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Summary report on the geological and geophysical characteristics of the Saarijärvi key area (29J Kiruna NO, NV, SO)

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Cover: Mountain view to the west, looking across lake Kaalasjärvi
(Saarijärvi area). Photo: Edward P. Lynch, SGU.

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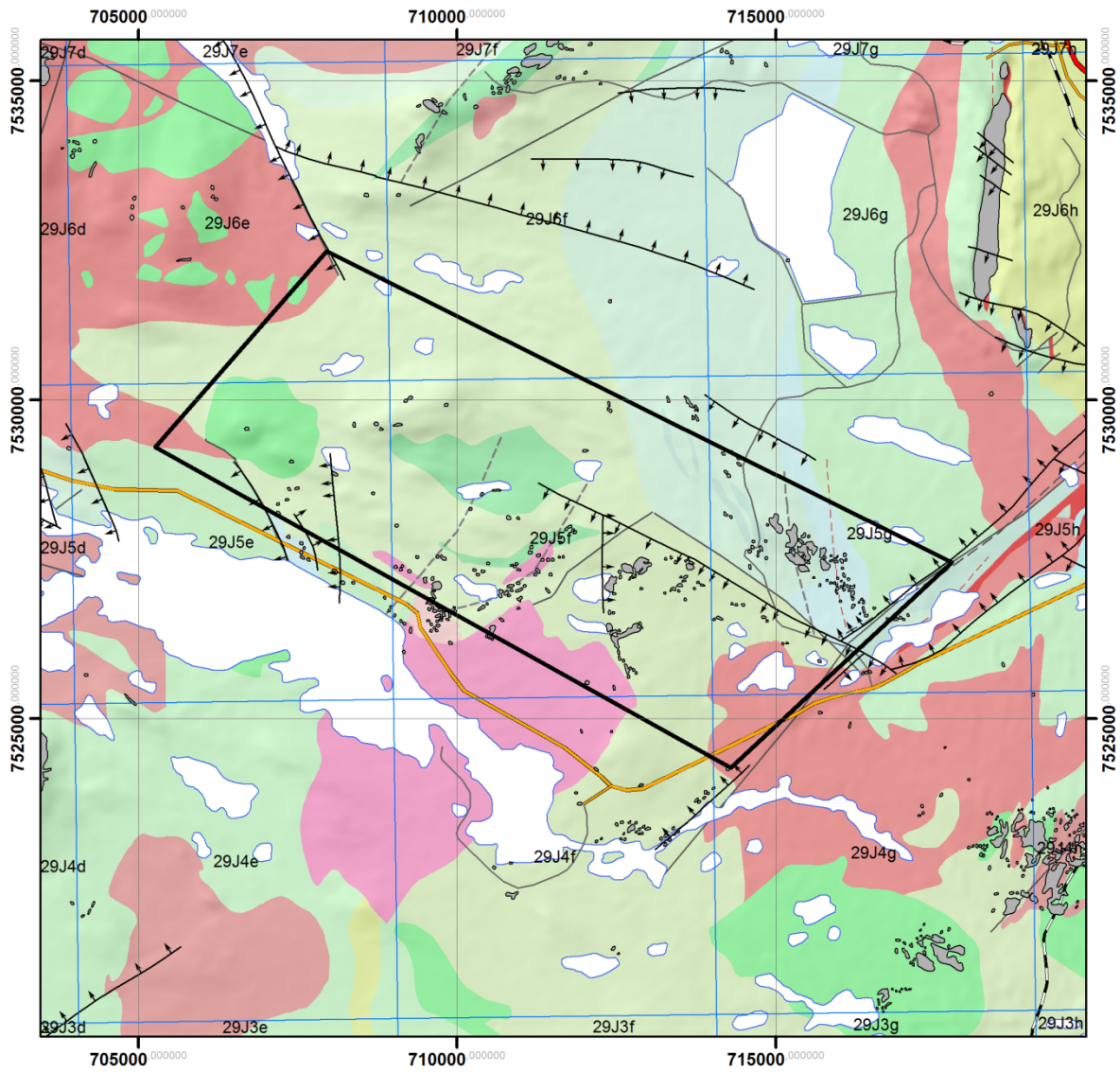
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INTRODUCTION

The Saarijärvi Key Area (SKA) is located approximately 15 km southwest of Kiruna (north-western Norrbotten County, Sweden), within map sheets 29J NO, NV and SO (Kiruna) and incorporates 7 5x5km lettered topographic grid squares (Fig. 1). The area is centered on a package of metamorphosed volcanic rocks that include part of the Karelian greenstones of northern Fennoscandia (ca. 2.40–1.96Ga) along with overlying Svecofennian volcano-sedimentary units (ca. 1.96–1.85 Ga). The latter units are composed of metamorphosed basalts, andesites and rhyolites of the Porphyrite and Porphyry lithostratigraphic groups (the Porphyry Group is also referred to as the Kiirunavaara Group or Kiruna Porphyries, see Table 2 in Bergman et al. 2001). Minor metasedimentary horizons also occur within the various volcanic sequences (e.g., Kurravaara conglomerate, Offerberg 1967, Kumpulainen 2000). About 8 km to the NE of the SKA, Porphyry Group metavolcanics host the Kirunavaara–(Luossavaara) Fe-oxide–apatite deposit, one of the world’s largest (e.g., Hallberg et al. 2012). Svecofennian (1.89–1.86 Ga) intrusive rocks also occur across the SKA and primarily consist of variably metamorphosed syenitoids and gabbroids belonging to the Perthite Monzonite intrusive suite (PMS, e.g., Witschard 1984). In the south–central SKA, a syenitic pluton linked to late-stage (ca. 1.81–1.78 Ga) Svecofennian granitoid–syenitoid magmatism is also found. Numerous doleritic, granitic and syenitic dykes and veins crosscut the area also. The rocks of the SKA are located at the southern end of a major, NNE-trending shear zone termed the Kiruna–Naimakka Deformation Zone. The SKA is best known for several Cu–Au occurrences including the Pahtohavare and Rakkurijärvi deposits (e.g., Lindblom et al. 1996, Smith et al. 2007), while the region as a whole is considered to be prospective for IOCG-type mineralization (e.g., Carlon 2000, Williams et al. 2003).

Access to the SKA is reasonably good. A paved road (Silfverbrandsgatan) running south from Kiruna carries on further west along the southern margin of the study area (unclassified local route running east–west between Kiruna and Puoltsa). Furthermore, a forest road crosses the eastern part of the area and provides access to the Pahtohavare open pit. Several ATV trails also extend north from the main paved road in the south. The least accessible areas are in the west and northwest. The terrain is a mixture of coniferous forest and marshland. The landscape is generally flat in the east, with elevations around 470m (a. s. l.) and becomes more hilly in the west, with the elevation reaching 691m at Ailatisvaara. Lake Kaal-asjärvi and the Kalixälven River are located to the south of the key area and represent the main hydrographic features. Small lakes and ponds are mostly located in the south and east. Outcrops are primarily found in the eastern and southern parts of the SKA (see Fig. 3). Thin soil cover also exists in the areas with the best exposure. The northern and western parts of the key area appear to be the least exposed, however outcrop exposure along lake edges may compensate for the general lack of exposure in these areas.

This report outlines the main geological and geophysical characteristics of the SKA. 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 Saarijärvi Key Area is a focus for targeted geological mapping and investigations under SGU’s Barents Mapping Project (2012–2015).



| <i>Svecokarelian supracrustals</i> | <i>Svecokarelian intrusives</i> |
|--|--|
| Dacit-ryolit, 1,88-1,84 Ga | Granit 1,88-1,84 Ga |
| Basalt-andesit 1,88-1,84 Ga | Syenitoid-granit 1,87-1,66 Ga |
| Basalt-andesit 1,92-1,87 Ga | Syenitoid-granit 1,88-1,84 Ga |
| Konglomerat 1,92-1,87 Ga | Gabbroid-dioritoid 1,88-1,84 Ga |
| Basalt-andesit 2,05-1,96 Ga | Ultrabasisk 2,40-1,96 Ga |
| Basalt-andesit 2,30-2,05 Ga | Granit >2,50 Ga |
| Skiffer 2,40-1,96 Ga | |

Fig. 1. Bedrock geology of the Saarijärvi key area (regional 1:250,000 scale level). Lakes, rivers and the main roads are also shown.

Geological Overview

The bedrock geology of the Saarijärvi Key Area (SKA) has been described in earlier SGU reports and maps by Geijer (1931), Ödman (1957) and Offerberg (1967), while a compilation and summary of Norrbotten geology and metallogeny from a regional perspective is presented by Lundqvist (1979), Carlon (2000), Bergman et al. (2001), Martinsson (2004), Weihed et al. (2005) and Billström et al. (2010). The SKA is dominated by a package of volcanosedimentary rocks (ca. 4–5 km thick) consisting of Karelian basalts belonging to the Kiruna Greenstone Group (KGG, ca. 2.600–2,000 Ma) and Svecofennian intermediate to acid volcanics (andesites, rhyodacites, rhyolites, along with associated sedimentary horizons) assigned to the Porphyrite and Porphyry Groups (ca. 1,960–1,850 Ma). In the eastern SKA, a distinct arenitic to conglomeritic unit (ca. 500–1,000m thick) termed the Kurravaara Conglomerate is also encountered (Geijer 1931, Witschard 1984). This horizon is considered to be a lateral sedimentary facies of the Porphyrite Group. In lowermost sections it contains clasts derived from the underlying greenstones as well as gneissic areas to the north, suggesting several sedimentary provenances (Martinsson & Perdahl 1995, Martinsson 2004). Further west close to Puoltsa, a dault-bounded conglomeritic wedge is also encountered. It is not known if this unit represents a basal sedimentary zone of the KGG, can be correlated with the Kurravaara Conglomerate in the east, or represents part of the underlying Kovo Group (cf. Kumpulainen 2000).

The basal part of the KGG volcanics is comprised of amygdaloidal basaltic flows and local komatiitic horizons that display a juvenile, within-plate basalt (WPB) geochemical signature. These rocks are followed further up the sequence by more mature, tholeiitic, mid-ocean ridge basalts (MORB) which locally display pillowed forms, indicating submarine extrusion in a subsiding basin (Martinsson 1997). The greenstones are considered to have formed in response to high temperature, decompression melting within a NNE-trending rift zone (Martinsson 1997). A mantle plume has been invoked to explain rifting initiation and subsequent flood volcanism (Martinsson 1991, Perdahl 1995, Martinsson 1997). The KGG volcanics are unconformably overlain by Porphyrite and Porphyry Group volcanosedimentary units, although the contacts between these sequences are not well described in the area. In the case of both Porphyrite and Porphyry Group volcanics, porphyritic textures are commonly seen in the more intermediate rocks, while several horizons of volcanoclastic (tuff, agglomerate) and sedimentary (schists, marble) material are also present. The entire volcanic sequence across the SKA is broadly considered to both young and become more intermediate to felsic from west to east, although local and regional deformation events have complicated the stratigraphy (cf. Offerberg 1967, Martinsson 1997, Bergman et al. 2001).

Intrusive rocks in the area mostly consist of syenitoids and lesser granitoids assigned to the Svecokarelian Perthite Monzonite Suite (ca. 1,880–1,860 Ma, Witschard 1984, Ahl et al. 2001). On a regional scale, this plutonic suite preferentially intrudes the western side of northernmost Sweden and the intrusions are considered to be plutonic equivalents of Porphyry Group volcanics (Bergman et al. 2001). Several smaller gabbroic bodies found in the area (e.g. north of the Puoltsa deposit, western SKA) are also assigned to the PMS. The area is cut by numerous dykes of both doleritic and granitic composition also (see Offerberg and Nilsson 1967).

The SKA has experienced several episodes of deformation and associated metamorphism during the Svecokarelian Orogeny (ca. 1,900–1,800 Ma). Regional-scale deformation

events, along with voluminous magmatism, likely facilitated episodic hydrothermal fluid flow, mineralization and alteration. Episodic brittle–ductile deformation has imparted a regionally pervasive ca. N–S structural foliation across the area (Wright 1988, Bergman et al. 2001) which appears to be preferentially focused within the NNE-striking greenstone sequence. Regional metamorphism attained upper greenschist facies with localized peak conditions that transect the greenschist–amphibolite facies boundary (Bergman et al. 2001).

Mineralization in the SKA predominantly consists of Fe-oxide (dominantly magnetite) and Cu–Au occurrences (chalcopyrite, pyrrhotite, auriferous Cu–Fe–sulphides, native gold, auriferous tellurides etc.). Stratiform skarn-related Fe-oxide mineralization is also known (e.g., Puoltsa prospect). Skarn mineralization occurs as disseminated, stratiform lenses (e.g., Pahtohavare Cu) or breccia- and vein-hosted forms (e.g., Rakkurijärvi Cu–Au). Both the Fe-oxide and Cu–Au mineralization is hosted in the greenstone and Svecofennian supracrustal units. Hydrothermal alteration in the area is dominated by a regionally pervasive scapolite-albite assemblage affecting most of the volcanic rocks. Local potassic and silicic alteration associated with Cu–Au mineralisation is also encountered (e.g., Smith et al. 2007). Structural pathways facilitating fluid flow appear to have played an important role in focusing mineralization and alteration (e.g., Smith et al. 2010).

AVAILABLE DATA FOR SAARIJÄRVI KEY AREA

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

Bedrock Geology

The SKA 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, 1:250,000 and smaller scales. Additional sampling or analyses (e.g., litho-geochemistry, age determinations) are generally represented as vector point layers or polygons showing the sample location and data result. The most detailed mapping is three 1:50,000 scale bedrock maps from SGU's Af map series. They are:

1. 29J Kiruna NV Af nr 1
2. 29J Kiruna NO Af nr 2
3. 9J Kiruna SO Af nr 4 (Offerberg 1967, Offerberg and Nilsson 1967).

Map databases

The following tables list the most important bedrock mapping for the Saarijärvi 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. Several of the vector datasets contain outcrop polygons.

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 SKA

| Code | Title | Scale | Reference | Location | Most relevant |
|--------|---|-------------|--|---------------------|------------------------------------|
| Af 1 | Bedrock map | 1:50,000 | Offerberg & Nilsson 1967 | Western SKA | Bedrock map |
| Af 2 | Bedrock map | 1:50,000 | Offerberg & Nilsson 1967 | Eastern SKA | Bedrock map, Profile II |
| Af 4 | Bedrock map | 1:50,000 | Offerberg & Nilsson 1967 | Southeastern SKA | Bedrock map |
| Ba56-1 | Regional bedrock map | 1:250,000 | Bergman et al. 2000 | Northern Norrbotten | Bedrock, stratigraphy, structures |
| Ca 41 | Berggrundskara över urberget i Norrbottens län | 1:400,000 | 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 SKA | Bedrock geology |
| n/a | Regional berggrundsinformation | 1:250,000 | SGU database (GIS) | All of SKA | Bedrock geology |
| n/a | Norrbotten NBDIG layer. Digital vector data of bedrock geology with outcrops, contacts and structures. 1:1,000,000? | | SGU database (GIS). (Sjöstrand and Henkel) | All of SKA | Bedrock geology |
| n/a | Norrbotten NBDIG layer. Digital vector data of bedrock geology with outcrops, contacts and structures. 1:1,000,000? | | SGU database (GIS). Sjöstrand and Henkel. | All of SKA | Bedrock geology |

Table 2. Additional bedrock-related information covering the SKA

| Layer/dataset | Description | Location | Reference |
|------------------------------------|--|--------------------|--------------|
| Hällar ur jordartskartor | Digital layer showing outcrop and thin soil cover areas from soil maps. | SKA | SGU database |
| Geology_1M | 1:1,000,000 scale digital vector data showing bedrock geology. No colour coding. | TKA | SGU database |
| Hällar | Digital vector data location of exposed outcrop areas (regional scale) | 29J5e/f/g, 29J6f | SGU database |
| Boulder data covering 29J | Locations and descriptions of boulders | TKA | SGU database |
| Förenklad jordartsindelning (JBAS) | soil/till geology map of Norrbotten 1:250,000 | TKA | SGU database |
| Jordartskartor | soil/till geology map of Norrbotten 1:250,000 and 1:1,000,000 | TKA | SGU database |
| Jorddjupsmodell | Soil depth model raster dataset | TKA | SGU database |
| Jorddjupsinformation | Soil depth vector point data. 35 points in the study area. | 29J5e/f/g | SGU database |
| Isräfflor | 8 flow directions recoded in the area or adjacent to the study area | 29J5e/f/g, 29J4f/g | SGU database |
| 1:100,000 blockletning map | boulder tracing? Covers western side of the study area. rec_G02700.tif | 29J5e/f/g | SGU database |

Scanned maps

Table 3 lists the scanned paper maps (field maps) used to identify outcrop locations and record previous field 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 Saarijärvi 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 SKA (listed in Table 6). For example,

Outcrops

Figure 2 shows the location of known outcrops and exposed rock areas across the SKA (outlined, shaded polygons). In general, the southern and eastern parts of the area have the most exposure. The north and west of the study area is the least exposed. Most of the outcrops correspond to the metavolcanic rocks in the area. There is some scattered exposure of plutonic rocks in the central and southern parts also. Southwest of the study area there is a large expanse of mapped greenstones with little to no exposure. In general, thin soil cover corresponds to areas with the best exposure.

Published material (papers and reports)

A list of the most important papers and reports describing the geology of the SKA is presented in Table 4. Additional exploration reports are also available from SGU's GeoRegister service. Several of the publications listed are review papers that summarize the broad geological framework of the SKA. Other papers relate to specific studies carried out within or adjacent to the SKA (in particular the Pahtohavare and Rakkurijärvi deposits), or regional studies that incorporated one or more samples from the various SKA rock units. The publications are listed in decreasing chronological order. References quoted in the text and tables of this report refer to the publications shown in the table and those in the reference list.

Table 3. List of scanned field maps covering the SKA

| Layer/dataset | Description | Scale | Reference |
|---------------|---|----------|--------------|
| G00275 | Scanned outcrop field map (not rectified) 29J,5-9, a-e | 1:20,000 | SGU database |
| G00283 | Scanned outcrop field map (not rectified) 29J,4-5, g-h | 1:20,000 | SGU database |
| G00284 | Scanned outcrop field map (not rectified) 29J,4-5, e-f | 1:20,000 | SGU database |
| G00285 | Scanned outcrop field map (not rectified) 29I, 4-5, g-h | 1:20,000 | SGU database |
| G00288 | Scanned outcrop field map (not rectified) 29I, 4-5, g-h | 1:20,000 | SGU database |
| G00626 | Scanned outcrop field map (not rectified) 29J NV | 1:20,000 | SGU database |
| Diaries_29J | 72 field notebooks from various SGU workers (1960-76) | Varies | SGU database |

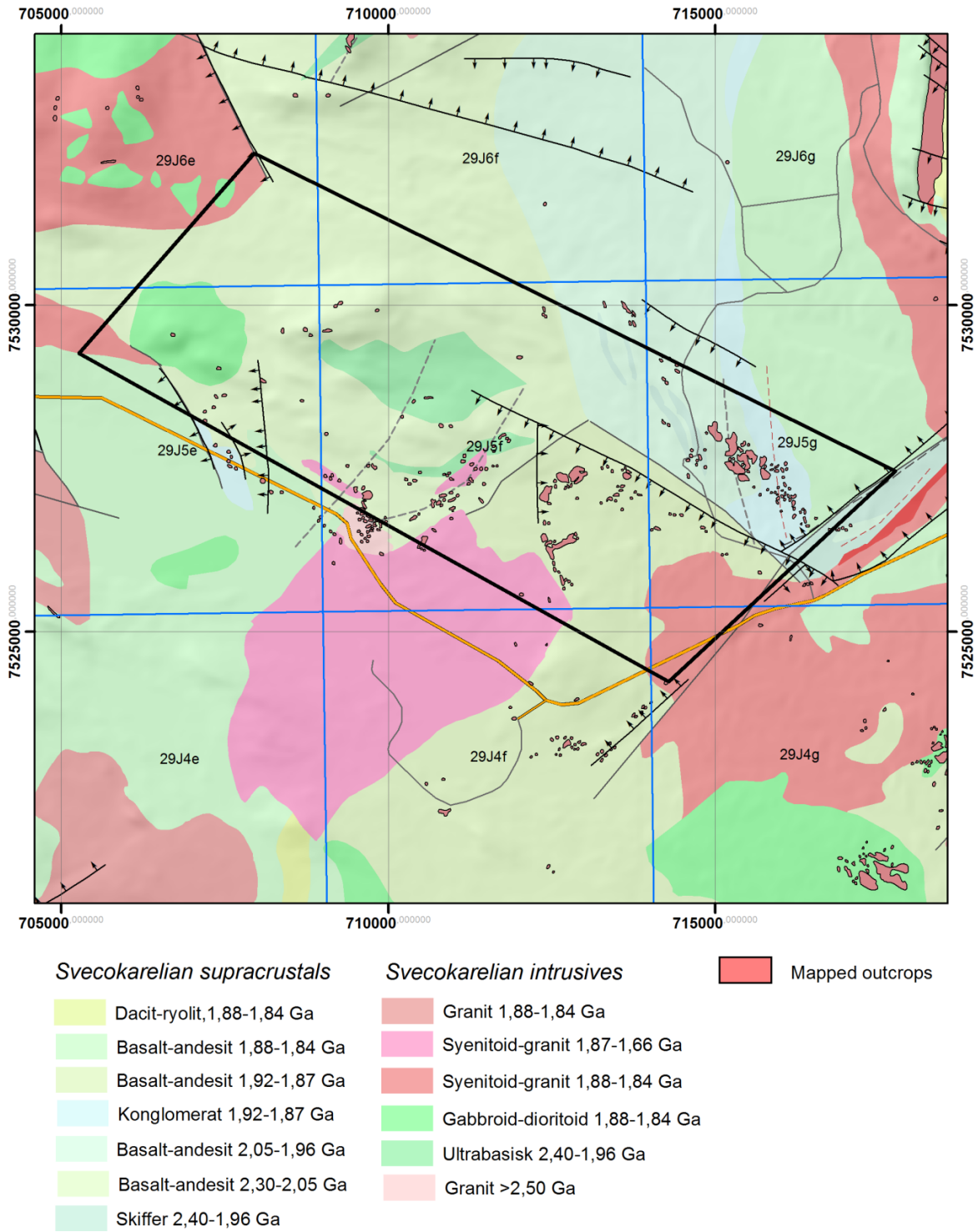


Fig. 2. Mapped outcrop locations and exposed areas in the SKA based on the various field maps listed in Table 3.

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

| Reference | Year | Title | Brief Overview |
|--|------|---|---|
| Smith et al, <i>Geochim. Cosmochim. Acta</i> , 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. Includes samples from the Pahtohavare deposit. |
| Hallberg et al., <i>GTK Special Publication 53</i> , p. 139–206 | 2012 | Metallogenic areas in Sweden | Review of mineral deposits and districts of Sweden. Area S035 (Kiruna) is the most relevant. |
| Bergman et al., <i>IAGS field excursion</i> , | 2011 | IOCG and Porphyry–Cu deposits in Northern Finland and Sweden: Geological and tectonic evolution of the northern part of the Fennoscandian Shield. | Review of regional-scale geology, tectonics and mineralization in northern Sweden. |
| Billström et al., in <i>Porter TM, Advances in Understanding of IOCG deposits</i> , v4 p. 381 | 2010 | IOCG and related mineral deposits of the northern Fennoscandian Shieldw | Review paper on the geological setting and metallogeny of IOCG deposits in northern Fennoscandia |
| Smith et al, <i>Hydrothermal Iron Oxide Copper–Gold and Related Deposits: A Global Perspective</i> , v. 4, pp. 427–440 | 2010 | THE GEOLOGY OF THE RAKKURIJÄRVI COPPER-PROSPECT, NORRBOTTEN COUNTY, SWEDEN | Deposit description and geochemistry (lithochemistry, apatite and biotite chemistry). Some geophysics. |
| Gleeson S & Smith M, | 2009 | The sources and evolution of mineralising fluids in iron oxide–copper–gold systems, Norrbotten, Sweden: Constraints from Br/Cl ratios and stable Cl isotopes of fluid inclusion leachates | Fluid inclusion study to characterise mineralizing fluids in Norrbotten. Includes Pahtohavare and Kirunavaara samples. ³⁷ Cl data also reported to identify Cl sources. |
| Smith et al, <i>J. of Petrology</i> , v. 50, p. 2063 | 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. | Titanite and allanite were analysed from an altered trachyandesite from the Rakkurijärvi Cu–Au prospect. U–Pb ages of 1854 and 1862 Ma presented for the timing of mineralization. |
| Bergman et al., <i>33rd IGC excursion guide no. 15</i> | 2008 | General Introduction to Geology and Metallogeny of Fennoscandian Shield | Review of the geology and metallogeny of N Sweden. Several deposits and their geological settings mentioned. |
| Smith et al., <i>Econ. Geol.</i> , v. 102, p. 393 | 2007 | The geology of the Rakkurijärvi Cu–(Au) prospect, Norrbotten: A new Iron-oxide–Copper–Gold deposit in northern Sweden | Deposit description and geochemistry (lithochemistry, apatite and biotite chemistry, ¹³ C values). Some geophysics. Re–Os ages also, ca. 1.86 Ga. |
| Storey et al., <i>Chem. Geol.</i> , v. | 2007 | In situ LA–ICP–MS U–Pb dating of metavolcanics of Norrbotten, Sweden: Records of extended geological histories in complex titanite grains | U–Pb dating of titanite by LA–ICPMS. Age of 1870 ± 24 Ma for titanite rims at Luossavaara Fe-oxide deposit. |
| Weihed et al., <i>Ore Geol. Rev.</i> , v. 27, p. 273 | 2005 | Precambrian geodynamics and ore formation: The Fennoscandian Shield | Review paper of tectonic setting and development of Fennoscandia and associated mineral deposits |
| Martinsson O, <i>SEG guidebook series vol. 33</i> , 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. Pahtohavare deposit and its geological setting mentioned. Svecofennian volcanics also discussed with geochemical classification (plutonic rocks also). |
| Weihed P, <i>SEG guidebook series vol. 33</i> , 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. |
| Sundblad, K, <i>Econ. Geol.</i> , v. 98, p. 1271–1290 | 2003 | Metallogeny of gold in the Precambrian of Northern Europe | Review paper of gold deposits including examples from northern Sweden |

Table 4. Continued.

| Reference | Year | Title | Brief Overview |
|---|-------|---|--|
| Williams et al, in Mineral exploration and sustainable development, p. 1127 | 2003 | The nature of iron oxide–copper–gold ore fluids. Fluid inclusion evidence from Norrbotten (Sweden) and the Cloncurry district (Australia). | Fluid inclusion study of IOCG samples from Norrbotten. |
| Ahl et al, SGU RM106, Uppsala, 86 p. | 2001 | Geochemical classification of plutonic rocks in central and northern Sweden | As the title suggests. Includes pluton samples from Norrbotten. |
| Bergman et al., SGU Ba 56, 110 pp. | 2001 | Description of regional geological and geophysical maps of northern Norrbotten County | Synthesis/review report on the bedrock geology and geophysics of Norrbotten based on 1:250,000 regional maps. Stratigraphy and mineral deposits summarised. |
| Bergman et al., SGU Ba 56–1, Uppsala | 2000 | Regional geological and geophysical maps of northern Norrbotten county: Bedrock map | Regional scale bedrock map at 1:250,000 |
| Broman C & Martinsson M, Luleå University of Tech, report | 2000 | Fluid inclusions in epigenetic Fe–Cu–Au ores in northern Norrbotten. | Overview of fluid for epigenetic Cu mineralization. Fluids aqueous NaCl–CaCl ₂ brines with high salinities. CO ₂ bearing fluids correlate with Au-rich systems. |
| Carlson CJ, in Porter TM, Aus. Min. Fed., p. 283–296 | 2000 | Iron oxide systems and base metal mineralisation in northern Sweden | Review of geology and mineralization in northern Sweden |
| Kumpulainen RA, SGU report, 94 p. | 2000 | The Palaeoproterozoic sedimentary record of northernmost Norrbotten, Sweden | Description of metasedimentary units in Norrbotten. Includes the Kurravaara conglomerate around Kiruna and in the SKA |
| Martinsson O and Wanhainen C, 2nd GEODE-Fennoscandian greenstone belt workshop and field-guide, p. 63 | 2000 | Excursion Guide, GEODE Workshop, August 28 to September 1, 2000. Metallogeny of the northern Norrbotten Fe–Cu–Au–ore province | Review of geology and metallogeny of Norrbotten. Conference field guide with deposit descriptions. |
| Martinsson O & Weihed P, | 1999 | Metallogeny of juvenile Palaeoproterozoic volcanic arcs and greenstone belts in rifted Archaean crust in the northern part of Sweden, Fennoscandian Shield. | Meeting abstract. Review of geology and tectonics. |
| Skiöld T & Page RW, NGV abstract vol, Århus, 273 | 1998 | SHRIMP and isotope dilution zircon ages on Archean basement-cover rocks in north Sweden | Several U–Pb age dates from Kiruna area rocks. 2682 Ma age for greenstone-hosted basalt at Saarijärvi. |
| 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. Includes scapolite and tourmaline mineral chemistry from Pahtohavare and Saarijärvi deposits |
| 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, 1:25,00000 | General review of iron ore deposits in Norrbotten. Includes summary of Rakkurijärvi deposit |
| Martinsson O, PhD thesis, Luleå | 1997 | Tectonic setting and metallogeny of the Kiruna greenstones | Detailed study (geochemistry, field relations, stratigraphy) relating to stratigraphy and mineralization of Kiruna greenstones |
| Martinsson et al., from Martinsson PhD, Luleå | 1997a | Pahtohavare – an epigenetic Cu–Au deposit in the Paleoproterozoic Kiruna greenstones | Detailed stratigraphy and geochemical study of the Pahtohavare Cu–Au deposit. Litho-geochemistry, mineral chemistry. 13C, 18O and 34S values also. |
| Martinsson et al., from Martinsson PhD, Luleå | 1997b | Viscaria – a syngenetic exhalative Cu–deposit in the Paleoproterozoic Kiruna Greenstones | Detailed study of the Viscaria Cu deposit and description of host metabasalts (Nth of SKA). Litho-geochemistry, mineral chemistry, fluid inclusions, 13C, 18O and 34S values also. |

Table 4. Continued.

| Reference | Year | Title | Brief Overview |
|---|------|---|---|
| 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. |
| Lindblom et al., Min. Dep., v. 31, p. 307–318 | 1996 | Magmatic-hydrothermal fluids in the Pahtohavare Cu–Au deposit in greenstone at Kiruna, Sweden | Detailed fluid inclusion study at the Pahtohavare Cu–Au deposit. |
| Romer et al., Min. Dep., v. 31, p. 134 | 1996 | Scapolite: a tracer for the initial isotopic composition in sulfide deposits with later additions of radiogenic lead. | Pb isotope study of scapolite from the Pahtohavare Cu deposit in Norrbotten. Tracer for ore fluid. |
| Talbot CJ and Koyi H., Precam. Res., v. | 1995 | Palaeoproterozoic intraplate 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 Pahtohavare, 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 (!). |
| Perdahl J.-A. and Martinsson O, in Perdahl, PhD thesis, Luleå | 1995 | Paleoproterozoic flood basalt magmatism in the Kiruna area, northern Sweden | Geological and geochemical constraints on the formation of the Kiruna porphyries. Bimodal basalt–rhyodacite sequence. Volcanism in a rift setting initiated by a mantle plume. |
| Martinsson O, PIM report # 2, Luleå, MINK 95118 | 1994 | Greenstone and porphyry hosted ore deposits in northern Norrbotten | Description of geology, stratigraphy and mineralization in northern Norrbotten. Focus on Cu mineralization inc. Pahtohavare |
| Martinsson O & Söderholm K | 1994 | The greenstone hosted Pahtohavare Cu–Au deposit at Kiruna, northern Sweden. | Meeting abstract giving an overview of the geological setting and description of the Pahtohavare deposit |
| 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 (1888 Ma). Also a titanite age for regional-scale titanite–actinolite–carbonate alteration (1876 Ma). A syenite at Saarijärvi intruding the volcanics has a U–Pb titanite + zircon age of 1792 ± 4 Ma. |
| Gustafsson B, NSG93003 report | 1993 | The Swedish Norrbotten greenstone belt | Stratigraphic variations in the greenstone belt |
| Martinsson O & Perdahl J.-A., in Martinsson et al., PIM report # 1, Luleå | 1993 | Preliminary classification of sulphide occurrences in northern Norrbotten | A brief description of various Cu sulphide deposits in Norrbotten with a general classification scheme proposed |
| Martinsson et al., PIM report # 1, Luleå | 1993 | Greenstone and porphyry hosted ore deposits in northern Norrbotten | Research report with stratigraphy, lithology, ore deposit descriptions including Saarijärvi area |
| 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. |

Table 4. Continued.

| Reference | Year | Title | Brief Overview |
|---|------|--|--|
| 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 |
| Gustafsson B, SGU PRAP 92016, Malå | 1992 | Saarijärvi diamantborrning 1992 | Account of diamond hole drilling at the Saarijärvi deposit. Several useful maps and assay data of drill core. |
| 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. Includes Swedish deposits. |
| Hallberg, A., SGU BRAP 92500, | 1992 | Paleoenvironmental conditions and hydrothermal alteration in Kiruna greenstone – a stable isotope study. | Carbon isotope study of Kiruna greenstones. |
| Martinsson O., SGU BRAP 92500, | 1992 | Exploration of greenstone hosted Cu-Au ores, conclusions from a study of the Viscaria and Pahtohavare deposits | Description of the geology of the Viscaria and Pahtohavare deposits |
| Martinsson O, NUTEK-PIM report, Luleå, 79 p. | 1992 | Greenstone hosted Cu-Au ores. The Viscaria and Pahtohavare sulfide deposits and the stratigraphy of the Kiruna greenstones | Report on the geological setting and characteristics of the Viscaria and Pahtohavare Cu sulfide deposits. |
| Carlson L, GFF, v. 113, p. 45–46 | 1991 | The Pahtohavare copper-gold prospect. | Abstract. Study of the Pahtohavare deposit. |
| Carlson L, SGU PRAP 91011, Uppsala | 1991 | Västra Pahtohajokk. Resultat av 1989-1990 års prospekteringsarbeten | Summary of exploration work at the Västra Pahtohajokk Cu prospect. Contains geological description, maps, drill hole and assay data. |
| 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. Brief mention of Pahtohavare. Discusses S isotope data on a regional scale east and west of the KADZ. |
| Martinsson O, GFF, v. 113, p. 58 | 1991 | Geological and geochemical evidence for the genesis of the Viscaria Cu-deposit, northern Sweden | Detailed study of the Viscaria Cu deposit NW of Kiruna. Hosted in KGG metabasalts. Proposal for the formation of Karelian basaltic volcanism. |
| Carlson L, SGU PRAP 90071, Uppsala | 1990 | Östra Pahtohajokkområdet. Resultat av 1989-90 års diamantborrning och förslag till prospektering | Summary of exploration work at the Östra Pahtohajokk and Pahtohavare Cu prospects. Drill hole data, assays and several maps. Geological descriptions also. |
| 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. | Age dating in and around the Kiruna deposit. A granophyric dyke cross-cutting the ore has U-Pb zircon age of 1880 ± 3 Ma. Sm-Nd isochron of host rocks gives 1890 ± 90 Ma. |
| Holmqvist, A., SGU PRAP 90020, Uppsala | 1990 | Talk i järnmalmnen Suolajokk | Short description of drill holes at the Suolajokk Fe-oxide deposit NW of Pahtohavare |
| Carlson and Lundqvist, SGU PRAP 89004, Uppsala | 1989 | Pahtohavare. Resultat av 1988 års djupmoränprovtagning | Results of deep moraine sampling and assaying. Several geochemical anomaly maps also presents. |
| Carlson L, SGU PRAP 89034, Uppsala | 1989 | Rakkurijärvi kopparfyndighet. En proterozoisk porphyry copper i Kirunaområdet. | Description of the Rakkurijärvi Cu prospect. Drill core logs and profiles and assay data. |
| Carlson L, SGU PRAP 89054, Uppsala | 1989 | Saarijärviområdets geologi och malmuppslag samt resultat av 1989 års prospektering. | Exploration activity at Saarijärvi area. Deep moraine sampling and geochemical anomaly plots presented. |
| Carlson L, SGU PRAP 89007, Uppsala | 1989 | Saarijärvi. Resultat av 1988 års diamantborrning | Diamond drilling program at Saarijärvi. Logs, assay data, profiles. |
| 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. |

Table 4. Continued.

| Reference | Year | Title | Brief Overview |
|--|------|---|--|
| Forsell, SGU C812, Uppsala | 1987 | The stratigraphy of the Precambrian rocks of the Kiruna district northern Sweden | Stratigraphy, relative age relations, depositional processes, tectonics of Kiruna area metavolcanics |
| 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 (1882 ± 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. |
| Carlson, SGU PRAP 86092, Uppsala | 1986 | Pahtohavare. Resultat av 1986 års diamantborring. Provtagningsprotokoll del 2 | Results of drilling at the Pahtohavare deposit |
| Skiöld, Precam. Res, v. 32, p. 35 | 1986 | On the age of the Kiruna Greenstones, northern Sweden | U-Pb zircon study of a doleritic sill intruding KGG metabasalts. Magmatic age of 2.2 Ga inferred. |
| Frietsch, SGU C802, Uppsala | 1984 | Petrochemistry of the iron-ore bearing metavolcanics in Norrbotten County northern Sweden | Petrology, geochemistry of metavolcanic rocks, tectonics |
| 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 1932 ± 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 1909 ± 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 litho-geochemistry of volcanic and plutonic rocks. Some discussion of deformation and structures based on geophysics data also. |
| Vollmer, GFF, v. 106, p. 109–118 | 1984 | Early deformation in the Svecofennian greenstone belt of the Kiruna district, northern Sweden | Field study on the deformation patterns in the Kiruna district |
| Martin J, MSc thesis, Westfälischen Technischen Hochschule, Aachen | 1980 | Mineralogisch-lagerstättenkundliche Untersuchungen an Bohrkernen aus der Eisenerz-lagerstätte Puoltsa bei Kiruna / Nordschweden | Study of the mineralogy and geology of the Puoltsa deposit |
| Frietsch, SGU C760, Uppsala | 1979 | Petrology of the Kurravaara area northeast of the Kiruna northern Sweden | Stratigraphy, petrology, Kurravaara conglomerate |
| Lilljequist R & Johansson L, SGU BRAP 79055, Uppsala | 1979 | Mineraliseringarna vid Rakkurijärvi | Description of drill holes, logs and assay data from the Rakkurijärvi Cu prospect. |
| 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 |
| Parak, SGU C709, Uppsala | 1975 | The origin of the Kiruna iron ores | Description of geology of Kiruna ores and (debated) hypothesis that the Kiruna-type deposits are SEDEX-related |
| Frietsch R, SGU C694, Uppsala | 1974 | The occurrence and composition of apatite with special reference to iron ores and rocks in northern Sweden | Comprehensive report on the chemistry of apatite from numerous prospects and deposits in northern Sweden. Includes the Rakkurijärvi prospect. |
| Damberg K & Nylund B, SGU BRAP 00789, Uppsala | 1973 | Suoljåkk järnmalmsfyndighet. Rapport rörande resultaten av SGU:s undersökningar 1964-1969 | Exploration report for the Suoljåkk Fe-oxide-Cu prospect. Contains several maps and assay data. |
| Hallgren et al., BRAP 796, Uppsala | 1973 | Puoltsa järnmalmsfyndighet. Rapport rörande resultaten av SGU:s undersökningar under åren 1961-1967 | Exploration report for the Puoltsa Fe-oxide-Cu prospect. Contains several maps, assay data, drill core logs etc. |

Table 4. Continued.

| Reference | Year | Title | Brief Overview |
|--|------|--|--|
| 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 showings in the SKA |
| Parak T, GFF, v. 93, p. 47 | 1971 | Bidrag till Kirunaområdets stratigrafi och tektonik. | Description of the geology and stratigraphy of the Kiruna area |
| 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 (1650 ± 90 Ma) is located close to the Tjärrojåkka key area. |
| Frietsch and Lindbergson, SGU BRAP 00886, Uppsala | 1970 | P. M. angående järnmalmsinventeringen i Norrbotten. Brev till departementsrådet Sven Swartling. | Overview of Fe-oxide and base metal mineralization in northern Sweden. Maps with mineralized localities shown and basic resource data, grades etc. |
| 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. |
| 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 |
| Sundius N, Uppsala, 237 p. | 1915 | Beitrage zur Geologie des slidlichen Teils des Kirunagebiets. Vetenskapliga och praktiska undersokningar i Lappland, arrangerade av Luossavaara-Kiirunavaara Aktiebolag. | Early detailed description of the geology of the Saarijärvi area. Thesis. |
| Geijer, Econ. Geol., v. 5, p. 699-718 | 1910 | Igneous rocks and iron ores of Kiirunavaara, Luossavaara and Tuolluvaara | Description of ore deposits in Kiruna district, field and thin section pictures. |
| Lundbohm, SGU report C 127, Uppsala | 1892 | Apatitförekomster I Norrbottens malmberg | One of the first regional geology assessments; description of ore deposits also |

Drill core

This section contains information on the drill core from the SKA that is available at SGU's Malå office. Table 5 lists the number of holes and historical drill core associated with the various mineral deposits and prospects within or adjacent to the SKA. In total, about 257 drill holes are available based on the most recent records, with the majority of holes relating to the Pahtohavare Cu–Au–graphite system. The majority of drill holes intersect various metavolcanic rocks (basalt, andesite, rhyolite) of the Kiruna Greenstone Group and Kiruna Porphyry Group. 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). Details on more recent drill core may be available from active exploration companies (e.g., in the Pahtohavare and Rakkurijärvi areas).

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

| Deposit/prospect | No. of holes available | Total length | Logs, assay data, reports |
|---|---|--------------|---|
| Pahtohavare (Cu-Au-Cg) Pahtohavare C-zon Pahtohavare Central Pahtohavare Eastern Pahtohavare Southeastern Pahtohavare Southern Pahtohavare västra 1 Pahtohavare västra 2 | 174 drill holes with core at Malå. Mostly drilled in the 1980's (NSG, Viscaria AB, Phelps Dodge). Mostly collard in KGG metabasalts and KPG metavolcanics | No data | 296 paper logs. PRAP 8508, 8604, 8609, 8801 and more |
| Ailatis 1 (Cu) | 19 drill holes from 1990 at Malå. Mostly collard in KGG metabasalts and KPG metavolcanics | No data | 1 pdf doc from SGAB showing logs. PRAP 91010, prap90023 |
| Pahtohajokk (Cu) | 5 drill holes with core in Malå. Drilled in 1991 (NSG). Collard in Porphyrite Group metaandesites | No data | No paper logs found. Possibly in Malå. |
| Puoltsa Fe-oxide | 15 drill holes with core in Malå. Drilled in the 1960's by SGU. Collard in KPG metaandesites | Ca. 2761 m | 47 paper logs and 1 overview file (pdfs). brap9,00009, SGU RM 92, MIS 2, brap796 |
| Rakkurijärvi (IOCG) Rakkurijärvi Fe Rakkurijärvi norra Rakkurijärvi västra | 17 drill holes with core in Malå. Drilled in 1960's–70's (SGU, NSG). Collard in KPG metavolcanics. | No data | 22 paper logs, 1 overview file and 1 about soil geochemistry. BRAP 79055. Smith et al 2010. |
| Saarijärvi (Cu-Au) Saarijärvi Gunilla Saarijärvi Stina Saarijärvi västra | 20 drill holes with core in Malå. 1986–1992 (NSG). Collard in KGG metabasalts and Porphyrite Group rocks. Some adjacent granite also. | No data | 2 pdfs in geodigitalia\Drillhole data\Saarijärvi relating to the drill core. PRAP 89007, PRAP 92016. PRAP 9002, PRAP 9201 |
| Suolajoki (Fe-oxide) | No drill holes for this area. 2 holes close by named 'Suolojaure' and 'Suolajäkk'. Could be same deposit. These 2 holes are in Malå | No data | 2 paper logs in geodigitalia\Drillhole data\Suolajokk folder. |
| Rakkurijoki (Fe-oxide) | 5 drill holes. 1986, 2001 (Equinox, Viscaria AB). Collard in KPG metavolcanics. | No data | Mink 99010, SGU C604 |

Mineralization and alteration

The SKA contains about 28 known mineral deposits, prospects or showings (Fig. 3). The majority of the mineralized localities are located in the central and eastern parts of the key area coincident with mapped metavolcanic sequences. Mineralised localities appear to correlate with the most exposed locations and may reflect more intensive exploration efforts in these areas. The NW and SE corners of the study area do not contain any known mineralization at present. Broadly speaking, the SKA is host to IOCG-type mineralization and forms part of the larger Kiruna metallogenic district. Iron-oxide (\pm apatite) occurs as breccia, BIF and skarn-related mineralization (e.g., Rakkurijoki, Kotnitjägge). Cu \pm Au mineralization (chalcopyrite, bornite) occurs as quartz vein-hosted and stratiform (Viscaria-type) disseminated, massive occurrences within host metavolcanics (Pahtohavare, Saarijärvi).

The location of the mineral deposits and prospects is shown in Fig. 3. Additional mineralization datasets are available on SGU's GIS database that relate to the Norrbotten mineral de-

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 | 29J6f, 29J5e/f/g | SGU database |
| Borrhål_20110405 | Historical drill core including Malå core and core no longer available at Malå | 29J6f, 29J5e/f/g | SGU database |
| Mineralresurser_mdep | Location and description of mineralisation prospects, showings and deposits | 29J6f, 29J5e/f/g | SGU database |
| FODD Barmin | 6 vector points of mineralised areas with basic descriptions taken from FODD database | 29J6f, 29J5e/g, 29J4g | SGU database |
| Metallogenetic areas | Vector polygons of metallogenetic areas. Study area is covered by Viscaria and Kiruna metallogenetic area | All SKA | SGU database |
| Undersökningstillstånd_beviljade | Granted prospecting licence blocks (polygons) in the study area. Various companies. | All SKA | SGU database |
| Mineralrättsregistret (MRR10) | Numerous polygons of mineral resource concession areas. Historical polygon areas also shown. | All SKA | SGU database |
| boulders_mineralized | Mineralised boulder locations and descriptions. 40 boulders or outcrop observations within or adjacent to study area | 29J5e/f/g, 29J4f | SGU database |
| alteration_SWEREF99 | Location and description of alteration mineral showings | | SGU database |
| Riksintressen mineral | 1 state interest mineral area clips the eastern side of the study area | 29J5f/g | SGU database |
| Mineral occurrence map | Malm och mineralförekomster i Norrbottens Län (all of Sweden) | All of the SKA | Frietsch & Järnefors 1962 |

posit inventory and these are listed in Table 6. These data include GIS layers relating to drill hole and drill core locations, prospecting licence blocks, alteration mineral locations and zones of metallogenetic importance.

Mineralized boulders are also found across the SKA and their locations are shown in Fig. 4. Most of the mapped boulders are located in the central and eastern part of the study area. A cluster of mineralized boulders also occurs just west of the N–S Kiruna railway line. There are no mapped boulders in the south and NW of the SKA. Boulder locations tend to correspond to the outcrop distribution and the correlation between mineralized boulder locations and known mineral prospects suggests that boulder mapping in the northwestern part of the SKA 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. 5). 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 whether there 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.

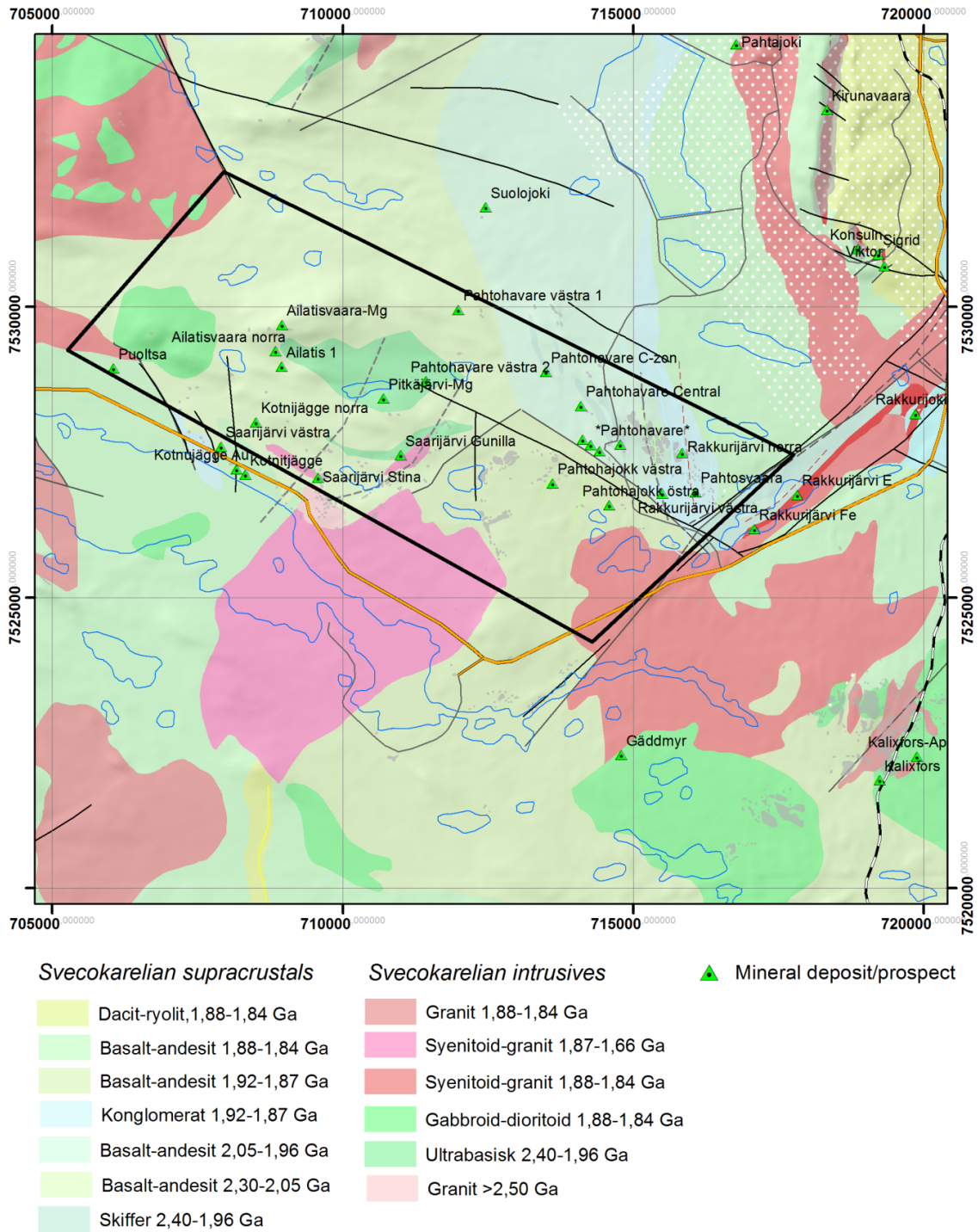


Fig. 3. The location of mineral deposits and prospects within the SKA. Background geology at regional scale.

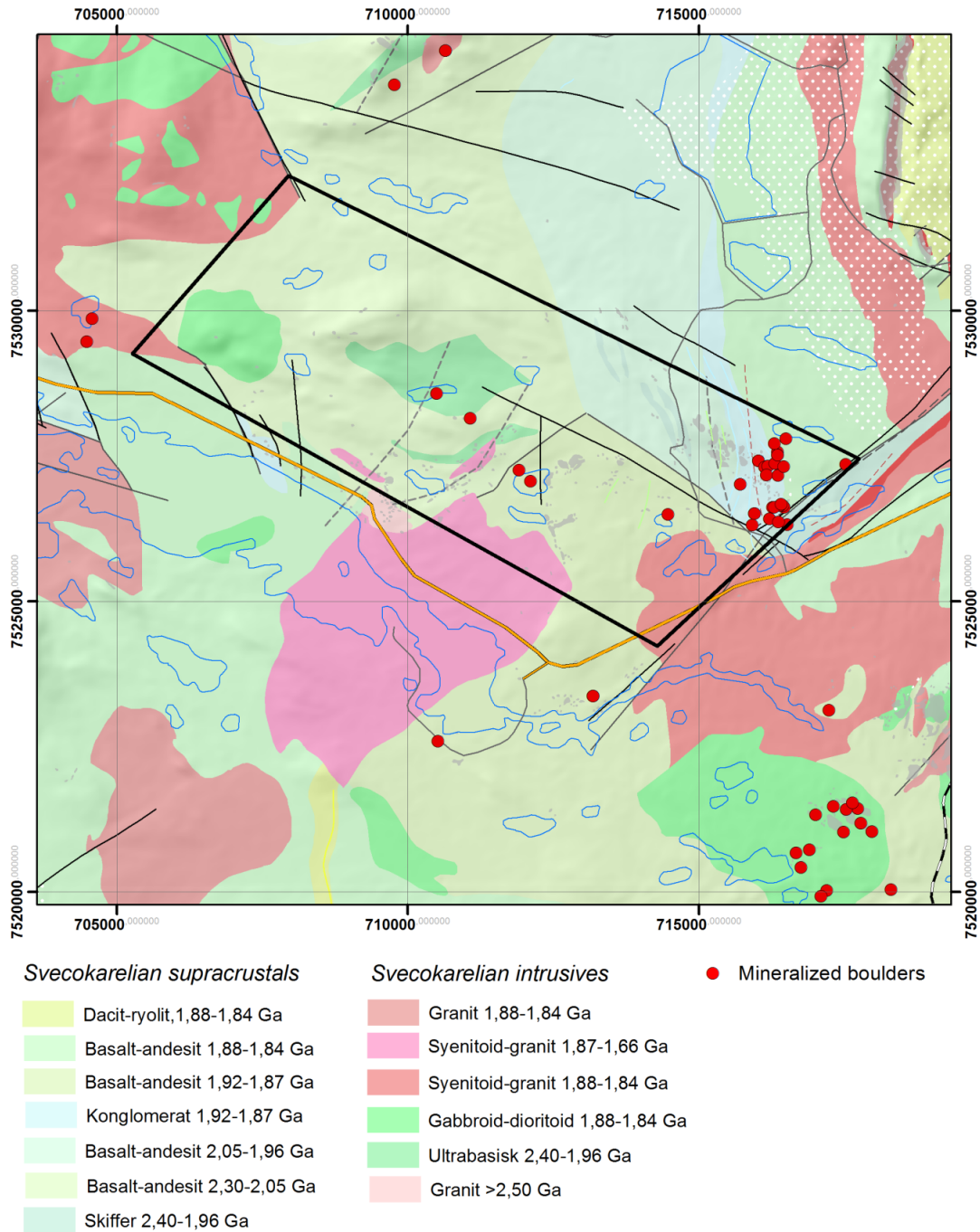


Fig. 4. Location of mineralized boulders in the SKA. The majority of boulders are described as containing sulfide mineralisation.

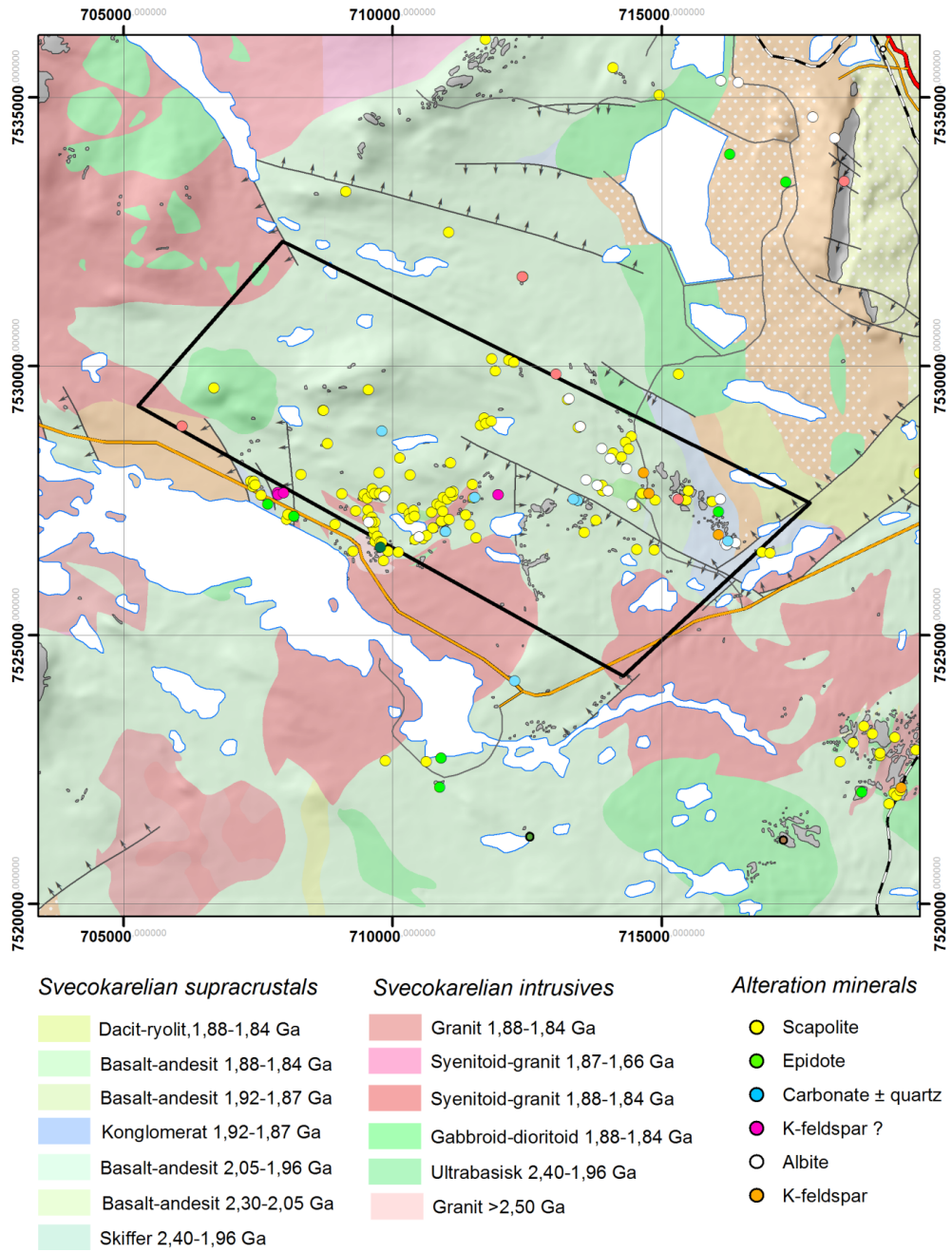


Fig. 5. Location of alteration minerals within the SKA and adjacent areas.

Geophysics

Airborne data (magnetics, EM, gamma spectrometry)

Several airborne geophysical surveys have been made over the SKA. A comprehensive list can be found in Table 7 and Fig. 6 illustrates the airborne magnetic data coverage. During 1960, SGU conducted airborne surveys over the entire map sheet 29J. Their geophysical instrumentation consisted of a fluxgate magnetometer. In 1973, LKAB made a new airborne survey over the SKA when they covered map sheet 29J NE. Their geophysical equipment consisted of a gamma spectrometer and a VLF-receiver which was capable of acquiring data from one transmitter. The next airborne survey over the SKA was made in 1975 by SGU in collaboration with LKAB. The aircraft was equipped with a trums magnetometer, gamma spectrometer and a VLF-receiver, capable of acquiring electromagnetic data from one transmitter. In 1979, LKAB made an airborne survey over the western part of map sheet 29J. Four years later, LKAB made airborne surveys which covered the majority of the map sheet 29J. Among their geophysical equipment was a VLF-receiver capable of acquiring electromagnetic data from two independent transmitters, thus making it possible to map conductive features in the ground independent of their strike direction with respect to the VLF-transmitter. In 1985, LKAB made an airborne survey over a small part of the map sheet 29J with a flight line separation of only 100 m. The most recent airborne survey over SKA was made in 1986 by SGU. These measurements were made during the Pahtohavare project work. They conducted the survey along flight lines with NNE–SSW direction and only 100 m apart.

Table 7. A complete list over the airborne geophysical surveys that have been made over the Saarijärvi key area.

| Year | Company | Geophysical methods used | Area | Flight direction | Flight line separation (m) | Flight altitude (m) |
|------|----------|---|---|------------------|----------------------------|---------------------|
| 1960 | SGU | Magnetics | Entire 29J | East-west | 200 | 30 |
| 1973 | LKAB | Gamma spectrometry, VLF (1-transmitter) | 29J NE | East-west | 200 | 30 |
| 1975 | SGU/LKAB | Magnetics, gamma spectrometry, VLF (1-transmitter) | 29J SE | East-west | 200 | 30 |
| 1979 | LKAB | Magnetics, gamma spectrometry, VLF (1-transmitter) | 29J NW & 29J SW (project R60) | East-west | 200 | 30 |
| 1983 | LKAB | Magnetics, gamma spectrometry, VLF (2-transmitters), slingram | Part of 29J SW & entire 29J SE (projekt R24) | East-west | 200 | 30 |
| 1983 | LKAB | Magnetics, gamma spectrometry, VLF (2-transmitters), slingram | Part of 29J NW & entire 29J NE (projekt R27) | East-west | 200 | 30 |
| 1985 | LKAB | Magnetics, gamma spectrometry, VLF (2-transmitters), slingram | Part of 29J NW & part of 29J NE (project R28) | East-west | 100 | 30 |
| 1986 | SGU | Magnetics, gamma spectrometry, VLF (2-transmitters), slingram | Part of 29J NW, part of 29J NE & part of 29J SE (project Pahtohavare) | NNE-SSW | 100 | 30 |

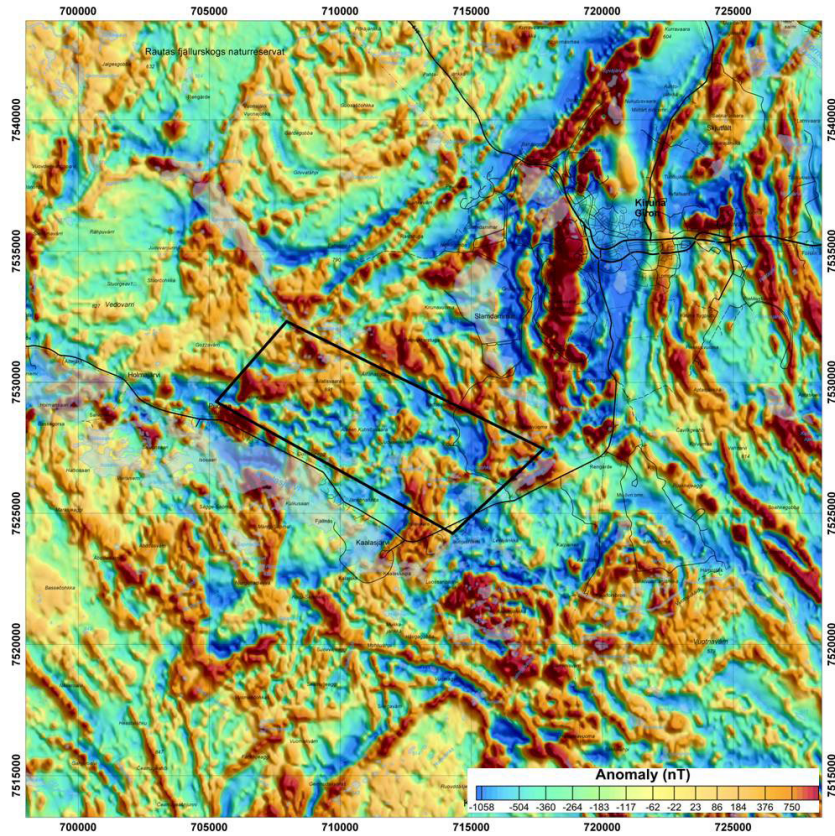


Fig. 6. The magnetic anomaly map within the SKA (shown as a black polygon in the middle of the map) and its surroundings. The map is derived from the newest airborne magnetic data and has been filtered in order to enhance the magnetic response from more shallow seated lithologies. The Kiruna iron ore is a prominent feature on this map.

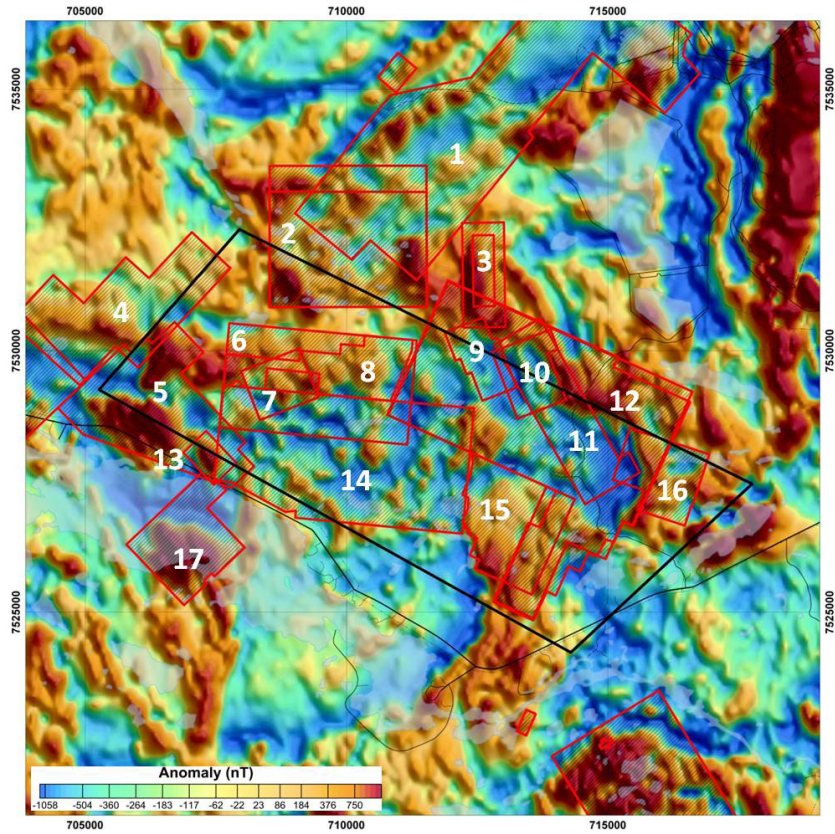


Fig. 7. The magnetic anomaly map within the SKA and its closest surroundings. The red polygons represent previously made ground magnetic surveys.

Table 8. A list of the magnetic ground surveys within the SKA and its surroundings. The numbers in column “Polygon nr” refer to those found in Fig. 7.

| Polygon nr | Name | Method | Operator | Year of measurement |
|------------|--------------|------------------------|--------------------|---------------------|
| 1 | Viscaria | Magnetometer | SEKRETESS OUOKUMPU | No information |
| 2 | Suolojaure | Magnetometer T-anomaly | SGAB | 1989 |
| 3 | Suoljåkk | Magnetometer Z-anomaly | SGU | 1965-1968 |
| 4 | Isojärvi | Magnetometer | No information | -1989 |
| 5 | Puoltsa | Magnetometer Z-anomaly | SGU | 1961 |
| 6 | Ailatisvaara | Magnetometer | No information | 1990 |
| 7 | Väst-Pahto | Magnetometer | SGAB | 1991 |
| 8 | Ajlatisvaara | Magnetometer | No information | 1990 |
| 9 | Väst-Pahto | Magnetometer | SGAB | 1988 |
| 10 | Väst-Pahto | Magnetometer | No information | 1988 |
| 11 | Pahtohavaara | Magnetometer | No information | 1977 |
| 12 | Pahtohavaara | Magnetometer | SGAB | 1984-1988 |
| 13 | Puoltsa | Magnetometer Z-anomaly | SGU | 1961 |
| 14 | Saarijärvi | Magnetometer | No information | 1986 |
| 15 | Pahtohajokk | Magnetometer | No information | 1990 |
| 16 | Rakkurijärvi | Magnetometer T-anomaly | SGU | 1972 |
| 17 | Kaalasjärvi | Magnetometer Z-anomaly | SGU | 1967 |

Recent airborne geophysical surveys over the SKA have acquired VLF information using two transmitters. VLF data can then be used to produce maps which show how electrical conductivity varies in the ground independent of how the conductor strikes with respect to the VLF-transmitter (Fig. 9). The red areas in background in Fig. 9 represent features with higher electrical conductivity compared to those shown in blue.

Ground-based magnetics

There have been extensive, detailed, ground based magnetometer surveys within the SKA (Fig. 7). Almost the entire area is covered by these measurements and a comprehensive list can be found in Table 8.

Ground-based gravity

The regional gravity measurements at the SKA have been made with station spacing of approximately 1 km. However, there are a couple of areas within the SKA and its closest surroundings where denser gravity measurements have also been made (Fig. 8). Two are in the western part, at the Puoltsa Fe–oxide deposit (7529000/706000) and at the Kotnijägge Cu–Au deposit (7528000/708500). The gravity measurements at Puoltsa were acquired in the early 1960s while those at Kotnijägge were made in 1989. Other areas can be found in the eastern part of SKA, at the Pahtohavare Cu–Au deposit (7528300/714000), extensive gravity measurements made by SGU at the request of LKAB. The latter measurements stretch from Kiruna down to Saarijärvi. The gravity measurements at Pahtohavare were made in 1988 while those made for LKAB probably were acquired in the early 1960s.

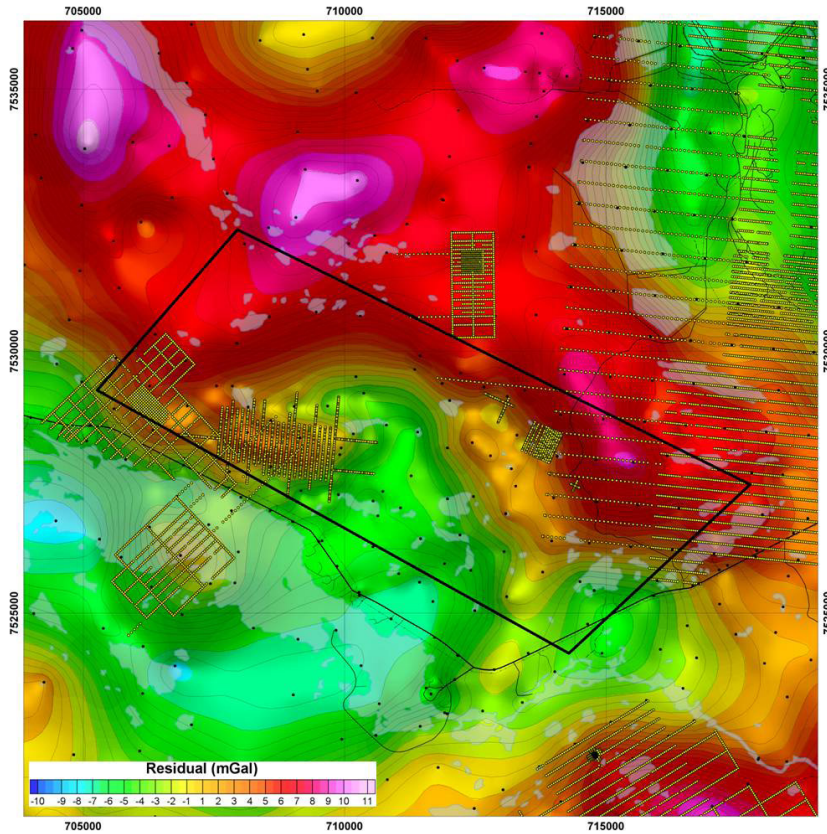


Fig. 8. The residual gravity field within the Saarijärvi key area and its closest surroundings. The gravity data has been filtered to enhance the density variations of shallower lithologies. Black dots represent regional gravity measurements while yellow dots show the location where more detailed investigations have been made. The gravity data from the measurements made by SGU at the request of LKAB have not been used to produce this gravity map.

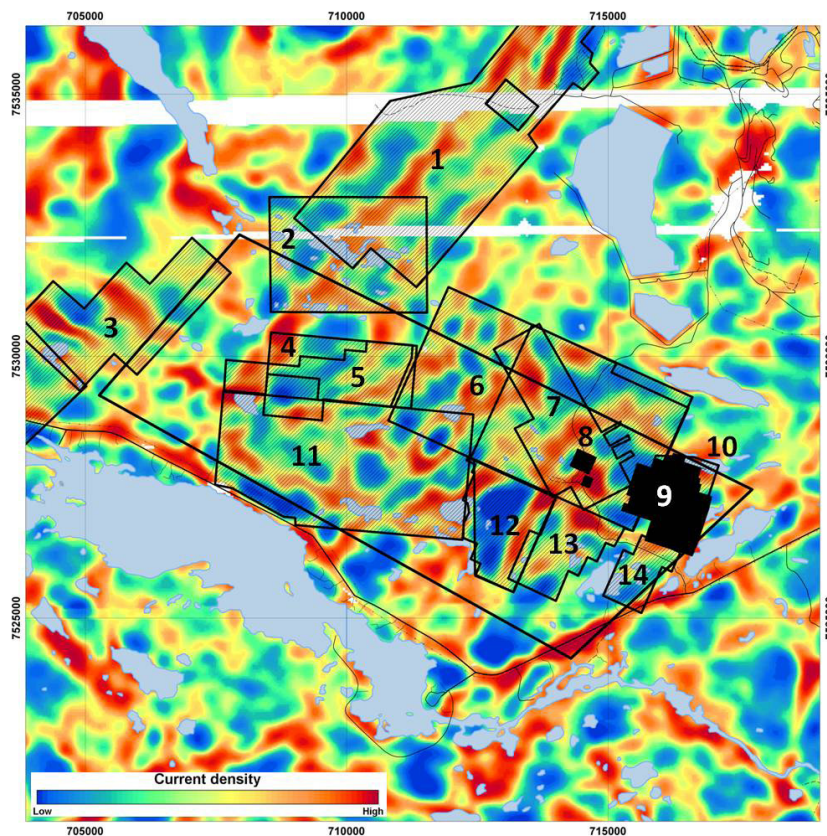


Fig. 9. Map over the current density within the Saarijärvi key area (SKA) and its closest surroundings. The map is based on VLF-data from two transmitters. The black polygons with hatches represent locations where ground slingram surveys have been made. The black polygons in the eastern part of SKA represent areas where IP or SP measurements have been made.

Table 9. A list over the magnetic ground surveys within the SKA and its closest surrounding. The numbers in column "Polygon nr" refer to those found in Fig. 9.

| Polygon nr | Name | Method | Operator | Year of measurement |
|------------|--------------|------------------|-----------------------|---------------------|
| 1 | Viscaria | Slingram | OUTOKUMPU, CLASSIFIED | -1973 |
| 2 | Suolojaure | Slingram | No information | 1989 |
| 3 | Isojärvi | Slingram | No information | 1990 |
| 4 | Ailatisvaara | Slingram | SGAB | 1990 |
| 5 | Ajlatisvaara | Slingram | No information | 1990 |
| 6 | Pahtohavare | Slingram | SGAB | 1984-1990 |
| 7 | Pahtohavaara | Slingram | LKAB | 1974 |
| 8 | Pahtohavare | Slingram | SGAB | 1987 |
| 8 | Pahtohavare | Mise à la masse | SGAB | 1988 |
| 9 | Rakkurijärvi | Mise à la masse | SGU | 1970 |
| 9 | Rakkurijärvi | IP, SP, R, Kond. | SGU | 1968-71 |
| 10 | Rakkurijärvi | Slingram | SGU | 1979 |
| 11 | Saarijärvi | Slingram | No information | -1986 |
| 12 | Pahtohajokk | Slingram | No information | 1990 |
| 13 | Pahtohavare | Slingram | No information | -1988 |
| 14 | Västpähto | Slingram | SGU | 1985 |

There have also been made dense gravity measurements adjacent to the SKA. One of these areas can be found southwest of the polygon which defines the SKA. Those measurements were acquired in 1969 and are located both on land and on the lake Kaalasjärvi. Another area is located just north of the SKA, at Suolojäkk, while the final one can be found further to the southeast, at Gäddmyr. The majority of the gravity measurements at Suolojäkk and Gäddmyr were acquired in 1968.

Ground-based electromagnetics (EM)

There are several areas within the SKA where detailed geoelectric or electromagnetic measurements have been made. A comprehensive list of these surveys can be found in Table 9.

Petrophysics

There are currently 53 petrophysical samples registered in SGUs database from the SKA. These samples have data regarding density, magnetic susceptibility and Königsberger ratio values. The geographical distribution of these samples can be seen in Fig. 10 along with the outcrops and topographic variations. A few of the petrophysical samples are oriented, thus making it possible to determine remanent magnetization directions with respect to the Earth's magnetic field.

Geochemistry

Table 10 lists the main geochemical data available for the SKA including bedrock and till analyses. 12 lithochemical analyses have been made of the various rock units across the area (Fig. 11). Most of the analyses were conducted on metavolcanic units and are presented in Offerberg (1967). Analyses primarily consist of major elements with a selection of trace elements (excluding the REEs). There have been few analyses of the granitoid to syenitoid plutons. Additional lithochemistry data for the area has been conducted by several works,

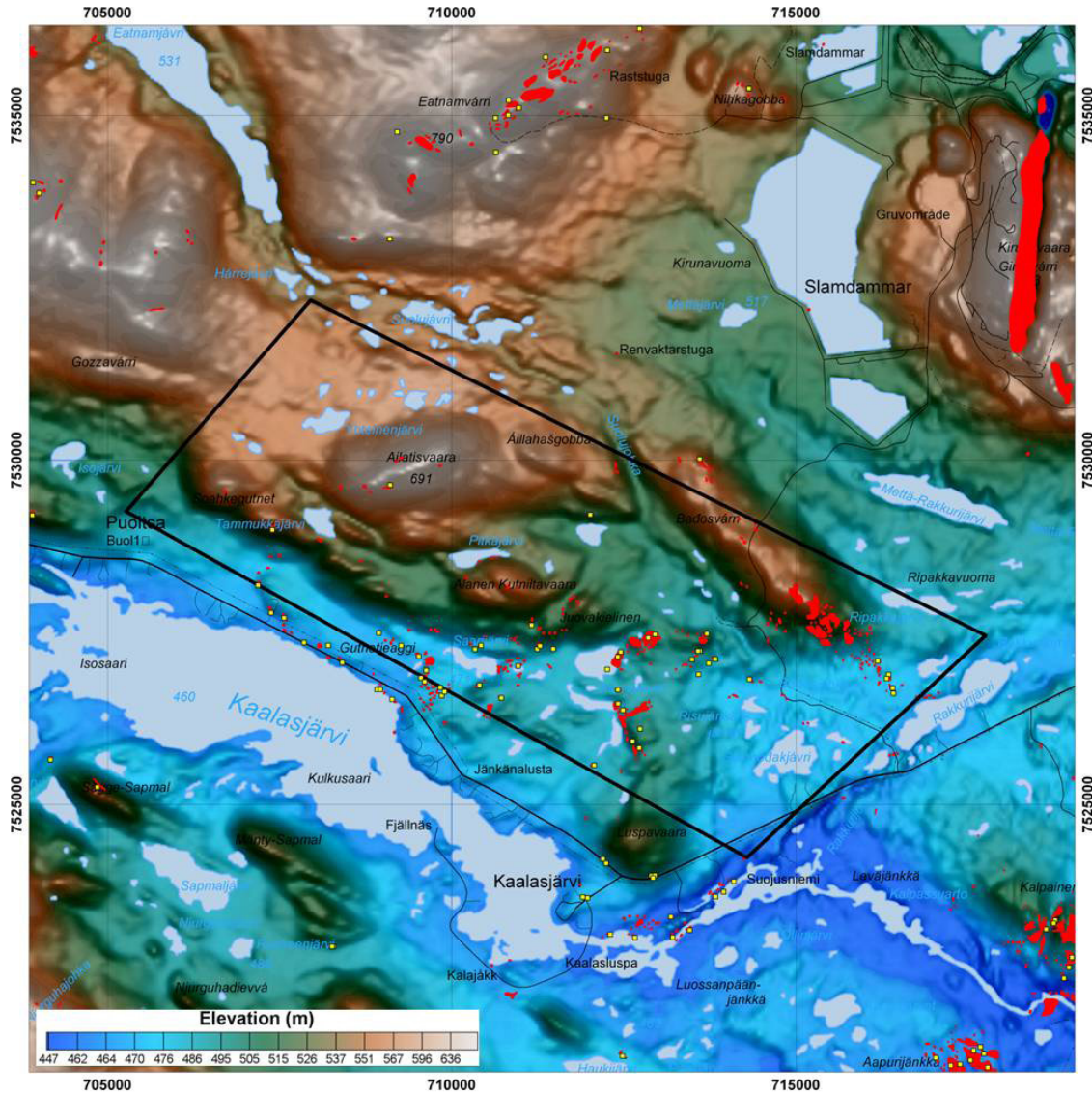


Fig. 10. The topography within the Saarijärvi key area and its closest surroundings. The variations in topography are based on 50x50 m DEM. There is new LiDAR data available but it does not cover the entire Saarijärvi key area. The red polygons represent outcrops and yellow dots represent existing petrophysical bedrock samples.

the majority of which are not represented in the SGU database. For example, Smith et al. (2007) presented lithogeochemistry of altered units from the Rakkurijärvi Cu–Au prospect, Bergman et al. (2001) presented regional-scale lithogeochemical classifications of the various rock units that partly comprise the SKA, Ahl et al. (2001) reported lithogeochemistry of granitoids which included a few samples adjacent to the SKA, Martinsson (1997) analysed 260 rock samples for major and trace elements to characterise the tectonic setting of the metavolcanic rocks in the Kiruna area. A further 80 samples from the Pahtohavare deposit were also analysed. Perdahl and Frietsch (1993) performed 164 lithogeochemical analyses of Porphyry Group metavolcanics from the Kiruna area (exact sample locations are difficult to ascertain). Numerous exploration reports from the 1970’s, 80’s and 90’s also contain assay data of drill core, boulders and till (e.g., Damberg and Nylund 1973, Lilljeqvist and Johansson 1979, Carlson 1986, Carlson 1989a, 1989b, 1989c, Carlson 1991a, 1991b). Several fluid

Table 10. Geochemistry datasets covering the rocks and overburden across the SKA

| Layer/dataset | Description | Grid location | Reference |
|---|---|---------------------------------|---|
| Lithochem | 12 sample locations with lithochem. REEs not always analysed. | 29J5e/f/g, 29J4f | Offerberg 1967; Perdhal & Frietsch 1993, Martinsson (unpublished) |
| LIKE_supracrustals | Points data of rock geochem- partial analysis of some metals. 8 point locations of analysed volcanic rocks for lithochem. Points overlap with lithochem data points | 29J5e/f/g | SGU database |
| LIKE_next_BARMIN | Points data of rock geochem- partial analysis of some metals. 10 point locations of analysed volcanic rocks for lithochem. Points overlap with lithochem data points. | 29J5e/f/g | SGU database |
| NK_mroes_Cu | Points data of rock geochem- Cu assay data. 4 points in or adjacent to the study area. | 29J6f, 29J5f/g | SGU database |
| kalktest | Point data of lime test locations on moraine fine fraction. 14 points located in study area or just adjacent. Corresponds to soil geochem analysis points also. | 29J6e, 29J5e/f/g, 29J4f/g | SGU database |
| markgeokemi_fysiska prov | Point data of soil geochem locations. 55 points located in study area or just adjacent. | 29J6e, 29J5e/f/g, 29J4f/g | SGU database |
| Morän < 2 mm | Point data for pH of till analysi (coarser fraction). 2 in study area | 29J5e/g | SGU database |
| Morän finfraktion | Point data for pH of till analysis (fine fraction). 15 in or close to study area | 29J6e/g, 29J5e/f/g, 29J4e/f/g | SGU database |
| Markgeokemi raster 250m | Raster dataset of shaded till geochem. | All of SKA | SGU database |
| Till geochem_NK_oes | Till geochem Nordkalott project by OES. 4 points close to or within study area | 29J6f, 29J5f/g | SGU database |
| moränkemi_NSJ | 5 data points within or adjacent to the key area with assay values | 29J5f/g, 29J4f | SGU database |
| moränkemi_xrf | 18 Points data of moraine geochem by XRF. Moraine fine fractions. | 29J6e/f/g, 29J5e/f/g, 29J4e/f/g | SGU database |
| till_SGU_xrf | moraine fine fraction XRF geochem data points. Majors and traces. 16 points within or beside the study area | 29J6e/g, 29J5e/f/g, 29J4e/f/g | SGU database |
| till_NSJ | till trace element data. Vector points. 4 points within or close to study area | 29J5f/g | SGU database |
| heavy mineral geokemi djumbo | 32 point locations for heavy mineral analysis within or adjacent to study area. | 29J5e/f/g, 29J4e/g | SGU database |
| heavy mineral geokemi xrf | 32 point locations for heavy mineral analysis within or adjacent to study area. | 29J5e/f/g, 29J4e/g | SGU database |
| Kartor över grundvattenmagasin | polygons of mapped aquifers. 2 cross or adjacent to the study area corresponding to main river | 29J6e/f, 29J4f/g | SGU database |
| Rikstäckande hydrogeologisk information | Nationwide hydrographical information | all of the study area | SGU database |
| Brunnar | water wells. 9 located south of the study area | 29J5f, 29J4f | SGU database |
| C_O isotopes data | 48 data points in the study area | 29J5e/f/g | SGU database |

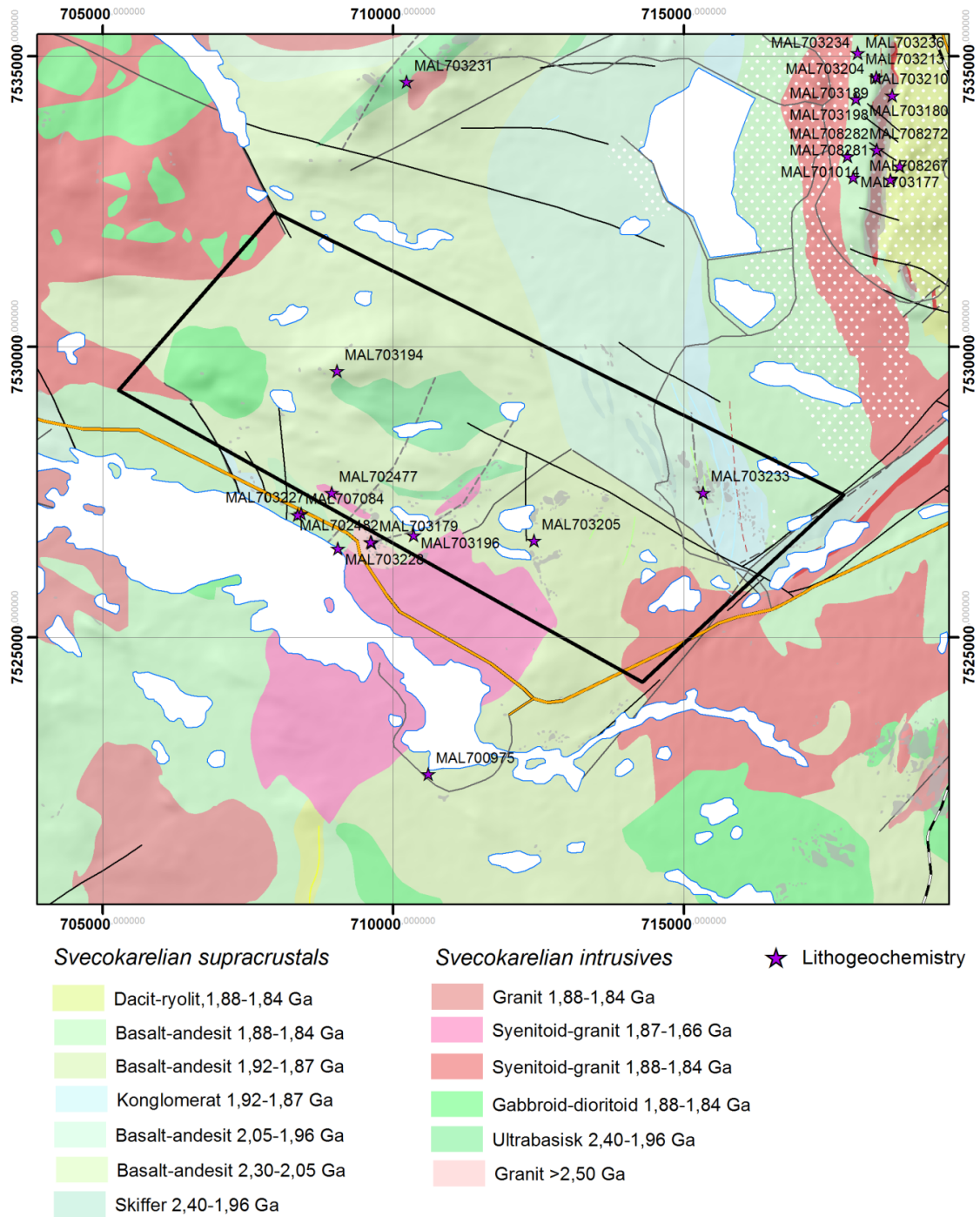


Fig. 11. Lithochemistry sample locations within the SKA with the majority of sampling conducted in the southern part. Sample ID numbers also shown.

inclusion investigations have also been conducted to constrain the nature of fluids linked to Fe-oxide and base metal mineralization in the general area (e.g., Lindblom et al. 1996, Williams et al. 2003, Gleeson and Smith 2009, Smith et al. 2013). The chemistry of allanite, titanite, apatite and biotite samples from the Rakkurijärvi Cu prospect has also been quantified (Smith et al. 2007, Smith et al. 2009).

Geochronology

12 age determinations have been made for the various rock units and minerals within or adjacent to the SKA (Table 11, Fig. 12). The ages listed in Table 11 include age dating at the Kirunavaara deposit to the NE. Most of the ages constrain the timing of Fe-oxide-apatite (IOA) and Cu–Au mineralization (and/or related alteration) and do not represent extrusion ages for the host metavolcanics. The timing of IOA mineralization at Kiruna is estimated to be ca. 1,880 Ga (Romer et al. 1994, Cliff et al. 1990). In the eastern SKA, epigenetic Cu–Au mineralization at Rakkurijärvi is dated at ca. 1,860 Ga (Smith et al. 2007, 2010). The significance of this metallogenic age bracket (1.88–1.86 Ga) with respect to other IOCG-type prospects elsewhere in the SKA is not yet known.

There have been few host rock age determinations within or adjacent to the SKA. Likewise, there has been little geochronology of plutonic rocks in the area. Skiöld and Page (1998) reported a U–Pb zircon age of ca. 2682 Ma for metabasalts of the Kiruna Greenstone Group at Saarijärvi. This Neoproterozoic age, if confirmed, has major implications for the geological and stratigraphical reconstructions in the area (cf. Martinsson et al. 1993). A similar age of ca. 2.687 Ma was also reported for a tuff unit at Viscaria further to the north (Skiöld and Page 1998). To the NE, basaltic greenstones were dated to $1,932 \pm 45$ Ma using the Sm–Nd isotopic system (Skiöld and Cliff 1984). Skiöld (1986) reported that the Kiruna greenstones located NE of Kiruna likely formed at ca. 2.2 Ga, based on the calculated age of a co-magmatic doleritic sill. Cliff et al. (1990) reported an imprecise, mixed sample, Sm–Nd isochron of $1,890 \pm 90$ Ma for Porphyry Group metavolcanic and granitoid rocks in the Kirunavaara deposit which included a granitic dyke (syn-mineralisation?). Welin (1987) reported a zircon age of ca. 1,882 Ma for Porphyry Group metarhyolites in the Kiruna area however the specific sample location was not given. The ages for most of the neighbouring plutons, as well as the alteration and mineralization at other localities across the SKA, are not constrained at present.

Isotope geology (excluding age dating)

There have been few dedicated isotopic studies of the rocks and mineralised localities within the SKA. Existing isotope data has been mostly focused on identifying the nature and source of mineralising fluids and alteration processes at the Pahtohavare and Rakkurijärvi deposits. The isotopic data were combined with other geochemical datasets to constrain the genesis of the mineralisation (e.g., fluid inclusion microthermometry, litho-geochemistry). Gleeson and Smith (2009) determined $\delta^{37}\text{Cl}$ values for inclusion fluids linked to IOA and Cu–Au mineralization in and around the SKA (including Pahtohavare). The majority of the stable Cl isotope values indicate a predominantly magmatic (mantle) source for Cl related to IOA and Cu–Au mineralisation, however a component of crustal Cl (metasedimentary or granitic) may also have had a role. At the Rakkurijärvi Cu–Au prospect (eastern SKA), Smith et al. (2007) conducted stable oxygen and carbon isotope analysis of carbonates associated with the alteration and mineralization. $\delta^{18}\text{O}$ values range from 9.4 to 19.9‰, while

Table 11. Geochronology of rocks and minerals from the SKA.

| Age (Ma) | ± | System | Material | Host rock | Litho. Unit | Area | Ref | Year |
|----------|----|-----------------------|--|---------------------------------|--|-------------------------|----------------|------|
| 1854 | 18 | U-Pb (LA-ICP-MS) | Titanite & allanite | Altered meta-trachyandesite | Porphyry Group | Rakkurijärvi prospect | Smith et al. | 2009 |
| 1862 | 16 | U-Pb (LA-ICP-MS) | Titanite and allanite | Altered meta-trachyandesite | Porphyry Group | Rakkurijärvi prospect | Smith et al. | 2009 |
| 1853 | 6 | Re-Os (N-TIMS) | molybdenite | Altered metavolcanic breccia | Porphyry Group | Rakkurijärvi prospect | Smith et al. | 2007 |
| 1862 | 6 | Re-Os (N-TIMS) | molybdenite | Altered metavolcanic breccia | Porphyry Group | Rakkurijärvi prospect | Smith et al. | 2007 |
| 2682 | ? | U-Pb (SHRIMP or TIMS) | Zircon | Metabasalt | Kiruna Greenstones | Saarijärvi | Skiöld & Page | 1998 |
| 1792 | 4 | U-Pb (TIMS) | Titanite & zircon | Syenite | Late Svecokar. syenitoid-granitoid assoc | Saarijärvi | Romer et al. | 1994 |
| 1876 | 9 | U-Pb (TIMS) | Titanite | Altered basalt | Porphyry Group | Kirunavaara deposit | Romer et al. | 1994 |
| 1880 | 3 | U-Pb (TIMS) | Zircon | Granophyric dyke | Porphyry Group | Kirunavaara deposit | Cliff et al. | 1990 |
| 1890 | 90 | Sm-Nd (TIMS) | Whole-rock | Acid metavolcanics & granitoids | Porphyry Group | Kirunavaara deposit | Cliff et al. | 1990 |
| 1882 | 24 | U-Pb (TIMS) | Zircon | Porphyritic meta-rhyolite | Porphyry Group | Kiruna area (no coords) | Welin | 1987 |
| 1932 | 45 | Sm-Nd (TIMS) | Amph, titanite, plag., basalt whole-rock | Metabasalt | Kiruna Greenstones | Viscaria area | Skiöld & Cliff | 1984 |
| 1605 | 65 | Rb-Sr (TIMS) | Whole-rock | Acid metavolcanics | Porphyry Group | Kirunavaara deposit | Welin et al. | 1971 |

$\delta^{13}\text{C}$ values range from -11.7 to 4.9‰ . These data suggest a magmatic fluid source that likely equilibrated with the metavolcanics country rocks. Martinsson et al. (1997a) conducted stable isotope analysis (O, C, S) at the Pahtohavare Cu deposit. $\delta^{13}\text{C}$ values ranged from -4.0 to 2.3‰ suggesting carbon from stratigraphically lower sedimentary horizons contributed to the mineralising system. The $\delta^{18}\text{O}$ values ranged from 9.2 to 12.0‰ , while three $\delta^{34}\text{S}$ measurements were between -2.9 to -0.2‰ . These data imply magmatism (plutonism?) was a significant factor in the mineralisation (cf. Viscaria-type base metal mineralisation, Martinsson et al. 1997b). Several marble horizons within the Kiruna Greenstones at Viscaria (north of the SKA) were analysed for their $\delta^{13}\text{C}$ values (Martinsson et al. 1997b). These data delineate a stable carbon isotope excursion toward the top of the basalt stratigraphy coincident with a recognised global shift in $\delta^{13}\text{C}$ values seen in 2.3 to 2.05 Ga carbonates. This shift toward isotopically heavier values was, in turn, been used to subdivide the Kiruna Greenstones into older (Jatulian) and younger (Ludikovian) sequences (Martinsson et al. 1997b). This subdivision is illustrated as a ca. N–S contact on the regional geological map of Bergman et al. (2000). Romer et al. (1996) performed Pb isotope analysis of alteration-related scapolite from the Pahtohavare Cu deposit to constrain the nature of the mineralising fluid. Hallberg (1992) conducted a stable isotope investigation of marble horizons in Kiruna greenstones to constrain depositional and alteration conditions.

Geographical data

Table 12 lists several topographic datasets that cover the SKA. The most useful information can be derived from the orthophotos, along with LiDAR-acquired DEMs produced at

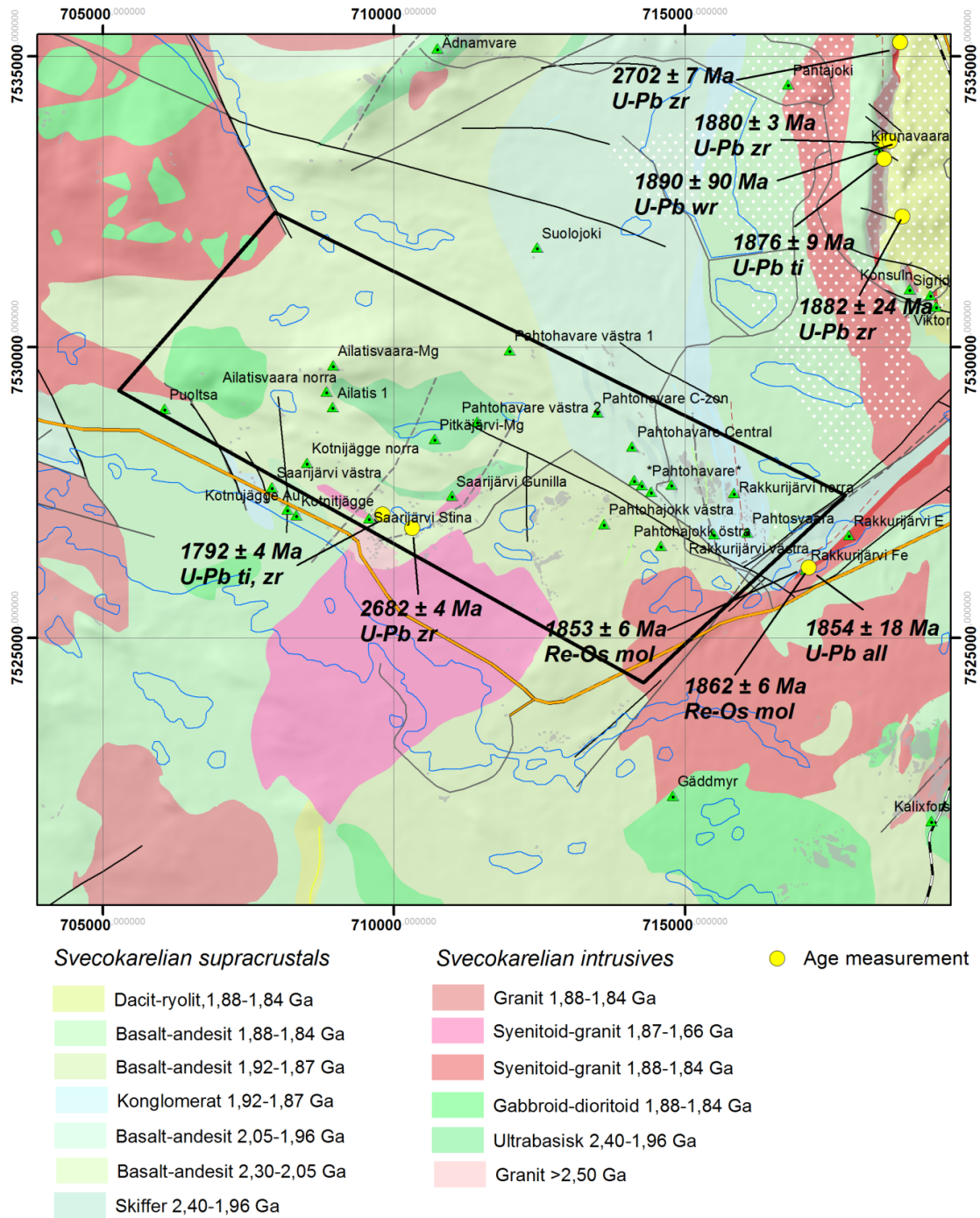


Fig. 12. Geochronology of rocks and minerals within the SKA and adjacent areas. all = allinite, mol = molybdenite, ti = titanite, wr = whole rock, zr = zircon.

Table 12. Topographic datasets covering the TKA.

| Layer/dataset | Description | Scale | Reference |
|--|--|----------------|--------------------|
| Översiktskartan 2007, SWEREF99 TM | Raster topographic overview map- small scale | | SGU database, 2007 |
| Väggkartan, 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 | 1:20,000,000 | SGU database |
| Sverige 1:10 milj (2012) | Polygon outline of Sverige at 1:10,000,000 | 1:10,000,000 | SGU database |
| Sverige 1:5 milj (2012) | Polygon outline of Sverige at 1:5,000,000 | 1:5,000,000 | 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 | 50m resolution | SGU database |
| Höjdmodell och terrängskuggning 2m | shaded relief DEM raster image at 2m resolution | 2m resolution | SGU database |
| RT90_kbl | RT90 grid | | SGU database |
| Kommunindelning från Fastighetskartan | Vector layer of main communication features (roads etc.) | | SGU database |
| Fastighet_2009 | polygon grid of map areas. | | SGU database |

resolutions of 2 and 50 metres (Fig. 13). The majority of the SKA is covered by the more detailed 2m DEM, which stops at the area's southern limit along the 7525,000m northing line. Additional elevation data is available in the Väggkartan layer which contains vector polygons of 10 m contours. The SKA 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 SKA 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 SKA are Karelian metabasalts belonging to the Kiruna Greenstone Group (KGG, ca. 2400–1960 Ma), and Svecofennian volcanosedimentary units assigned to both the Porphyrite and Porphyry Groups (ca. 1,960–1860 Ma). The KGG metabasalts are mostly amygdaloidal flows with lesser pillowed varieties (upper sections), display predominantly tholeiitic or MORB-type chemistry, and contain intercalations of metaargillite, marbles, schists, tuffs and ultramafic (komatiitic) rocks (Martinsson 1997). The sequence has been subdivided into six formations based on lithological and geochemical characteristics (see Fig. 31 in Bergman et al. (2001), along with Martinsson (2004) for summary

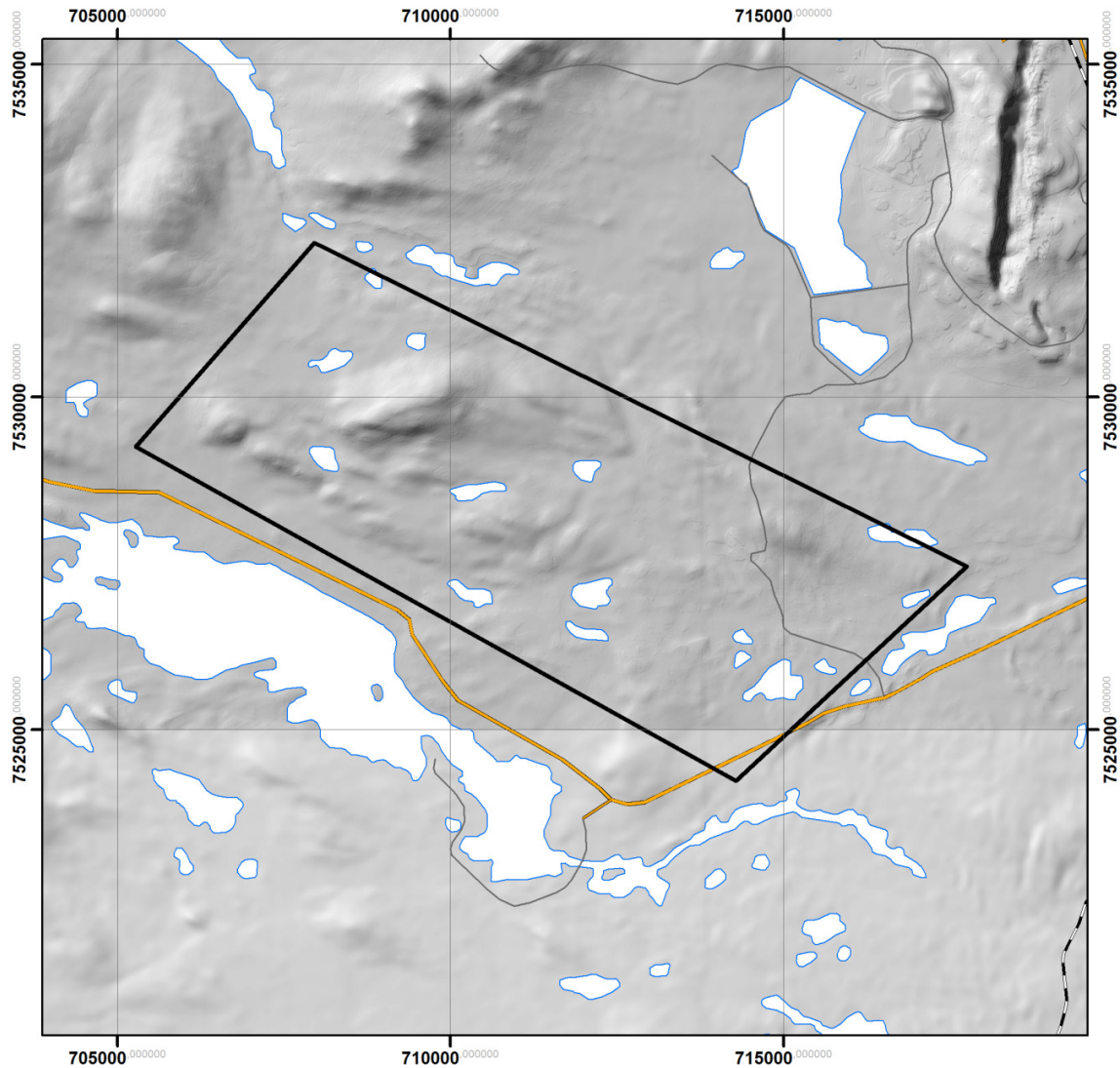


Fig. 13. Extent of the 2m and 50 m DEMs covering the SKA.

descriptions). The entire KGG pile is part of a volcanosedimentary sequence deposited on the Archean basement during continental rifting and incipient basin formation. It is regionally extensive and can be correlated with other greenstones to the north and east in Norrbotten (as well as elsewhere in northern Fennoscandia). The overlaying Porphyrite and Porphyry Group metavolcanics consist of metamorphosed porphyritic andesites to basaltic andesites (Porphyrite Group), and porphyritic andesites, syenites (?), rhyodacites and rhyolites (Porphyry Group). The general younging direction for the volcanosedimentary sequences at the SKA is from west to east. In the north eastern SKA, a volcanosedimentary horizon termed the Kurravaara Conglomerate lies between KGG metabasalts and Porphyry Group metavolcanics. This transition is interpreted to be unconformable, with basal conglomeritic sections containing lithic clasts derived from the KGG basalts (e.g., Martinsson 1997). Kumpulainen (2000) reported that clasts within the Kurravaara Conglomerate are dominantly intermediate in composition (i. e., not KGG derived) and interpreted the conglomerate as a fan delta deposit. In the southwestern SKA, a wedge of conglomeritic material also crops out. The

composition and structure of this unit is not well understood and its stratigraphic position has several possibilities (e.g., basal KGG, Kovo Group, Kurravaara conglomerate).

Svecokarelian intrusions assigned to the Perthite Monzonite suite of plutons (ca. 1,880–1860 Ma) surround the SKA. Original mapping (Offerberg and Nilsson 1967) classified these intrusions as migmatitic granites and syenites. Subsequent assessments classified them as syenitoids of the PMS (Bergman et al. 2000). A pluton in the south–central SKA is presently assigned to the Late-Svecokarelian granitoid–syenitoid–gabbroid association based on geochronology (Romer et al. 1994, Bergman et al. 2000). This intrusion crosscuts a small granitic gneiss with an Archean age along its western contact. Gabbroid intrusives assigned to the PMS plutons mainly occur in the western SKA. A lensoidal-shaped, ultramafic intrusion (picritic?), centred on the southern flank of Ajlatisvaara hill, appears on the regional bedrock map of Bergman et al. (2000), however the area was originally mapped as a chlorite–actinolite-altered metabasalt by Offerberg and Nilsson (1967). Furthermore, this location does not coincide with significant gravity or magnetic highs (cf. Fig. 7 and 8).

Protolith ages

The timing of basaltic volcanism that formed the Kiruna Greenstones is estimated to have occurred sometime between ca. 2.7 and 2.0 Ga (Sköld and Cliff 1984, Skiöld 1986, Skiöld and Page 1998). More precise dating of specific stratigraphic horizons using *in situ* U–Pb methods (zircon, titanite, monazite) would lead to a better understanding of the development of these basalts, provide clearer regional stratigraphic correlations (e.g., comparisons with the Vittangi Greenstones) and confirm the significance of the Neoproterozoic ages at Saarijärvi. Formational ages for Porphyrite and Porphyry Group metavolcanics within the SKA are not known. Ages inferred from the Kiruna area to the north suggest Porphyry Group volcanism occurred at ca. 1.89 Ga (Welin 1987, Cliff et al. 1990). However, this estimate has a relatively large uncertainty (cf. Table 11). Storey et al. (2007) inferred an age of ca. 2.0 Ga for porphyritic metavolcanics in the Kiruna area based on the analysis of titanite cores interpreted as primary, magmatic grains. IOCG-type mineralization within the SKA is well constrained at ca. 1.86 Ga (Smith et al. 2007, 2009). The age is slightly younger than the accepted age of ca. 1.88 Ga for the formation of the Kiruna IOA deposit (Romer et al. 1994). Smith et al. (2010) recognise an early magnetite breccia stage in the Rakkurijärvi area that pre-dates the ca. 1.86 Ga Cu mineralization event.

Structural framework (including geophysics)

The SKA is located at the southern end of the Kiruna–Naimakka Deformation Zone (KNDZ), a major NNE-trending ductile shear zone transecting the eastern half of northern Norrbotten (Fig. 14). Regional-scale deformation along this structure is interpreted to have been active during early Svecokarelian orogenesis (ca. 1.88 Ga), coincident with peak metamorphism, Haparanda and PMS plutonism (Bergman et al. 2001). KGG metabasalts in the SKA fall within this deformation zone and both regional and local structures are strongly influenced by the prevailing regional deformation fabric. In detail, the zone appears to be comprised of several inter-related, brittle–ductile structures which have likely undergone several phases of movement and activation (e.g., Wright 1988, Bergman et al. 2001). The general shear sense is conveyed by steeply plunging lineations that indicate western-side-up kinematics. This sense of movement is analogous with other regional-scale deformation zones in

Norrbottnen (e.g., the KADZ, Fig. 14). In the eastern SKA, a NE-trending deformation zone represents an apparent splay of the KNDZ, and corresponds with several sub-parallel, linear geophysical anomalies (cf. Figs. 6 and 9). This local deformation zone appears to have had an influence on the siting of IOCG-type mineralization in the area (e.g., Smith et al. 2010). A preliminary investigation of this structural system is presented in Bergman (1993).

The SKA falls within the SW part of structural Domain E proposed by Bergman et al. (2001), which is characterised by numerous N- to NNE-orientated, steeply dipping lineations and fabrics (Wright 1988). Several generations of brittle (or brittle–ductile?) faulting also cut the SKA. The dominant trend of these faults is a NE-orientated set and a conjugate, NW-striking set. Brittle faults in the area have been linked to a ca. NW–SE directed regional compressive event in the Kiruna area (Wright 1988), although the exact timing of brittle faulting is presently not known. The general strike of bedding and other primary depositional structures across the SKA is an approximate NE- to NNE-alignment, with apparent younging toward the east and SE (cf. Offerberg and Nilsson 1967).

Metamorphism

Regional metamorphism in the SKA has not been studied in detail, although the lithologies are interpreted to have been metamorphosed at low to medium grade, upper greenschist to

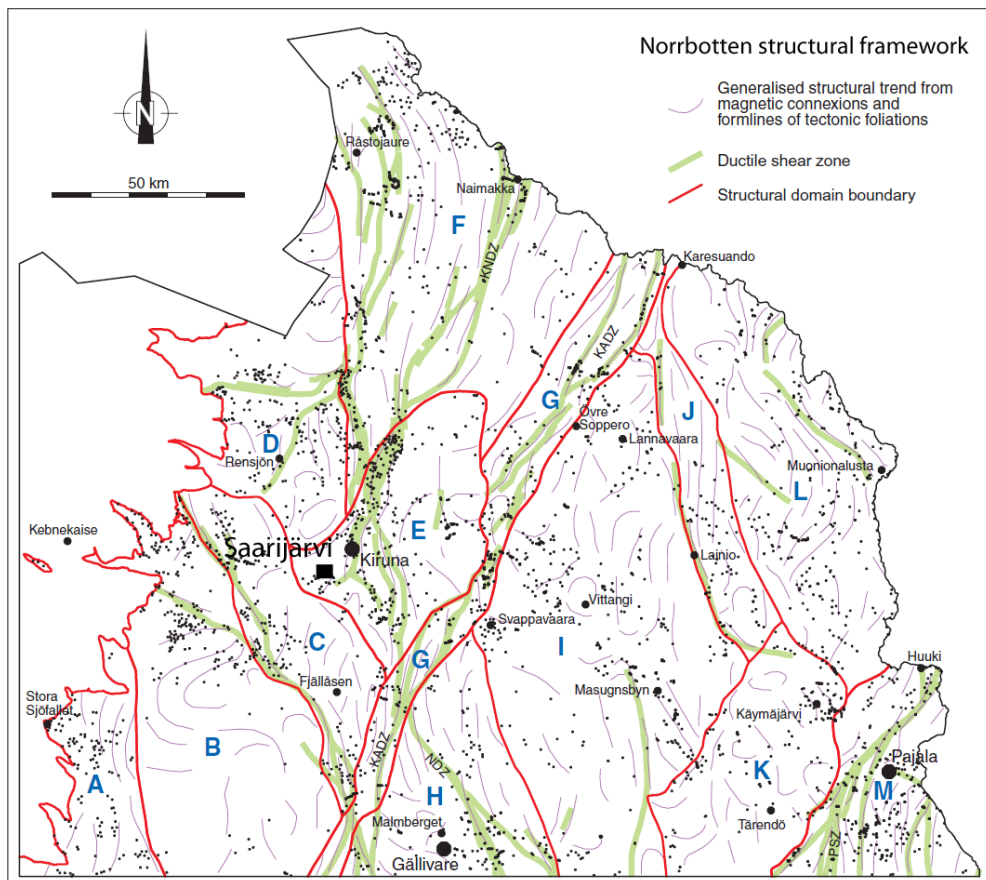


Fig. 14. Regional structural and tectonic setting of the SKA and northern Norrbotten. The structural domains referred to in the text are lettered. Modified after Bergman et al. 2001.

lower amphibolite facies, based on the observed mineral assemblages (Bergman et al. 2001). KGG metabasalts display a medium grade regional metamorphic overprint and generally preserve original depositional features. Mineral pressure–temperature analyses of Greenstone and Porphyry Group volcanics to the east and south of the SKA suggest prograde metamorphism generally reached ca. 550°C and 3 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 SKA 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 SKA have not been produced. Furthermore, there have been no detailed investigations of contact metamorphism affecting the metavolcanic rocks of the SKA, although garnet porphyroblasts developed in mafic tuffs close to plutons have been reported from the Kiruna area. Finally, secondary hydrothermal sericite–muscovite is a feature of shear zone-hosted lithologies.

Mineralization and alteration

The SKA contains eight known mineralised localities, which include several spatially related sub-prospects (Table 5, Fig. 3). Mineralisation predominately consists of Fe-oxide and Cu–Au occurrences (e.g., Rakkurijoki and Pahtohavare deposits, respectively). At the Puoltsa prospect, in the western SKA, skarn-type Fe-oxide mineralization is also encountered (Hallgren et al. 1973). Graphite-bearing schist horizons are also known from several localities (e.g., Pahtohavare). Mineralisation is exclusively hosted in KGG metabasalts or the metavolcanics of the Porphyrite and Porphyry Groups. At Pahtohavare (central SKA), several stratiform Cu–Au lenses (Viscaria-type) occur within an antiformal structure affecting Viscaria Formation greenstones (ca. 5–6 Mt at 2.0–2.8% Cu, 1.2–2.2 g/t Au, Hannas Reward 2013). Mineralization is dominated by auriferous chalcopyrite and pyrite which occurs as disseminations, breccias and veins. Gold-bearing tellurides are also encountered (Bergman et al. 2001). The main alteration is an albite–biotite–scapolite assemblage affecting the host metavolcanics. Mineralization was controlled by the development of suitable chemical and structural traps for the mineralising hydrothermal fluids (Martinsson et al. 1997a). Fe-oxide (magnetite) mineralisation is also encountered at the Östra Pahtohavare prospect. In the eastern SKA, IOCG-type mineralization in several areas is encountered at the Rakkurijärvi prospect (Discovery Zone – ca. 11 Mt at 39% Fe, 0.3% Cu, 0.09 g/t Au, Rakkurijärvi Zone – 70 Mt at 29% Fe, Hannas Reward 2013). The mineralization (magnetite, chalcopyrite, pyrite, native Au) is hosted by altered metavolcanic rocks within a NE-trending shear zone and generally occurs as earlier Fe-oxide-rich lenses along with later sulphide-bearing breccia and veins (Smith et al. 2007).

DISCUSSION

Current understanding

In the Saarijärvi key area, KGG metabasalts and related sedimentary horizons were deposited within an extensional setting during rifting of an Archean basement (e.g., Perdahl and Martinsson 1995, Martinsson 1997). The greenstone sequence represents a lower to middle stratigraphy within the supracrustal units of Norrbotten (Fig. 15). This early phase of rift-to-drift tectonics produced abundant lava flows within a developing NNE-orientated seaway

(present day coordinates) which is represented today by the greenstone belt extending north from the study area. Even though volcanism evolved to produce MORB-type extrusions within a maturing basin, rifting appears to have been relatively short lived and the greenstone belt is interpreted as a failed rift arm that extended NNE from a postulated triple junction located somewhere near the Kiruna area (Martinsson 1997).

The tectonic environment switched to a compressive regime in the Late Paleoproterozoic. Porphyrite Group metavolcanics represent early Svecofennian arc volcanism developed within a subduction setting and generally have a calc-alkaline, low Ti and enriched 'high field strength element' composition (Martinsson & Perdahl 1995, Bergman et al. 2001). Local erosion, sedimentation and re-deposition contributed epiclastic and re-worked pyroclastic horizons to the volcanic pile (e.g., Martinsson 2004). The Porphyry Group represents a bimodal volcanic suite consisting of intercalated basalts, andesites and rhyodacites. Geochemically, the mafic units have a more within-plate, flood basalt-type character, while the intermediate to felsic rocks have a high Ti, alkalic chemistry. These observations suggest that Svecofennian subduction may have developed localised extensional regimes and back arc-type rift environments. The intermediate to felsic volcanics with a more alkalic composition are suggested to have formed within these localized extensional settings with a source contribution from preexisting continental material (Martinsson & Perdahl 1995, Perdahl 1995).

Witschard (1984) noted that Porphyrite Group basic to intermediate volcanics are a slightly older version of the more acid units found within the Porphyry Group and both groups form part of a thick, volcanosedimentary succession displaying variations in depositional facies. This setting produced lithological variation with time, from alkaline basalts and andesites to calc-alkaline dacites and rhyolites. Witschard (1984) suggested 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 the east. Perdahl (1995) presented geochemical evidence in support of the subdivision of the Svecofennian volcanics in the Kiruna area. Based on the presently available geochronology, both the Porphyrite and Porphyry Groups appear to be contemporaneous (Fig. 15). Perdahl and Martinsson (1995) hypothesized that the Porphyry Group volcanics in the Kiruna area represent a 'flood basalt' province and that magmatism was driven by mantle plume dynamics with accompanying high temperature crustal melting. Martinsson (1997) also invoked a mantle plume that resulted in the extrusion of the greenstones in the Kiruna area (and SKA). It is not clear at present if both volcanic events relate to the same extended mantle plume process or separated (in time) tectonothermal events.

The majority of the plutons occurring on the margins of the SKA are intrusive rocks associated with the PMS (Offerberg 1967, Witschard 1984, Bergman et al. 2001, Ahl et al. 2001). These plutons are generally massive and weakly metamorphosed although detailed studies of the intrusives in the area is lacking at present. Petrologically, the PMS mainly consists of monzonite, quartz monzonite and monzodiorite (i. e., the 'monzo-intrusions' of Weihed 2004), however around the SKA, syenites are the main intrusive lithology. A characteristic feature of the intermediate to acid plutons is the presence of perthitic feldspar phenocrysts. More mafic varieties (diorites, gabbroids, peridotite) also form part of this suite, with examples occurring in the western SKA. Magma mingling and mixing features support some level of bimodal or compositionally hybrid magmatism (e.g., Weihed 2004). PMS intrusives are considered to be plutonic equivalents of Porphyry Group metavolcanics, based on certain

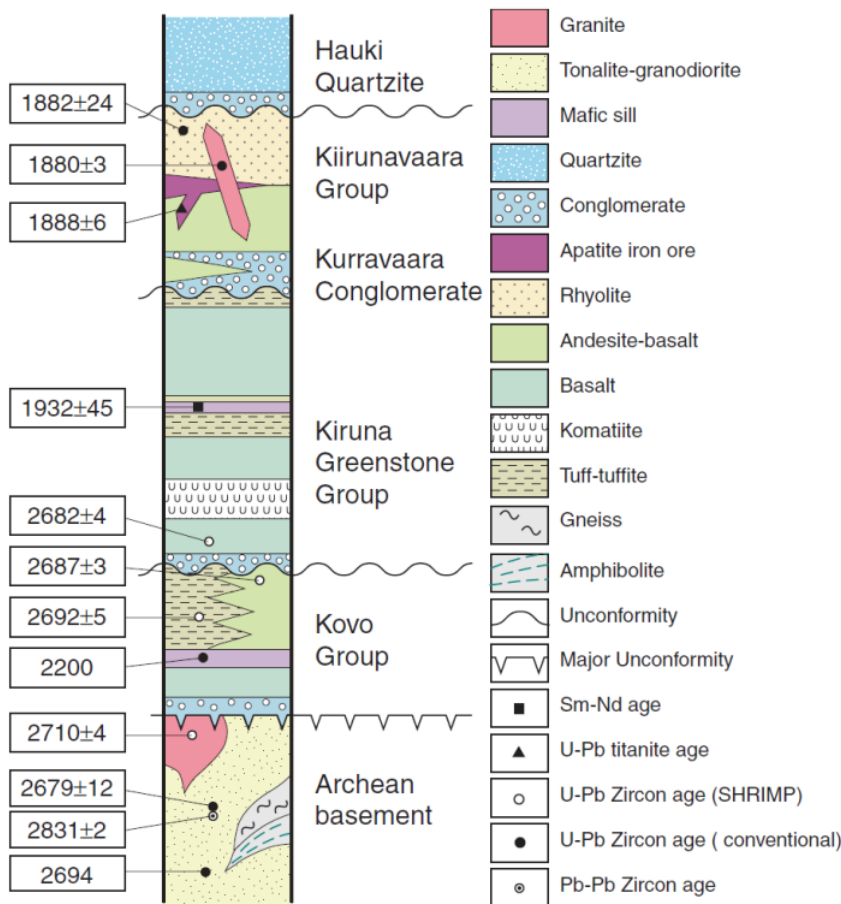


Fig. 15. Regional stratigraphy of Karelian and Svecofennian supra-crustal units in the Kiruna area (Martinsson 2004).

lithochemical characteristics and geochronological constraints (e.g., Witschard 1984, Martinsson 2004). Emplacement ages range from ca. 1,880–1,850 Ma, although no dating in the SKA has been undertaken (cf. Fig. 12). A syenitoid intrusion in the south-central SKA has been dated at ca. 1,792 Ma (Römer et al. 1994) and it is assigned to the Late Svecokarelian granitoid–syenitoid–gabbroid plutonic association (Bergman et al. 2000). An Archean granite–gneiss inlier crops out in the south-central SKA with access provided by the main paved road (Fig. 1). At present there is no detailed description or analyses of this unit.

A significant IOCG mineralisation event is recognized from the western SKA at ca. 1,860 Ma (Smith et al. 2007; 2010). The age of mineralization from other prospects elsewhere in the SKA is presently not constrained (e.g., Saarijärvi, Puoltsa). Smith et al. (2010) also recognise an earlier phase of mineralization (forming magnetite breccias) in the area (perhaps coincident with the 1.88 Ga mineralization event at Kiirunavaara?). Mineralization at the Rakkurijärvi Cu–Au, the Discovery Zone (Rakkurijärvi) Fe-oxide prospect and Rakkurjoki Fe-oxide prospect (eastern end of SKA) occur within a NE-trending deformation zone hosted by altered metavolcanic rocks of the Porphyry Group. Breccia- and vein-hosted mineralization and related sodic and potassic alteration are a consequence of concentrated hydrothermal activity developed within regional deformation structures (Smith et al. 2010). A magmatic source is suspected for the mineralising fluid (e.g., Gleenson and Smith 2009; Smith et al. 2013), although which specific magmatic event is still a matter of speculation. The Pahtohavare prospect (northern SKA) is hosted in greenstones and is interpreted to have formed during syn-depositional exhalative processes on the ocean floor (e.g., Martinsson 2004).

Potential issues to be addressed

The rock units across the SKA have been variously described by earlier workers (e.g., Ödman 1957, Offerberg 1967, Martinsson 1997). In addition, a stratigraphy for volcanosedimentary sequence has been proposed within the context of the regional stratigraphy of Norrbotten (Offerberg 1967, Lundqvist 1979, Witschard 1984, Martinsson 1995, Martinsson 1997). Furthermore, IOCG-type mineralization in the SKA has undergone several investigations (e.g., Gustafsson 1992, Lindblom et al. 1996, Martinsson et al. 1997a, Smith et al. 2007). Notwithstanding these results, several aspects of the SKA 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 need to be addressed are outlined below under several headings.

Stratigraphy

The KGG metabasalts have been subdivided into six formations in the Viscaria area (10km north of the SKA). Are these formations laterally consistent and do they extend south into the SKA. Assessment of KGG outcrops (and drill core?) may help to answer these issues. Can the picritic intrusion presented on the regional scale bedrock map (Bergman et al. 2000) be correlated with exposures on the ground? How abundant are komatiites in the area? How contemporaneous are Porphyrite and Porphyry Group metavolcanics in the area? Do they represent different facies of the same volcanic event? How do they compare to the porphyritic volcanics to the SW (e.g., Tjärrojåkka area). What are the characteristics of the Archean inlier in the southern SKA? Can it be correlated with specific Archean areas in the north? Does the conglomerate unit in the western SKA represent part of the KGG or does it belong to the Kovo Group? How does it compare with the Kurravaara conglomerate in the east?

Structure

The NE-trending shear zone at the eastern SKA hosts several IOCG-type mineral occurrences. However, detailed field studies of this shear zone are lacking at present. What is the deformational nature of this shear zone? What are its kinematic properties? How many deformation episodes does it preserve? Can the nature of this deformation zone be visualized by constructing geophysical profiles across the zone and can this lead to a better understanding of the mineralisation processes?

Formational Environments

The Kiruna greenstones are interpreted to have formed in an extensional environment that evolved from early continental, within-plate rifting, to a more mature, mid-ocean ridge-type setting (Martinsson 1997). Rifting and mafic-ultramafic volcanism was caused by decompression melting initiated by a mantle plume. Continued extension developed rapid basin subsidence with local erosional scarps (Martinsson 2004). Porphyrite and Porphyry Group metavolcanics are inferred to have formed under a broadly compressive tectonic regime which developed subaerial, volcanic arc-type magmatism. Perdahl and Martinsson (1995) suggest that the bimodal flood volcanism that produced the Porphyry Group volcanosedimentary pile was also driven by mantle plume geodynamics. Can isotopic analysis (Nd, Hf, Os) of the greenstones from the SKA shed light on the mantle plume hypothesis? What

caused the transition from rifting to localized compression and arc magmatism? Can we better constrain the timing and nature of these events? How did local erosion depocentres (Kurravaara conglomerate) develop in a broadly extensional environment or does this mark the transition to a phase of compression and subaerial uplift? Martinsson (2004) states that litho-geochemistry does not equivocally constrain the formational environment of the Porphyry Group volcanics. The application of in situ mineral chemistry and isotopic analysis may contribute to a better understanding of this important volcanic unit.

Litho-geochemical and Isotopic Characteristics

The majority of litho-geochemical analyses and isotopic work has been focused on the supracrustal rocks in the area. Smith et al (2007) proposed that plutonism may have been a driving factor in the development of IOCG mineralization in the eastern SKA. Geochemical and isotopic analyses of plutons in the area may contribute to a better understanding of these mineralisation events. Combined litho-geochemical and isotopic investigation of lower KGG metabasalts from the western SKA could enable comparisons with similar results from metabasaltic rocks from the Vittangi greenstones located east of the KADZ. What is the significance of komatiitic horizons in the greenstones? More detailed investigations of these rocks may shed light on early rifting events and related flood volcanism.

Geochronology

A Neoproterozoic age for KGG metabasalts in the western SKA has been proposed. Is this age constraint correct? A priority for SGU should be to establish if Neoproterozoic metabasalts occur within the SKA. A major mineralization event has been constrained in the area at between 1.88 and 1.86 Ga. Did other mineralization across the SKA form at the same time? How old are the plutonic units surrounding the SKA? Can age determinations indicate a temporal and genetic link to IOCG mineralisation.

Metamorphic Grade

Observations of the main metamorphic indicator minerals within the various rock units across the SKA should be made. Is the metamorphic grade consistent or does it vary as we go up the stratigraphy? How is main type of contact metamorphism in the area? Is there a systematic change toward the plutonic units?

Mineralization and Alteration

Can changes in alteration styles and alteration assemblages be systematically mapped along the Rakkurijärvi shear zone? Is there a 'background' regional shear zone alteration assemblage and do we see a systematic change to an overprinting assemblage as we approach areas with IOCG mineralization? Drill core data from the Puoltsa Fe-oxide skarn deposit (western SKA) indicate numerous granitoid dykes and lenses intruding strataform skarn horizons (Hallgren et al. 1973). Analysis (whole-rock, mineral chemistry, geochronology, isotopes) of these intrusions may identify a causative link to the skarn Fe-oxide mineralisation and, if so, help to characterise the mineralogical and geochemical signature of a 'fertile', metalliferous plutonic systems driving IOCG- and skarn-type mineralization in the area.

Field characterisation (petrography, structural measurements) and sampling of plutonic rocks in the eastern SKA for age dating, geochemical analysis and alteration investigations. Potential for isotopic characterisation of syenitoids also in order to test the link to IOCG mineralisation. Link this data with drill core samples of granitoid intrusives from the Puoltsa Fe-oxide deposit. 2–3 days (additional 4–5 days at Malå).

Field characterisation (petrography, logging, structural measurements) and sampling of KGG metabasalts in the western SKA for age dating, geochemical analysis and alteration investigations. This data will be used to test if the lithological formations established to the north at Viscaria can be extended south to the SKA. Potential for isotopic characterisation of metabasalts also (formational setting). In addition. Observations and sampling can be used as a comparative dataset with greenstones at the Nunasvaara key area. A focus on komatiitic units would also be of interest. Field characterisation, logging and sampling of the conglomerate wedge in the western SKA to establish depositional and stratigraphic setting (combine with age dating also?) 3–4 days.

Investigate outcrops in the central SKA that correspond with a proposed location of a metapelite intrusion. half a day.

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