (p. 24-SG3302)	Vittangivaara regional	Some fault lines		No
Detaljkara över kopparmineralisering	SGU 1975	Brap95013 (p. 25)	Linkaluoppal	Mineralization	1:500	No
Myrkantsprovtaging och geokemisk dyprovsanamoli	SGU 1975	Brap95013 (p. 29-SG3304)	Vittangivaara regional	Geochemistry / Mineralization		No
Tungmineralprov	LKAB	Brap95013 (p. 31-SG3305)	Vittangivaara regional	Geochemistry / Mineralization		No
Linkaluoppal	LKAB	Ki578, pp 30	Linkaluoppal	Bedrock	1:20.000	yes
Linkaluoppal	LKAB	Ki578, pp31	Linkaluoppal, Påkketanjaure	Geophysics comp.		no
Vittangivaara	LKAB	Ki578, pp54	Vittangivaara	Bedrock	1:20.000	Yes
Vittangijoki	LKAB	Ki578, pp65	Vittangijoki	Bedrock	1:50.000	Yes
Projekt “Visacriatyp i Grönsten”	LKAB?	Ki7933	Kiruna to Vittangivaara	Bedrock and Regional names	1:200.000	Yes
Pussijärvi	O. Martinsson 1991		Pussivjärvi	Bedrock and structure	1:20.000	Yes
Projekt 5111 Harrijärvi-Linkaluoppal (2 maps)	LKAB	K8712	Kurravaara to Vittangivaara	Drill core locations, structure	1:50.000	Yes
Påkketanjaure	?	?	Directly south of Vittangivaara	Bedrock	?	yes
Kartskiss över området NO Vuoloslomolo	R. Frietsch	SGU pärm	Vittangivaara and Harrijärvet	Stratigraphy	1:20.000	No

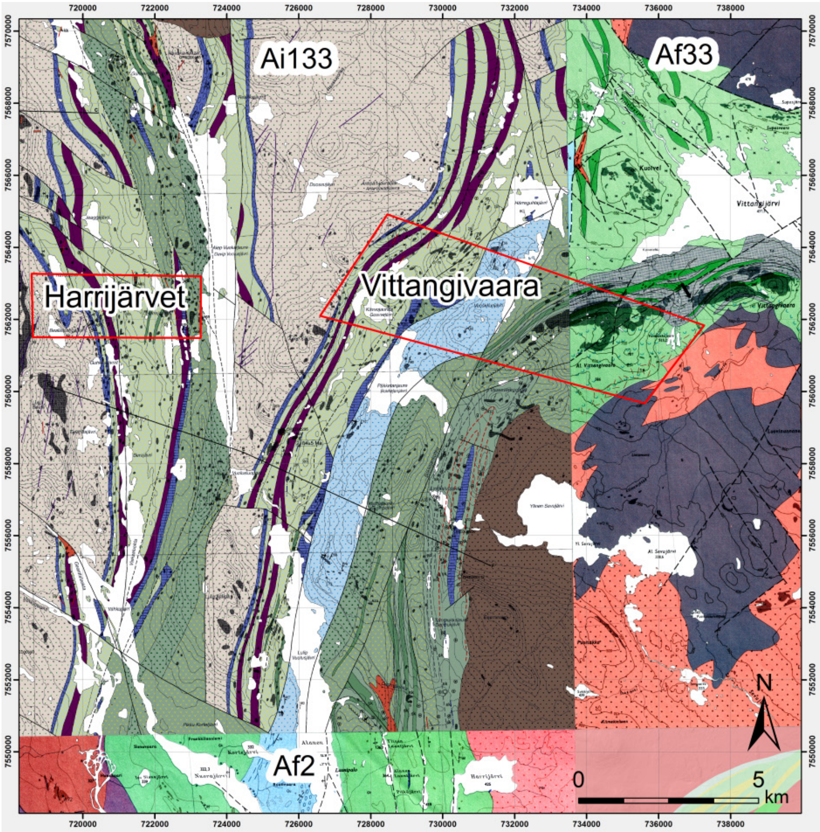


Fig. 1. Regional map showing the Harrijärvet and Vittangivaara key areas outlined in red. The background maps are the different maps sheets published by SGU. Most of the area of interest has been mapped in 1999 by Martinsson (Ai133, see table 5), whereas mapping of the eastern part of the Vittangivaara key area took place in1970 (Af33).

Maps databases

Bedrock maps

The SGU "local bedrock map database" is based on a large number of mapping projects, which main outputs were map sheets at a scale of 1:50.000 as well as descriptions on the stratigraphy and structures. The relevant map sheets for the Harrijärvet–Vittangivaara region are Ai133 and Af33 (Table 2 and Fig. 1 & 2). Along the border between the two map sheets occur "map faults" as a result of different interpretations on the extent of several lithological units.

Drill cores

The discovery of the Visacria copper deposit by LKAB in 1973 led to a phase of intensive prospecting in the search for similar mineralization within the Kiruna Greenstone Group. This resulted in many detailed maps, reports, and drill logs, which contributed to a better understanding of the geology of the higher stratigraphy in the Kovo zone. Documentation from many different companies is mostly preserved and is now available in digital format.

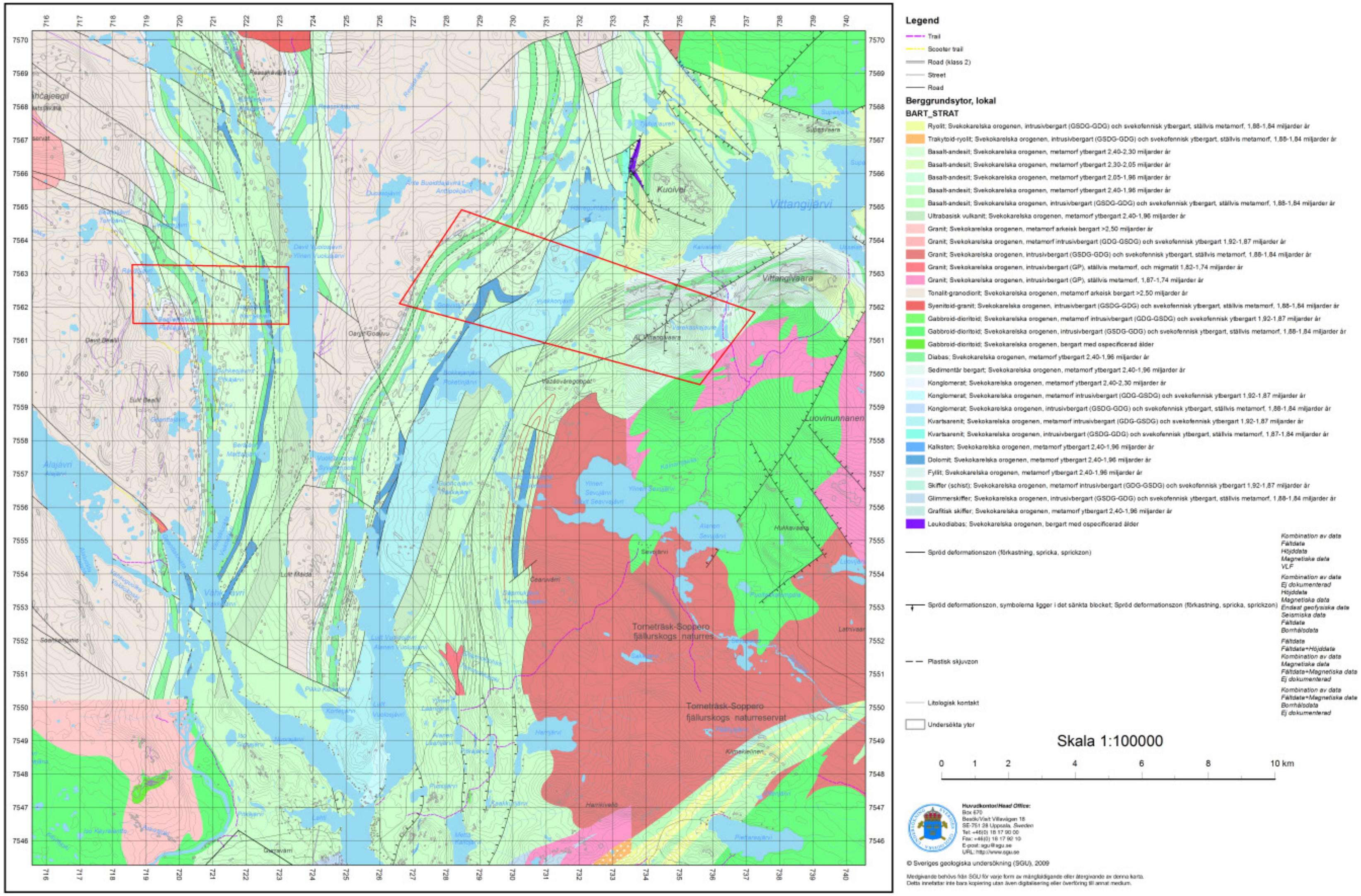


Fig. 2. Bedrock map of the Vittangivaara and Harrijärvet key areas (red squares) extracted from the SGU "Local bedrock" database (legend on last page of this document).

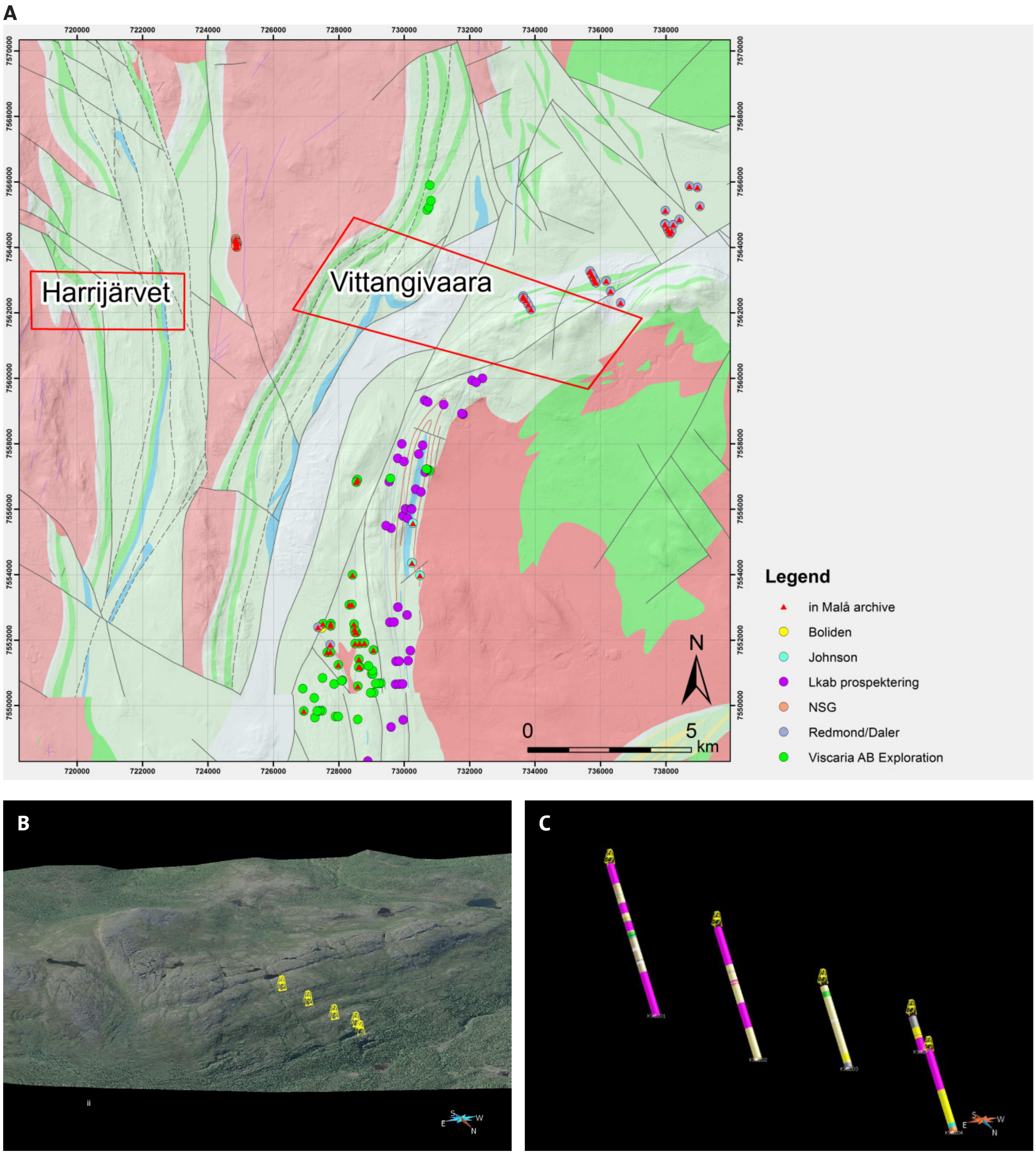


Fig. 3. **A.** Drill locations in the Kovo zone coloured after prospecting company. Red triangles indicate storage of the drill core in the SGU Malå archive. **B.** Drill locations within the Vittangivaara key region carried out by Redmond in 1998 (K98201-05) projected onto an aerial photo combined with a DEM surface. c) Associated drill logs displayed in Gocad. Colors refer to the different rock types. Purple: dolorite; light grey: volcanic tuff; yellow: sandstone; green: lava..

In the folder "Drilllogs" the logs are organized in subfolders named after company and the locations are shown in Figure 3a. Most of the drilling was done south of the Vittangivaara key area at a dip of 45° towards the north, and with a depth range between 150–300 metres. Some of the drill cores are stored in the SGU archive in Malå (Fig. 3). This extensive amount of drilling together with the detailed documentation of both the geophysical properties and geochemistry of core- and surface samples makes this region attractive for a 3D geological interpretation. As such, tracing stratigraphic marker horizons (e.g. magnetite-rich layers) further northwards should be an important aim during the upcoming field studies within the Vittangivaara key area (See also next section on mineralization and alteration).

Mineralization and alteration

No mineral deposits of economic value have been found in or directly nearby the Harrijärvet-Vittanigvaara key areas. The character of some trial pit or prospect is briefly described in Chapter 4. Some blocks / boulders with mineralization have been found in both the Vittangivaara and Harrijärvet areas (Fig. 4). The findings and search regions are contoured on 30 J Renjön topographic maps. Blocks numbered 30J-2 and 30J-3 are located in the Harrijärvet area, and 30J-5 is located in the Vittangivaara region.

Litho- and soil geochemistry

Fig. 5. Distribution of samples taken for both litho- (stars) and soil- (circles) geochemistry in the Harrijärvet–Vittangivaara region. Note that the orange circles refer to litho geochemistry analysis stored in the SGU database.

New till samples have been taken by SGU within the Vittangivaara key area during the summer of 2012 (Fig. 5). The samples are being processes by the time of writing, and the results from the SGU laboratory are expected in autumn 2013. Since sampling was done by using a helicopter, the sample locations plotted in figure 5 can be useful in terms of planning landing sides for the upcoming field season.

Most of the samples within the Harrijärvet–Vittangivaara region taken for litho-geochemistry have been collected by O. Martinsson. He implemented these samples into a

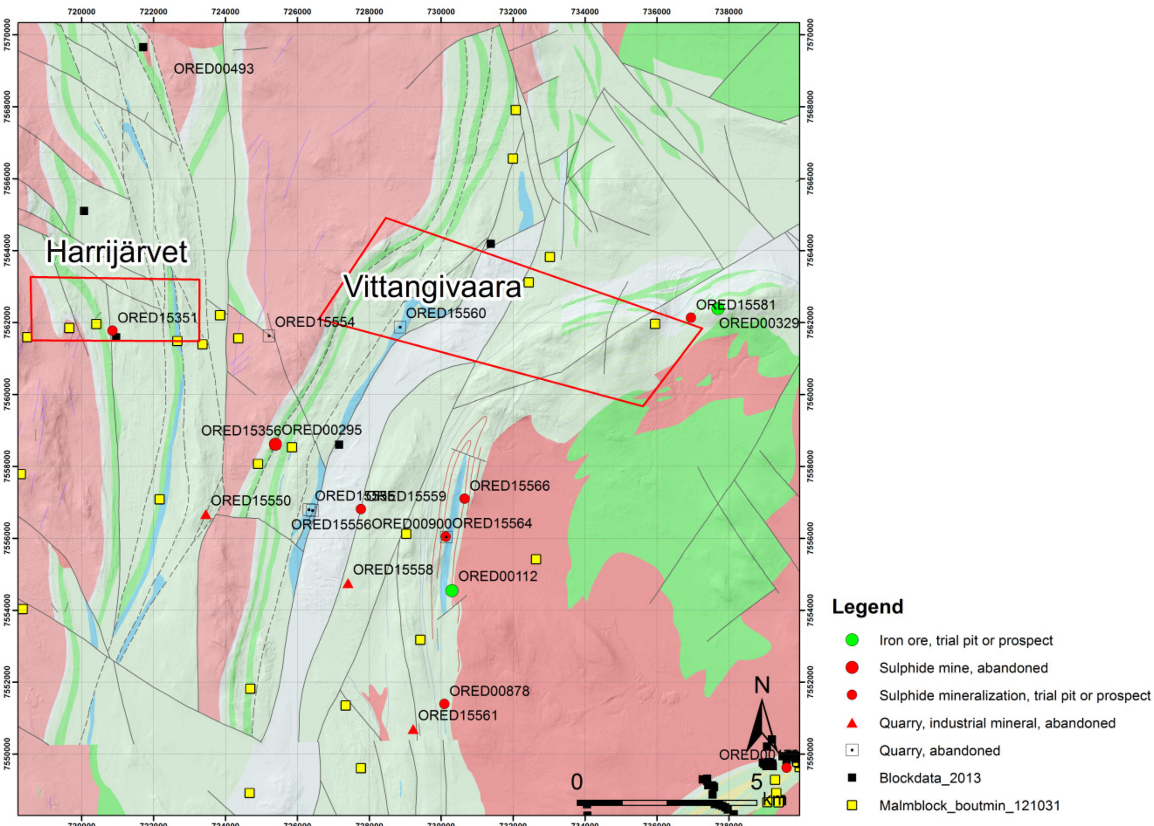


Fig. 4 Distribution of mineral resource information in the Harrijärvet-Vittanigvaara region.

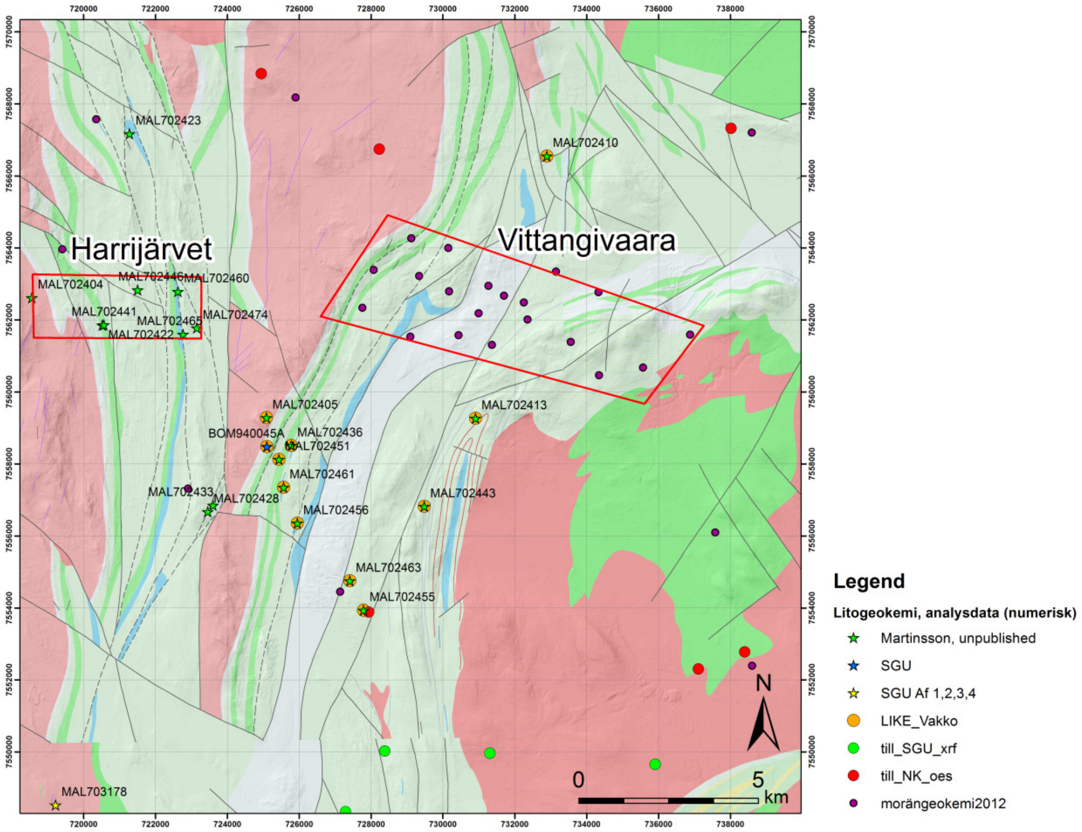


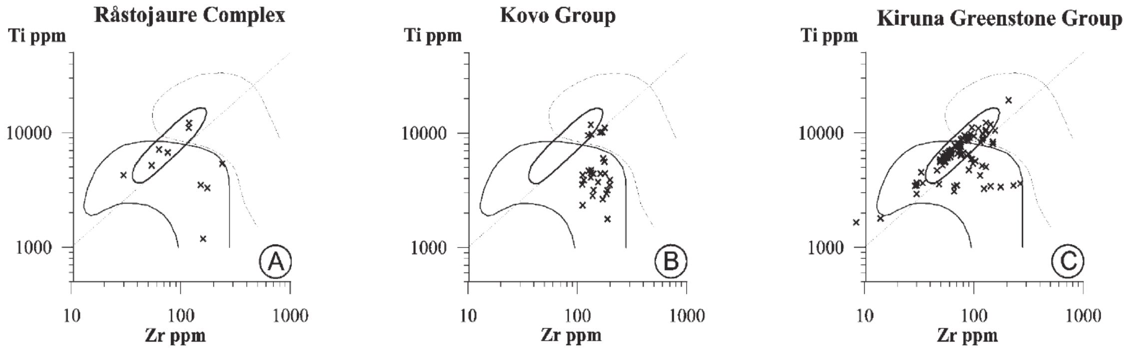
Fig. 5. Distribution of samples taken for both litho- (stars) and soil- (circles) geochemistry in the Harrijärvet–Vittangivaara region. Note that the orange circles refer to litho geochemistry analysis stored in the SGU database.

more regional study to classify the different lithological units according to tectonic setting (Fig. 6 from Martinsson, 2004). It seemed that the chemistry of the volcanic rocks from the Kovo group signal an arc setting, whereas the MORB imprint of Kiruna greenstone group implies deposition during a more mature rift stage. More samples are needed from especially the Vittangivaara key area for a better constrain, and to distinguish between a possible contaminations (inherited imprint) from the older Råstajaure Complex (Hallberg, pers comm.)

Geochronology

No geochronological data has been collected within the Vittangivaara or Harrijärvet area (Fig. 5). However, about 15 km south of the Vittangivaara area, the minimum age of the Kovo group is contrained to 2181 ± 5 Ma by U-Pb dating of zircons derived from an albite diabase (Skiöld, 1986). Just a few hundred metres westward an older age of 2692 ± 5 Ma was obtained from SIM analysis on zircons from an andasitic tuff by Skiöld and Page (1998). However, the interpretation of this age is debated, and the zircons may have derived from the intruded basement.

A sample taken from the Archean basement northeast of the Härrijärvet area, record a magmatic age of 2760 Ma based on U-Pb dating of zircons hosted in granite (Welin et al, 1971). A granitic pluton within the Archean basement exposed on the western side of the Vakko-zone is dated at 1877 ± 14 Ma, and belongs probably to the Haparanda suite (Martinsson, 1999, SGU C-831).



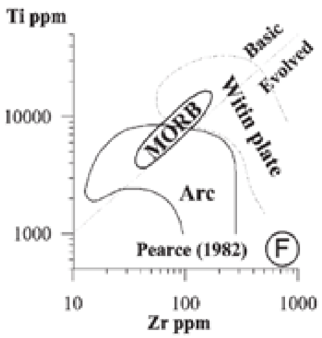


Fig. 6. Pearce diagrams relating the chemical imprint of the main lithologic units in the Harrijärvet–Vittangivaara region with the tectonic setting. Taken from Martinsson (2004).

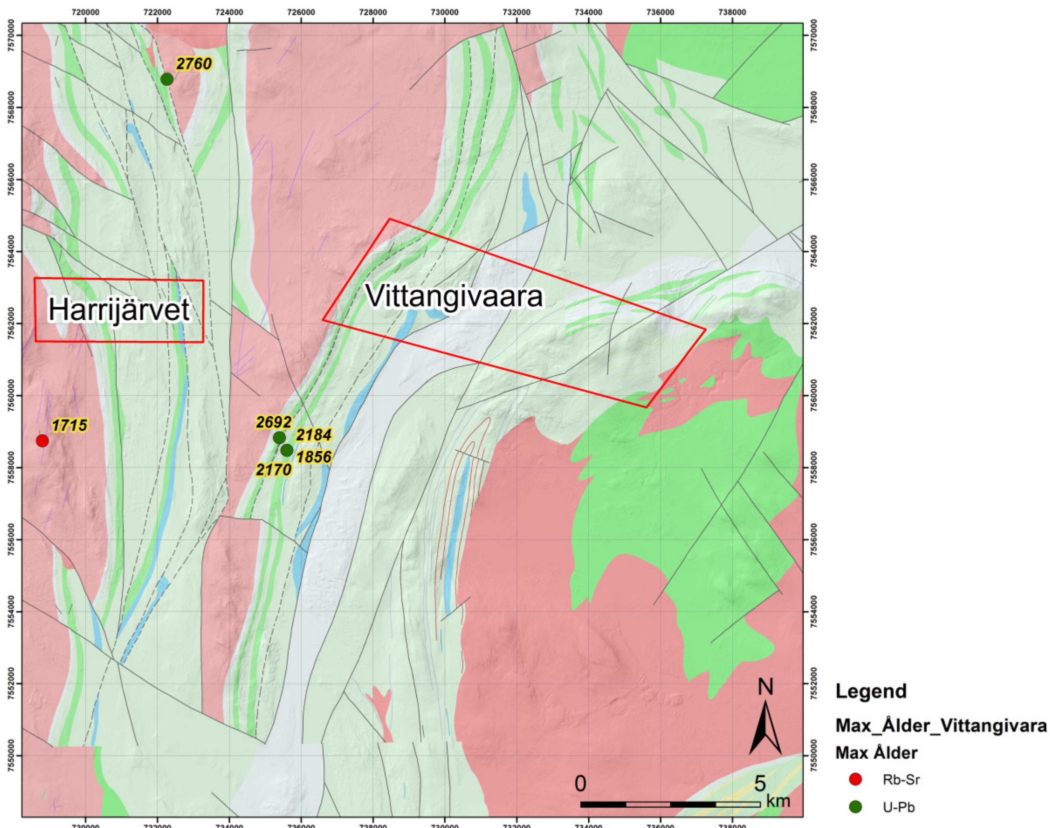


Fig. 7. Distribution of age information in the Harrijärvet-Vittanigvaara region.

Hänvisning saknas i texten.

Topographic maps

Topographic maps from Lantmäteriet are presented in the SGU database as both raster- and vector formats. The most detailed maps available for the Harrijärvet–Vittangivaara region are the "Vägkartan, SGU-maner" and the "Fjällkartan". Unfortunately no "Terrängkartan" exist for this part of Sweden, which shows even greater detail.

Orienteringkartan

As an alternative for the missing "Terrängkartan" detailed "Orienteringskartan" from the Kiruna area, are available at http://ifk.kiruna.se/omgm/map.php. Available maps are: Luossavaara/Kurravaara, Laxforsen, Kalixfors and Luspavaara.

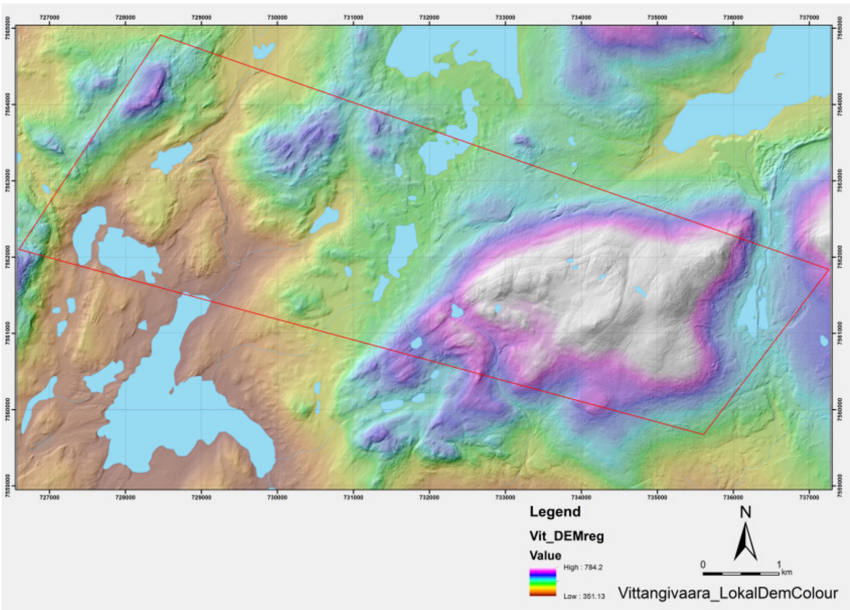


Fig. 8. DEM with local color symbology for the Vittangivaara region.

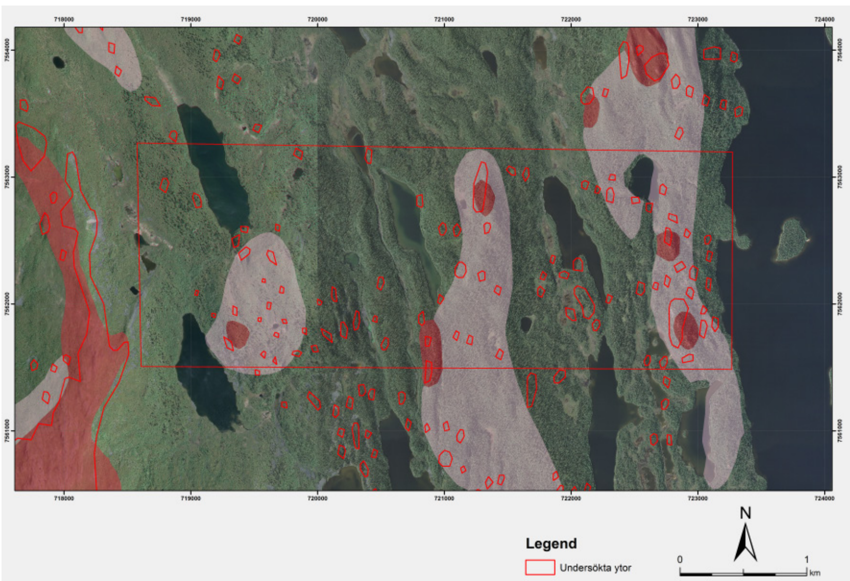


Fig. 9. Example from the Harrijärvet area where outcrops from the lokal berggrund layer (hollow lines) and jordartskartor layer (outcrop in dark red, thin soil layer in transparent red) are combined and plotted onto an aerial photograph.

Aerial photos and outcrop maps

Aerial photos are available in digital format from Lantmäteriet. Their format allows for normal view as well as in the infrared spectrum. Outcrop maps were compiled by a combination of outlines taken from existing geological maps as well as soil maps (Fig. 8)

Digital Elevation Model (DEM and Lidar)

Fortunately, the Harrijärvet–Vittangivaara region is covered by 2 m resolution digital elevation data (Lidar), which can be processed in ArcGis in order to extract a local color symbology (Fig. 8).

Geophysical databases

Airborne data

Airborne geophysical measurements in the area were carried out by the Geological Survey of Sweden (SGU) during 1960–1964. The magnetic field was measured by SGU as a part of the iron inventory program. Loussavaara–Kiirunavaara AB (LKAB) collected airborne data during 1973 to 1985. LKAB measured the magnetic field, the electromagnetic field, both with VLF- and Slingram methods and gamma ray radiation. The survey direction was east–west. The VLF measurements collected by LKAB in the 1980s were made with two different transmitters, which means that the peaker and apparent resistivity maps can be transformed. (Pedersen et al, 1994). All airborne surveys in the area were made with a line separation of 200 m, a point distance of 40 m and a ground clearance of 30 m.

The magnetic anomaly map over the area is shown in Fig. 10. Four key areas, Harrijärvi, Vittangivaara, Kiruna–Jukkasjärvi and Saarijärvi , which will be studied in the Barents project are superimposed on the magnetic field. The most prominent magnetic anomaly in the area is caused by the Kiruna iron ores. Both iron and sulphide mineralisations, appear in areas with patterns of banded magnetic anomalies mostly caused by supracrustal rocks. The intrusive rocks appear mostly as circular, more homogenous patterns with lower magnetisation.

Electromagnetic (VLF- peaker and Slingram) data are shown in Figs. 11 and 12. Highly conductive horizons clearly appear in both VLF (Fig. 11) and slingram data (Fig. 12). Sedimentary rocks (black shales) can be identified in the Viscaria area, northwest of Kiruna and in the area northeast of Kurravaara. The VLF data contains more details than slingram data, for example in addition to the conductive horizons even brittle deformation zones can be identified using the VLF information. Resistivity and current density over the area can also be estimated from VLF data.

Ground based data

Regional gravity measurements have been carried out during 1960 and 1989. The point separation for the measurements varies considerably in the area; a good regional coverage is available in the Kiruna and Jukkasjärvi area, but point density is very sparse in the northern part of the region (Fig. 13).

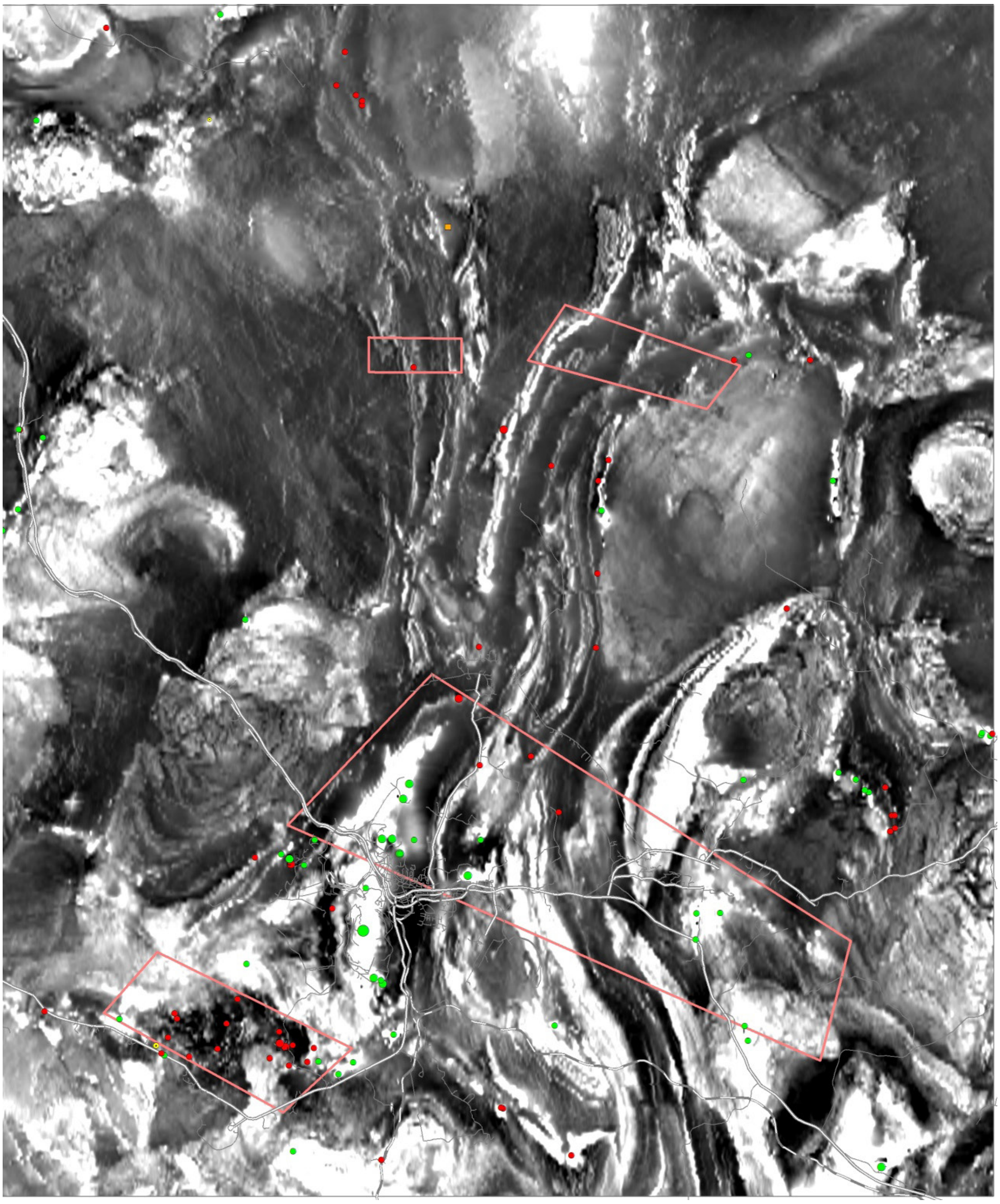


Fig. 10. Airborne magnetic map over the area. Green dots show iron ores and mineralisations, red dots show sulphide mineralisations. The red polygons show four of the fifteen key areas to be studied in the Barents project. Vittangivaara in the northeast and Harrijärvet in the northwest.

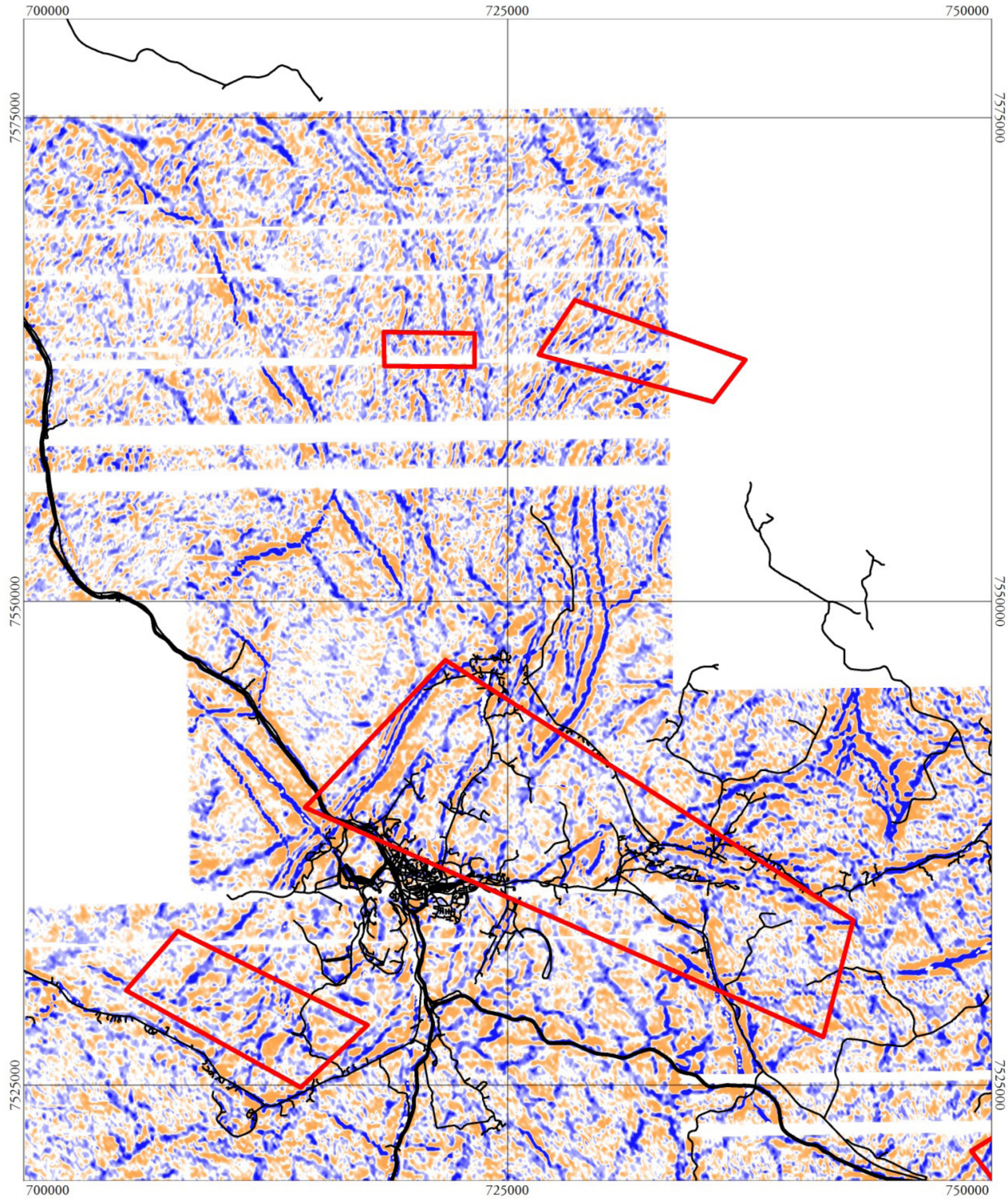


Fig. 11. Peaker VLF map over the area. Blue colour indicates conductive structures. The red polygons show four of fifteen key areas to be studied in the Barents project.

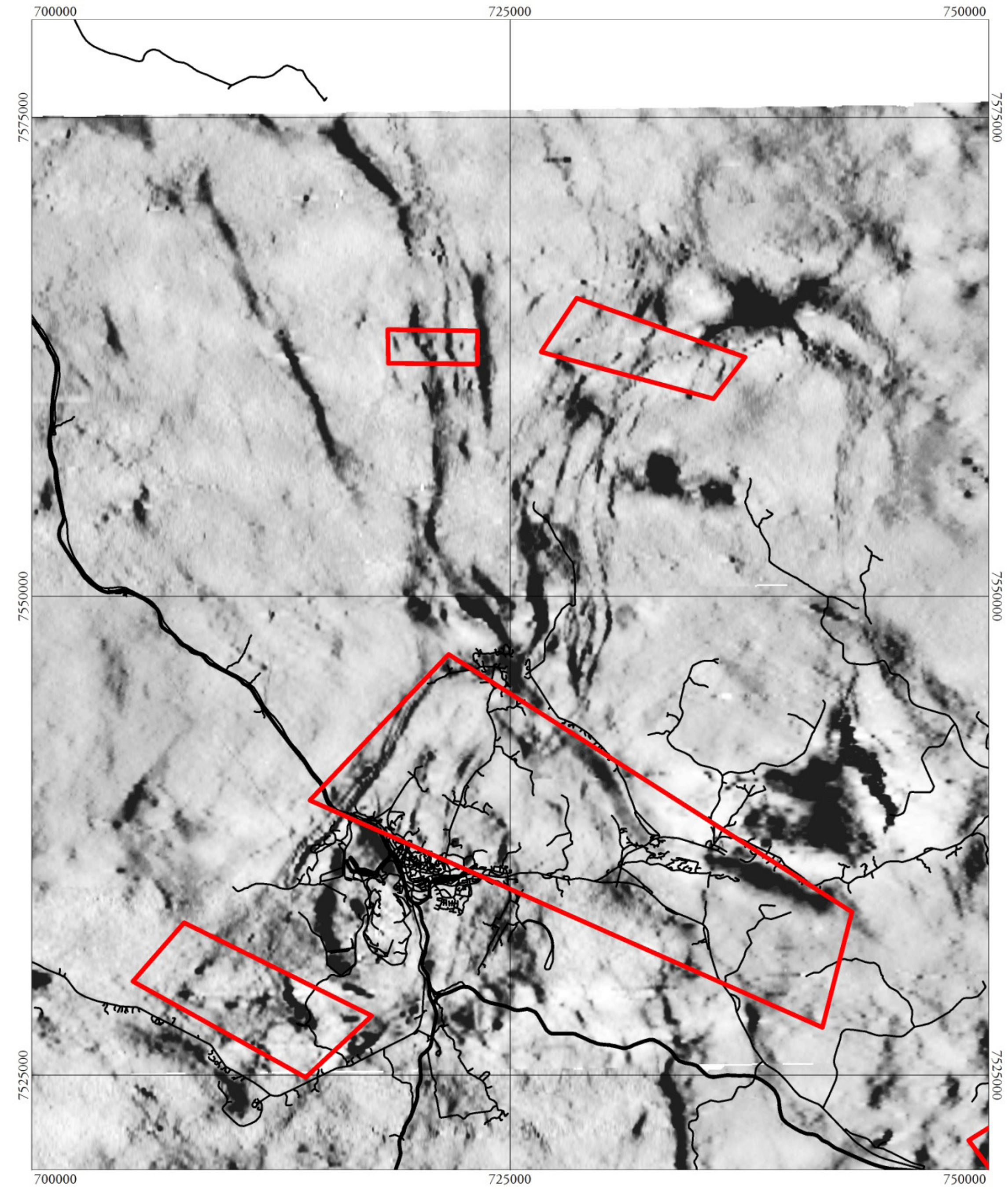


Fig. 12. Electromagnetic (slingram, imaginary part, 3720 Hz) map over the area. Black colour indicates conductive structures. The red polygons show four of fifteen key areas to be studied in the Barents project.

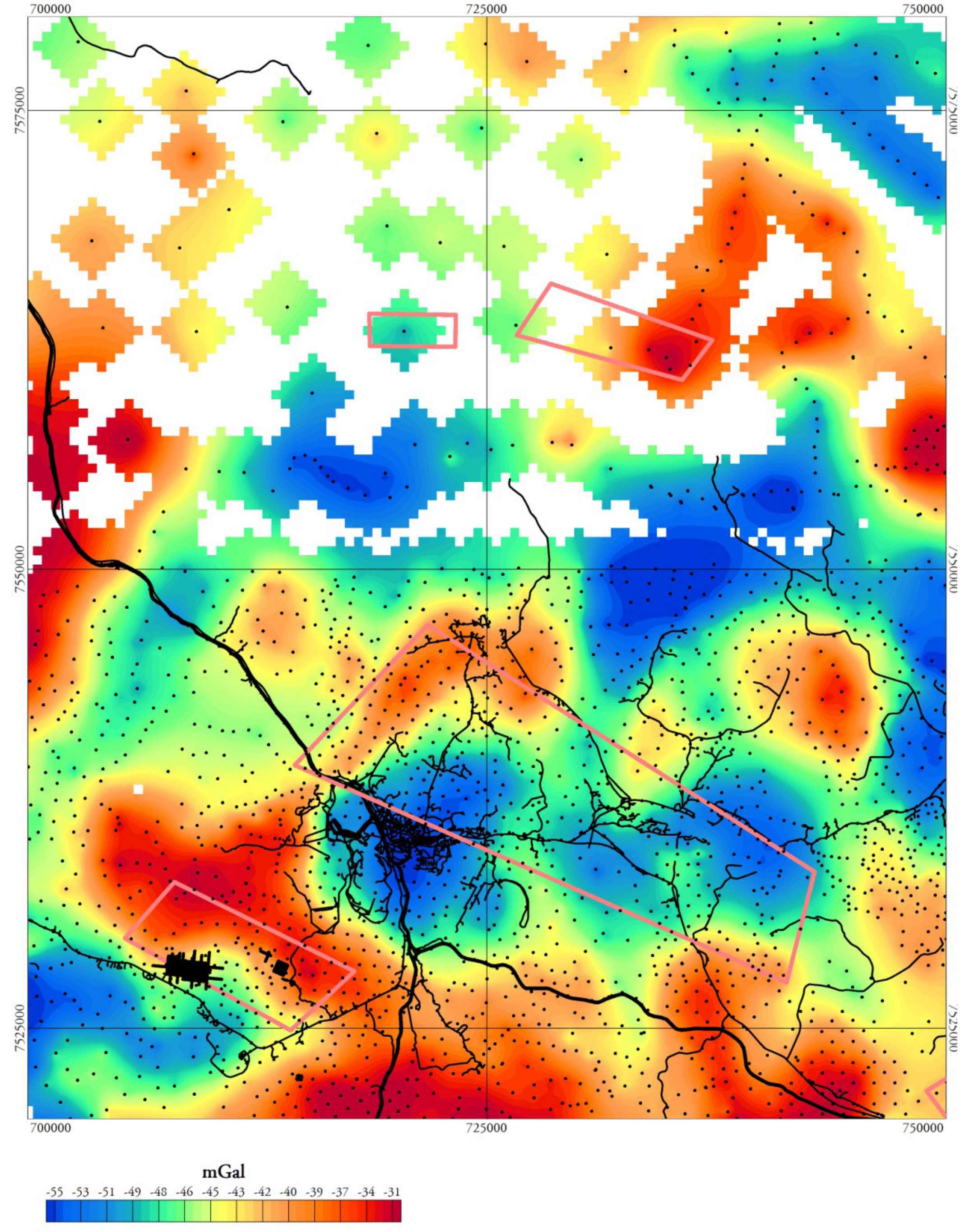


Fig. 13. Bouguer anomaly map over the area. The black dots represent gravity data points. The red polygons show four of fifteen key areas to be studied in the Barents project.

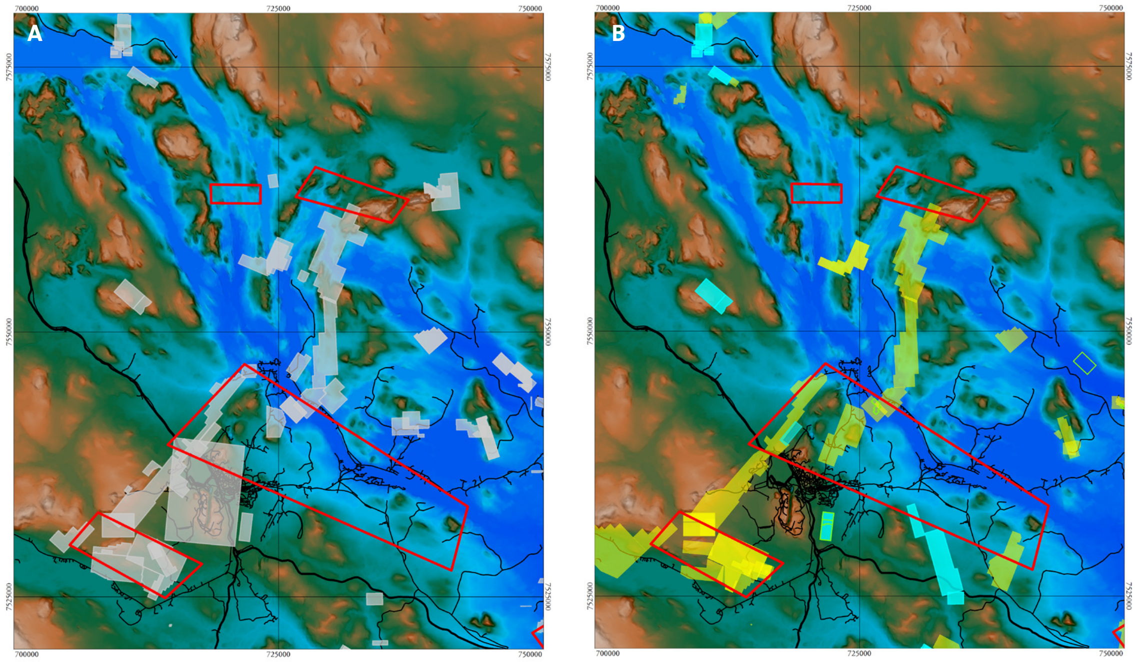


Fig. 14. **A.** White polygons indicate ground magnetic surveys superimposed on the topography map. . **B.** Yellow polygons indicate slingram measurements. Blue polygons show the locations of VLF- measurements. Key areas in red..

During the past 60 years, various geophysical ground measurements were made by different companies in the area. An overview of historical ground geophysical data stored at SGU is given in this report. Geophysical measurements of the magnetic-, and electromagnetic field with different methods and induced polarisation were carried out between 1963 and 1987. The data were collected with a line separation of 50 or 100 m and at a point distance of 10 or 20 m. In certain areas the measurements was done with a line separation of 40 m. The distribution of the ground magnetic and electromagnetic measurements in the area in Fig. 14.

Examples of the magnetic and the electromagnetic (slingram) field measurements in the Kiruna–Juakkasjärvi area and further north are shown in Figs. 15 and 16. A fold structure can clearly be seen in both the magnetic and electromagnetic maps. The high magnetic anomalies, caused by volcanic rocks in the fold structure, do not coincide with the slingram anomalies caused by sedimentary rocks in the area (Fig. 17). A combination of the magnetic and the electromagnetic data results in a good overview of the spatial distribution of the highly magnetic volcanic rocks and highly conductive sedimentary rocks in the area.

Petrophysics

Petrophysical samples were collected in earlier projects, such as regional mapping activities and prospecting campaigns since the 1960s. Susceptibility, remanent magnetisation and density were measured. Compilation of the petrophysical data over northern Norrbotten was done for example during the Nordkalott Projekt by Granar et al. (1986), and by Bergman et al. (2001). The sample sites can be seen in Fig. 18 together with the magnetic anomaly map and the four key areas.

There are 1706 petrophysical samples stored in the SGUs database in the area. The distribution of the susceptibility and density is shown in Fig 19.

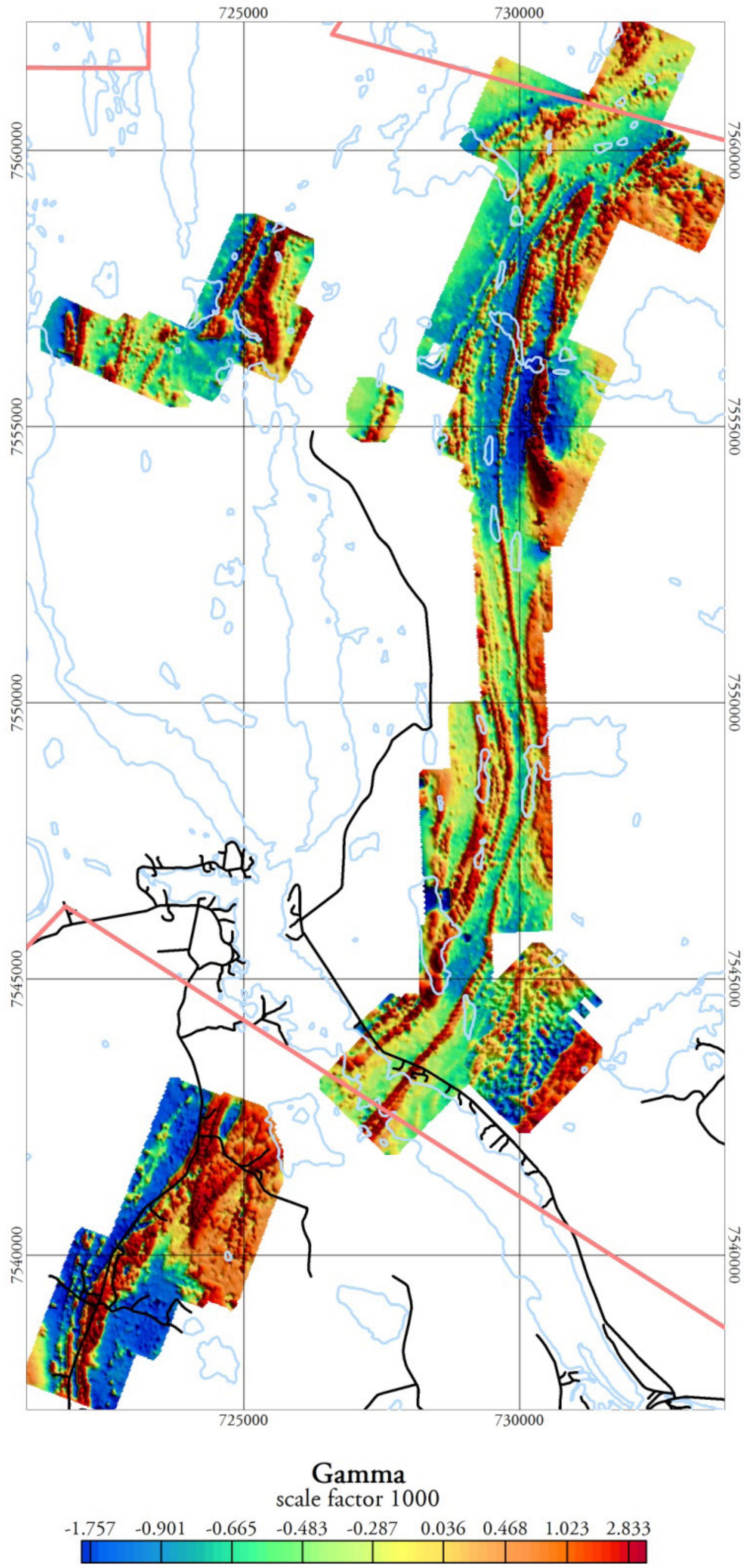


Fig 15. Ground magnetic measurements to the south of the Vittangivaara area. Parts of the key areas shown in light red colour.

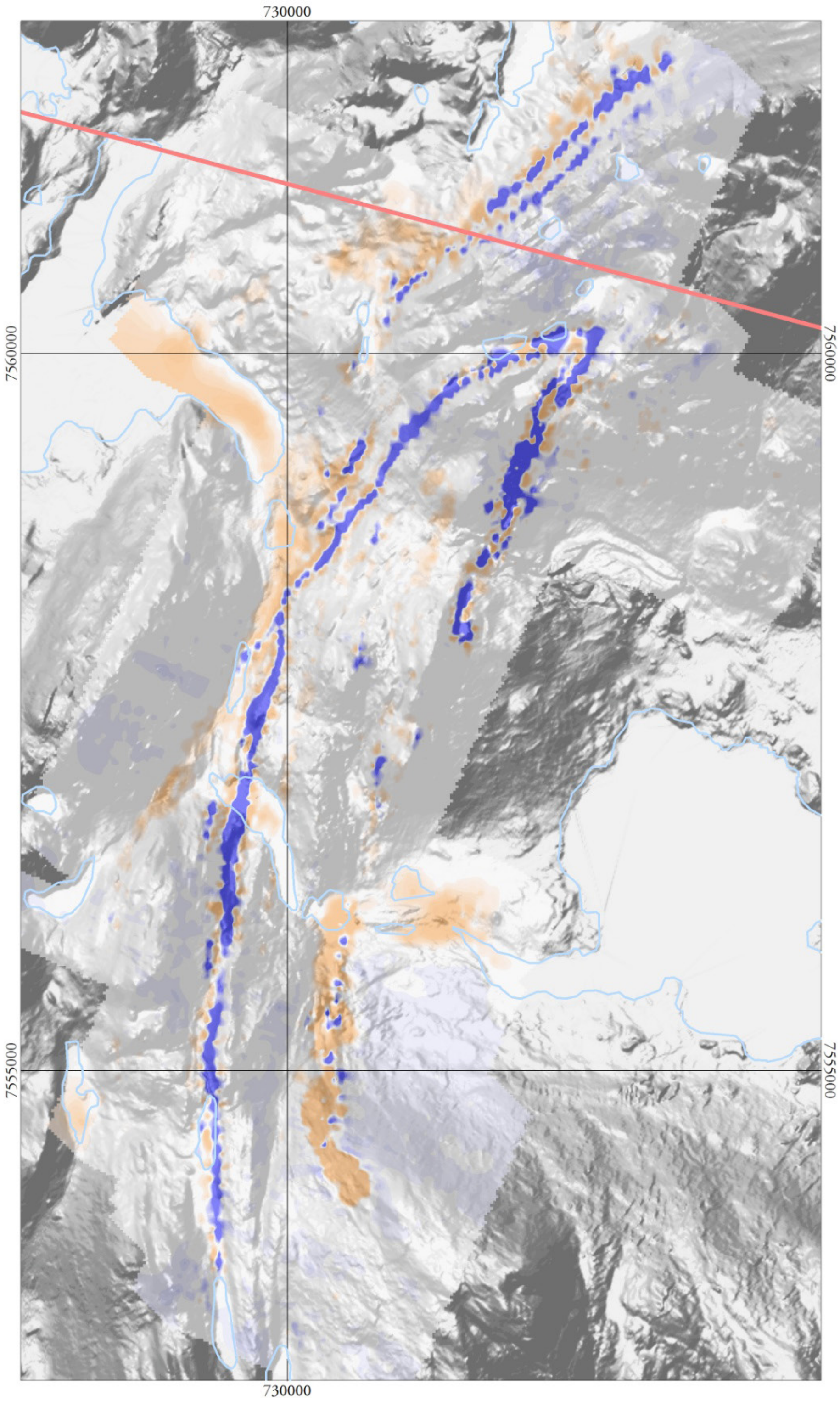


Fig. 16. Ground electromagnetic (slingram) measurements superimposed on topography data from Lantmäteriet, over parts of the Vittangivaara area. Blue colour shows electrically conductive layers.

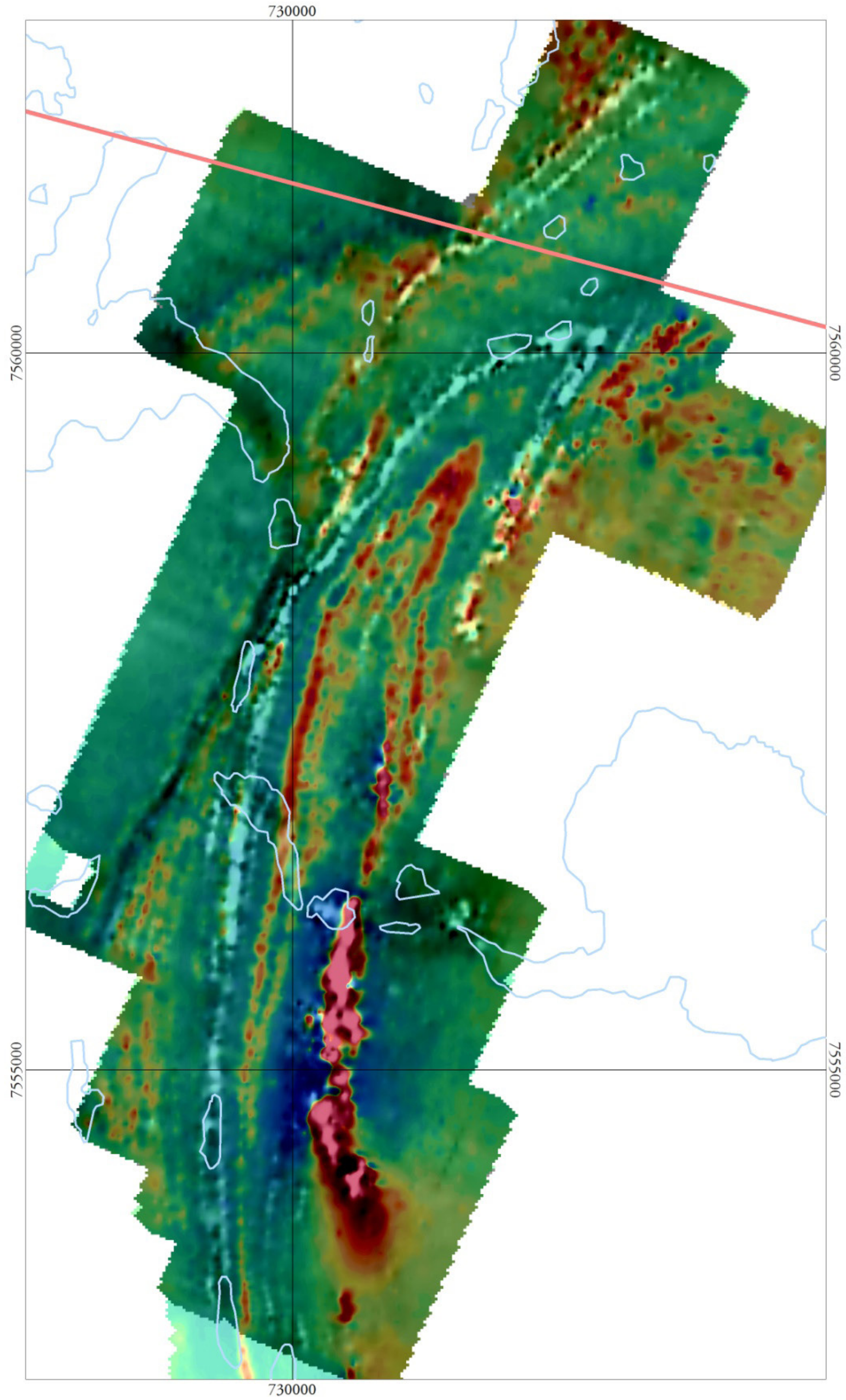


Fig. 17. Ground magnetic measurements in colour, superimposed ground on electromagnetic (slingram) measurements in grey south of the Vittangivaara area. High magnetic anomalies in red, electrically conductive structures in white.

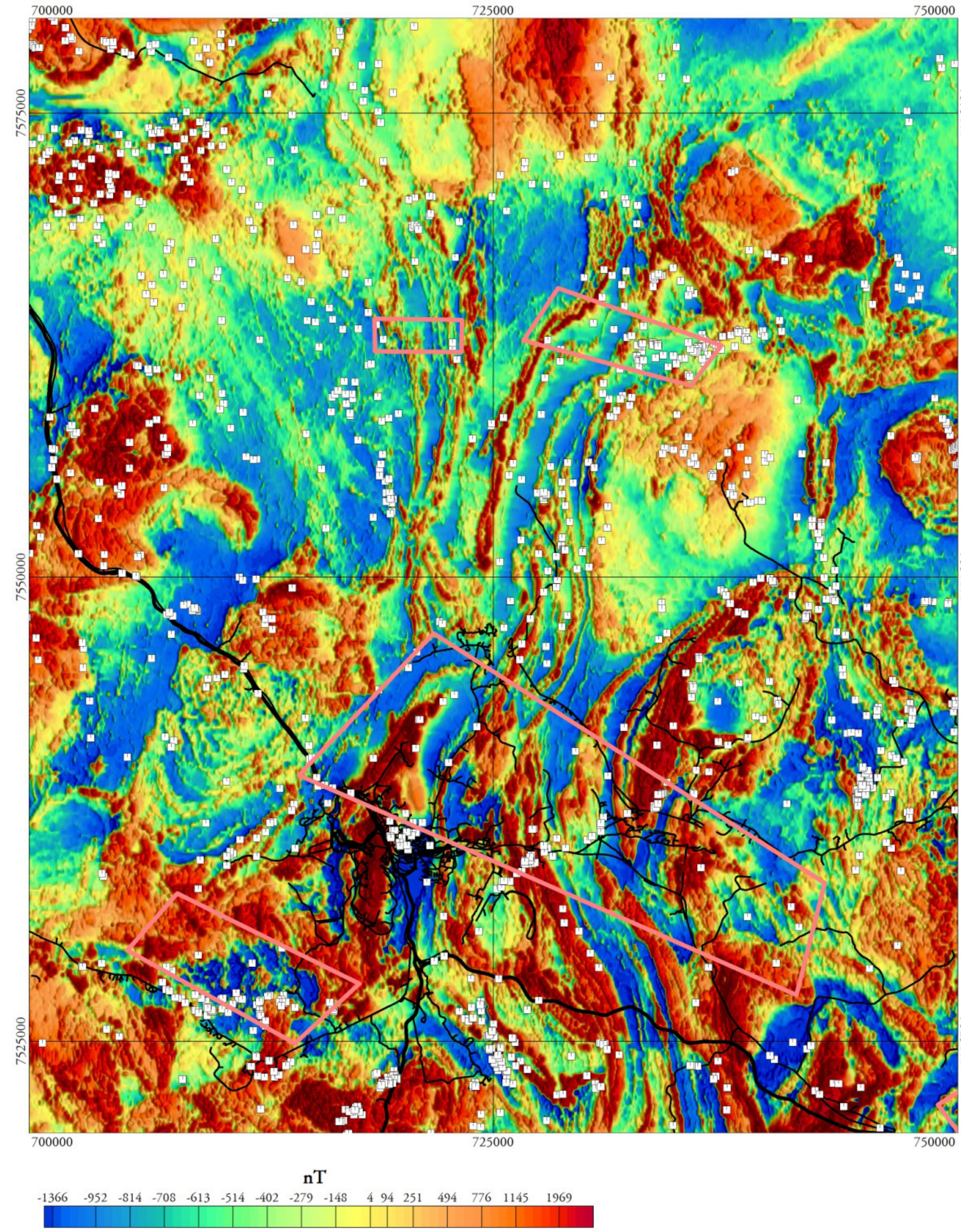


Fig. 18. Magnetic anomaly map over the area, reduced to the pole. White symbols show the petrophysical sample locations.

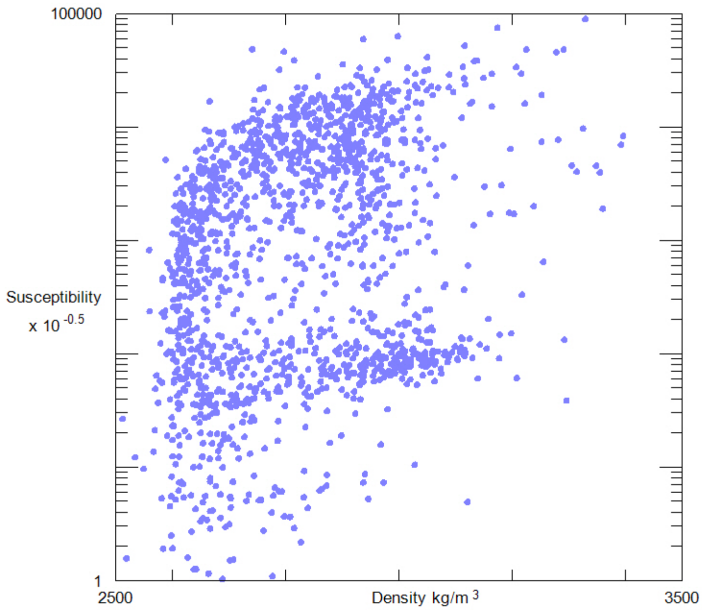


Fig. 19. Magnetic susceptibility (SI) vs. density in semi-logarithmic diagram. Total population.

SUMMARY

Lithology and Stratigraphy

The key area Vittangivaara covers a part of the Kovo zone, which starts at Lulep Vuolusjaure and trends north–north-east until Harrekutjaure. The key area Harrijärvet covers a small part of the Vakkozone, which trends north–northwest between Vakkojaure and Lulep Stalojaure. The geology of both zones comprises late Archean to early Paleoproterozoic sediments, which have been earlier described by Geijer (1927, 1931), Ödman (1957), Frietsch (unpublished), and later by Martinsson (1999) and Kumpulainen (2000). The following summary on the regional stratigraphy is mainly based on Martinsson (1999).

The oldest rocks in the region are part of the Råstojaure complex, and primarily consist of moderately foliated, tonalitic granodiorites, which are dated 2.8 Ga (Welin et al. 1971, Skiöld 1979, and Martinsson et al. 1999) (Fig. 20). Other abundant rock types are biotite gneiss, reddish granite, and even metavolcanic rocks and quartzite. The distribution as well as the age of those varying lithologies are poorly constrained.

The Kovo group is exposed on the western flanks of both the Kovo- and Vakkozones (Fig. 2). This sequence consist of volcanic and sedimentary rocks that overlie the Archean basement (Fig. 20). The Kovo group is subdivided into two formations, which are mostly separated by by an albitic dolorite, which is dated 2184±5 Ma (Skiöld, 1986). The Raurojaure formation (or Vakko unit in Kumpulainen, 2000) consists of a bottom conglomerate and quartzite. The size of the mainly granitic pebbles varies between 0.5 and 20 cm. The cement is rich in carbonate and stream currents are locally well preserved in the pebble-poor interlayers of quartzite and meta arkosics. The total thickness of the formation ranges

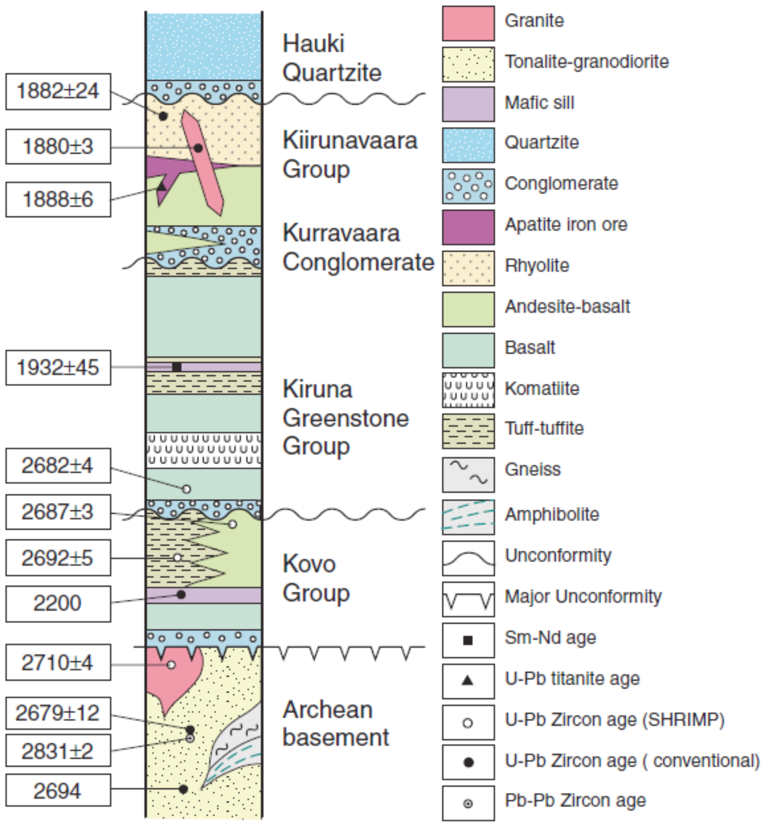


Fig. 20. Stratigraphy and geochronology of the Kiruna area, modified from Martinsson (1997). Chronological data from Skiöld (1979a, 1986), Skiöld & Cliff (1984), Welin (1987), Cliff et al. (1990), Romer et al. (1994), Skiöld & Page (1998) and Martinsson et al. (1999).

between 200 and 300 m and probably represent alluvial and fluvial deposits sourced by the Archean terrain in the west (Kumpulainen, 2000). The main part of the Kovo group consists of the Harrejaure formation, which comprises volcanoclastic sediments interlayered with basaltic, tholitic lava, of which its 2–6 mm sized amygdaloids are commonly filled with quartz or carbonate. The volcanoclastic rocks are predominantly siltstones and greywackes with feldspar and quartz grains in a carbonatic matrix. The lava layers can reach a thickness up to 200 meter. The formation thickness ranges between 1 and 2 km and is, especially in the Kovo zone, characterized by a well developed schistosity.

The Kovo group is overlain by the Kiruna greenstone group, which is described in detail in the Kiruna region by Martinsson (1997) (Fig. 20). The dominant rock types are basic to ultrabasic metavolcanic rocks, which may represent an phase of intensive rifting and associated faulting (e.g. Kumpulainen, 2000). Martinsson (1997) subdivided the Kiruna greenstone group in six formations, primarily based on differences in lithology or chemistry. The formations as well as their main characteristics are listed in table 6. For a more detail description the reader is referred to Martinsson (1997, 1999).

The Kiruna greenstone group is in turn overlain by the Kurravaara Group, which consists of a conglomerate at the base overlain by intermediate metavolcanic rocks. This formation is mainly exposed in the Kiruna region and further southward and has no great relevance for the geology of the Vakko- and Kovo zones. For a detailed description of the rocks the reader is referred to Offerberg (1967) and Martinsson (1997, 2004).

Table 6. Formations of the Kiruna Greenstone Group after Martinsson (1997). The youngest formation tops the list.

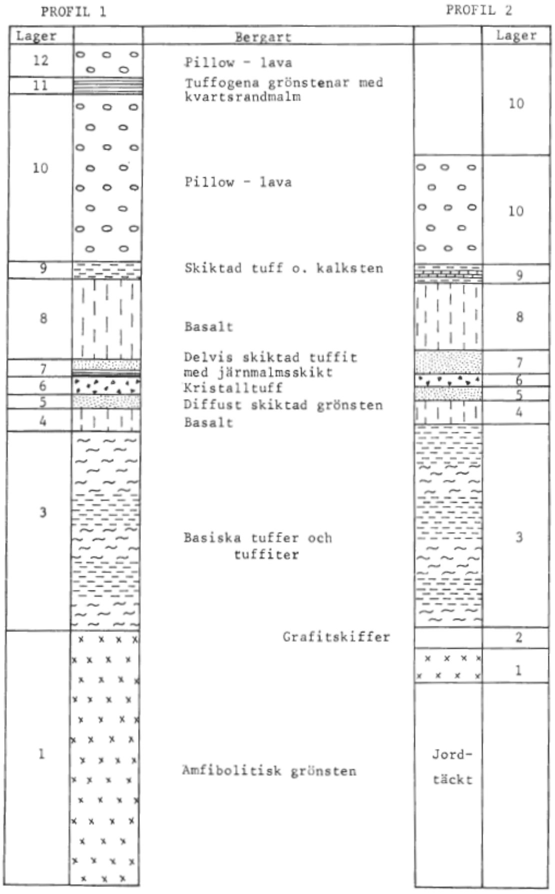
Formation	Dominant lithology	Thickness range or maximum
Linkaluoppal	Tholitic volcanclastics, with layers of graphite schists, magnetite, skarn, and dolomite (up to 50 m)	?
Peuravaara	Tholitic pillow basalts	500-1500 m
Viscaria	Basaltic tuff and thin layers of graphite schist	600 m
Piaske	Tholitc basalt	500-1000 m
Ädnamvare	Peridotitic and basaltic komatite	500 m
Såkevaratjah	Dolomite (up to 200 m) and basaltic lava	200-400 m

The intrusion located directly east of the Kovo zone belongs to the Perthite–monzonite suite, which is dated 1868±55 and 1874±12 Ma (Martinsson et al, 1999) (Fig. 2). The granites main minerals are plagioclase, K-feldspar, amphibole, biotite and some quartz. Accessory minerals are magnetite, apatite and pyrite. Its texture is porphyritic with 8–15 mm sized feldspars. A fluidic parallel orientation of minerals is commonly found near the borders of the intrusions. A gradation towards more acidic composition towards the center is found in many of these intrusions. Sheared contacts between monzogabbro and granite indicate a multistage intrusion.

The first field documentation from the Vittangivaara area was done by Göran Folcker and was published in 1974 in the SGU C series (C-697). Although this work was later revised by among others Martinnson (e.g. 1998), its detailed descriptions on the different lithologies are considered an important starting point for upcoming field studies. The textbox section is based on the descriptions on two profiles on Mount Vittangivaara, located just west of the key area's northeast corner.

Stratigraphy of the Kovo zone and Mount Vittangivaara

The Kovo zone's westernmost unit of is an old grayish to reddish, mikroklin–fyric granit, which is partly gneissic. Towards the east the granite is overlain by the lowermost unit of the Vakkojärvi–Kovo zone consisting of arkosik granite debris and conglomerates containing pebbles of granite. The succession is dipping between 55° and 75° to the E and SE, respectively. This unit is overlain by sandstones and schists, which are in turn intruded by sills of greenstones of type uralitdolorites and leukodolorites. According to Folcker, Ödman classified these rocks earlier as Lapponiska volcanic rocks. On more recent maps, this succession, which is directly overlying the granitic basement, belongs to the Kovo group (Martinsson). Further eastward, the unit is overlain by a quartzite with well preserved structures and horizons of granite-rich conglomerate. Note that according to Martinsson (1999) this quartzite belongs to the younger (>1882 Ma) Hauki quartzite unit, and should be considered as a tectonically emplaced sliver (see also Witschard, 1984). Towards the northeast, Folcker (1974) interpreted a cut off of the Vakkosediments / Kovo group by a N–S trending fault located directly east of lake Påkketanjaure. The significance of such faulting was later rejected and a continuation of the Vakkosediments / Kovo group further towards the north as well as towards the east is now favored. Ulf Hallgren (1979) included these rock units on map sheet 30 K Soppero SV in the Vittangi Greenstone Group. This group is bounded to the east by an Archean terrain consisting mainly of undifferentiated gneisses. To the south, the succession of metavolcanic rocks terminates along a differentiated gabbro and perthitic granite



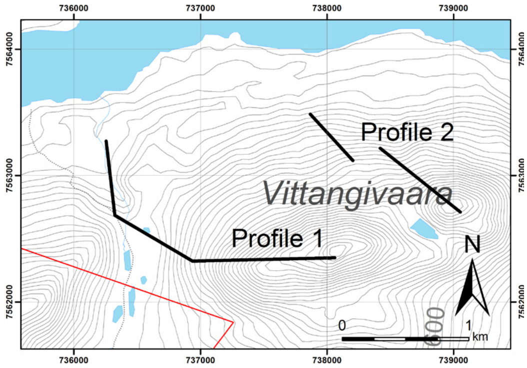


Fig. 21. The total stratigraphic succession of volcanic rocks and sedimentary interlayers is more than 500 metres thick. Göran Folcker distinguished 12 different units:

of the Perthite monzonite suite. Offenberg called the volcanic rocks between the quartzite unit and the the perthitic granite for Kiruna-type, which was later renamed into Kiruna Greenstone Group (Martinsson?). A detailed description of these mainly effusive volcanic rocks was among others obtained from two profiles located on the northern slope of Mount Vittangivaara. The following paragraph summarizes the stratigraphy along these profiles as documented in G. Folcker (Ser C. Nr. 697) (Fig. 21).

The stratigraphic sequence of Mount Vittangivaara is well exposed and comprises mainly effusive greenstones such as pillow lavas, finegrained lavas and tuffaceous rocks. Many original structures of these basic volcanic rocks can be studied. Locally, the volcanic sequence alternates with different types of sedimentary rocks, such as impure limeskarn to pure dolomite limestones, graphite bearing sediments and quartz-rich schists. In addition, quartz-banded iron-rich layers are found between pillow lava beds as well as between beds of metabasalts. These thin beds have an Fe content of approx. 30–33 per cent and consist mainly of magnetite and hematite in equal amounts. The banded iron-rich sediments are strongly recrystallized and also alternate with thin layers containing garnet (andradite). Martitization structures are commonly found.

Structural framework

The rocks in the Kovo- and Vakko zones are incorporated into a series of synform structures. Axial planes mainly trend in a southward direction. Locally, fold axis have been recognized with gentle dips towards the south. The area is affected by several fault zones trending parallel to the stratigraphy, and appear mainly in valleys often filled by long narrow lakes. The rocks within these zones contain a pervasive foliation and are often mylonitic. In addition to the plastic shear zones are there many brittle faults, which are mainly interpreted from airborne magnetic surveys. They usually displace the N–S trending anomalies and are often characterized as low anomaly zones.

The amount of deformation phases in the Kovo- and Vakkozones is still a matter of debate, and should be further addressed in the upcoming field studies. In a regional context, it has been stated that the Karelian rocks in Norrbotten underwent at least two ductile deformation phases (Martinsson 2004). Locally, these deformation patterns interfere in a dome and basin pattern, but more commonly one fold generation dominates in a specific area. Age relations between the deformation patterns are not well constrained, but according to Bergman et al. 2001a and O. Martinsson, unpub.data , southeast-orientated folds might be older that south–southwest trending folds. Obtaining a better constrain on the different ductile and brittle deformation patterns should be one of the main targets for the upcoming investigations. In addition, deformation in the Kovo zone is associated with displacements along the Kiruna–Naimakka deformation zone (KNDZ) as interptreted by Bergman et al. (2001). This shearzone is mapped as a south-southeast trending shear zone with associated mylonites mainly observed in the Archean terrain between Kiruna and Naimakka. How this shear zone affected the deformation pattern in the Kovo zone is less well known. For example, was the deformation localized along discrete zones, or did it affect the entire Kovo zone? And are there strain indicators present that may contribute to better constrain the kinematics of the KNDZ? And how do they relate to the deformation pattern observed along the Karesuando–Arjeplog deformation zone? These issues might be resolved by comparing the style and degree of deformation within the Kovo zone. It is to be expected that the degree of deformation might vary between a strong penetrative foliation in the volcanic sediments and texturally and structurally well-preserved quartzites and intrusive rocks. Special attention should be given to the eastern and western boundaries of the Kovo zone, since this might be a region of strain localization due to the high competence difference between sediments and crystalline rocks. The eastern boundary can be an old inherited lineament formed during the Karelian rifting episode at 2.1 Ga, and probably has been reactivated during subsequent tectonic events.

The mapped quartzite layer in the centre of the Kovo zone has been interpreted as the Hauki quartzite. Considering its relative young age compared to its surrounding rocks it should be tectonically emplaced (see Fig. 20). However, evidence for emplacement from field observations along its contacts does not exist. During the upcoming field work we should try to find and precisely map its boundaries. In the best case scenario kinematic indicators may help us to further constrain the idea that these sedimentary rocks were once formed in small grabens as suggested by Witschard (1984).

The intrusive rocks located directly west of the Kovo zone belong to the Perthite Monzonite suite. These rocks are typically porphyritic granites with only a weak foliation compared to the Haparanda suite. Based on the fact that the former suite is slightly younger, a regional event of metamorphism and deformation as been suggested at c. 1.88 Ga (Bergman 2001a). However, both suites are considered syn-orogenic (1.89–1.87 Ga). As deformation continued after solidification, the relative soft greenstones became most likely wrapped around the intrusions. In fact, intrusion might have taken place during progressive shearing, and its path may have been along a foliated zone of pre-existing weakness. As such, the deformation pattern in the adjacent greenstones might show a regional fabric overprinted by a more local fabric related to the intrusion. Upcoming field studies should address this hypothesis. In previous studies by Vollmer et al. (1984) it has been suggested that the deformation pattern observed in the volcano–sedimentary pile in the Kiruna district could relate to granite emplacement in the following ways:

1. deformation could have occurred mainly prior to intrusion of the granite, which would thus show little or no deformation
2. it could have occurred after granite intrusion with the granite more resistant to deformation
3. deformation resulted directly from diapirism.

Pinching and folding of the sedimentary sequence around and between the plutons makes the first option unlikely. Unless there have been several phases of deformation. However, Vollmer et al (1984) associated emplacement with a single deformation event, during which the granitic bodies formed the anticlinal cores of the major structures. In addition, his strain trajectories of shallow plunging compressional, and steeply dipping extensional components show consistency with models of diapirism from e.g Ramberg (1967) and Dixon (1975).

Furthermore, the region might have been intruded by a younger dike swarm (e.g. 1.79 to 1.71 Ga) belonging to the Transovennian igneous belt. If this is the case, dating dikes or sills that cross-cut the foliation can help to further contain the age of deformation.

Metamorphism

The metamorphic grade varies between upper greenschist facies and lower amphibolite facies. The central regions of the Kovo- and Vakkozones are characterized by a relatively low metamorphic grade, which increases toward amphibolite facies in the direction of the surrounding intrusions. This contact metamorphism resulted in the formation of garnet porphyroblasts within the mafic tuffs located in the vicinity of the intrusions. The grading in contact metmorphism should be addressed in nearby future field studies. A regional metamorphic event in Norrbotten is constrained by 1.88 Ga titanite in andesite from the Sammakkovaara Group, whereas a second metamorphic event at 1.81 to 1.78 Ga is recorded by chronological data from zircons and monazite in the Pajala area (Bergman and Skiöld 1998; O. Martinsson 2004 and upub. data). Sampling in the Haarivjärvet and Vittangivaara region should be based on confirming the age and degree of metamorphism.

Alteration and mineralization

Several kinds of alteration have affected the rocks of the Kovo- and Vakko zones. Along shear- and fault zones appear locally extensive albite- and ankerite alteration, and quartz and carbonate dykes and breccias may contain chalcopyrite. Skapolite appears as porphyroblasts within the Kiruna greenstones along the eastern border of the Kovo zone, but they occassionally also occur within the lowgrade metamorphic mafic intrusions and dolerites. Epidotisation of amygdal-rich basalts is common in the Kovo zone and within the lower part of the Kiruna Greenstone group. In the Vittangivaara Mountain region, Göran Folcker (1974) described a selective skapolitization where the more porous basic volcanic rocks were in general altered more. He suggested that the fluids were responsible for the skapolization, which were associated with the perhite–monzonite intrusion. These fluids were mainly transported along fractures. In this perspective, fractures showing skapolitization should be at least as old as the intrusion, and a distinction with younger, unaffected, fractures might be possible.

Mineral deposits of mainly copper and iron have been found in the Vakko- and Kovo zones. These deposits have no economic value. Some of the abandoned quarries date back to the 1600–1700, like for instance the "Kovogruvan" (ORED00295, SGU numbering), where the deposits exists of small concentrations of chalcopyrite, pyrite and barite within quartz veins. These veins occur in albite dolerites and are associated with faulting in the lower part of the Kovo group. Most of the deposits were discovered by prospecting carried out in the seventies. The highest concentrations of copper (1.23%, Godin 1979a) were found at Linkaluoppal (ORED00900), and are associated with a skarn-altered dolerite that intruded into a dolomite, which is characteristic for the upper part of the Linkaluoppal formation. This dolomite is locally altered into a skarn containing high concentrations of barite. To the south of Linkaluoppal, iron mineralization at Tjärro (ORED00112) were found through drilling and geophysics and occur as accumulations of magnetite within amphibolite skarn- and biotite-rich tuffs of the Kiruna greenstone group. A high magnetic anomaly can be followed by magnetic survey data along a trace of approximately 9 km. In addition, the reflectors in combination with the Lidar data reveal a tight syncline wrapping along the border, which is partly cut-off by the perthite monzonite intrusion to the east.

Directly northeast of the Vittangivaara region is a sulfide deposit mapped based on drilling by the prospecting company Redmond in 1998. (ORED15581; see logs). The drill cores reveal several accumulations of pyrite, pyrhhotite and chalcopyrite associated with skarn-altered pelites. Concentrations of copper within these 2–5 meters intervals never exceeded 2%. The iron deposit (ORED00329) is described by Göran Folcker as a thin layer of altered tuff, which contains the iron-rich minerals ilmenite, hematite and goethite (see horizon 7 in his profile).

The graphite bearing pelites and schists are generally fine grained and have only a low content of graphite.

DISCUSSION

Issues to be addressed (specific key questions for the Vittangivaara and Harrijärvet key areas)

Following up on the discussion and suggestions outlined in the previous section the general points of interest for the upcoming field studies for the Vittangivaara and Harrijärvet key areas are:

Questions on stratigraphy:

- What are the time constraints of deposition and metamorphism of the stratigraphic succession in the Vakko- and Kovo zones?
- What is the metamorphic facies of the rocks? P-T-t conditions?

- Are the rocks altered? If so, what kind of alteration and what caused it?
- What kind of mineralization are present?

Questions on deformation:

- Obtaining a better understanding on the different ductile- and brittle deformation patterns within the Vakko- and Kovo zones.
- Is deformation localized or distributed within the Kovo- and Vakko zones?
- Did a local deformation pattern developed around the perthite-monzonite intrusion? If so, did it form as a result of diapirism, or is it a younger imprint? And how does it relate to the regional deformation pattern? Can we put relative time constrains?
- How does the deformation pattern observed in the Kovo zone relate to the fault kinematics and style of deformation along the Kiruna–Naimakka deformation zone further north, and with the Arjeplog–Karesuando deformation zone to the northeast?
- Is there field evidence for the tectonic emplacement of the "Hauki quartzite" within the Kovo zone?
- Can the Archean basement be subdivided into different units? And what is the dominant deformation pattern in the Archean domains? Secondly, how does it relate to the deformation pattern(s) within the Vakko- and Kovo zones.
- What is the geological meaning and filling of the high amount of fractures seen on DEM data? And how do these relate to geophysical anomalies?

Some methods to address these questions:

- Detailed mapping along profiles by using aerial photos, DEM, GPS, and geophysical interpretations.
- Sampling in order to confirm the age, chemistry, and degree of metamorphism as well as the formation age of the different stratigraphic units.
- Dating dikes or sills that cross-cut the foliation to further contain the age of deformation.
- Putting relative time constraints through a distinction between fractures showing skapolitization or other hydrothermal alteration, and unaffected fractures.
- AMS is an option to determine if the granites contain a structural fabric. (if not seen macroscopically, or in thin-sections).
- Structural modelling (numerical and analogue) to understand the mechanisms behind the observed deformation pattern.
- 3D visualization by implementing field observations, geophysical data, and drill cores in a Gocad environment.

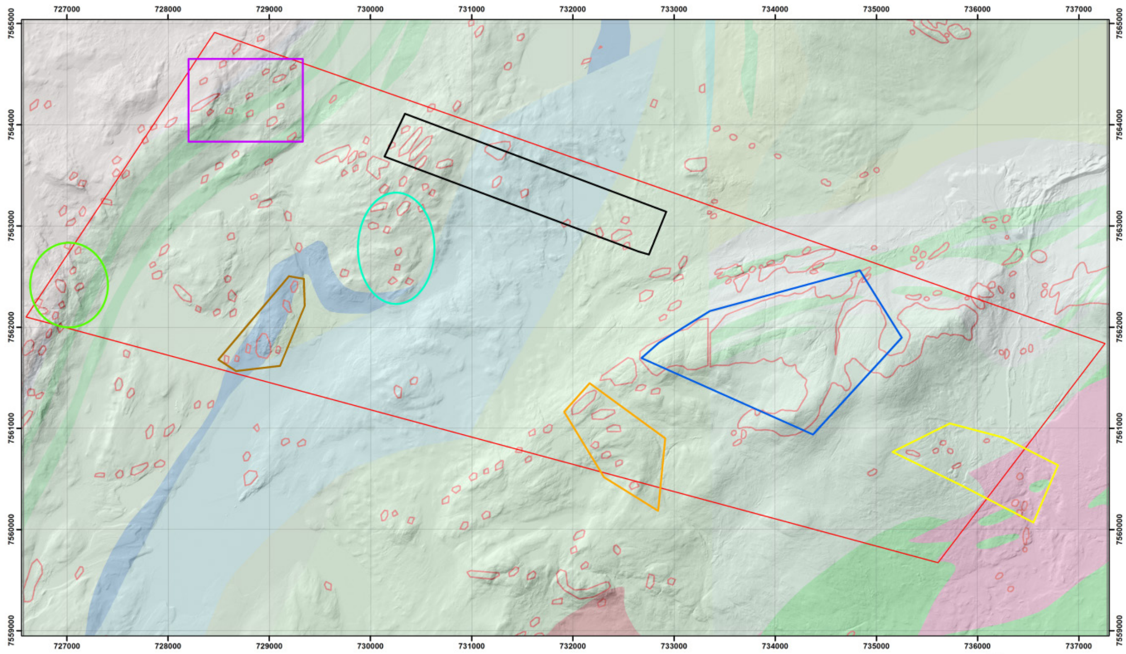


Figure 21. Map of the Vittangivaara key area (red square) with potential sites of interest (sectors) shown in different colours referring to the text in table 7. Outcrops are outlined in red. Background colours refer to the bedrock geology from the SGU local bedrock map database.

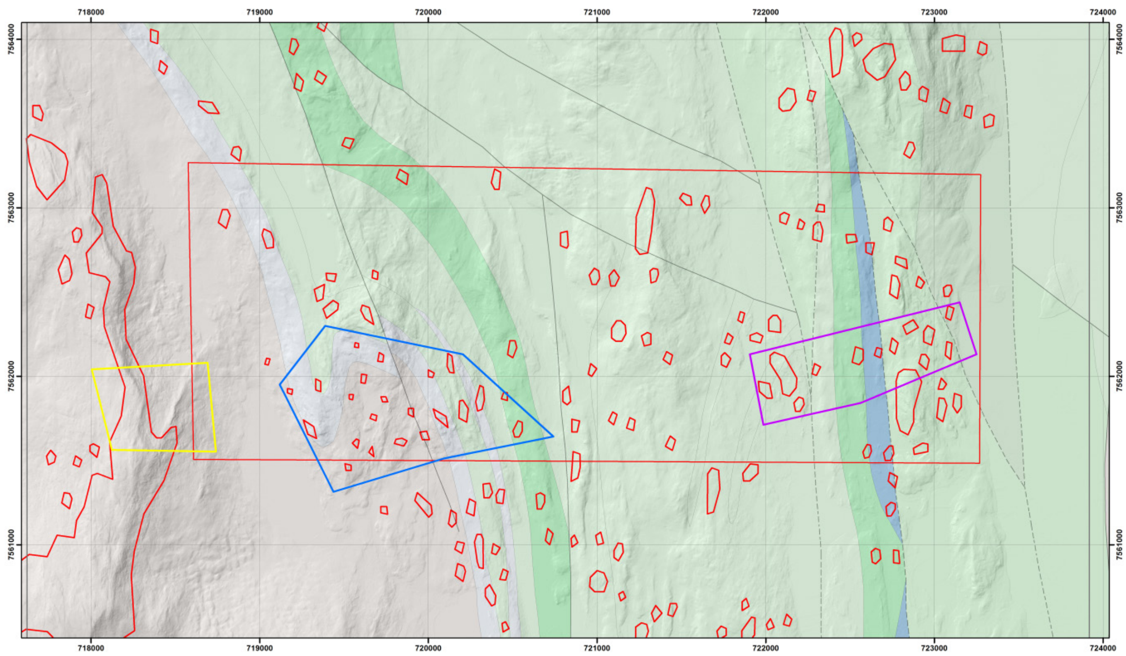


Figure 22. Map of the Harrijärvet key area (red square) with potential sites of interest (sectors) shown in different colours referring to the text in table 8. Outcrops are outlined in red. Background colours refer to the bedrock geology from the SGU local bedrock map database.

Table 7. Summary of the potential focus points and their estimated time effort within different sectors in the Vittangivaara key area shown in figure 21.

Sector	Interesting issues	Time estimate
Purple	Kovogroup, congolomerates, albite dolerites, Råstojauregroup (Archean), strain localization.	One day
Green	Råstajauregroup (Archean), Strain localization, Riedel shears (?)	One day
Black	Profile orthogonal to stratigraphy and foliation, contacts between Kovogroup - Hauki quartzite - Kiruna greenstone group.	One day
Turquoise	Large fold in Kovogroup, tectonic contact Hauki quartzite.	One day
Brown	Folded dolomite, Kiruna greenstone group, contact Hauki quartzite.	One day
Blue	Large scale folding (continuation of the eastern flank (?)), good exposure allows for fracture study (e.g. orientations and hydrothermal fillings)	One to three days
Orange	High magnetic susceptibility correlation north and southward (?), tight syncline	One to two days
Yellow	Contact zone between Kiruna greenstone group and Perthitic monzonite pluton. Granitic dykes and deformation pattern.	One day

Table 8. Summary of the potential focus points and their estimated time effort within different sectors in the Vittangivaara key area shown in figure 4.3

Sector	Interesting issues	Time estimate
Blue	Råstojauregroup (Archean), Kovo group, congolomerates, albite dolerites, strain localization. Folding of the Archean (?)	One day
Purple	Kovo group volcanic rocks (tholeiitic vs. komatite?), albite dolerites (same or different from blue (?)), dolomite, Kiruna greenstone group, tectonic contacts (?)	One to two days
Yellow	Optional (outside key area). Thrusting within the Archean (?). Subdividing and dating the Archean (?)	One day

PLANNED WORK

The outcrops that may contribute to our points of interest are mainly located within the Vittangivaara key area. Most of our time should therefore be spent on studying this region in greater detail. A subdivision in sectors, shown in figures 22 and 23, could help to address the specific questions listed in tables 7 and 8. Note that this list is incomplete and no geophysical topics are included.

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