BARENTS PROJECT 2014

Geological and geophysical field work in the Käymäjärvi-Ristimella key area

Susanne Grigull & Robert Berggren

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Cover: Young moose (Berta) in swamp near Kaunis-
vaara. 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

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ABSTRACT

This report summarises the geoscientific field work that was done during the summer of 2014 in the Käymäjärvi-Ristimella key area as a part of the Barents project in northern Sweden. The key area lies within the Pajala-Kolari Fe-Cu-Au metallogenic district and contains greenstones that host at least one banded iron formation (BIF), as well as stratiform, skarn-hosted iron ore deposits. The geological field work focused on structural geological investigations of the bedrock in order to understand the structural framework and evolution of the area, including folding events and localised deformation. For a better understanding of the stratigraphy of the greenstones and the overlying Svecofennian rocks, bedrock samples were taken for analysis of lithogeochemistry and geochronology, and for thin section microscopy. The geophysical field work focused on collecting magnetic and electromagnetic data along profiles adding to the available airborne and ground geophysical data in order to interpret geological structures in areas with low outcrop density. Outcrop magnetic susceptibility measured at most locations and petrophysical samples for further analyses help constrain the geophysical models.

SAMMANFATTNING

Denna rapport sammanfattar det fältarbete som utfördes sommaren 2014 i nyckelområdet Käymäjärvi-Ristimella som en del av Barentsprojektet i norra Sverige. Nyckelområdet ligger inom det metallogenetiska området Pajala-Kolari som är mineraliserat med järn, koppar och guld. I området finns grönstenar som är värd för minst en bandad järnmalm. Dessutom finns stratiforma järnmineraliseringar i skarn. Fokus för det geologiska fältarbetet var strukturgeologiska undersökningar av berggrunden med syfte att förstå den strukturella uppbyggnaden och utvecklingen av området, inklusive veckfaser och lokaliserad deformation. För att få en bättre förståelse för grönstenarnas och de överlagrande svekofenniska bergarternas stratigrafi togs bergartsprover för litogeokemiska och geokronologiska undersökningar samt för tunnslip. Det geofysiska fältarbetet fokuserade på att samla in magnetiska och elektromagnetiska data längs profiler som komplement till den befintliga flygmätta och markmätta informationen för att hjälpa tolkningen av de geologiska strukturerna i områden med lite häll. Mätningar av magnetisk susceptibilitet på de flesta observationspunkter och petrofysiska prover har hjälpt till att förbättra de geofysiska modellerna.

INTRODUCTION

Within the framework of the Barents project (http://www.sgu.se/mineralnaring/barentsprojektet), SGU carried out field work in six of fifteen key areas in Norrbotten county during the summer of 2014. The Barents project concentrates on the Paleoproterozoic cover rocks as well as on some Archean basement rocks of the region. In each area the project aims to understand and characterise the following general points:

- Stratigraphic organisation and development
  - volcanology,
  - sedimentology,
  - chemical characterisation,
  - dating of metavolcanic rocks,
  - dating of detrital zircons in sedimentary rocks,
  - 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 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 planar and linear geological features, shear zone kinematics, folding structures),
  - sampling for lithogeochemistry and geochronology.
- Geophysical observations
  - ground geomagnetic measurements,
  - ground electromagnetic measurements (e.g. VLF),
  - radiation,
  - magnetic susceptibility measurements,
  - sampling for petrophysical analyses.

This report summarises the field work done during 2014 in and around the Käymäjärvi-Ristimella key area north of Pajala. The collected geological and geophysical data are presented in the form of maps, field photographs and stereographic projections. Some preliminary geophysical models of ground magnetic data are also included. All interpretations will be verified against results of ongoing thin section microscopy, and lithogeochemical and geochronological analyses. Further interpretation of geophysical data will also be used in the verification process.

BEDROCK GEOLOGICAL OVERVIEW

A summary of available geological and geophysical background data as well as an introduction to the geology of the Käymäjärvi-Ristimella key area is provided in Grigull et al. (2014).

The study area is located in the Norrbotten and Överkalix lithotectonic domains of the Fennoscandian shield (Fig. 1). Paleoproterozoic pre-and syn-Svecokarelian volcanic, epiclastic and clastic sedimentary rocks constitute the main bedrock units in the area. These rocks are intruded by different generations of syn-Svecokarelian magmatic rocks (Fig. 2). All rocks except the youngest intrusive rocks have undergone at least greenschist and up to upper amphibolite facies metamorphism. For the sake of conciseness, the prefix "meta" has been omitted from all rock type names if the protolith could be discerned. In other cases, metamorphic terminology has been applied to describe the rock types.

The rocks in the area show a polyphase deformational history including an early folding phase as well as later localised deformation probably related to the so-called Pajala shear zone

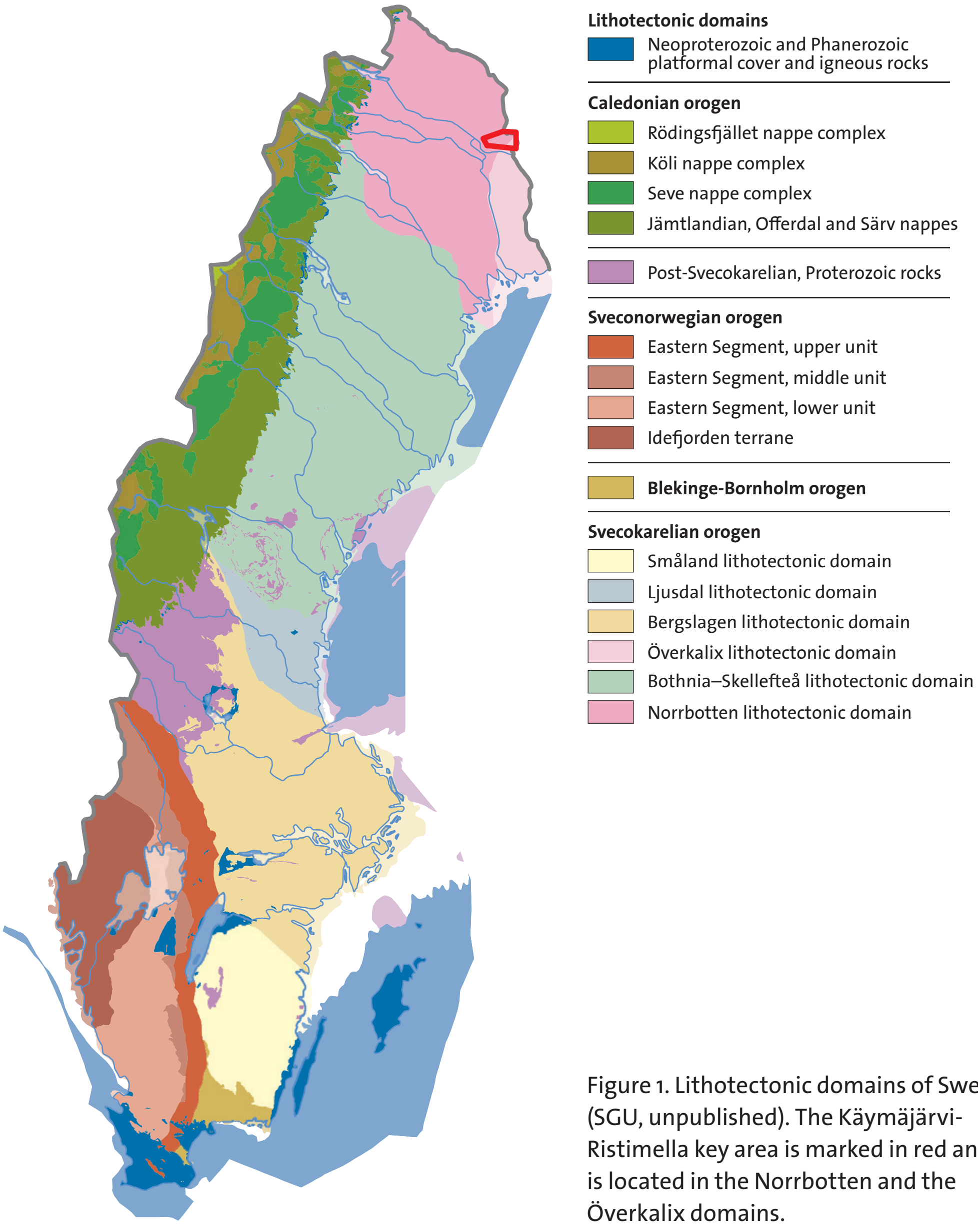

Figure 1. Lithotectonic domains of Sweden (SGU, unpublished). The Käymäjärvi-Ristimella key area is marked in red and is located in the Norrbotten and the Överkalix domains.

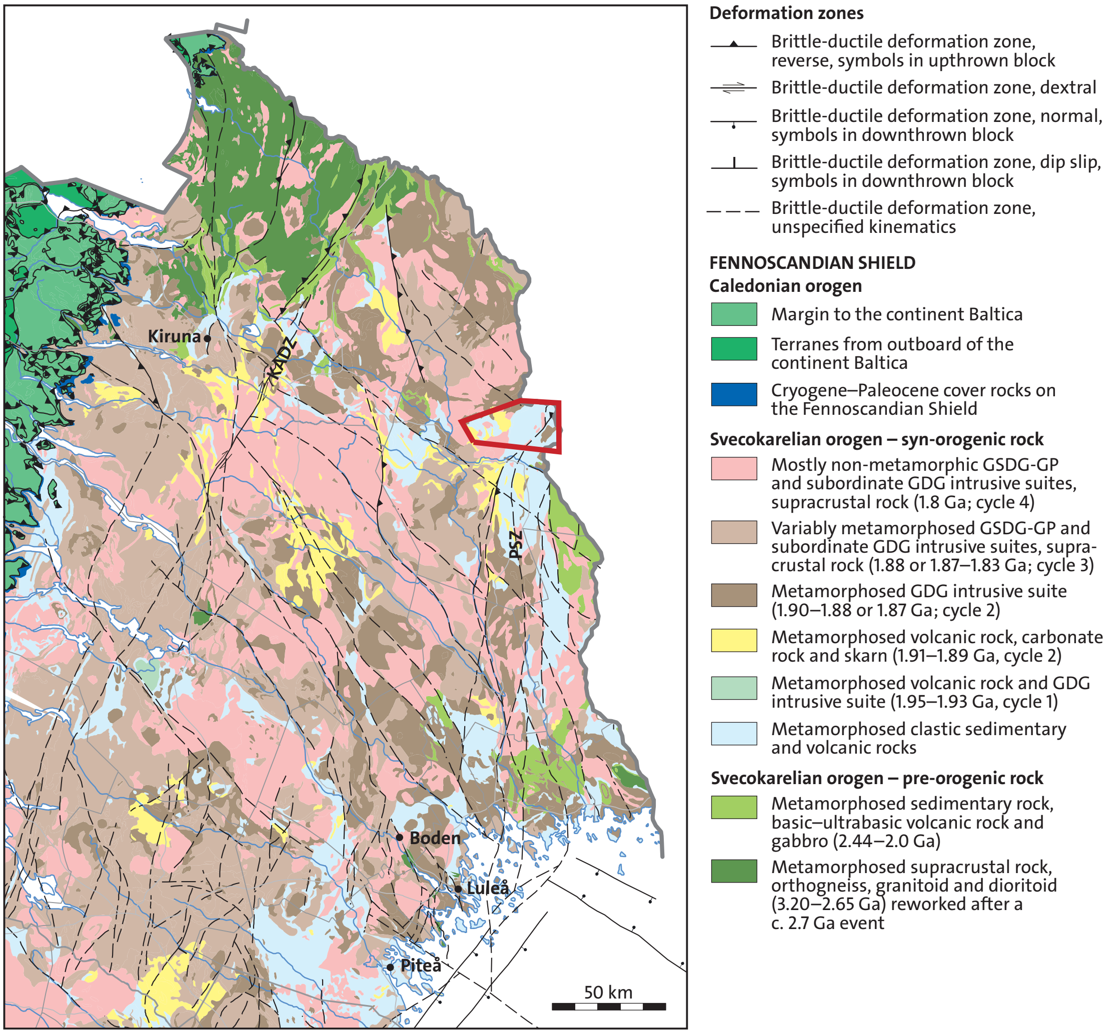

Figure 2. Simplified lithological map (modified from Bergman et al. 2012). The Käymäjärvi-Ristimella key area is marked in red. KADZ: Karesuando-Arjeplog deformation zone. PSZ: Pajala shear zone. GSDG: Granite-syenitoid-dioritoid-gabbroid. GP: granite-pegmatite. GDG: granitoid-dioritoid-gabbroid.

(Fig. 2), or to a later phase of localised deformation along a north-east trending deformation zone.

The key area lies within the Pajala-Kolari Fe-Cu-Au metallogenic district and contains the well-known Kaunisvaara ore belt that includes the stratiform skarn-hosted iron ore deposits Stora Sahavaara and Tapuli. A banded iron formation (BIF) occurs in the area around Käymäjärvi and Jupukka (Fig. 3).

Main bedrock units

The Paleoproterozoic supracrustal rocks can be divided into two major groups (Martinsson 2004, Grigull et al. 2014 and references therein). From oldest to youngest, these are the Karelian greenstone group and the Sammakkovaara group (Martinsson 2004, Martinsson et al. 2013). A summary of the main characteristics and inferred tectonic setting of these two formations is provided in Grigull et al. (2014). Here, Tables 1 and 2 are taken from Grigull et al. (2014). They present some of the characteristics of the main bedrock units.

Table 1. Stratigraphic overview of the rocks in the Käymäjärvi-Ristimella key area.

Formation	Subunit	Main rock types	Thickness	Mineral deposits	Notes
Sammakkovaara group (1.9–1.88 Ga) (Martinsson 2004) Equivalent to combination of Pahakurkkio group and Porphyrite group (e.g. Padget 1970)	Hosiovaara fm.	Volcanic rocks. Andesitic to dacitic composition. Locally clast-supported conglomerates; clasts mostly andesitic pebbles of local origin.	?		
	Hosiokangas fm.	Dominated by clastic sediments deposited in shallow water. Arenitic to pelitic composition. Locally up to 10 m thick quartzite pebble conglomerates. Cross-bedding, ripple marks.	?		
	Muotkamaa fm.	Volcanic rocks with minor intercalated clastic sediments. Andesitic composition.	?		
Karelian greenstone group (c. 2.1 Ga) (Martinsson et al. 2013)	Vinsa fm. (Martinsson et al. 2013) Equivalent to Käymäjärvi group (Padget 1977) Equivalent to Iron ore formation (Lindroos 1974, Hallberg et al. 2012)	Marble, magnetite, skarn, dolomite	150–200 m	Tapuli, Stora Sahavaara, Runtijärvi, Palotieva	
		Mainly mafic tuffites and graphite units	c. 100 m	none	
		BIF*	150–200 m	Sahavaara Södra, Sahavaara Östra*, Käymäjärvi*	*Only in Käymäjärvi. Seems to be missing in Kaunisvaara belt. Instead replaced by Sahavaara Östra skarn iron ore
		Mainly mafic tuffites and graphitic units	>50 m		
	Käymäjärvi fm. (Martinsson et al. 2013) Equivalent to Kolari greenstone (Padget 1977)	Greenstones consisting of partly graded picritic lapilli tuff. Basaltic rocks (volcaniclastic and basaltic lava), mafic sills and dykes.	>150 m		

Table 2. Members M1 to M4 of the Vinsa formation (after Martinsson et al. 2013).

Member	Rock types and minerals	Thickness
M4	Dolomite Skarn iron ore	150–200 m
M3	Basic tuffites Includes graphitic and calc-silicate bearing units Partly laminated on a mm scale Scapolite common + diopside (major component in some beds) Disseminated graphite and Fe-sulphides	c. 100 m
M2	BIF with locally developed oxide facies Distinct 5–30 cm thick bands of recrystallised chert alternating with silicate beds (px, amp, gt, fa), grünerite most dominant in silicate bands Magnetite locally as micro-scale banding or disseminated	150–200 m
M1	Top: Scapolite alteration Tuffites, basic composition, locally graphite-bearing Fe-sulphide quite high; graphite only a few percent Middle part: beds rich in garnet porphyroblasts	>50 m (?)

FIELD OBSERVATIONS AND GEOPHYSICAL MEASUREMENTS 2014

Grigull et al. (2014) formulated a list of key questions to be addressed during field work. These questions are summarised and repeated below. For locality names, the reader is referred to Figure 3.

- Have the rocks of the Sammakkovaara group undergone the same amount and style of deformation as rocks of the underlying Karelian greenstone group?
- What are the kinematics of the north-east to south-west oriented shear zone between Ristimella and Erkheikki? How is this structure related to the Pajala shear zone? How does it continue into Finland?
- What has caused the deflection in orientation of the south-eastern closure of the Käymäjärvi anticline?
- How are the Käymäjärvi anticline and the Kaunisvaara ore belt structurally related?
- How are the Kaunisvaara ore belt and the Ristimella syncline structurally related?
- What kind of tectonic structure does the Pajala shear zone represent?
- What is the age of migmatisation on both sides of the Pajala shear zone?

In total, 124 geological field observations were made in the area. 47 samples were taken for lithogeochemical analyses and 10 samples for potential geochronological analyses. 49 samples are available for the preparation of thin sections and 29 of these samples are oriented. Of the 47 lithogeochemical samples, 23 samples were also analysed for their petrophysical properties in order to investigate if they have physical properties that distinguish different rock types from each other and can be used to model geophysical ground data. Figure 3 shows the distribution of observation and sampling sites. The focus of the geophysical field work was on ground measurements of the magnetic total field and VLF-EM (very low frequency electromagnetic) measurements and resulted in 11 magnetic profiles and 6 VLF-EM profiles. A total of 75 km of ground measurements were collected. Figure 4 shows the location of the acquired geophysical profiles. The targets of the different profiles were as follows:

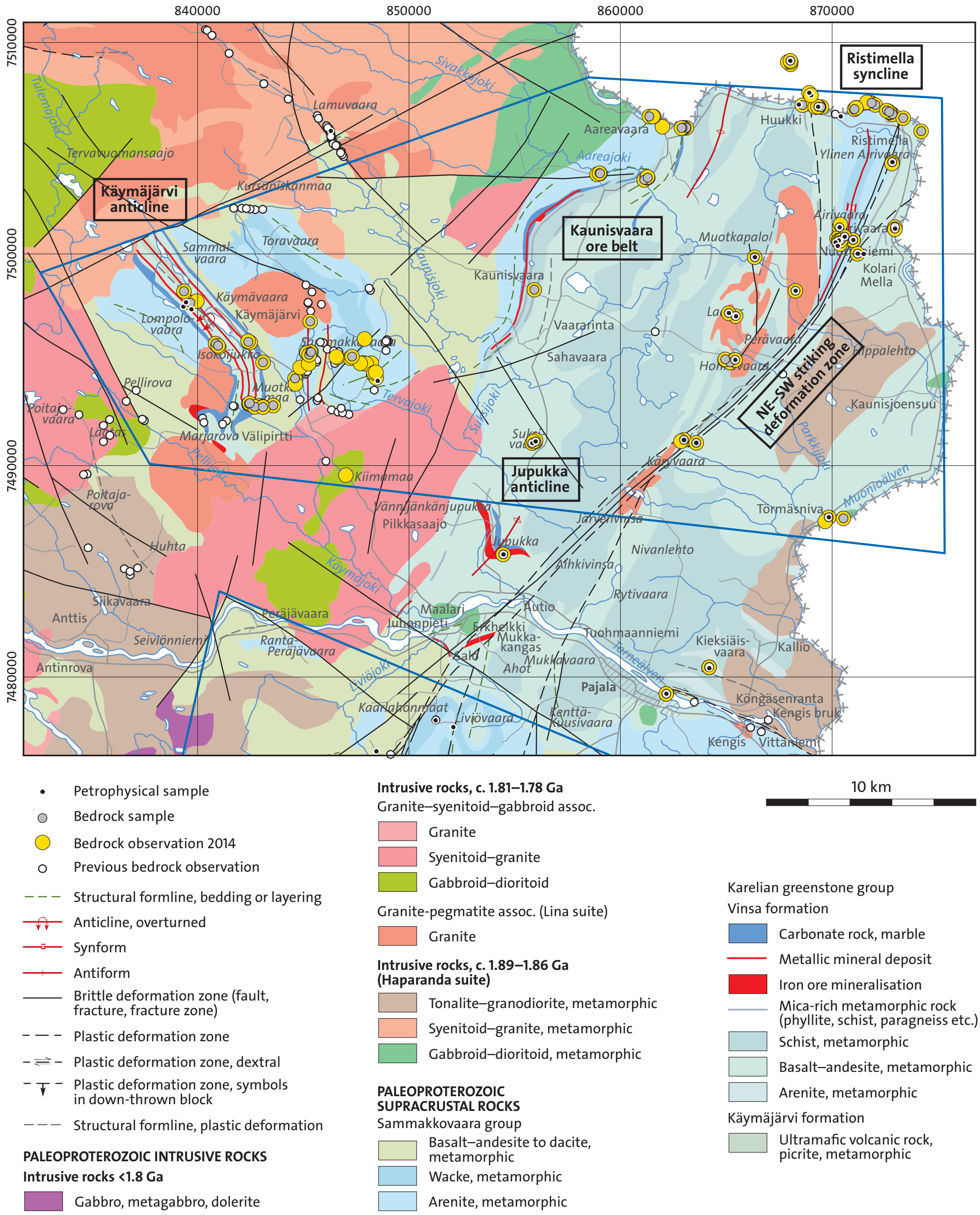

Figure 3. Regional geological map of the Käymäjärvi-Ristimella key area (marked in blue). Observation and sample sites are indicated. Map based on SGU's 1:250000 map database.

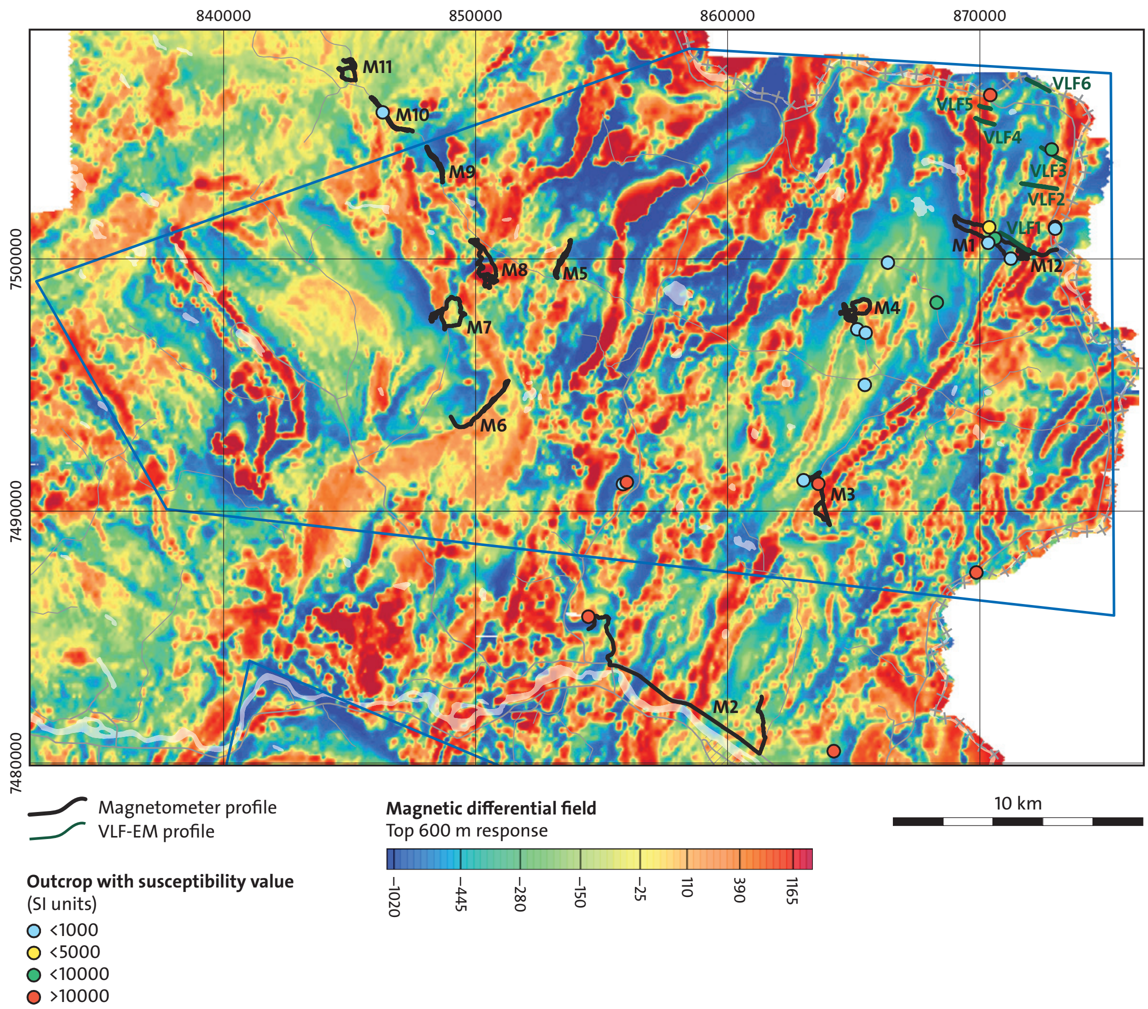

Figure 4. Overview map of airborne measurements of the total magnetic field with flight direction east–west.

- Magnetic and electromagnetic data along profiles M1, M12 and VLF1-3 were collected in order to clarify the relationship between the north-east trending deformation zone and the Ristimella syncline, as well as to gather information on the dip direction of the north-east–south-west striking deformation zone.
- Magnetic profile M2 was measured in order to cross the southern part of the north-east–south-west striking deformation zone and potentially transition into the Pajala shear zone. This profile was also gathered in order to connect structures south-east and north-west of the north-east-trending deformation zone.
- Magnetic profile M3 was intended to clarify the relationship between the north-east trending deformation zone and folding to the south-east of the zone.
- Magnetic profile M4 was measured in order to investigate if the presumed folding pattern is cut by a brittle fault.
- Magnetic profiles M6 and M7 were intended to understand whether there is a cause for the abrupt change in magnetic field strength other than a change in rock type.

Figure 5. Basic lapilli tuff with picritic composition of the Käymäjärvi formation. Near Käymäjärvi (N7497684, E839675). Photo: Susanne Grigull.

- Magnetic profile M8 was measured to find the cause of a relatively linear north-east trending magnetic low that might represent a deformation zone.
- Magnetic profiles M5 and M9 were intended to result in information on areas without exposure where lithological boundaries are marked on the geological map. Information about dip direction and angle of geological units and structures were also a target.
- Along electromagnetic profiles VLF4–6, use was made of graphite layers (good conductor) as tracer for complicated folding patterns.

Karelian greenstone group

Käymäjärvi formation

In the field area, the oldest rocks of the Karelian greenstone group can be found near Käymäjärvi. They are grey to green, volcanic rocks with a picritic composition. The groundmass of the rocks is very fine-grained and locally the rocks occur as lapilli tuff, probably of pyroclastic origin. This is most obvious on weathered surfaces in places where the lapilli are stretched due to deformation (Fig. 5). The rocks contain phenocrysts that are up to 1 mm size. The phenocrysts are probably pyroxene or pseudomorphs after pyroxene. This needs to be determined under the microscope. The picrites belong to the Käymäjärvi formation.

Vinsa formation

The Vinsa formation is a mixed unit of mafic volcanic and volcaniclastic rocks, calcsilicate rocks, dolomite, graphite-bearing schists, skarn-hosted iron ore and banded iron formation. Four

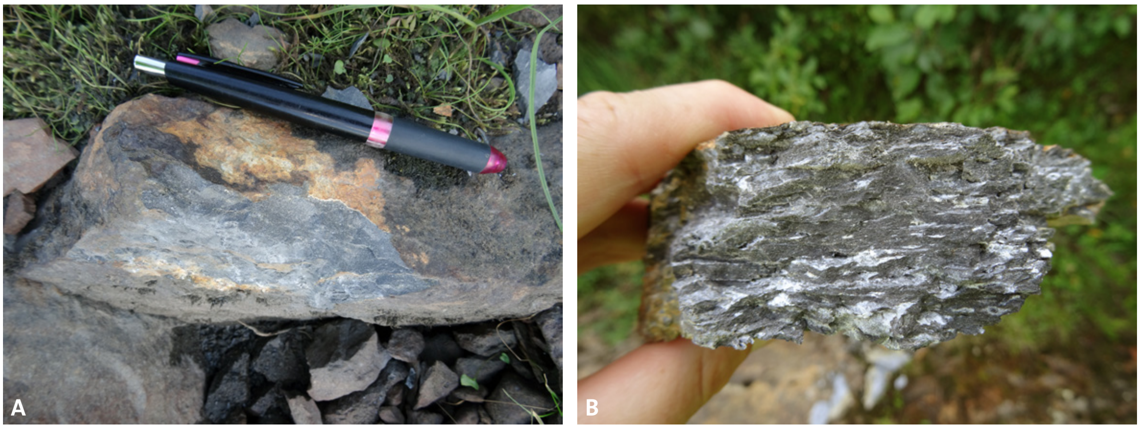

Figure 6. **A.** Fine-grained basalt of the lowest member (M1) of the Vinsa formation. Location N7506781, E872598. **B.** Graphite-bearing schist of M1. Location N7506607, E872865. Photo: Susanne Grigull.

members (M1 to M4) have been distinguished in the Vinsa formation (Martinsson et al. 2013, see also table 2). They are described below.

M1

Rocks of the lowest member of the Vinsa formation (M1) occur within the core of the Käymäjärvi anticline and possibly in the very north-eastern part of the key area. Grey, fine- to medium-grained tuffites with basic composition as well as grey, fine-grained basalts (Fig. 6A) comprise the main part of the lowest member of the Vinsa formation. Partially strong alteration and deformation makes it challenging to retrieve more information on these rock types without lithogeochemical analyses. Graphite-bearing schists are intercalated in the tuffites. These are dark grey and very fine-grained (Fig. 6B). The schists contain sulphide mineralisation such as pyrite, chalcopyrite and pyrrhotite, which leads to a typical rusty weathering. Graphite-bearing schists of M1 are exposed in a c. 20 m wide outcrop along the river Muonioälv.

M2

The second member of the Vinsa formation consists of a banded iron formation (BIF) with a locally developed oxide facies. These rocks are banded with 10–20 cm thick layers of recrystallised chert and silicates. At Jupukka, the BIF is strongly laminated and deformed, and it contains round to ellipsoidal chert concretions or nodules (Fig. 7).

The BIF occurs in limbs of both the Käymäjärvi anticline and the Jupukka anticline. In places where it is magnetite-bearing, it has a strong magnetic susceptibility which is prominent in maps of the magnetic field (see Fig. 4, high magnetisation in limbs of the Käymäjärvi anticline).

M3

The third member of the Vinsa formation consists of mafic tuffites, graphite-bearing schists and impure limestone intercalations. These rocks occur mostly to the east of the Kaunisvaara ore belt and to a lesser extent in the Käymäjärvi anticline.

Tuffites make up the main rock volume of M3. They are grey to green, fine-grained to very fine-grained and often laminated on a millimetre scale (Fig. 8A). Graded bedding and soft-sediment deformation structures may be preserved in the laminated tuffites (Fig. 8B). The deformation structures include decimetre-scale faults, slumping structures and sedimentary collapse structures. Centimetre-sized chert or quartzite lenses locally occur within the tuf-

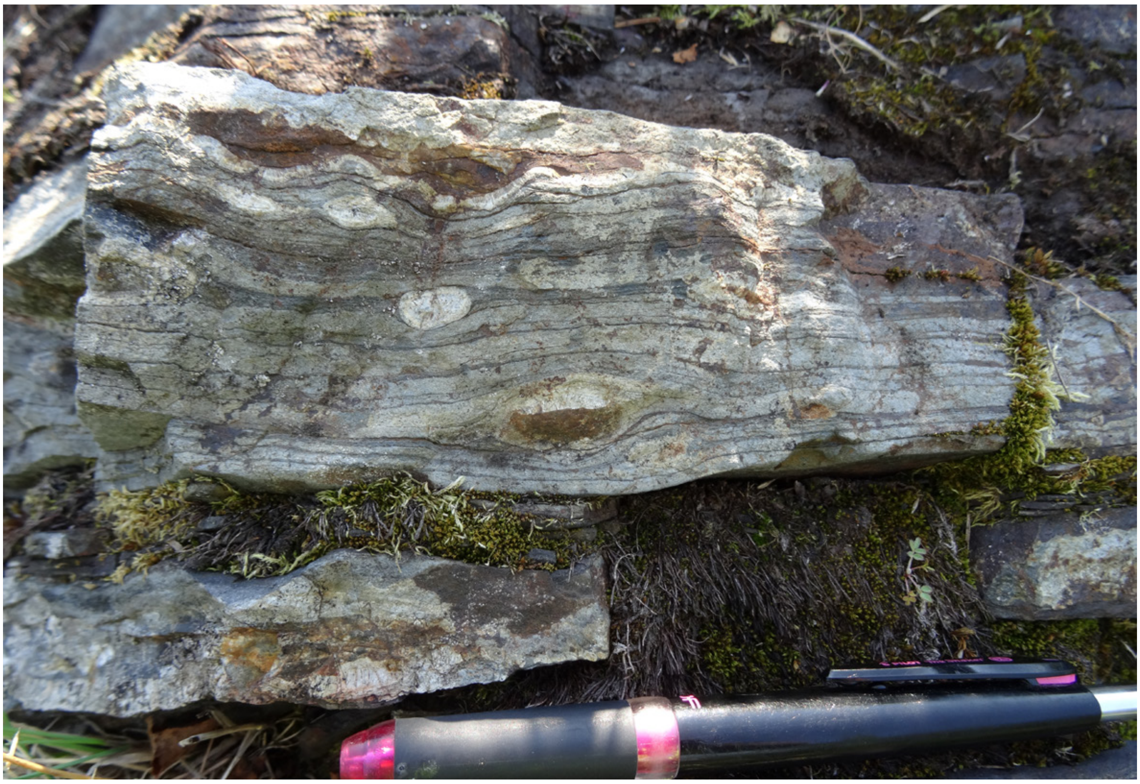

Figure 7. Banded iron formation (BIF) of the second member (M2) of the Vinsa formation. The round to ellipsoidal nodules consist of quartzite or recrystallised chert. Location Jupukka (N7485799, E872865). Photo: Susanne Grigull.

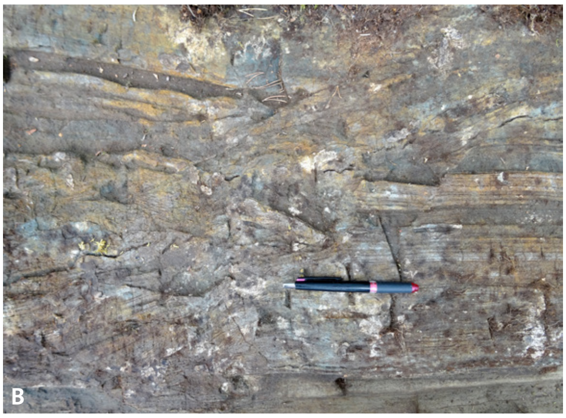

Figure 8. Basic rocks of the third member (M3) of the Vinsa formation. **A.** Laminated basic tuffitic volcanic rocks, near Suksivaara (N7491063, E855835). **B.** Soft-sediment faulting in laminated tuffites, near Suksivaara (N7491063, E855835). **C.** Massive, unbedded basic rock which is strongly altered and slightly magnetic. This could either be a basaltic layer or a basic sill that was metamorphosed to amphibolite facies, north of Kaunisvaara (N7503506, E861123). Photo: Susanne Grigull.

fite layers. The presence of soft-sediment structures indicates that the laminated tuffites were deposited under water, either as primary volcanic sedimentary rocks or re-deposited as epiclastic sedimentary rocks. Locally, the tuffites contain layers of massive, unbedded mafic rocks (Fig. 8C). It is unclear if these are basaltic layers or basic sills because the contact between the massive layers and the tuffites has not been observed in situ. Both the tuffites and the mafic sills can be slightly magnetic.

The impure limestones are light grey and usually coarse-grained. It is not clear what the material is that makes up the impure, more competent layers and lenses (Fig. 9). It may be basic volcanic rocks or another silicate-bearing material. The limestone intercalations can reach significant thickness of up to about 100 m or more, for example in Finland just north of the river Muonioälv, where the limestone has been quarried in two open pits. Within the key area on the Swedish side, impure limestones were observed at two localities along the Muonioälv shore between Aareavaara and Huuki.

The graphite-bearing schists (Fig. 10) are probably basic tuffites that are enriched in graphite. These rocks are mostly very fine-grained and show typically rusty to orange weathering due to a high content of iron sulphides. For example, pyrite occurs disseminated through the graphite-bearing schist. Spectrometer measurements show that these graphite-bearing schists have a higher uranium content (around 4–6 ppm) than the graphite schists from the first member (M1) of the Vinsa formation. The graphite-bearing schists of M3 and the impure limestone intercalations usually occur in close spatial proximity.

M4

A coarse-grained, light grey, locally calcitic dolomite forms the top of the Vinsa formation. The dolomite contains layers of more competent material (silicates?). Fractures in the dolomite

Figure 9. The light coloured rocks are impure limestones of member M3 of the Vinsa formation. The limestone is easily deformed around more competent lenses of dark coloured material. Near Huuki (N7506963, E869370). Photo: Susanne Grigull.

Figure 10. Graphite-bearing schists of the third member (M3) of the Vinsa formation. Near Huuki (N75 06950, E869482). Photo: Susanne Grigull.

are coated with sulphide minerals (chalcopyrite and pyrrhotite) and a yellowish green mineral (maybe diopside or forsterite). In an outcrop near Käymäjärvi, the dolomite contains lenses and nodules of actinolite or tremolite crystals indicating skarn alteration (Fig. 11A). A banded skarn horizon underlies the dolomite lens here (Fig. 11B). At this location, the dolomite has a magnetic susceptibility that is ten times higher than elsewhere indicating that the magnetite content is higher. The dolomite-hosted skarn iron ore deposits around Kaunisvaara (e.g. Tapuli) were not visited during this field period.

Sammakkovaara group

Rocks of the Sammakkovaara group (Martinsson 2004) occur mainly in the western part of the key area, to the west of the Kaunisvaara ore belt. In the eastern part of the key area, they are only exposed in the core of the Ristimella syncline (Fig. 3). However, in Finland, directly to the north of the key area, large amounts of clastic sedimentary rocks occur as well as a body of an intermediate volcanic rock (Väänänen 1984, GTK map sheet 2713, Kolari). To the south of the key area, in the Liviöjärvi key area (Luth & Jönsson 2014), both clastic sedimentary rocks and volcanic rocks belonging to the Sammakkovaara group are abundant.

Muotkamaa formation

Basic to intermediate volcanic rocks observed just east of Muotkamaa are interpreted as belonging to the Muotkamaa formation (Fig. 12A). However, the rocks in this outcrop are strongly deformed so it is difficult to determine whether the rocks belong to the Sammakkovaara group or whether they are part of the Karelian greenstone group. Lithogeochemical analyses and potentially U-Pb isotope geochronology of these rocks will help to determine this. Other volcanic rocks belonging to the Muotkamaa formation were not observed during this field period.

Figure 11. **A.** Dolomite of the fourth member (M4) of the Vinsa formation, south-east of Käymäjärvi (N7492760, E843104). **B.** Skarn-altered dolomite near Käymäjärvi (N7495668, E840982). Lenses of hornblende (actinolite or tremolite?) withstand weathering better than the dolomite. Photo: Susanne Grigull.

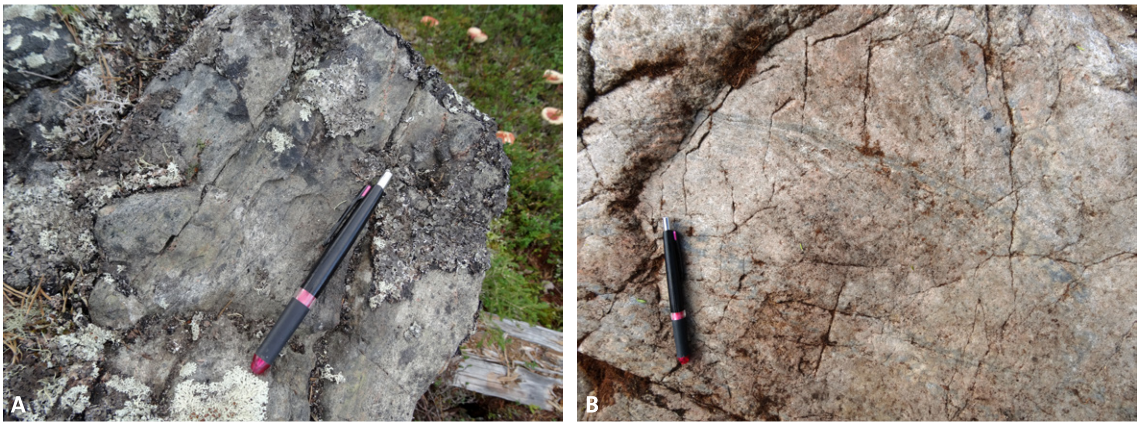

Figure 12. **A.** Strongly deformed basic to intermediate volcanic rocks preliminarily attributed to the Muotkamaa formation, south-east of Käymäjärvi (N7492841, E843579). **B.** Quartzitic to arkosic arenites of the Hosiokangas formation. Cross-bedding indicates younging towards the east. Along road to Käymäjärvi (N7493863, E844634). **C.** Clast-supported conglomerate of the Hosiokangas formation. The pebbles consist predominantly of quartz or quartzite. Local boulders on Hosiovaara (N7495334, E845175). Photo: Susanne Grigull.

Hosiokangas formation

Rocks of the Hosiokangas formation are predominantly of a clastic sedimentary origin. A preliminary stratigraphic succession of the Hosiokangas formation was established using the geological observations made along a profile from the road leading to Käymäjärvi up to the top of Hosiovaara mountain. The observations along the profile were made in an overturned limb of a syncline. Here, the rocks are younging towards the east whereas the beds dip towards the west.

Light-grey to pink quartzitic to arkosic and sublithic arenites occur at the bottom of the depositional succession. Heavy mineral layers in these beds trace cross-bedding on the centimetre to decimetre scale and horizontal lamination on the millimetre to centimetre scale (Fig. 12B). Magnetite layers occur locally. The rock also contains muscovite and pink K-feldspar. Locally, the rock has been migmatised. A clast-supported conglomerate (Fig. 12C) is deposited on top of the arenites or occurs as lenses. More than 95% of the clasts consist of quartz or quartzite and the pebbles can be up to 30 cm in diameter. The quartz is either clear and transparent or milky, and some of the quartz pebbles show hematite staining. Less than 5% of the pebbles consist of basic volcanic rock. These pebbles are generally smaller than the quartz pebbles. The conglomerate matrix is relatively coarse-grained. During this field period, the conglomerate was only observed in the form of local boulders, but has been reported in situ from other locations in the area (e.g. Kumpulainen 2000, Martinsson 2004). It is probable that the conglomerate occurs as lenses within the arenites rather than as continuous layers.

The arenites are overlain by sublitharenitic sandstones and siltstones. These show distinct hummocky cross-bedding, indicating sedimentation under tidal conditions. Some beds are green-coloured which may indicate that they contain Ca-amphibole and originally were more

Figure 13. **A.** Local blocks of arenitic sandstones belonging to the Hosiokangas formation. Hummocky cross-bedding indicates sedimentation under tidal conditions. The green-coloured layer may contain Ca-amphibole. The white fragments in the sedimentary rock consist of quartz and feldspar. Local boulders on Hosiovaara (N7495325, E845187). **B.** Pelitic siltstones of the top of the Hosiokangas formation. Ripple marks are preserved in this local block on Hosiovaara (N7495373, E845336). **C.** Example of a granite of the Granite-pegmatite association, near Käryvaara (N7491074, E863585). **D.** Quartz-poor, albite-rich granite or syenite with amphibole and biotite patches tracing a foliation and lineation. Near Laatas (N7497205, E865128). Photo: Susanne Grigull.

carbonate-rich than the other sedimentary rocks. The rocks also contain randomly oriented centimetre-sized fragments of quartz and white feldspar (Fig. 13A). Also these sand- and siltstones were not found in situ. However, they occur as local blocks along a narrow strip on Hosiovaara.

Pelitic siltstones were deposited on top of the arenitic sandstones. These deposits are locally laminated and ripple marks have been observed (Fig. 13B). The siltstones become richer in mafic material towards the top and the biotite content increases. White quartzites without any recognisable sedimentary structures occur as intercalations within the pelitic rocks.

Hosiovaara formation

Basic to intermediate volcanic rocks of the Hosiovaara formation (Martinsson 2004) were not observed in situ during this field period. However, volcanic rocks with an andesitic to dacitic composition are reported to occur in the valley between Hosiovaara and Sammakkovaara mountains as well as on the shores of lake Kursujärvi in the north-western part of the key area (SGU bedrock observations database).

Intrusive rocks

The majority of observed intrusive rocks in the key area seem to belong to the Granite-pegmatite association. These rocks are light red to red, locally porphyritic granites and pegmatites with a variable grain size and composition (Fig. 13C). The granites locally contain magnetite patches.

A white, quartz-poor, albite-rich granite to syenite occurs at Laatas in the centre of the key area. This rock usually exhibits a ductile foliation and lineation indicating significant deformation. It may be cross-cut by coarse-grained pegmatites. The lineation and parts of the the foliation are sometimes traced by amphibole and biotite patches (Fig. 13D). It is unclear which magmatic suite these rocks belong to. The albite-granite was sampled for zircon geochronology.

Metamorphism and alterations

Karelian greenstone group

The following metamorphic mineral assemblage was observed in basic tuffites and basaltic rocks of the Karelian greenstone group (Figs. 14A–B): hornblende, plagioclase and biotite, and locally garnet (possibly almandine) and epidote. Additionally, diopside has been reported in some of the tuffitic layers (Martinsson et al. 2013). This mineral assemblage indicates at least amphibolite to hornblende hornfels metamorphic facies.

Scapolite alteration of the basic rocks is common and locally very strong (Fig. 14C). It is questionable whether the diopside is a product of hydrothermal alteration or contact metamorphism or a combination of these.

Sammakkovaara group

The metamorphic mineral assemblage muscovite-biotite±cordierite±andalusite was observed in the pelitic sedimentary rocks of the Sammakkovaara group (Fig. 14D–E). Millimetre-sized garnets occur locally. In the arenitic, psammitic rocks, the mineral assemblage hornblende-biotite-muscovite±andalusite±K-feldspar was determined in the field. In the only outcrop possibly exposing andesitic volcanic rocks of the Sammakkovaara group, epidote and K-feldspar were found in veins.

In the Ristimella syncline, the pelitic and psammitic sedimentary rocks of the Sammakkovaara group have been intruded by pegmatite veins which probably belong to the Granite-pegmatite association. Some of the pegmatites are folded together with the sedimentary rocks which indicates that the intrusion preceded deformation. The sedimentary rocks also show local migmatisation with leucosome veins parallel to the dominant foliation.

The degree of metamorphism in both the Karelian greenstone group and the overlying Sammakkovaara group varies between greenschist facies, amphibolite facies and probably hornblende or even pyroxene hornfels facies, indicating Barrovian to Buchan style metamorphism. The metamorphic grade seems to increase towards the major north-east to south-west striking deformation zone. However, even north-west of Kaunisvaara and on the mountain Hosiovaara, cordierite was observed in sedimentary rocks of the Sammakkovaara group indicating higher temperatures in this area during metamorphism. Solely based on field observations, it is difficult to determine coherent regional metamorphic isograds because the grade of metamorphism varies locally.

Figure 14. **A.** Hornblende (dark green minerals) and plagioclase (white in matrix) in amphibolite-facies basaltic rock of the Karelian greenstone group. Near Aareavaara (N7505956, E862886). **B.** Garnet in basic tuffite of the Karelian greenstone group. Muonioälv shore near Ristimella (N7506426, E873369). **C.** Strong scapolite alteration of basic volcanic rock of the Karelian greenstone group. Muonioälv shore near Törmäsniva (N7487555, E869853). **D.** Metamorphosed pelitic rocks of the Sammakkovaara group with randomly oriented cordierite crystals. At Hosiovaara (N7495373, E845336). **E.** Andalusite blasts in metamorphosed and deformed pelitic rocks, on Airivaara (N7500640, E870405). Photo: Susanne Grigull.

Structural inventory

The poor outcrop situation in the Käymäjärvi–Ristimella key area makes it extremely difficult to interpret and understand the measured geological structures in the field with respect to regional scale structures. Additionally, deformation in the key area was polyphase and strain is partitioned into high-strain and low-strain areas. Deformation is mostly taken up by folding, but high-strain deformation zones also occur. A reasonable structural interpretation of the entire area will be possible by further studying drill cores, geophysical data and oriented thin sections as well as by 3D geological and geophysical modelling, which is beyond the scope of this field report. Therefore, only the structural data and preliminary interpretations of some target areas are presented below.

The available airborne magnetic data allows the delineation of several local scale folds such as the Käymäjärvi anticline and the Ristimella syncline (cf. Figs. 3–4 and Grigull et al. 2014). One of the most obvious features in the eastern part of the key area is a north-east to south-west trending pattern of several subparallel and nearly linear high-magnetic and low-magnetic anomalies. This anomaly pattern is considered to represent the north-east trending deformation zone marked in Figure 3. It is still unclear if this zone is part of the major Pajala shear zone or whether it is a separate structure that developed independently from this major deformation zone.

Folds at Sammakkovaara

Between Käymäjärvi and Sammakkovaara, deformation of the rocks of both the Karelian greenstone group and the Sammakkovaara group resulted in folds with north-west–south-east to north–south trending axial traces. On the available bedrock maps, the clastic sedimentary rocks of the Hosiokangas formation and the andesitic to mafic rocks of the Hosiovaara formation are shown as folded into a synform to the west of Sammakkovaara and into an antiform containing the volcanic rocks in its core (Fig. 15). However, the new structural measurements in combination with interpretation of geomagnetic data suggest that this interpretation needs to be revised (Fig. 16).

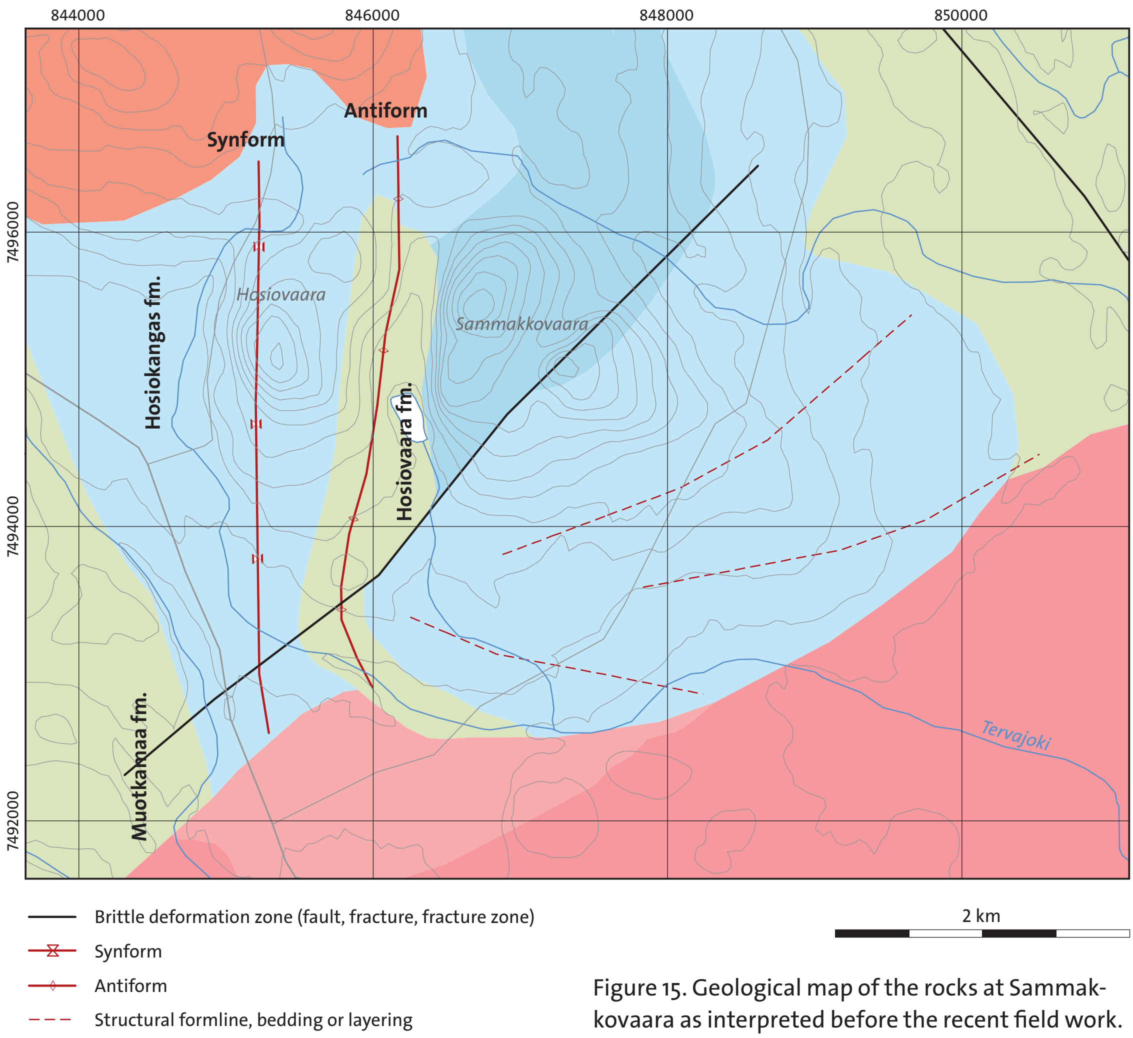

Figure 15. Geological map of the rocks at Sammakkovaara as interpreted before the recent field work.

One of the most important observations is that the clastic sedimentary rocks of the Hosiokangas formation are overturned on the western side of Sammakkovaara where cross-bedding in quartzitic arenites shows younging towards the east whereas bedding dips to the west (Fig. 16). The change in dip angle from steep (c. 60–70°) to shallow (c. 30°) and then to near-vertical from west to east is interpreted as two east-vergent, overturned folds (Fig. 16). These may be parasitic folds to a regional scale syncline formed during north–south folding caused by east–west compression. The syncline to the east of a presumed north–south striking brittle fault contains andesitic to dacitic rocks of the Hosiovaara formation in the core. It is unclear whether this syncline is also overturned. When plotted in a stereogramme, it is clear that most bedding surfaces

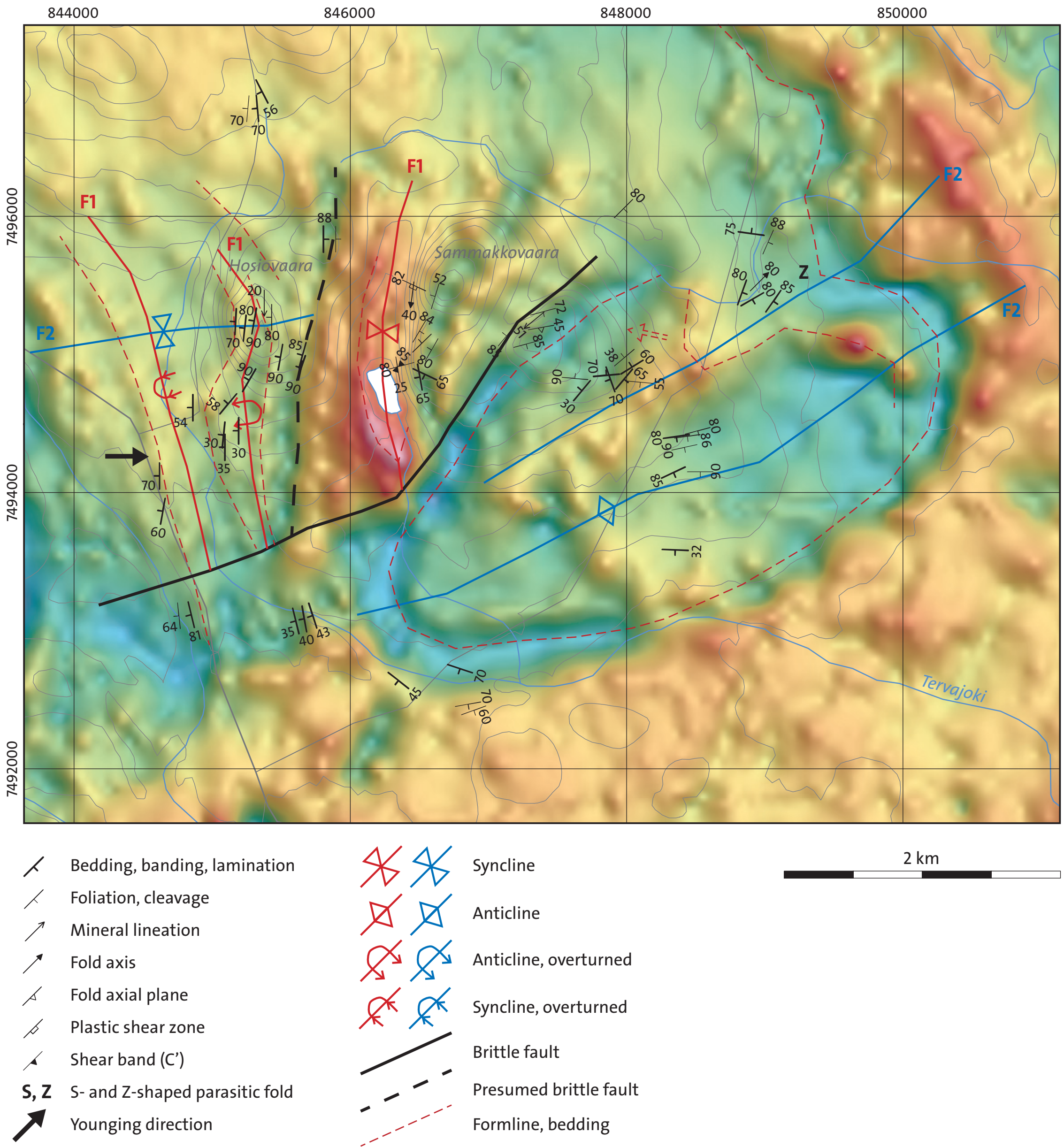

Figure 16. Interpretation of structural data around Sammakkovaara. F1, F2: folding phases 1 and 2. Magnetic anomaly map in the background. Red colours: high magnetisation, blue colours: low magnetisation. The volcanic rocks of the Hosiovaara formation are clearly seen as a magnetic anomaly with high magnetisation in the core of an isoclinal to slightly overturned syncline.

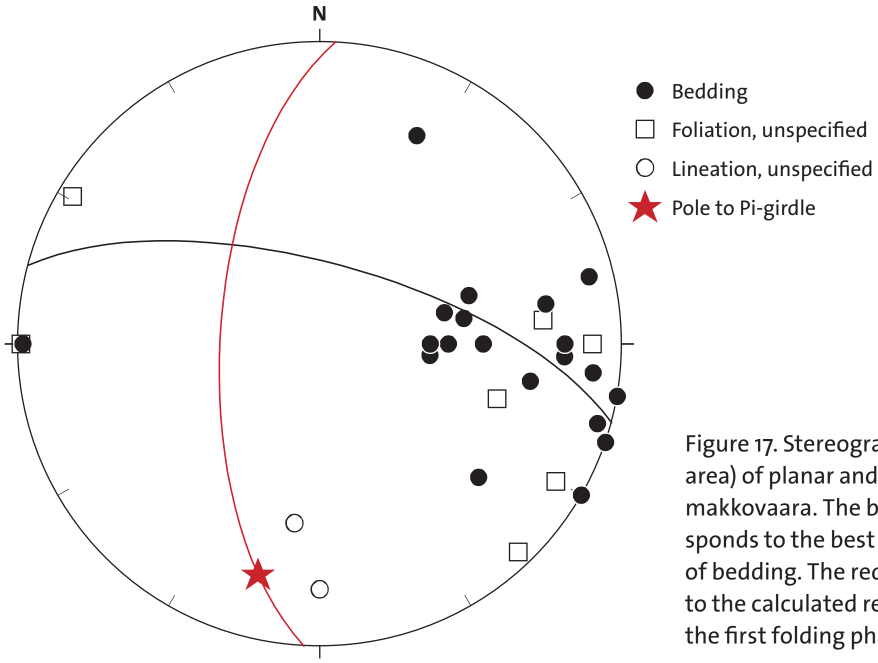

Figure 17. Stereographic projection (equal area) of planar and linear structures at Sammakkovaara. The black great circle corresponds to the best fit Pi-girdle to the poles of bedding. The red great circle corresponds to the calculated regional fold axial plane of the first folding phase (F1).

north-west of a major north-east to south-west striking brittle fault dip shallowly or steeply to the west (Fig. 17). Cleavages and tectonic foliations generally dip steeply to the west. The pole to the best fit great circle of the poles to bedding has the orientation 195/22 (Fig. 17). A principle orientation analysis of the bedding attitudes indicates a regional fold axial plane which dips c. 60° to the west (183/63).

The slight spread in bedding attitudes is probably due to a second folding event (F2) during north-north-west to south-south-east compression. These folds have a larger wavelength and lower amplitude than the F1 folds. An F2 folding event may explain the puzzling egg-shaped structure that is observed in the magnetic anomaly map to the south-east of the major brittle fault (Fig. 16). The egg–shaped structure is here interpreted as corresponding to a doubly plunging antiform in quartzitic arenites.

In summary, there is evidence for a first folding event which resulted in east-vergent, overturned folds and a second, localised folding event which resulted in folds with east-north-east trending axial traces. The latter folds slightly refold the F1 folds in the south-western part of the area.

Ristimella syncline

One aim of the field work was to understand the structural architecture of the "Ristimella syncline" (cf. Fig. 3) in the north-eastern part of the key area. In its core, the syncline contains metamorphosed sedimentary rocks such as paragneisses, mica schists and quartzitic arenites. These sedimentary rocks are locally migmatised and some contain pegmatite veins that can probably be attributed to the Granite-pegmatite association. It is unclear whether or not the sedimentary rocks belong to the Sammakkovaara group.

The western and eastern limbs of the syncline are made up of metamorphosed basic and graphite-bearing rocks predominantly of the Vinsa formation. To the west, the syncline is bounded by a subvertically dipping brittle fault against migmatitic paragneisses and granites occurring in an antiform. The paragneisses have been attributed to the lower part of the Karelian greenstone group. Only one outcrop was observed within these paragneisses. To the east, the

Figure 18. **A.** Psammitic metasedimentary rocks on Airivaara. The foliation S1 is parallel to what is interpreted as original bedding (S0, horizontal in the photograph). A second foliation (S2) cuts through the earlier foliation at an acute angle. The pencil is parallel to S2. Airivaara (N7501253, E870365). **B.** Pegmatite vein folded around a fold axis plunging south-west. Note how the S1 foliation wraps around the more competent pegmatite vein. Airivaara (N7500809, E870595). **C.** Slightly asymmetric strain shadows around andalusite (?) porphyroblasts in psammitic metasedimentary rocks potentially indicate sinistral movement along S0/S1. The second foliation S2 is also indicated and a minor dextral displacement has taken place along this foliation. Both foliations are nearly vertical. A muscovite mineral lineation along S0/S1 plunges south-south-west. Airivaara (N7500640, E870405). Photo: Susanne Grigull.

Ristimella syncline appears to be bound by the major north-east trending deformation zone, although this has not been observed in the field.

The available geophysical data for this area, such as slingram and aeromagnetic maps, are very detailed and necessary for the interpretation of the structures around Ristimella.

Several structural measurements of deformed clastic sedimentary rocks were made on the mountain Airivaara in order to better understand the structure of the Ristimella syncline as well as to investigate how the syncline has been affected by the north-east striking deformation zone to the east of the syncline.

Field observations in pelitic and psammitic metasedimentary rocks on Airivaara show that two tectonic foliations at an acute angle have developed in the rocks (Fig. 18A). The older foliation (S1) is parallel to the original sedimentary bedding (S0) and strikes north-north-east whereas the younger foliation (S2) strikes north-east. Both foliations dip subvertically. A muscovite mineral lineation coats some of the S1-surfaces and plunges moderately (20–45°) to the south-south-west. The orientation of small-scale fold axes is somewhat variable. Two fold axes trend

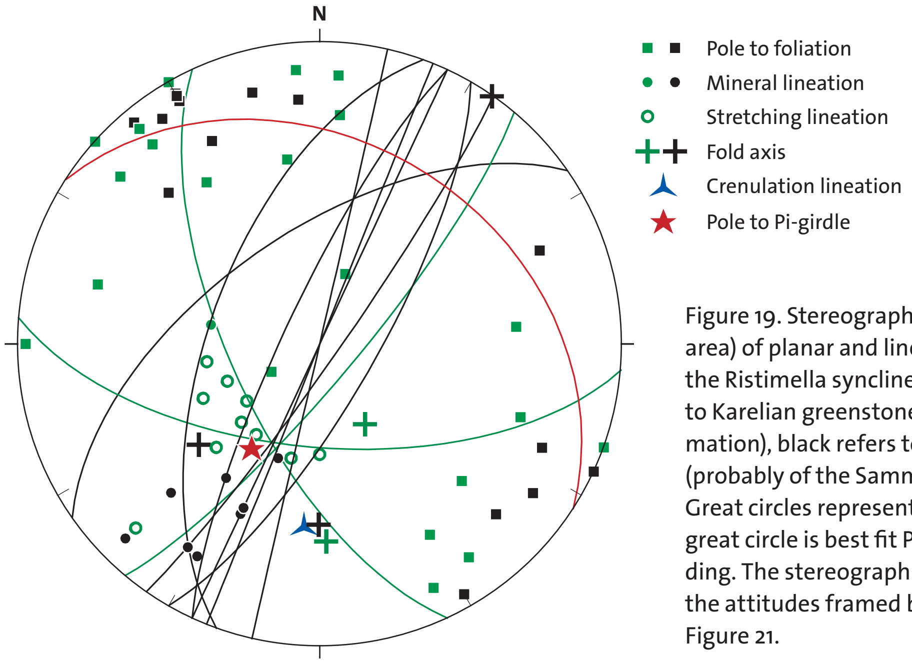

Figure 19. Stereographic projection (equal area) of planar and linear structures within the Ristimella syncline. Green colours refer to Karelian greenstone group (Vinsa formation), black refers to sedimentary rocks (probably of the Sammakkovaara group). Great circles represent bedding (So). Red great circle is best fit Pi-girdle to the bedding. The stereographic projection includes the attitudes framed by the blue polygon in Figure 21.

parallel to S2 and plunge moderately to shallowly (0–45°) to the south-west as measured e.g. in a folded pegmatite that cuts through pelitic sedimentary rocks (Fig. 18B). One measured fold axis in a pelitic sedimentary rock plunges 40° to the south.

The kinematic interpretation of metamorphic porphyroblasts (andalusite) and mica fish in the metasedimentary rocks is difficult because most of them are nearly symmetrically deformed parallel to S1. Some of them show strain shadow precipitates parallel to S1 indicating sinistral movement along that plane. However, a few prophyroblasts seem to have been rotated slightly and show asymmetric tails parallel to S2, potentially indicating dextral movement along S2 (Fig. 18C). This interpretation is still tentative and needs to be verified against results from the microscopy of oriented thin sections.

The collected structural data allows the interpretation that the outcrops at Airivaara are located in a series of tight to isoclinal, south-west-plunging synclines and anticlines. This is supported by the interpretation of newly collected geophysical data (see below). It is, however, still unclear what relationship the second foliation has to the regional Ristimella syncline and whether or not it is related to the synform or to a second deformation event.

Towards the northern part of the Ristimella syncline, the strike of the bedding and foliation planes change in both the greenstones and the sedimentary rocks. This can also be seen in the magnetic and slingram anomaly patterns. Therefore, and attempt was made to measure structural attitudes (Fig. 19) along an east–west profile along the river shore of Muonioälven between Huuki and Ristimella. The interpretation of the structural data is not straightforward. The original layering (S0) of the rocks is folded at least once around a steeply south-west plunging fold axis indicated by the intersection of the great circles to bedding at c. 205/60 (Fig. 19).

An S1 foliation is parallel to the original bedding and can be observed in the sedimentary rocks (Fig. 20A). A second foliation, S2, has also developed in the rocks (Fig. 20A). The majority of measured S2 foliation planes strike north-east and dip steeply. These foliation planes are probably equivalent to the S2 foliation observed on Airivaara (see above). It is not always easy to distinguish between S0/S1 and S2. However, an asymmetric crenulation cleavage and a crenulation

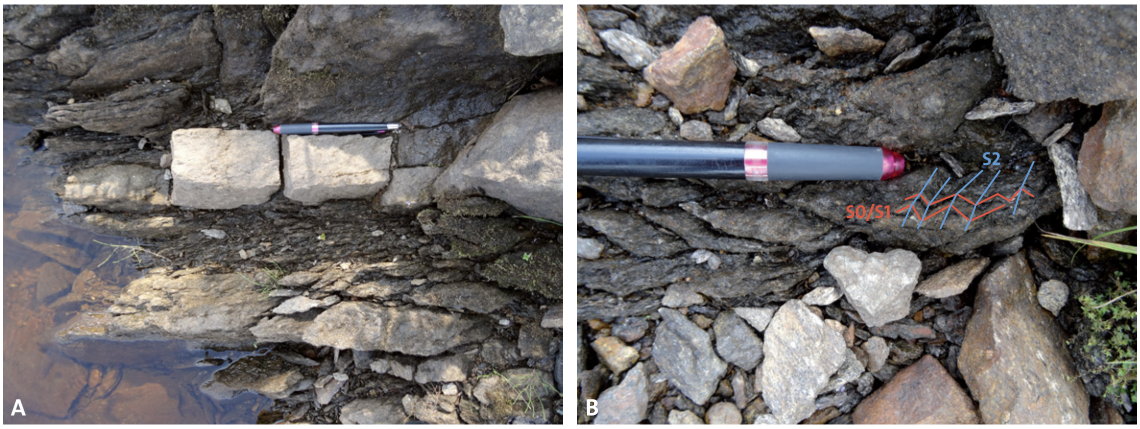

Figure 20. A. Two foliations have developed at an acute angle in the metasedimentary rocks. S1 is parallel to the original bedding S0. B. Asymmetric crenulation cleavage in metasedimentary rocks. Near Ristimella (N7507048, E872043).

lineation have developed in the more micaceous layers of some sedimentary rocks, indicating refolding of a pre-existing foliation (Fig. 20B).

Another indication that the rocks near Ristimella are affected by two folding events is found in the combined magnetic and slingram anomaly maps (Fig. 21). Here, the graphite-rich beds of the Vinsa formation can be used as tracers for bedding formlines because of their high conductivity and mostly high magnetisation. In combination with the structural measurements made along the river shore and on Airivaara (Fig. 22), the structures can be interpreted as a refolded F1 fold whose fold axial trace originally trended north-east to south-west , and that has been folded subsequently around F2 folds with more or less south- to south-west-plunging fold axes. It is likely that the F2 folds form the core of the Ristimella syncline. However, more structural measurements are necessary to confirm this. Further west, between Ristimella and Huuki, the interpretation of the anomaly patterns and the structural data is difficult because it is not clear in which direction the F1 fold continues.

In a stereographic projection (Fig. 19), the majority of measured mineral stretching lineations in the greenstones plunge steeply (c. 60°) to the south-west and fall on a great circle with an orientation of approximately 155/65. The fact that these lineations do not lie on a small circle may indicate that they have been rotated around a fold axis belonging to a non-cylindrical fold.

Most of the mineral lineations and fold axes measured in the sedimentary rocks were observed parallel to the S0/S1 surfaces. They plunge moderately to shallowly towards the south-west. The intersection lineations that are formed between S0/S1 and S2, however, plunge steeply (c. 80°) to the south and south-west. If these intersection lineations are parallel to the fold axis of a second folding event, it is possible that the lineations observed in the greenstones were rotated around that fold axis. This would indicate an older deformation event in the greenstones.

Two fold axes, one measured in the greenstones and one in the sedimentary rocks, plunge moderately (c. 40°) towards the south. These fold axes are parallel to the measured crenulation lineation in the sedimentary rocks mentioned earlier. It is unclear which folding event these fold axes belong to.

The geophysical profiles M1a and M1b on Airivaara cross the north-east trending shear zone and the southern part of the Ristimella syncline (Fig. 21). A model of the collected ground magnetic data along these two profiles is presented in Figure 23. A challenge during the modelling has been the lack of outcrops along the profile lines which leads to uncertainty when determin-

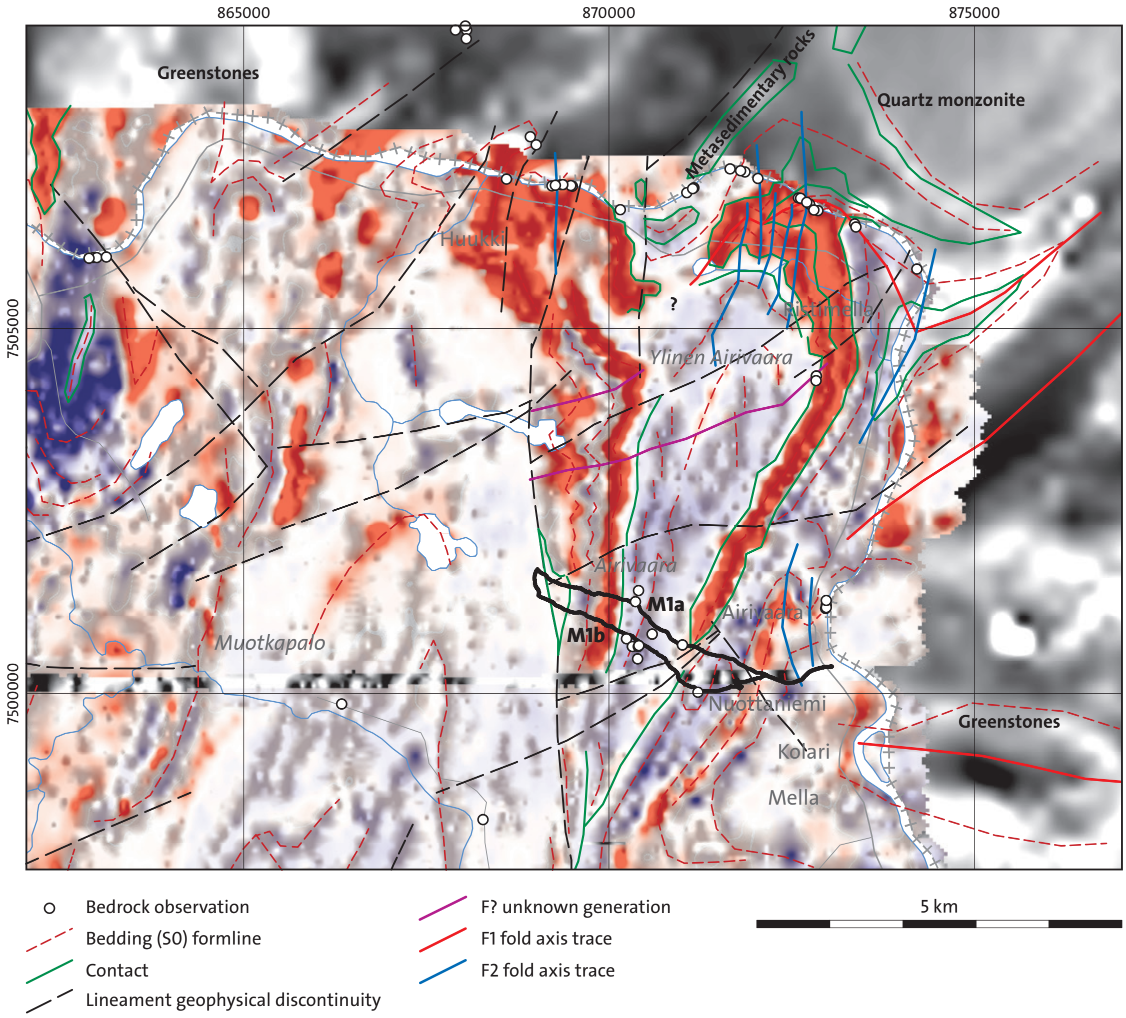

Figure 21. Formline interpretation of bedding, fold axial traces and discontinuities based on geological field observations and geophysical anomalies. The grey shaded map in the background shows the magnetic field. Dark colours indicate high magnetisation, bright colours correspond to low magnetisation. A slingram map is superimposed over the magnetic anomaly maps. The red and blue colours correspond to high and low conductivity in the ground respectively. Note, that no slingram data was available for Finland and that the magnetic anomaly map has a much coarser resolution in Finland than in Sweden. M1a and M1b are magnetic profiles that refer to Figure 23.

ing the petrophysical properties in the model. It was possible, however, to make plausible estimates of the magnetic susceptibility by comparing the magnetic field strength of rocks exposed in areas where samples were collected close to the profile line. The petrophysical units that were used to model profile M1a across the north-east trending deformation zone have been attributed the susceptibility values that are listed in Table 3.

The magnetic remanence related to rocks in the profile was generally quite low (40-180 mA/m). The highest remanence values measured on samples in this profile was 300 mA/m which is not high, but enough to cause a change in measured field strength compared to the low remanence of the surroundings.

It is possible to represent the magnetic signal recorded along profiles M1a and M1b with seven or eight susceptibility ranges (Fig. 23). The modelled thicknesses of bodies as well as their dip angles and dip directions depend on the shapes of the recorded magnetic signal. Some anomalies

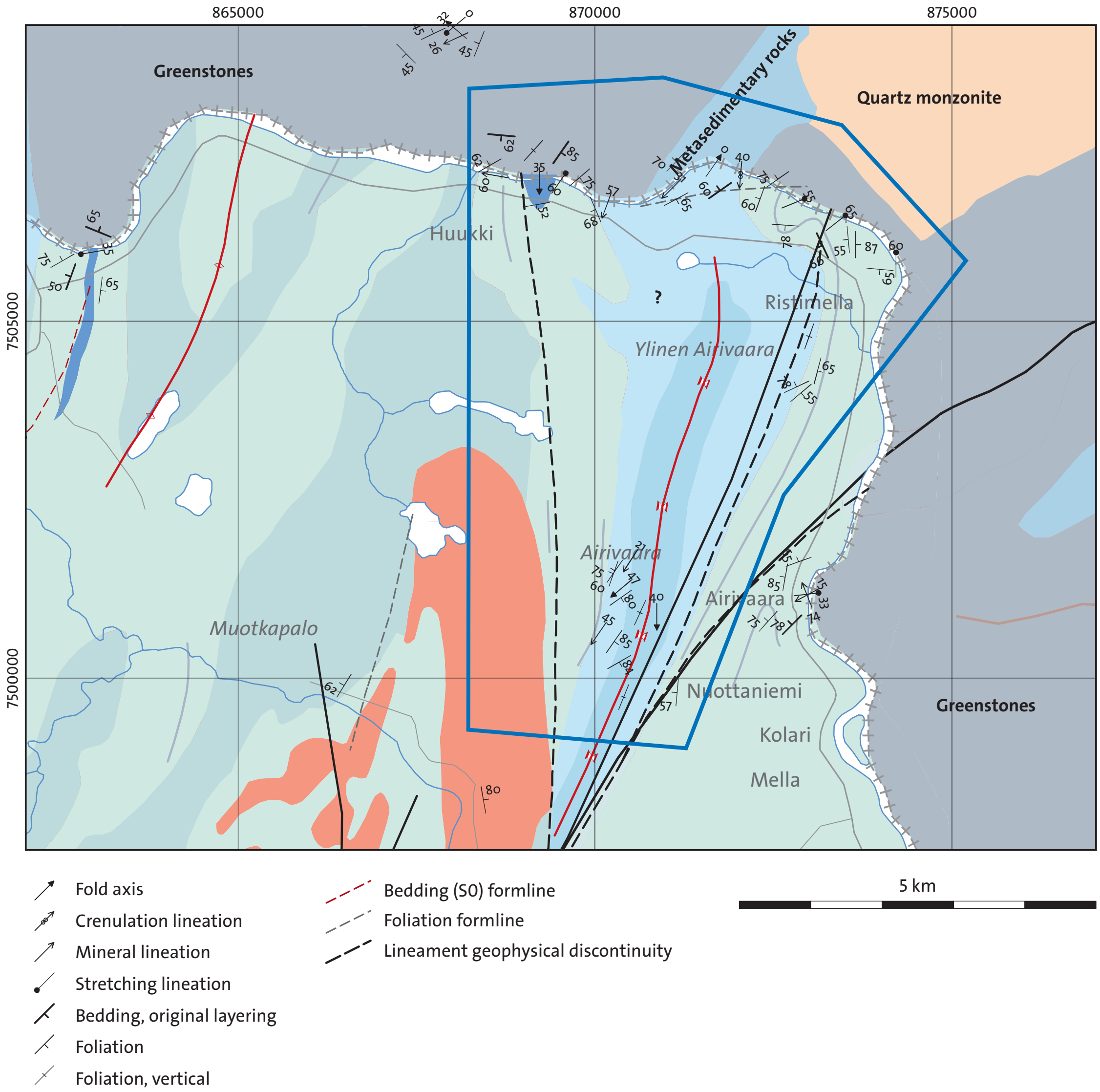

Figure 22. Geological map of the area around Ristimella showing some of the structural measurements made during the field season. The geological units in Finland are taken from the Fennoscandian map database (1:5000000). The blue polygon encircles approximately the area where the structures were measured that are shown in the stereographic projection in Figure 19. See Figure 3 for legend to bedrock.

Table 3. Susceptibility values (based on both field and laboratory measurements) of different rock types used in the modelling of profiles M1a and M1b.

Susceptibility (SI units)	Location	Interpreted rock type and outcrop information
0–500	Close to profile M1	Interpreted as gneiss and schist
~2000	Not exposed	Likely to be sediment (western part of profile M1a)
3000–5000	Close to profile M1	Sediment, highest susceptibility in profile is 2400
5000–30000	Käymäjärvi area (cf. Fig. 3)	Banded iron formation
>50000	Jupukka (cf. Fig. 3)	Banded iron formation

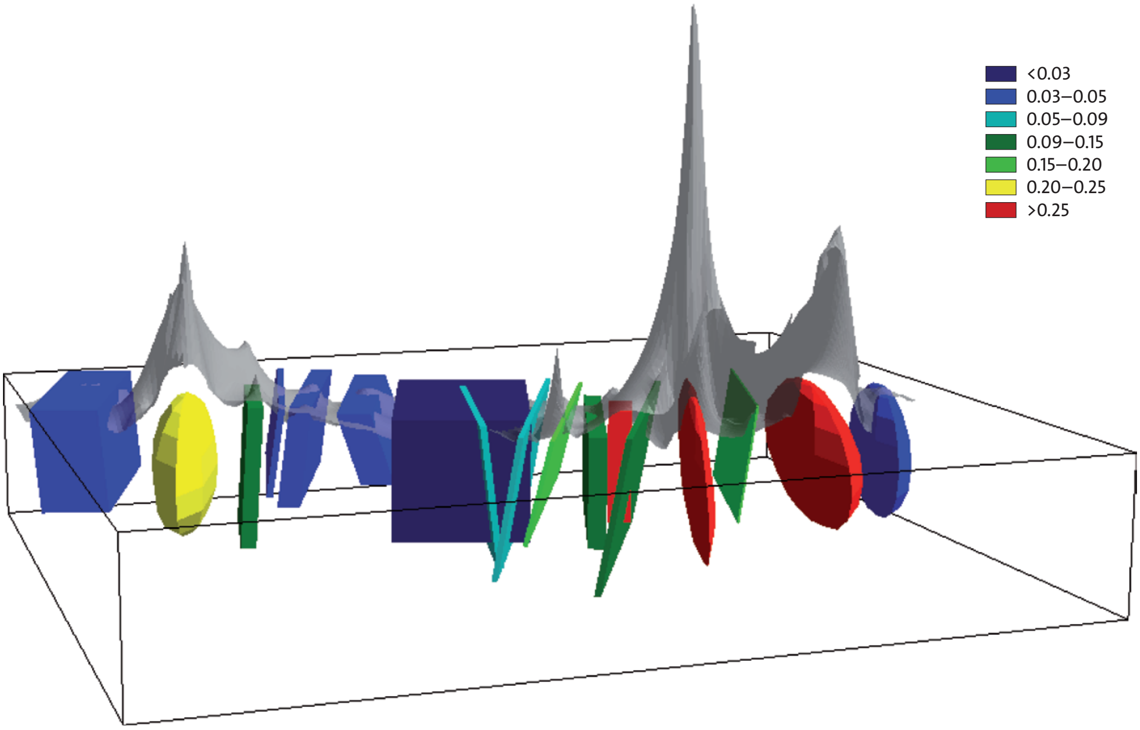

Figure 23. Interpretation of magnetic field strength along profiles M1a and M1b in 3D-view with the magnetic field strength shown as the grey surface on top of the petrophysical bodies. Profile b is located about 300 m south of profile a. The wireframe box is c. 4000 m long.

may be represented by simple thin sheets of c. 10–100 m thickness. Where the magnetic signal is wider and stronger, a body which is both wider and has a higher magnetic susceptibility may be required to achieve an acceptable model fit (Fig. 23). The modelled profiles fit well with the measured structural geological data and the interpretation of the Ristimella syncline as a set of tight to isoclinal folds, at least in the southern part of the syncline.

DISCUSSION AND SUMMARY

If the sedimentary rocks within the Ristimella syncline belong to the Sammakkovaara group, they may be related to the sedimentary rocks observed to the west of the Kaunisvaara ore belt. Similar sedimentary rocks occur north of Muonioälven in Finland. When roughly traced, these sedimentary rocks frame the rocks of the greenstone group (and maybe older rocks), and it is therefore possible that they are connected through a large non-cylindrical, south-plunging anticline with its core consisting of the paragneisses and granites mentioned earlier.

The fold interference pattern near Ristimella may have formed due to a pressure disturbance in the pressure shadow of a quartz monzonite intrusion (Haparanda suite) on the Finnish side of Muonioälven (cf. Fig. 22) . This intrusive body is obviously folded itself but may have acted as a competent body causing the less competent supracrustal rocks to “flow” around it.

In summary, the profile along Muonioälven, albeit still incomplete, resulted in the interpretation of a series of locally refolded folds that occur from Aareavaara in the west to Ristimella in the east.

Both the rocks of the Karelian greenstone group and of the Sammakkovaara group are affected by at least two deformation events as indicated by fold interference patterns, rotated lineations and fold axes, and the presence of two foliations.

Unfortunately, it was not possible to find many informative outcrops along the presumed north-east to south-west trending high strain deformation zone to the east of the Ristimella syncline. The rocks of the Granite-pegmatite association that lie within this deformation zone are hardly deformed and are unsuitable for retrieving kinematic information. It is, however, suggested that this zone exists, inferred from the magnetic anomaly pattern and from migmatised, mica rich sedimentary rocks that are found within or close to the zone. The sedimentary rocks show folding on a decimetre scale and are strongly foliated parallel to the slingram and magnetic anomalies. However, it was not possible to determine whether the foliation and folding is caused by the high strain deformation zone or the F2 folding mentioned earlier.

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