KARTERING BARENTS 2013

Background information Tjårrojåkka key area (29I Kebnekaise SO & 29J Kiruna SV)

Edward P. Lynch & Robert Berggren

October 2013

SGU-rapport 2013:14

Sveriges geologiska undersökning
Geological Survey of Sweden

Cover image: South-central Tjårrojåkka area looking SSE toward Kaitumälven. Photo: Edward P. Lynch, SGU.

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

INNEHÅLL

INTRODUCTION

The Tjårrojåkka Key Area (TKA) is located approximately 50 km southwest of Kiruna (Norrbotten, Sweden), within map sheets 29I SO (Kebnekaise) and 29J SV (Kiruna), and incorporates 17 5 × 5km lettered topographic grid squares (Fig. 1). The area is centered on a package of metamorphosed volcanic rocks that belong to the Svecofennian supracrustal sequence in northern Fennoscandia (ca. 1.96–1.85 Ga). These rocks are composed of metamorphosed basalts, andesites and rhyolites of the Porphyrite and Porphyry lithostratigraphic groups (the latter is also referred to as the Kiirunavaara Group or Kiruna Porphyries, see Table 2 in Bergman et al. 2001). Svecokarelian (1.89–1.86 Ga) intrusive rocks also occur in the area and primarily consist of metamorphosed quartz monzonites, syenites and granitoids belonging to the Perthite Monzanite intrusive suite (PMS, e.g., Witschard 1984). Minor metagabbroid intrusives with an affinity to the Haparanda Suite of plutons (HS) are also present. In the eastern part of the TKA, metabasalts correlative with older Karelian greenstones (Kiruna Greenstone Group) have been mapped as an elongate, E–NE-trending inlier within Porphyrite Group metaandesites (Offerberg 1967). The TKA is best known for Fe-oxide and Cu mineralization (IOCG-type) at the Tjårrojåkka deposits (≈ 56 Mt combined) in the western part of the key area (e.g., Ros 1979, Frietsch 1997, Edfelt et al. 2005, Sandrin and Elming 2006). The Tjårrojåkka Fe deposit was discovered in 1963 by SGU (e.g. Quezada and Ros 1971) while the most recently completed phase of exploration was conducted by Phelps Dodge Exploration Sweden AB in the mid 2000's (e.g., Perdahl 2006).

Access to the TKA is difficult. The closest paved road is located about 20km to the north and northeast (an unclassified local route running east–west between Kiruna and Nikkaluokta). Furthermore, forest/dirt roads are generally lacking in the area. Thus, helicopter is the most viable access method. Based on an assessment of orthophotos, the terrain appears to be a mixture of deciduous forest and bog in the east, grading into more upland heath and scrub in the west. The landscape is undulating to hilly in the east, with elevations around 550m (a.s.l.), and becomes more mountainous in the west with elevations up to 1,055m (Täunatjåkka). The Liettiksavu River flows through the key area (from west to east) and represents the main hydrographic feature. Small lakes and ponds are mostly located in the east and northeast. Outcrops are primarily located in the eastern and western ends of the TKA (see Fig. 3). Thin soil cover also exists in the areas with the best exposure. The central and northern parts of the key area appear to be the least exposed, however outcrop exposure along the banks of the Liettiksavu River in the south–central part of the key area may compensate for the general lack of exposure.

This report outlines the main geological and geophysical characteristics of the TKA. It presents an outline of existing maps, geological datasets, reports and publications available, and summarises the present understanding of the geological setting and evolution of the area. It also identifies potential avenues of research and investigation to resolve outstanding geological questions and further our understanding of the geology, stratigraphy and mineral potential of this part of Sweden. The Tjårrojåkka Key Area is a focus for targeted geological mapping and investigations under SGU's Barents Mapping Project (2012–2015).

GEOLOGICAL OVERVIEW

The bedrock geology of the Tjårrojåkka Key Area (TKA) is summarized in earlier SGU reports and maps by Geijer (1931), Ödman (1957), Offerberg (1967) and Witschard et al.

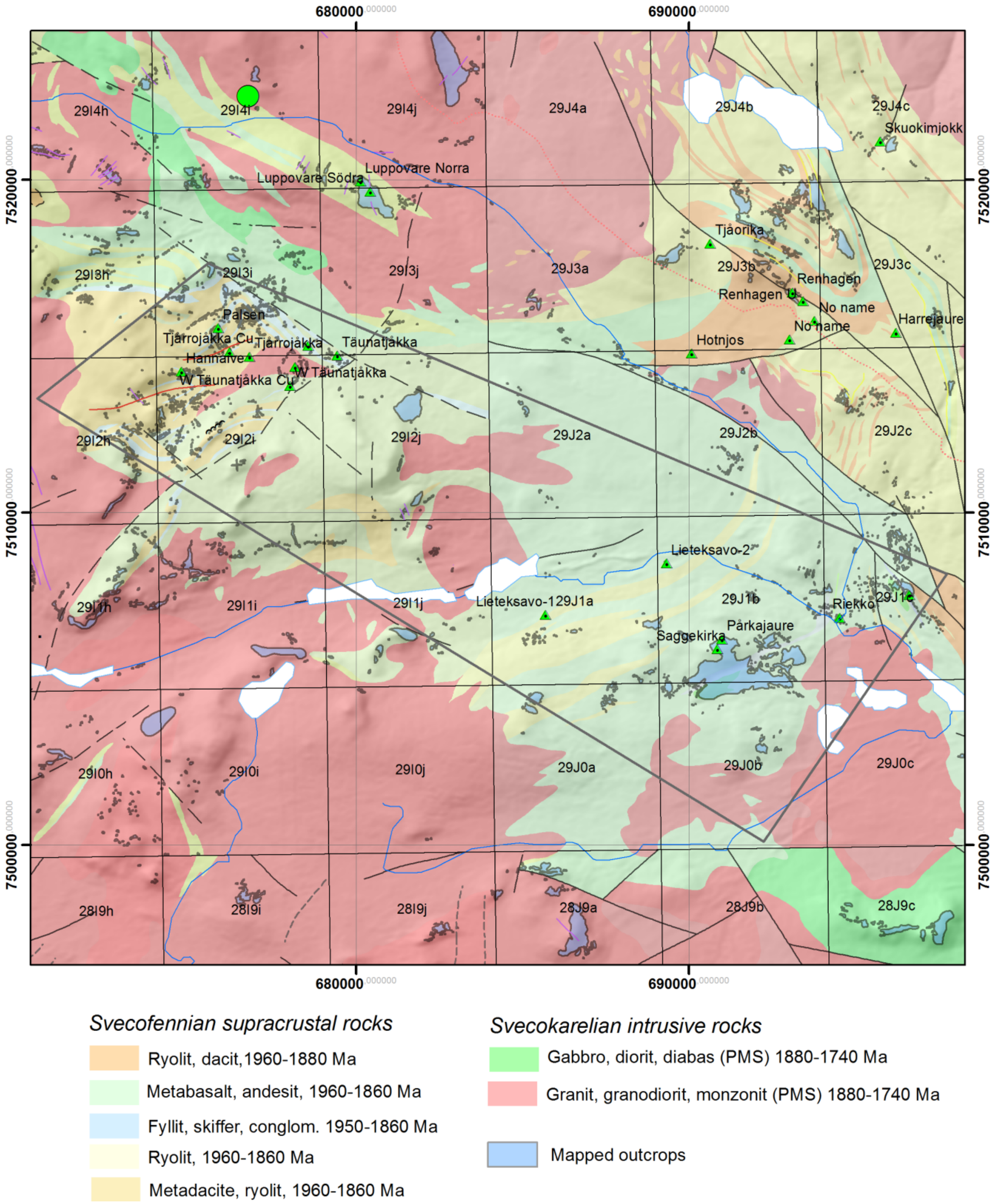

Figure 1. Bedrock geology of the Tjårrojåkka key area (local 1:50.000 scale level). Lakes and rivers also shown.

(2004), while a compilation and summary of Norrbotten geology from a regional perspective is presented by Lundqvist (1979), Bergman et al. (2001) and Martinsson (2004). The area is dominated by an approximately rectangular package of metavolcanic rocks consisting of basalts, basaltic andesites, andesites, rhyodacites and rhyolites which form part of the regionally extensive, ca. 10km thick, Svecofennian supracrustal sequence in northern Sweden (ca. 1,960–1,850 Ma). Porphyrytic textures are commonly seen in the more intermediate volcanics, while several horizons of volcaniclastic material (tuff, agglomerate) are also present within this succession. The volcanic sequence is broadly considered to both young and become more felsic from west to east, although local and regional deformation events have complicated the stratigraphy (cf. Offerberg 1967, Bergman et al. 2001, Edfelt 2003). Intrusive rocks across the area mostly consist of monzonites, quartz monzonites, syenites and perthitic granitoids, with a few gabbro and diorite intrusions also represented. The area is cut by numerous dykes of both doleritic and granitic composition. In the western TKA, doleritic dykes are considered to represent feeder conduits for the mafic volcanics (Edfelt 2003). Lithogeochemical analyses suggest that the majority of both the volcanic and intrusive rocks have a subduction-type, continental arc signature (cf. Bergman et al. 2001, Edfelt et al. 2005, Edfelt et al. 2006), although some workers have suggested localized, back-arc-type rifting processes may also have contributed to the geological development (e.g., Martinsson et al. 1993, Perdahl 1995).

The metavolcanic rocks within the TKA have been assigned to two traditional lithostratigraphic units termed the Porphyrite and Porphyry Groups (Offerberg 1967, Witschard et al. 2004). The latter is host to Fe-oxide-apatite mineralization to the NE at Kiruna. The Porphyrite Group volcanics are interpreted to have been extruded during a phase of tectonic compression/subduction directed toward the NE (present-day coordinates). This accretionary stage (ca. 1,900–1,880 Ma) superseded earlier Karelian continental rifting, sedimentation and basaltic magmatism (ca. 2,400–2,000 Ma) that produced the various greenstones belts of northern Sweden (e.g., Martinsson 1997, Weihed 2004). The overlying Porphyry Group volcanics developed during a later rifting/extensional regime which produced bimodal volcanism consisting of basalts and rhyolites (Martinsson 2004). In the easternmost TKA, intermediate and acid metavolcanic rocks originally assigned to the Porphyrite Group (Offerberg 1967) were subsequently reclassified within the Porphyry Group (i.e. Kiruna porphyries), based on lithogeochemical characteristics and the regional distribution of the various lithologies (Bergman et al. 2001, see sections Summary and Discussion). The intrusive rocks in the area are mostly assigned to the Perthite Monzonite Suite (PMS) of plutons. On a regional scale, this plutonic suite preferentially intrudes the western side of northernmost Sweden. In addition, several small gabbroic bodies (e.g. north of the Tjårrojåkka deposits, western TKA) have been assigned to the Haparanda Suite (HS) of intrusive rocks (Witschard et al. 2004).

The study area has experienced several episodes of deformation and associated metamorphism during the Svecokarelian Orogeny (ca. 1,900–1,800 Ma), which likely facilitated episodic hydrothermal fluid flow and related mineralization and alteration. The area is bound to the north by a WNW-trending, sub-regional, deformation zone (see Summary), while extensive folding and brittle fracturing is also locally developed. Regional metamorphism attained peak conditions that transect the greenschist-amphibolite facies boundary (Bergman et al. 2001).

The TKA hosts several sub-economic Fe-oxide-apatite (IOA) and Cu deposits, prospects and showings. Most of the mineralization is hosted in the metavolcanic units and appears to be structurally controlled. The best known and most studied deposit is the Tjårrojåkka IOCG system located at the western end of the TKA (e.g., Sandrin 2003, Edfelt 2007). The timing of mineralization at Tjårrojåkka is constrained to ca. 1,780 Ma (Edfelt et al. 2007). This age suggests that late-stage Svecokarelian magmatism (e.g., Lina-type granite-pegmatite association) may have played a role in the development of some of the mineralization across the TKA (cf. Edfelt et al. 2007).

AVAILABLE DATA FOR TJÅRROJÅKKA KEY AREA

The following subsections present a summary of the available geological, geophysical, geochemical and topographic data.

Bedrock Geology

The TKA is covered by several bedrock geology maps and datasets located on SGU's GIS database. Many of the GIS layers are derived from digitized versions of previous bedrock mapping programmes at 1:50,000 or 1:250,000. Additional sampling or analyses (e.g., lithogeochemistry, age determinations) are generally represented as vector point layers or polygons showing the sample location and analysis/data result. The most detailed mapping is two 1:50,000 scale bedrock maps from SGU's Af and Ai map series. They are (i) 29J Kiruna SV (Af nr 3) in the east from Serie Af, Nr 1–4, Kiruna NV, NO, SV, SO (Offerberg 1967) and (ii) 29I Kebnekise SO (Ai nr 198) in the west (Witschard et al. 2004).

Map databases

The following tables list the most important bedrock mapping for the Tjårrojåkka area along with additional bedrock information derived from SGU's GIS. The maps listed in Table 1 represent both scanned and rectified paper maps, and several digitized vector databases located on SGU's network.

Additional bedrock-related information is listed in Table 2 (including several till datasets). These consist of vector data representing geological observations and analysis of the bedrock, including outcrop locations with basic observational information and metamorphic indicator minerals.

Table 1. Published maps and pap databases covering the TKA

Code	Title	Scale	Reference	Location	Most relevant
Ai 198	Bedrock map	1:50,000	Witschard et al. 2004	Western TKA	Bedrock map, NW–SE profile
Af 3	Bedrock map	1:50,000	Offerberg 1967	Eastern TKA	Bedrock map, SW–NE profiles
Ba56–1	Regional bedrock map	1:250,000	Bergman et al. 2000	Northern Norrbotten	Bedrock, stratigraphy, structures
K222–1	Kaledoniderna i norra Sverige, norra delen	1:250,000	Thelander 2009	Western TKA	Bedrock geology of Caledonides only
Ca 41	Berggrundskara över urberget i Norrbottens län	1:400,000	O. Ödman 1957	Norrbotten	Regional geology
K423	Bedrock map of Sweden	1:1,000,000	Bergman et al. 2012	Sweden	Regional geology, tectonic domains
n/a	Nordkalotts bedrock geology map. 1:1,000,000	1:1,000,000	GTK–SGU–NGU	N. Sweden	Regional geology
n/a	Metallic mineral deposit map of the Fennoscandian Shield	1:2,000,000	Eilu et al. 2008	Fennoscandia	Regional geology, mineralization
n/a	Geology of the Fennoscandian Shield.	1:2,000,000	Koistinen et al. 2001	Fennoscandia	Regional geology, tectonic domains
n/a	Lokal berggrundsinformation	1:50,000	SGU database (GIS)	All of TKA	Bedrock geology
n/a	Regional berggrundsinformation	1:250,000	SGU database (GIS)	All of TKA	Bedrock geology

Scanned maps

Table 3 lists the scanned paper maps (field maps) used to identify outcrop locations and record geological mapping data. These maps formed the basis for the 1:50,000 mapping programme and show the location of outcrops, areas of thin soil cover and mineralized localities (Fig. 2). The majority of information was recorded at 1:20 000. The available field diaries for the Tjårrojåkka area are also listed.

Additional scanned maps can be found within the various BRAP and PRAP reports for several of the mineralized areas that occur within or adjacent to the TKA (listed in Table 6 below). For example, Ros and Rönnbäck (1971) show a 1:5,000 map of mineralized horizons at the Tjårrojåkka Fe-oxide-Cu deposit based on drill hole intersections. Cornwell (1966) shows local gravity anomaly map at 1:10,000 over the Tjårrojåkka deposit. Quezada and Ros (1971) show maps of the locations of drill holes and various graphs relating to assay data for the Tjårrojåkka deposit. Niva (1978) shows a Bouger anomaly map over the Tjårrojåkka area based on gravity measurement grid.

Outcrops

Figure 1 shows the location of known outcrops and exposed rock areas across the TKA (outlined, shaded polygons). In general, the area is poorly exposed, however, the metavolcanics in the western and easternmost parts, along with areas of higher ground, appear to be the best exposed. There is some scattered exposure of metavolcanic rocks in the central and southern parts also. The northern margin of the TKA (metabasalt/andesite, granitoids) has the least

Table 2. Additional bedrock-related information covering the TKA

Layer/dataset	Description	Location	Reference
Hällar ur jordartskartor	Digital layer showing outcrop and thin soil cover areas from soil maps.	TKA	SGU database
Berggrundsobservationer	Point dataset of location and description of outcrop and structural observations.	Western part only covered	SGU database
Geology_1M	1:1,000,000 scale digital vector data showing bedrock geology. No colour coding.	TKA	SGU database
Drumliner	Digital vector data location of drumlin polygons and description	29J0c	SGU database
Hällar	Digital vector data location of exposed outcrop areas (regional scale)	Eastern side mostly covered	SGU database
Boulder data covering 29I	Locations and descriptions of boulders	TKA	SGU database
Förenklad jordartsindelning (JBAS)	soil/till geology map of Norbotten 1:250,000	TKA	SGU database
Jordartskartor	soil/till geology map of Norbotten 1:250,000 and 1:1,000,000	TKA	SGU database
Bergartsstuffer, fysiska prov	Hand specimens in the SGU collection. 27 samples from the western side of the TKA. Granitoids have few samples	TKA	SGU database
Jorddjupsmodell	Soil depth model raster dataset	TKA	SGU database
Jorddjupsinformation	Soil depth vector point data. 35 points in the study area.	Western TKA	SGU database

Table 3

Layer/dataset	Description	Scale	Reference
G10656	Scanned outcrop field map (not rectified) 29I, 4-5, i-j	1:20,000	SGU database
G10655	Scanned outcrop field map (not rectified) 29I, 4-5, i-j	1:20,000	SGU database
G10654	Scanned outcrop field map (not rectified) 29I, 4-5, i-j	1:20,000	SGU database
G10653	Scanned outcrop field map (not rectified) 29I, 4-5, g-h	1:20,000	SGU database
G10652	Scanned outcrop field map (not rectified) 29I, 4-5, g-h	1:20,000	SGU database
G10651	Scanned outcrop field map (not rectified) 29I, 4-5, g-h	1:20,000	SGU database
G10647	Scanned outcrop field map (not rectified) 29I, 2-3, i-j	1:20,000	SGU database
G10646	Scanned outcrop field map (not rectified) 29I, 2-3, i-j	1:20,000	SGU database
G10645	Scanned outcrop field map (not rectified) 29I, 2-3, i-j	1:20,000	SGU database
G10644	Scanned outcrop field map (not rectified) 29I, 4-5, g-h	1:20,000	SGU database
G10643	Scanned outcrop field map (not rectified) 29I, 2-3, g-h	1:20,000	SGU database
G10642	Scanned outcrop field map (not rectified) 29I, 2-3, g-h	1:20,000	SGU database
G10641	Scanned outcrop field map (not rectified) 29I, 2-3, i-j	1:20,000	SGU database
G10640	Scanned outcrop field map (not rectified) 29I, 2-3, i-j	1:20,000	SGU database
G10639	Scanned outcrop field map (not rectified) 29I, 2-3, i-j	1:20,000	SGU database
G10638	Scanned outcrop field map (not rectified) 29I, 2-3, g-h	1:20,000	SGU database
G10634	Scanned outcrop field map (not rectified) 29I, 0-1, i-j	1:20,000	SGU database
G10633	Scanned outcrop field map (not rectified) 29I, 0-1, i-j	1:20,000	SGU database
G10632	Scanned outcrop field map (not rectified) 29I, 0-1, i-j	1:20,000	SGU database
G10631	Scanned outcrop field map (not rectified) 29I, 0-1, g-h	1:20,000	SGU database
G00260	Scanned outcrop field map (not rectified) 29J, 2-3, c-d	1:20,000	SGU database
G00261	Scanned outcrop field map (not rectified) 29J, 2-3, a-b	1:20,000	SGU database
G00274	Scanned outcrop field map (not rectified) 29J, 0-4, a-e	1:50,000	SGU database
G00276	Scanned outcrop field map (not rectified) 29J, 0-1, e-f	1:20,000	SGU database
G00277	Scanned outcrop field map (not rectified) 29J, 0-1, c-d	1:20,000	SGU database
G00278	Scanned outcrop field map (not rectified) 29J, 0-1, a-b	1:20,000	SGU database
G00281	Scanned outcrop field map (not rectified) 29J, 2-3, e-f	1:20,000	SGU database
G00284	Scanned outcrop field map (not rectified) 29J, 4-5, e-f	1:20,000	SGU database
Diaries_29I	70 field notebooks from various SGU workers (1950-75)	Varies	SGU database
Diaries_29J	72 field notebooks from various SGU workers (1960-76)	Varies	SGU database

exposure. Furthermore, granitoids along the southern margin of the area appear poorly exposed. The mapped outcrop locations are mainly derived from original field mapping in the 1960's carried out at 1:20,000 scale and shown on the various field mapping sheets listed in Table 3.

Published material (papers and reports)

A list of the most important papers and reports for the TKA is presented in Table 4. Additional exploration reports are also available and can be found on SGU's GeoRegister service. Several of these publications are review papers that summarize the broad geological framework of the TKA. Other papers relate to specific studies carried out within or adjacent to the TKA (in particular the Tjårrojåkka IOCG deposit), or regional studies that incorporated one or more samples from the various TKA rock units. The publications are listed in decreasing chronological order. References quoted in the main text of this report refer to those publications listed in the references.

Table 4. Publications and reports relating to the geology of the TKA.

Reference	Year	Title	Brief Overview
Smith et al, Geochim. Cosmochim. Acta, v.102, p.89–112.	2013	Hydrothermal fluid evolution and metal transport in the Kiruna District, Sweden: Contrasting metal behaviour in aqueous and aqueous–carbonic brines	Regional-scale hydrothermal fluid study constraining the nature of mineralizing hydrothermal fluids in Norrbotten. Briefly refers to the Tjårrojåkka IOCG-type deposit containing host rocks with Ba-rich feldspars.
Hallberg et al., GTK Special Publication 53, p. 139–206	2012	Metallogenic areas in Sweden	Review of mineral deposits and districts of Sweden. Area S035 (Kiruna) briefly mentions the Tjårrojåkka deposits.
Wanhainen et al., Ore Geol. Rev., v.48, p. 306–331	2012	Modification of a Palaeoproterozoic porphyry-like system: Integration of structural, geochemical, petrographic, and fluid inclusion data from the Aitik Cu–Au–Ag deposit, northern Sweden	Figure 1 shows the location of the Tjårrojåkka deposit w.r.t. other mineralization in the Norrbotten ore field.
Sandrin et al., J. Geochem. Ex., v.103, p.80–96	2009	Physical properties and petrologic description of rock samples from an IOCG mineralized area in the northern Fennoscandian Shield, Sweden	Petrophysical (MS, RM, density) analysis of 24 rock samples from the Tjårrojåkka deposit. Also microprobe analysis of magnetite. Hematite is secondary after magnetite.
Bergman et al., 33rd IGC excursion guide no. 15	2008	General Introduction to Geology and Metallogeny of Fennoscandian Shield	Review of the geology and metallogeny of N Sweden. Tjårrojåkka deposit and it's geological setting mentioned.
Edfelt et al., (in Edfelt, 2007)	2007	Origin and fluid evolution of the Tjårrojåkka apatite-iron and Cu (-Au) deposits, Kiruna area, northern Sweden	Fluid inclusion and isotopic study at the Tjårrojåkka IOCG deposit to characterize the mineralizing hydrothermal system. Part of Edfelt PhD thesis.
Edfelt, Å, PhD thesis, Luleå University, Sweden	2007	The Tjårrojåkka apatite-iron and Cu (-Au) deposits, northern Sweden – products of one ore forming event	PhD study focusing on the Tjårrojåkka IOCG deposit. Several papers dealing with stratigraphy, timing, geochemistry and hydrothermal fluids.
Sandrin, A and Elming, S-A, Ore Geol. Rev. v.30, p. 56–73	2007	Physical properties of rocks from borehole TJ71305 and geophysical outline of the Tjårrojåkka Cu-prospect, northern Sweden	Petrophysical study of rock samples from exploration borehole TJ71305, which intersects the Cu prospect in the Tjårrojåkka IOCG mineralised area. The Cu-prospect is also indicated by high gravity and magnetic anomalies, by clear positive anomalies in induced polarisation data.
Edfelt et al, GFF, v.128, p. 221–232.	2006	Stratigraphy and tectonic setting of the host rocks to the Tjårrojåkka Fe-oxide Cu-Au deposits, Kiruna area, northern Sweden	Study of host rocks to Tjårrojåkka IOCG deposit. Presents mineralogy and lithogeochemistry of metavolcanics and intrusions, U-Pb age of andesite (1,878 Ma) and petrophysical data (MS, density) for rock units.
Sandrin, A. and Elming, S.-Å., Ore Geol. Rev., v.29, p.1–18	2006	Geophysical and petrophysical study of an iron oxide copper gold deposit in northern Sweden	Geophysical and petrophysical study of the Tjårrojåkka IOCG deposit.
Perdahl, J-A, MINK 5749, Bergstaten, Malå	2006	REDOVISNING AV RESULTAT AV UNDERSÖKNINGSARBETEN	Brief report on rock sampling and exploration activity. No results given.
Edfelt, Å and Martinsson, O, Ore Geol. Rev., v.27, p.	2005	Box 8–3: Fennoscandian Shield–Iron Oxide–Copper–Gold deposits Tjårrojåkka, northern Sweden	Outline of the geological setting of the Tjårrojåkka IOCG system with lithogeochemistry results of host meta-andesites.
Edfelt et al, Min. Dep., v.40, p. 409–434.	2005	Alteration paragenesis and mineral chemistry of the Tjårrojåkka apatite-iron and Cu (-Au) occurrences, Kiruna area, northern Sweden	Study of the Tjårrojåkka IOCG deposit using alteration and mineral chemistry data.
Edfelt et al., GFF, v.126, p.148	2004	A preliminary fluid inclusion study of the Tjårrojåkka IOCG-occurrence, Kiruna area, Northern Sweden.	As the title suggests. A meeting abstract. Data shown in Edfelt 2007.

Table 4. Continued.

Reference	Year	Title	Brief Overview
Edfelt Å & Martinsson, O., IAVCEI General Assembly 2004,	2004	The Tjårrojåkka Fe-oxide and Cu-Au occurrences, northern Sweden – products of one ore-forming event?	Abstract describing the mineralization at Tjårrojåkka
Martinsson, O, SEG guidebook series vol. 33, p. 131–148	2004	Geology and Metallogeny of the Northern Norrbotten Fe-Cu-Au Province	Review paper on the geology and metallogeny of N Sweden. Tjårrojåkka deposit and it's geological setting mentioned. Svecofennian volcanics also discussed.
Weihed P, SEG guidebook series vol. 33, p. 1–15	2004	Overview of the geology and tectonic setting of northern Sweden	Review paper of the broad tectonic and stratigraphic development of Norrbotten and other areas in N Sweden.
Witschard, F. et al., SGU Ai nr 198	2004	Beskrivning till berggrundskartbladen 29I Kebnekaise SO	Summary of the geological and geophysical characteristics of map sheet 29I Kebnekaise SO (western TKA)
Edfelt, Å. MSc thesis. Luleå University of Technology	2003	Geology, alterations, and mineral chemistry of theTjårrojåkka Fe-oxide Cu–Au occurrences, N Sweden	Study of the geology and geochemistry of the Tjårrojåkka deposit(s)
Sandrin E, MSc thesis, Luleå University, Sweden	2003	Geophysical and petrophysical characterisation of the Tjårrojåkka IOCG mineralization, Sweden.	Detailed geophysical study of the Tjårrojåkka deposits.
Coppard T., Bergsstaten, Luleå. ID: 212-919-2003	2003a	Riekko nr 1. Redovisning av resultat av undersökningsarbeten enligt 14 kap 3 § minerallagen (1991:45)	Research results based in investigations of the Riekko nr 1 Cu deposit, eastern TKA.
Coppard T., Bergsstaten, Luleå. ID: 212-919-2003	2003b	Riekko nr 2. Redovisning av resultat av undersökningsarbeten enligt 14 kap 3 § minerallagen (1991:45)	Research results based in investigations of the Riekko nr 2 Cu deposit, eastern TKA.
Bergman et al., SGU Ba 56, 110 pp.	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. Tjårrojåkka deposit(s) summarised.
Broman C and Martinsson M, Luleå University of Technology, Research report 2000:6 p.7	2000	Fluid inclusions in epigenetic Fe-Cu-Au ores in northern Norrbotten.	Overview of hydrothermal fluid characteristics for epigenetic Cu mineralization in Norrbotten. Fluids are generally aqueous NaCl-CaCl2 brines with high salinities. CO2-bearing fluids appear to correlate with the more Au-rich systems.
Frietsch R et al., Ore Geol. Rev, v.12, p.1–34.	1997a	Early Proterozoic (Cu-)(Au) and Fe ore deposits associated with regional Na-Cl metasomatism in northern Fennoscandia	Study of scapolite and tourmaline alteration in N Norrbotten and interpretation w.r.t. mineralization and metasomatism.
Frietsch R, SGU RM 92, 77 p.	1997b	The Iron Ore Inventory Programme 1963-1972 in Norrbotten County. TI: Map, iron ore inventory programme 1963-1972, 1:250,0000	General review of iron ore deposits in Norrbotten. Includes summary of Tjårrojåkka, Pattok and Pattovare deposits.
Nironen M, Precam. Res, v.86, p. 21–44	1997	The Svecofennian Orogen: a tectonic model	Review of the tectonic history of Svecofennian Orogen. Big-picture tectonic development.
Talbot CJ and Koyi H., Precam. Res., v.	1995	Palaeoproterozoic intraplating exposed by resultant gravity overturn near Kiruna, northern Sweden	Structural assessment of map sheet 29J with implications for Svecofennian volcanism and plutonism in the Kiruna area.
Martinsson O, PIM report # 3, 58 p.	1995	Greenstone and porphyry hosted ore deposits in northern Norrbotten	Description of the Tjårrojåkka deposits with a basic geological map of the area included showing ore body.
Martinsson O and Perdahl J-A, in Perdahl (1995)	1995	Paleoproterozoic extensional and compressional magmatism in northern Norrbotten, northern Sweden	Lithogeochemical study of metavolcanic rocks from the Porphyrite and Porphyry (Kiruna Porphyries) Groups. No sample location map or individual sample descriptions presented. Provides geochemical evidence for the division of the Porphyrite and Porphyry Groups.
Perdahl J-A, PhD thesis, Luleå University, Sweden	1995	Svecofennian volcanism in northernmost Sweden	PhD thesis focused on the Svecofennian metavolcanic rocks in Norrbotten. Contains 9 papers (!).

Table 4. Continued.

Reference	Year	Title	Brief Overview
Romer RL, Econ. Geol., v.89, p. 1249–1261.	1994	Geochronology of the Kiruna Iron Ores and Hydrothermal Alterations	U-Pb titanite age constraints of the ores and host rocks at Kiruna (1,888 Ma). Also a titanite age for regional-scale titanite-actinolite-carbonate alteration (1,876 Ma). A syenite in the area intruding the volcanics has a U-Pb titanite age of 1,792 Ma.
Martinsson O & Perdahl J-A, in Marinsson et al., PIM report # 1	1993	Preliminary classification of sulphide occurrences in northern Norrbotten	Brief mention of the Tjårrojåkka Cu deposit in Table 1 and classified as 'Unclassified' epigenetic Cu-dominated deposit.
Perdahl J-A, Licentiate thesis, Luleå University	1993	Geological diversities within the Kiruna–Arvidsjaur Porphyry groups. Implications for age and facies dependence	Lithogeochemical study of Kiruna Porphyry Group metavolcanics and correlative units elsewhere in northern Sweden (e.g., Skellefte District). Sample coordinates listed in Appendix.
Perdahl J-A and Frietsch R 1993, Precam Res., v.64, p. 239–252.	1993	Petrochemical and petrological characteristics of 1.9 Ga old volcanics in northern Sweden.	Lithogeochemistry of "KAPG" rocks (i.e., Kiruna Porphyries or Porphyry Group metavolcanics). 164 analyses made in the Kiruna area inc. 43 for REEs (?). No sample location map, sample coordinates or petrographic descriptions reported. Samples grouped together within 4 sub-districts. Difficult to follow what exactly was analysed and from where.
Romer RL and Wright JE, GCA, v.57, p. 2555–2570	1993	Lead mobilization during tectonic reactivation of the western Baltic Shield	Caledonian orogeny caused lead remobilization during orogenic fluid pumping. Implications for U-Pb geochronology in N Sweden.
Öhlander et al., Precam. Res., v.64, p. 67–84	1993	Delineation and character of the Archaean-Proterozoic boundary in northern Sweden	A Sm–Nd study of extrusive and intrusive rocks across Norrbotten to identify basement crustal blocks and magma sources. One sample from the TKA analysed.0
Hitzman et al, Precam. Res., v.58, p. 241–287	1992	Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits.	Summary of the geology of IOCG-type deposits. First mention of the Tjårrojåkka deposits in the context of IOCG-type deposits.
Frietsch R., GFF, v.113, p.46–48	1991	New ore types in the northern part of the Fennoscandian Shield	Short review of mineralization in Sweden, Finland and Norway
Cliff et al., Economic Geology, v.85, p. 1073–1083.	1990	Isotope systematic of the Kiruna magnetite ores, Sweden: Part 1. Age of the ore.	
Wright SF, PhD thesis, University of Minnesota, 170 pp.	1988	Early Proterozoic deformation history of the Kiruna District of northern Sweden	Detailed structural study of the Kiruna area and discussion of local and regional tectonic development.
Welin E, Precam. Res., v.35, p.95–113	1987	The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden.	U-Pb zircon age (1,882 ± 24 Ma) of a metarhyolite (quartz porphyry) in the Kiruna area is presented, however no sample location map, sample description or sample coordinates or stratigraphic context is given (?).
Skiöld T, Precam. Res., v.35, p.161	1987	Aspects of the Proterozoic Geochronology of Northern Sweden	Review paper based on U-Pb zircon (TIMS) ages for various rock units in N Sweden with assessment of stratigraphy and crustal processes.
Skiöld T and Cliff RA, Precam. Res., v.26, p. 1–13	1984	Sm–Nd and U-Pb dating of Early Proterozoic mafic-felsic volcanism in northernmost Sweden	Sm–Nd mineral and WR isochron ages are presented for Kiruna basalts. The measured age of 1,932 ± 45 Ma is interpreted to be both a metamorphic age and a formation age for the Kiruna greenstone basalt. Also, U-Pb zircon dating of rhyodacitic volcanics SW of Kiruna area within the Porphyrite Group give 1,909 ± 17 Ma.
Witschard, Precam. Res., v.23, p.273	1984	THE GEOLOGICAL AND TECTONIC EVOLUTION OF THE PRECAMBRIAN OF NORTHERN SWEDEN -- A CASE FOR BASEMENT REACTIVATION?	Regional overview paper with review of stratigraphy including lithogeochemistry of volcanic and plutonic rocks. Some discussion of deformation and structures based on geophysics data also.
Lundqvist T, SGU C768, 87 p.	1979	The Precambrian of Sweden	Review report on the bedrock geology of Sweden including summaries of Norrbotten geology and stratigraphy

Table 4. Continued.

Reference	Year	Title	Brief Overview
Ros, F., SGU BRAP 82567, 13 p., Uppsala/Malå	1979	Tjårrojåkka kopparmalmsfyndighet	Summary description of the Tjårrojåkka Cu deposit with an estimate of grades and tonnage based on assay data.
Niva, B, SGU FM 7808, Uppsala/Malå	1978	Geofysisk malmberäkning över Tjårrojåkka järnmalmsfyndighet	Gravity measurement survey conducted over the Tjårrojåkka deposit(s)
Ambros, M et al., SGU BRAP 00776, 88 pp.	1973	Pattok järnmalmsfyndighet – resultaten av SGU:s undersökningar 1963–1972	Comprehensive assessment of the Pattok IOA deposit based on a drilling program. Geology and mineralization described.
Grip, E and Frietsch, R. Almqvist and Wiksell, Stockholm	1973	Malm i Sverige. 2 Norra Sverige	Review of various ore deposits in N Sweden with a description of the Tjårrojåkka IOA deposit
Ros, F., SGU BRAP 82566, 7 p., Uppsala/Malå	1971	Järnmineraliseringen Luppovare (Luopovare) vid Ailatis 29I Kebnekaise	Summary description of the Luppovare Fe-oxide mineralization. Geochemical data for ore and host rock listed. Map of the mineralization extent also.
Ros, F and Rönnbäck, L, SGU BRAP 82570, 9 pp.	1971	Rörande malmobjektet Tjårrojåkka.	Summary description of the Tjårrojåkka mineralization.
Quesada, R. and Ros, F., SGU BRAP 82569, 13 p., Uppsala/Malå	1971	Malmberäkning av Tjårråjokka järnmalmsfyndighet.	Summary geology and mineralization at the Tjårrojåkka Fe-oxide deposit with an estimate of grades and tonnage based on assay data.
Welin et al., SGU C666, 40 pp., Uppsala/Malå	1971	Rb-Sr radiometric ages of extrusive and intrusive rocks in northern Sweden. I.	Presents Rb-Sr whole-rock ages. An imprecise age for acid volcanics at Kaska Tjåurek (1,650 ± 90 Ma) is located close to the Tjårrojåkka key area.
Offerberg, J., SGU Af 1-4, 146 pp.	1967	Beskrivning till berggrundskartbladen Kiruna NV, NO, SV, SO	Description of the geology of 1:50,000 bedrock map Af nr 3. Most detailed description of the geology of this area.
Cornwell I, SGU BRAP 85110	1965	Preliminary Estimate of the size of the main ore body at Pattok	General description and resource estimate of the Pattok IOA deposit.
Stacey, P.F, SGU BRAP 00766, Uppsala/Malå	1965	The ore mineralogy of some copper sulphide ore deposits on the Kiruna and Kebnekajse map sheets of Norrbotten, Sweden	Petrographical and mineral paragenesis description of Cu-Fe-oxide ores from Norrbotten including the Hannåive deposit.
Frietsch, R., SGU C592, 35 pp.	1963	Järnmalmsförekomster inom Norrbottens län.	Description of Fe-oxide and IOA deposits in northern Sweden with grades and tonnages
Ödman, OH, SGU Ca 41, 151 pp.	1957	Beskrivning till berggrundskarta över urberget i Norrbottens Län	Description of the bedrock geology of Norrbotten County to accompany bedrock map at 1:400,000 scale
Geijer, SGU C366,226 pp.	1931	Berggrunden inom malmtrakten Kiruna-Gällivare-Pajala	Regional review of the geology of Norrbotten with focus on Kiruna-type greenstones and ore deposits

Drill core

This section contains information on the drill core from the TKA that is available at SGU's Malå office. Table 5 lists the number of holes and drill core associated with the various mineral deposits or prospects within or adjacent to the TKA. In total, 252 drill holes are available (inc. the Hotnjos Fe-oxide deposit to the north of the TKA), the majority of which intersect various metavolcanic rocks (basalt, andesite, rhyolite) of the Porphyrite and Porphyry Groups. 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 (if available). More recent drill core may be available from exploration companies.

Mineralization and alteration

The TKA contains 18 known mineral deposits, prospects or showings. The majority of the mineralized localities are located in either the eastern or western parts of the key area. This observation appears to correlate with outcrop locations and may reflect more intensive explo-

Table 5. Drill core associated with mineral deposits in the TKA.

Deposit/prospect	No. of holes available	Total length	Logs, assay data, reports
Hannåive Cu-Mo	33 drill holes in vicinity of deposit (SGU). Part of Tjårrojåkka drilling. Mostly collard in Porphyrite Group metadacite-andesite	No data	160 paper logs available for Tjårrojåkka holes. BRAP 00766, BRAP 82570, BRAP 82567
Kuosatjvare Fe-oxide	4 drill holes (Anglo 1999). Part of Riekko drilling. Collared in metabasalt of either the Porphyrite Group (Offerberg 1967) or Porphyry Group (Bergman et al. 2000) (?)	Min. 502 m	Only 1 paper log available (72001), SGU C604, Coppard (2003)
Lieteksavo-1 Cu-Ag-Au	16 drill holes (LKAB, 1981–84). Collared in metabasalts and metarhyolites of the Porphyry Group (basalts mapped as Porphyrite Group by Offerberg 1967)	No data	19 scanned paper logs. Various LKAB reports e.g., K85-06
Lieteksavo-2 Cu-Au	10 drill holes (LKAB, 1981–84). Collared in metabasalts and metarhyolites of the Porphyry Group (basalts mapped as Porphyrite Group by Offerberg 1967)	No data	19 scanned paper logs. Various LKAB reports e.g., K85-06
Täunatjåkka IOA	2 drill holes (Rio Tinto, 1998). Part of Tjårrojåkka drilling. Collared in Porphyrite Group metabasalt and 'redeposited' metavolcanic rocks (?).	Min. 400m	1998 drill hole logs may be in Malå. C366
NW Täunatjåkka Fe-oxide	4 drill holes (Rio Tinto, 1998) inc. 2 holes listed above. Part of Tjårrojåkka drilling. Collared in Porphyrite Group metabasalt and 'redeposited' metavolcanic rocks (?).	Min. 400m	1 paper log available (74328). 1998 drill hole logs may be in Malå. C366
W Täunatjåkka Fe-oxide	3 drill holes (SGU, Rio Tinto, Phelps Dodge, 1970, 1998, 2004). Part of Tjårrojåkka drilling. Collared in Porphyrite Group metabasalts and 'redeposited' metavolcanic rocks (?).	No data	Paper logs may be available at Malå. C366
W Täunatjåkka Cu	2 drill holes (NSG, Phelps Dodge, 1976, 2004). Part of Tjårrojåkka drilling. Collared in quartz monzonite of the PMS	Min. 65 m	Paper logs may be available at Malå. C366
Palsen Cu	4 drill holes (SGU, Phelps Dodge, 1973, 2004). Part of Tjårrojåkka drilling. Collard in Porphyrite Group metadacite, metabasalt and 'redeposited' metavolcanics (?).	Min. 250 m	Paper logs may be available at Malå.
Pattok IOA	24 drill holes (SGU, 1967, 68, 69). Collared in metabasalt of either the Porphyrite Group (Offerberg 1967) or Porphyry Group (Bergman et al. 2000) (?)	Approx. 5000m	25 paper logs available. SGU BRAP 00776
Pattovare IOA	3 drill holes (LKAB) + Pattok holes adjacent. Collared in metabasalt of either the Porphyrite Group (Offerberg 1967) or Porphyry Group (Bergman et al. 2000) (?)	No data	2 scanned drill hole sections from the 1950's. Paper logs may be available at Malå.
Pårkajaure Cu-Ag	None	n/a	n/a
Riekko Cu	13 drill holes (SGU, Anglo, 1972, 2001). Collared in metabasalt of either the Porphyrite Group (Offerberg 1967) or Porphyry Group (Bergman et al. 2000) (?)	No data	1 overview document and 1 paper log available. Additional paper logs may be available at Malå. Ki8419
Saggekirka Cu	None	n/a	n/a
Tjårrojåkka Fe-oxide	165 drill holes (SGU, NSG, Rio Tinto, Phelps Dodge, 1967–76, 1998–99, 2004). Mostly collared in Porphyrite Group metabasalt and meta-andesite.	No data	160 paper logs + overview document. Numerous SGU reports and papers (see Table 4).
Tjårrojåkka Cu	165 drill holes (SGU, NSG, Rio Tinto, Phelps Dodge, 1967–76, 1998–99, 2004). Mostly collared in Porphyrite Group metabasalt and meta-andesite.	No data	160 paper logs + overview document. Numerous SGU reports and papers (see Table 4).
Hotnjos IOA	5 drill holes (BHP). Part of Leavka drilling. Collard in Porphyry Group syenite porphyry to andesite (Offerberg 1967) or Porphyry Group metabasalt (Bergman et al. 2000).	No data	Paper logs may be available at Malå.

ration efforts at either end of the study area. Iron-oxide (± apatite) and copper sulfide occurrances are the main types of mineralization found in the TKA (e.g., Tjårrojåkka and Lieteksavo-1-2, respectively). The spatial association of these two commodities has led to the suggestion that the area is an important locality for IOCG-type mineralization (e.g., Sandrin and Elming 2006, Edfelt 2007). Fe-oxide (and IOA) mineralization (magnetite, hematite, apatite) is generally banded or disseminated within the host metavolcanic rocks, while minor breccia and stockwork-type mineralization is also reported. Cu mineralization (chalcopyrite, bornite) occurs as both quartz vein-hosted and disseminated in the metavolcanics. At Täunatjåkk, Cu-sulfide mineralization is also hosted within a syenitic intrusion belonging to the Perthite-Monzonite Suite of intrusive rocks.

The location of the mineral deposits and prospects is shown in Figure 2. Additional mineralization datasets are available on SGU's GIS database that relate to the Norrbotten mineral deposit inventory and these are listed in Table 6 below. These data include GIS layers relating to drill hole and drill core locations, prospecting licence blocks, alteration mineral locations and zones of metallogenic importance.

Numerous mineralized boulders are also found across the TKA. Their locations are shown in Figure 3. Again, the correlation between mineralized boulder locations and those areas with the most outcrop exposure and exploration activity suggests that boulder mapping in the central part of the TKA has been less intensive. Cu-sulfide and Fe-oxide mineralization are the main types reported for the mapped boulders and a basic description of the type of mineralization accompanies the point dataset available through SGU's GIS database.

Alteration across the TKA is dominated by a regional scapolite-epidote assemblage affecting most lithologies although it is most developed within the metavolcanics (Fig. 4). Sericite, tourmaline, hematite (secondary?) and carbonate alteration is also present. There appears to be a spatial correlation between the hydrothermal alteration and mineralization. However, detailed investigations of the alteration paragenesis in the area have not been conducted or wether their are several alteration generations and the nature of their temporal and genetic relationship to Fe-oxide and Cu mineralisation. Likewise, the distribution of alteration minerals seen in Fig. 5 suggests that the alteration types affecting the intrusive rocks in the TKA have not been investigated or reported.

Geophysics

In the early 1960's, Sveriges Geologiska Undersökning (SGU) surveyed parts of the TKA using airborne geophysics. A few years later, within the framework of the Iron Ore Inventory Programme (1963–1972), several mineral occurrences were investigated by SGU including Luppovare, Tjårrojåkka, Kirasjåkko, Riekko, Hotnjos, Pattok and Renhagen. The Tjårrojåkka Fe-oxide occurrence was investigated the most with several surveys during the years 1966 through to 1974. During the 1980's the study area was explored by LKAB who performed airborne measurements from 1979 and through to 1984. The airborne campaign was rapidly followed by ground surveys. The main areas of interest were Haukajaure, Lieteksavon and Saggekirka, which all are situated about 18 km ESE of the Tjårrojåkka IOCG occurrences.

In the late 1990's the area was revisited again by several exploration companies. Rio Tinto started exploring the Tjårrojåkka and Kirasjåkka occurrences. Later in 2002, BHP in-

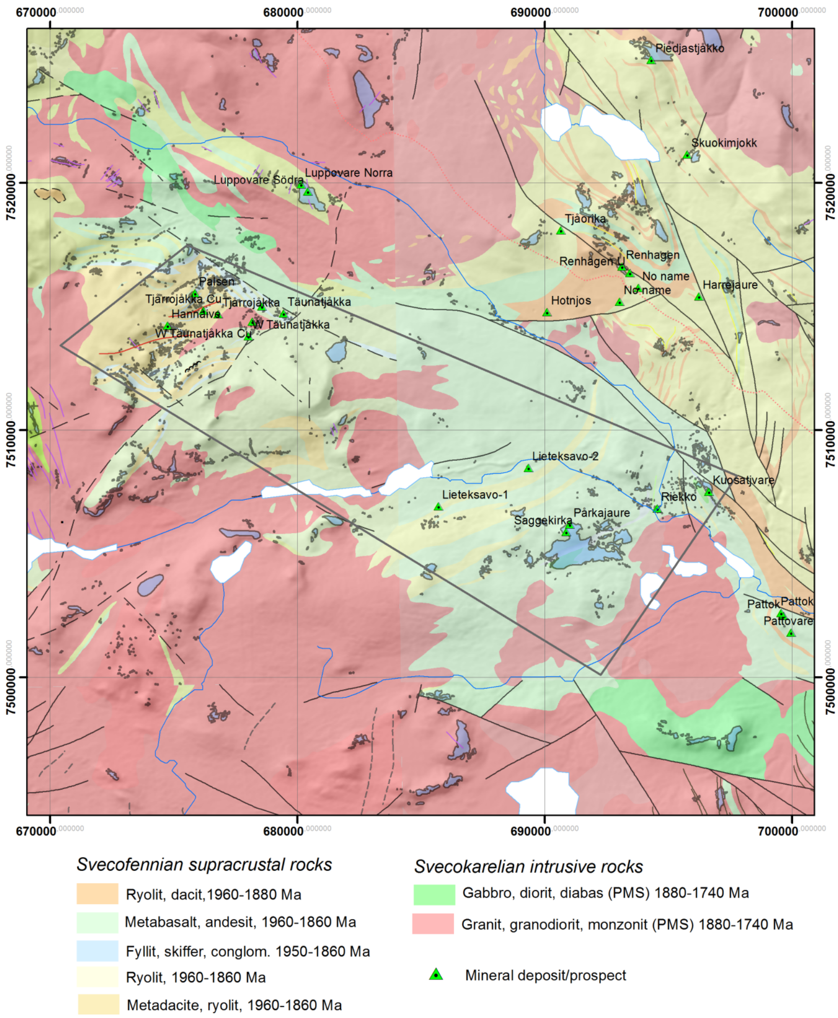

Figure 2. The location of mineral deposits and prospects within the TKA. Background geology at local scale (1:50.000).

Table 6. Datasets relevant to mineral resources and exploration

Layer/dataset	Description	Grid location	Reference
Borrkärna_20110405	Location and description of drill core available at SGU's Malå office	29I 3i/2h/2i, 29J 2b/, 29J 1a, 29J 1c	SGU database
Borrhål_20110405	Historical drill core including Malå core and core no longer available at Malå	29I 3i/2h/2i, 29J 2b/, 29J 1a, 29J 1c	SGU database
Mineralresurser_mdep	Location and description of mineralisation prospects, showings and deposits	29I 3i/3j, 29I 2i/2j, 29J 2b, 29J 1a/1b/1c	SGU database
FODD Barmin	Vector point of mineralisaed areas with basic descriptions taken from FODD database	29I 3i/2i, 29J 1a	SGU database
Metallogenetic areas	Vector polygons of metallogenic areas	29I 3h/i/j, 29I 2h/2i/2j, 29J 2a/2b, 29I 1i/1j, 29J 1a/1b/1c/0a/0b/0c	SGU database
Undersökningstillstån_ beviljade	Granted prospecting licence blocks (polygons)	29I 3h/3i, 29I 2h/2i, 29J 2a/2b/1b/1c	SGU database
Mineralrättsregistret (MRR10)	Polygons of mineral resource blocks	29I3h/i, 29I2h/i, 29J1b/c	SGU database
boulders_mineralized	Mineralized boulder locations	29I 3h/i/j, 29I 2h/2i/2j, 29J 2a/2b, 29I 1i/1j, 29J 1a/1b/1c/0a/0b/0c	SGU database
alteration_SWEREF99	Location and description of alteration mineral showings	29I 3i/2h/2i, 29J 2b/1a/1b/1c/0b	SGU database

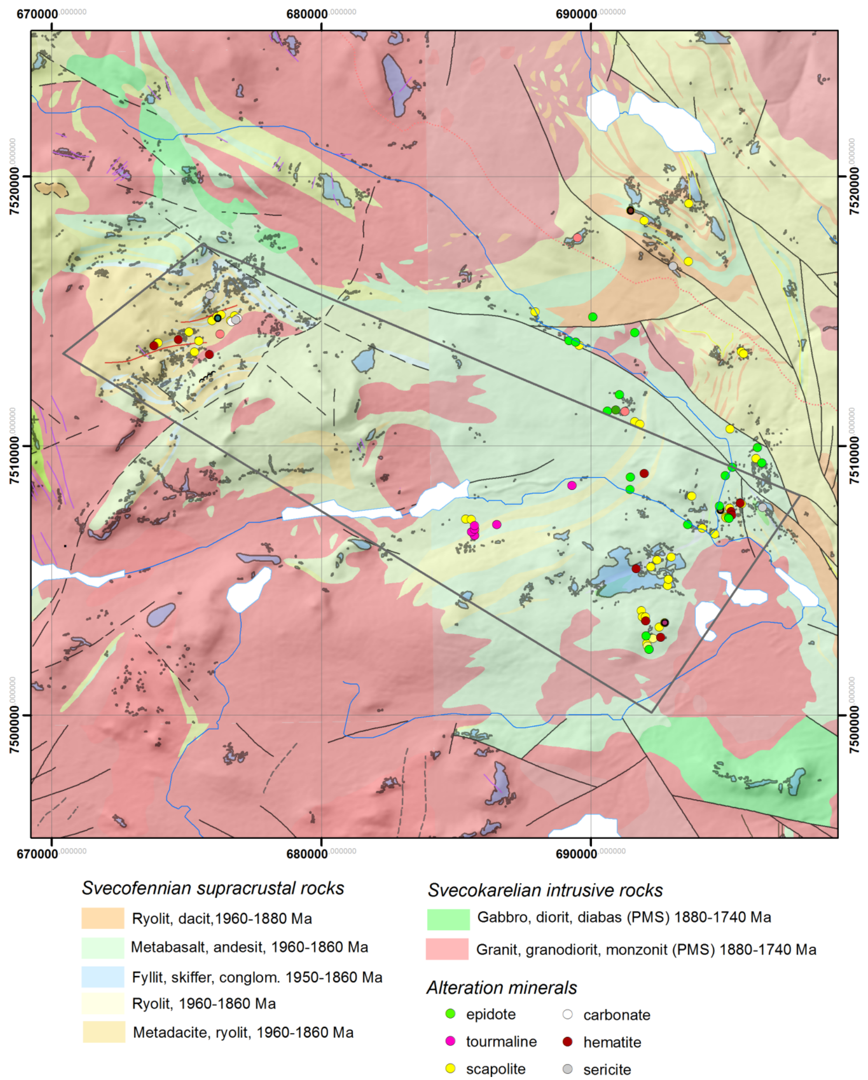

Figure 4. Location of various alteration minerals within the TKA and adjacent areas.

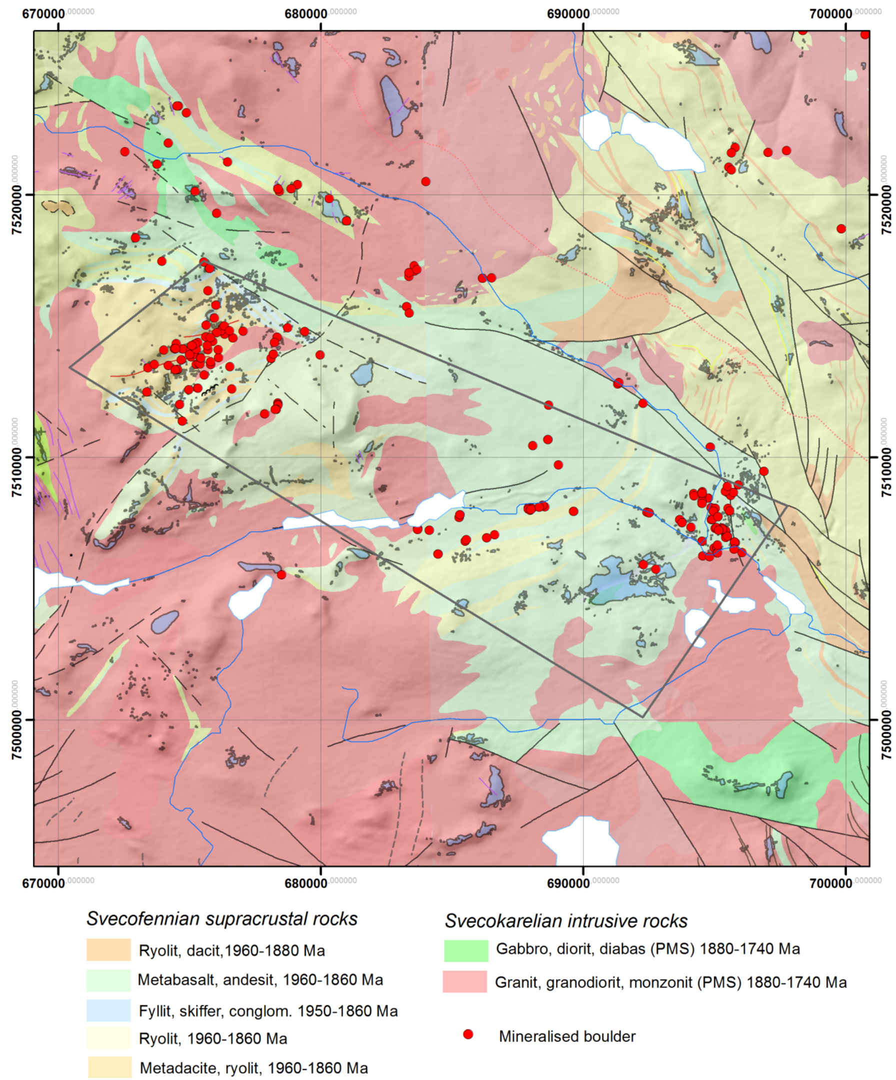

Figure 3. Location of mineralized boulders in the TKA. The majority of boulders are described as containing sulfide mineralisation.

vestigated an area under the name Leavka which is situated about 12 km east of the Tjårrojåkka occurrences. The data acquisition then continued the year after by Equinox Resources with profiles in an area identified as Stuor–Ratek. A new license was picked up by North-Atlantic Natural Resources (NAN) in 2006. Even though NAN has been known to collect airborne electromagnetic data in other areas the only records of data from the Tjårrojåkka area are ground based surveys. In what could be seen as a third revisit to the area around 2010 two companies (Kiruna Iron and Scandinavian Iron) hold a total of six exploration permits in the area.

Airborne data (magnetic, electromagnetic and gamma spectrometry)

Records of airborne geophysical data in the area include surveys from two periods. The first period was 1960–1965 and the second was 1979–1984. During this first period SGU surveyed the whole of map sheet 29J (Kiruna) using a fluxgate magnetometer. The direction of the flight lines was east–west and the line separation and elevation were 200 and 30 m, respectively. The same parameters are valid for the 1963 magnetic survey by SGU over the east part of map sheet 29I and also for the 1965 magnetic survey of map sheets 28I (Stora sjöfallet) & 28J (Fjällåsen). The fluxgate magnetometer used is specified to ±10 nT accuracy.

The next generation airborne data from the area was collected mainly by LKAB, starting in 1979 in the western part of map sheet 29J (Kiruna). LKAB gathered not only magnetic data but also gamma spectrometry and slingram magnetics, as well as VLF electromagnetic measurements using a system capable of tracking signals from two different receivers. The magnetometer (G803) was capable of a precision of +-1 nT. The elevation of the craft was 30 m and the separation of the flight lines was 200 m. The direction of the flights was east to west. LKAB continued in 1980 by surveying a smaller area in the south–west of map sheet 29J (Kiruna SW). The parameters for the survey were the same with the exception of the flight direction, which was north–south. The reason for the 1980 re-survey is judged to account for changes in strike of the magnetic anomaly pattern to the northwest.

In 1980 SGU launched the Nordkalotten project with the intention of covering the mountainous western part with magnetic data. The positioning system in the craft now offered higher accuracy to that which previously had been used. The elevation of the craft was 1800m and the line separation was 2000m. Even though the data is not dense the objective to cover the mountain range was met and in such can be seen as highly valuable. Two years later, in 1982–84, LKAB continued its surveying of the Tjårrojåkka area. The parameters used for map sheets 29J (Kiruna S, 1983), 29I (Kebenekaise E) and 29J (Kiruna V, 1984) were the same as for the 1979 survey. However, for the 1982 survey of 29I (Kebenekaise SE) and 29J (Kiruna SW) the flight direction was changed to north–south, again to account for changes in magnetic anomaly strike-direction.

To date, six private exploration companies have investigated the area and, even though several of them have been known to utilize modern exploration techniques, there have been no records of further airborne surveying. However, as will be discussed below, several ground surveys has been carried out.

Ground-based magnetics

Magnetic ground surveys within the TKA began in 1964 by SGU and were continued in the early 1980's by LKAB. Unsurprisingly, most geophysical ground surveys post date each airborne campaign. SGU were active with geophysical survey in the Tjårrojåkka area during the years 1964 through 1974. Subsequently, LKAB surveyed magnetic data between 1981 and 1985. In the early 2000's several exploration companies revisited the area once more and a number of new areas were surveyed, as well as some re-surveying (e.g., Rio Tinto (1998–2001), BHP (2002), Equinox (2003) and NAN (2006) contributed to the bank of data from the area). The recent permit owners in the area (Kiruna Iron and Scandinavian Iron) have maintained their exploration rights up to the start of 2013, however, their contribution to the geophysical background database is therefore uncertain at this point.

Table 7 and Figure 5 below show a complete record of the ground-based magnetic surveys from the TKA. The 'Nr' field refers to the numbered areas shown in Figure 5 which outline the extent of each survey. The magnetic field in Fig. 5 shows four prominent magnetic features: (1) a general E–NE trending of the magnetic anomaly pattern: (2) a few circular structures and 'bulls-eye' anomalies: (3) NW-trending anomalies that appear to be partially truncated by the E–NE pattern mentioned above and (4) several lineaments (possibly faults) occur primarily in the N–NE direction. Sandrin (2003) and Sandrin et al. (2007) give a more detailed description of the magnetic anomalies and magnetic fabric of the area.

Table 7. List of ground-based magnetic surveys carried out across the TKA.

No.	Object	ID	Area (km²)	No. of points	Year	Easting	Northing	Company
1	Tjårrojåkka		10.5	7.115	1964, 1969, 1973	672300	7516000	SGU
2	Tjårrojåkka		13.5	13.034	1964, 1968	677000	7514300	SGU
3	Luppovare		8	5.847	1966	674200	7521100	SGU
4	Renhagen		12	1.4849	1966	693100	7515500	SGU
5	Skåukemjokk		6.2	4.695	1966	696100	7521200	SGU
6	Skajtetjåkko		2	2.401	1967	682800	7516400	SGU
7	Pattok		1.5	4.291	1967	699800	7502100	SGU
8	Piedastjåkko		4	3.575	1967	695000	7523000	SGU
9	Riekko		4.5	3.281	1969	694900	7506600	SGU
10	Tjårrojåkka		0.4	1.201	1971	676100	7514400	SGU
11	Tjårrojåkka		8	2.0942	1974	675600	7514700	SGU
12	Haukkajaure		0.5	1.076	1981	691000	7510,000	LKAB
13	Lieteksavon	1-40A	0.2	327	1981	687800	7508000	LKAB
14	Lieteksavon	1-4020A	2.3	1.216	1982	685700	7507000	LKAB
15	Lieteksavon	1-4020B	1.6	1.798	1983	686300	7507300	LKAB
16	Lieteksavon	2-A	2.9	3.037	1983	689000	7508000	LKAB
17	Saggekirka	4A	1	1.925	1984	691700	7506500	LKAB
18	Saggekirka	4B	n/a	245	1984	691900	7506200	LKAB
19	Saggekirka		n/a	491	1985	691500	7506700	LKAB
20	Tjårrojåkka	Tjk1	5	201	1998–2001	677100	7514500	Rio Tinto
21	Tjårrojåkka	Tjk2	0.3	120	1998–2001	676300	7512500	Rio Tinto
22	Kirasjåkka	Nr1	n/a	834	2001	679000	7514900	Rio Tinto
23	Renhagen	Prog. 1	n/a	909	2001	692300	7515600	Equinox
24	Renhagen	Prog. 2	n/a	117	2001	692300	7515600	Equinox
25	Leavka		0.8	407	2003	690,000	7514700	BHP
26	Lieteksavon		1.9	1.661	2006	685700	7506700	NAN

The geophysical ground surveys have been mostly focused in the part of the magnetic anomaly pattern trending E–NE. Examples of this are Saggekirka, Lieteksavon, Tjårrojåkka, Kirasjåkko, Haukkajaure and, in part, also the Hotnjos surveys. The exceptions are Pattok, Riekko and Kuosatjvare which are located in the NW trending magnetic anomaly pattern. In addition, a magnetic survey made by LKAB, which is indicated in the SGU-polygon catalog, has not yet been located. According to the survey polygon the study is located in the Saggekirka–Riekko area and is relatively large (ca. 10 km^2).

The Tjårrojåkka deposit (Fig. 5) is the most surveyed area with over 40,000 magnetometer observations. Also clearly visible on the airborne magnetic map (Fig. 6) is the Pattok prospect which is perhaps the most prominent magnetic feature in the easternmost TKA. The 1971 survey at Tjårrojåkka (No. 10 in Fig. 6) was conducted in an N–NW direction using 20 m line separation and 20 m in-line spacing. The 1974 (No. 11) survey covered a larger area but had the same parameters as the earlier survey. When examining the extent of these surveys it seems suspicious that the 1974 survey partially overlaps the 1971 survey, instead of positioned alongside it. A reason may be problems in the transformation from the RT90 map system to SWEREF99tm. It is clear that the positioning of data should be addressed before proceeding to interpretation.

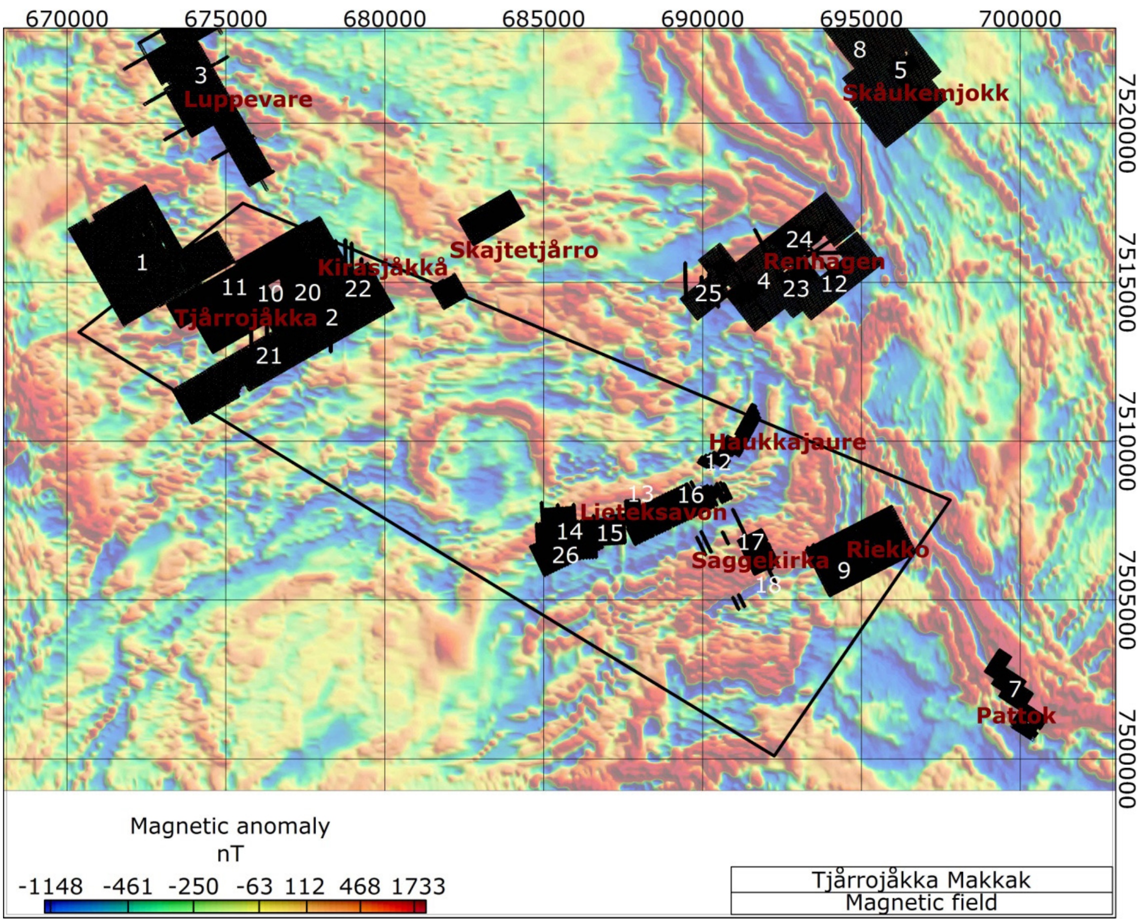

Figure 5. The magnetic ground survey outlines is shown on top of the airborne magnetic data. The white numbers shows the approximate center of each survey and refer to table 7 where the details for each survey are found. The polygon gives a rough estimate of the area of interest during the Barents-project.

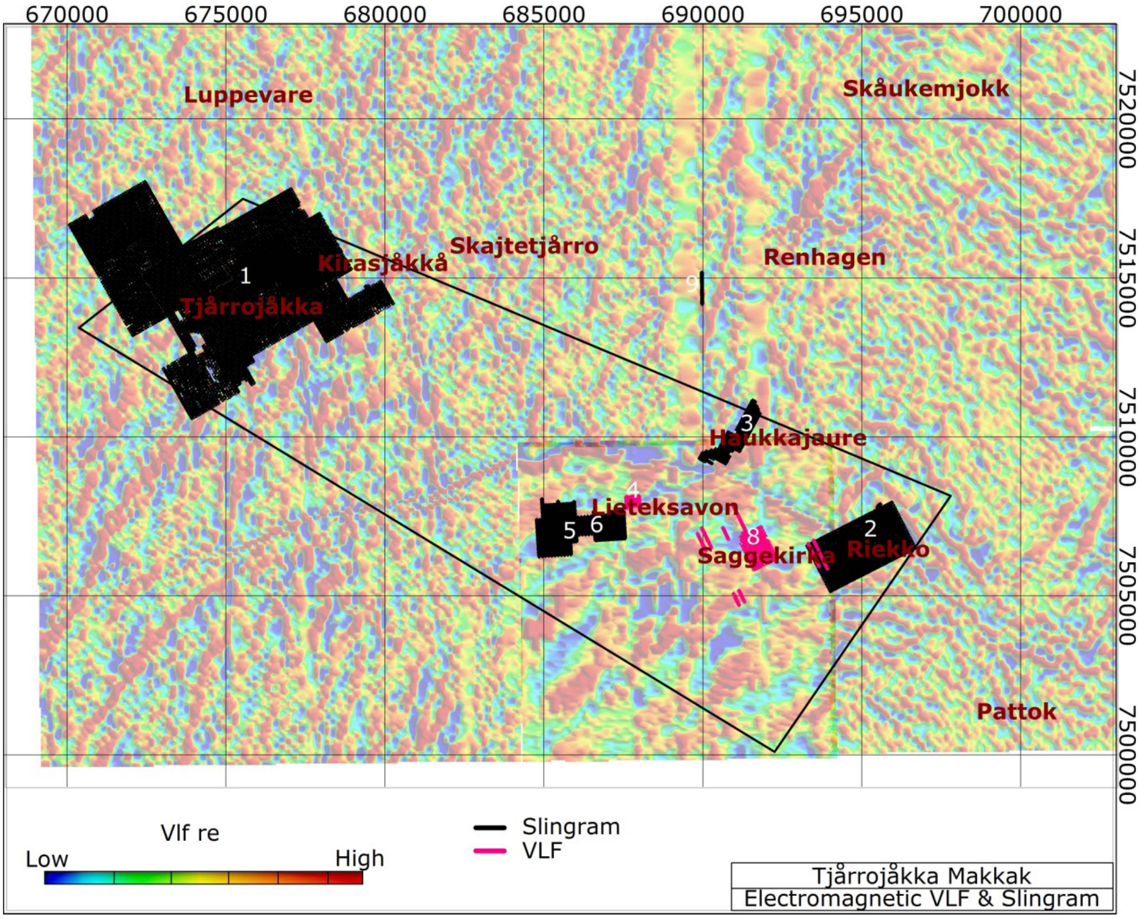

Figure 6. Electromagnetic surveys is shown on top of airborne VLF real component data collected by the LKAB. Black indicates slingram survey and pink indicate VLF survey. The numbers in white refers to table 8.

Table 8. Different electromagnetic survey methods have been used through the years and by the different exploration companies.

No.	Object	Method	ID	Area (km²)	No. of points	Year	Easting	Northing	Company
1	Tjårrojåkka	Slingram		30	24.180	1968	675100	7515000	SGU
2	Riekko	Slingram		4.8	7.232	1969	695000	7506600	SGU
3	Haukkajaure	Slingram		1	2.078	1981	691000	7510,000	LKAB
4	Lieteksavon	VLF	1	0.2	297	1981	687800	7508000	LKAB
5	Lieteksavon	Slingram	1A	1.2	972	1982	685400	7507000	LKAB
6	Lieteksavon	Slingram	1B	1	1.805	1983	686700	7507200	LKAB
7	Saggekirka	VLF	4A	0.7	444	1984	691700	7506500	LKAB
8	Saggekirka	VLF		n/a	300	1985	691400	7506700	LKAB
9	Leavka	MF EM		n/a	35	2002	69000	7514700	BHP

Ground-based electromagnetics (EM)

There are three types of electromagnetic data partly covering the TKA (Table 8 and Figure 6). The first type is slingram data that was surveyed by SGU in the 1960's by LKAB in the 1980's. The transmitter-receiver separation and survey frequency is documented in the SGU archives. The second type is VLF data acquired in the 1980's by the LKAB. This used a higher frequency than the slingram surveys. The third type is the multi-frequency system used by BHP in the Leavka (Riekko) area that uses several frequencies simultaneously. This gives the possibility to distinguish between different types of conductors. Table 8 gives an overview of the electromagnetic data from the area. The number in the first row refers to the survey polygons in Figure 8 which gives an overview of the survey density and extent.

Ground-based electrics (IP)

Induced potential geophysics has been used quite extensively over many of the mineral occurrences in the TKA (Fig. 7). Unfortunately the documentation on the separation of the electrodes and the survey parameters is incomplete. The data collected by Rio Tinto and provided to the Swedish mining inspectorate does not contain any of this documentation. Likewise, data from Equinox was submitted in a format that it is difficult to tell what the electrode distances were. However, the Equinox data did outline the survey extent has been specified to pole-dipole. Survey data submitted by NAN specifies both the coordinate points used for the current electrodes and the distance between the potential electrodes. Table 9 below lists the IP surveys from the TKA. The Tjårrojåkka occurrence is the most surveyed target. As might be expected many of the surveyed targets are known to host sulphide minerals.

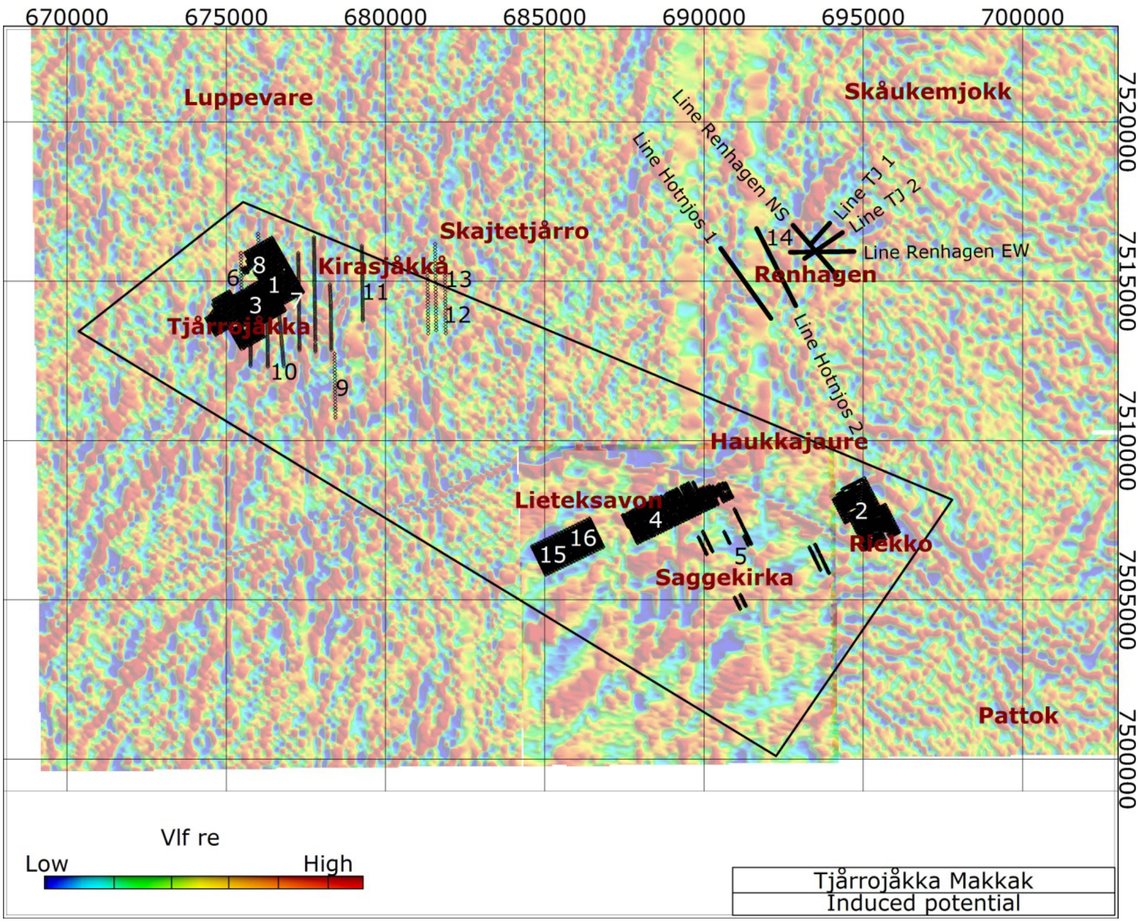

Figure 7. Induced polarization survey outlays are outlined in black and marked with a number which refer to table 9. The data in the background is the airborne electromagnetic VLF data collected by the LKAB.

Table 9. Induced polarization surveys in the area where the Nr column refer to the map in figure x. Note the column ID which identify different IP campaigns in the same area.

No.	Object	ID	Area (km²)	No. of points	Year	Easting	Northing	Company
1	Tjårrojåkka		3.5	2.966	1969–1971	675800	7514700	SGU
2	Riekko		2	1.360	1970	695000	7507700	SGU
3	Tjårrojåkka		1.2	1.237	1974	675800	7514300	SGU
4	Lieteksavon	2	3	1.545	1983	689000	7508000	LKAB
5	Saggekirka		n/a	297	1985	690750	7506850	LKAB
6	Tjårrojåkka	1-jvx	n/a	16	1999–2001	675460	7515000	Rio Tinto
7	Tjårrojåkka	1-riotinto	2.5	332	1999–2001	677000	7514000	Rio Tinto
8	Tjårrojåkka	1-smoy	n/a	26	1999–2001	676000	7515200	Rio Tinto
9	Tjårrojåkka	2-jvx	n/a	21	1999–2001	678400	7511800	Rio Tinto
10	Tjårrojåkka	2-riotinto	0.3	23	1999–2001	676300	7512500	Rio Tinto
11	Kirasjåkkå	Jvx	n/a	42	2001	681600	7514300	Rio Tinto
12	Kirasjåkkå	Riotinto	n/a	48	2001	679275	7514900	Rio Tinto
13	Kirasjåkkå	Smoy	n/a	28	2001	681565	7514900	Rio Tinto
14	Stour-Ratek	Lines	n/a	c. 250	2003	692700	7515700	Equinox
15	Lieteksavon	1	1	460	2006	685260	7506400	NAN
16	Lieteksavon	2	1	460	2006	686200	7506900	NAN

Table 10. Gravity surveys have been undertaken by SGU and Rio Tinto resulting in a total of almost 15000 stations in the area.

No.	Object	ID	Area (km²)	No. of points	Year	Easting	Northing	Company
1	Luppovare		8	1.189	1966	674300	7520600	SGU
2	Pattok		7	2.253	1967	70,0000	7501800	SGU
3	Skajtetjårro		2.2	788	1967	683800	7517200	SGU
4	Renhagen		10	2.170	1967	693000	7515700	SGU
5	Renhagen		1.2	780	1968	693300	7516400	SGU
6	Tjårrojåkka		6	1.702	1968	677200	7514400	SGU
7	Kuosatjvare		9	1.103	1969	697400	7506400	SGU
8	Pattok		0.6	672	1971	699600	7502400	SGU
9	Hotnjos		28	4.059	1972	693000	7512800	SGU
10	Tjårrojåkka	Tjk1	4	228	2000	677000	7514000	Rio Tinto
11	Kirasjåkka		n/a	23	2000	678750	7514550	Rio Tinto

Ground-based gravity

Gravity surveys have only been conducted by two explorers, with SGU responsible for the vast majority of the work (Table 10). The data collected by SGU can be traced down to the field notes and compilation sheets where the original value and corrections for height etc. can be found. This makes it quite likely that the accuracy of the correction which depends on elevation could be further improved on using more recent terrain models. For the Rio Tinto gravity data parameters submitted to the Swedish mining inspectorate, elevation is mentioned as "GPS" and as "grid" but no information is provided regarding which GPS measurement technique or elevation grid was used.

The gravity survey layouts (Fig. 8) make use of a wider grid, most likely designed to capture regional variations, and a denser grid in the central part of the occurrence. This setup makes it possible to subtract a regional gravity field from the local anomaly. The result can then be used together with petrophysical data from drilling to make volume estimates.

Petrophysics

There are 876 petrophysical samples from the area and most of them in the western part (Fig. 9). The likely focus of these measurements was the Tjårrojåkka and Kirasjåkkå mineral occurrences. The NW–SE striking structures from Pattok to Luppevare and from Pattok through Renhagen have also been investigated, showing a fair amount of samples. Showing poor coverage is the central and south–east part of the area. It is interesting to note that a number of samples have been taken to the SW of the TKA. The objective for this sampling is not known and there are no known mineral prospects from the area.

The majority of the petrophysical samples have only been investigated for their density and a little less than ten percent of the samples have magnetic remanence measurements. Only 10 samples have oriented and where the direction of magnetic remanence has been measured. Only one of the 10 samples, collected in a well defined magnetic low (E689500 N7513800), shows a strong magnetic remanence but the direction of magnetization has not been identified.

Geochemistry

Table 11 lists the main geochemical data available for the TKA. 44 lithogeochemical analyses have been made by SGU and other workers of various rock units within and adjacent

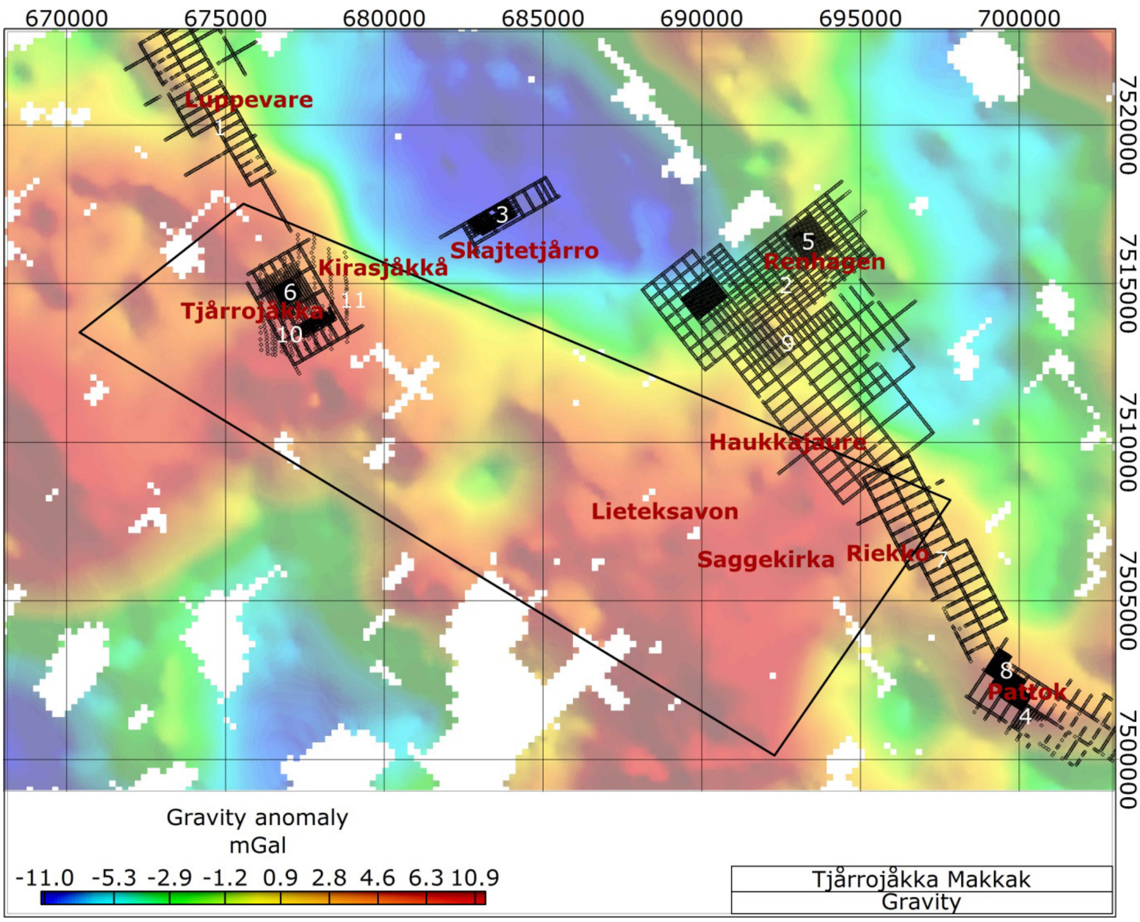

Figure 8. In black the stations of the gravity surveys are shown on top of a grid from the regional gravity database. The numbers in white refer to table 10.

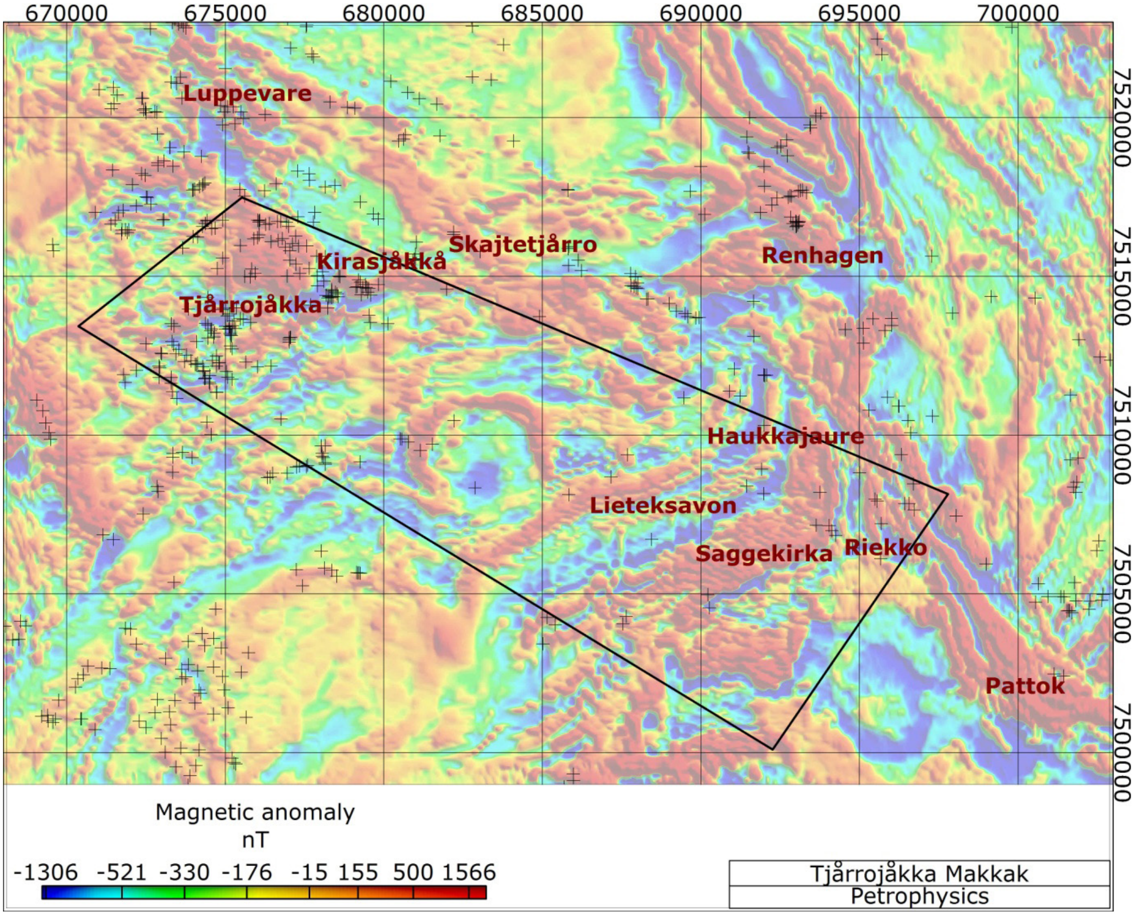

Figure 9. Petrophysical samples are shown as crosses. Note the uneven distribution of samples in the area with a strong focus on the western part.

to the area (Fig. 10). The majority of analyses were determined on metavolcanic lithologies (basalt, andesite, rhyolite). Three analyses exist for granitoids, while two gabbroid samples have been analysed. The analyses consist of major and limited trace element determinations, while 11 samples also including REE concentrations. The lithogeochemistry of volcanic and plutonic rocks in the TKA have been reported by Offerberg (1967). Further lithogeochemistry is reported in Perdahl and Freitsch (1993). Martinsson and Perddahl (1995) presented additional lithogeochemistry of metavolcanic rocks from the Porphyrite and Porphyry groups which included older analyses also. Edfelt et al. (2006) performed lithogeochemical analysis of 66 samples in the Tjårrojåkka area to characterise the major and trace element compositions of the main lithologies (summarized in their Table 2). In addition, several lithogeochemical analyses of select, ore-related rock units are reported in early SGU exploration reports from the Tjårrojåkka area (e.g., Quezada and Ros 1971, Ros 1979). Sandrin et al. (2009) performed mineral chemistry analysis of Fe-oxides from the Tjårrojåkka Fe-oxide deposit and showed that hematite replaces magnetite in the ore. Edfelt (2003) also performed mineral chemistry analysis from the Tjårrojåkka deposit with an emphasis on mineralization and alteration characterization and shows potassic alteration overprinting an early sodic alteration. Edfelt and Martinsson (2005) reported some lithogeochemistry for meta-andesites hosting the Tjårrojåkka Fe-oxide and Cu deposits and showed increased Na concentrations in the Fe-oxide-bearing units due to hydrothermal albitization. Edfelt et al. (2005) also reported lithogeochemistry results of 89 drill core samples of several rock units from the

Tjårrojåkka area. In addition, these workers reported mineral chemistry data for feldspar, scapolite, biotite, amphibole, apatite, several sulphides and Fe-oxides from the Tjårrojåkka system. Broman and Martinsson (2000), Edfelt et al. (2004) and Edfelt et al. (2007) report fluid inclusion geochemistry data from the Tjårrojåkka deposits.

The majority of the remaining geochemical analyses in the area relate to till geochemistry measurements determined as part of SGU's regional till geochemistry programme (Table 11). Mapped anomalies of Cu, V and Zn represent the main geochemical anomalies in the area and likely reflect their elevated concentrations in the metavolcanics. Isolated till and moraine sampling has also been conducted mostly in the eastern part of the study area

Geochronology

Seven age determinations have been made for the various rock units and minerals within or adjacent to the TKA (Table 12, Figure 11). Most recently, Edfelt et al. (2007) conducted U–Pb titanite and Sm–Nd (mineral) geochronology at the Tjårrojåkka IOCG deposit. Hy-

Table 11. Geochemistry datasets covering the TKA

Layer/dataset	Description	Grid location	Reference
Lithogeochemistry	44 sample locations with lithogeochemistry.	29I 3h/3i/, 29J 3b, 29I 0h/2h/2i/1h/1i, 29J 1a/1b/1c/4c, 28J 9a/9c	Offerberg 1967, Perdhal & Frietsch 1993, Edfelt et al. 2006
LIKE_supracrustals	Points data of lithogeochemistry – partial analysis of some metals. 36 point locations of analysed volcanic rocks for lithogeochemistry.	29I 3h/3i/, 29J 3b, 29I 0h/2h/2i/1h/1i, 29J 1a/1b/1c/4c, 28J 9a/9c	SGU database
LIKE_next_BARMIN	Points data of rock geochem – partial analysis of some metals. 36–40 point locations of analysed volcanic rocks for lithogeochem. Ponints overlap with lithogeochem data points.	East and west area covered – central part no samples	SGU database
NK_mroes_Cu	Points data of rock geochem – Cu assay data. 8–10 points in or adjacent to the study area.	29I2g/j, 29I1h/j, 29I0i/j, 29J0b/c	SGU database
kalktest	Point data of lime test locations on moraine fine fraction. 5 points located in study area or just adjacent. Corresponds to soil geochem analysis points also.	29J1a/b, 29J2b, 29J0a/b	SGU database
markgeokemi_fysiska prov	Point data of soil geochem locations. 5 points located in study area or just adjacent.	29J1a/b, 29J2b, 29J0a/b	SGU database
Morän < 2 mm	Point data for pH of till analysi (coarser fraction). 1 in study area	29J1b	SGU database
Morän finfraktion	Point data for pH of till analysis (fine fraction). 5 in or close to study area	29J2b, 29J1a/b, 29J10a/b	SGU database
Markgeokemi raster 250m	Raster dataset of shaded till geochem. Covers the eastern side of the study area	most of the study area except the far west	SGU database
Till geochem_NK_naa	Till geochem Nordkalott project by NAA. 2 points close to or within study area	29I2g, 29J0a	SGU database
Till geochem_NK_oes	Till geochem Nordkalott project by OES. 8 points close to or within study area	29I3g/h/i, 29I2g/j, 29I1h/j, 29I0j/b	SGU database
Till geochem_NK_xrf	Till geochem Nordkalott project by XRF. 2 points close to or within study area	29I2g, 29J0a	SGU database
heavy mineral geokemi djumbo	84 point locations for heavy mineral analysis within or adjacent to study area. East side is covered, not west	29I2j, 29J2a/b/c, 29I0j, 29J0a/b/c	SGU database
heavy mineral geokemi xrf	84 point locations for heavy mineral analysis within or adjacent to study area. East side is covered, not west	29I2j, 29J2a/b/c, 29I0j, 29J0a/b/c	SGU database

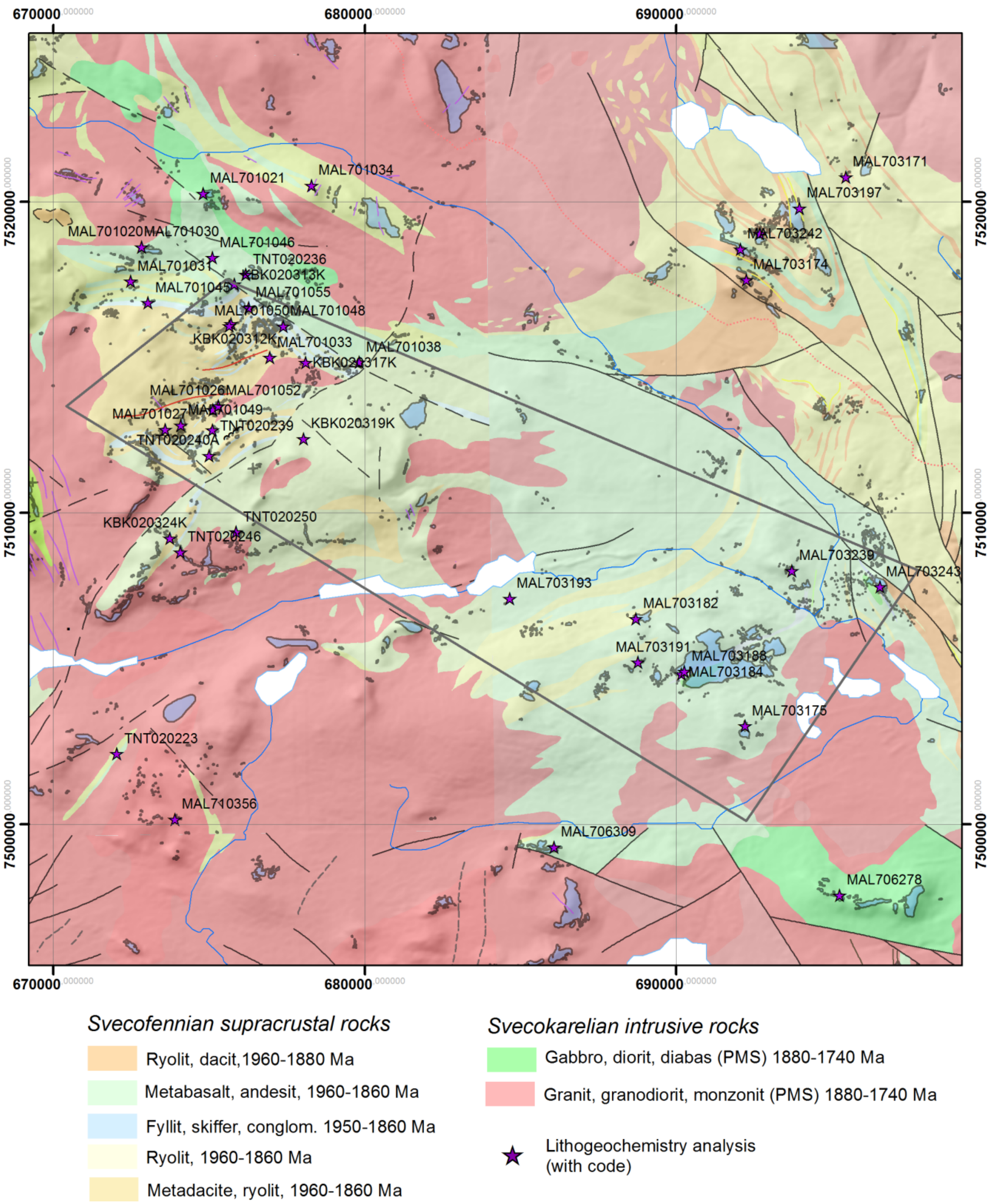

Figure 10. Lithogeochemistry sample locations within the TKA with the majority of sampling conducted in the western part.

drothermal titanites were dated at ca. 1,780 Ma, while two magmatic titanite samples from an adjacent granitoid gave ages of 1865 and 1,846 Ma. Sm–Nd geochronology of a suite of minerals representing the Fe-oxide ± apatite ore assemblage at Tjårrojåkka gave an imprecise age of 1,690 ± 120 Ma. In addition, Edfelt et al. (2006) determined a U–Pb zircon age of 1,878 ± 7 Ma for the metaandesite unit hosting the Tjårrojåkka Cu deposit. This age is interpreted to represent the formational (magmatic) age of the intermediate Porphyrite Group volcanics in the area. The age is also consistent with the 1,880 ± 3 Ma age determined for an

Table 12. Geochronology data from the TKA.

Age (Ma)	±	System	Material	Host rock	Litho. Unit	Area	Ref	Year
1,780	3	U-Pb (LA-ICPMS)	Titanite	Fe-oxide-apatite ore sample	Hydrothermal age	Tjårrojåkka IOA	Edfelt et al.	2007
1,865 & 1,846	5	U-Pb (LA-ICPMS)	Titanite	Quartz monzodiorite	Perthite Monzonite Suite	Tjårrojåkka	Edfelt et al.	2007
1,690	120	Sm–Nd (TIMS)	Apatite, amphibole, magnetite	Fe-oxide-apatite ore sample	Mineralization age	Tjårrojåkka IOA	Edfelt et al.	2007
1,878	7	U-Pb (LA-ICPMS)	zircon	Porphyritic meta-andesite	Porphyrite Group	Tjårrojåkka Cu	Edfelt et al.	2006
1,909	17	U-Pb (TIMS)	zircon	Porphyritic rhyodacite	Porphyrite Group	Saggekirka hill	Skiöld and Cliff	1984
1,635	90	Rb-Sr (TIMS)	Whole-rock	Porphyritic syenite (intrusive?) and rhyolite	Porphyry Group	South of Stuor Ratek lake	Welin et al.	1971

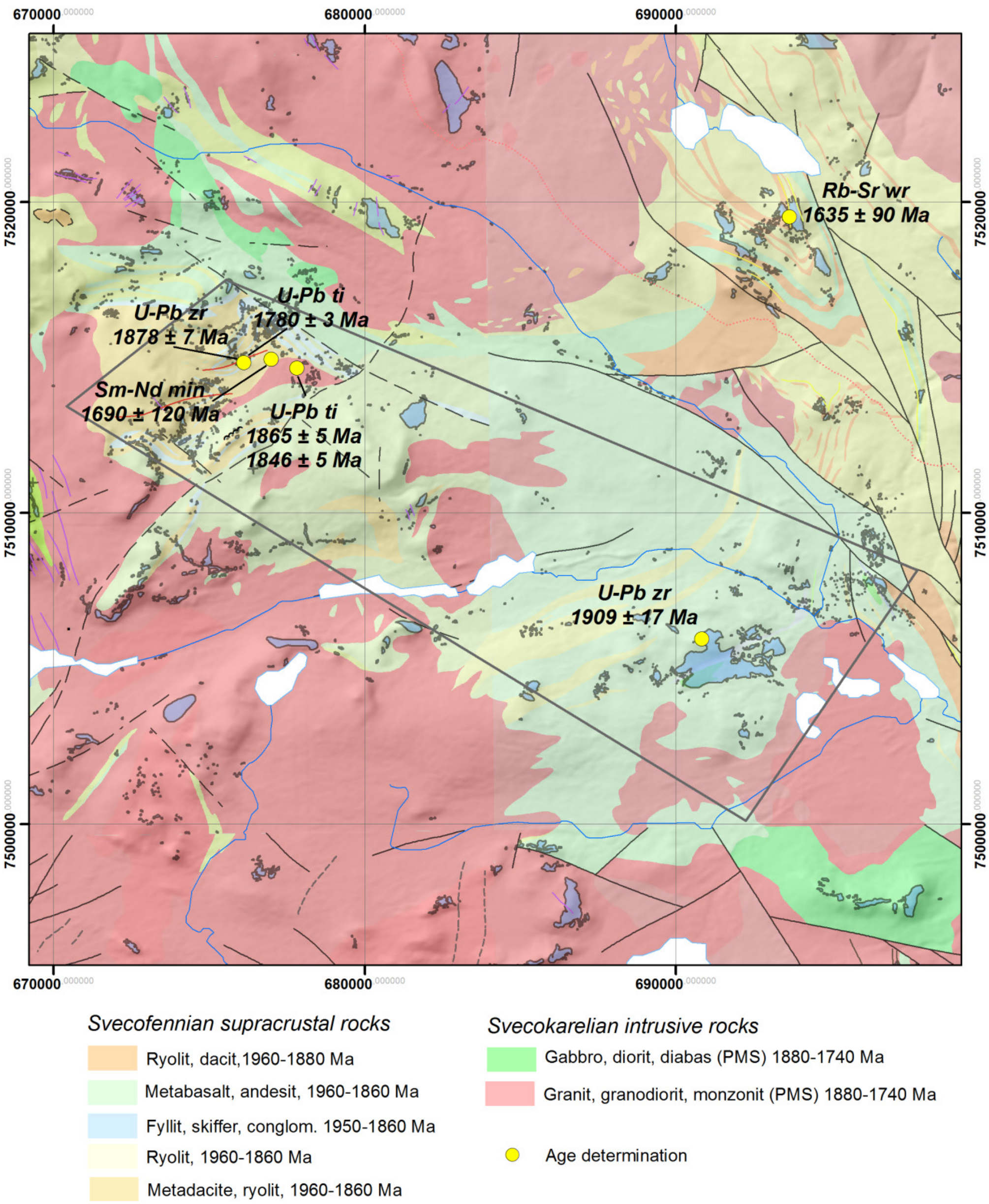

Figure 11. Geochronology of rocks and minerals within the TKA and adjacent areas. min = mineral, ti = titanite, wr = whole rock, zr = zircon.

intermediate volcanic rock assigned to the Porphyrite Group in the Käymäjärvi/Pajala area, eastern Norrbotten (Bergman et al. 2001). Previously, Edfelt and Martinsson (2005) reported that the Tjårrojåkka Cu deposit formed at ca. 1,780 Ma (i.e., late-stage Svecokarelian), which was likely based on the preliminary results of the U–Pb titanite geochronology discussed by Edfelt et al. (2007). Overall, the geochronology at Tjårrojåkka indicates that the IOCG-type deposit formed close to ca. 1,780 Ma and that Fe-oxide-apatite and Cu-Au mineralization have a temporal and genetic link (Edfelt et al. 2007, Edfelt 2007). Furthermore, mineralization is younger than the host metavolcanic units in the area and may have formed during a late-stage, Svecokarelian, magmatic event. The direct dating of mineralization, hydrothermal and related magmatic events elsewhere in the TKA has not been undertaken, thus the extent and regional significance of the ca. 1,780 Ma mineralization event identified at Tjårrojåkka is not well constrained.

Further east, a U–Pb zircon age of 1,909 ± 17 Ma was obtained for an intermediate volcanic unit at Saggekirka Hill (Skiöld and Cliff 1984). The dated rock was a K-feldspar- and quartz-porphyritic rhyodacite occurring within Porphyrite Group basaltic andesites. However, the calculated seven point regression (Fig. 2, Skiöld and Cliff 1984) included three zircon fractions from an additional, analogous sample taken some 30 km to the SW of Tjårrojåkka, at Mt. Puollamtjåkka. This latter sample (described as a quartz–feldspar porphyritic 'acid volcanic') is presently mapped as a meta–rhyodacite that belongs to the Porphyry Group by Bergman et al. 2001. Thus, the regressed U–Pb age of 1,909 ± 17 Ma for the Porphyrite Group intermediate volcanics at the eastern end of the TKA may represent a mixed age determination influenced by several formational processes. Welin (1987) also dated a similar metarhyolite from the Kiruna area to the NE which gave an age of 1,882 ± 24 Ma (no. 75037, no sample coordinates or description reported). Thus, both U–Pb ages overlap within the reported uncertainties. Finally, Welin et al. (1971) calculated an imprecise Rb-Sr whole-rock age of 1,630 ± 90 Ma for porphyritic syenite and rhyolite samples (three each) from south of Stuor Ratek lake, about 15 km north of the TKA in an attempt to constrain the age of Porphyry Group metavolcanics. This relatively young age is inconsistent with older U–Pb-dated plutons that intrude the volcanic pile and likely reflects isotopic resetting and/or Sr loss by late metamorphic events (or uplift), and has been generally disregarded in the more recent literature (cf. Skiöld and Cliff 1984, Witschard 1984). To date, no systematic dating of the granitoid plutons or granitic dykes within or adjacent to the TKA has been undertaken. Thus, any temporal and genetic links between PMS (or Lina-type) magmatism and IOCG-type mineralization in this part of Norrbotten is still to be tested using high precision geochronology.

Isotope geology (excluding age dating)

There have been few dedicated isotopic studies carried out within the TKA. The most comprehensive study, conducted by Edfelt et al. (2007), was an integrated radiogenic and stable isotope investigation of IOCG-type mineralization at the Tjårrojåkka deposits (western TKA). Sm–Nd analysis of six mineral separates from two apatite–magnetite–amphibole ore samples provided initial εNd values ranging from -5.3 to -12.3. These data suggest that the ore-forming fluid associated with the apatite-iron system had its source in the Archean basement (i.e., basement rocks as a source of magmas, metals and fluids), or the mineralizing fluid equilibrated with the existing metavolcanic country rocks during the evolution of the hydrothermal system. Oxygen, hydrogen and sulphur isotope analyses were also conducted at the Tjårrojåkka deposit to further constrain the genetic properties of the mineralization and alteration. $\delta^{18}O$ values for amphibole, apatite, K-feldspar, magnetite, and quartz range from -0.5 to 18.7 per mil. Using oxygen isotope geothermometry, Fe-oxide mineralization occurred between 410°C and 660°C, whereas Cu mineralization formed at close to 470°C. Hydrogen isotope analyses on twelve amphiboles gave δD values ranging from -57 to -74 per mil. The combined $\delta^{18}O$ and δD data suggest the hydrothermal system was similar for both the Tjårrojåkka Fe-oxide and Cu deposits based on overlapping isotopic values. However, the $\delta^{18}O$ and δD data do not unequivocally identify a single source for the hydrothermal fluids at Tjårrojåkka and suggest either magmatic and/or metamorphic fluids were the dominant fluid source. A negligible role for meteoric water was concluded, however. Sulphur isotope analysis was also performed at Tjårrojåkka (Edfelt et al. 2007). 17 analyses of chalcopyrite, bornite and pyrite show $\delta^{34}S$ values between -4.9 to -0.1 per mil suggesting sulphur derivation from an igneous (magmatic) source.

Öhlander et al. (1993) reported Sm–Nd data for a metavolcanic sample (79099 – a quartz porphyritic intermediate volcanic) taken from Saggekirka in the eastern TKA. This sample formed part of a regional Sm–Nd isotopic study of plutonic and volcanic units in northern Sweden. The calculated initial εNd value (T = 1,900 Ma) of -6.1 for the Porphyrite Group metavolcanic rock was the most negative value measured for the suite of Svecofennian metavolcanics in northern Sweden. Combined with the regional results, these data suggest volcanic magmas were derived from a predominantly crustal source (i.e., melted Archean basement) within a continental arc-type setting during northeastward-directed subduction (present day direction) in the Paleoproterozoic.

Table 13. Topographic datasets covering the TKA

Layer/datset	Description	Scale	Reference
Översiktskartan 2007, SWEREF99 TM	Raster topographic overview map – small scale		SGU database, 2007
Vägkartan, LMV-manér	Raster topographic road\driving map – small scale		SGU database
Visningstjänst topografiska webbkartan och fastighet	Raster topographic map, small scale for Europe. Main topo features	1:100,000 (?)	SGU database
Visningstjänst allmänna kartor	Raster small scale topo map – general topo features		SGU database
Landskap	Vector polygons of counties or landscapes? Regions in Sweden		SGU database
Sverige 1:20 milj (2012)	Polygon outline of Sverige at 1:20,000,000	1:20,0,00000	SGU database
Sverige 1:10 milj (2012)	Polygon outline of Sverige at 1:10,000,000	1:10,0,00000	SGU database
Sverige 1:5 milj (2012)	Polygon outline of Sverige at 1:5,000,000	1:5,0,00000	SGU database
Sverigekartan 1 milj (2012), LM-manér	Vector lines and polygons topo map of Sweden at 1:1,000,000	1:1,000,000	SGU database
Sverigekartan 1 milj (2012), SGU-manér	Vector lines and polygons topo map of Sweden at 1:1,000,000	1:1,000,000	SGU database
Svenska Marktäckedata	Vector polygons of landuse for Sweden		SGU database
Visningstjänst ortofoton	Orthophotos, colour and IR		SGU database
Höjdmodell	Shaded relief DEM raster image at 50m resolution		SGU database
RT90_kbl	RT90 grid		SGU database

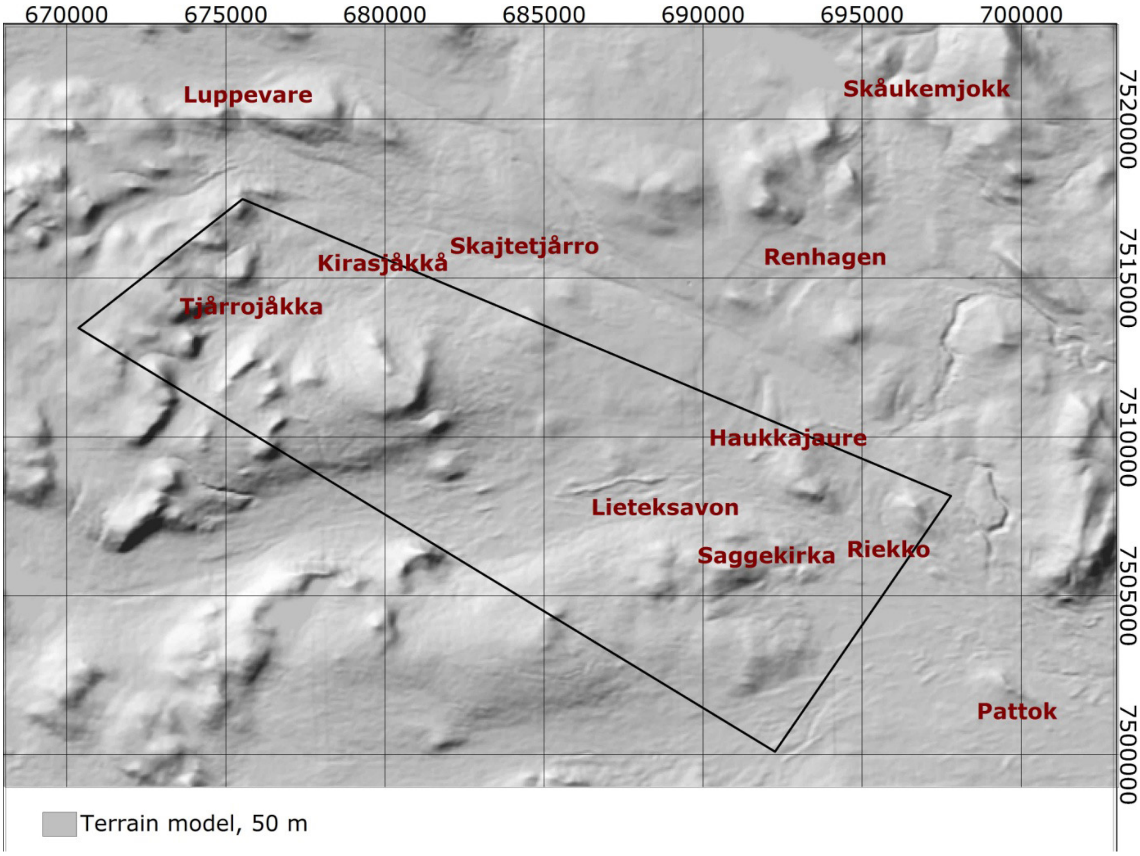

Figure 12. Extent of the 50 m DEM for the TKA.

Geographical data

Table 13 below lists several topographic datasets that cover the TKA. The most useful information can be derived from the orthophotos and a raster DEM developed at a height resolution of 50 metres (Fig. 12). Recent LiDAR scanning has so far not reached the area. The TKA is thus not covered by a more detailed 2 m DEM. Vägkartan contains vector polygons of contours with a 10 m interval. The TKA is not covered by the Terrängkartan map series.

SUMMARY

The following sections give a brief summary of the main geological and geophysical characteristics of the TKA with emphasis on the various rock units, stratigraphy (with respect to Norrbotten geology as a whole), ages, metamorphism, major structures, mineralization and alteration.

Lithology and stratigraphy

The main rock types in the TKA are Svecofennian metavolcanics, belonging to both the Porphyrite and Porphyry Group supracrustal sequences (ca. 1,960–1,860 Ma), and Svecokarelian intrusions assigned to the Perthite Monzonite suite of plutons (ca. 1,880–1,860 Ma). The metavolcanic rocks in the eastern TKA (which host the Tjårrojåkka deposits) consist of variably porphyritic to aphanitic andesites and basaltic–andesites with intercalations of volcaniclastic tuff and reworked conglomerate. These intermediate extrusives transition to more mafic volcanics (basalts and basaltic andesites) further east toward the centre of the study area. Minor occurrences of marble are also known from the Tjårrojåkka area, as well as pillowed basalts (Edfelt et al. 2005). In the eastern part of the TKA, a bimodal succession of metabasalt and metarhyolite occurs. These units were originally assigned to the Porphyrite Group (PG) by Offerberg (1967), but subsequently, Bergman et al. (2001) assigned these rocks to the overlying Porphyry Group (i.e., Kiruna porphyries) on their regional bedrock geology map (Ba56-1, 1:250,000 scale). Based on the latter stratigraphic assignment, the nature of the transition between the Porphyrite and Porphyry Group metavolcanics across the TKA is not well understood (i.e., whether a conformable, erosional, structural, geochemical transition etc.). The boundary between both volcanic groups is a NE-trending contact in the mid-eastern part of the study area. The nature of this contact requires further investigation. Also within the eastern TKA, Offerberg (1967) mapped several ENE-aligned basaltic units within the Porphyry Group (nomenclature of Bergman et al. 2001) which were assigned to the Kiruna Greenstone Group. However, these mapped units do not reappear on subsequent regional scale maps (cf. Bergman et al 2001). Once more, the nature and extent of these basalts may require further study. Intrusive rocks in the TKA consist of metamorphosed gabbros, perthitic quartz monzodiotites and syenites. Scapolite-altered dolerite dykes and local granitic pegmatites and veins also occur (Edfelt et al. 2006).

Protolith ages

In the western TKA, a porphyritic andesite (Porphyrite Group metavolcanics) is dated at 1,878 ± 7 Ma (Edfelt et al. 2006). This rock type hosts IOCG-type mineralization at the Tjårrojåkka deposits. Mineralization at Tjårrojåkka is inferred to have formed at ca. 1,780 Ma, based on a suite of hydrothermal U–Pb titanite ages and a Sm–Nd mineral isochron (Edfelt et al. 2007). In addition, a quartz monzodiorite intrusion (PMS-type intrusion) in the Tjårrojåkka area is dated at ca. 1,860 Ma (U–Pb titanite, Edfelt et al. 2007). In the eastern TKA, a sample of porphyritic rhyodacite, presently assigned to the Porphyry Group (Bergman et al 2001), has been dated at 1,909 ± 17 Ma (Skiöld and Cliff 1984). Further to the NE at Kiruna, a minimum age for Porphyry Group metavolcanics is constrained to 1,880 ± 3 Ma based on age dating of a granophyric dyke that crosscuts several of the volcanic horizons (Cliff et al. 1990).

Structural framework (including geophysics)

The TKA is located adjacent to a WNW-trending deformation zone (herein termed the *Tjårrojåkka Deformation Zone*, TDZ) which forms the northern boundary of the study area (Fig. 1). This zone also corresponds to a sharp, linear break in the gravity field corresponding to the contact between mafic rocks of the Poprhyrite Group to the south, and the more felsic volcanics of the Porphyry Group to the north (cf. Figure 8). The TDZ appears to represent the western splay of a regional-scale, NW-trending brittle-ductile deformation zone further to the E and NE (i.e., the boundary between structural Domains B and C in Figure 13). This latter deformation zone is strongly delineated by a broad, curvilinear, magnetic anomaly that transects the Pattok prospect (Fig.s 5 and 9). Both these shear zones were unnamed in the summary report of Bergman et al. (2001) and no detailed study of the type of deformation within these zones or the relative timing of movements between them has been

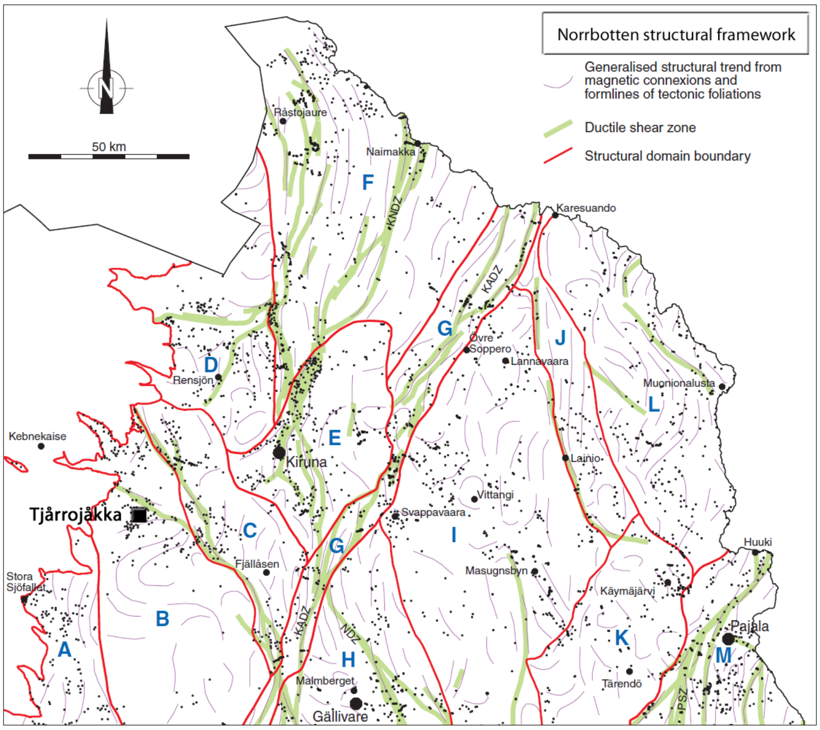

Figure 13. Regional structural and tectonic setting of the TKA and northern Norrbotten. The structural domains referred to in the text are lettered. Modified after Bergman et al. 2001.

undertaken. However, initial observations SW of Kiruna indicate steep foliations and a shear sense indicating western-side-up kinematics (Bergman et al. 2001). In addition, variably developed mylonitic rocks with steep foliations are also reported from within the deformation zones (Witschard et al. 2004).

The TKA falls within structural Domain B of Bergman et al. (2001) which is characterised by numerous NW-orientated fold axes and S- to SW-aligned, steeply plunging lineations. Folding is often disrupted by later shear zone-type deformation (Offerberg 1967). Several generations of brittle faulting also cut the TKA. The dominant trend of these faults is a NW to WNW orientated set and a second, NE-striking set. These latter faults have been linked to a ca. NW–SE directed regional compressive event in the Kiruna area (Wright 1988). Furthermore, the general strike of bedding and primary depositional structures across the TKA is an approximate NE–SW alignment with apparent younging toward the SE and E.

In terms of more detailed structural studies, Edfelt (2003) and Edfelt et al. (2006) report that the western end of the TKA (i.e., around Tjårrojåkka deposits) experienced at least three stages of deformation which included one, or perhaps two, compressional events. These are summarised as: (1) a D_1 event that developed a NE-aligned, steep foliation during NW–SE directed compression. The orientation of this foliation is similar to the strike of IOCG mineralized zones in the area. (2) a D_2 event forming steep, E–W orientated foliations within an E–W trending shear zone, and (3) a D_3 event that produced ENE–WSW-directed compression, developing the prominent folding of the D_1 sheared metaandesites seen in the Tjårrojåkka area. Sandrin and Elming (2006) also recognised three major tectonic events in the Tjårrojåkka deposits area based on AMS and geophysical data. These are summarised as: (1) A NE-alignment of mineralised zones and magnetic foliations formed during a ca. NW–SE directed compression (equivalent to D_1 above), (2) An E–W striking brittle-ductile faulting event with a dextral transpressive kinematic sense (equivalent to D_2 above) and (3) a NE-directed thrusting event (equivalent to D_3 above?). Further detailed investigations of the structures located within the central and eastern TKA are lacking at present.

Neotectonic, postglacial faulting occurs across the western end of the TKA and produced brittle structures that generally trend sub-parallel to the Caledonian front. Uplift during isostatic rebound likely provided a mechanism for these late-stage faults (Witschard et al. 2004).

Metamorphism

Regional metamorphism in the TKA has not been studied in detail, although the lithologies are interpreted to have been metamorphosed to medium grade upper greenschist facies, based on the observed mineral assemblages (Bergman et al. 2001). Reports of amphibole porphyroblasts (hornblende?) and epidote also suggest that higher grades to lower amphibolite facies were locally attained (Ros 1979, Edfelt et al. 2006). Mineral pressure–temperature analyses of analogous supracrustal volcanics further to the east suggest prograde metamorphism reached ca. 550°C and 2.5 kbar (Bergman et al. 2001). The timing of peak regional metamorphism (and plutonism) has been inferred at ca. 1,880–1,800 Ma (Skiöld 1987).

Overall, the general metamorphic grade in the TKA corresponds to the broad regional metamorphic picture seen across western and central Norrbotten, although detailed mineral chemistry (e.g., amphibole, garnet) or regional-scale P-T-t paths for the TKA have not been produced. Furthermore, there have been no detailed investigations of contact metamorphism affecting the metavolcanic rocks of the TKA. In the western TKA, metasomatic scapolite and albite alteration is seen overprinting the observed metamorphic fabrics and is associated with a later hydrothermal events (e.g., Edfelt et al. 2005).

Mineralization and alteration

Mineralization in the TKA can be classified into two broad deposit categories: (1) Kiruna-type Fe-oxide-apatite (IOA) mineralization, and (2) epigenetic-type Cu-Au mineralization. Some 18 deposits or prospects are known in the area with the majority occurring in the eastern or westernmost ends (Fig. 2). The central part of the study area thus appears to be underrepresented in terms of the known mineralization which *may* be a consequence of less exploration in this part of the TKA. The known mineralization is predominantly hosted in intermediate to acid metavolcanic rocks and a structural control on the mineralization is strongly developed with fault zone, stockwork and breccia-related occurrences being common.

The most significant mineralization occurs at the Tjårrojåkka IOCG system in the western part of the TKA. The Tjårrojåkka IOA deposit (ca. 53 Mt at 52% Fe and 0,8% P, cut-off grade not reported) consists of a steeply dipping, NE-aligned lens of massive magnetite, along with apatite-magnetite veins and minor disseminated Cu mineralization at the margins (Quezada and Ros 1971, Freitsch 1997b, Edfelt et al. 2005). The mineralization is hosted in sheared, porphyritic metaandesite. Overlying metabasalt and numerous doleritic feeder dykes also occur in the area. Several of these dykes crosscut the ore body and are also mineralized. The Tjårrojåkka Cu deposit (3 Mt at 0,9% Cu, with a 0,4% cut-off) is located about

800m NW of the IOA system. Here, disseminated and vein hosted chalcopyrite, bornite and pyrite form a ca. 700m mineralized zone with a similar orientation to the Fe-oxide deposit. Minor magnetite and apatite is also associated with the vein-hosted Cu mineralization. The mineralization is also hosted within porphyritic metaandesites. The age of mineralization and associated alteration at Tjårrojåkka is estimated to be ca. 1,780 Ma, and both deposits are interpreted to have formed from a single, protracted, magmatic-hydrothermal event consistent with an IOCG-type genetic model (Edfelt & Martinsson 2004, Edfelt 2007).

Alteration at the Tjårrojåkka deposits consists of an early, regionally pervasive scapolite-biotite assemblage that predominantly overprints the mafic volcanic rocks and appears concentrated within deformation and mineralization zones. A later K-feldspar-epidote-albite assemblage is associated with the IOA and Cu mineralization and preferentially affects the intermediate volcanics (Edfelt et al. 2006). In general, however, alteration at Tjårrojåkka is somewhat variable with numerous overlapping stages and multiple generations, indicating a complex hydrothermal history (Edfelt et al. 2005). Albitization has also been reported for the granitoids and syenitoids in the area and is inferred to be connected with PMS plutonism and associated metasomatism (Freitsch 1997a).

DISCUSSION

Current understanding

The metavolcanic rocks of the TKA formed within a continental arc-type setting during a period of tectonic compression in the Paleoproterozoic (e.g., Perdahl and Martinsson 1995, Edfelt et al. 2006). Earlier rift-to-drift tectonics, affecting the Archean basement and producing voluminous greenstones, gave way to a period of ocean-continent and/or arc-continent collision during subduction, forming abundant subaerial volcanism (Martinsson 1995). Local erosion, sedimentation and re-deposition contributed epiclastic and re-worked pyroclastic horizons to the volcanic pile (e.g., Martinsson 2004, Witschard et al 2004). In addition, intermediate to acid volcanics with a more alkalic composition are suggested to have formed within a localized extensional setting with a source contribution from preexisting continental material (Martinsson and Perdahl 1995, Perdahl 1995).

At present, the metavolcanics across the TKA are stratigraphically assigned to both the Porphyrite and Porphyry groups (Bergman et al. 2001). The western volcanics fall within the Porphyrite Group and generally have a calc-alkaline, low Ti and enriched ‘high field strength element’ composition (Martinsson and Perdahl 1995, Bergman et al. 2001). The intermediate to acid rocks at the eastern end of the study area are considered to be a SE extension of the high Ti, alkalic, Kiruna porphyries (i.e. Porphyry Group). In contrast, Offerberg (1967) and Witschard et al. (2004) placed the majority of the metavolcanics occurring across the TKA within the Porphyrite Group (i.e., the metavolcanics south of the TDZ). Earlier, Witschard (1984) noted that Porphyrite Group basic to intermediate volcanics are a slightly older version of the more felsic/rhyolitic units found in the Porphyry Group and that both groups form part of a thick, volcanosedimentary succession displaying variations in depositional facies. This produced gradual variation with time, from alkaline basalts and andesites to calc-alkaline dacites to rhyolites. Thus, Witschard (1984) argued that the entire succession should simply be termed the Porphyry Group. Perdahl (1993) noted regional scale petrological and geochemical variations in Svecofennian volcanics across Norrbotten, from more mafic and mildly alkalic in the west, to more intermediate to felsic and calc-alkalic in

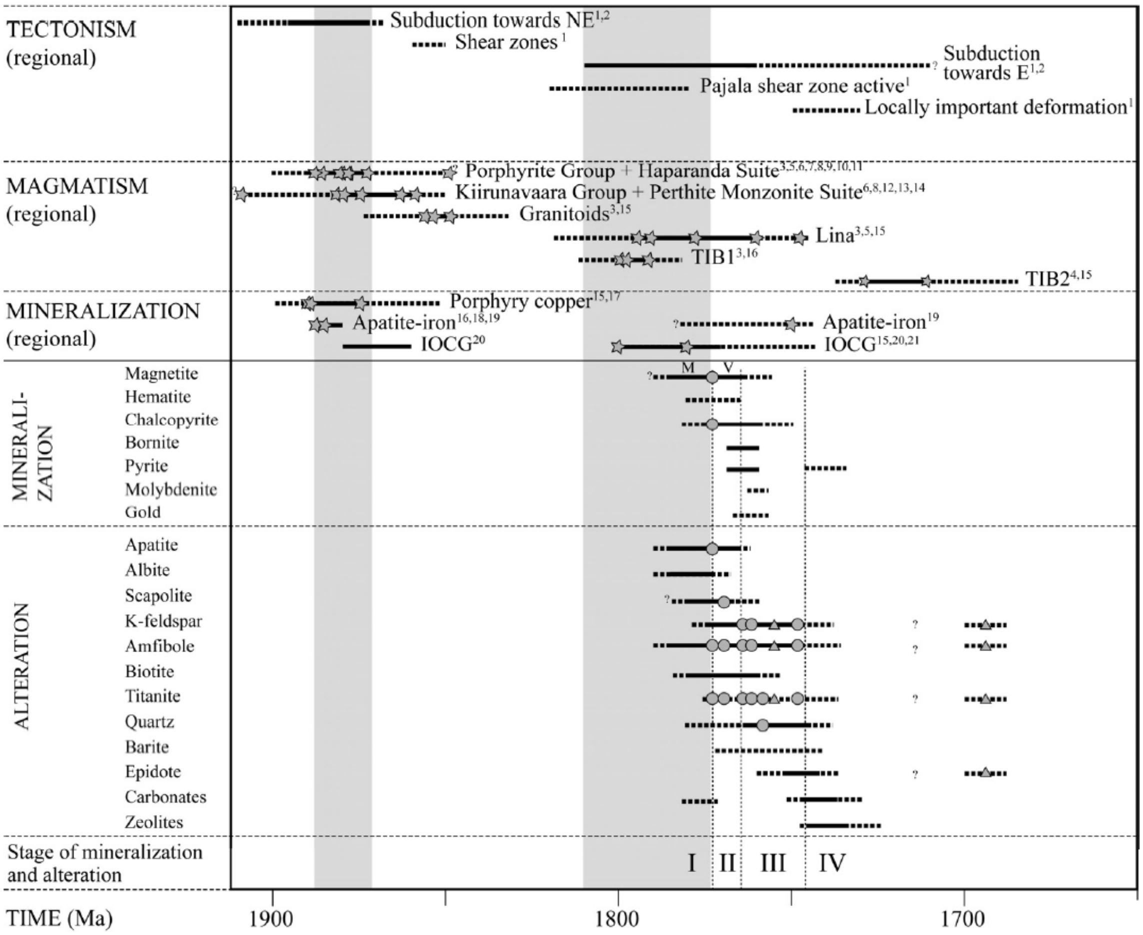

Figure 14. A summary of the various magmatic, deformation and mineralization events across northern Norrbotten (taken from Edfelt et al. 2007 and references therein). The mineralization and alteration ages are from the Tjårrojåkka deposits.

the east. Based on the presently available geochronology, both the Porphyrite and Porphyry Groups appear to be contemporaneous (Fig. 14).

The majority of the Svecokarelian plutons occurring within TKA are PMS intrusives (Geijer 1931, Offerberg 1967, Witschard 1984, Witschard et al. 2004). These plutons are generally massive and weakly metamorphosed. Petrologically, they predominantly consist of monzonite, quartz monzonite and monzodiorite (i.e., the 'monzo-intrusions' of Weihed 2004). A characteristic feature of the intermediate to felsic verities is the presence of perthitic feldspar phenocrysts. More mafic verities (diorites, gabbroids, peridotite) also form part of this suite but are generally more abundant to the north. Magma mingling and mixing features support some level of bimodal and/or compositionally hybrid magmatism (e.g., Weihed 2004). PMS intrusives are considered to be plutonic equivalents of Porphyry Group metavolcanics, based on certain lithogeochemical characteristics and geochronological constraints (e.g., Witschard 1984, Martinsson 2004). Emplacement ages range from ca. 1,880–1,850 Ma (Fig. 14).

IOCG-type mineralization at the western end of the TKA is the most investigated mineral occurrence in the area. Spatially separate zones rich in IOA and Cu mineralization are interpreted to have formed during a single, episodic process. Geochemical and isotopic studies indicate that the mineralization is the result of a magmatic-hydrothermal event linked to late-stage Svecokarelian magmatism at ca. 1,780 Ma (Edfelt 2007). Two major IOCG ore forming events are recognized in Norrbotten at ca. 1,87 and 1,77 Ga coincident with major episodes of regional-scale magmatism and fluid flow (Billström and Martinsson 2000, Edfelt et al. 2007, Smith et al. 2009, Figure 14). Detailed studies of other mineralized locations elsewhere in the TKA are lacking at present and it is unclear whether the 1,780 Ma event can be applied to these mineralized localities. Likewise, the role late-orogenic granitoid magmatism (e.g., Lina-type) and contemporaneous (or earlier) deformational processes plays in the formation of mineralization across the study area remains unclear. Hydrothermal alteration in the TKA is dominated by a regionally pervasive scapolite-biotite assemblage affecting most of the lithologies (Fig. 4). Selective potassic alteration is associated with the IOCG mineralization in the western end. Detailed alteration studies related to other mineralized areas are presently lacking.

Potential issues to be addressed

The rock types and units across the TKA have been variously described by earlier workers (e.g., Ödman 1957, Offerberg 1967, Witschard et al. 2004). In addition, a stratigraphy for the porphyritic volcanics and associated sediments dominating the area has been proposed within the context of the regional stratigraphy of Norrbotten (Offerberg 1967, Lundqvist 1979, Witschard 1984, Martinsson 1995). Furthermore, IOCG-type mineralization at the western end of the key area has undergone extensive investigations since the early 2000's (e.g., Edfelt 2003, Sandrin 2003, Edfelt et al. 2005, Sandrin and Elming 2006, Edfelt 2007, Sandrin et al 2009). Notwithstanding these results, several aspects of the TKA geology require additional investigation to resolve specific questions that have broader implications relating to Paleoproterozoic volcanism, alteration and mineralization in the area. Some potential issues that may need to be addressed are outlined below under several headings.

Stratigraphy

Svecofennian metavolcanics in the western half of the TKA are presently assigned to the Porphyrite Group. In the eastern half of the area, the metavolcanics are assigned to the Porphyry Group and represent an apparent SW extension of the Kiruna Porphyry Group. Are these stratigraphic assignments correct? If so, what is the nature of the contact between these two groups? Can a systematic change in the petrology and geochemistry of these rocks be observed from one group to the other, and can this information be used to reconstruct the tectonic and geologic factors that controlled this phase of extrusive magmatism? Does the magnetic banding seen in the eastern TKA (Fig. 10) correspond to alternating, bimodal volcanic horizons?

Structure

What are the dominant structural characteristics of the TDZ? Is there any kinematic variation along strike? How does it compare with other shear zones? What role has this shear zone played on fluid flow, alteration and mineralization events? How many movements have occurred along this shear zone and how has it influenced has it played on the development of brittle deformation in the TKA? What are the main depositional/extrusive features and structures that can be seen across the area? Do magnetic and other geophysical lineaments correspond to original bedding horizons and/or brittle fractures?

Formational Environments

The TKA volcanics are inferred to have formed under a broadly compressive tectonic regime which developed subaerial, volcanic arc-type magmatism. However, an extensional setting has also been proposed for Porphyry Group volcanics. How can two contrasting geotectonic settings have developed within a relatively small area and what is the relative and/or absolute timing of these processes? What is the relative contribution of submarine and subaerial volcanism to the development of the volcanic pile?

Lithogeochemical and Isotopic Characteristics

The volcanic rocks within the TKA provide an opportunity to use lithogeochemical and isotopic techniques to understand some of the key geological controls and processes that produced Svecofennian volcanism in western Norrbotten. Geochemical analysis of TKA metavolcanics, combined with good petrologic controls, could also be used to develop a definitive nomenclature for Svecofennian metavolcanic horizons which could help minimise the use of ambiguous, subjective descriptions for these rock types (e.g., basic, intermediate, alkali, porphyry, etc.)

Geochronology

The age of Porphyrite Group metaandesites (ca. 1,878 Ma) in the western TKA corresponds to a minimum age for Porphyry Group volcanics NE at Kiruna (ca. 1,880 Ma). Thus volcanism for both groups appears contemporaneous and differs principally by their depositional facies. In situ dating methods (e.g., U–Pb titanite, monazite, zircon) should be used by SGU to establish a geochronologic framework for volcanism, plutonism, alteration and mineralization in this part of Norrbotten with emphasis on constraining ages in the eastern TKA and linking the results with the Kiruna porphyries to the NE. Is the ca. 1,780 Ma mineralization event identified at the Tjårrojåkka IOCG system replicated elsewhere across the TKA? Can we use geochronology to infer a pluton-related mechanism for on driving fluid flow, alteration and mineralization?

Metamorphic Grade

What metamorphic conditions were reached at the TKA? Is it the same as the conditions calculated further to the east? How consistent is the regional metamorphism across the TKA or does it vary between units or with stratigraphy? Which rock units are best for understanding the regional metamorphic picture?

Mineralization and Alteration

The Tjårrojåkka IOCG system in the western TKA indicates that magmatic–hydrothermal processes were operating at a time after the formation of the host volcanic rocks (ca.

1,780 Ma). Are the other mineralized areas also part of this mineralization event? What are the lithological and structural controls on mineralization and associated alteration and how many generations can be identified?

PLANNED WORK

The following section briefly outlines field work plans in order to answer some of the key questions proposed above. The numbered tasks listed below correspond to the numbered polygons in Figure 15, which approximately delineate areas within the TKA where the field work will be conducted. In addition to the listed tasks, routine petrophysical and gamma spectrometry measurements at visited outcrops across the TKA will also be undertaken.

1. Undertake field mapping (petrography/alteration, logging of depositional structures) and lithogeochemical sampling of volcanic rocks along two, sub-parallel transects across the TKA. This work will help characterise the lithological and geochemical nature of the various volcanic units within the Porphyrite and Porphyry groups. In addition, the data will help test the validity of the assignment of the volcanic rocks in the eastern TKA to the Porphyry Group volcanic suite. Furthermore, the two profiles will help constrain the nature of the contact between these two lithostratigraphic groups and provide an opportunity to characterise the transition between these regionally important volcanic successions. Sampling for age dating will also be performed (4–5 days).

2. Perform selective mapping (petrography, structures, alteration) and sampling (potential lithogeochemistry, dating) of specific Porphyry Group (sensu stricto) volcanic horizons to the north of the TKA (i.e. north of the TDZ). This information will be used as a comparative dataset and will be compared to the sampled volcanic units in the eastern TKA. This field work will help to better characterise the Porphyry Group volcanics of the eastern TKA and will facilitate regional comparisons with volcanics closer to Kiruna (1–2 days)

3. Investigate, using ground-based geophysical methods, a strong, 'horse shoe'-shaped magnetic anomaly surrounding a PMS-type quartz monzonite intrusion at the centre of the TKA (Fig. 6 and 10). The geological characterisation (petrography, alteration, mineralization?) of corresponding outcrops in the area will also be performed. Preliminary interpretations suggest the potential for skarn-type mineralization and/or intrusion-related deformation (diaperism?). This work will test the nature and geological significance of this interesting magnetic anomaly (2–3 days, geophysics focus)

4. Investigate the structural and kinematic properties of the Tjårrojåkka Deformation Zone. Outcrops within specific areas that straddle the TDZ will be investigated to characterise the nature of the deformation and the relationship to fluid flow and/or mineralization (e.g., Pattok). In addition, several ground geophysical profiles will be made orthogonal to this sub-regional structure to help further constrain the deformation (3–4 days, including geophysics).

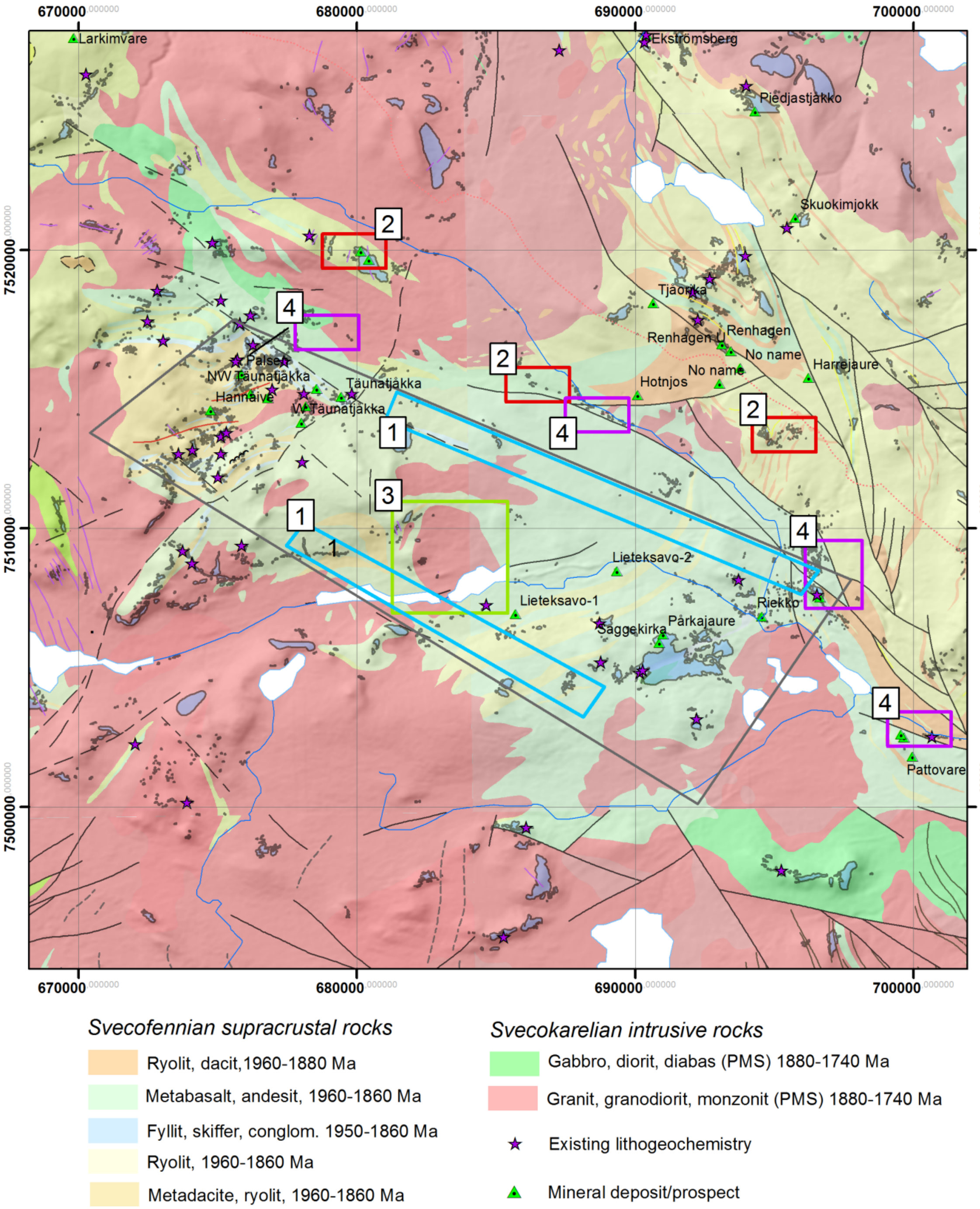

Figure 15. Planned field work areas 1 to 4 within and adjacent to the Tjårrojåkka Key Area. Numbers correspond to tasks listed in Section 5.

REFERENCES

Bergman, S., Kubler, L. & Martinsson, O., 2000: Regional geological and geophysical maps over northern Norrbotten County: Bedrock map. *Sveriges geologiska undersökning Ba 56–1*.

Bergman, S., Kubler, L. & Martinsson, O., 2001: Description of regional geological and geophysical maps of northern Norbotten County. *Sveriges geologiska undersökning Ba 56*, 110 pp.

Bergman, S., Stephens, M.B., Andersson, J., Kathol, B. & Bergman, T., 2012: Sveriges berggrund. 1:1 miljon. *Sveriges geologiska undersökning K423*.

Billström, K. & Martinsson, O., 2000: Links between epigenetic Cu–Au mineralizations and magmatism/deformation in the Norrbotten County, Sweden. 2nd annual GEODE-Fennoscandian shield field workshop on Palaeoproterozoic and Archaean greenstone belts and VMS districts in the Fennoscandian Shield. Program and abstracts.

Broman, C. & Martinsson, O., 2000: Fluid inclusions in epigenetic Fe–Cu–Au ores in northern Norrbotten. *Report 2000:6*, p. 7.

Cliff, R. A., Rickard, D. & Blake K., 1990), Isotopic systematics of the Kiruna magnetic ores, Sweden: Part 1. Age of the ore, *Economic Geology v. 85*, 1770–1776.

Cornwell, I., 1965: Preliminary Estimate of the size of the main ore body at Pattok. *Sveriges geologiska undersökning BRAP 85110*.

Edfelt, Å., 2003: Geology, alterations, and mineral chemistry of theTjårrojåkka Fe-oxide Cu–Au occurrences, N Sweden. Unpublished MSc thesis, Luleå University.

Edfelt, Å., 2007: The Tjårrojåkka apatite–iron and Cu., -Au) deposits, northern Sweden - products of one ore forming event. Ph.D. thesis, Luleå University, Sweden.

Edfelt, Å., Broman, C. & Martinsson, O., 2004: A preliminary fluid inclusion study of the Tjårrojåkka IOCG-occurrence, Kiruna area, northern Sweden. *GFF, v.126*, p. 148.

Edfelt, Å. & Martinsson, O., 2004: The Tjårrojåkka Fe-oxide and Cu-Au occurrences, northern Sweden – products of one ore-forming event? *IAVCEI General Assembly 2004, Program and abstracts*.

Edfelt, Å. & Martinsson, O., 2005: Box 8–3: Fennoscandian Shield – Iron Oxide–Copper–Gold deposits Tjårrojåkka, northern Sweden. Ore Geol. *Rev., v.27*, p. 328

Edfelt, Å., Armstrong, R.N., Smith, M. & Martinsson, O., 2005: Alteration paragenesis and mineral chemistry of the Tjårrojåkka apatite–iron and Cu (-Au) occurrences, Kiruna area, northern Sweden. *Mineralium Deposita v.40*, p. 409–434.

Edfelt, Å., Sandrin, A., Evins, P., Jeffries, T., Storey, C., Elming, S.A. & Martinsson, O., 2006: Stratigraphy and tectonic setting of the host rocks to the Tjårrojåkka Fe-oxide Cu–Au deposits, Kiruna area, northern Sweden. *GFF, v.128*, p. 221–232.

Edfelt, Å., Billström, K., Broman, C., Rye, R.O., Smith, M.P. & Martinsson, O., 2007: Origin and fluid evolution of the Tjårrojåkka apatite–iron and Cu (-Au) deposits, Kiruna area, northern Sweden. In Edfelt Å, Ph.D. thesis, Luleå University, Sweden.

Eilu, P., Hallberg, A., Bergman, T., Bjerkgård, T., Feoktistov, V., Korsakova, M., Krasotkin, S., Kuosmanen, E., Lampio, E., Litvinenko, V., Nurmi, P. A., Often, M., Philippov, N., Sandstad, J.S., Stromov, V. & Tontti, M. (comp.) 2008: Metallogenic Map of the Fennoscandian Shield, 1:2,000,000. Geological Survey of Finland, Geological Survey of Norway, Geological Survey of Sweden, The Federal Agency of Use of Mineral Resources of the Ministry of Natural Resources and Ecology of the Russian Federation.

Frietsch, R., Tuisku, P., Martinsson, O. & Perdahl, J.A., 1997a: Early Proterozoic (Cu-)(Au) and Fe ore deposits associated with regional Na–Cl metasomatism in northern Fennoscandia. *Ore Geology Review v.12*, p. 1–34.

Frietsch, R., 1997b: The Iron Ore Inventory Programme 1963–1972 in Norrbotten County. TI: Map, iron ore inventory programme 1963–1972, 1:250,0000. *Sveriges geologiska undersökning R&M 92*, 77 p.

Geijer, P., 1931: The iron ores of the Kiruna type. Geographical distribution, geological characters and origin. *Sveriges geologiska undersökning C 367.*

Koistinen, T., Stephens, M.B., Bogatchev, V., Nodgulen, O., Wennerström, M. & Korhonen, J., 2001: Geology of the Fennoscandian Shield. 1:2,000,000 scale map. GTK, Sveriges geologiska undersökning, NGU, DNRR.

Lundqvist T., 1979: The Precambrian of Sweden. *Sveriges geologiska undersökning C 366*, 87 pp.

Martinsson, O., 1995: Greenstone and porphyry hosted ore deposits in northern Norrbotten. *PIM report # 3*, 58 p.

Martinsson, O., 1997: Tectonic setting and metallogeny of the Kiruna greenstones. Ph.D. thesis, Luleå University.

Martinsson, O., 2004: Geology and Metallogeny of the Northern Norrbotten Fe–Cu–Au Province. *SEG guidebook series vol. 33*, p. 131–148.

Martinsson, O. & Perdahl, J.A., 1995: Paleoproterozoic extensional and compressional magmatism in northern Norrbotten, northern Sweden. In Perdahl J.A., 1995), Ph.D. thesis, Luleå University.

Niva, B., 1978: Geofysisk malmberäkning över Tjårrojåkka järnmalmsfyndighet. *Sveriges geologiska undersökning FM 7808*, Uppsala/Malå.

Offerberg, J., 1967: Beskrivning till berggrundskartbladen Kiruna NV, NO, SV, SO. *Sveriges geologiska undersökning Af 1–4*, 146 pp.

Ödman, O.H., 1957: Beskrivning till berggrundskartbladen över urberget i Norrbottens Län. *Sveriges geologiska undersökning Ca 41*, 151 pp.

Öhlander, B., Skiöld, T., Elming. S.A., BABEL Working Group, Claesson, S. & Nisca, D.H., 1993: Delineation and character of the Archaean–Proterozoic boundary in northern Sweden. *Precambrian Research v.64*, p. 67–84.

Perdahl, J.A., 1993: Geological diversities within the Kiruna–Arvidsjaur Porphyry groups. Implications for age and facies dependence. Licentiate thesis, Luleå University.

Perdahl J.A., 1995: Svecofennian volcanism in northernmost Sweden. Ph.D. thesis, Luleå University, Sweden.

Perdahl, J.A., 2006: Redovisning av resultat av undersökningsarbeten. MINK 5749, Bergstaten, Malå.

Perdahl, J.A. & Martinsson, O., 1995: Paleoproterozoic flood basalt magmatism in the Kiruna area, northern Sweden. In Perdahl J.-A., Ph.D. thesis, Luleå.

Perdahl, J.A. & Frietsch, R., 1993), Petrochemical and petrological characteristics of 1.9 Ga old volcanics in northern Sweden. *Precambrian Research v.64,* p. 239–252.

Quezada, R. & Ross, F., 1971: Malmberäkning av Tjårrojåkka järnmalmsfyndighet. *Sveriges geologiska undersökning BRAP 82569*, Uppsala.

Ros, F., 1979: Tjårrojåkka kopparmalmsfyndighet. *Sveriges geologiska undersökning BRAP 82567*, 13 p., Uppsala/Malå.

Ros, F. & Rönnbäck, L., 1971: Rörande malmobjektet Tjårrojåkka. *Sveriges geologiska undersökning BRAP 82570*, 9 pp.

Sandrin, E., 2003: Geophysical and petrophysical characterisation of the Tjårrojåkka IOCG mineralization, Sweden. MSc thesis, Luleå University, Sweden.

Sandrin, A. & Elming, S.Å., 2006: Geophysical and petrophysical study of an iron oxide copper gold deposit in northern Sweden. *Ore Geology Review* v.29, p. 1–18.

Sandrin, A., Edfelt, Å., Waight, T.E., Berggren, R., Elming, S.Å., 2009: Physical properties and petrologic description of rock samples from an IOCG mineralized area in the northern Fennoscandian Shield, Sweden. *Journal of Geochemical Exploration* v.103, p. 80–96.

Skiöld, T., 1987: Aspects of the Proterozoic geochronology of northern Sweden. *Precambrian Research v.35*, p. 161.

Skiöld, T. & Cliff, R.A., 1984: Sm–Nd and U–Pb dating of Early Proterozoic mafic–felsic volcanism in northernmost Sweden. P*recambrian Research v.26*, p. 1–13.

Smith, M.P., Storey, C.D., Jefferies, T.E. & Ryan, C., 2009: In situ U–Pb and trace element analysis of accessory minerals in the Kiruna district, Norrbotten, Sweden: New constraints on the timing and origin of mineralization. *Journal of Petrology, v.50*, p. 2063.

Thelander, T., 2009: Kaledoniderna i norra Sverige, norra delen. *Sveriges geologiska undersökning K 222:1.*

Weihed, P., 2004: Overview of the geology and tectonic setting of northern Sweden. SEG guidebook series vol. 33, p. 1–15.

Welin, E., 1987: The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden. *Precambrian Research v.35*, p. 95–113.

Welin, E., Christiansson K & Nilsson Ö., 1971: Rb–Sr radiometric ages of extrusive and intrusive rocks in northern Sweden. I. *Sveriges geologiska undersökning C666*, 40 pp., Uppsala/Malå.

Witschard, F., 1984: The geological and tectonic evolution of the precambrian of northern Sweden – A case for basement reactivation? *Precambrian Research v.23*, p. 273.

Witschard, F., Thelander, T., Kübler, L., Stölen, L.K. & Perdahl, J.A., 2004: Beskrivning till berggrundskartbladen 29I Kebnekaise SO. *Sveriges geologiska undersökning Ai 198*.

Wright, S.F., 1988: Early Proterozoic deformation history of the Kiruna District of northern Sweden. Unpublished Ph.D. thesis, University of Minnesota, 170 pp.