BARENTS PROJECT 2013

Geological and geophysical field work in the Kiruna–Jukkasjärvi and Svappavaara key areas, Norrbotten

Susanne Grigull & Johan Jönberger

March 2014

SGU-rapport 2014:10

Sveriges geologiska undersökning
Geological Survey of Sweden

Cover: Signboard on Luossavaara hill.
Photo: Susanne Grigull.

Sveriges geologiska undersökning
Box 670, 751 28 Uppsala
tel: 018-17 90 00
fax: 018-17 92 10
e-post: sgu@sgu.se
www.sgu.se

CONTENTS

ABSTRACT

Within the framework of the Barents project, a first field work campaign was carried out during the summer of 2013. This report summarises some of the main field observations made in the key areas Kiruna–Jukkasjärvi and Svappavaara. Field work in these two areas predominantly focused on geological structures affecting the rocks. The report is mostly suitable for an audience with advanced geoscientific knowledge.

SAMMANFATTNING

Inom ramen för Barentsprojektet har en första fältsäsong genomförts sommaren 2013. Denna rapport summerar de observationer som gjorts i nyckelområdena Kiruna–Jukkasjärvi och Svappavaara. Fälarbetet i dessa områden fokuserade huvudsakligen på de geologiska strukturer som påverkar bergarterna i områdena. Rapporten är riktad mot läsare med geologisk bakgrund.

INTRODUCTION

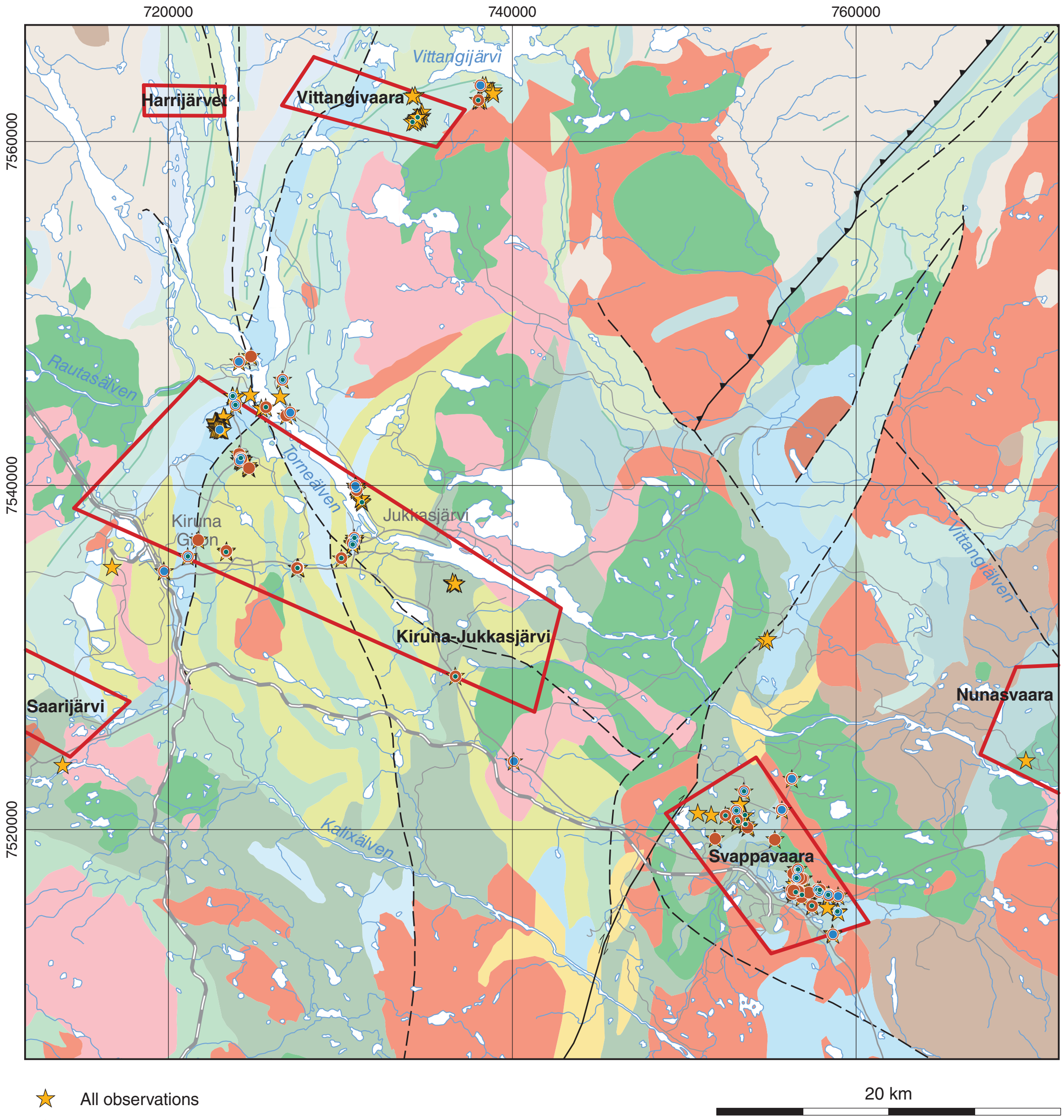
Within the framework of the Barents project, SGU began to carry out geological field work and geophysical ground measurements in seven of fifteen key areas in Norrbotten county during the summer of 2013. The Barents project concentrates on the Paleoproterozoic cover rocks as well as on some of the Archean basement rocks of the region. In each area the project aims to understand and characterise the following general points:

- Stratigraphic organisation and development
  - volcanological,
  - sedimentological,
  - chemical characterisation,
  - dating of metavolcanic rocks,
  - dating of detrital zircons in sediments,
  - structural investigation to understand stratigraphy.
- Regional development of the bedrock
  - large fold structures and deformation zones,
  - metamorphic parageneses,
  - dating of metamorphic events.
- Hydrothermal alterations
  - chemical and mineralogical characterisation of alterations.
- Mineralisations
  - characterisation,
  - description of occurrences.

The type of information collected during field work can be grouped as follows:

- Geological observations:
  - lithological information (protolith, metamorphism),
  - mineralogical information (protolith, metamorphism, alterations, mineralisations),
  - structural information (types and attitudes of planes and lineations, shear zone kinematics, folding structures),
  - sampling for geochemistry and geochronology.
- Geophysical information:
  - ground geomagnetic measurements,
  - ground electromagnetic measurements,
  - radiation,
  - magnetic susceptibility measurements,
  - petrophysical sampling.

This report summarises the work done during 40 days in summer 2013 in and around the Kiruna–Jukkasjärvi and Svappavaara key areas. In total, 190 locations were visited within and around the two areas described here, and in the Saarijärvi, Nunasvaara, and Vittangivaara key areas (Fig. 1). 79 samples were taken for potential lithogeochemical analyses and 42 samples for potential geochronological analyses (Fig. 1). 43 samples have been taken for oriented thin section preparation (Fig. 1) in order to help unravel paleokinematics. The data is presented in the form of maps, field photographs and stereographic projections. All interpretations are preliminary and will be verified against results of ongoing thin section microscopy and lithogeochemical and geochronological analyses.



- ★ All observations
- ● Sample taken for geochemical analysis
- ● Sample taken for geochronological analysis
- • Oriented sample

Hauki group
- Sandstone, mudstone, conglomerate, volcanic rocks (c. 1.91–1.87 Ga and possibly younger)

Granite-syenitoid-gabbroid association
- Granite, granodiorit, syenitoid, quartz monzodiorite (1.8 Ga)

Granite-pegmatite association
- Granite, pegmatite (1.85–1.75 Ga)

Perthite monzonite suite
- Granite, syenitoid (c. 1.88–1.87 Ga)

Haparanda suite
- Granitoid and subordinate syenitoid (c. 1.91–1.87 Ga)
- Gabbro, dioritoid, dolerite, ultramafic rocks (c. 1.91–1.87 Ga)
- Gabbro, dioritoid, dolerite, ultramafic rocks (c. 1.91–1.87 Ga)

Kiirunavaara group
- Rhyolite, dacite (c. 1.88–1.86 Ga)
- Basalt, trachyandesite, andesite, komatiite (c. 1.88–1.86 Ga)
- Rhyolite, dacite (c. 1.91–1.88 Ga)
- Basalt, andesite and subordinate dacite (c. 1.91–1.88 Ga)

Kurravaara conglomerate
- Metagreywacke, mica schist, graphite- or sulphide-bearing schist, paragneiss, migmatite, quartzite, amphibolite (c. 1.96–1.87 Ga)

Kiruna greenstone group
- Shale, dolomite, basalt, sandstone (c. 2.05–1.96 Ga)
- Basalt, andesite (c. 2.05–1.96 Ga)
- Gabbro, dolerite (c. 2.3–2.0 Ga)
- Gabbro, dolerite (c. 2.3–2.0 Ga)
- Basalt, komatiite (c. 2.3–2.05 Ga)
- Basalt, andesite, komatiite (c. 2.44 Ga)

Kovo group
- Quartzite, mic. schist. mica-rich gneiss, metaconglomerate, metabasalt (c. 2.4–2.05 Ga)
- Metasandstone, psammitic gneiss, mica-rich gneiss, metaconglomerate (c. 2.4–2.3 Ga)

Archaean rocks
- Granitoid, diorite, quartz diorite (c. 2.80–2.65 Ga)
- Paragneiss, metagreywacke (c. 3.20–2.65 Ga)
- Tonalite-trondhjemite-granodiorite gneiss, quartz-feldspar gneiss, migmatitic gneiss (c. 3.20–2.65 Ga)

The current understanding of the geological units and stratigraphy (Table 1) in the Kiruna–Jukkasjärvi and Svappavaara areas is largely based on research done by Olof Martinsson and co-workers in the past decades (e.g. Martinsson 1999, Martinsson 2004) and is summarised in Table 1. All supracrustal units listed in Table 1 have been intruded by Paleoproterozoic magmatic rocks. The different intrusive suites are generally separated according to their age and geochemical characteristics. They are summarised in Table 2, of which an extended version can be found in Grigull & Lundin (2013). All supracrustal rocks have undergone at least greenschist facies metamorphism. For the sake of conciseness, the prefix "meta" has been omitted from all rock type names.

KIRUNA–JUKKASJÄRVI KEY AREA

A summary of available background data as well as an introduction to the geology of the Kiruna–Jukkasjärvi key area is provided in Grigull & Antal Lundin (2013). The key area contains rocks from the Kovo group in the westernmost corner, overlain by rocks of the Kiruna greenstone group along the western margin. The Kiruna greenstone group is unconformably covered by rocks of the Kurravaara conglomerate. The Kurravaara conglomerate is overlain by rocks of

Table 1. Lithostratigraphic units in the Kiruna–Jukkasjärvi and Svappavaara key areas.

Group	Formation	Rock types	Thickness (m)	
Hauki quartzite group		arenite, conglomerate, shale	?	?
Kiirunavaara group	Matojärvi formation	Felsic tuffite, hematite, basalt, conglomerate, greywacke, phyllite	450–500	2500
	Luossavaara formation	Porphyritic dacite	800	
	Hopukka formation	Amygdaloidal andesite to trachyandesite	300–1400	
	Kurravaara conglomerate	Conglomerate, sandstone, andesite	500–1000	500–1000
Kiruna greenstone group	Linkaluoppal formation	Volcanoclastic basalt, dolomite	>50	1900–4050
	Peuravaara formation	Pillow basalt	50–1500	
	Viscaria formation	Volcanoclastic basalt, chemical sediment, carbonate rocks	600	
	Pikse formation	Amygdaloidal basalt	500–1000	
	Ädnamvare formation	Peridotitic to basaltic komatiite	500	
	Såkevaratjah formation	Carbonate rocks, conglomerate, amygdaloidal basalt	200–400	
Kovo group	Harrejaure formation	Andesitic siltstone and greywacke, basalt	1000–2000	1200–2300
	Rautojaure formation	Conglomerate with carbonate matrix, quartzite	200–300	

Table 2. Paleoproterozoic intrusive rocks from oldest to youngest. Based on Ahl et al. (2001) and Bergman et al. (2001).

Suite	Age (Ga)	Geochemical character	Rock types
Haparanda suite (HPS)	1.90–1.86	Calc-alkaline	Granite, granodiorite, tonalite, diorite, gabbro
Perthite-monzonite suite (PMS)	1.88–1.86	Alkaline	Granite, monzonite, diorite, gabbro, peridotite
Granite-pegmatite association (GPA) or Lina suite (LS)	1.81–1.78	Calcic(?)	Monzogranite, syenogranite, adamellite
A-, I-type intrusions	1.80–1.77	Alkaline	Granite, monzonite, granodiorite, diorite, gabbro

Figure 1. Geological map based on SGU's 1:1 million bedrock database. The key areas presented in this report are marked in red. Observation sites are marked as stars. Sampling sites for lithogeochemistry, geochronology and oriented samples are also indicated.

the Kiirunavaara group, which covers most of the key area to the east of Kiruna. A strip of sedimentary rocks belonging to the Hauki quartzite group unconformably overlies both the Kiirunavaara group and the Kurravaara conglomerate in the western part of the area.

During summer 2013, 71 observation points within the area were visited with a focus on understanding the geological structures in three subareas within the Kiruna–Jukkasjärvi key area. These observations are summarised below.

Subarea 1: Fold structures in the Kiruna greenstone group at Kallosalmi

The main challenge in the area around Kallosalmi (Fig. 2) was to understand the structural architecture of the rocks of the Kiruna greenstone group (mainly Pikse, Viscaria and Peuravaara formation) and their relationship to the adjacent Kiirunavaara group in the south. A combination of existing geophysical data (mostly magnetic and electromagnetic measurements), new structural geological measurements and the results in a prospecting report by Gustafsson (1991) were used to understand the folding and faulting pattern in the area. New geomagnetic ground data were also collected in the area to the west of lake Kirkkoväärtijärvi.

The rocks north-east of Torneälven are predominantly mafic rocks from the Kiruna greenstone group as expected from the available bedrock maps of the area. In the studied outcrops, the rocks occur as amygdaloidal basalt, pillow basalt and basaltic volcanoclastic sedimentary rocks. The original bedding in the volcanoclastic sedimentary rocks is locally still recognisable (Fig. 3a) as are pillow structures in the basalts (Fig. 3b). Vesicles in basaltic lava flows intercalated with the volcanoclastic sedimentary rocks locally indicate younging directions.

The rocks are generally folded and contain decimetre-sized near-isoclinal folds in more massive, fine-grained, mafic rocks near the shore of Torneälven (Fig. 3c). Here, the fold axes plunge moderately to the south-west. The "Z"-shape of these folds indicates dextral movement and fold closure of a lower-order fold, F1, towards the west. The dominant foliation, S1, in the rocks is a pervasive, axial planar cleavage and it is subparallel to the original volcanic layering or bedding, S0. Layering and foliation strike north-north-east and dip steeply between 70° and 90° to both sides (Fig. 4). The structural measurements in Figure 4 show that there are two sets of fold axes and intersection lineations between cleavage and the dominant foliation. One set plunges near-vertically, whereas the other set plunges moderately to shallowly to the south-south-west or south-west.

A second, decimetre-spaced cleavage, S2, cuts all older structures at a low angle and indicates a second folding event. This is supported by what has been interpreted as fold interference patterns observable in both the magnetic and the electromagnetic (VLF) field maps (Fig. 5). Furthermore, two folding phases are in agreement with the fold interference pattern presented in the map provided as attachment 4 in the prospecting report by Gustafsson (1991). It is therefore tentatively suggested that at least two folding events have affected the area and created the structural pattern seen today as a south-south-west-plunging synformal antiform. However, more detailed structural measurements are necessary to support this model.

Subarea 2: Fold patterns in Hauki metasedimentary rocks at Kurravaara

The doctoral thesis by Wright (1988) contains a large number of structural geological measurements in the Kiruna district, especially within the metasedimentary rocks of the Hauki quartzite group and the Kurravaara conglomerate. Unfortunately, the thesis is only available in printed format. One goal was therefore to collect new structural measurements to verify the folding patterns described by Wright (1988). Another goal was to check whether the rocks of the Hauki quartzite group have undergone the same deformation as the underlying rocks of the Kiruna greenstone group, Kurravaara conglomerate and Kiirunavaara group.

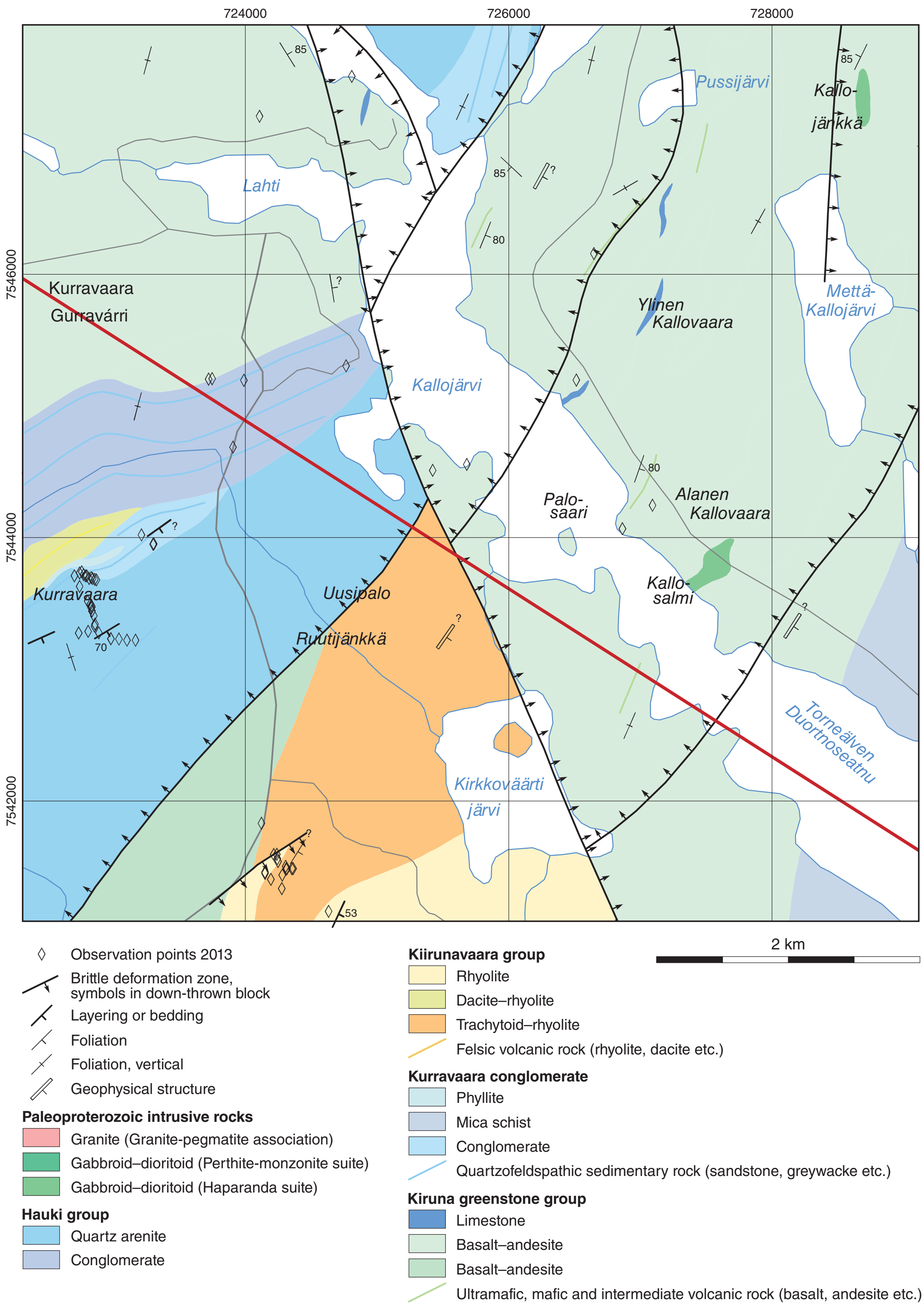


Figure 2. Local bedrock map of the area around lake Kirkkoväärtijärvi.

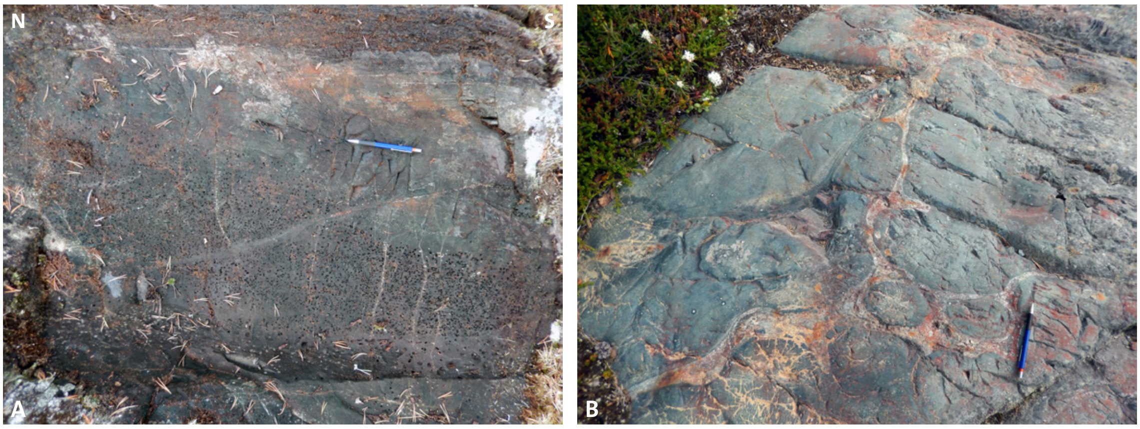


Figure 3. **A.** Volcanoclastic sedimentary rocks and basalt with bubbles. Younging is towards west. The primary layering (S0) and a foliation parallel to it (S1) are recognisable. A second cleavage (S2) cuts the rocks at a high angle (7544069/726864). **B.** Pillow structures in basalts from the Kiruna greenstone group (7545196/726516). **C.** Z-shaped folding pattern in metabasalts of the Kiruna greenstone group. A second cleavage cuts the folding pattern (white stippled lines, 7544069/726864).

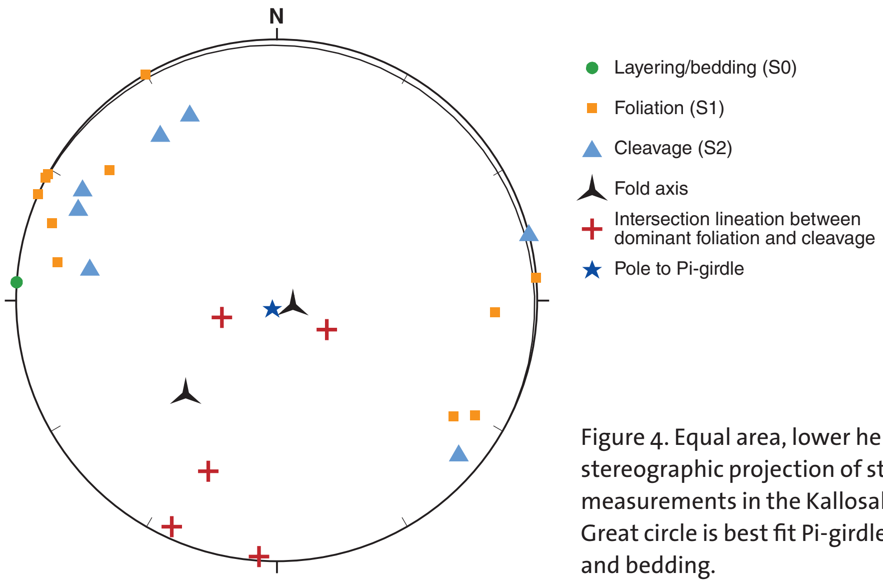


Figure 4. Equal area, lower hemisphere stereographic projection of structural measurements in the Kallosalmi area. Great circle is best fit Pi-girdle to foliation and bedding.

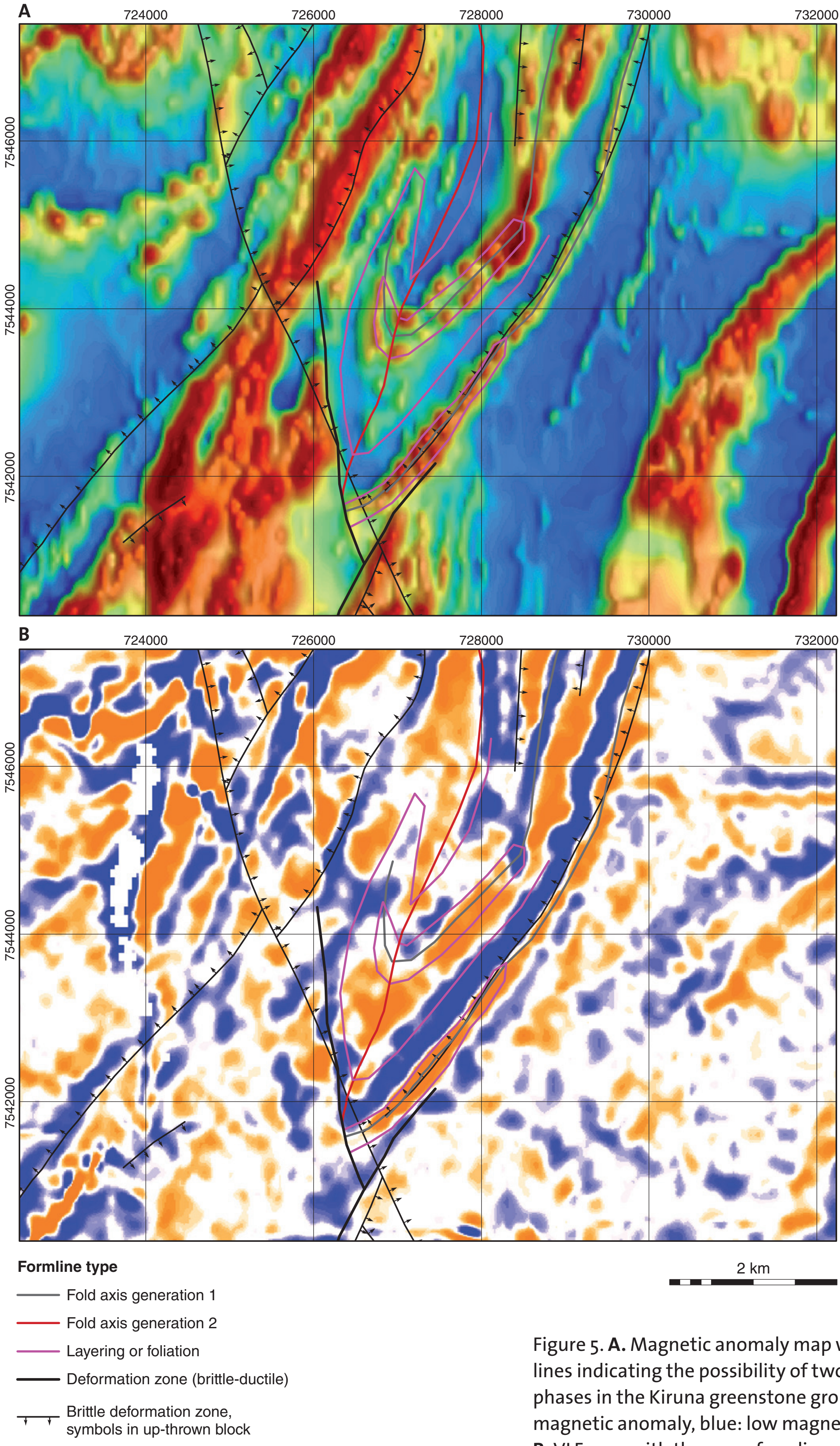


Figure 5. **A.** Magnetic anomaly map with formlines indicating the possibility of two folding phases in the Kiruna greenstone group. Red: high magnetic anomaly, blue: low magnetic anomaly. **B.** VLF map with the same formlines as in A. Blue: low conductivity, red: low conductivity.

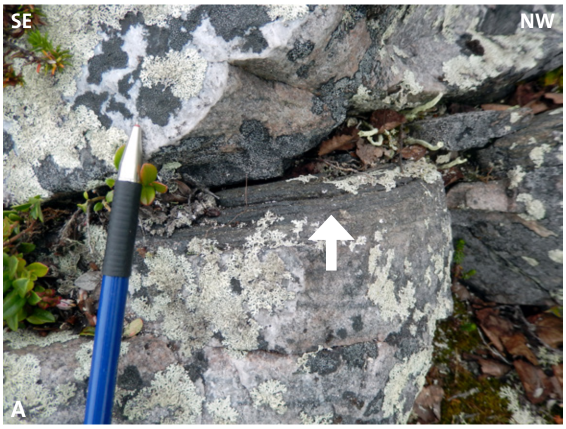


Figure 6. **A.** Quartzitic arenite of the Hauki group. Grain size decreases towards the top of the bed, indicating younging towards the south-west (7543680/722870). **B.** Hauki quartzite at northern wall of quarry near Nukutusjärvi. The bedding dips towards the east. In the metasandstone layers, the cleavage dips opposite to the bedding. Due to flexural shear, the cleavage refracts from the coarser-grained metasandstone beds into a sub-vertically dipping cleavage in the fine-grained metasiltstone bed. The observed bedding–cleavage relationships indicate closure of an anticline to the west and therefore younging to the east (Nukutusvaara, 7540377/721071).

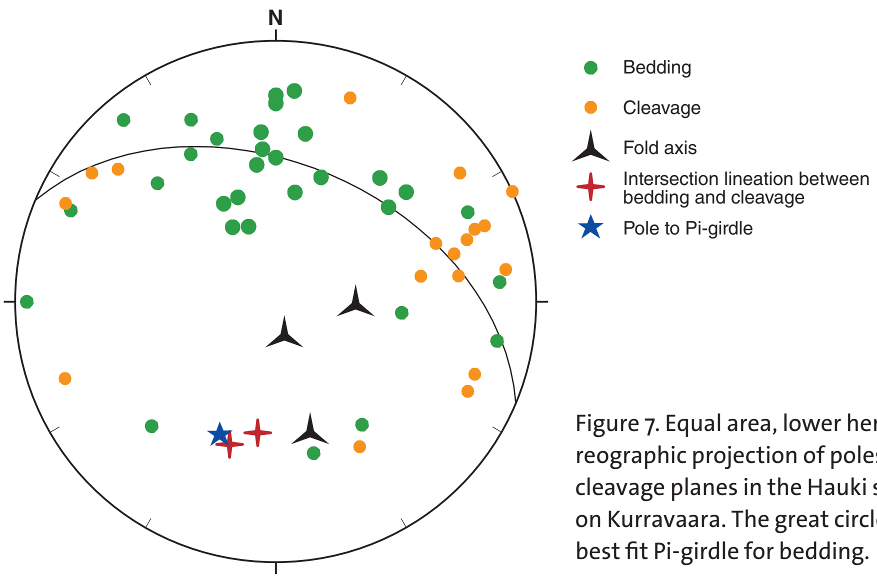


Figure 7. Equal area, lower hemisphere stereographic projection of poles to bedding and cleavage planes in the Hauki sedimentary rocks on Kurravaara. The great circle corresponds to best fit Pi-girdle for bedding.

The rocks exposed on the Kurravaara mountain are predominantly quartzitic arenitic metasandstones that are white-grey to light pink and locally grade into fine-grained silty layers (Fig. 6a). Cross-bedding is common and provides a reliable method to determine younging directions.

The Hauki metasedimentary rocks are folded about south-south-west plunging fold axes (see also Wright 1988). A spaced cleavage is usually recognisable in the metasandstone beds, refracting into a more closely spaced cleavage in the finer-grained and less competent metasiltstone beds. In the Nukutusjärvi quartzite quarry, a slaty cleavage has developed in the silt beds (Fig. 6b).

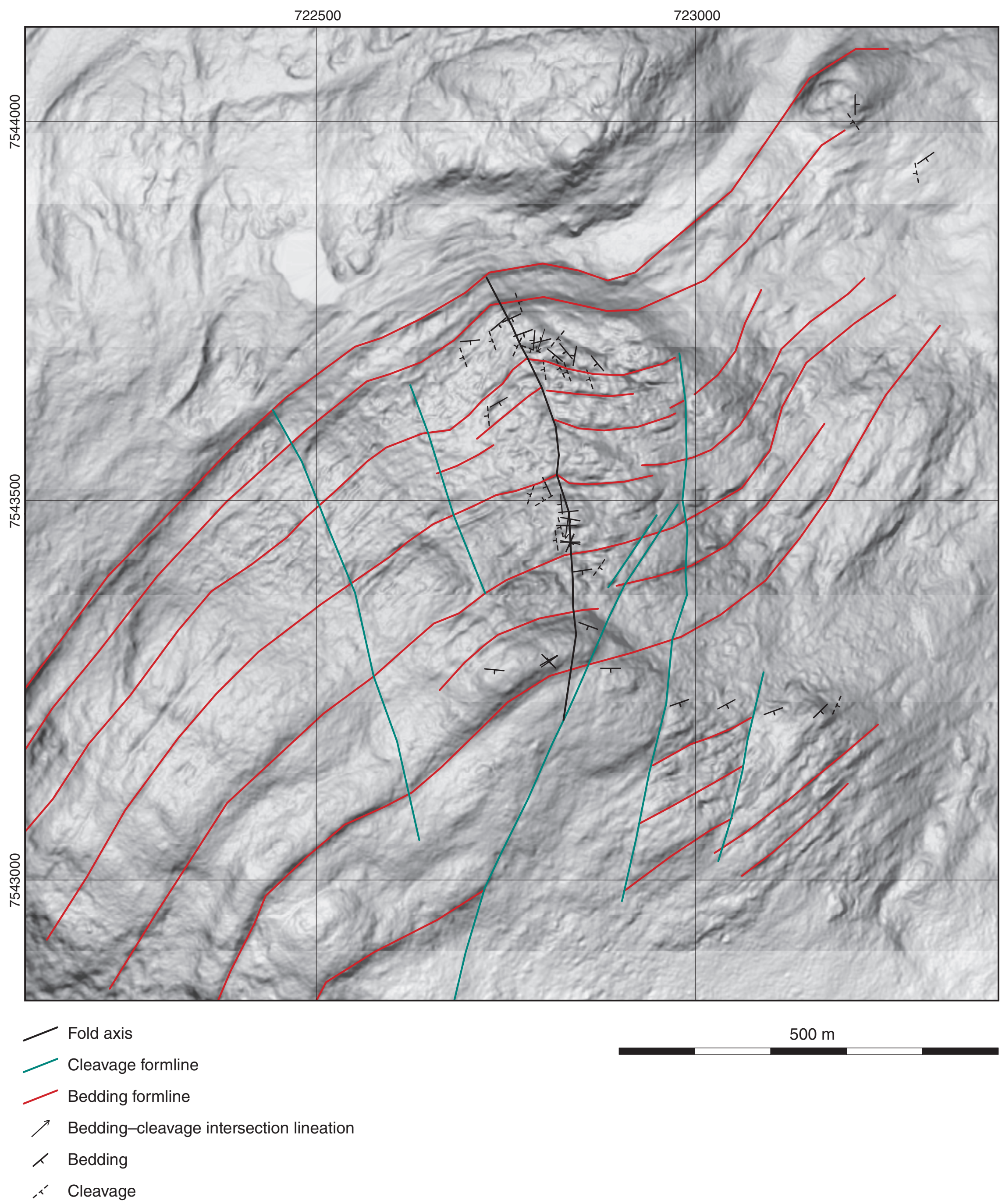


Figure 8. Folding pattern of the Hauki sedimentary rocks as seen in high resolution LiDAR data.

On Kurravaara, cleavage planes are axial planar and dip steeply to the west, indicating upright or slightly east-vergent folding (Fig. 7). The folding pattern in the Hauki sedimentary rocks can be traced in the high resolution elevation data provided by Lantmäteriet (Fig. 8). It seems that these rocks underwent only one folding phase. The pole to the best fit Pi-girdle in the stereographic projection in Figure 7 indicates that the regional fold axis plunges c. 45° to the south-south-west. The observed bedding-cleavage intersections support this. The two steeply plunging fold axes observed in small scale folds on Kurravaara (Fig. 8) are therefore somewhat puzzling.

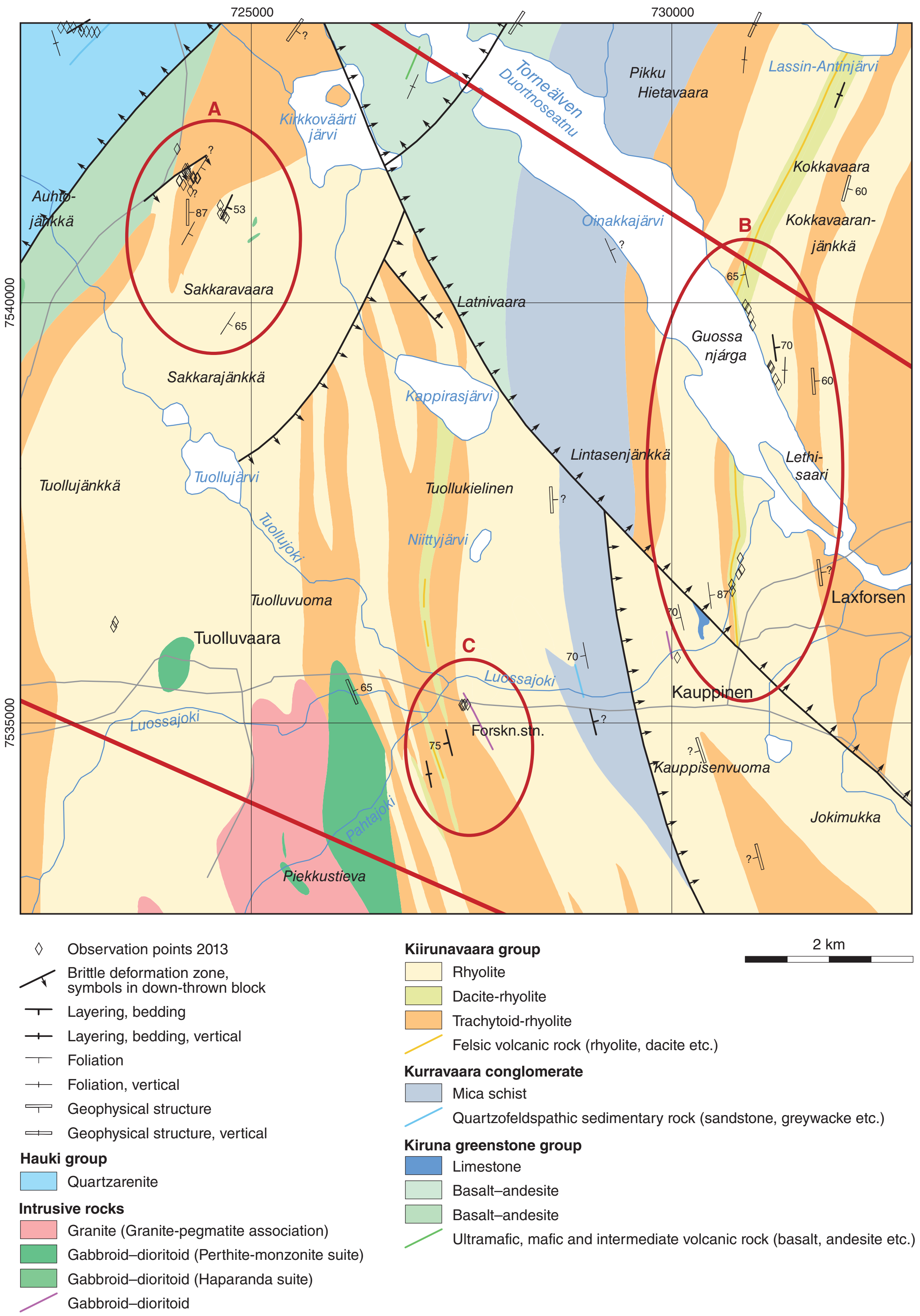


Figure 9. Bedrock map showing areas where structures in the Kiirunavaara group could be measured.

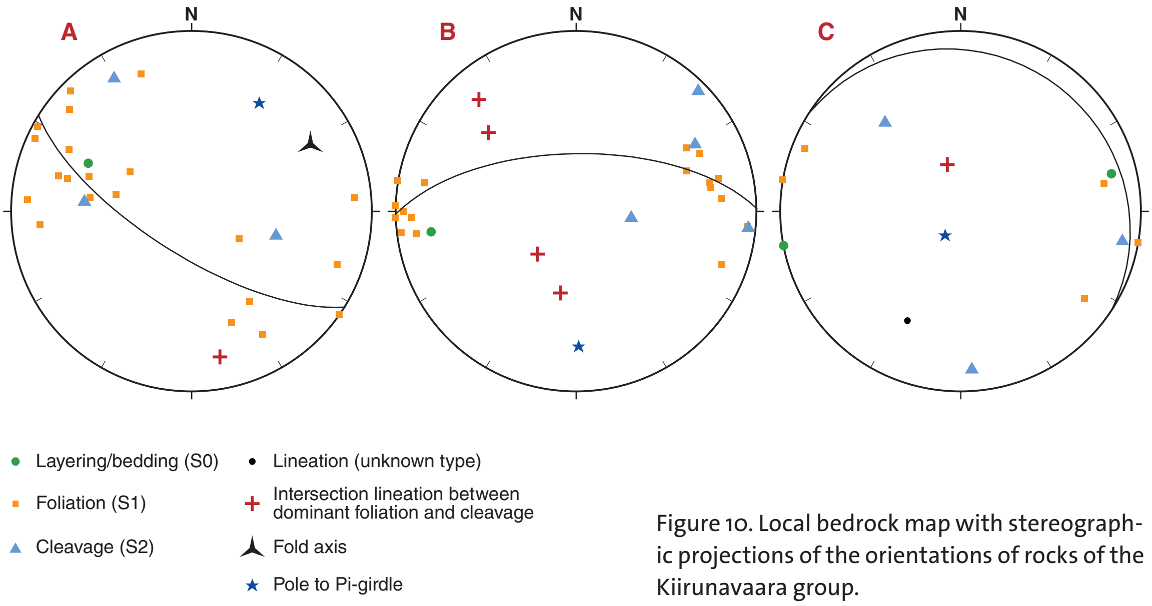


Figure 10. Local bedrock map with stereographic projections of the orientations of rocks of the Kiirunavaara group.

Subarea 3: Shear zones and folds in the Kiirunavaara group east of Kiruna

In the part of the key area that lies to the east of Kiruna, mostly volcanic rocks of the Kiirunavaara group crop out. To further understand the structural framework of these rocks, detailed geological orientation measurements were undertaken on outcrops at Sakkaravaara, along E10 near the space campus, around Laxforsen and along the northern shore of Torneälv (Fig. 9).

At Sakkaravaara, bedding, foliation and cleavage dip moderately to steeply to the north-west and south-east. The pole to the best fit great circle of the bedding planes indicates a regional fold axis that plunges 30° to the north-east (Fig. 10). A fold axis measured in basaltic layers, probably of the Matojärvi formation, plots close to the calculated regional fold axis (Fig. 11a). It is still unclear whether the cleavages that were measured correspond in fact to the dominant foliation or whether they developed during a second folding event.

At the outcrops along E10, near the space research campus, mostly K-feldspar altered rhyolitic dacites and mafic metatuffites with basalt intercalations occur. These rocks are tightly folded as well as sheared. The dominant foliation strikes more or less north-south and dips subvertically (Fig. 10). A foliation-parallel shear zone with a protomylonitic fabric has developed in the rhyolitic dacites (Fig. 11b), and asymmetric strain shadows around feldspar porphyroclasts as well as book shelf structures of fractured feldspar clasts indicate dextral shearing (Fig. 11c). In the mafic metatuffites, asymmetric tails around porphyroclasts also indicate dextral shearing. This is supported by small-scale folds in the mafic rocks that show mostly Z-fold patterns but also W-patterns, corresponding to the hinge region of a parasitic fold (Fig. 11d). The pole to the Pi-girdle of the dominant foliation plunges near-vertically (Fig. 10). It is questionable whether this corresponds to a regional fold axis or, more likely, to the local axes of drag folds that may have developed in the shear zone observed in the rhyolitic dacites. More detailed investigations are necessary here.

Along Luossajoki river near Laxforsen and on the northern shore of Torneälven mostly andesites (probably of the Hoppuka formation), dacites and rhyolites of the Luossavaara formation crop out (Fig. 9). One type of conglomerate with an unclear stratigraphic position, but probably belonging to the Luossavaara formation, has also been observed. The conglomerate is matrix-supported and contains three major types of clasts: scapolitised mafic metavolcanic

Figure 11. **A.** Folded basaltic layers in mafic volcanic rocks of the Kiirunavaara group (presumably Matojärvi formation). The axial planar cleavage is clearly recognisable. **B.** Mylonitic fabric with feldspar porphyroclasts developed in rhyolitic metadacite of the Luossavaara formation (7535221/727541). **C.** Close-up of D. Asymmetric strain shadows around feldspar porphyroclasts indicate that the movement in the shear zone was dextral (7535221/727541). **D.** Z- and W-fold patterns in mafic volcanic rocks of the Kiirunavaara group (Matojärvi formation?). The majority of kinematic indicators in this outcrop support dextral shearing. The W-fold pattern probably corresponds to the hinge of a parasitic fold (7535216/727505). **E.** Sheared and flattened conglomerate probably of the Luossavaara formation. The dismembered clasts indicate east–west flattening and dextral ductile kinematics (7536571/730720). **F.** Semi-brittle sinistral shear zone in porphyritic rhyolites of the Luossavaara formation (7539239/7311872).

rocks, potassium-altered fine-grained intermediate metavolcanic rock, and metaandesite. The clasts can measure up to 30 cm. The rocks around Laxforsen strike north–south and dip steeply to both sides. The calculated pole to the best fit girdle to the main foliation plunges shallowly to the south indicating isoclinal folding about north–south trending regional fold axes. Slightly asymmetrically deformed clasts in the metaconglomerate indicate a dextral shear sense (Fig. 11e). It was possible to roughly estimate the average axial ratios of the clasts. In a north–south direction they are stretched to a ratio of c. 3.5 to 1, whereas the axial ratio in the east–west direction is c. 1 to 3. This indicates almost pure uniaxial flattening in an east–west direction consistent with the predicted near-isoclinal folding.

Along the north-east shore of Torneälven, rhyolites of the Luossavaara formation have been sheared in a semi-brittle manner and now exhibit an SC-fabric or an imbricated fabric suggesting sinistral shearing with south-west side down movement (Fig. 11f). This shear zone is c. 20–30 m wide.

In summary, the vast majority of kinematic markers in the Kiirunavaara group indicate dextral shearing along steeply dipping shear-planes, but more importantly very tight to isoclinal folding about more or less north–south trending fold axes.

SVAPPAVAARA KEY AREA

A summary of available background data as well as an introduction to the geology of the Svappavaara key area is provided in Grigull & Jönberger (2013). The key area contains mostly mafic rocks, epiclastic volcanic sedimentary rock and metacarbonate rocks of the upper Vittangi greenstone group. In the south-eastern part of the key area, these rocks are overlain by the metasedimentary rocks of the Kiilavaara group, which may be an equivalent to the Kurravaara conglomerate in the Kiruna–Jukkasjärvi area. Basalts, mafic tuffites and other metavolcanic rocks of the Porphyrite group (in the sense of Bergman et al. 2001) also occur. All stratigraphic units have been intruded by Paleoproterozoic intrusive rocks of the Haparanda suite, the Perthite-monzonite suite and the Granite-pegmatite association.

The contacts between the rocks of the Vittangi greenstone group and the Porphyrite group are tectonic in nature. In general, the greenstones occur in horsts bounded by vertical faults. The Paleoproterozoic intrusive rocks are also affected by the brittle faulting.

Three areas of interest have been investigated during the 2013 field campaign and some of the field observations are summarised below.

Subarea 1: Folding patterns in the Vittangi greenstone group

Metabasaltic, meta-volcanoclastic and metacarbonate rocks of the upper Vittangi greenstone group occur in Svappavaara township (Fig. 12). A map created by Frietsch (1966) shows complicated fold interference patterns, indicating that the rocks of the Vittangi greenstone group were subject to at least two folding phases. Detailed structural measurements were therefore taken in and around Svappavaara in order to understand the structural architecture of the greenstone group (Fig. 13). However, finding suitable rock exposures turned out to be difficult, because Svappavaara township has grown significantly since the last map of the area was created by Eriksson & Hallgren (1975), and many outcrops are not accessible any more.

The apparent lack of a preferred structural orientation of foliations and cleavages seems to support the theory of two folding phases as suggested by Grigull & Jönberger (2013). However, deformation of the rocks in a sheath fold as an alternative possibility cannot be ruled out. A more detailed evaluation of the gathered structural data needs to be done.

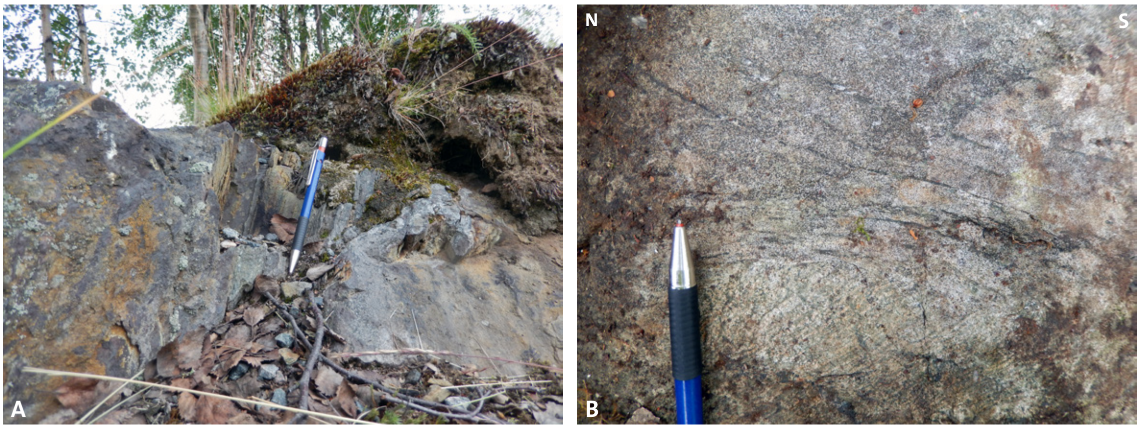


Figure 12. **A.** Graphite-bearing schist and metabasaltic rocks of the upper Vittangi greenstone group (7516083/756830). **B.** Meta-volcaniclastic sedimentary rocks or epiclastic sedimentary rocks of the upper Vittangi greenstone group. Note the cross-bedding indicating younging towards the east (7516494/756259). **C.** Metacarbonate rock of the upper Vittangi greenstone group. Where the metacarbonates consist almost purely of calcite, they often show a characteristic black weathering crust (7513984/758629).

Subarea 2: Folding patterns in the Porphyrite group at Särkirova

In the area around Särkirova and Bergmannivaara, metavolcanic rocks of the Porphyrite group crop out. In summary, these are metabasalts, metatuffites and andesine-porphyrites (Fig. 14a–c). The rocks around Särkirova are partly affected by the Karesundo-Arjeplog deformation zone that cuts the key area in its north-west corner. However, not much structural data is available in this area. An attempt was therefore made to understand the structural framework in the metavolcanic rocks of the Porphyrite group.

In the north-westernmost part of the key area, the dominant foliation strikes mainly north–south and the rocks seem to have been folded about north–south trending fold axes with trachytoid–rhyolites forming the core of the synclines and the basaltic rocks the core of the anticlines. However, closer towards a major fault extending north-east–south-west (south of Bergmannivaara), the strike of the dominant foliation turns into a more north-west–south-east or even north-east–south-west direction (Fig. 15). Here, stretching lineations in the andesine-porphyrites plunge moderately towards the west or north-west, i.e. not conformably with the overall north–south folding direction. At some localities, small-scale folding could be observed in the andesine-porphyrites. The stretching lineations correspond to the fold axes of these small-scale folds (Fig. 14d). Magnetic anomaly maps also indicate a folding and shear zone pattern in this area that is not easy to interpret (see geophysics section) and further evaluation of the newly available geophysical and geological data is necessary.

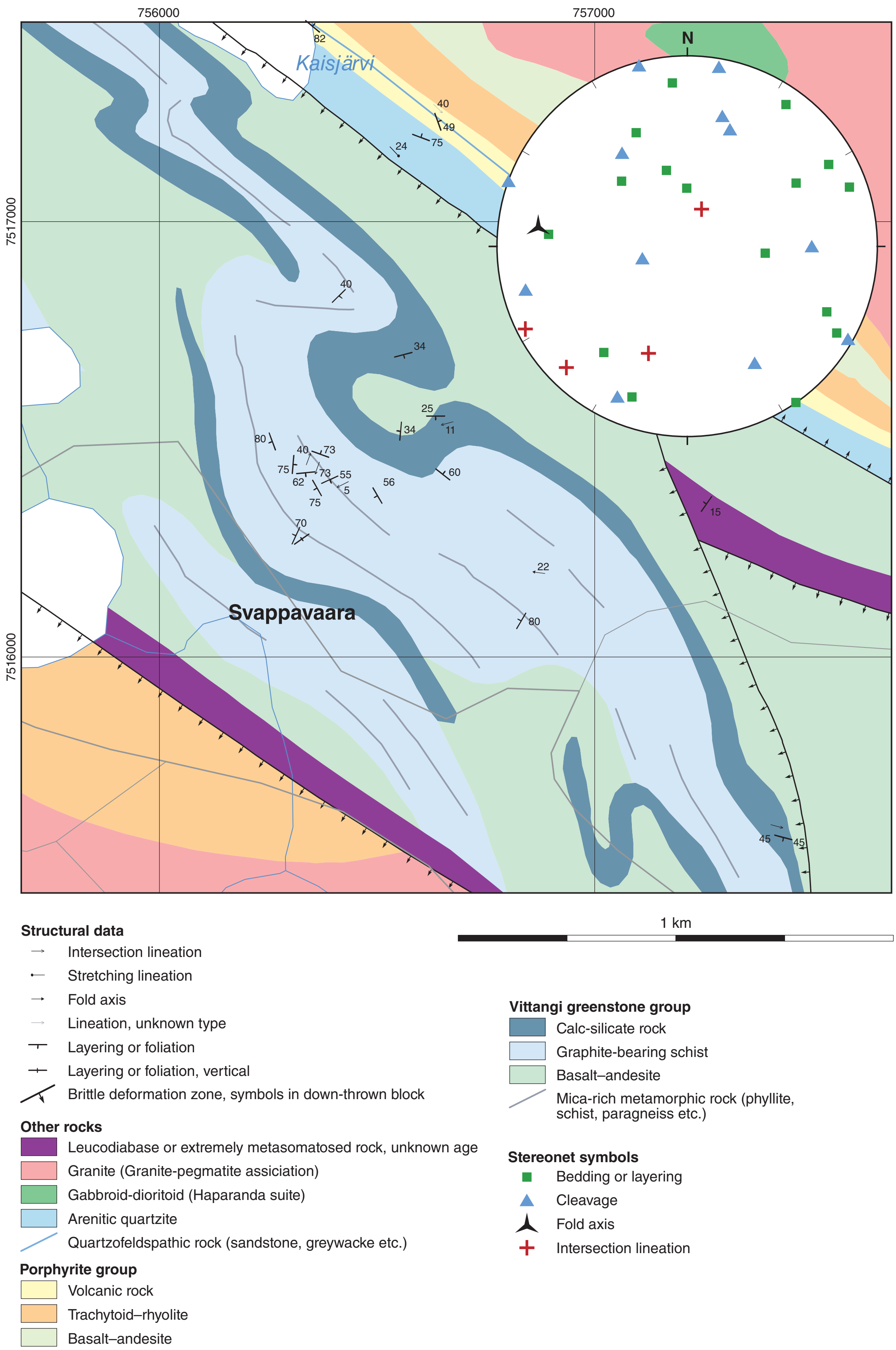


Figure 13. Local bedrock map of the Svappavaara key area. The stereographic projection shows no preferred orientation of foliations or cleavages.

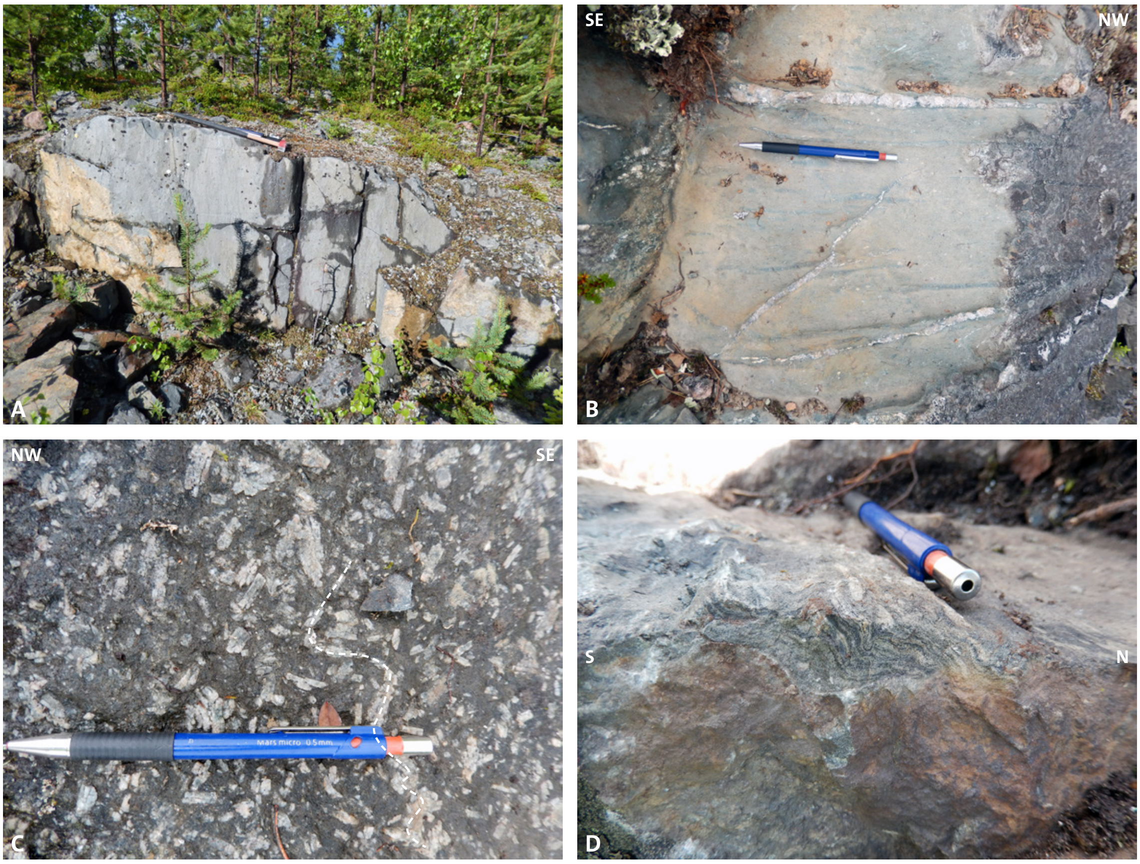


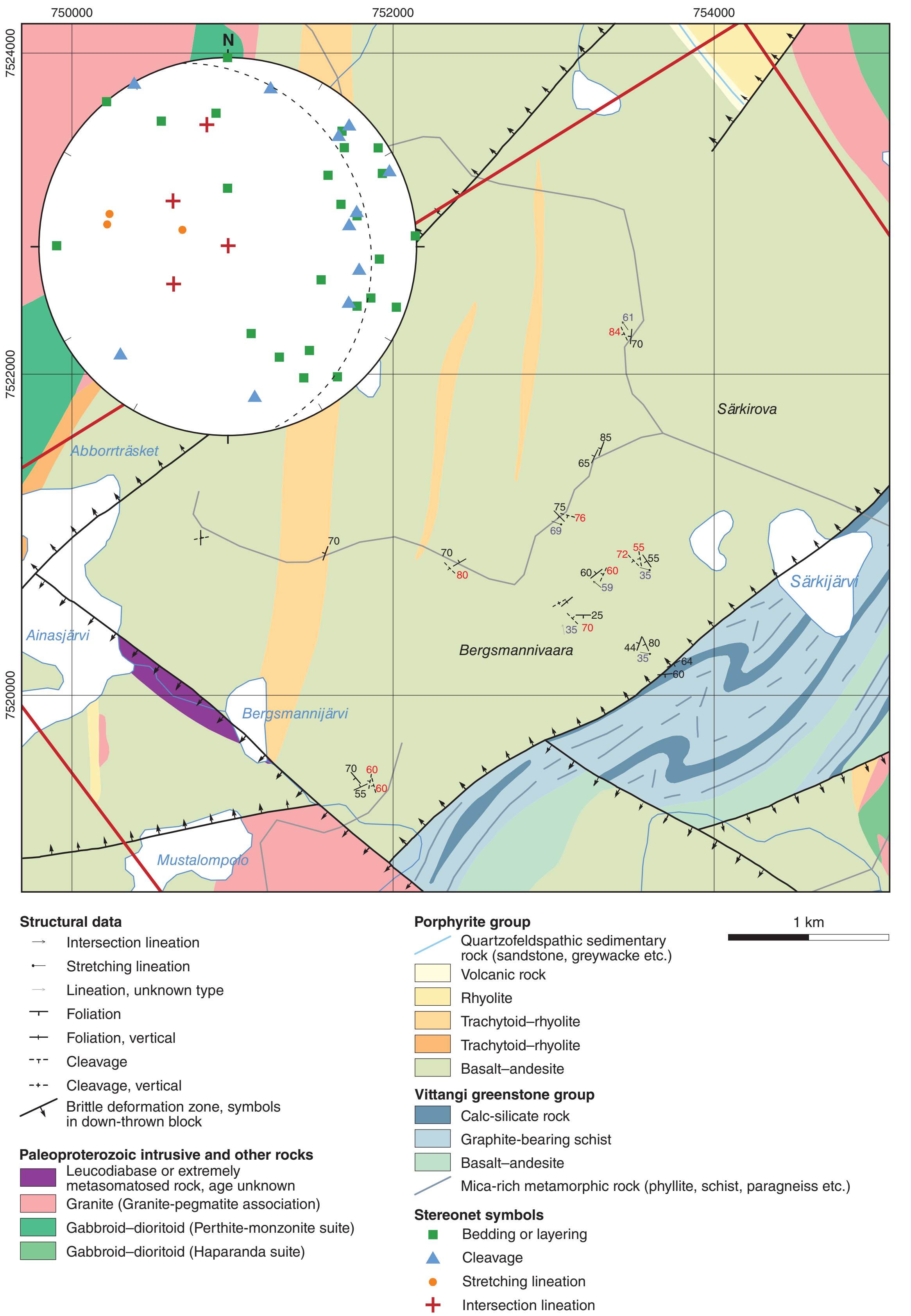
Figure 14. **A.** Massive, poorly foliated metabasalt of the Porphyrite group (7520830/752412). **B.** Metatuffite of the Porphyrite group. Note the slightly oblique extension of the quartz veins (752113/753032). **C.** Andesine-porphyrite with feldspar megacrysts. A vague folding pattern is visible (752113/753032, same location as B). **D.** Tight small-scale folds in andesine-porphyrite. The pencil tip points approximately westwards, down-plunge of the stretching lineation that is parallel to the small-scale fold axes (7520323/753533).

Subarea 3: North-west–south-east oriented shear zone north-east of Svappavaara

North of Svappavaara township, rocks of the Porphyry group as well as intrusive rocks of the Granite-pegmatite association have undergone strong ductile deformation. A north-west–south-east striking fault places these rocks adjacent to older rocks of the upper Vittangi greenstone group (Fig. 16). The fault is visible as a magnetic minimum in magnetic anomaly maps and is morphologically prominent as a depression filled by a marsh.

Both foliations and cleavages strike north-west (Fig. 16). Close to the fault, the dominant foliation dips steeply (c. 70°) towards the north-east, whereas further away from the fault, the dip angle is more moderate (c. 45°). Stretching lineations as well as the pole to the best-fit Pi-girdle to bedding plunge moderately towards the south-east (Fig. 16). If the assumption is made that the stretching lineations are parallel to the fold axis, the structural data collected in the area north-east of the brittle fault may support the interpretation of the larger scale deformation structure as a south-east-plunging, south-west vergent, overturned anticline.

At one location, north-east of lake Kaisjärvi, felsic veins of the Granite-pegmatite association have intruded mafic rocks of the Porphyry group. These rocks have been intimately folded and sheared resulting in a banded appearance of the rocks (Fig. 17a). This shows that the intrusion of the granite precedes the folding of the rocks in that area. This is further confirmed by the occurrence of stretching lineations also in the granite further away from the mafic rocks.



Figrue 15. Local bedrock map of the area around Bergmannivaara. The equal area, lower hemisphere stereographic projection shows measurements taken north-west of the major north-east–south-west trending horst. The great circle represents best fit Pi-girdle to poles of foliation planes.

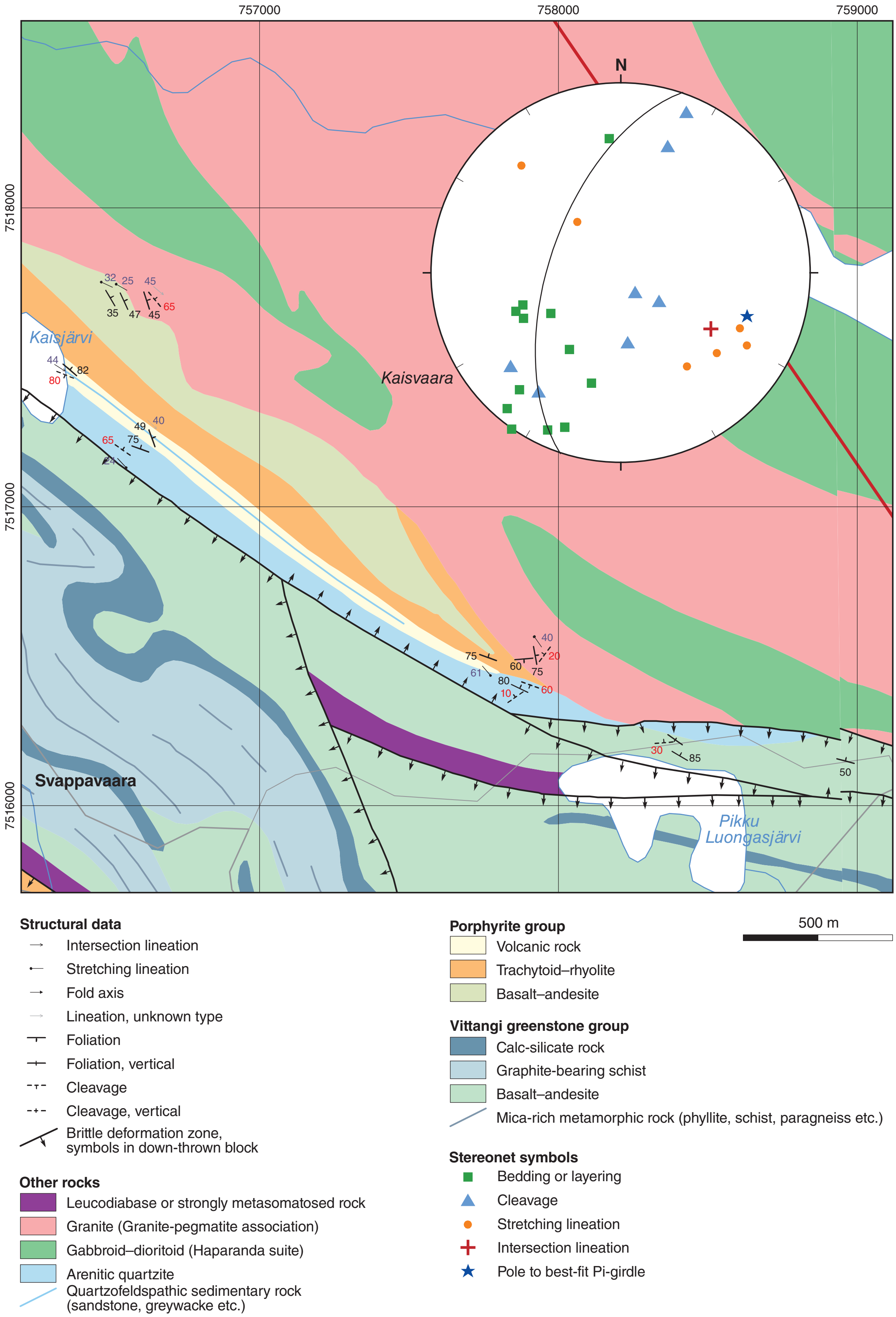


Figure 16. Local bedrock map of the area north of Svappavaara. The stereonet represents only orientations of geological structures in the Porphyrite group and Paleoproterozoic intrusive rocks (north-east of the north-west striking fault).

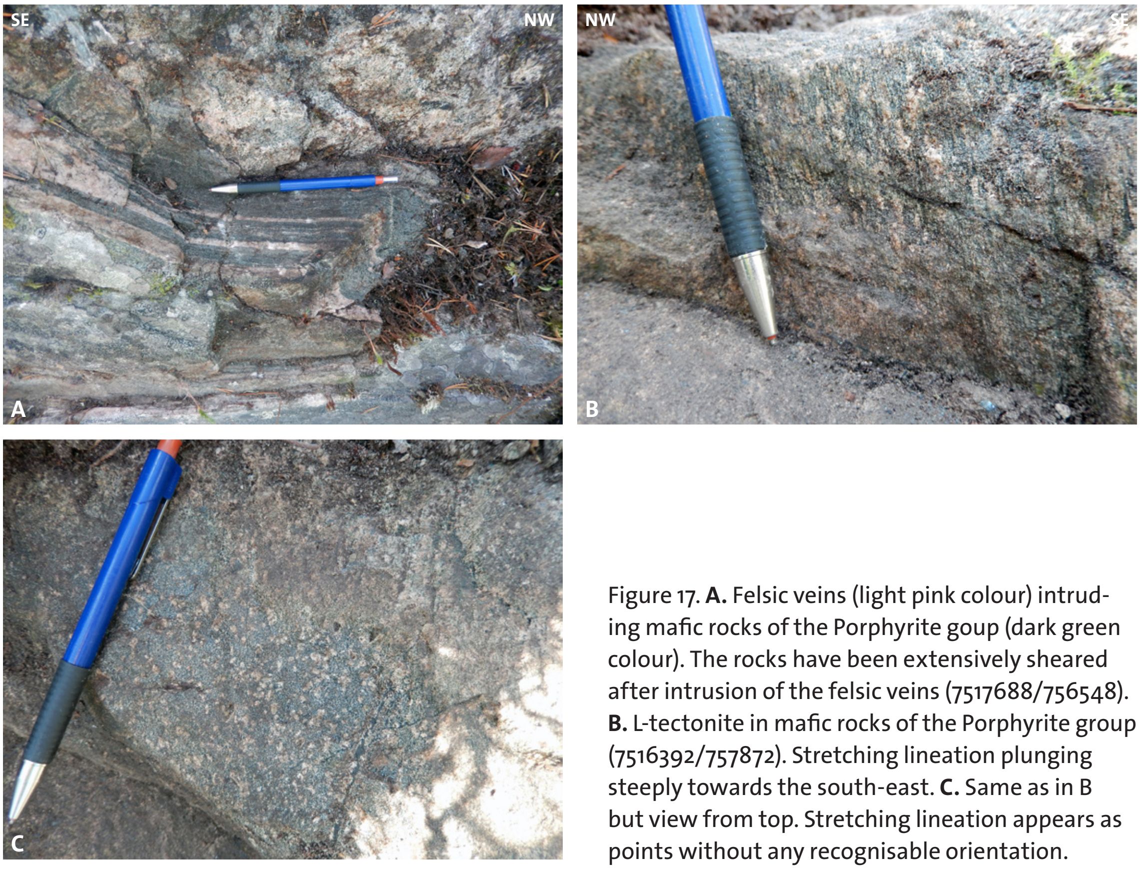


Figure 17. **A.** Felsic veins (light pink colour) intruding mafic rocks of the Porphyrite goup (dark green colour). The rocks have been extensively sheared after intrusion of the felsic veins (7517688/756548). **B.** L-tectonite in mafic rocks of the Porphyrite group (7516392/757872). Stretching lineation plunging steeply towards the south-east. **C.** Same as in B but view from top. Stretching lineation appears as points without any recognisable orientation.

The majority of the stretching lineations are observed in almost pure L-tectonites, indicating pure constriction (Fig. 17b–c). This can be interpreted as a close proximity to the core of the fold (e.g. Sullivan 2013). For a generally south-east plunging stretching lineation in a north-east dipping plane, this means that transport was dextral-oblique with top to the south-west movement.

GEOPHYSICAL MEASUREMENTS IN THE SVAPPAVAARA AREA

Geophysical overview

Most of the bedrock around the Svappavaara area is composed of intrusive rock. There are large areas of gabbroic composition north-west and east of the area. These areas have a relatively high signature in the airborne magnetic data (Fig. 18) which corresponds to local gravity highs (Fig. 19). Relatively large felsic intrusions in the north-east and south of the Svappavaara area have a homogenous, low-magnetic signature and low gravity anomalies. The Svappavaara area is situated east of the Karesuando-Arjeplog deformation zone and supracrustal rocks dominate along and especially east of this zone. On the magnetic map (Fig. 18), there is a pattern of magnetic structures coming down from the north and into the Svappavaara area. This pattern can be seen in more detail in the magnetic map which contains data from the ground measurements made in the 1950s, 1960s and 1970s (Fig. 20). The magnetic pattern coincides with a local positive anomaly on the gravity map, thus indicating a mafic composition in the rocks, which is in agreement with geological observations.

The apatite iron ores of Leveäniemi (7514400/755600) and Gruvberget (7515600/754000) are clearly visible on the magnetic anomaly maps.

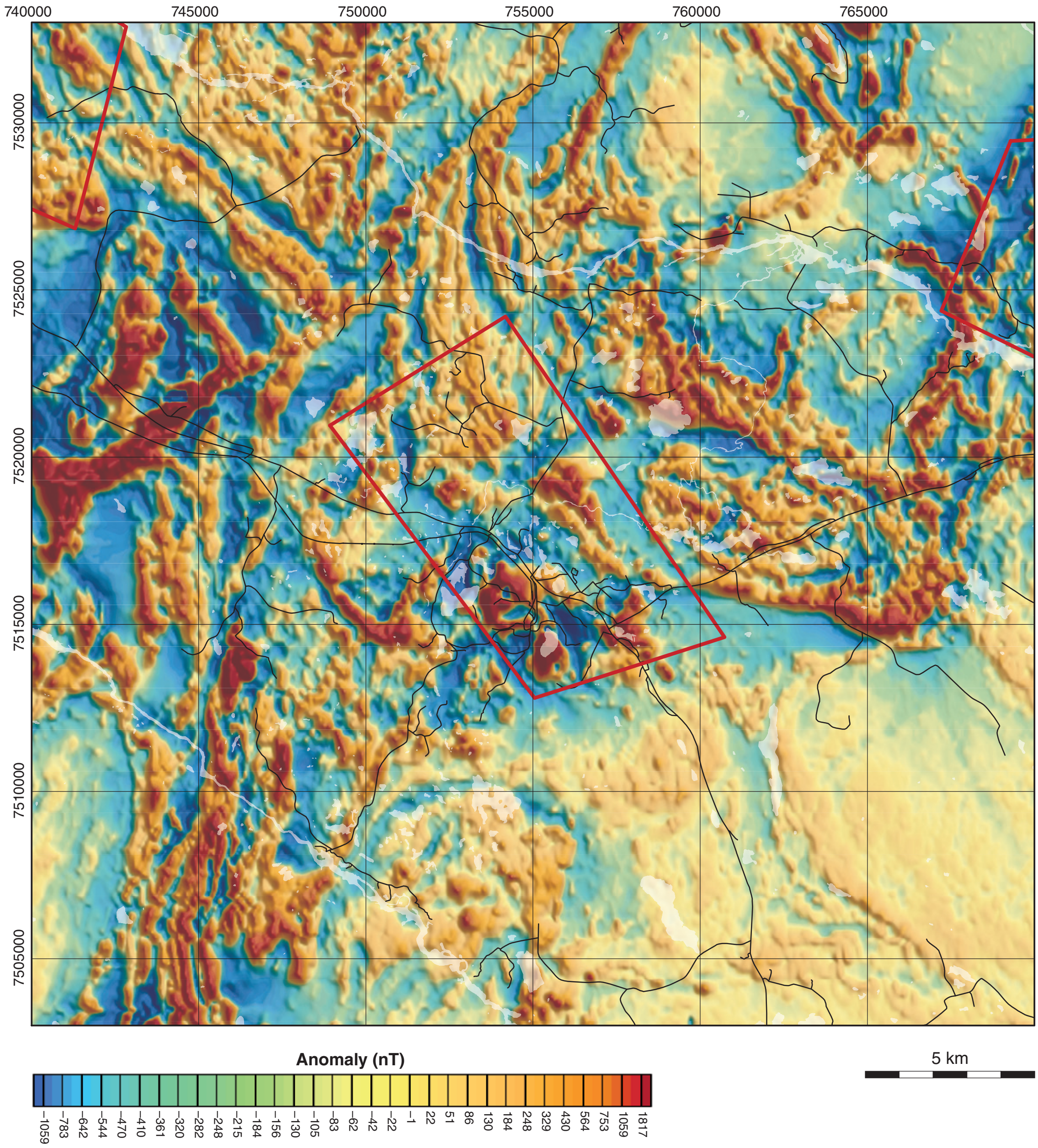


Figure 18. The magnetic anomaly map of the Svappavaara area and its closest surroundings. The white lines represent the Karesuando-Arjeplog deformation zone.

Geophysical fieldwork in 2013

The geophysical field work in the Svappavaara area was carried out during eight days. The field work included gamma spectrometer measurements on bedrock surfaces, acquisition of petrophysical samples, and ground geophysical measurements with magnetometer and VLF instruments. The goal of the field work was to trace magnetic and conductive structures which can be seen in the airborne data. The area where extensive ground magnetometer measurements were carried out is marked with a red rectangle in Figure 20, and the resulting grids are shown in Figure 21.

Long profiles with both magnetometer and VLF instruments were measured along the road at Särkirova, between coordinates 7521500/753990 and 7520800/755670. The measure-

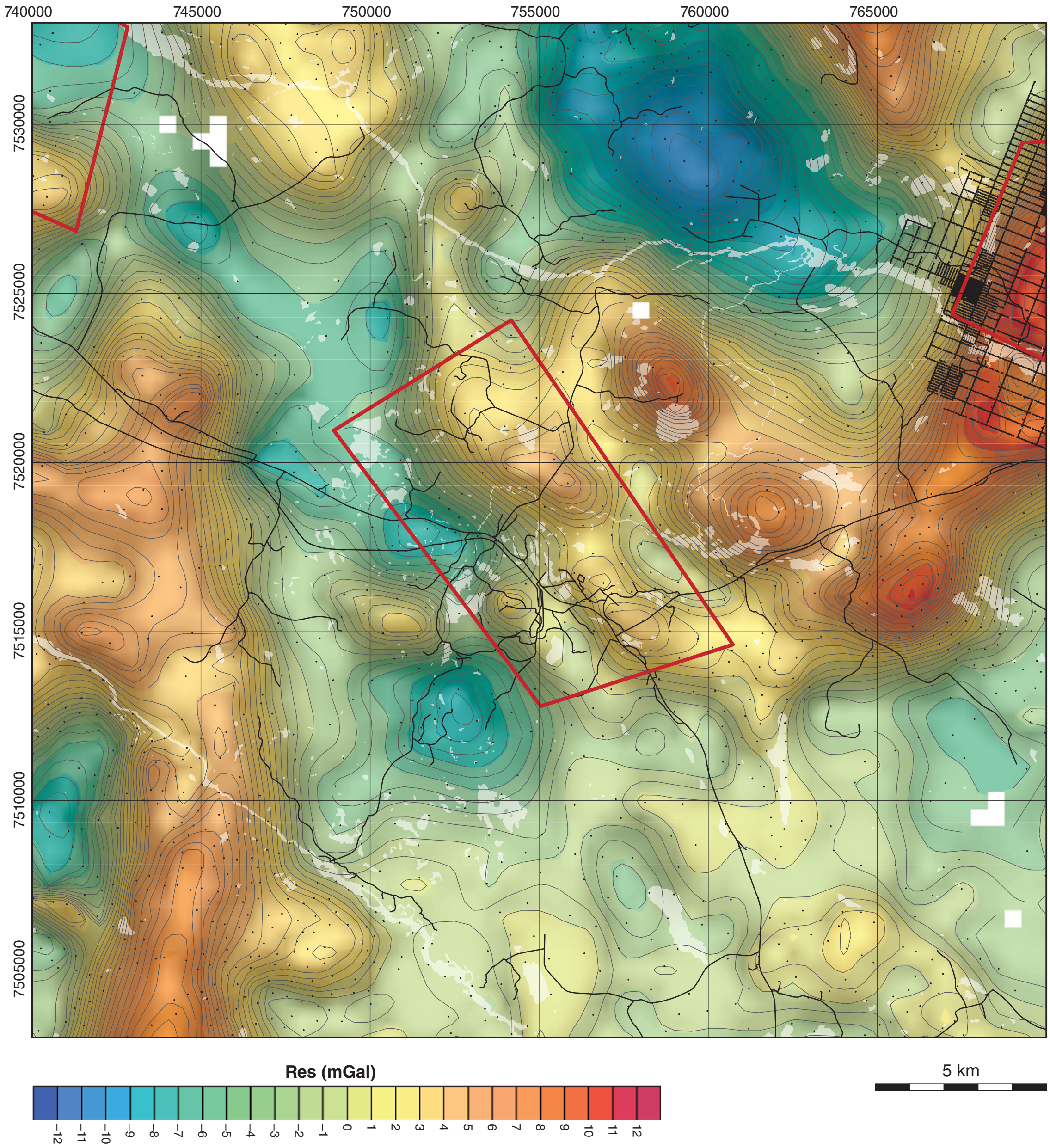


Figure 19. The gravity anomaly map of the Svappavaara area and its closest surroundings. The gravity field is expressed as the difference between the Bouguer anomaly and an analytical continuation upwards to 3 km. The small black points represent gravity measurement points. The distance between the isolines is 0.5 mGal.

ments were made across a pronounced deformation zone with a strike almost perpendicular to the road. The zone is clearly visible on both the magnetic anomaly map and the current density map (Fig. 22), derived from airborne geophysical measurements. The magnetic field varies extensively along one part of the magnetic profile which corresponds mainly to a large conductive zone, seen in the inversion model based on data from the VLF profile. Further to the north-west, another conductive zone which dips to the south-east is visible in the inversion model. At this zone, the magnetic field varies gently with local minima. Along the same conductive structure, almost 1,5 km to the south-south-west, the Särkivaara Mo-Cu-Au sulphide deposit is located.

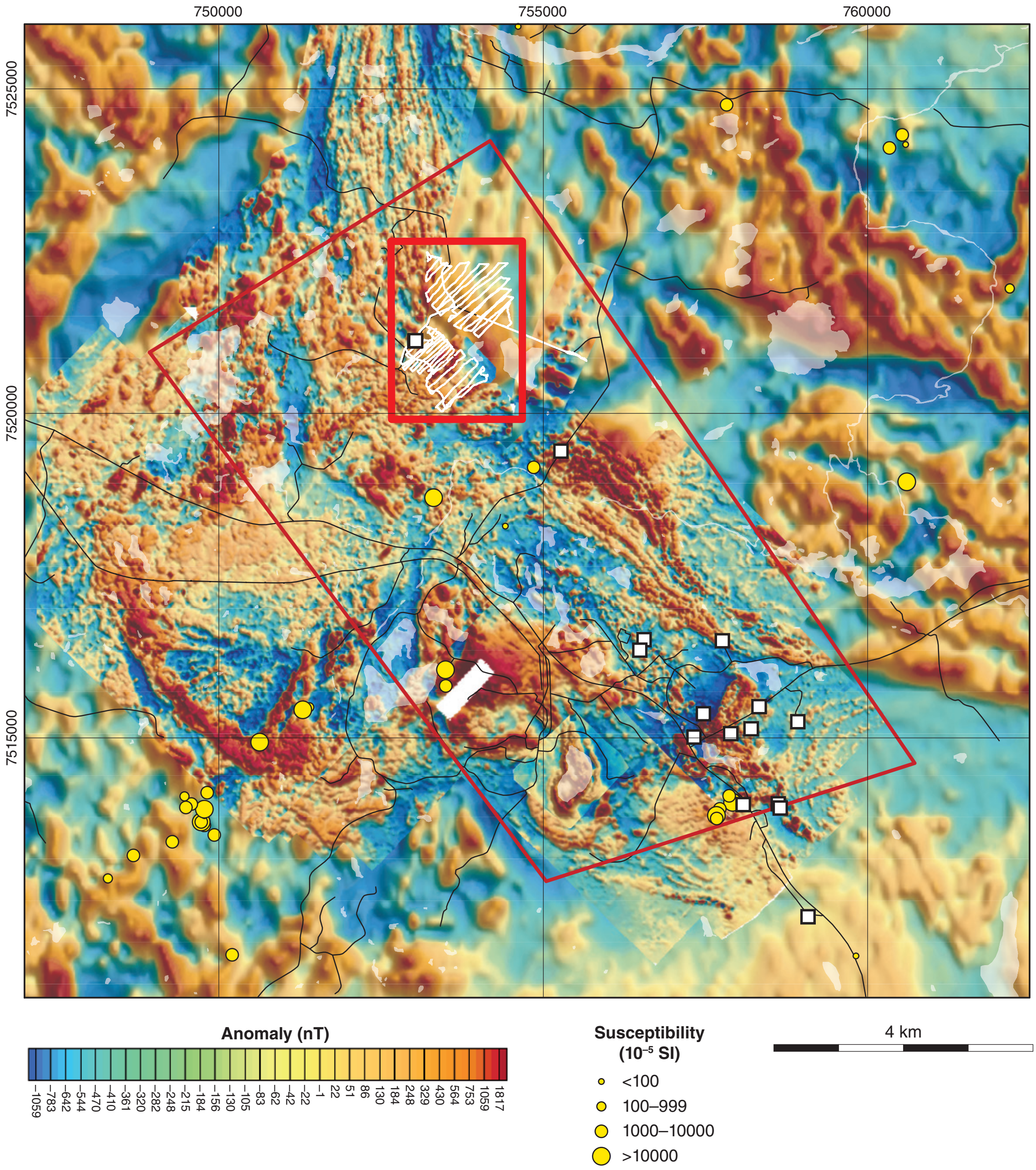


Figure 20. The magnetic anomaly map of the Svappavaara area. The backdrop shows the magnetic anomalies derived from airborne measurements. The more detailed data, mainly from within the Svappavaara area, shows the magnetic anomalies from ground measurements. The yellow circles represent, by proportional size, susceptibilities from existing petrophysical samples. The white lines show where ground magnetic measurements have been made in 2013, while the white squares show the locations for gamma spectrometer measurements on bedrock surfaces or where additional petrophysical samples have been acquired.

Gamma spectrometer measurements on bedrock surfaces were carried out at twelve localities within the Svappavaara and surrounding areas, and twelve bedrock samples for petrophysical measurements were acquired. The airborne data show mostly a low amount of uranium from within the Svappavaara area (Fig. 24). Higher values can be seen over the large felsic intrusions south-west of Svappavaara.

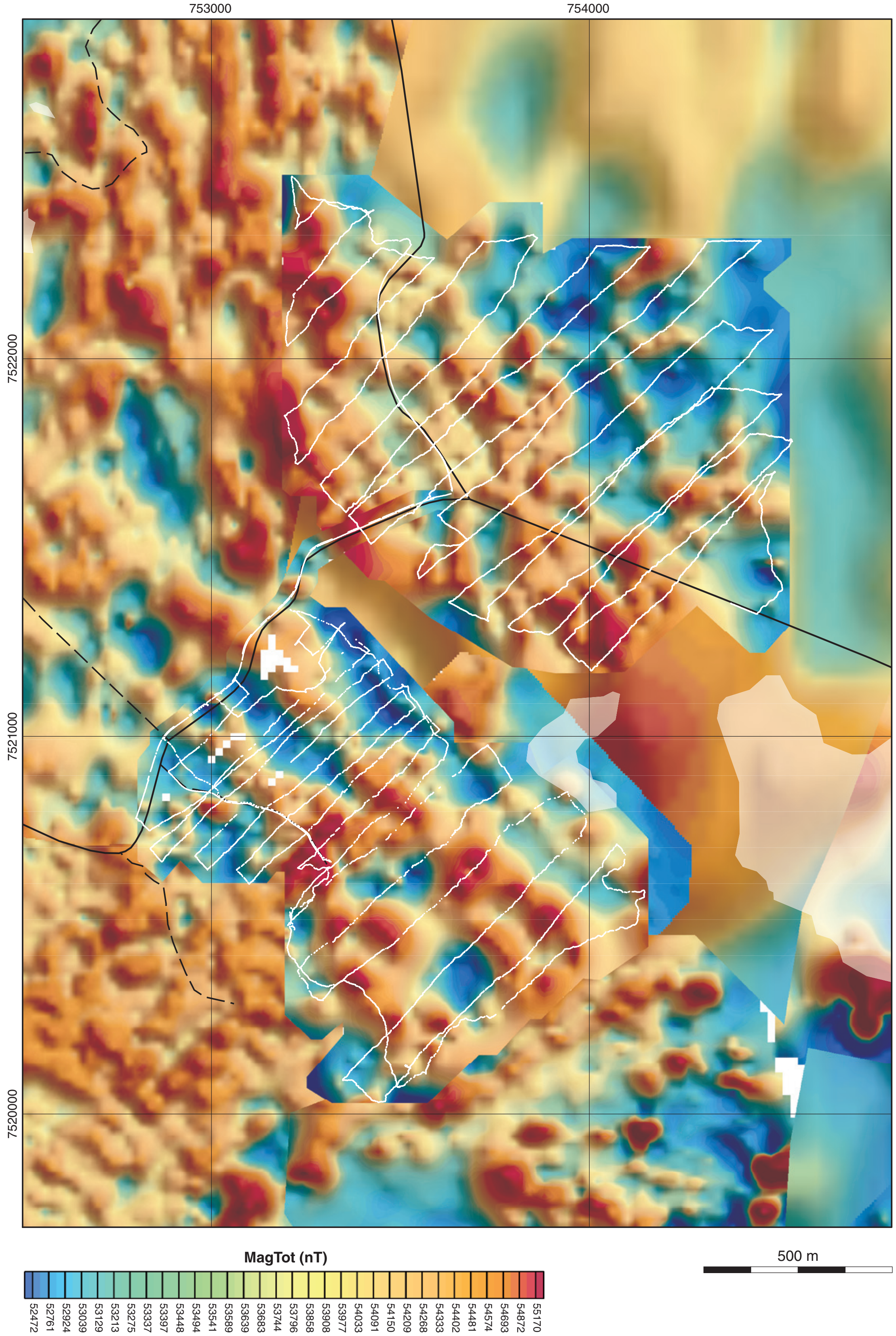


Figure 21. The resulting magnetic grids from ground measurements visualized as thin white lines. The backdrops are airborne magnetic anomaly or previously made ground magnetic measurements.

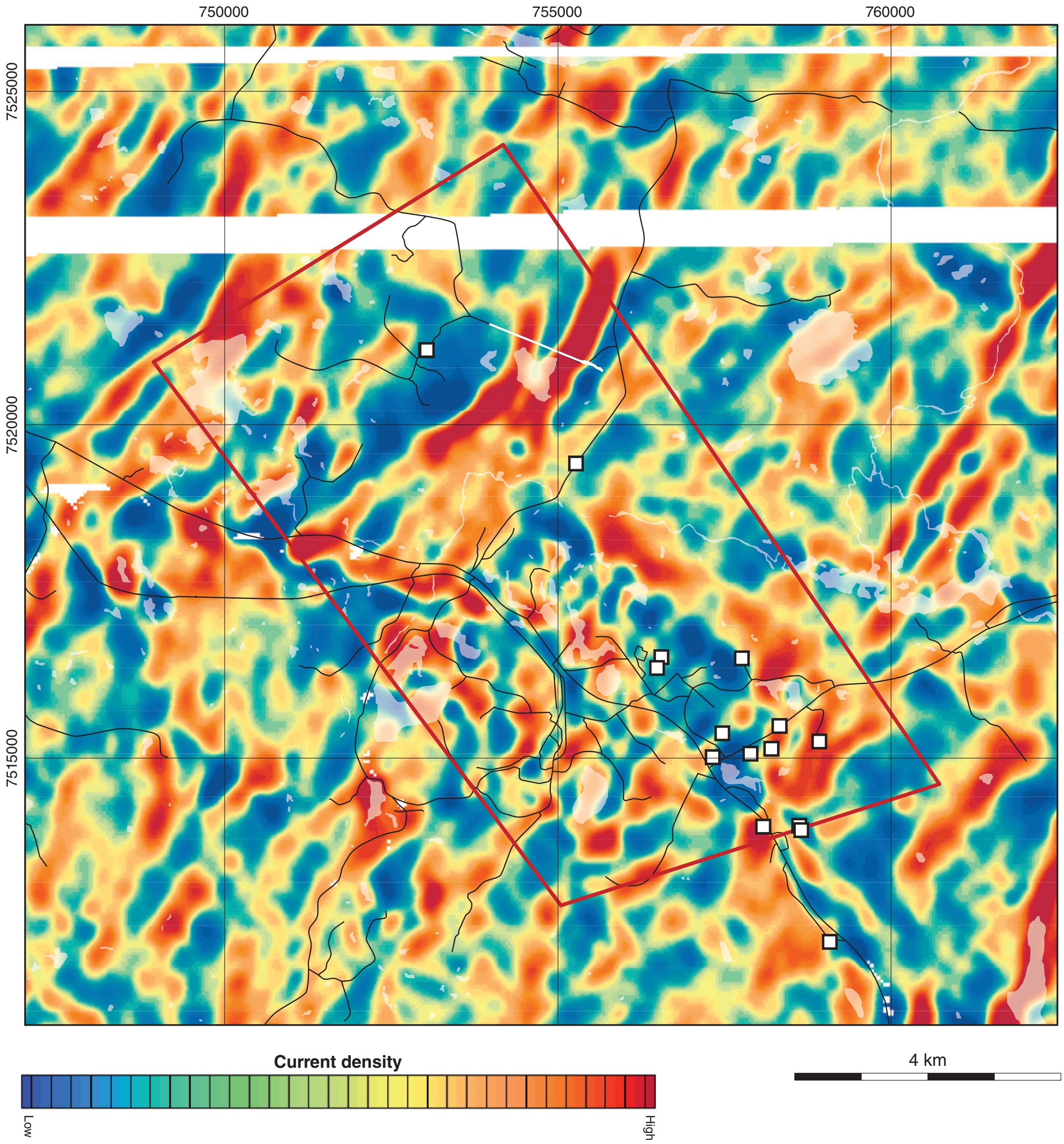


Figure 22. Map of the current density of the Svappavaara area, derived from airborne VLF-measurements. Red areas indicate good conductors. The white line shows where ground VLF measurements were carried out in 2013, while the white squares show the locations for gamma spectrometer measurements on bedrock surfaces or where additional petrophysical samples have been acquired.

Almost every observation in the Svappavaara area was made on mafic rock, either volcanic or intrusive. The potassium, uranium and thorium concentrations for these rock types are generally quite low. Six localities with mafic rock were visited and nine gamma spectrometer measurements were carried out showing 0.5–2.1% potassium, 0.8–2.3 ppm uranium and 1.3–5.5 ppm thorium. However, there are several places near Svappavaara were altered basaltic–andesitic, sulphide bearing rocks have significantly higher amounts of uranium (e.g. 7515144/758210, 7515016/757323, 7513923/758655, 7515482/758331). Ten gamma spectrometer measurements were carried out at these localities and their average uranium contents are 0.6–2.7% potassium, 13–21 ppm uranium and 2.7–7.2 ppm thorium.

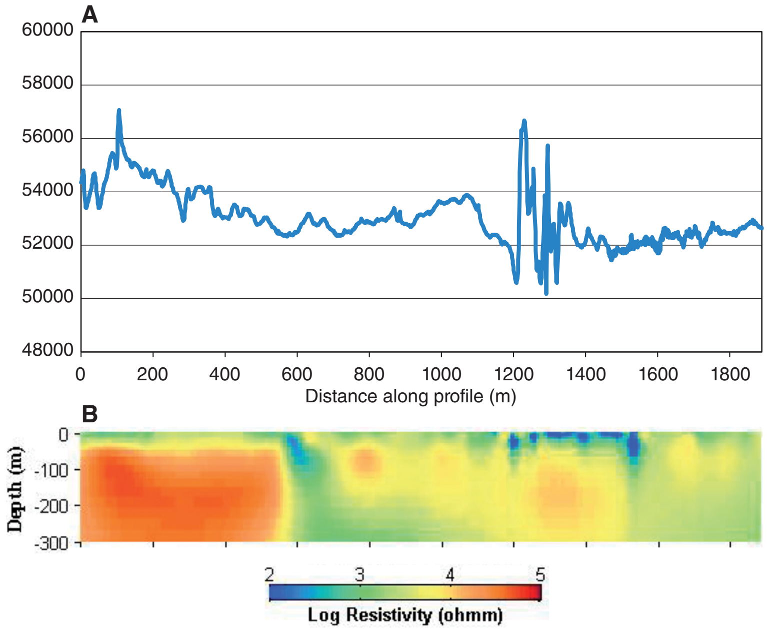


Figure 23. **A.** Variations in the magnetic field. **B.** Inversion model of the data from the VLF-profile. The location of the profile is shown in Figures 20 and 22.

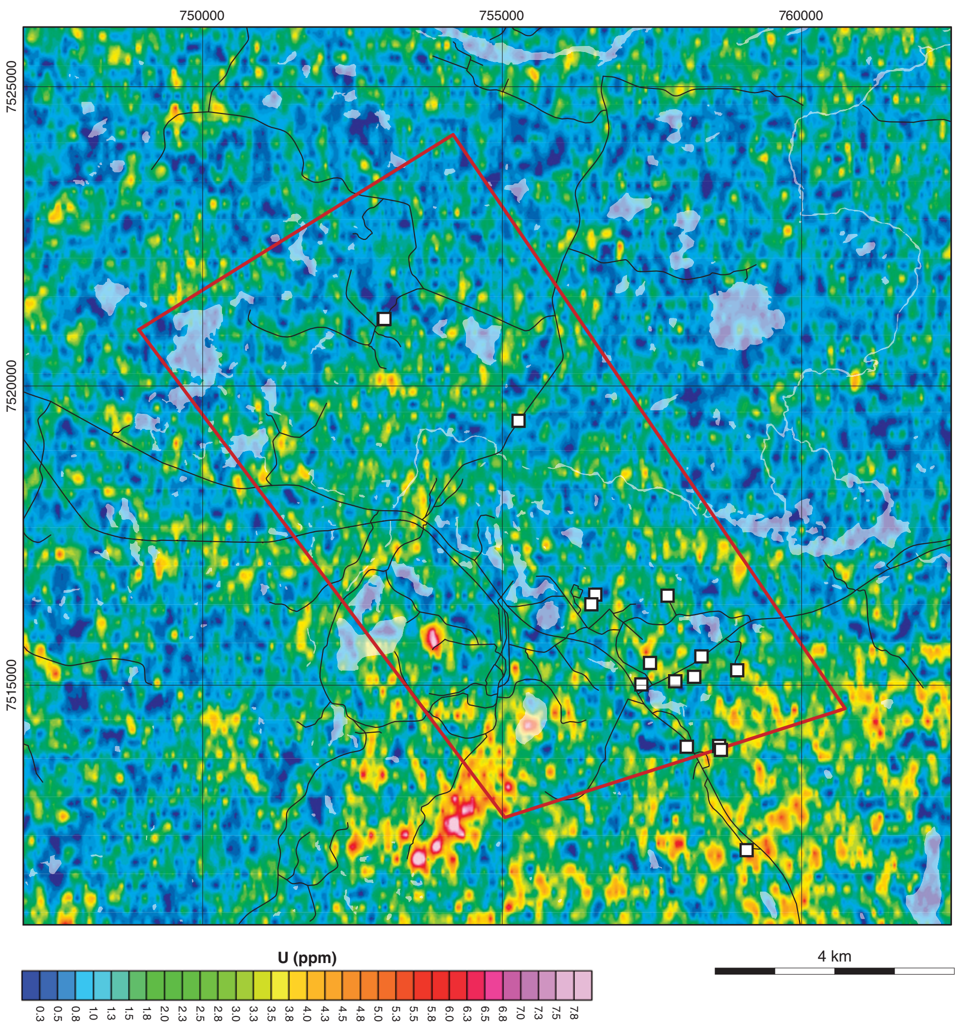


Figure 24. The uranium map of the Svappavaara area and its closest surroundings. White squares show the locations for gamma spectrometer measurements on bedrock surfaces or where additional petrophysical samples have been acquired.

REFERENCES

Ahl, M., Bergman, S., Bergström, U., Eliasson, T., Ripa, M. & Weihed, P., 2001: Geochemical classification of plutonic rocks in central and northern Sweden. *Sveriges geologiska undersökning Rapporter och meddelanden 106*, 82 pp.

Bergman, S., Kübler, L. & Martinsson, O., 2001: Description of regional geological and geophysical maps of northern Norrbotten County (east of the Caledonian orogen). *Sveriges geologiska undersökning Ba 56*, 110 pp.

Eriksson, B. & Hallgren, U., 1975: Beskrivning till Berggrundskartbladen Vittangi NV, NO, SV, SO. *Sveriges geologiska undersökning Af 13–16*, 203 pp.

Frietsch, R., 1966: Berggrund och Malmer i Svappavaarafältet, Norra Sverige. *Sveriges geologiska undersökning C 604*, 282 pp.

Grigull, S. & Antal Lundin, I., 2013: Kartering Barents. Background information Kiruna-Jukkasjärvi key area. *Sveriges geologiska undersökning SGU-rapport 2013:08*, 43 pp.

Grigull, S. & Jönberger, J., 2013: Kartering Barents. Background information Svappavaara key area. *Sveriges geologiska undersökning SGU-rapport 2013:09*, 39 pp.

Gustafsson, B., 1991: Kallosalmi diamantborrning VT 1991. Sveriges Geologiska AB Prospekteringsrapport PRAP 91020, 146 pp.

Martinsson, O., Vaasjoki, M. & Persson, P.-O., 1999: U-Pb zircon ages of Archaean to Palaeoproterozoic granitoids in the Torneträsk–Råstojaure area, northern Sweden. *In* S. Bergman (ed.): Radiometric dating results 4. *Sveriges geologiska undersökning C 831*, 70–90.

Martinsson, O. & Hansson, K.-E., 2004: Apatite iron ores in the Kiruna area. *In* R.L. Allen, O. Martinsson & P. Weihed (eds.): Svecofennian ore-forming environments. Volcanic-associated Zn-Cu-Au-Ag, intrusion-associated Cu-Au, sediment-hosted Pb-Zn, and magnetite-apatite deposits of northern Sweden. *Society of Economic Geologists Guidebook Series 33*, 173–175.

Sullivan, W.A., 2013: L tectonites. *Journal of Structural Geology 50*, 161–175.

Wright, S.F., 1988: *Early Proterozoic deformational history of the Kiruna district, northern Sweden*. Unpublished PhD thesis, University of Minnesota, 170 pp.