KARTERING BARENTS 2013

Summary report on the geological and geophysical characteristics of the Akkiskera–Kuormakka key area

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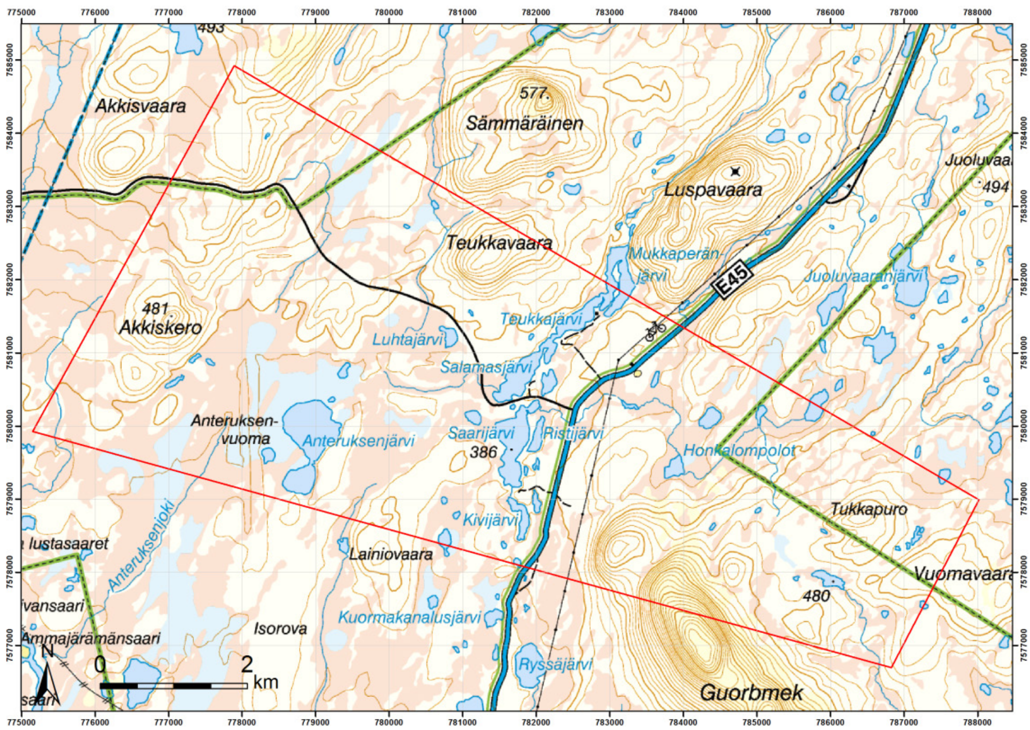

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Cover picture: Topographic map showing the Akkiskera–Kuormakka key area outlined in red.

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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 Akkiskera-Kuormakka area, 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

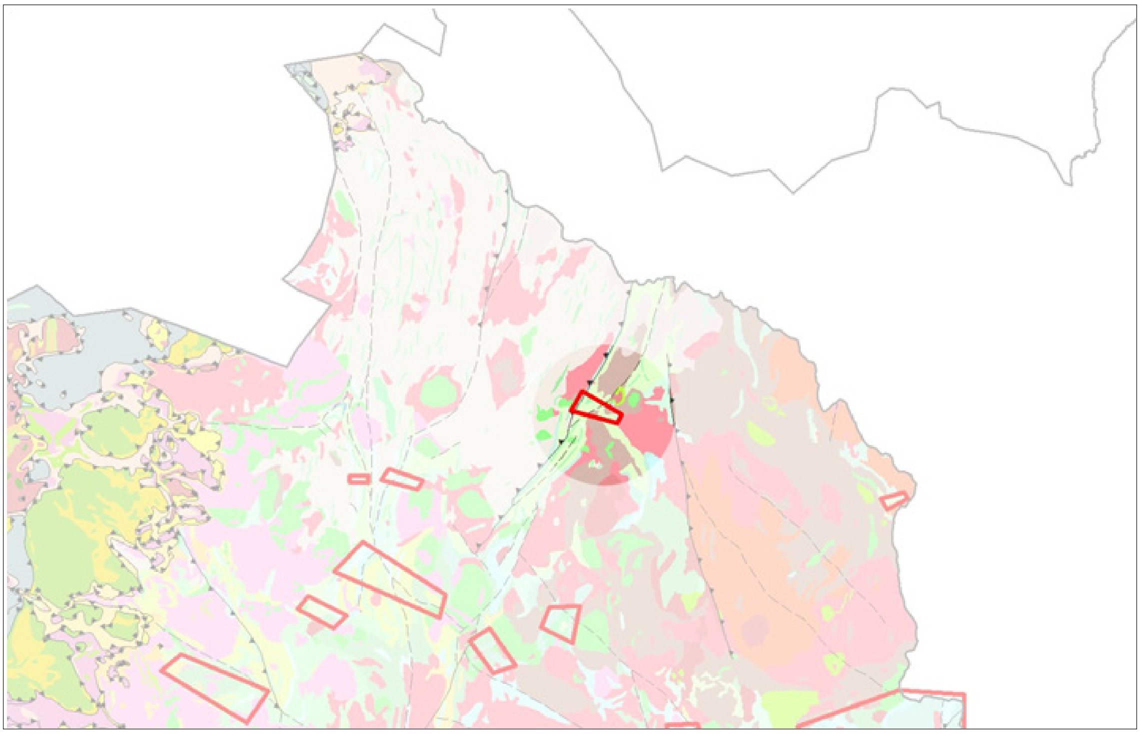
- geological and geochemical characterization
- geophysical characterization
- dating of metavolcanic rocks
- dating of detrital zircons on sediments
- depositional environment

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



The Akkiskera-Kuormakka area is located in northernmost Sweden (bright red) and is one of the 12 key areas in the Kartering Barents project. Background map is the bedrock map (1:1M)

AVAILABLE DATA FOR THE AKKISKERA–KUORMAKKA REGION

Published material

Table 1. SGU reports relevant to the Akkiskera–Kuormakka key area.

Code	Title	Year	Author	Location	Most relevant
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– Kovozones
C 834	Radiometric dating results volume 5	2002	S. Bergman	Kiruna–Gällivare–Pajala	Regional Geochronology, results from Bergman et al.
Memorandum of understanding for cooperation between GTK and SGU	Temporal constraints for the geological and metallogenic evolution of the Norrbotten–Käsivarsi area, northern Sweden and northwestern Finland.	2012	L.S. Lauri,F. Hellström, R. Lahtinen and S. Bergman	Northern Norrbotten–Käsivarsi area (Swedish–Finnish border)	Geochronology, and idea's on future cooperation with GTK, ore potential
Field guide	Metallogeny and tectonic evolution of the Northern Fennoscandian Shield	2008	T. Törmänen, S. Bergman, O. Martinsson, R. Nordin	Norrbotten	Introduction p. 8–32

Table 2. SGU map sheets relevant to the Akkiskera–Kuormakka key area.

Code	Title	Year	Author	Relevant to key area	Descriptions	GIS
Af 33	30K Soppero NO (1:50.000)	1967–1970	U. Hallgren	West and central Akkiskera–Kuormakka	No	yes
Af 25	30L Lannavaara NV (1:50.000)	1966–1972	M. Ambros	Eastern Akkiskera–Kuormakka	Stratigraphy, Structure, Geophysics	yes
Ba 56	Regional geological and geophysical maps of Northern Norrbotten (1:250.000)	2001	S. Bergman	Akkiskera–Kuormakka	Regional geology, stratigraphy, deformation history	yes
Ca 41	Berggrundskara över urberget i Norrbottens län	1957	O. Ödman	Akkiskera–Kuormakka	Regional geology	no
Ba 56	Regional geological and geophysical maps of Northern Norrbotten (1:250.000)	2001	S. Bergman	Akkiskera–Kuormakka	Regional geology, stratigraphy, deformation history	yes
Ca 41	Berggrundskara över urberget i Norrbottens län	1957	O. Ödman	Akkiskera–Kuormakka	Regional geology	no

Table 3. Prospecting reports relevant to the Akkiskera–Kuormakka key area.

Title	Author	Year	Company	Location	Type	Relevant part
Brap80026,	Robert Lilljequist	1980	SGU	Keukeskero (west of Akkiskera)	Stratigraphy: antofyllite rich ultrabasic rocks with up to 1% Ni och Cr. Geochemistry, Boulders, Drill cores, Geophysics.	Hypotheses on the origin of the ultramafic rock (p. 5) Conclusions and map (Fig. 11). They try to link these rocks into Finland, which consider them as the lower part of the greenstones.

Table 3. Continued.

Title	Author	Year	Company	Location	Type	Relevant part
Ultrabasitstråken Keukiskero och Kurkovare	Robert Lilljequist	1980	SGU	Keukeskero (west of Akkiskera)	Stratigraphy: antofyllite rich –ultrabasic rocks with up to 1% Ni och Cr. Geochemistry, Boulders, Drill cores, Geophysics.	Hypothesis on the origin of the ultramafic rock (p. 5) Conclusions and map (Fig. 11). They try to link these rocks into Finland and treat them as the lower part of the greenstone group.
Brap82107, Glacifluviala guldförekomster i övre Soppero–Idivuoma området och förslag till prospekteringsinsatser	Leif Carlson and Hans Lindberg	1982	NSG	Övre Soppero, Könkämäälven	Prospecting of glacial gold deposits.	Fig. 2. Map of Fluvial gold in key area and surroundings. Very detailed maps. With trails.
Ki3178 Koppar i vulkanitstråket Vittangi–Karesuando	Tapio Lehto	1978	LKAB	Teukkavaara i Akkiskera key area. Linjavaara and Keukesikero	Copper mineralisation in a tectonised basic volcanite.	Bilage (Map) 25 and 26, p. 58. Descriptions on p.14.15
Ki8447 Nordöstra Norrbotten–Lannavaara–Lainio	R. Virkkunen, K. Rönkkö, K.E. Hannson	1984	LKAB	Kuormakka in Akkiskera key area and towards the southeast.	Copper in greenstones, Stratigraphy, Geochemistry	Descriptions on p. 6–8.
Maps with outcrop data 17–24. Chemistry results p. 33–34	B. Gustafsson	1993	NSG	Soppero–Lannavaara, Teukkavaara in the key area.	Stratigraphy and geochemistry. References	p. 23–29 incl. stratigraphic columns
Mink96169 Outavaara, resultat av borrningar april 1987	–	1987	STC Minerals AB	Outavaara, southeast of key area	Drill logs from Greenstones, and geochemistry	–
NSG93003 The Swedish Norrbotten Greenstone Belt. A compilation concerning exploration	Bosse Gustafsson	1993	NSG	Soppero–Lannavaara, Teukkavaara in the key area.	Stratigraphy and geochemistry. References	p. 23–29 incl. stratigraphic columns
Mink95119 Greenstone and porphyry hosted ore deposits in northern Norrbotten	O. Martinsson	1995	NUTEK, PIM report. Proj. 9200752-3	Northern Norrbotten	Stratigraphy	p.45–48. Stratigraphic columns

Table 4. Scientific publications relevant to the Akkiskera–Kuormakka key area.

Title	Author	Year	Journal	Relevance
Magnetic crustal structures in northern Fennoscandia	H. Henkel	1991	Tectonophysics, 192, p 57–1979	Geophysical characteristics of the region, and recognized the KADZ (Porsangen lineament) on magnetic maps.
Radiometric ages of plutonic and hypabyssal rocks from the Vittangi–Karesuando area, northern Sweden	T. Skiöld	1982	GFF, Vol. 103, p. 317–329	Geochronology of the Paleoproterozoic plutons
Zircon ages from an Archean gneiss province in northern Sweden	T. Skiöld	1979	GFF, Vol. 101, p 169–171	Geochronology of the Archean.

Table 4. Continued.

Title	Author	Year	Journal	Relevance
Interpretation of the Proterozoic Kautokeino Greenstone Belt, Finnmark, Norway from combined geophysical and geological data	O. Olesen, J.S. Sandstad	1993	Norges geologiske undersökelse Bulletin 425, p 41–62	Northward extension of the KADZ into Norway
Seismo- and neotectonics in Finnmark, Kola Peninsula and the southern Barents Sea. Part 1: Geological and neotectonic framework	D. Roberts, O. Olesen, M.R. Karpuz	1997	Tectonophysics 270. p 1–13	Drilling and neotectonics of the northern continuation of the KADZ into the Stuoragurra (part of the MFDZ) Fig. 7, and conclusions
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
1.9–1.8 Ga Old strike-slip megashears in the Baltic Shield, and their plate tectonic implications	A. Berthelsen and M. Marker	1986	Tectonophysics 128, p 163–181	Regional context of the KADZ
The geological and tectonic evolution of the Precambrian of northern Sweden – a case for basement reactivation	F. Witschard	1984	Precambrian Research 23, 273–315	Regional deformation and stratigraphy

Map databases

Bedrock maps

The relevant SGU bedrock map sheets (scale 1:50,000) for the Akkiskera–Kuormakka key area are Af32 Soppero NO (1970) and Af25 Lannavaara NV (1972), see Table 2 and Fig. 2). Along the border between the two map sheets occurs a “map fault” as a result of different interpretations on the eastern extent of the central pluton.

Drill cores

Within the Akkiskera–Kuormakka key area no drilling has been carried out, however, drill cores obtained from the surrounding areas may contribute in obtaining a better understanding of the regional geology (Fig.3). Southeast of the key area in the Outavaara region, the higher part of the Greenstone group was drilled by LKAB in 1986. Drilling did not exceeded 250 meters. Mineralization of copper and gold were found within the graphite bearing schists and quartzites: respectively 0.9% copper and 2.55 gram Au per ton within a meter layer interval. However, these concentrations were exceptional and found only within 1 out of 20 analysis (STC Minerals AB report, 1987). Some of these drill cores are stored in the SGU archive in Malå. Further southward drilling in the Huomaisenvuoma area by LKAB discovered lenses of zinc–lead–silver mineralization, but these lenses appeared to be only local features and with a highly variable metal content (Virkkunen, 1984). East of the key area, drilling of ultra mafic rock took place in the Keukiskero region (Lilljequist, 1980). These rocks occur as north trending lenses within the Archean basement and contain mineralization of nickel (up to 0.28%) and chromium (up to 0.78%). The rocks are very rich in antophyllite (60–80%). By the time of writing no documentation has been found reporting the drilling carried out in the Palovaara and Paljasjärvi areas (Fig. 3).

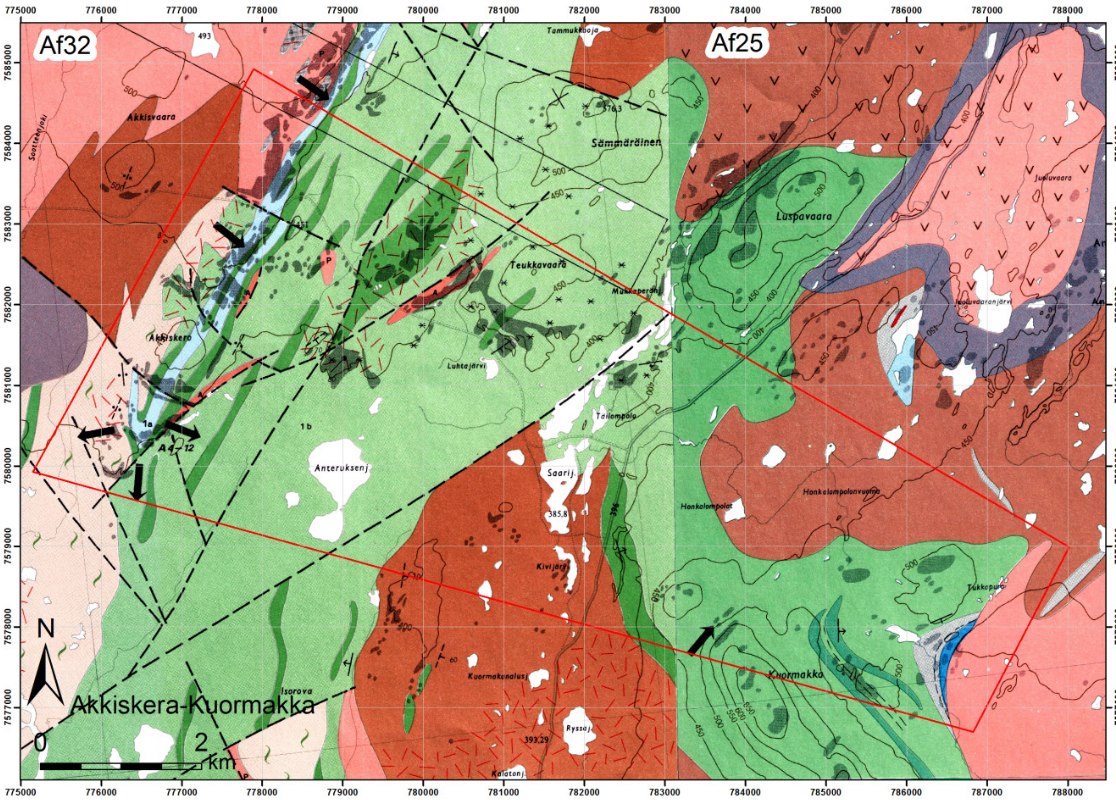


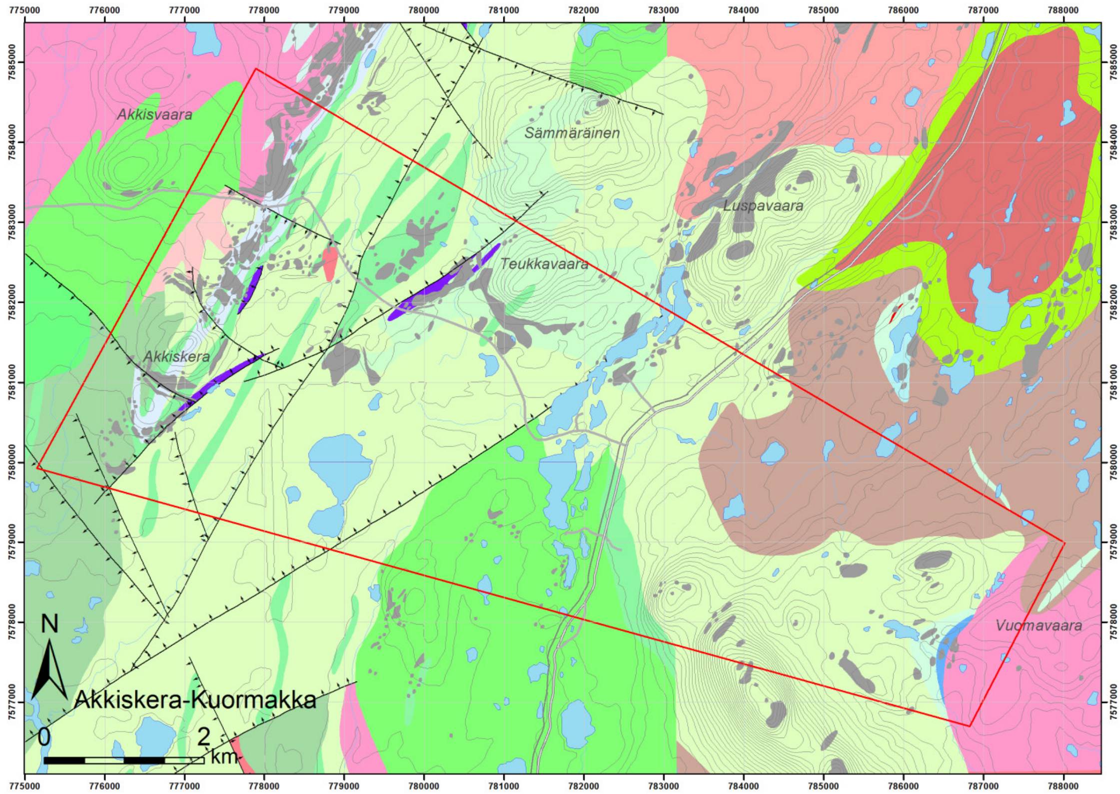
Figure 2a. Map showing the Akkiskera–Kuormakka key areas outlined in red. The background maps are the two relevant bedrock maps sheets published by SGU on which the digital "local bedrock database" is based (see table 2 and Fig. 2b).

Mineralization and alteration

No mineral deposits of economic value have been found in or directly nearby the Akkiskera–Kuormakka key areas. Mineralized blocks and boulders occur mainly in the key area's northwestern part. Three outcrop-scale deposits were found directly outside the key area and are briefly summarized below (Fig. 4).

The Juoluvaaranjärvi deposit (ORED00335, Fig. 4) as described by Frietsch (1967) is a small iron deposit, which measures 10 m in width and has a length of about 100 meter, based on aeromagnetic anomalies (Fig. 5). The iron ore is a fine-grained magnetite occurring in a skarn consisting of diopside and tremolite–actinolite with small amounts of garnet and epidote. The epidote occurs also as 1 centimeter wide bands, which are folded. The iron ore is intruded by a unfoliated quartz–diorite belonging to the Haparanda suite (Frietsch, 1967). This quartz–diorite forms up to 0.5 meters wide veins, which cut the folding of the ore. In the intrusive diorite occur also fragments of the ore up to 1 meter in size. No contact metamorphisms affecting the ore has been observed. As such, Frietsch (1967) stated that the skarn iron ore cannot have formed from this intrusive source. In fact, he assigned a sedimentary origin to these skarn-banded iron ores.

The deposit "ORED15391" (SGU numbering) located near the top of Kuormakka is a local occurrence of copper within silicified greenstones (Fig. 5). The analysis outcome revealed 1.34% Cu, 0.1 ppm Au, 5 ppm Ag, 1.78% S, 0.05% Zn. Silicified greenstones seems to be a poorly known alteration type in Norrbotten that needs to be further characterized.



- Basalt-andesit; Svekokarelska orogenen, metamorf ytbergart 2,30-2,05 miljarder år
- Basalt-andesit; Svekokarelska orogenen, metamorf ytbergart 2,05-1,96 miljarder år
- Basalt-andesit; Svekokarelska orogenen, metamorf ytbergart 2,40-1,96 miljarder år
- Granit; Svekokarelska orogenen, metamorf arkeisk bergart >2,50 miljarder år
- Granit; Svekokarelska orogenen, intrusivbergart (GP), ställvis metamorf, och migmatit 1,82-1,74 miljarder år
- Granit; Svekokarelska orogenen, intrusivbergart (GP), ställvis metamorf, 1,87-1,74 miljarder år
- Tonalit-granodiorit; Svekokarelska orogenen, metamorf intrusivbergart (GDG-GSDG) och svekofennisk ytbergart 1,92-1,87 miljarder år
- Syenitoid-granit; Svekokarelska orogenen, metamorf intrusivbergart (GDG-GSDG) och svekofennisk ytbergart 1,92-1,87 miljarder år
- Syenitoid-granit; Svekokarelska orogenen, intrusivbergart (GSDG-GDG) och svekofennisk ytbergart, ställvis metamorf, 1,84-1,77 miljarder år
- Gabbroid-dioritoid; Svekokarelska orogenen, metamorf intrusivbergart (GDG-GSDG) och svekofennisk ytbergart 1,92-1,87 miljarder år
- Gabbroid-dioritoid; Svekokarelska orogenen, intrusivbergart (GSDG-GDG) och svekofennisk ytbergart, ställvis metamorf, 1,88-1,84 miljarder år
- Gabbroid-dioritoid; Svekokarelska orogenen, intrusivbergart (GSDG-GDG) och svekofennisk ytbergart, ställvis metamorf, 1,84-1,77 miljarder år
- Diabas; Svekokarelska orogenen, metamorf ytbergart 2,40-1,96 miljarder år
- Kvartsarenit; Svekokarelska orogenen, metamorf ytbergart 2,40-2,30 miljarder år
- Kvartsarenit; Svekokarelska orogenen, metamorf intrusivbergart (GDG-GSDG) och svekofennisk ytbergart 1,92-1,87 miljarder år
- Kalksten; Svekokarelska orogenen, metamorf ytbergart 2,40-1,96 miljarder år
- Fyllit; Svekokarelska orogenen, metamorf ytbergart 2,40-1,96 miljarder år
- Amfibolit, grönsten; Svekokarelska orogenen, metamorf arkeisk bergart >2,50 miljarder år
- Järnmineralisering; Svekokarelska orogenen, metamorf ytbergart 2,40-1,96 miljarder år
- Leukodiabas; Svekokarelska orogenen, bergart med ospecificerad ålder
- Undersökta ytor

Fig. 2b. Local bedrock map of the Akkiskera–Kuormakka key area (outlined in red). Topographic elements were extracted from Lantmäteriet's Vägkartan.

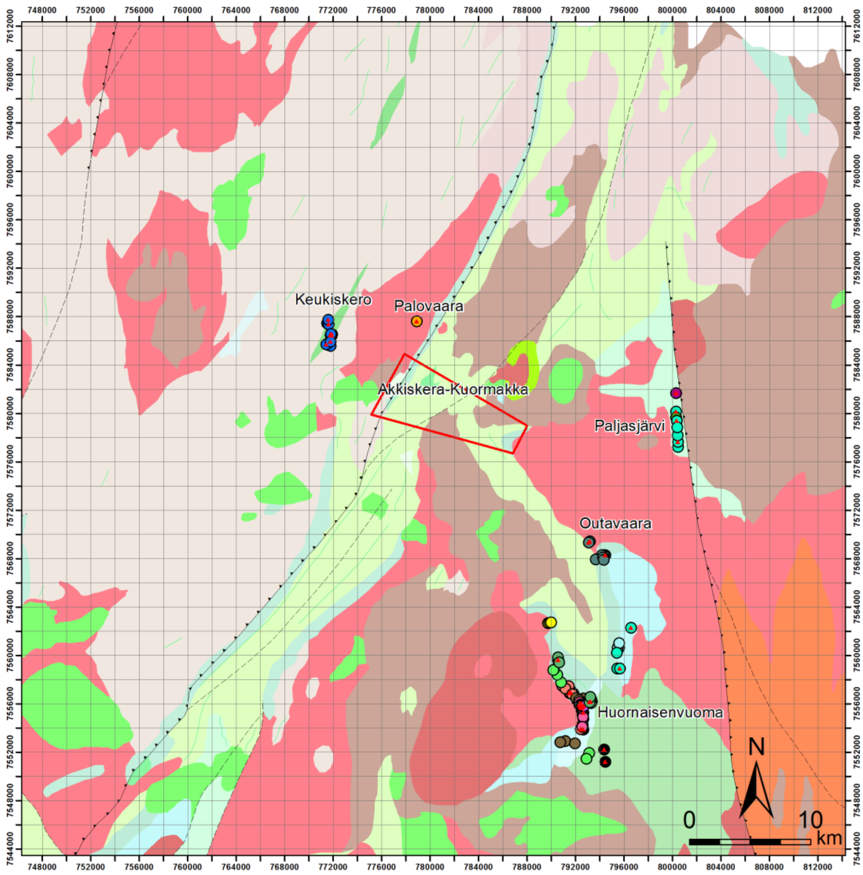


Fig. 3. Drill locations in the vicinity of the Akkiskera–Kuormakka key area coloured after drill log reference. Red triangles indicate storage of the drill core in the SGU Malå archive. Basemap shown is the bedrock map of Sweden 1:1.000.000

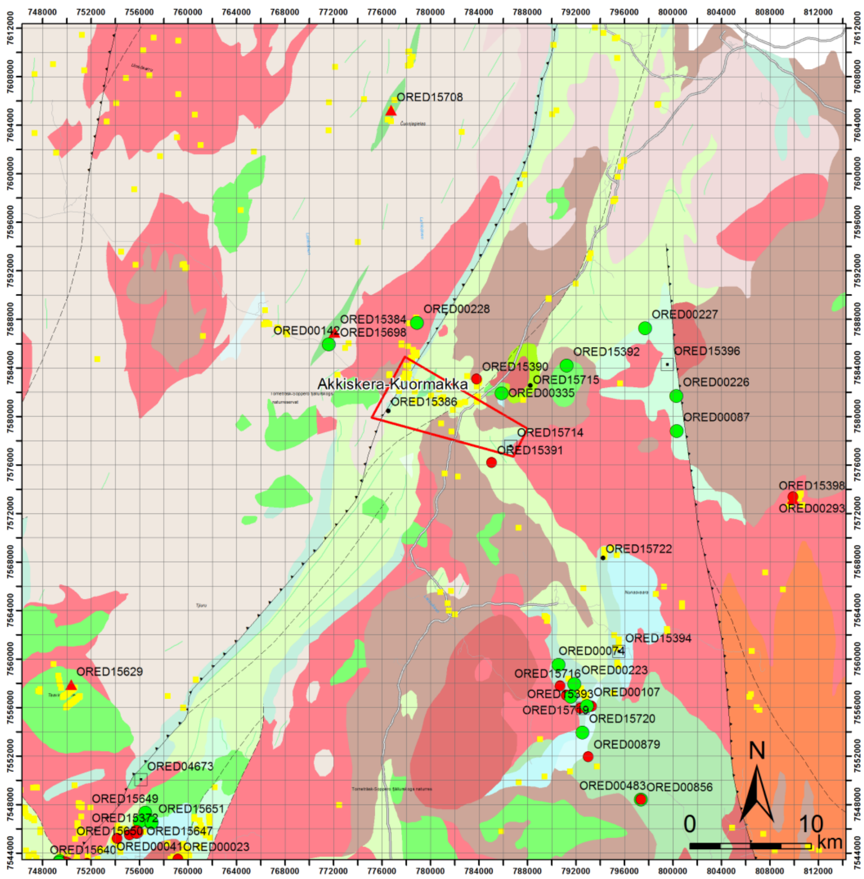


Fig. 4. Distribution of mineral resources in the vicinity of the Akkiskera–Kuormakka region.

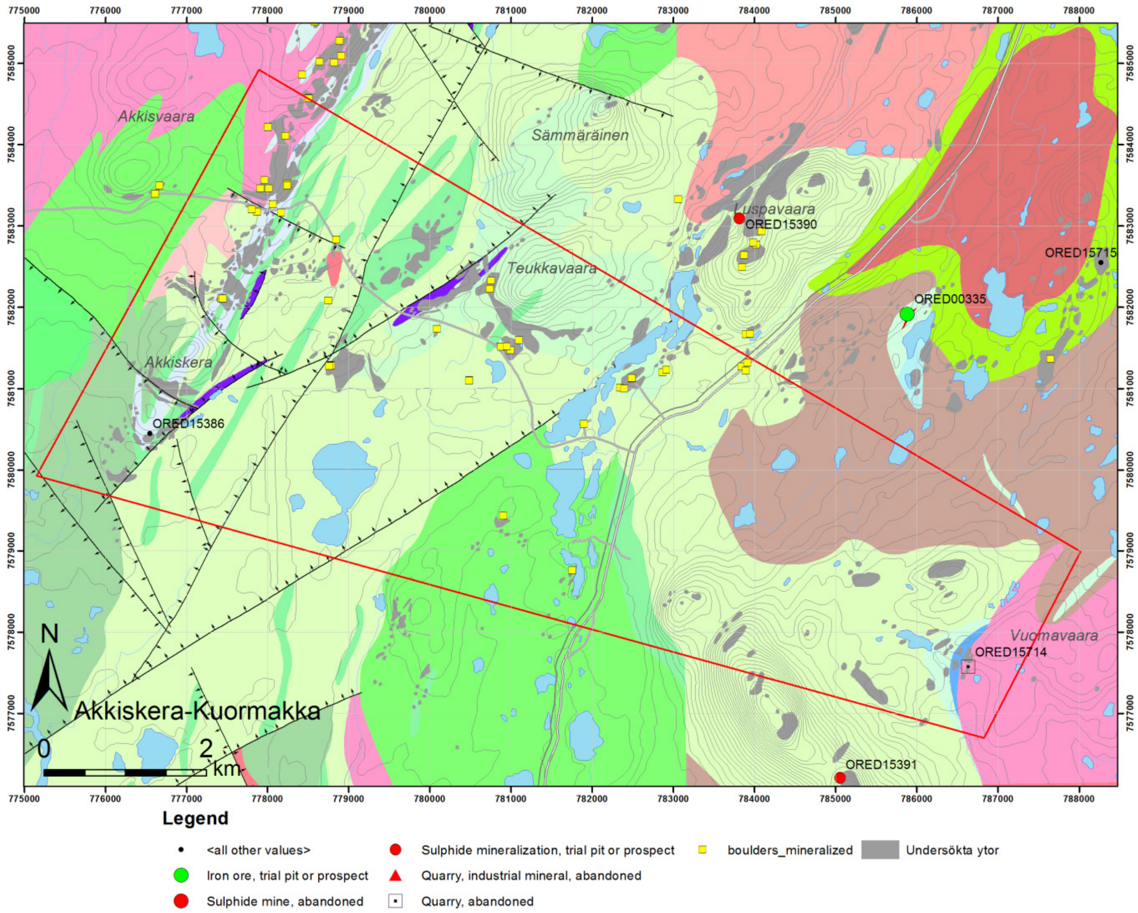


Fig. 5. Distribution of mineral resources within the Akkiskera–Kuormakka region.

Deposit "ORED15390" near Luspavaara comprises a copper and gold bearing quartz vein within the basalts of the greenstone group. No detailed information on this deposit was found during the compilation of the present report.

Furthermore, some deposits associated with the Karesuando–Arjeplog defromation zone (KADZ) are located just over the border with Finland. For example, the Ruossakero is a Neoarchaean orogenic copper–gold deposit with economic importance. The deposit comprises two lodes in a shear zone at the contact between komatites, mica schist and granodiorite. In the same sequence, there is also a komatiite-hosted nickel deposit of 5.44 Mt and 0.53 % Ni. Understanding the nature and setting of these deposits can be a great help to further constrain the deformation history along the KADZ as well as on its control on mineralization in Sweden. For more information on these deposits the reader is referred to the GTK deposit information service: (http://new.gtk.fi/informationservices- /commodities/Gold/ruossakero.html), or Lahtinen (1996).

Lithogeochemistry and soil geochemistry

Two till samples have been taken by SGU within the western part of the Akkiskera–Kuromakka key area during the summer of 2012 (Fig. 6). The samples are being processed by the time of writing, and the results from the SGU laboratory are expected in autumn 2013.

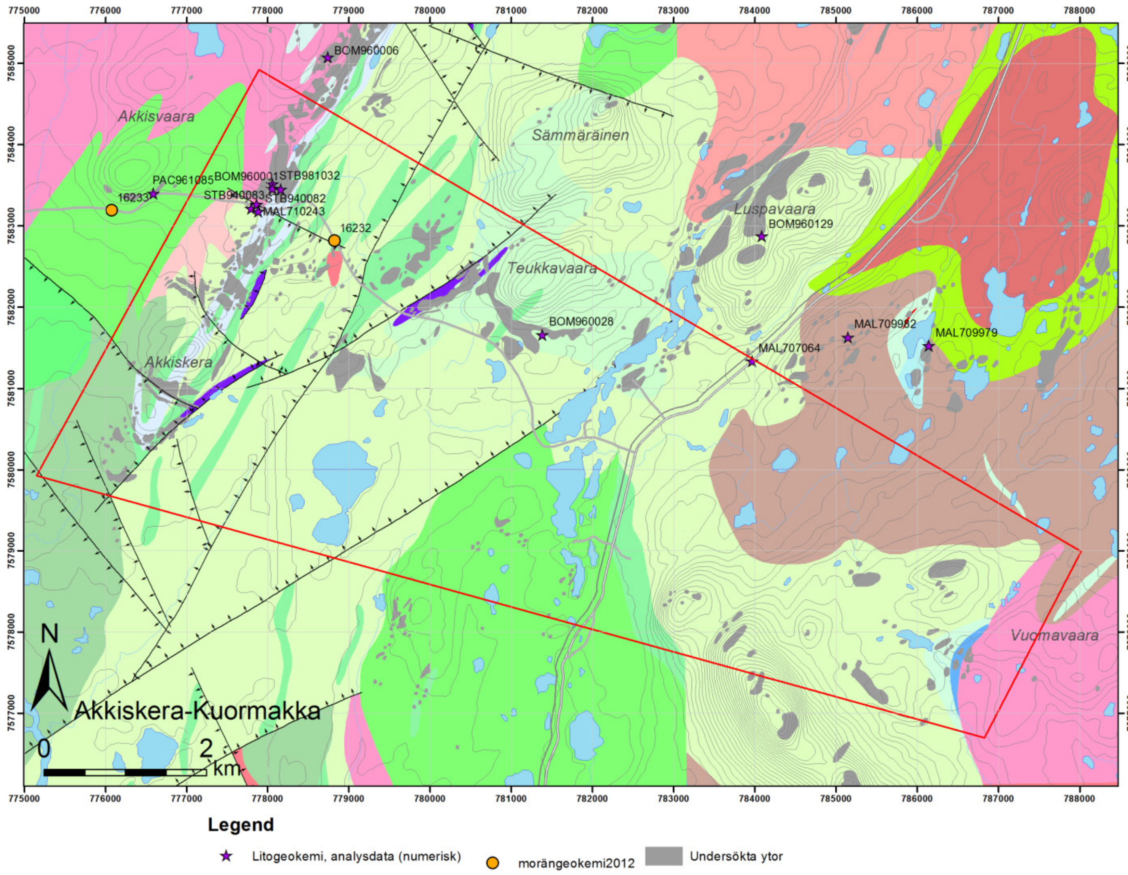


Fig. 6. Distribution of samples taken for both litho- (stars) and soil- (circles) geochemistry.

Most of the litho-geochemistry samples have been analyzed and described in Öhlander et al. (1987a) and Skiöld et al. (1988). Öhlander et al. (1987a) analyzed two samples from the granitioid in the northwestern most corner (Fig. 6). Their mineralogical and geochemical characteristics make it very likely that these granodiorites belong to the older group of Svecokarelian granitoids (1.89–1.84 Ga). These rocks have a high uranium and very high thorium content compared to the Archean rocks further towards the west. However, both rocks show a fractionated REE pattern characterized by light REE enrichments and low content of heavy REE. According to Öhlander et al. (1987a) this indicates that the rocks were generated by partial melding of basic rocks, presumably amphibolites. Based on the Sm–Nd isotopic data from the Archean gneisses , this process occurred only a short time after initial segregation from the mantle (εNd values between 0.9 and 3.5, Öhlander et al, 1987a). The litho-chemistry of the samples taken northeast of the key area is described in Skiöld et al. (1988). The quartz monzodiorites belong to the older group (1.89–1.87 Ga) and show a calc-alkaline trend. Based on their negative εNd-values (-8 and -5) they represent variable contamination of isotopically juvenile mantle melts with Archean crustal material.

Geochronology

The geochronological data within the Akkiskera–Kuormakka key area is of poor quality and therefore mostly unreliable. Many of these ages were published by Skiöld (e.g. 1979, 1982, 1986, 1987), using both Rb/Sr and U/Pb isotope technique. Applying the former technique

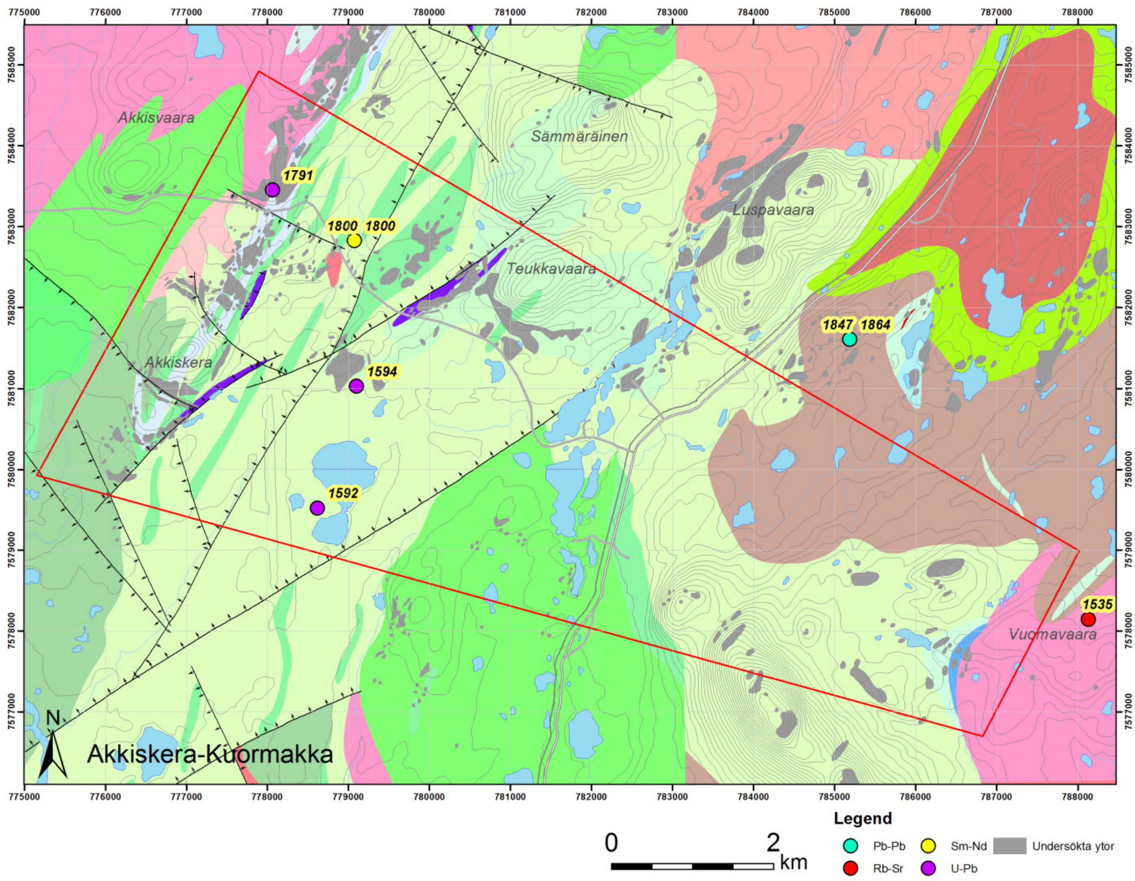


Fig. 7. Distribution of age information in the Akkiskera–Kuormakka region.

on a whole-rock sample leads often to the question on what event has been dated, and a distinction between crystallization, metamorphism, deformation, and cooling is difficult to make. As a result, the relative young ages derived from rocks within the key area are often underestimations and actually represent mixed ages (Fig. 7). In addition, high uncertainties by the use of the U/Pb analyses on zircons by Skiöld (1979) were caused by: concordias based on only a few points, the use of strongly deformed and overprinted zircons, and a large geographic spreading between the samples. However, the development of new dating techniques such as in situ probing techniques like SIMS and LA-ICPMS of single mineral grains, give more reliable outcomes and allow for multiple-events determination. A collection of samples suitable for dating within the Akkiskera–Kuormakka area is therefore an important target during the upcoming fieldwork.

Topographic maps

Topographic maps from Lantmäteriet are available as both raster- and vector formats. The most detailed maps available for the Akkiskera–Kuormakka region is the "Vägkartan" (Fig. 8). Unfortunately no "Fjällkartan" or "Terrängkartan" exist for this part of Sweden, which show much greater detail.

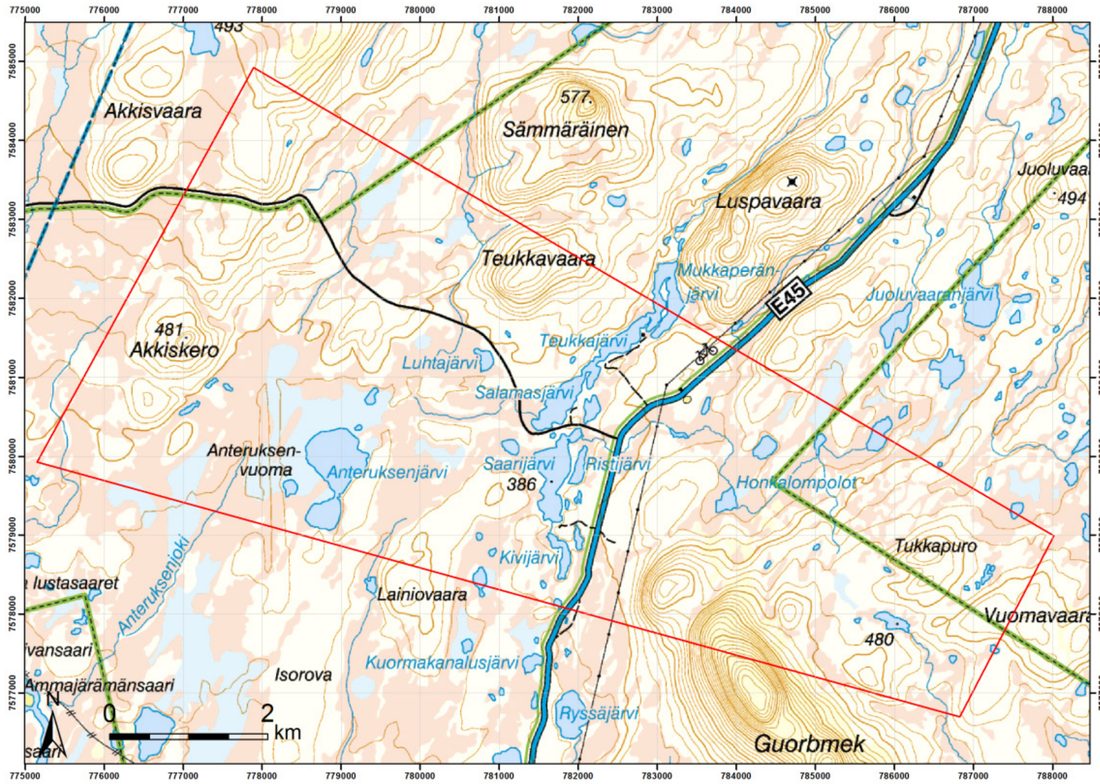


Fig. 8. Lantmäteriets Vägkartan is the most detailed topographic map available for the Akkiskera–Kuormakka region.

Aerial photos

Aerial photos are made available in digital format by Lantmäteriet. The provided group layer allows for normal view as well as in the infrared spectrum (Fig. 9).

Digital Elevation Model (DEM)

50 meter resolution elevation data is provided by Lantmäteriet. This data can be processed in ArcGis to extract a local color symbology (Fig. 10). Unfortunately, the Akkiskera–Kuormakka region is not yet covered by the 2 meter resolution data (Lidar).

Outcrop data

Outcrop maps were created by combining data from the local bedrock database and the quaternary geology database (Fig. 11).

Geophysics

Airborne data

The area in focus in this report is situated across the north part of map sheet 30K and 30L (refers to the map sheets in the old RT90 grid). In the early sixties the SGU surveyed the area with airborne geophysics. The 1963 survey covered the whole of map sheet 30L (Lannavaara) and in 1964 30K (Soppero) was surveyed. These surveys used east–west flight direction, 200

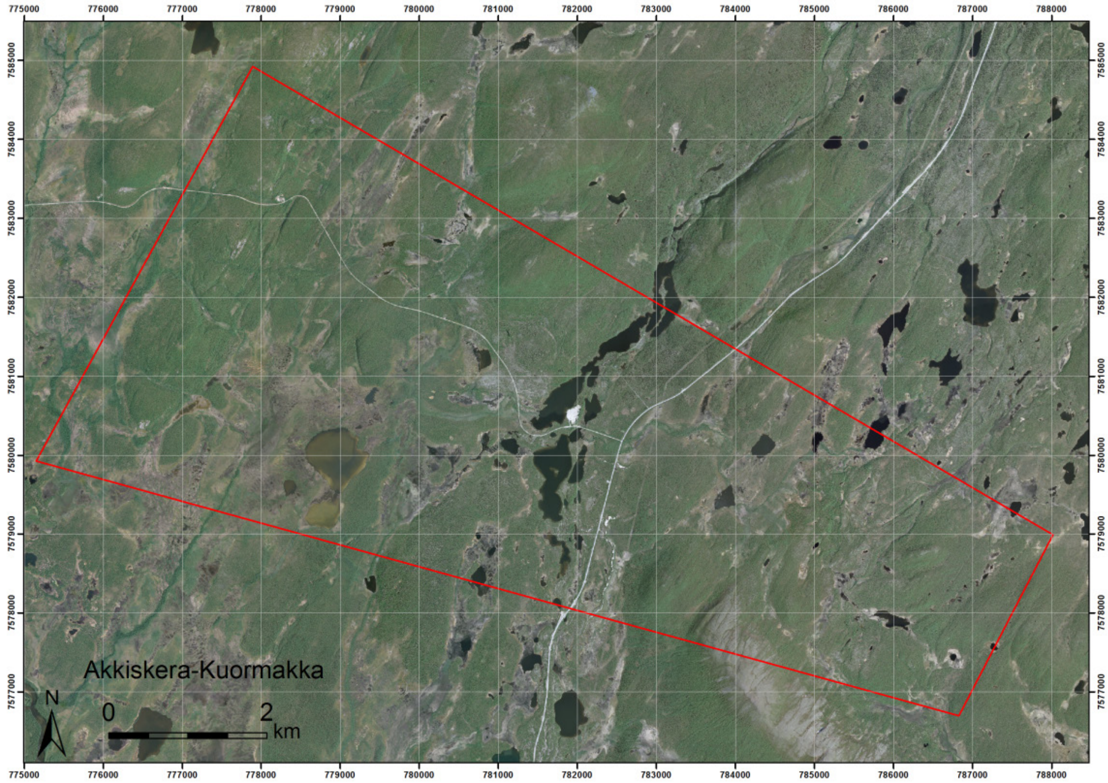


Fig. 9. Aerial picture showing the Akkiskera–Kuormakka region outlined in red.

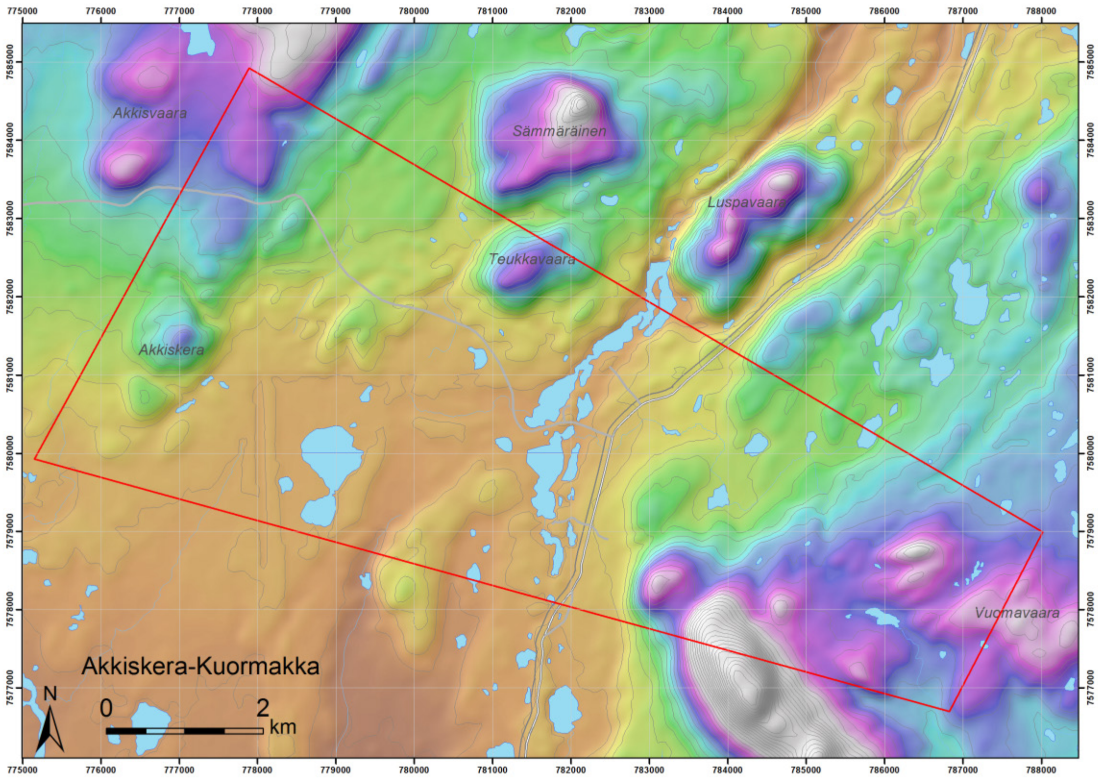


Fig. 10. DEM with local color symbology adjusted for the Akkiskera–Kuormakka region.

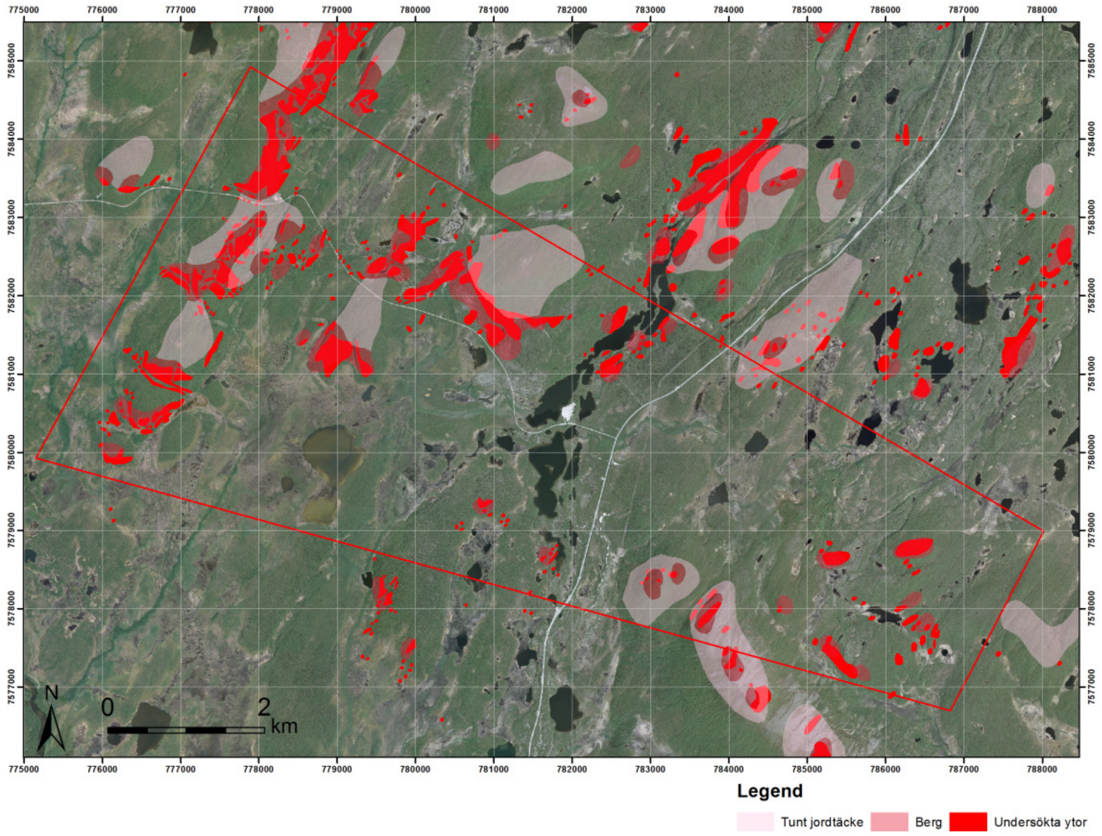


Fig. 11. Example from the Akkiskera–Kuormakka area where outcrops from the local bedrock database (red area) and quaternary geology database (outcrop in light red, thin soil layer in transparent red) are combined and plotted on an aerial photo.

meter line separation and 30 m flight altitude and recorded only the magnetic field.

LKAB recognized potential for ore in the area and in 1975 the SE part of 30K and SW part of 30L were surveyed. In the following year even the NE part of 30K and the northwestern part of 30L were completed. Both these areas were surveyed by east–west flight direction, 200m line separation and 30m flight altitude. LKAB collected magnetic data, electromagnetic VLF, and spectrometry. Even though their electromagnetic system was capable of tracking two receivers the data from the second channel was only considered as a backup, at the time, and it is not possible to calculate apparent resistivity from these data.

Barely touching the northwestern part of this area is an LKAB survey which covers the north part of the map sheets 30J and 30K. The survey covers part of the Keukiskero occurrence and recorded magnetic, electromagnetic and spectrometry data. As with the previous surveys the flight direction was east–west, the flight altitude 30m and the line separation 200m. The main difference with this survey compared to the older ones was the introduction of Doppler positioning which gave a better positional accuracy.

The newest known record of airborne data collected in the area is an LKAB survey from 1985. In this survey not only magnetic field, electromagnetic VLF and spectrometry data were collected but also electromagnetic slingram (low right of Fig. 12). It does not differ from the earlier LKAB surveys in other aspects.

As will be discussed below three private companies hold exploration permit in the area but no data has been handed in to the mining inspectorate up to the date of writing this compilation.

Ground-based data

The magnetic map (Fig. 12) shows very clearly a lineament striking NNE in the western part between, what is geologically mapped as volcanic rocks and quartzite, and what has been mapped as granite and basement of Archean age.

Also prominent is the kink in the central part that changes strike of the magnetic anomalies as you go south, from NNE to SE. This is also visible in the electromagnetic data (Fig. 13).

In the NE corner the complexity of the magnetic field increases and this is also the area where some occurrences have been investigated. The regional gravity data is very scarce in the eastern part of the area but thanks to the exploration surveys it is possible to get a very detailed view in some parts.

At the date of making this compilation there are five valid exploration permits in the area. The permit owners are Arctic Gold, Boliden Mineral and Kiruna Iron. The areas that have come under interest recently are, in part, the areas around the known occurrences Outavaara, Sautusvaara and Kallojärvi. Although the above mentioned occurrences have been in focus during exploration there are several other known occurrences of different styles, e.g. sulphide, Iron–oxide and industrial mineral. Hence it is interesting that also areas where occurrences are unknown are now investigated. One of those permits is in the area between Ollinjärvi and Outavaara and the other is SE of Palovaara.

As can be seen in the table 5 geophysical ground survey has been ongoing during the years 1967–1969 in Palovaara, Kallojärvi and Keukiskero, and through 1977–1979 in Ollinjärvi, Outavaara and Tsounamavare and between 1982–1985 in Tsuonemavare, Sautusjärvi and Outavaara (see Fig. 13)

The recent permit owners in the area have not disclosed any data from eventual geophysical surveys to the mining inspectorate at the point of writing.

Magnetics

Only two explorers have provided detailed information about the magnetic field in the area. As can be seen in table 6 SGU explored the occurrences Palovaara and Kallojärvi between 1967 and 1969. LKAB were active in the area during seventeen years, first in 1969, then through 1977–1979 and lastly through 1982–1985. The total area of magnetic survey is over 45 km^2 in over 35000 stations.

Electromagnetics (EM)

Only LKAB has been surveying the electromagnetic properties on the ground and did so during eight years from 1977 up to 1985 (table 5). The data from Outavaara can more readily be compared to airborne slingram data while other parts of the area is only covered by the airborne 1-ch VLF (Fig. 13).

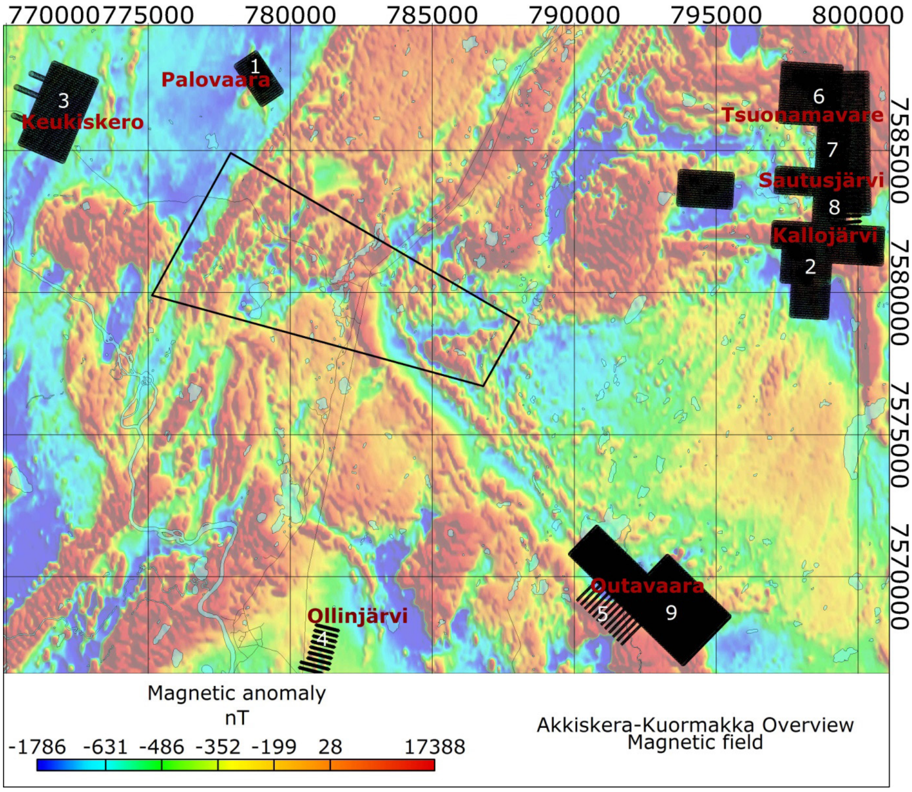


Figure 12. Magnetic ground surveys shown on top of the airborne magnetic survey (stations marked in black dot). The polygon roughly describes the area of focus in this compilation and the numbers refer to table 5.

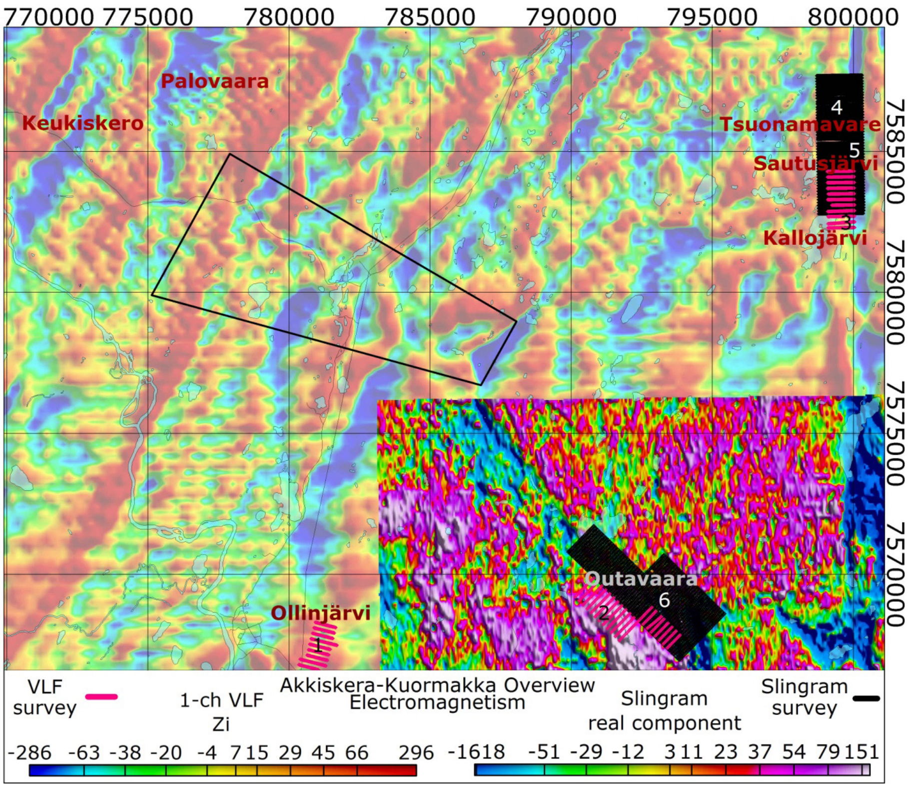


Figure 13. Ground electromagnetic VLF surveys (stations in pink and slingram in black). The numbers relate to table 6. The base map is airborne vlf 1-ch data except for the NE corner, which shows LKAB slingram data.

Gravity

Table 7 shows the only areas that were covered with detailed gravity surveys. Both Palovaara and Kallojärvi were surveyed by SGU. Unfortunately for the interpretation of the geology of the area the regional gravity network is very scarce in this area and, as is clear from figure 14, especially so in the eastern part where barely more than ten stations are present east of the E 45 road. However, the over 4500 stations measured in the Kallojärvi campaign uncover more detail in the massive ca. 30 mGal gravity anomaly that makes up the NE-part of the area.

Petrophysics

There are 685 petrophysical samples taken in the area with density measurements on all of them. The majority of the samples also have susceptibility measured and about 630 have measurements of magnetic remanence. Unusual is the high frequency to which oriented samples have been taken and there are over 130 of these. Most of the samples have been taken close to the road that goes west in the central part of the area (Fig. 15). The reason for this is that there is a high amount of outcrop in that part of the area and that the results from the samples can be handily associated to geophysical measurements along the same road.

Table 5. This is a compilation of magnetic surveys in the area where the number relates to the map in figure 12.

Nr	Object	Area apx. (km²)	Nr of points	Year	E (apx.)	N (apx.)	Operator
1	Palovaara	1.3	1427	1967	778900	7587500	SGU
2	Kallojärvi	16	14600	1968–1969	799000	7584000	SGU
3	Keukiskero	5.2	3387	1969	771800	7586400	LKAB
4	Ollinjärvi	1.3	379	1977	781000	7567450	LKAB
5	Outavaara	2.7	900	1978	791460	7568550	LKAB
6	Tsuonamavare	2	552	1979	799600	7583300	LKAB
7	Tsuonamavare	4	2025	1982	799500	7586500	LKAB
8	Sautusjärvi	4	2024	1983	799500	7584000	LKAB
9	Outavaara	10.1	10380	1985	792700	7569400	LKAB

Table 6. Electromagnetic properties have been investigated by LKAB using both the VLF and slingram techniques.

Nr	Object	Method	f (kH)	Area apx. (km²)	Nr of points	Year	E (apx.)	N (apx.)	Operator
1	Ollinjärvi	VLF	-	1.3	361	1977	781000	7567500	LKAB
2	Outavaara	VLF	-	2.6	840	1979	791600	7568400	LKAB
3	Tsuonamavare	VLF	-	2	513	1979	799550	7583300	LKAB
4	Tsuonamavare	SR	18	3.8	2025	1982	799500	7586500	LKAB
5	Sautusjärvi	SR	18	3.8	2018	1983	799550	7584000	LKAB
6	Outavaara	SR	3.6	9.7	5190	1985	792900	7569400	LKAB

Table 7. The table shows the only two detailed gravity surveys in the area. However, the Kallojärvi survey covers a large area. Numbers relate to figure 12.

Nr	Object	Area apx. (km²)	Nr of points	Year	E (apx.)	N (apx.)	Operator
1	Palovaara	1.28	534	1967	778850	7587500	SGU
2	Kallojärvi	17.6	4541	1968	798150	7583800	SGU

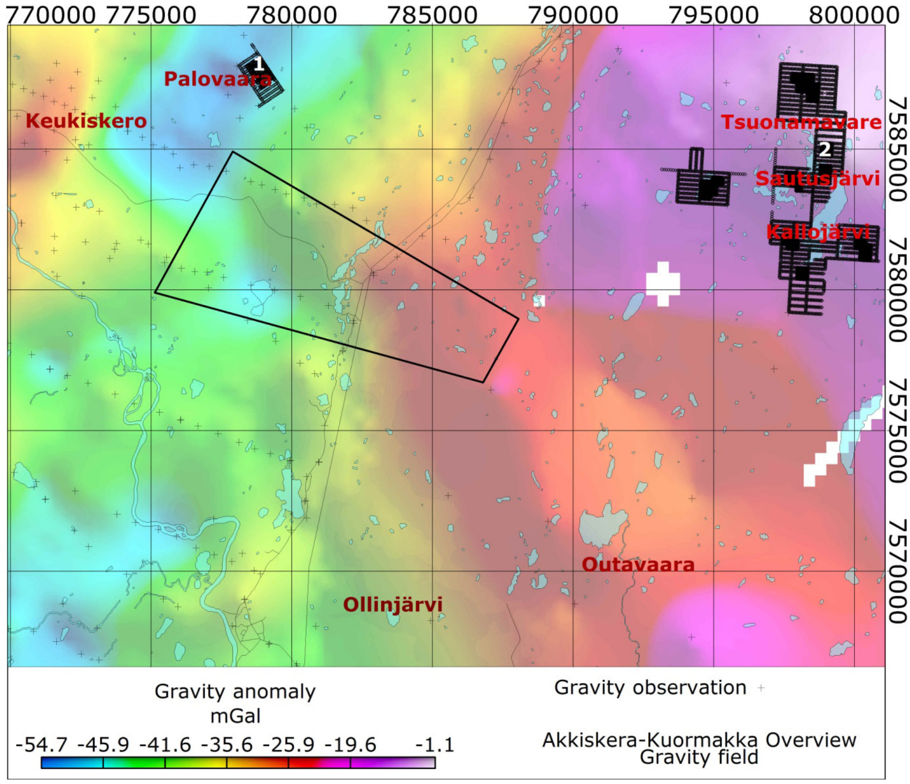


Figure 14. Gravity anomaly grid based on the regional gravity stations marked as crosses. Black dots mark gravity stations in detailed ground surveys. The number relates to table 7.

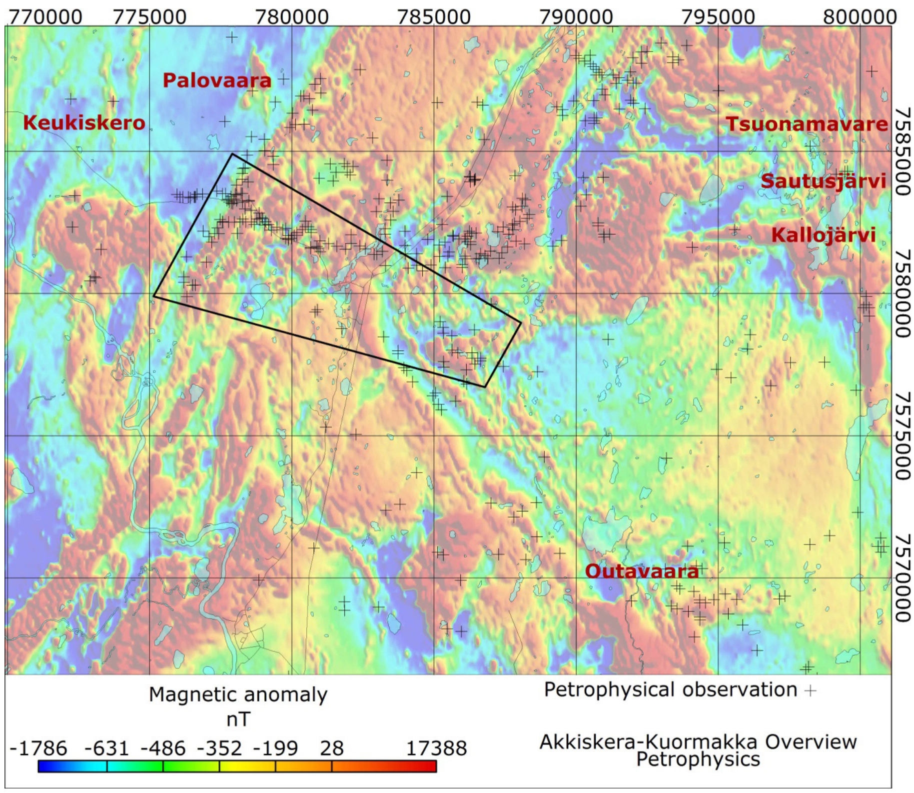


Figure 15. Magnetic anomaly map. Each cross in the figure represents a petrophysical sample. Note the density of samples along the road from the E 45 going west toward Keukiskero.

A quick glance at the results from the petrophysical analyses reveals a number of samples with high magnetic remanence and it seems like this will have to be taken carefully into account in any kind of modeling attempt involving the magnetic field.

SUMMARY

Lithology and Stratigraphy

The key area Akkiskera–Kuormakka is located in the northernmost part of Sweden, about 30 km southwest of Karesuando. The key area covers approximately 40 km^2 and is divided into a west and east domain by the main road (E45). The west domain is in turn intersected by an E–W road towards Pulsujärvi. The region is named after the hills Akkiskero (481 m) in the west and Kuormakka in the southeast, of which only the northern slope falls within the region. The area is relatively well exposed with most outcrops located in the west; along the secondary road as well as along the NE–SW trending stratigraphic and structural borders marked by the Karesuando–Arjeplog deformation zone (KADZ). West of the KADZ, a domain consisting mainly of gneisses has been earlier mapped as Archean basement (Råstojaure complex, Fig. 2). Towards the east the Archean basement is overlain by a series of clastic sediments consisting of feldspar gravel, mica- and feldspar-rich quartzite and conglomerate. These sediments belong to the Tjärro Quartzite Group (Ödman 1939, Ambros 1980, Kumpulainen 2000, Fig. 16).

The thickness of the Tjärro Quartzite Group varies from 300 to 500 meters. The quartzite layer is the most persistent layer and can be followed for 70 km from Nalmuinen southwest of Övre Soppero (Fig. 2.) to Maunu west of Karesuando. Low-angle cross-bedded arkoses clearly reveal an overall stratigraphic younging towards the east and current directions towards the south to southwest (Kumpulainen 2000). Note that on the southern slope of mount Akkiskero the unit is tightly folded, and possibly reappears further westward. The unit's lower contact with the underlying gneisses is according to Ödmand (1939) and Ambros (1980) tectonically, and was subjected to the intrusion of pegmatites as well as mafic- to ultramafic dykes. However, according to Kumpulainen (2000) the original depositional basement-cover relationships are preserved locally showing conglomerate resting on the Archean basement (e.g. Kattilakoski and north of Soppero, see his Fig. 7). The nature of those contacts should be more closely addressed in the planned field studies. In addition, the possible occurrences of mafic sills within the Tjärro quartzite group, as appears from the Soppero NO maps sheet, but are not incorporated in the stratigraphic column, should be investigated.

Further towards the east the Tjärro quartzite group is overlain by the Kiruna Greenstone Group (KGG). At the contact between the two units, occurs a tuffitic, banded or stratified, occasionally skarn bearing greenstone (Fig. 16). However, the main rock type of the KGG that is covering most of the key area, is represented by a fine-grained, homogeneous and commonly amygdaloidal lava. Intrusions of mafic sills are frequent. In addition, zones and veins of ankerite-albite rich rocks can be found and seem often bounded by faults. In the uppermost part of the KGG, in the easternmost part of the key area, occur carbonate horizons, and graphic schists alternating with tuffitic layers. The carbonate horizons consist of skarn-bearing rocks, limestones and dolomites.

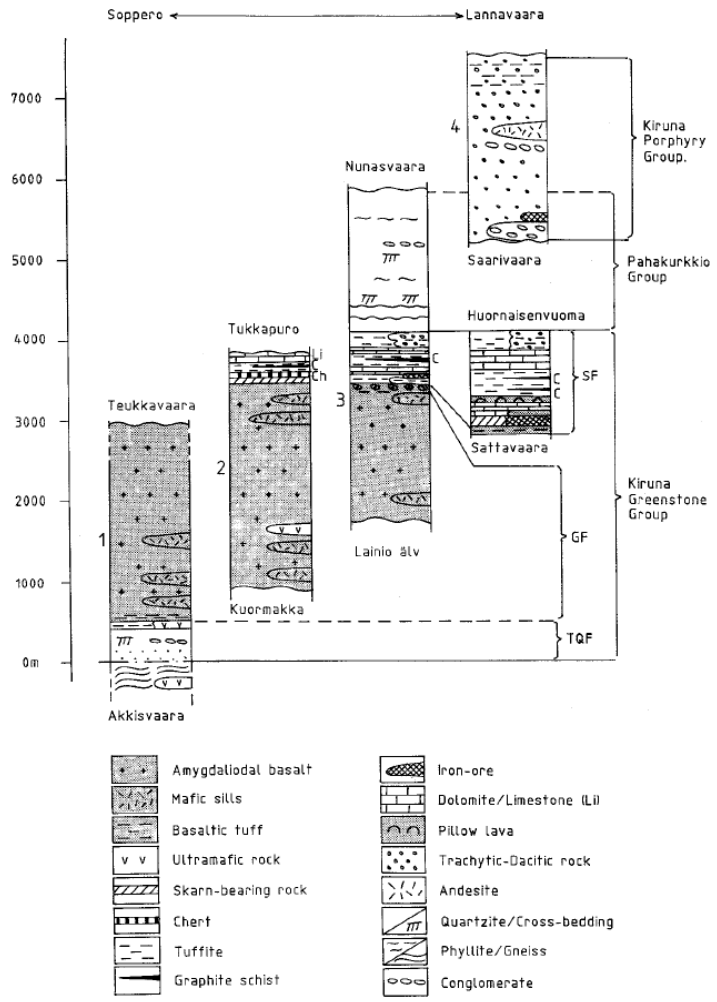


Fig. 16. Stratigraphic succession in the Soppero-Lannavaara region after Ambros (1980) and Hallgren (1979). The localities of the two columns on the left lie inside the key area.

Plutons and dike swarm

The Archean basement as well as the supracrustal rocks in the Akkiskera–Kuormakka key area are intruded by granite and gabbros belonging to both the Haparanda suite (west and northeast of Mount Kuormakka) and the somewhat younger Perthite–Monzonite suite (extreme northwest and east). In addition, NNE trending dolerites have intruded both the basement and the supracrustal rocks. These dikes commonly consist of amphibolites with antophyllite, olivine, antigorite, and chlorite (Ambros, 1980). Martinsson (1997) related the dike swarm to the 2.3–2.0 Ga Jatulian rifting event. Directly west of the key area the "Keukoskero and Kurkovarestråket" are ultramafic dykes, which can be traced all the way into Finland. Prospecting in this region by NSG pointed out concentrations of Ni (<0.28%) and Cr (<0.78%, Lilljequist, 1980). In the same report some hypotheses on the origin of these ultramafic rocks are summarized on page 5. Whether the dikes present within the key area represent: 1) displaced slivers of the Tjärro Quartzite Group; 2) intruded all around the same time, and are 2a) related to the Jatulian rifting event (2.3–2.0 Ga), or 2b) much older, 2c) after the deposition of the Greenstone Group, needs to be further constrained by sampling for geochronology and geochemistry during the upcoming field studies.

Depositional environment

According to Martinsson (1997) the clastic sediments, evaporites (are they there?), carbonate rocks and WPB basalts, were deposited in local and irregular basins formed at the onset of the Jatulian rifting event (2.3–2.0 Ga). The conglomerates and cross-bedded arkoses resting on the Archean basement are probably fluvial, whereas the sandstones of the upper part of the Tjärro group may have a shallow marine origin (Kumpulainen 2000). As rifting intensified, the clastic succession was covered by a smooth lava plain of komatiites and tholeiitic lava of LKT to MORB affinity, indicating a more mature continental rifting stage. In his interpretation the magnesium-rich komatiites may have derived from a hot mantle plumes, and were later overlain by tholeiitic flood basalts with T-MORB affinity as the lithosphere moved away from the active mantle plume. Together with the occurrence of NNE-trending dike swarm, this lead to the interpretation of deposition within a NNE-directed failed rift arm with a mantle plume generated triple junction located south of Kiruna (Fig. 18 in Martinsson, 1997). If komatiites or picrites occur within the Akkiskera–Kuormakka key area should be addressed in the upcoming field study. In addition, the extent of the quartzite layer (>70 km) overlying the Archean basement seems not in agreement with the interpretation as being deposited in a local, irregular basin.

Structural framework

Within the Akkiskera–Kuormakka key area, the Karesuando–Arjeplog deformation zone (KADZ) is the main structural feature. The shear zone appears on most regional maps northeast of Kiruna as a lineament bordering the Archean basement to west and the overlying greenstones to the east (Fig. 17). However, its exact location is unclear as most deformation was probably accommodated along several sub-parallel branches, splays, and relative weak layers of the Greenstone group.

On a more regional scale the KADZ was recognized by Henkel (1991) as a 800 km long lineament dislocating both gravity and magnetic anomalies between the small towns Arjeplog and Karesuando (see also next section scenario 2). Bergman (2001) mapped the segment between Gällivare and Karesuando as an 8 km wide zone consisting of several ductile shear zones and brittle fault steps. According to his documentation the mylonitic foliation is steep and stretching lineations vary from steeply to locally gently plunging southwards. Western-side-up movement and local dextral movements have been inferred from mainly s-c fabrics. Within most of the sheared rocks retrograde chlorite and white mica is present, quartz has been recrystallized, and magnetite porphyroblasts were formed.

The KADZ connects further northwards with the Mierujávri–Svaerholt shear zone in Norway (Henkel, 1991; Olesen and Sandstad, 1993). According to Martinsson (1997) formed both shear zones along a former NNE–NE trending failed rift arm (see also section "Depositional environment"). The existence of these major Svecofennian to post-svecofennian shear zones parallel to the former rift arms suggest reactivation of deep crustal structures established during the Jatulian rift event. As such, the upcoming field studies should aim for a better understanding on the architecture of the KADZ, and how deformation was accommodated through time and space.

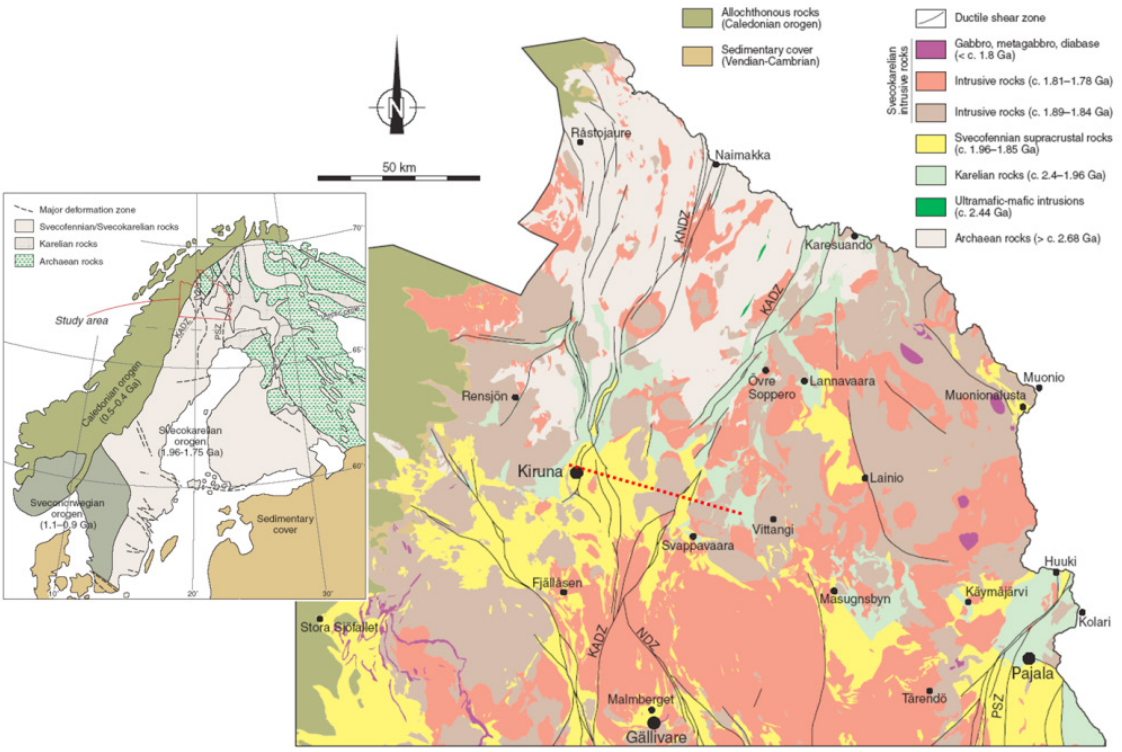


Fig. 17. Overview of the major tectonic features in northern Norrbotten (after Bergman et al. 2001). KADZ; Karesuando-Arjeplog deformation zone. Red dashed line marks the location for the seismic transect.

Regional tectonics

The tectonic context of the KADZ has been interpreted differently in the literature. Three interpretations on the outline of the deformation zone are summarized below.

Scenario 1. The KADZ is the most western segment of the Baltic–Bothnian megashear (e.g. Berthelsen and Marker 1986, Fig. 18). In this scenario, the KADZ branches into the Nautanen shear zone and a connection with a southern segment towards Arjeplog does not exist or is less relevant. This may imply also a kinematic history similar to the Baltic–Bothnian megashear: early dextral shear followed by lots of sinistral shear between 1.86 and 1.80 Ga. The timing of the latter is based on a difference in deformation intensity shown by the plutons of the Haparanda and Perthite monzonite suites megashear (Berthelsen and Marker 1986).

Scenario 2. Based primarily on geophysical anomalies, the KADZ represents a continuous NNE–trending lineament between Arjeplog and Karesuando (e.g. Henkel 1991, Fig. 19). Henkel (1991) continues his interpretation of the KADZ further into Norway and a connection between the deformation zone and the Mierujávri Svaerholt fault zone (MSFZ) is suggested by Olesen and Sandstad (1993). Note that in this scenario the KADZ is probably sinistrally displaced by the Baltic–Botnian shear zone, somewhere near the Finish–Norwegian border (Fig. 20). This implies a relatively younger activation of the latter. Recently obtained airborne geomagnetic data on the Norwegian side (Fig. 21) may help to further constrain this scenario.

Scenario 3. Regional tectonic interpretation where the KADZ trends towards the northwest

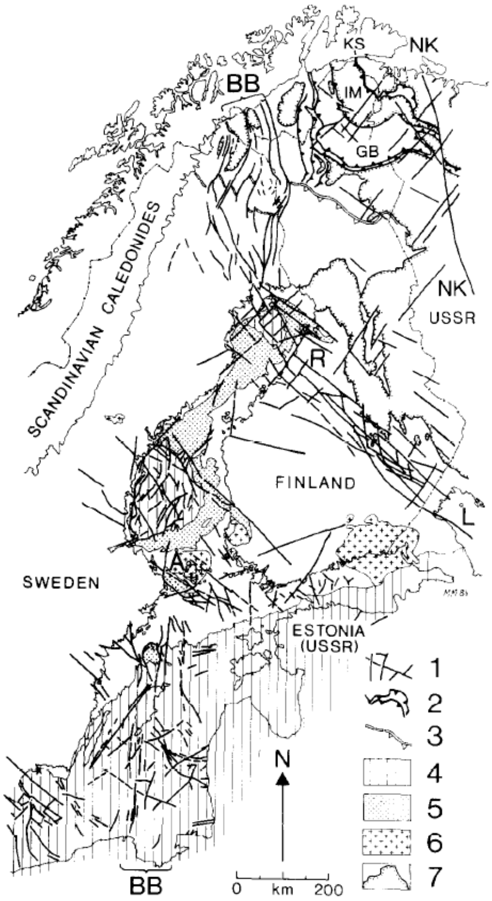


Fig. 18. Scenario 1: The KADZ is part of the Baltic-Bothnian megashear. From Berthelsen and Marker (1986).

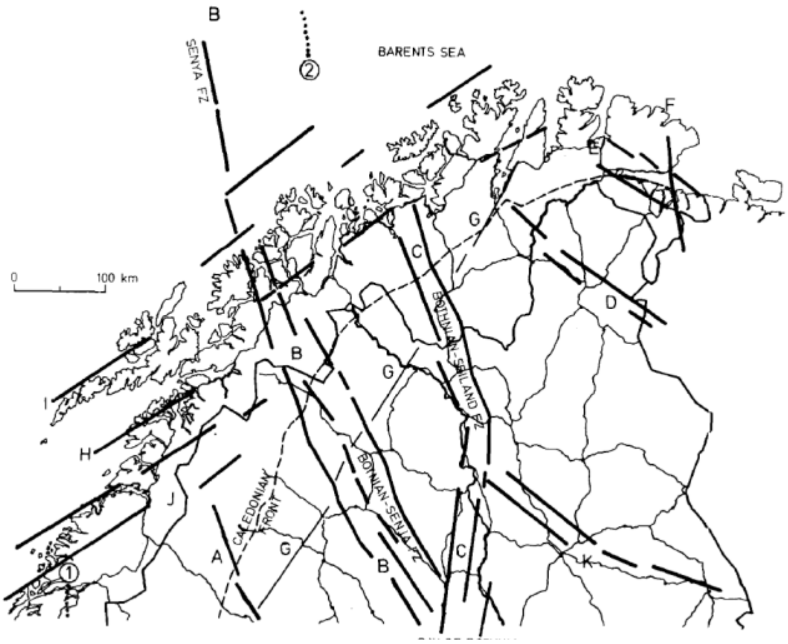


Fig. 19. Scenario 2: The KADZ (line G) is a continuous NNE-trending lineament between Arjeplog and Karesuando. From Henkel (1991). Lines are generalized magnetic dislocations.

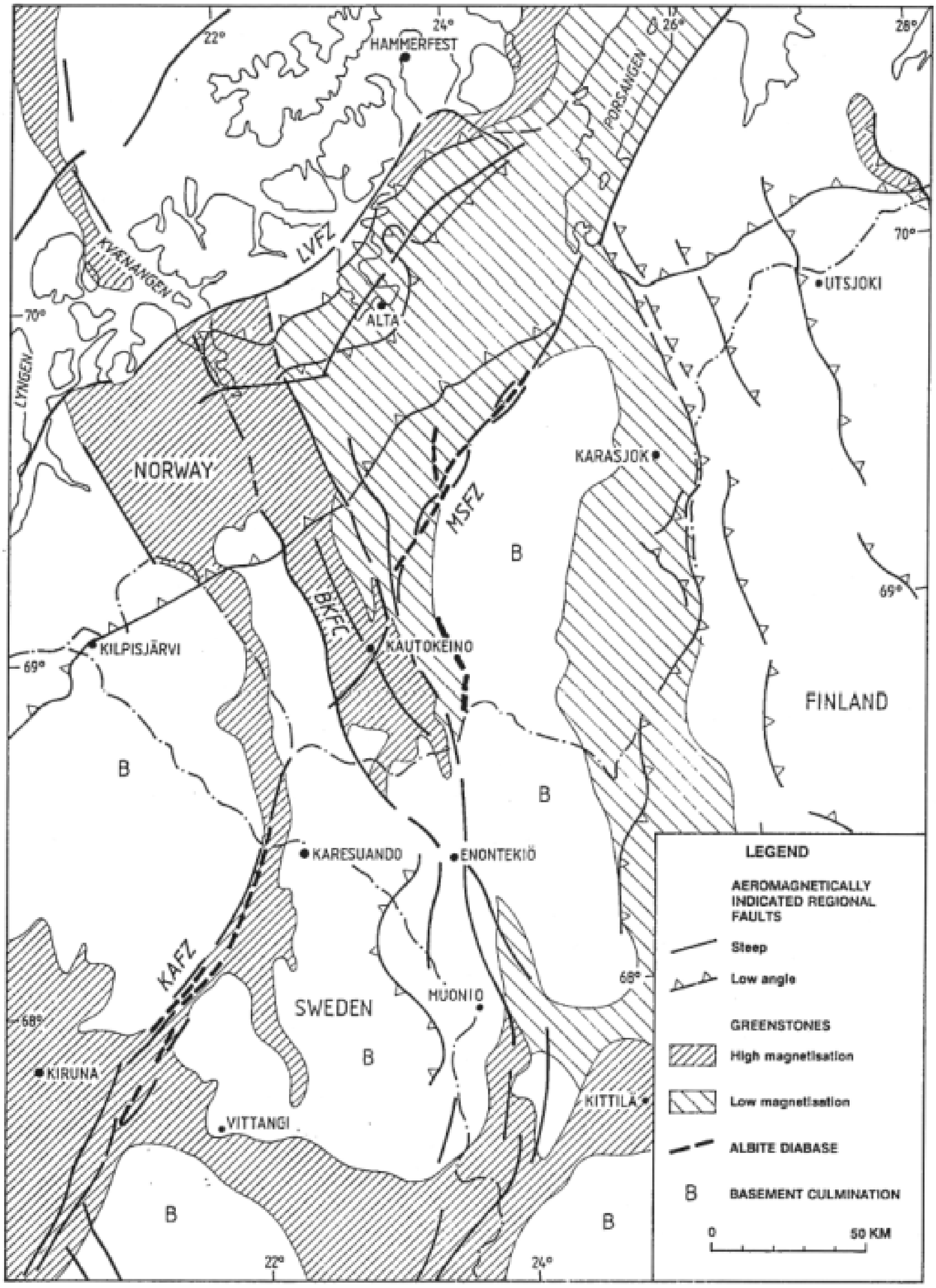


Fig. 20. Regional structural elements interpreted from aeromagnetic and gravity data in Finnmark. KAFZ: Karesuando-Arjeplog Fault Zone. MSFZ: Mierujávri Svaerholt Fault Zone. BKFC: Bothnian-Kvaenangen Fault Complex. From Olesen and Sandstad (1993).

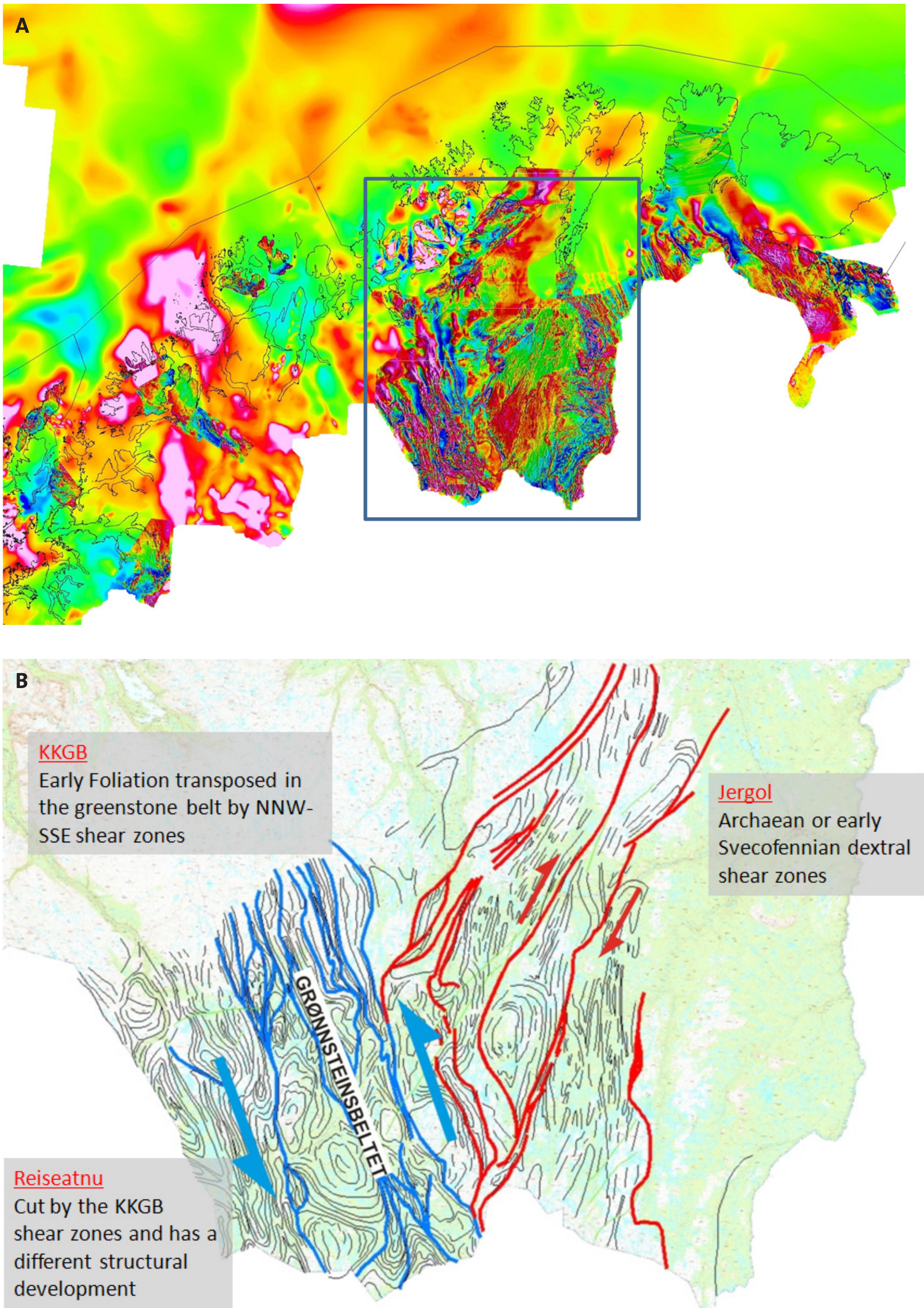


Fig. 21**A.** Compilation of airborne magnetic data in Norway. From J.-S. Sandstad et al (2013). **B.** Lineament interpretation based on geophysical data in the Kautokeino region, Norway (Iain Henderson, Rovaniemi meeting spring 2013). The sheared domain coloured in red may be connected to the KADZ further southward, whereas the sheared blue domain probably connects with the Baltic-Botnian shearzone. Source NGU.

in Finland and Norway (Fig 22). More research on both the KADZ as well as on the Ruossakero shear zone is needed to confirm this idea.

Seismic transects

Preliminary interpretations on the seismic transect between Kiruna and Svappavaara in 2013 indicate that the main structure is characterized by a sheet-dip to the south, upright folds and steeply dipping shear zones. However, the Karesuando–Arjeplog deformation zone seems listric and dipping towards the east. Ongoing processing of the seismic data should further constrain this first order observation. In Norway, the seismic transect "Snowstreamer" records a ESE-dipping Mierujávri Svaerholt fault zone and is consisted with the possibility of a southward connection with the KADZ (Sandstad et al. 2013).

Tectonic model for the KADZ

The deformation history of the KADZ is poorly constrained. The field-based interpretation of western-side-up movement and local dextral movements as inferred from s-c fabrics is derived from only a few observations along the 800 km long lineament. In order to better constrain the kinematics and significance of the deformation zone with respect to the regional geology more observations and structural analysis are needed. As such, only accurate structural mapping combined with the collection of age data along regular spaced profiles perpendicular to the deformation zone can contribute to unravel its deformation history.

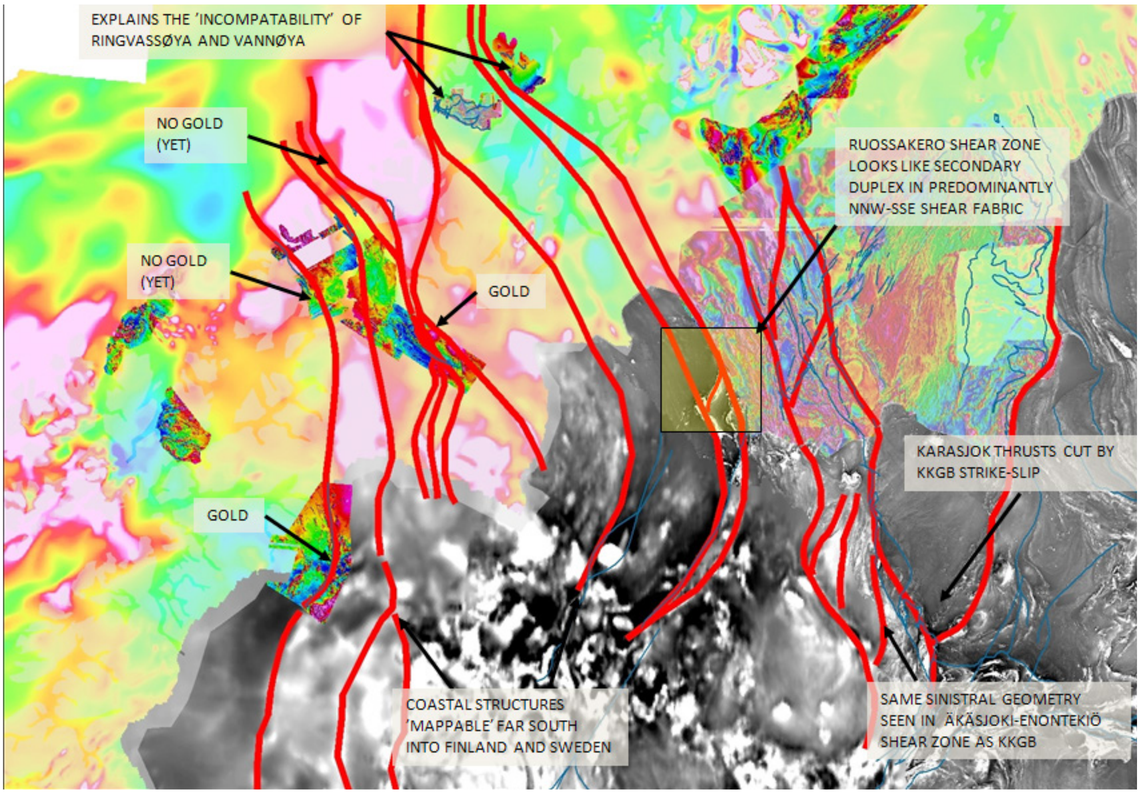


Fig. 22. Interpretation of the KADZ bending towards the northwest in Finland and Norway. From J.-S. Sandstad et al (2013).

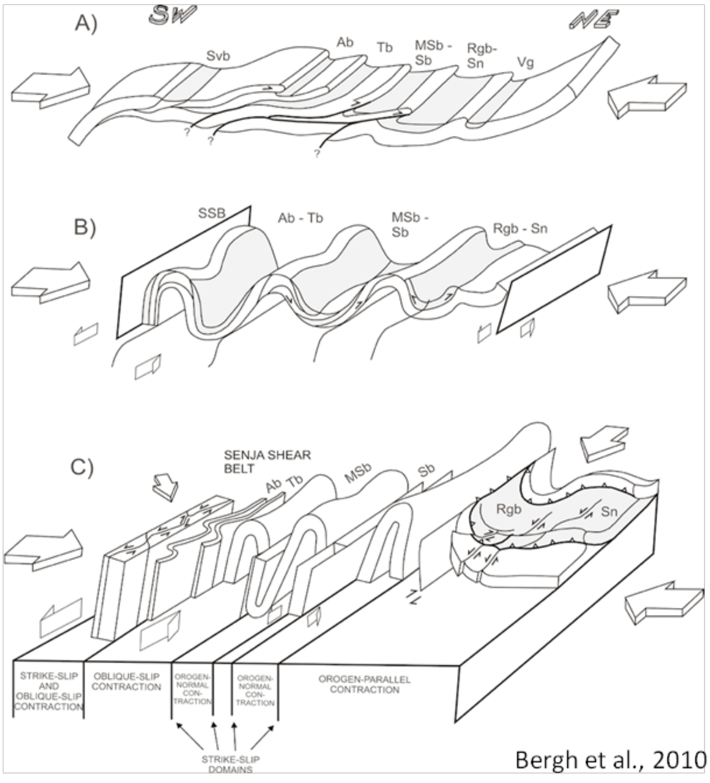


Fig. 23. Tectonic model of Bergh et al (2010) to highlight the transposition of localized strike-slip deformation onto a fold and thrust belt in the West Troms Basement Complex. A similar scenario may have affected the strain pattern along the KADZ.

In this context, a more detailed study on the northward extension of the KADZ into the Baltic–Botnian shearzone and the Mierujávri–Svaerholt shear zone in Finland and Norway, respectively, is significant. This is in particular important considered the fact that the latter is described as an extremely long-live fault zone with displacements dating back to the Proterozoic to less than 9.000 years ago (Olesen and Sandstad, 1993). In addition, it would be interesting to see if the tectonic model for the Kautokeino Greenstone Belt (Norway) and the West Troms Basement Complex as suggested by Bergh et al. (2010), is also relevant to explain the strain patterns observed along the KADZ (Fig. 23). This model primarily implies the transposition of oblique to orthogonal compression by later oblique to strike-slip transpression. The former phase resulted in a NE-directed fold and thrust belt whereas the later overall sinistral transpression was strongly partitioned and led to the formation of local sinistral- and dextral orogen-parallel zones (Bergh et al. 2010). Note that the KADZ probably formed initially as a major normal fault associated with the Neoarchean rifting and the formation of the Greenstone formation. From that moment onward the zone acted as a weakness causing strain localization during the subsequent deformation phases. Such intensive localization of strain may have overprinted the strain patterns related to earlier deformation. In order to unravel the entire deformation history it is therefore important to study also the strain patterns located outside the deformation zone. By carrying out a detailed structural analysis of the apparent dome-and-basin pattern observed within in the Svappavaara key area the timing of this early deformation phases may be better constrained.

Alteration and mineralization potential along the KADZ

Based on its dimension, tectonic setting and age, it is likely that the KADZ acted as a major conduit for fluids associated with metamorphic devolatilization and intrusions. These fluids may have had high concentrations of Au and metals such as Mo, W, and Cu, and might have caused alteration and mineralization within the wall rock. In addition, gold is associated with the latest Paleoproterozoic ductile strike-slip structures in the Kauokeino Greenstone Belt (Sandstad et al. 2013). As such, the processes at work along the KADZ may be comparable to those along faults associated with well-mineralized systems like for instance the Boulder Lefroy fault zone in the Yilgarn Craton of Western Australia. The sites of these mineralization are often marked by zones of intense carbonation and chloritization that can extend for hundreds of meters around the conduit. Conditions for mineralization can also be created by repeatedly reworking of a zone by high strain (especially strike-slip) or stress switches causing fracture permeability (Miller et al. 2007, Blewett, 2010). In addition, gold mineralization is often associated with the brittle–ductile transition, based on relevant P–T conditions along parts of the H2O–CO_2 solves (Robb, 2005). All together, studying the interrelation between the ductile- and brittle structures as well as the possible occurrence of pseudotachylyte within and in the vicinity of the KADZ is therefore of great importance to answer the following questions: 1) What are the geodynamic and P–T histories of the system? 2) What is the architecture of the system? 3) What are the fluid reservoirs? 4) What are the fluid flow drivers and pathways? 5) What are the metal and sulfur transport and depositional processes? These questions were outline in Blewett (2010) and are relevant to investigate the components of most hydrothermal deposits around the world.

DISCUSSION

Issues to be addressed (specific key questions for the Akkiskera–Kuormakka key area)

Following up on the discussion and suggestions outlined in the previous section the general points of interest for the upcoming field studies for the Akkiskera–Kuormakka key area are:

Questions on stratigraphy

- What was the duration of greenstone volcanism?
- Is the origin (source) of the ablite-rich dolerites magmatic or related to metasomatism? What was the role of the associated brittle faults?
- What is the origin of the ferretic dolomite in the quartzite region?
- What is the metamorphic facies of the rocks?
- When and at what depth did the intrusive bodies crystallized? P–T–t conditions?
- Are the rocks altered? If so, what kind of alteration and what was the cause of the alteration?
- What kind of mineralization are present?

Questions on defromation:

- What is the regional geometry of the KADZ and how does it connect with other regional structures? (e.g. Baltic–Bothnian megashear)
- How was deformation accommodated along the KADZ through time and space? Are there mylonites or fault breccias?
- What is the structural relation between the NW-trending and NNE-trending faults and folds?
- What is the interrelation between the ductile- and brittle structures, and what does it mean in terms of deformation phases and P–T conditions?
- Do pseudotachylytes exist within and in the vicinity of the KADZ?
- What are the fluid reservoirs, and what are the fluid flow drivers and pathways?

What is the latest recorded age of displacement along the KADZ? Can we use the 40Ar/39Ar laser or stepwise heating technique on recrystallized muscovites from mylonites? (e.g. Billström et al. 2002). Combined with cooling ages from both the footwall and hanging wall (e.g. Steltenpohl et al. 2011).

What is the age of brittle faulting, and how can it be better constrained? Possibly by K–Ar analysis of clay minerals in fault gauges? Or dating hydrothermally altered K-feldspars surrounding epidote veins, which occur in the host rock directly near the fault (e.g. C. Davids et al. 2012)?

Many of the questions above can be addressed by accurate structural mapping combined with the collection of age data along regular spaced profiles perpendicular to the deformation zone.

PLANNED WORK

A subdivision in sectors, shown in figure 24, may help to address the specific questions listed in table 8. Note that this list is incomplete and no geophysical topics are included.

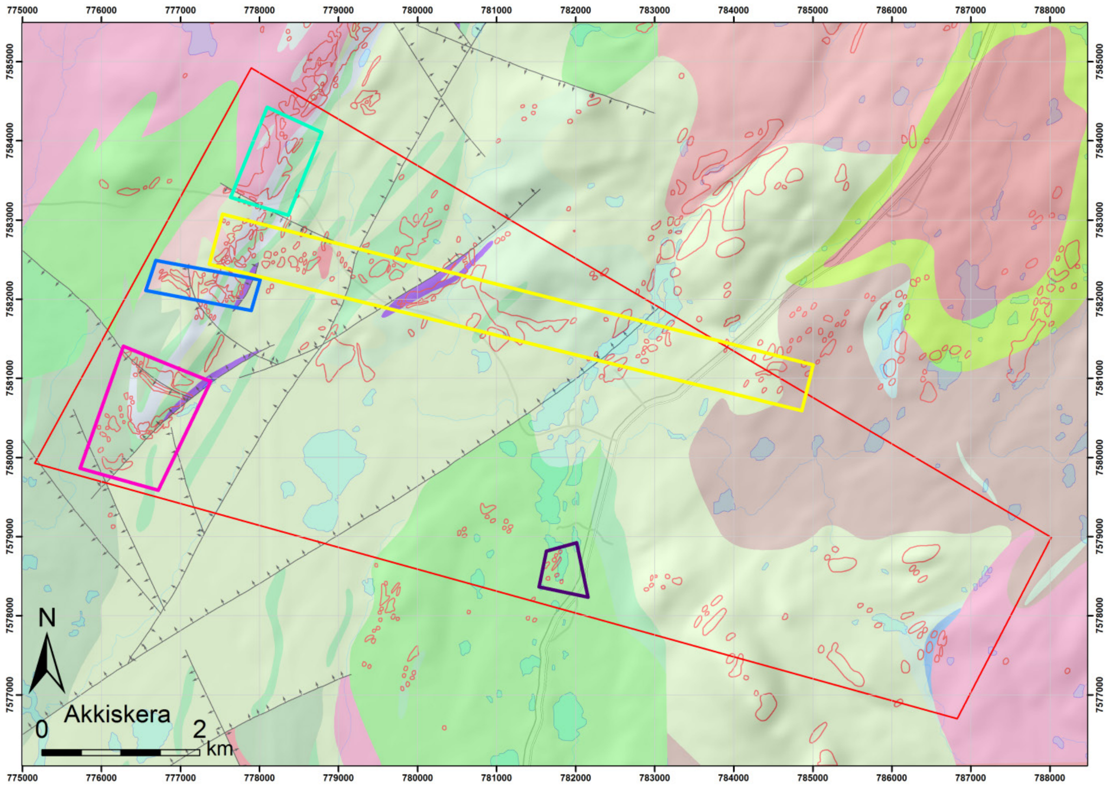


Figure 24. Map of the Akkiskera–Kuormakka key area (red square) with potential sites of interest (sectors) shown in different colours referring to the text in table 8. Outcrops are outlined in red. Background colours refer to the bedrock geology from the SGU local bedrock map database.

Table 8. Summary of the potential focus points and their estimated time effort within different sectors in the Akkiskera–Kuormakka key area shown in figure 24.

Sector	Interesting issues	Time estimate
Yellow	Profile orthogonal to the stratigraphy and main structural fabrics. Architecture of the KADZ, deformation intensity gradients, detail study on the nature of the lithological and structural contacts, e.g. unconformities, intrusives, brittle faults and ductile shear zones. Dating and geochemical signature of the greenstones.	Three days
Blue	Nature of the contact between the Archean basement, Kovo group, and Greenstones. Sedimentary or Tectonically?	One day
Purple	Style of folding of the quartzite layer. Possibly associated with fracturing and fluid flow. Is the Archean west of this fold also folded? Dating the Archean (cooling ages)	One day
Turquoise	Deformations, PT conditions, and contacts associated with the Perthite Monzonite suite. Did associated fluids penetrate the wallrock?	One day
Black	Deformation and PT conditions of the Haparanda suite.	Half day

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