BARENTS PROJECT

Summary report on available geological, geochemical and geophysical information for the Allavaara key area, Norrbotten

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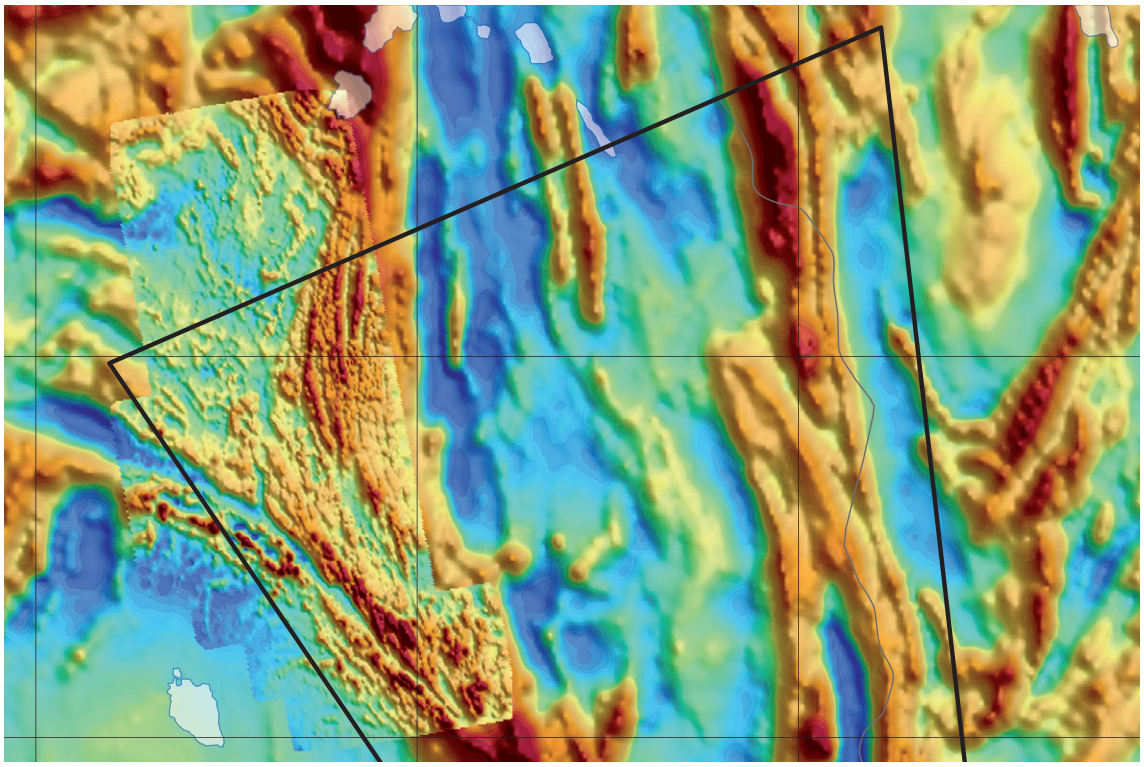

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Cover: Magnetic map of the northern part of the Allavaara area showing ground magnetic measurements (north-west corner) overlain on the regional airborne magnetic data.

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SAMMANFATTNING

Allavaaraområdet ligger ca 30 km nordväst om Gällivare i norra och centrala Norrbottens län. Områdets berggrund består av Paleoproterozoiska metavulkaniska och underordnat metasedimentära bergarter som bildades under den Svekofenniska orogenen (för ca 1,9 miljoner år sedan). Svekofenniska intrusiva bergarter med monzonitisk och granitisk sammansättning förekommer också i området. Berggrunden vid Allavaara ligger i en regionalt viktig deformationszon. En mindre koppar-guldmineralisering finns i området (Fjällåsen) medan längre åt nordväst, i förlängningen av Allavaaradeformationszonen, finns järnoxid-koppar-guldmineralisering (IOCG-typ).

Denna rapport är en sammanställning av Allavaaraområdets viktigaste geologiska, geokemiska och geofysiska egenskaper . Den ger en översikt över befintliga kartor, geologiska datamängder och publikationer som finns för området och kortfattat sammanfattar vår nuvarande kunskap om dess geologiska miljö. Vissa olösta geologiska frågor och förslag för framtida forskning presenteras också. Nyckelområdet Allavaara ingår i SGUs Barentsprojekt (2012–2015) som har fokus på riktad geologisk kartläggning och utredning.

ABSTRACT

The Allavaara area is located c. 30 km north-west of Gällivare in north-central Norrbotten County, Sweden. The bedrock in the area consists of a package of Paleoproterozoic metavolcanic and metasedimentary rocks that formed during the Svecofennian orogeny (at c. 1.9 Ga). Svecofennian intrusive rocks with a monzonitic and granitic composition also occur in the area. The rocks at Allavaara are situated within a regionally significant deformation zone. Minor copper-gold mineralisation is known from the Allavaara area (Fjällåsen), while further to the north-west, within an extension of the deformation zone at Allavaara, iron oxide-copper-gold style mineralisation occurs.

This report reviews the main geological, geochemical and geophysical characteristics of the Allavaara area. It presents an overview of existing maps, geological datasets and publications available for the area, and briefly summarises our present understanding of its geological setting. Some unresolved geological questions and suggestions for future research are also presented. The Allavaara key area is a focus for targeted geological mapping and investigation in SGU's *Barents Project* (2012–2015).

INTRODUCTION

The Allavaara area is located approximately 30 km north-west of Gällivare, in north-central Norrbotten County, Sweden (Fig. 1). The area falls within the 1:50 000-scale map sheets 28J Fjällåsen NO and SO (using the traditional RT90 map sheet index for Sweden) and covers approximately ten 5 × 5 km grid squares representing a geographical area of about 200 km^2.

This report reviews the main geological, geochemical and geophysical characteristics of the Allavaara area. It presents an overview of available maps, geological datasets and publications for the area and briefly summarises our present understanding of its geological setting. The report also identifies unresolved geological questions that may further our knowledge of the geology, stratigraphy and mineral potential of this part of Sweden. The Allavaara key area (one of 14) is a focus for targeted geological mapping and investigation as part of the Barents Project run by the Geological Survey of Sweden (SGU) during 2012–2015.

Access to the Allavaara area is provided by an unnamed paved road that runs west from Malmberget and continues north-west approximately parallel to the Gällivare–Kiruna railroad. The road branches northward along the eastern margin of the key area before Allavaara village and provides access to outcrops in the eastern half of the study area. No paved or gravel roads extend westward from this eastern access road. Therefore, access to the western and north-western parts of the key area is best gained by helicopter.

In general, the landscape in the north-east, east and south-east is a mixture of deciduous and coniferous forests, with marshy areas located between the forested parts. In the west, the landscape becomes progressively boggier and less forested. One of Sweden's largest marshes called Sjaunja-ape, underlain by a granite massif, is located on the western margin of the study area. Access to this area is difficult and outcrop exposure is minimal at best.

Figure 1. Location of the Allavaara key area (small red polygon) in Norrbotten County, northernmost Sweden. The black square corresponds to map sheet 28J (Fjällåsen) representing an area of 2 500 km^2.

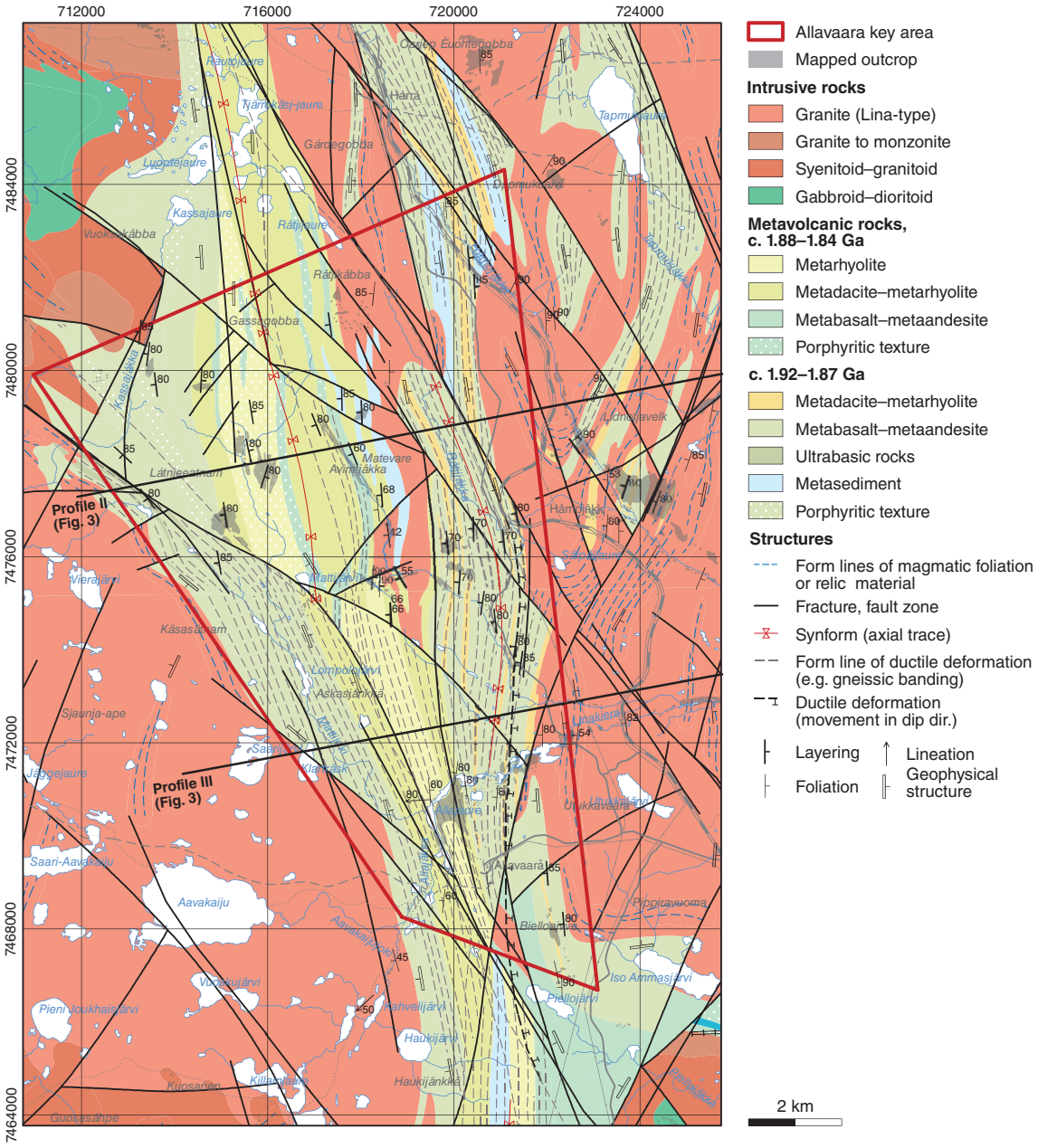

Figure 2. Bedrock geology of the Allavaara key area, north-central Norrbotten. Profile lines II and III correspond to the cross-sections shown in Figure 3. Based on Witschard (1975a).

The terrain is undulating to hilly in northern and southern parts, with elevations ranging between 500 and 640 m above sea level. In the central and western areas, the terrain is generally flatter averaging about 450 m above sea level (see section *Petrophysics*). The Linakiera river crosses the southern part of the study area (flowing adjacent to Allavaara village) and is the main hydrographic feature. Several smaller rivers and streams also flow in a general north-west to south-east direction across the study area (parallel to the dominant structural fabric). Lakes and ponds are mostly located in the south and west (Fig. 2).

GEOLOGICAL OVERVIEW OF THE ALLAVAARA AREA

The following geological summary is mainly based on Witschard (1975b) and Bergman et al. (2001). The Allavaara area is centred on a linear zone of north- to north-west-aligned, deformed

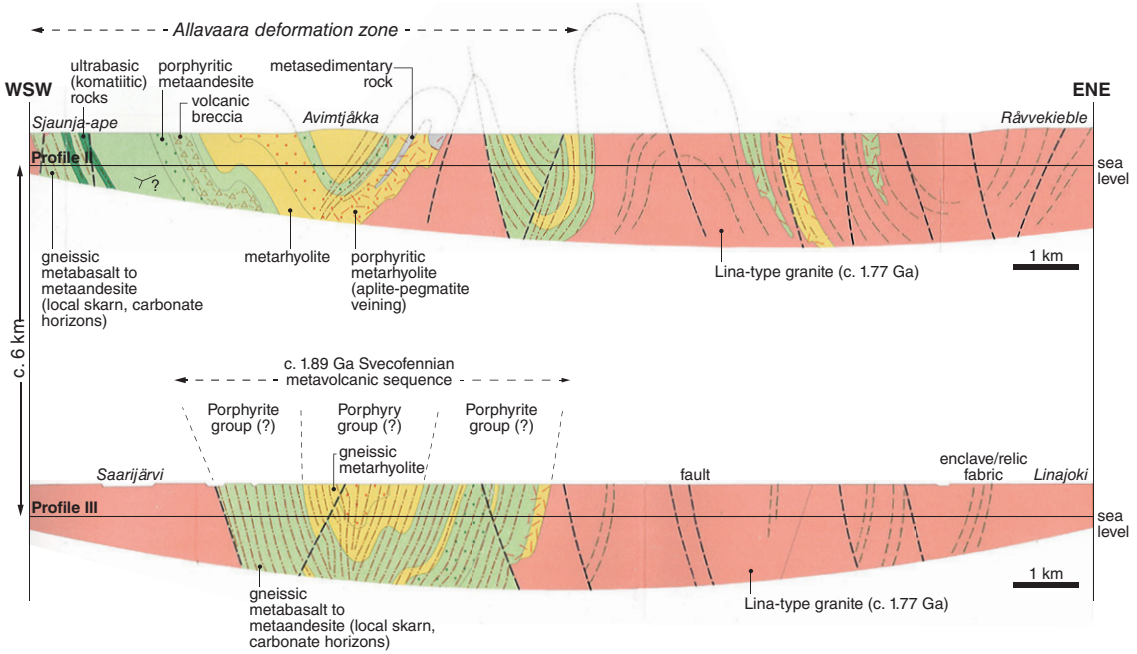

Figure 3. Geologic cross-sections (profiles II and III) through the Allavaara deformation zone (modified after Witschard 1975a). Profile lines are shown on the bedrock map in Figure 1.

Paleoproterozoic metavolcanic rocks which are part of a regionally extensive supracrustal sequence in northern Sweden that formed during the Svecofennian orogeny at c. 1.96–1.75 Ga. The metavolcanic rocks comprise basaltic andesites, andesites, dacites and rhyolites, along with rare ultrabasic (komatiitic) lavas (Fig. 2). Porphyritic textures are common in the andesitic rock types, while horizons of volcaniclastic material (tuff, agglomerate) also occur. Minor metasedimentary (schistose quartz-feldspar rocks), skarn and carbonate horizons also form part of the metavolcanic sequence.

The metavolcanic rocks at Allavaara were initially assigned to the Porphyry group by Witschard (1975a, b). This lithostratigraphic unit is also referred to as the Kiirunavaara group or Kiruna porphyries (see Table 2 in Bergman et al. 2001) and hosts economically important iron oxide-apatite deposits at Kiruna and Malmberget. Subsequently, Bergman et al. (2001) reassessed the metavolcanic sequence and assigned the rocks of intermediate composition (basaltic andesites to andesites) to the stratigraphically lower Porphyrite group, and the more dacitic to rhyolitic rocks to the overlying Porphyry group. This subdivision, based on lithological characteristics, geochemical properties and regional rock distributions, restored the metavolcanic rocks at Allavaara to the classification scheme originally proposed by Offerberg (1967) for analogous metavolcanic rocks in the Kiruna area (cf. Martinsson & Perdahl 1995).

At present, the contact between Porphyrite and Porphyry group rocks at Allavaaara is mapped as a conformable, transitional sequence with horizons from both groups intercalated within the other (Figs. 2 and 3). This suggests a possible genetic and temporal link between the rocks assigned to the two groups. Furthermore, the somewhat variable composition of these rocks indicates a phase of bimodal volcanism played a role in forming the metavolcanic rocks at Allavaara. However, the exact nature of the lithostratigraphic relationship between these units remains unclear. For example, the lithological and geochemical characteristics of the break used to divide the two groups, along with the nature of their contemporaniety, are poorly constrained.

The Allavaara area is bound to the east and west by Svecofennian intrusive rocks which occur as extensive plutonic massifs (cf. Figs. 2 and 4). They primarily consist of monzonitoids, syenitoids and granitoids belonging to the Perthite monzonite suite (c. 1.88–1.86 Ga, e.g. Witschard 1984) and younger granite of the Lina suite (c. 1.77 Ga). Haparanda suite dioritoid intrusions (c. 1.89–1.86 Ga) are generally lacking in this area.

The bedrock at Allavaara is situated along a major north-north-west orientated deformation zone, here termed the Allavaara deformation zone (ADZ). The rocks in the area have probably undergone several phases of deformation and reworking during their geological evolution. The ADZ is c. 10 km wide in the north of the study area (profile II, Fig. 3) and narrows to a width of about 4 km at a high-strain "pinch zone" in the south of the key area (profile III, Fig. 3). The ADZ consists of several sub-vertical, north-north-west striking folds that affect the metavolcanic rocks. More weakly developed east–west orientated folding also occurs (cf. Fig. 9 in Witschard 1975b). This ductile deformation is overprinted by brittle faulting that is generally sub-vertical, with predominately north-north-east and north-north-west orientations.

Metamorphism in the area is estimated to have reached medium to high grades (upper greenschist to amphibolite facies) based on reported mineral assemblages, with metamorphic grade increasing from west to east across the ADZ (cf. Fig. 60 in Bergman et al. 2001). However, calculated pressure–temperature estimates for metamorphic minerals at Allavaara have not been made. A well developed north-north-west orientated, sub-vertical schistosity, locally grading into a gneissic banding, occurs in the metavolcanic rocks and tends to parallel primary depositional features (e.g. bedding contacts) and major structures.

Known mineralisation at Allavaara is confined to Cu-Au occurrences in the north-west at Fjällåsen (cf. Fig. 4). Gerdin et al. (1980) considered copper sulphide mineralisation (chalcopyrite, chalcocite, bornite) to be syngenetic, having formed contemporaneously with the volcanic sequence. Remobilisation of copper-bearing minerals subsequently occurred during one or more deformational phases concentrating the mineralisation within fracture and fault zones. More detailed investigations of the mineralisation and related alteration are presently lacking.

AVAILABLE DATA FOR THE ALLAVAARA AREA

The following sections present a summary of available geological, geochemical and geophysical data covering the Allavaara key area. Some useful topographic datasets are also listed.

Bedrock geology information

The Allavaara area is covered by several bedrock geology maps and digital datasets. Many of these are available as vector layers and georeferenced raster images for use in geographical information system (GIS) and mapping software. The digital datasets are mainly derived from digitised versions of bedrock maps published at 1:50 000, 1:250 000 and smaller scales. Additional bedrock sampling and analyses (e.g. lithogeochemistry, age determinations) by SGU and other workers are generally represented as vector point or polygon layers that show the sample location and associated analytical results (see sections *Geochemistry* and *Geochronology* below).

Geology maps and related data layers

Tables 1 and 2 list some important bedrock mapping projects for the Allavaara area along with additional bedrock information derived from SGU's databases. The maps listed in Table 1 represent both georeferenced scanned paper maps and digitised vector databases. The most detailed mapping for Allavaara is two 1:50 000-scale bedrock maps from SGU's Af series covering map sheets 28J Fjällåsen NO and SO (map sheet nomenclature relates to the old RT90 map index system).

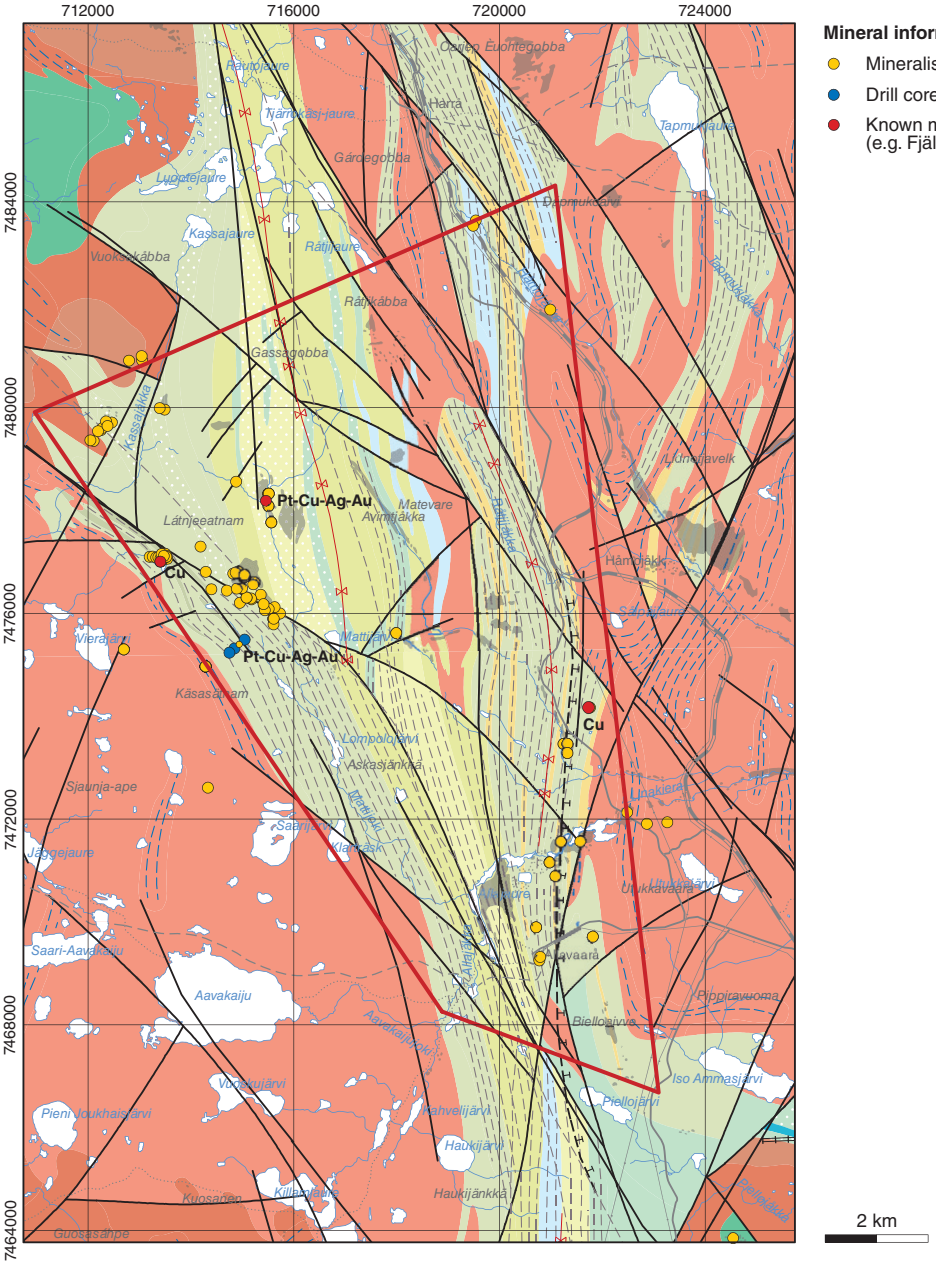

Figure 4. Geological map showing the locations of known mineral prospects and mineralised boulders. The locations of several drill holes at the Fjällåsen prospect are also shown. The associated drill core from these holes is available at SGU's Malå office.

Scanned field maps and other map information

Table 3 lists scanned field maps (mostly from the 1960's) used during the 1:50 000 mapping campaigns in and around Allavaara. The field sheets show the location of outcrops, areas of thin soil cover, mineralized boulders and other geological information. The majority of information was recorded at 1:20 000-scale. Available field diaries for the Allavaara area are also listed.

Additional scanned maps can be found within the various *Brap* and *Prap* reports (historical SGU exploration reports), particularly for the mineralised areas in the western Allavaara area

Table 1. Published bedrock maps and related databases covering the Allavaara area.

Code	Title	Scale	Reference	Map or data extent
Af 18	Bedrock map 28J NO	1:50 000	Witschard 1975a	Northern Allavaara key area
Af 20	Bedrock map 28J SO	1:50 000	Witschard 1975a	Southern Allavaara key area
Ba 56:1	Regional bedrock map	1:250 000	Bergman et al. 2000	Northern Norrbotten
Ca 41	Berggrundskarta över urberget i Norrbottens län	1:400 000	Ödman 1957	Norrbotten County
K 423	Bedrock map of Sweden	1:1 000 000	Bergman et al. 2012	Sweden
n/a	Nordkalott bedrock geology map	1:1 000 000	Silvennoinen et al. 1987	N. Sweden
n/a	Metallic mineral deposit map of the Fennoscandian Shield	1:2 000 000	Eilu et al. 2008	Fennoscandia
n/a	Geology of the Fennoscandian Shield.	1:2 000 000	Koistinen et al. 2001	Fennoscandia
n/a	Lokal berggrundsinformation	1:50 000	SGU database	Allavaara key area
n/a	Regional berggrundsinformation	1:250 000	SGU database	Allavaara key area

Table 2. Other geology-related layers and datasets covering the Allavaara area.

Layer or dataset	Description	Location
Häll, ytor ur Jordartskartan 1:250 000 Norrbotten	Digital polygon layer showing outcrop and thin soil cover areas from soil maps.	Allavaara key area
Jordarter 1:250 000, Nordligaste Sverige	Digital layer showing outcrop and soil cover types. Ice flow directions also.	Allavaara key area
Berggrundsobservationer	Point dataset of location and description of outcrop and structural observations. 8 points at key area.	Southern Allavaara key area
Geology_1M	1:1 000 000 scale digital vector data showing bedrock geology. No colour coding.	Sweden
Swedish Radiometric Age Database	Point locations of age dating samples with methods and results	Two locations east of AKA
Fennoscandian Shield (komplett WGS84 TM)	Digital polygon layer showing small scale bedrock geology	Fennoscandia
Förenklad jordartsindelning (JBAS)	Soil/till geology map of Norbotten 1:250 000	Norrbotten
Norrbotten NBDIG	Digital polygon layer showing small scale bedrock geology with outcrops highlighted also	Norrbotten
Sveriges berggrund 1:1M	Digital polygon layer showing small scale bedrock geology	Sweden

(see Table 4). For example, several bedrock and geophysical maps and drill hole cross sections are available in Gerdin et al. (1980) relating to the exploration programme for Cu-Au mineralisation at the Fjällåsen (Sjaunja) prospect.

Outcrop locations

Figures 2, 4 and 5 show the location of known outcrops and exposed rock areas across the Allavaara area. In general, the area is poorly exposed, particularly in the west towards the Sjaunjaape marsh. The metavolcanic rocks in the southern, eastern and north-western parts of Allavaara appear to be the best exposed. There is also some scattered exposure of metavolcanic rocks and granite in the north-east. Exposures along the southern bank of the Linakeria river (southernmost Allavaara area) provide an opportunity to assess the stratigraphy and deformation of the

Table 3. Scanned field maps and other map information for the Allavaara area.

Scanned map or information	Description and coverage (RT90 map system)	Scale
G12738	Scanned outcrop field map (not rectified) 28J 8–9 g–h	1:20 000
G12739	Scanned outcrop field map (not rectified) 28J 8–9 i–j	1:20 000
G12742	Scanned outcrop field map (not rectified) 28J 6–7 g–h	1:20 000
G12743	Scanned outcrop field map (not rectified) 28J 6–7 i–j	1:20 000
G12746	Structural data (not rectified) 28J NO, SO	1:100 000
G12747	Bedrock geology (not rectified) 28J NO, SO	1:100 000
G12748	Structural data (not rectified) 28J NO, SO	1:100 000
G12751	Aeromagnetic interpretation map (not rectified) 28J SO	1:50 000
G12752	Aeromagnetic interpretation map (not rectified) 28J SO	1:50 000
G12753	Aeromagnetic interpretation map (not rectified) 28J NO	1:50 000
G12754	Aeromagnetic interpretation map (not rectified) 28J NO	1:50 000
G12758	Boulder location map (not rectified) 28J	1:100 000
G12759	Boulder location map (not rectified) 28J	1:100 000
G12760	Boulder tracing map (not rectified) 28J	1:100 000
G12767	Mineralised boulders and ore locations (not rectified) 28J SO	1:50 000
G12768	Boulders and mineralised outcrops (not rectified) 28J SO	1:50 000
G12770	Boulders and mineralised outcrops (not rectified) 28J NO	1:50 000
G12771	Mineralised boulders and ore locations (not rectified) 28J NO	1:50 000
G12772	Ore targets (not rectified) 28J NO	1:50 000
G12776	Scanned outcrop field map (not rectified) 28J 0–1 e–f	1:20 000
G12777	Scanned outcrop field map (not rectified) 28J 0–1 g–h	1:20 000
G12778	Scanned outcrop field map (not rectified) 28J 0–1 i–j	1:20 000
G12779	Scanned outcrop field map (not rectified) 28J 0–1 i–j	1:20 000
G12780	Scanned outcrop field map (not rectified) 28J 0–1 i–j	1:20 000
G12784	Scanned outcrop field map (not rectified) 28J 2–3 g–h	1:20 000
G12785	Scanned outcrop field map (not rectified) 28J 2–3 i–j	1:20 000
G12789	Scanned outcrop field map (not rectified) 28J 4–5 g–h	1:20 000
G12790	Scanned outcrop field map (not rectified) 28J 4–5 i–j	1:20 000
Diaries_28J_Åkerblom-77_m	Field notebooks from SGU workers	Varies
Diaries_28J_Lindberg-63_m	Field notebooks from SGU workers	Varies
Boulders_28J	Gives location and description of mapped boulders (28J, no maps)	Varies

metavolcanic rocks within a high strain deformation zone. A north-north-west orientated linear outcrop located in the north-central part of the study area corresponds to a fault zone escarpment and may provide an opportunity to investigate deformation styles and related kinematics. Granitoids along the western margin of the area are generally not exposed.

Published material (papers and reports)

A list of the most relevant papers and reports for the Allavaara key area is presented in Table 4. Several of these publications are review papers that summarise, on a regional scale, the broad geological, tectonic and metallogenic setting of Norrbotten. In general, there has been little primary research conducted at Allavaara since the publication of the 1:50 000-scale bedrock map sheets and accompanying description (i.e. Witchard 1975a, Witchard 1975b). Exploration activity in the 1970's, which included a diamond drilling programme, is the last major work conducted in the area (e.g. Gerdin et al. 1980, Gustafsson 1984).

The publications and reports in Table 4 are listed from newest to oldest. References quoted in the main text of this report refer to those in Table 4 and the reference list at the end of this report.

Table 4. Publications and reports relating to the geology of the Allavaara area.

Reference	Title	Brief overview and relevance to the Allavaara area
Martinsson & Wanhainen 2013	Fe oxide and Cu-Au deposits in the northern Norrbotten ore district	Review of the geology and metallogeny of northern Norrbotten
Bergman et al. 2011	Geological and tectonic evolution of the northern part of the Fennoscandian Shield	Regional scale review of the geological and tectonic setting of the Fennoscandian Shield
Weihed et al. 2005	Precambrian geodynamics and ore formation: The Fennoscandian Shield	Broad review paper of metallogeny and geotectonic setting of mineral deposits in N Sweden.
Martinsson 2004	Geology and Metallogeny of the Northern Norrbotten Fe-Cu-Au Province	Review paper of metallogeny and geological setting of IOCG deposits Norrbotten.
Bergman et al. 2001	Description of regional geological and geophysical maps of northern Norrbotten County ...	Synthesis report on the bedrock geology and geophysics of Norrbotten based on 1:250 000 regional maps
Ahl et al. 2001	Geochemical classification of plutonic rocks in central and northern Sweden	Classification and petrogenesis of various plutonic suites based on whole-rock geochemistry
Lindholm 1986	28J Fällåsen och 28K Gällivare, sammanställning av myrtorvanalyser 1982–1984	Report on peat bog sampling and analysis results. Contains map showing sampling and analysis for 28J NO and SO with anomalous metal values.
Gustafsson 1984	28J Fjällåsen SO-NO and 28 K Gällivare prospekteringsförslag 1984	Review of exploration work conducted on map sheets 28J Fjällåsen and 28K Gällivare. Contains two maps showing location of mineralised showing, prospects and boulders in map sheets 28J NO and SO.
Carlson et al. 1984	Metallogenetisk karta, fas i block- och mineraliserade häller i Nordöstra Norrbotten	Inventory and description of 692 mineralised boulders and outcrops with some assay data across Norrbotten. Contains section on map sheet 28J Fjällåsen (n = 20).
Lagerbäck 1982	Isrörelser inom kartbladen 26L Palkem SV, NV, 27L Lansjärv SV, NV, 28J Fjällåsen SV, NV, SO, NO, 28K Gällivare SV, NV, SO, NO, 28L Tärendo SV, NV, 29K Vittangi SV, NV, SO, NO, 29L Lainio SV, NV	Ice flow directions and geomorphology analysis for 20 map sheets covering various areas across central Norrbotten. Covers map sheet 28J Fällåsen.
Carlson 1982	Guld i Norrbotten. Del 2.	Compilation of gold showings and prospects in Norrbotten. No. 34 related to Fjällåsen mineralisation (several maps).
Gerdin et al. 1980	Fällåsen. Resultat av utförda prospekteringsarbeten	Summary report outlining exploration activity in the Fällåsen map sheet 28J. Describes geological setting, mineralised localities, drilling and analysis. Several maps and cross sections also included.
Wilson & Sundin 1979	Isotopic age determinations on rocks and minerals in Sweden 1960–1979	Summary report reviewing age dating for whole of Sweden during period 1960–1979. Item 30 relates to a Rb-Sr age (inaccurate) for a sample close to the Allavaara area (Lina granite = 1530 ± 35) and taken from Welin et al. 1971
Witschard 1975	Description of the geological maps Fjällåsen NV, NO, SV, SO with an appendix on geophysical aspects by Herbert Henkel	Most detailed description of the geology of the 28J Fjällåsen map sheets including the Allavaara area (accompanies the 1:50 000-scale bedrock maps). Key reference.
Ambros & Henkel 1973	Titanjärnmalmsfydingheten Akkavare (Melko). Kartbladet 28J Fjällåsen.	Mostly geophysical information relating to exploration of a titanium-iron-oxide prospect within map sheet 28J SV. Some background geology.

Reference	Title	Brief overview and relevance to the Allavaara area
Welin et al. 1971	Rb-Sr radiometric ages of extrusive and intrusive rocks in northern Sweden. 1.	Presents Rb-Sr geochronology results. Some ages (inaccurate) presented for Lina-type granites close to Allavaara area.
Ödman 1957	Beskrivning till berggrundskarta över urberget i Norrbottens län	Synthesis report on the regional bedrock geology of Norrbotten County accompanying the 1:400 000 published map
Geijer 1931	Pre-Cambrian geology of the iron-bearing region Kiruna-Gällivare-Pajala	Early synthesis report on the bedrock geology of the Kiruna-Gällivare-Pajala area and related mineralisation. Includes Fjällåsen area.
Geijer 1924	Some Swedish occurrences of bornite and chalcocite	Early report on Cu-sulphide mineralisation for Sweden including the Nautanen area of northern Sweden

Table 5. Drill core associated with mineral prospects within the Allavaara area.

Deposit or prospect	No. of holes available	Total length	Logs, assay data, reports
Fjällåsen Au (Sjaunja)	3 of 8, drilled by NSG in late 1970's. Holes 78002, 78006, 79001.	543 m (of 1079 m)	Scanned paper logs for 8 drill holes, cross sections, see Gerdin et al. 1980
Fjällåsen III (Sjaunja)	1 of 3, drilled by NSG. Hole 79004.	195 m (of 573 m)	Scanned paper logs for 3 drill holes, cross sections, see Gerdin et al. 1980

Drill core

Table 5 lists the number of exploration drill holes and related drill core acquired during prospecting work in the north-western part of the Allavaara key area. In total, 11 holes were drilled by NSG at the Fjällåsen (Sjaunja) Cu-Au prospect in the late 1970's (Gerdin et al. 1980, Gustafsson 1984). Four of these holes are available for inspection at SGU's Malå office and their collar locations are plotted in Figure 4. All of the holes intersect the steeply west-south-west dipping metavolcanic and metasedimentary rocks. These rocks were assigned to the Porphyry group by Witschard (1975a, b) and subsequently to the Porphyrite group by Bergman et al. (2000). Skarn, limestone (marble?) and ultrabasic volcanic horizons were also intersected by the drill holes. In Table 5, the length of the available drill holes is estimated (where recorded), along with the number of available drill logs and the most relevant exploration reports. There has been no recent drilling in the Allavaara area.

Information relating to alteration and mineralisation

Unlike other Svecofennian deformation zones in Norrbotten (e.g. Nautanen), the Allavaara area contains few known mineral prospects or showings. Four mineralised localities are recorded in SGU's mineral deposits database (Mineralresurser_Mdep) which collectively correspond to the Fjällåsen Cu-Au prospect. The locations of these mineralised areas are shown in Figure 4. Additional datasets relevant to mineralisation and exploration are available and are listed in Table 6 below. These data include GIS layers relating to drill hole locations, available drill core at SGU's Malå office, mineralised boulders and that status of prospecting licence blocks. The location of mineralised boulders is shown in Figure 4, and Gustafsson (1984) also presents information about mineralised boulders in the Allavaara area. Many of the boulder locations appear to cluster close to the Fjällåsen prospect in the north-west of the study area. This may reflect a greater level of mapping activity in that area.

Table 6. Datasets relevant to mineral resources and exploration within the Allavaara area.

Layer or dataset	Description	Coverage or location
Borrkärna_20110405	Location and description of drill core available at SGU's Malå office	Western Allavaara area (4 drill holes related to Fjällåsen prospects)
Borrhål_20110405	Historical drill holes including Malå drill core and drill core no longer available at Malå	Western Allavaara area (8 drill holes related to Fjällåsen prospects)
Mineralresurser_mdep	Location and description of mineralisation prospects, showings and deposits	NW Allavaara area at Fjällåsen prospects (3 locations). SE Allavaara area at Risbäck prospect
boulders_mineralized	Point database of location and basic description of mineralised boulders	NW and southern Allavaara area
Undersökningstillstånd_beviljade	Granted prospecting licence blocks (polygons)	Western Allavaara area
Mineralrättsregistret (MRR10)	Polygons of metallic mineral resource blocks with current and past licence holders	Western and southern Allavaara area
prospekteringsdata_Bergsstaten	Polygons of exploration blocks with current and past licence holders	NW and southern Allavaara area
undersökningstillstånd_beviljade	Exploration permits granted	Western Allavaara area
undersökningstillstånd	Exploration permits	Western Allavaara area

Table 7. Geochemical datasets (for bedrock and overburden) covering the Allavaara area.

Layer or dataset	Description	Location or coverage	Reference
Litogeokemi, analysdata	19 analyses of plutonic, metavolcanic and metasedimentary rocks with lithogeochemistry. Consists of major elements with a few base metals, V and Sr. No REE. An additional 61 whole-rock geochemical analyses exist for areas adjacent to the Allavaara key area that correspond to the analyses presented on the 28J Fjällåsen map sheets.	Mainly northen and southern Allavaara area	Witschard 1975b
Markgeokemi, raster 250m	Raster dataset of shaded till geochemistry for the elements Au, Cd, Co, Cr, Cu, Ni, Pb, V, Zn	Covers the eastern side of the study area only	Ladenberger et al. 2009

Systematic descriptions of the style or degree of hydrothermal alteration have not been made for the rocks at Allavaara. Witschard (1975b) states that sericitisation, saussuritisation (fine-grained albite, muscovite ± epidote ± carbonate replacing plagioclase) and chloritisation (replacing biotite) represents the main alteration affecting the metavolcanic rocks.

Carlson (1982) discusses aspects of the geology at the Fjällåsen prospect in relation to gold mineralisation. Ambros & Henkel (1973) present some information (mainly geophysical) on the gabbroid-hosted Akkavare Ti-Fe prospect located about 16 km to the south-west of Allavaara.

In terms of exploration activity, Rio Tinto Mining and Exploration Ltd (1990's) and Teck Cominco Ltd (2000's) have held historical exploration permits for the Allavaara area. At present, no exploration permits are held in the area.

Geochemical data

Table 7 lists several geochemical datasets available for the general Allavara area. 80 lithogeochemical analyses of various rock units were made by SGU as part of the 1:50 000-scale mapping project across map sheet 28J (data presented in Witschard 1975b). The geochemical data consists of major element oxide concentrations and a limited number of trace element analyses (Cu, Pb,

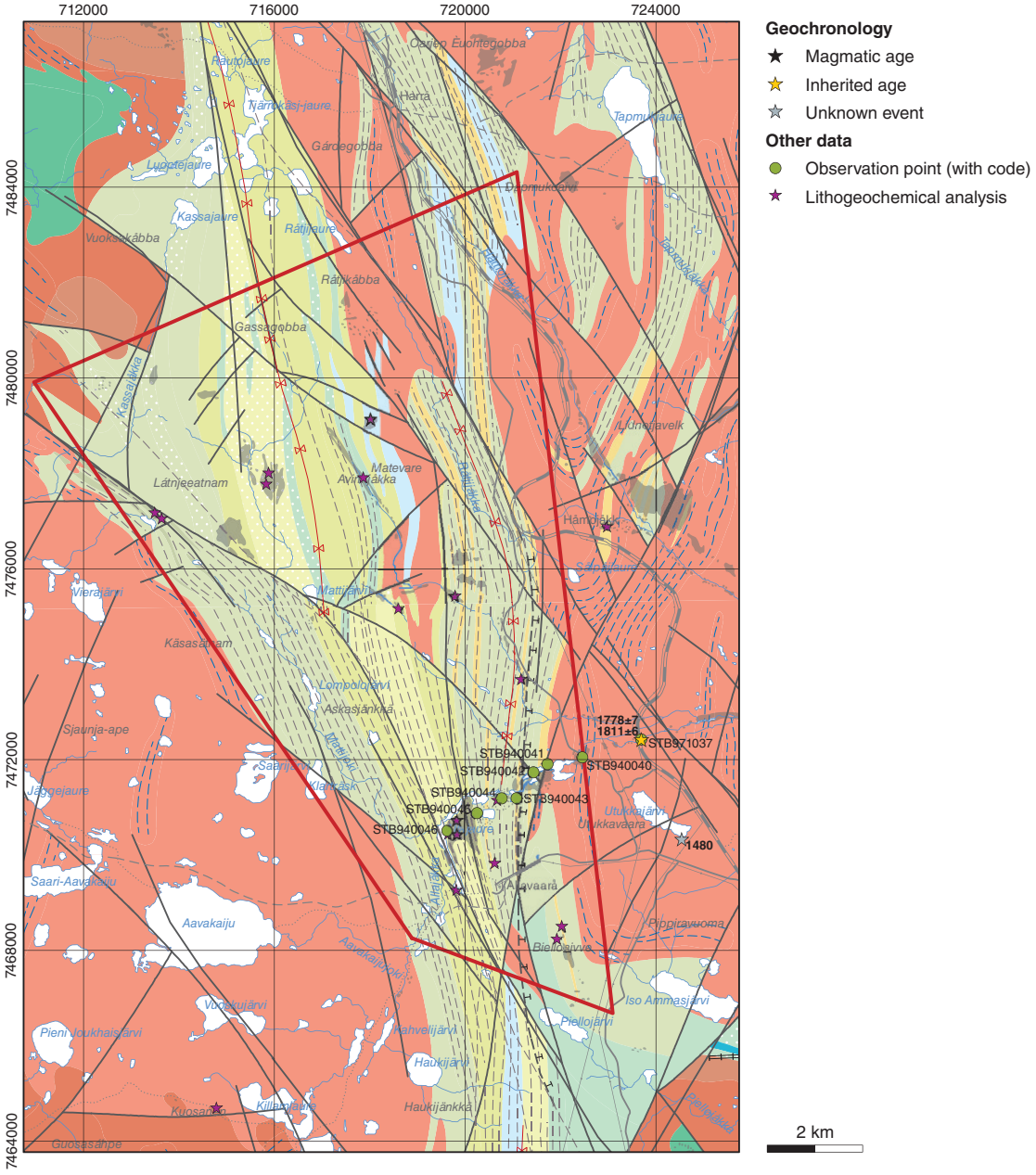

Figure 5. Geological map showing the locations of bedrock observation points, age dating samples and lithogeochemistry samples.

Zn, Mo, V, Sr, Ni and As). Analytical methods and precisions are presented in Witschard (1970). Extended trace element and rare earth element data are not available for the rock units. The majority of the analyses (37) were determined for metavolcanic rocks (e.g. andesite, dacite, rhyolite and ultrabasic rocks). Additionally, 14 analyses were made of quartz monzonite samples, seven of dioritic monzonite (monzodiorite?), five of gabbro, four of granodiorite, three of diorite, two each of Lina-type granite, monzonite, skarn-type rocks and metasedimentary rocks, and finally one analysis of dolerite. 18 geochemical analyses from this dataset are for samples that occur within or adjacent to the Allavaara key area. The locations of these samples are plotted in Figure 5.

More recently, Bergman et al. (2002) presented lithogeochemistry for a sample of Lina granite collected just to the east of the Allavaara area which was used for a geochronology in-

vestigation (see the *Geochronology* section below). Some relevant regional lithogeochemical data for Svecofennian metavolcanic rocks from areas to the north and north-west (closer to Kiruna) can be found in Martinsson & Perdahl (1995). These workers proposed the subdivision of the metavolcanic rocks into Porphyrite and Porphyry groups primarily based on variations in Ti and Zr concentrations. While this study thus supported the major subdivision of Svecofennian metavolcanic rocks in Norrbotten originally proposed by Offerberg (1967), the lithogeochemical characteristics of the metavolcanic rocks from both groups tend to overlap making lithostratigraphic distinctions based on geochemical grounds equivocal (cf. Martinsson 2004).

Additional lithogeochemical data for intrusive rocks is presented by Ahl et al. (2001). These workers provide a regional summary of lithogeochemistry of various intrusive rocks occurring across northern Sweden. This study includes analyses of Perthite monzonite suite and Lina granite suite intrusions similar to the intrusive rocks occurring around the Allavaara area.

The majority of other geochemical analyses in the area relate to till geochemistry measurements determined as part of SGU's regional till geochemistry programme (Table 7, e.g. Ladenberger et al. 2009). Mapped anomalies of Cu, V and Zn represent the main geochemical anomalies in the area and may reflect their elevated concentrations in the metavolcanic rocks. Isolated till and moraine sampling has also been conducted mostly in the eastern part of the study area. Stream and peat geochemical analysis was conducted as part of the exploration of the Fjällåsen prospect. The preliminary results of this work are presented and discussed in Gerdin et al. (1980). Additional information relating to the geochemical analysis of peat samples can be found in Lindholm (1986).

Geochronology

Table 8 lists the results of age dating close to Allavaara and its surrounding area. Few geochronology studies have been made for the bedrock in or around the study area. Thus, the absolute timing of the various magmatic, metamorphic, mineralisation and deformation events is poorly constrained. No absolute ages exist for the metavolcanic rocks in the area. Likewise, the absolute ages of intrusive magmatism, Cu-Au mineralisation at Fjällåsen, and ductile and brittle deformation within the ADZ is not known.

Table 8. Geochronology for the Allavaara and surrounding areas.

Age (Ma)	±	System	Material	Host rock	Unit or suite	Area	Reference
1878	7	U-Pb (LA-ICP-MS)	zircon	Porphyritic metaandesite	Porphyrite Group	Tjårrojåkka Cu (c. 60 km NW of Allavaara, regional age constraint)	Edfelt et al. 2006
1811	6	U-Pb (TIMS)	zircon	Granite	Lina-type granite	Eastern Allavaara area	Bergman et al. 2002
1771	+7/–5	U-Pb (TIMS)	titanite	Granite	Lina-type granite	Eastern Allavaara area	Bergman et al. 2002
1909	17	U-Pb (TIMS)	zircon	Porphyritic rhyodacite	Porphyry Group	Saggekirka hill (c. 40 km NW of Allavaara, regional age constraint)	Skiöld & Cliff 1984
1565	35	Rb-Sr	whole-rock	Granite	Lina-type granite	General Allavaara-Malmberget area (several samples)	Welin et al. 1971
1540	none given	K-Ar	whole-rock	Granite	Lina-type granite	Eastern Allavaara area (exact location unknown)	Magnusson 1960

Most recently, Bergman et al. (2002) determined a magmatic age of 1771^{+7}_{-5} Ma for a Lina-type granite to the east of Allavaara using U-Pb titanite dating (sample location plotted in Fig. 5). In the same study, several zircons were dated at 1811±6 Ma. This latter result was interpreted to represent the age of a population of inherited zircons in the granite.

The ages in Table 8 referenced to Skiöld & Cliff (1984) and Edfelt et al. (2006) are the results of dating of metavolcanic rocks to the north-west that are analogous to the metavolcanic sequence at Allavaara. These U-Pb dates (1909 Ma and 1878 Ma, respectively) are included here to provide some regional constraint for the timing of volcanism at Allavaara (i.e. Svecofennian volcanism at c. 1.89 Ga). It should be noted that the age presented by Skiöld & Cliff (1984) is based on the analysis of volcanic samples from three different locations across Norrbotten and may represent a mixed age of one ore more geological processes. Some older, imprecise and inaccurate Rb-Sr and K-Ar ages for Lina-type granites are also listed in Table 8 for completeness (Magnusson 1960, Welin et al. 1971). No geological significance is placed on these historical radiometric measurements.

Isotope geology (excluding age dating)

No tracer isotopic studies (radiogenic or stable isotopes) have been conducted on the various rocks or minerals in or around the Allavaara key area.

Geophysical data

The following sections provide a summary of available geophysical data (e.g. magnetic, gravity, electromagnetic and petrophysics) covering the Allavaara key area.

Airborne measurements

Three airborne geophysical campaigns have been made over the Allavaara key area (Table 9). In 1965, SGU conducted an airborne magnetic survey over map sheet 28J using a fluxgate magnetometer. The next airborne survey was conducted in 1980 by LKAB over the eastern parts of map sheet 28J and parts of 28K NV. They acquired magnetic field measurements, along with slingram-data, gamma spectrometry measurements and VLF-data from one transmitter. The most recent airborne survey was conducted by SGU in 2013, when most of the map sheets 28I Stora Sjöfallet and 28J Fjällåsen were measured. In this campaign, SGU acquired magnetic data, gamma-ray spectrometry and VLF-data from two transmitters. The airborne magnetic anomaly map over the Allavaara and surrounding areas is shown in Figure 6.

Ground magnetic data

Historical ground magnetic measurements have been made in the north-western corner of the key area corresponding to SGU's exploration work at the Fjällåsen (Sjaunja) Cu-Au prospect (e.g. Gerdin et al. 1980). This work was conducted in 1976 using a magnetometer Z-anomaly

Table 9. Airborne geophysical surveys conducted over the Allavaara key area.

Year	Company	Geophysical methods used	Area	Flight direction	Flight line separation (m)	Flight altitude (m)
1965	SGU	Magnetics	Entire 28J	East–west	200	30
1980	LKAB	Magnetics, slingram, gamma spectrometry, VLF (1-transmitter)	Parts of 28J NE, SE and 28K NW (project R72)	East–west	200	30
2013	SGU	Magnetics, gamma spectrometry, VLF (2-transmitters)	Majority of 28I and 28J	East–west	200	60

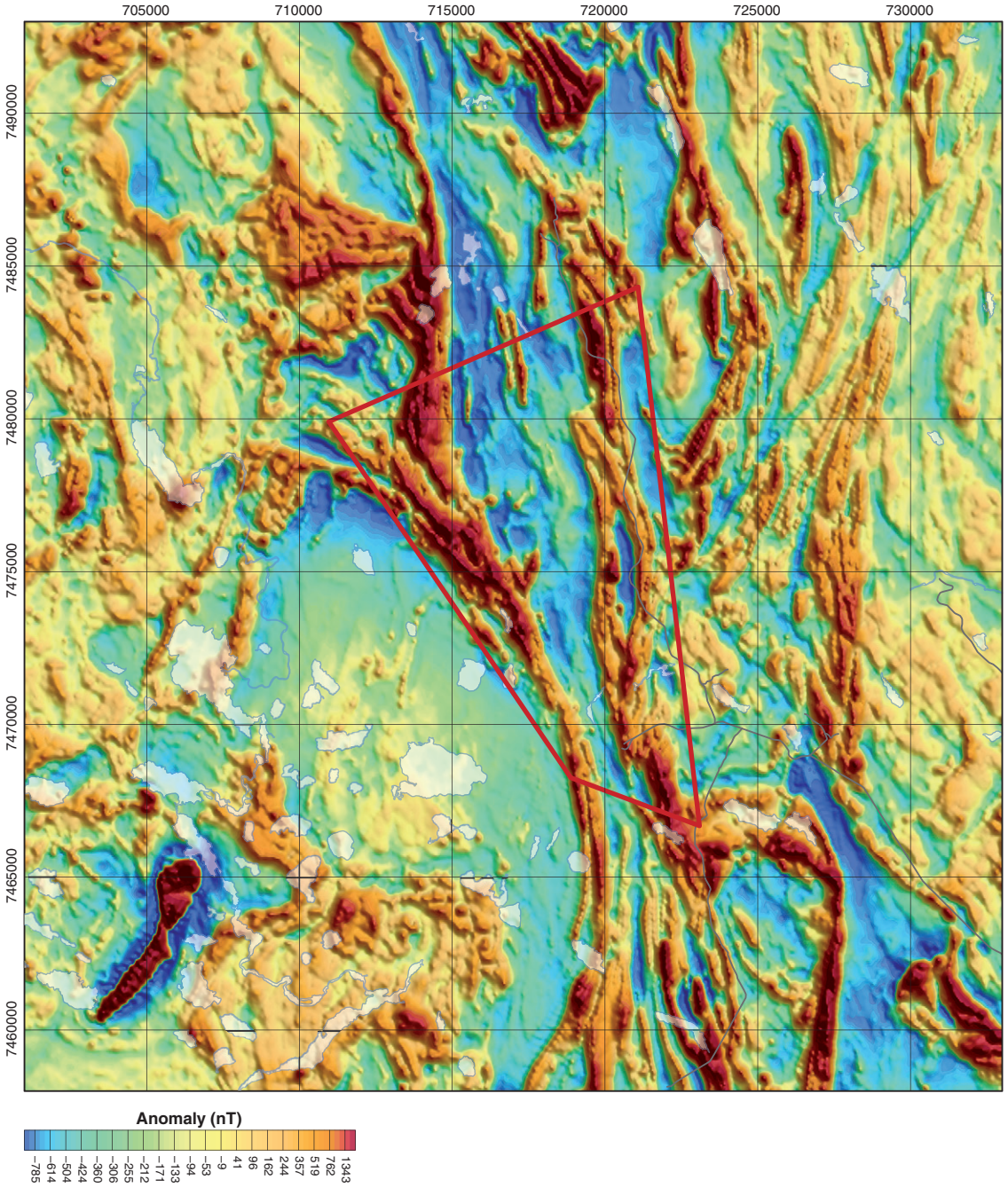

Figure 6. Magnetic anomaly map (airborne data) covering the Allavaara key area (black polygon) and its surroundings. The magnetic data has been filtered to enhance the magnetic response from more shallowly seated lithologies.

survey method. An aeromagnetic map showing the geographical extent of the ground survey area (polygon 1) is shown in Figure 7, while the results of the ground magnetic measurements are presented in Figure 8.

Gravity measurements

In general, the Allavaara area is sparsely covered by gravity measurements. The majority of existing measurements were acquired along north–south and east–west aligned survey lines, with a

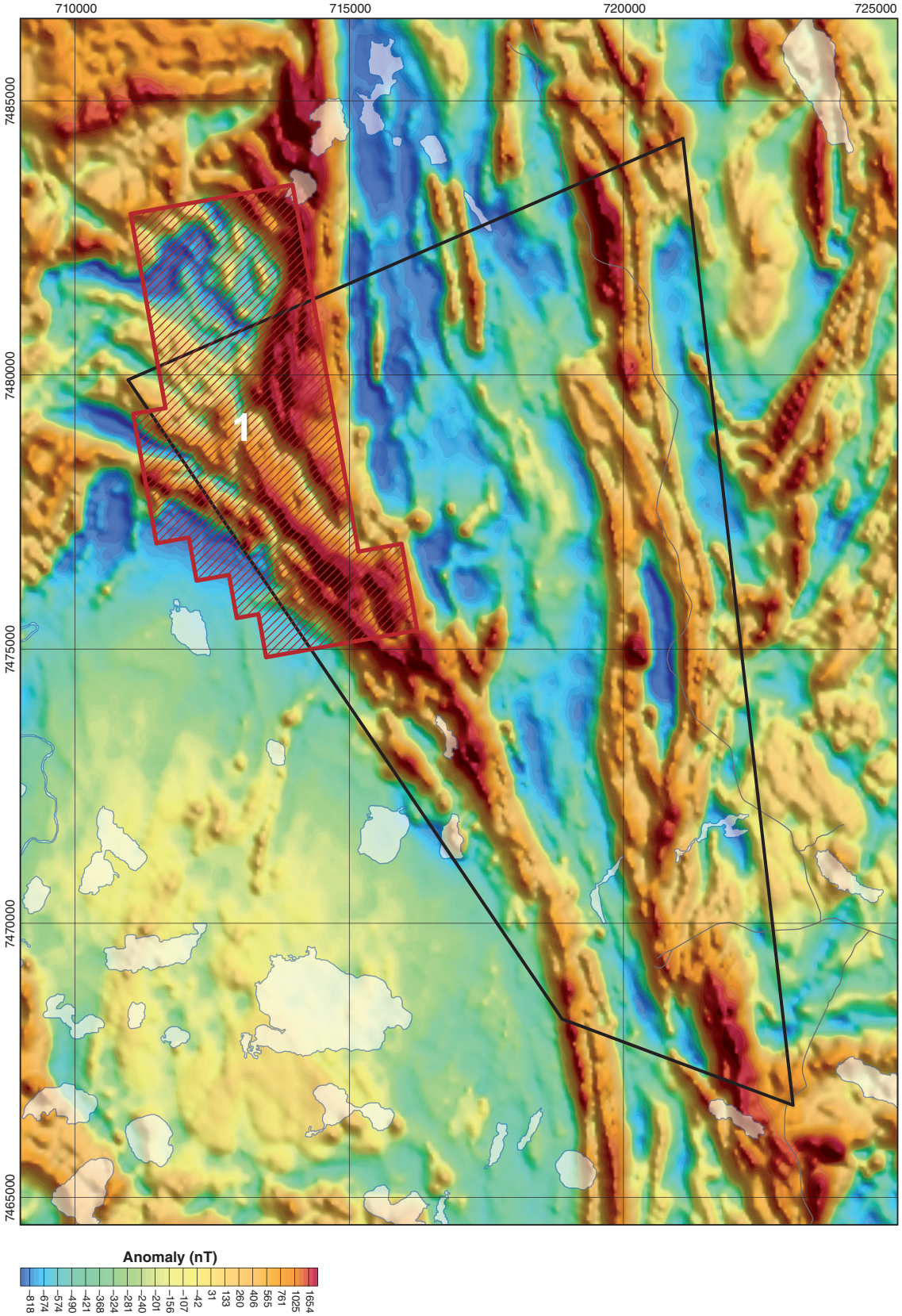

Figure 7. Airborne magnetic anomaly map of the Allavaara area showing the geographical extent of existing ground magnetic measurements in the north-west (red polygon).

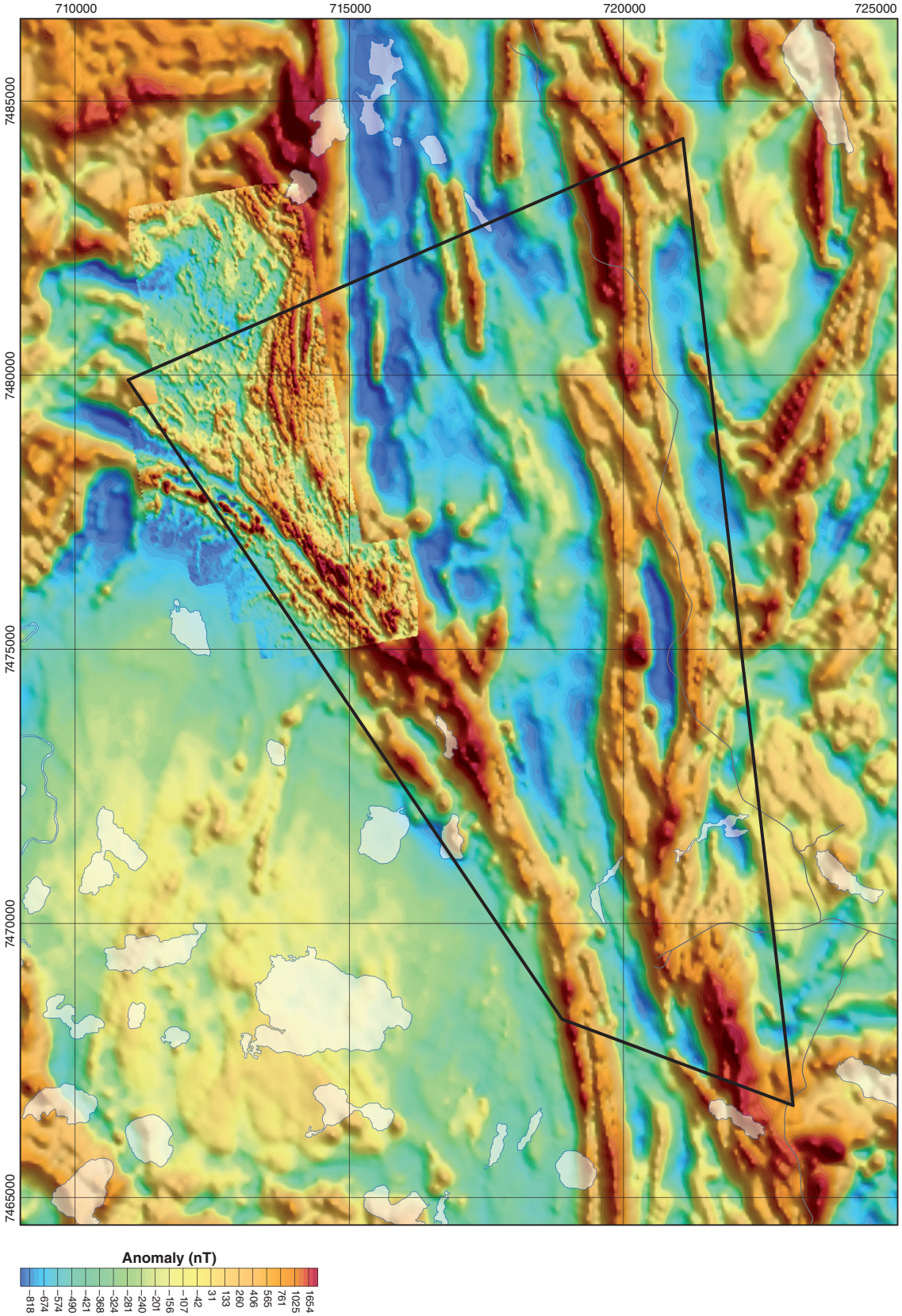

Figure 8. Magnetic map of the Allavaara area showing ground magnetic measurements (north-west corner) overlain on the regional airborne magnetic data.

Table 10. Summary of the geoelectric and electromagnetic ground surveys made within the Allavaara key area. The numbers in column "Polygon nr" refer to those found in Figure 10.

Polygon nr	Name	Method	Operator	Year of measurement
1	Sjaunja	Slingram	SGU	1976
2	Fjällåsen	Slingram	No information	1977
3	Sjaunja	Slingram	SGU	1980
4	Fjällåsen	Slingram	No information	1978
5	Kassekåbba	IP	SGU	1980
6	Sjaunja-Ape	IP	SGU	1980

Table 11. Topographic datasets covering the Allavaara area.

Layer or datset	Description	Scale
Indexrutor RT90 2,5 gon V	RT90 map sheet index polygons	
Rutor_5x5_km	RT90 map sheet index 5x5 km subdivision squares	
Översiktskartan 2007 SWEREF99 TM	Overview vector topographic map (small scale)	
Vägkartan	Overview vector topographic map (medium scale)	
Visningstjänst allmänna kartor	Overview raster topographic map (medium scale)	
Sverigekartan 1 milj (2012)	Overview vector topographic map (small scale)	1:1 000 000
GSD-Höjddata, grid 2+	Raster LiDAR digital elevation model. Slope and aspect data also included.	2 m height resolution
GSD-Höjddata, grid 50+	Raster LiDAR digital elevation model.	50m height resolution
Svenska Marktäckedata	Vector dataset for landuse classification	
Sveriges landskap	Swedish landskap administrative boundaries	
Visningstjänst ortofoton	Raster layer of visible and near infrared orthophotography	

spacing of approximately 1 km between measurement stations and 5 km between survey lines (Fig. 9). Most of this historical gravity data was acquired during the mid 1970's by SGU. In early 2014, additional gravity data was acquired to increase the gravity coverage for the area. At the time of writing these data have not been processed. The locations of the new measurement points are shown in Figure 9.

Geoelectric and electromagnetic measurements

Several ground geoelectric and electromagnetic surveys have been made in the north-western part of the Allavaara area (Fig. 10). Once again, these measurements correspond to geophysical investigations conducted at the Fjällåsen Cu-Au prospect. Table 10 lists information about the various geoelectric and electromagnetic surveys, while Figure 10 shows a resistivity map for the study area derived from airborne VLF measurements.

Petrophysics

There are currently 62 petrophysical samples available from the Allavaara key area (Fig. 11). Rock density, magnetic susceptibility and Königsberger ratio data exist for these samples. Several samples also have data for remnant magnetisation directions with respect to the Earth's magnetic field.

Topographical data

Table 11 lists several topographic datasets covering the Allavaara area. The most useful information can be derived from orthophotographs (both visible and infrared images) and LiDAR elevation data acquired at a height resolution of 50 m and 2 m. The map *Vägkartan,* produced by

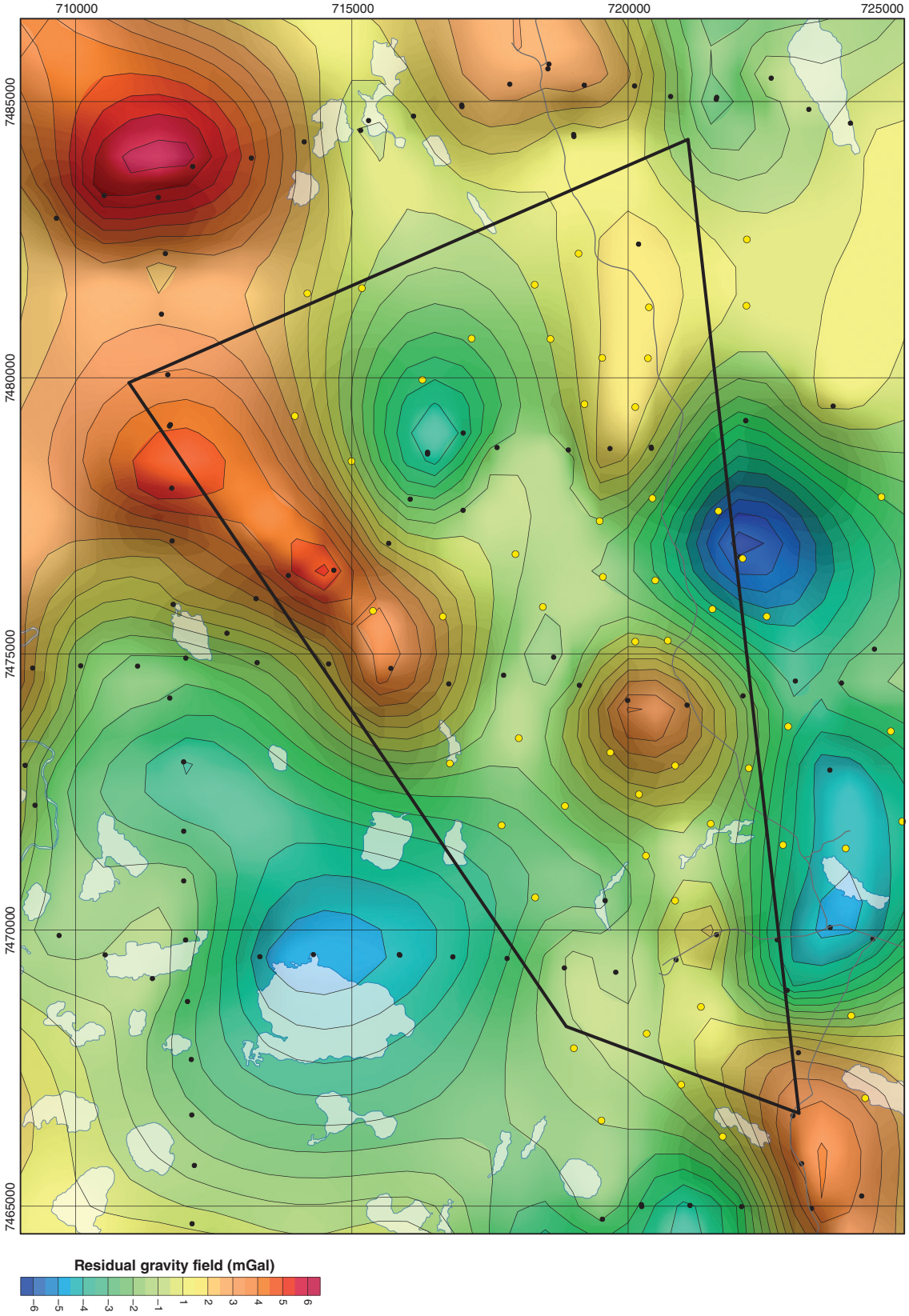

Figure 9. The residual gravity field of the Allavaara key area. Black dots represent gravity measurements currently available in SGUs database. Yellow dots represent gravity data acquired during the winter of 2014 (not yet processed).

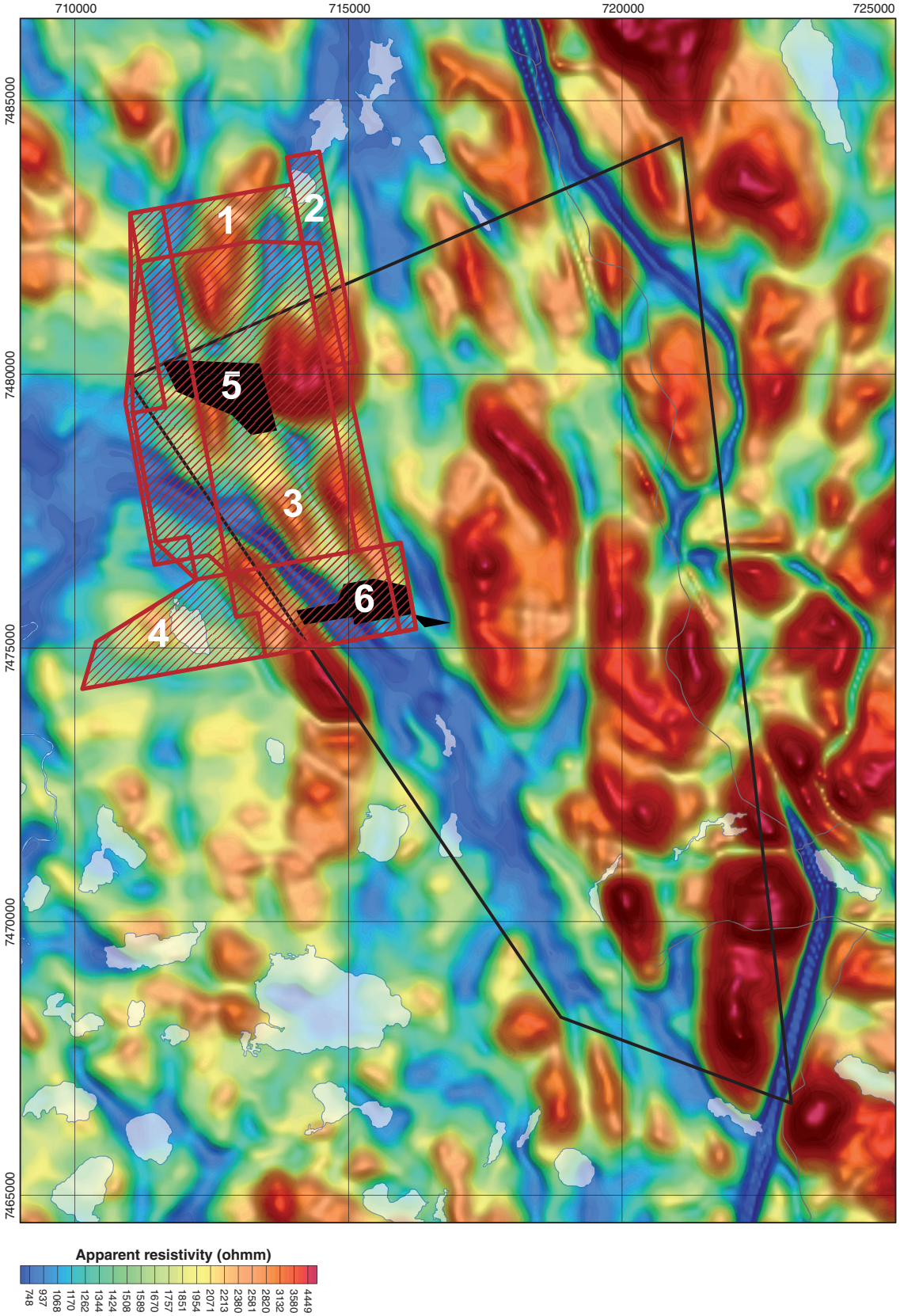

Figure 10. Apparent resistivity map of the Allavaara area. The apparent resistivity is derived from airborne VLF-data from two transmitters. The black polygons with hatches represent areas where ground electromagnetic surveys have been made while the filled black polygons show the extent of previously made geoelectric surveys. Numbers correspond to those shown in Table 10.

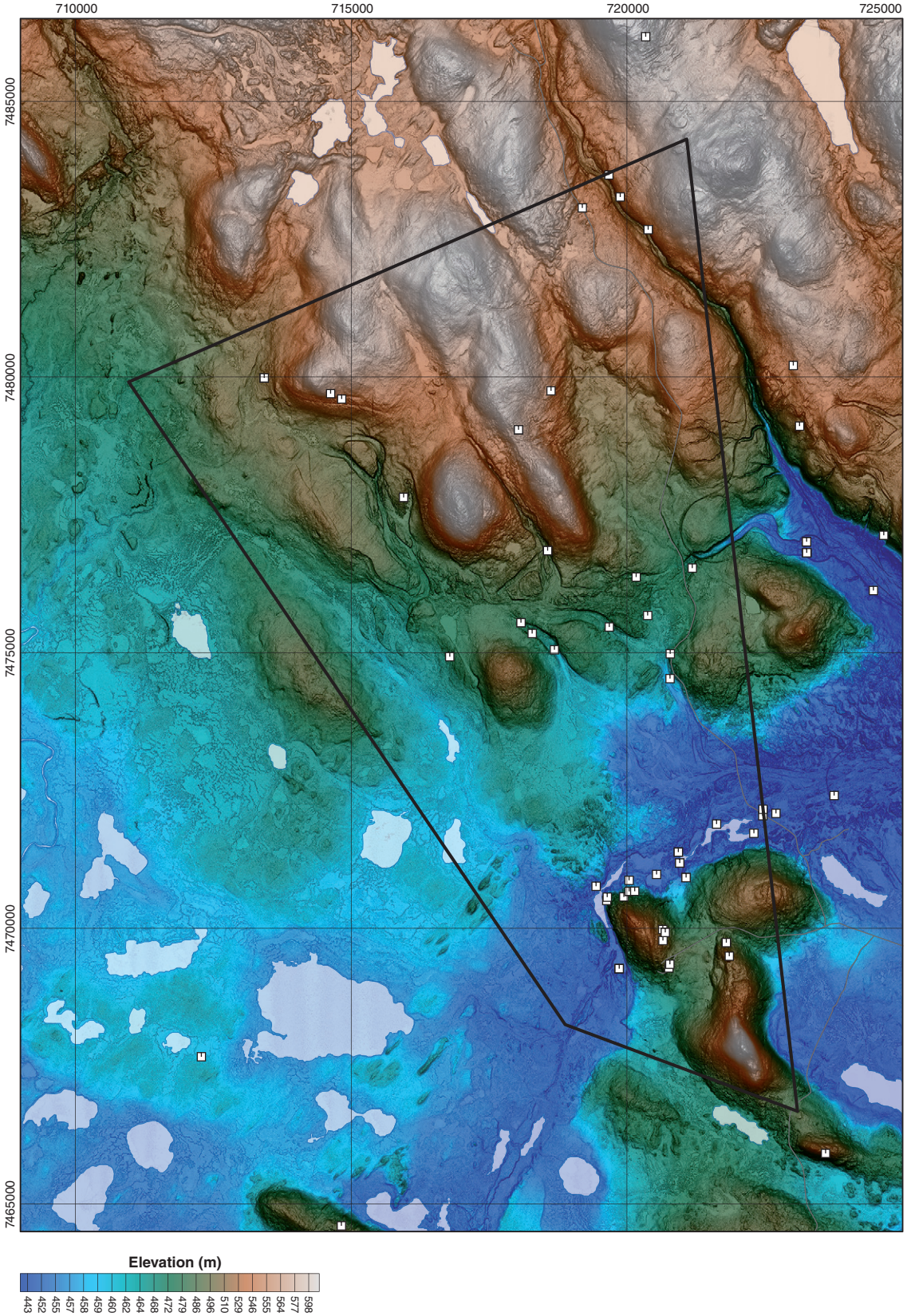

Figure 11. Location of existing petrophysical bedrock samples from the Allavaara area and surroundings. The background elevation model is based on LiDAR data (2x2 m resolution).

Lantmäteriet (Sweden's topographic survey agency), contains vector polygon height contours with a 10 m interval. The Allavaara area is not covered by the topographic map series *Terrängkartan*.

GEOLOGICAL SUMMARY AND SOME REMAINING ISSUES

The geology of the Allavaara area is comprised of a package of Paleoproterozoic metamorphosed volcanic and sedimentary rocks located within a high strain deformation zone. The volcanosedimentary sequence, formed during the earlier stages of the Svecofennian orogeny (c. 1.9 Ga), subsequently underwent several phases of deformation resulting in metamorphism and recrystallisation to produce the deformed metavolcanic sequence seen today. To the east and west of the study area, monzonitic and granitic intrusive rocks occur, while elongate fragments of intrusive rocks are also present within the deformation zone. Mineralisation is limited to a few Cu-Au occurrences in the north-western part of the key area (i.e. Fjällåsen prospect).

Metavolcanic rocks with an intermediate, calc-alkaline composition (andesites and dacites, minor rhyolites) occur along the margins of the key area and are presently assigned to the Porphyrite group lithostratigraphic unit of Norrbotten (Bergman et al. 2000, 2001). Porphyrite group rocks are considered to have formed during regional-scale tectonic compression within a subduction zone setting, with subduction directed toward the north-east (present-day coordinates). This accretionary stage (c. 1.95–1.88 Ga) followed earlier Karelian continental rifting (c. 2.4–2.0 Ga) that produced voluminous basaltic magmatism across northern Fennoscandia (e.g. Martinsson 1997, Weihed 2004).

In the north-western part of the Allavaara area, a conformable sequence of ultrabasic, skarn and carbonate rocks are intercalated within a basic to intermediate metavolcanic package (Witschard 1975a, Gerdin et al. 1980). Based on the relatively high concentrations of MgO in two analysed samples (>20 wt-%) the ultrabasic lavas have a peridotitic to komatiitic signature. Similar volcanosedimentary sequences are generally not known from Porphyrite group rocks elsewhere in Norrbotten. However, a similar stratigraphy is known from the middle to upper parts of the Kiruna greenstone group, particularly in eastern Norrbotten (e.g. Käymäjärvi area, Martinsson 1994). Thus, the rocks along the western margin of the key area around the Fjällåsen Cu-Au prospect may represent a fragment of older, Karelian greenstones. Further investigations are needed to test this hypothesis.

The more acid metavolcanic rocks (rhyolites and minor andesites), occurring within the centre of the key area, are assigned to the Porphyry group lithostratigraphic unit (e.g. Figs. 2 and 3). Porphyry group rocks are considered to have formed within a younger, extensional regime during the Svecofennian orogeny which produced bimodal volcanism consisting of rhyolites with a more alkaline character (Martinsson 2004).

In relation to the intrusive rocks at Allavaara, early work considered that the perthitic monzonite intrusions were derived from the older metavolcanic rocks via an isochemical "granitisation" process (e.g. Witschard 1975b). Subsequent interpretations have considered both rocks to be broadly co-magmatic and contemporaneous based on regional geochemical and age constraints (Witschard 1984, Bergman et al. 2001). New age constraints for the monzonitic intrusions and the intermediate and acid volcanic rocks at Allavaara would help to better establish the geological history of the area and identify temporal and genetic links between these major rock units. In addition, new age dating would help to establish regional correlations with other areas in Norrbotten and enable the unequivocal assignment of the various rock units to their correct stratigraphical position.

The rocks at Allavaara are located within a regionally significant zone of deformation (ductile shear zone with brittle overprinting). This north-north-west trending zone is subparallel to the Nautanen deformation zone, located about 30 km to the east (Fig. 12), and continues north-

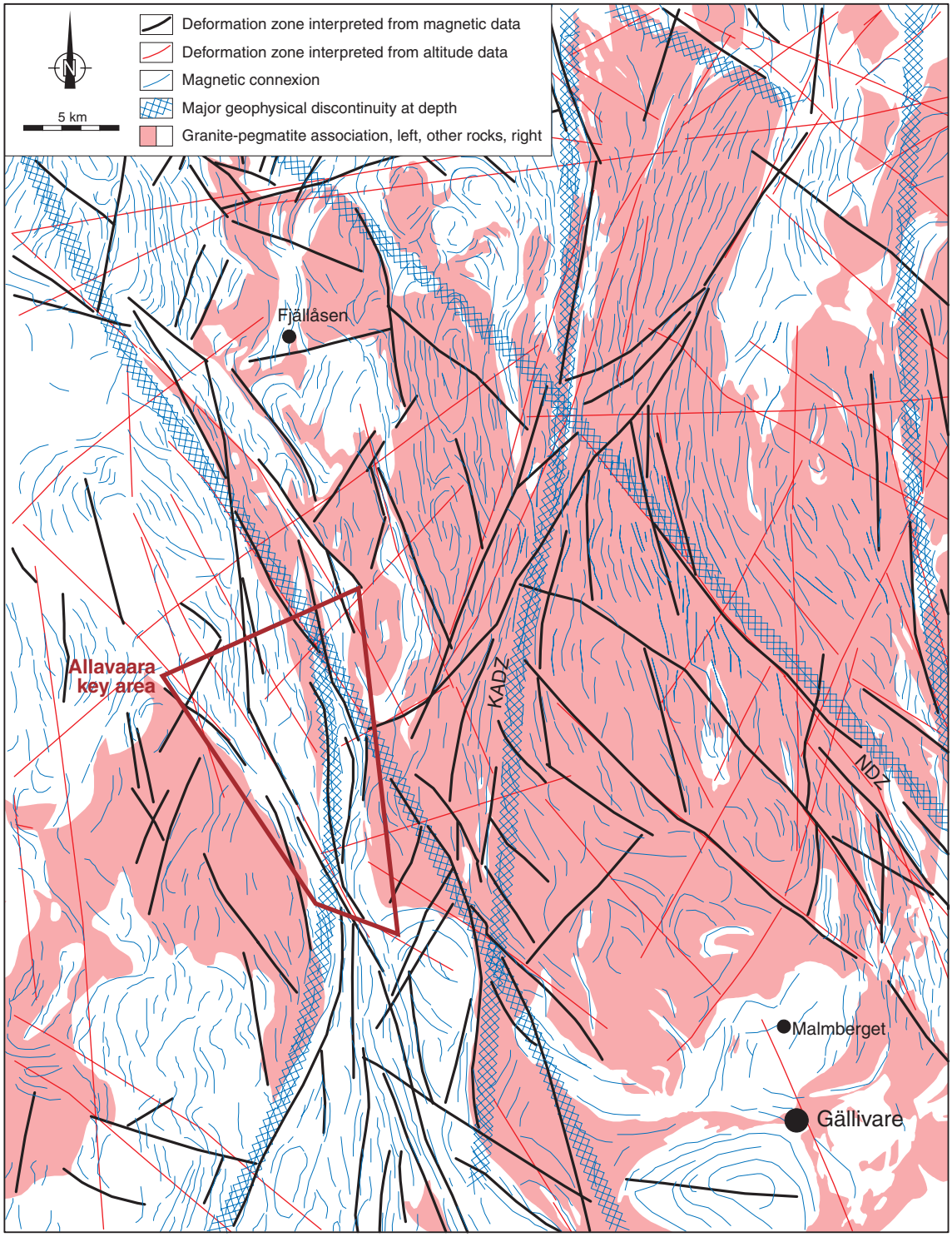

Figure 12. Structural map of the Allavaara area showing interpreted form lines and zones of deformation derived from aeromagnetic data. Modified after Bergman et al. (2001).

westward along an arcuate path for c. 60 km, where structural splays host known IOCG-type mineralisation (e.g. Tjårrojåkka deposit, Edfelt et al. 2006). Bergman et al. (2001) placed the rocks at Allavaara within their structural domains "C" and "G", with the latter representing the southern extension of the Karesuando-Arjeplog deformation zone (Fig. 12, see also Fig. 49

in Bergman et al. 2001). Domain C-related rocks contain steeply dipping foliations and lineations which indicate a western side up shear sense, similar to that observed in the Nautanen area (Bergman et al. 2001).

An interesting aspect of the Allavaara area is that the area is, in general, poorly mineralised (excluding Cu-Au mineralisation at Fjällåsen). This is in contrast to other deformation zones in Norrbotten containing analogous supracrustal rocks. For example, in the Nautanen deformation zone, some 30 km to the east, abundant epigenetic Cu-Au mineralisation is found in structurally favourable zones hosted by Porphyrite and Porphyry group metavolcanic rocks which are broadly analogous to the rocks at Allavaara. A contrasting aspect between both zones is that the Nautanen area contains numerous Haparanda suite dioritic intrusions which do not occur in the Allavaara area.

The following points identify some unresolved geological questions and areas of investigation for the Allavaara key area. An examination of these issues will develop a more comprehensive understanding of the geological evolution of the area and help establish regional lithological and stratigraphic correlations with other parts of Norrbotten. In addition, resolving such fundamental geological questions can have implications for the development of local and regional metallogenic models and improve our understanding of mineralisation processes in this area.

- What age are the various rock units at Allavaara? Sampling for geochronology of the metavolcanic, metasedimentary and intrusive rocks is an important priority for the area. Focus should be made on the lower and uppermost parts of the volcanosedimentary sequence in order to constrain the age of this sequence and the duration of its formation.
- Is there a temporal and genetic link between the monzonitic intrusions to the west of Allavaara and the intermediate Porphyrite group metavolcanic rocks? Combined geochronological, geochemical and isotopic sampling will help to better understand this.
- Establish a lithogeochemical profile across the Allavaara deformation zone with respect to alteration and lithology to assess the response of the bedrock to overprinting hydrothermal and metasomatic events etc.
- The Allavaara key area provides an opportunity to compare the characteristics of Svecofennian metavolcanic rocks within a generally barren deformation zone (Allavaara) with analogous rocks within a generally mineralised and altered deformation zone (e.g. at Nautanen to the east).
- What are the characteristics of the deformation zone at Allavaara? What are the dominant deformation styles and kinematic indicators? Can the timing of deformation be established? The high strain pinch zone located at the southern part of the key area provides an opportunity to image a Svecofennian deformation zone using multiple ground-based geophysical techniques.
- Assessment of the komatiitic, carbonate and skarn rocks in the north-western Allavaara area is needed to establish if they should be reassigned to the Kiruna greenstone group. Do Archean basement rocks occur to the west of this sequence, similar to areas north of Kiruna?
- What factors have led to relatively few known Cu-Au mineralisation occurrences at Allavaara? Is it a function of the lack of favourable structural and lithological traps?

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