KARTERING BARENTS 2013

Summary report on the geological and geophysical characteristics of the Nunasvaara key area (29K Vittangi NO & SO)

Edward p. Lynch & Johan Jönberger

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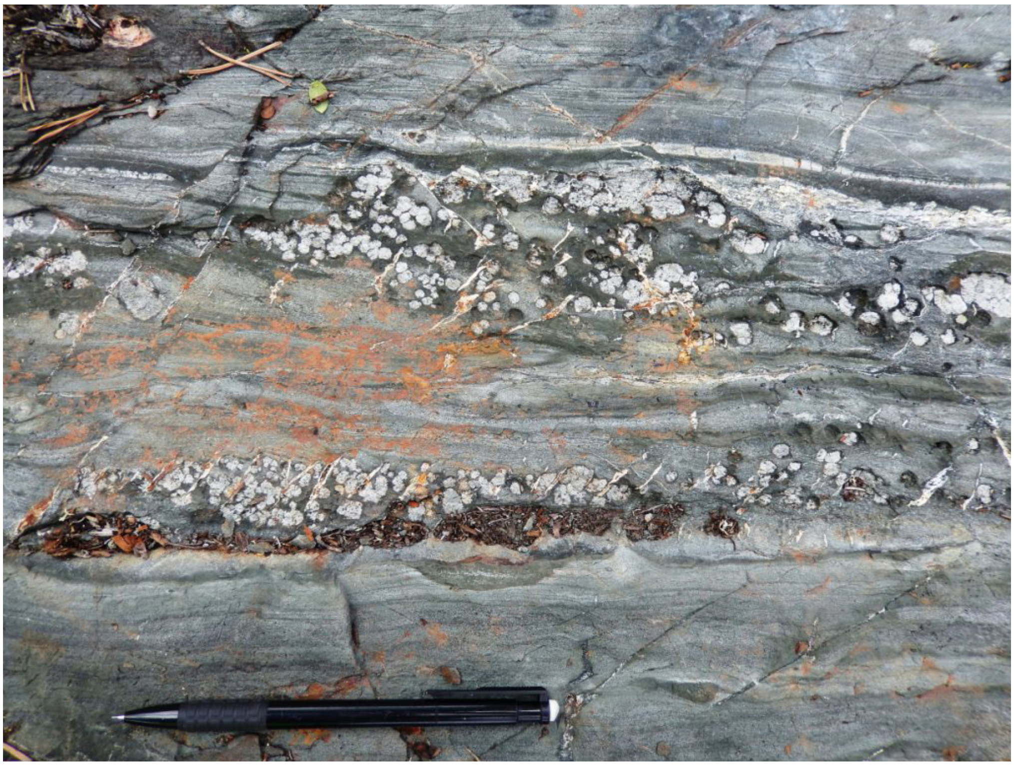

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Cover: Scapolite-altered tuff, western Nunasvaara. View to the SW. Photo: Edward Lynch, SGU.

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

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INTRODUCTION

The Nunasvaara Key Area (NKA) is located approximately 10 km west of Vittangi (north-central Norbotten County, Sweden) within map sheets 29K NO and SO and incorporates eight 5 × 5 km lettered grid squares (Fig. 1). It is centered on an approximately rectangular zone of volcanosedimentary rocks termed the Vittangi Greenstone Group which form part of the Karelian supracrustal sequence in northern Sweden (ca. 2.40–1.96 Ga). These units are surrounded by a variety of felsic and mafic intrusive bodies emplaced during Svecokarelian orogenesis (ca. 1.92–1.75 Ga). The area is best known for its schist-hosted graphite deposits (e.g., Nunasvaara) which represent the largest known graphite resource in Sweden (Shaikh, 1972, Eriksson and Hallgren 1975).

Access to the area is reasonably good and is provided by route E45 in the south (Svapavaara–Vittangi section) and east (Vittangi–Nedre Soppero section). Access to the interior is possible using several forest roads. The terrain is mostly mature forest on the western side and mixed forest and marshland to the east. Two major rivers flow through the key area in the south (Torneälven) and northeast (Vittangiälven). Lakes and ponds are mostly located in the west and northwest. Outcrops are primarily located in the northeast, west and southwest, with some areas having relatively good exposure (Fig. 2). Thin soil cover also exists in the areas with the best exposure. The central part of the key area appears to be the least exposed. An open pit aggregate quarry is located approximately 5 km north of E45 on the northern side of Torneälven (E770943, N7524006) and is accessible by forest roads. A second quarry pit is located in the east (E778481, N7528045) with access off the N–S segment of road E45 (about 5 km N of Vittangi).

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

GEOLOGICAL OVERVIEW

The bedrock geology of the NKA has been summarized in earlier SGU reports by Geijer (1918), Ödman (1957) and Eriksson and Hallgren (1975). The geology is dominated by greenstones (basalts to andesites), metasediments (quartzite, schist, marble) and metadolerites which form part of the Vittangi Greenstone Group (VGG). These units represent part of the Palaeoproterozoic volcanosedimentary domain of northern Sweden (ca. 2.40–1.96 Ga) which unconformably rest on an Archean basement (e.g., Witschard 1984). These regionally extensive supracrustal rocks were subdequently deformed and metamorphosed during the Svecokarelian Orogeny at ca. 1880 Ma (e.g., Bergman et al. 2001). The Kilavaara Quarzite Group (KQG) unconformably sits above the VGG and represents a phase of continental weather and deposition of arenitic rocks. These quartzites do not occur within or adjacent to the NKA.

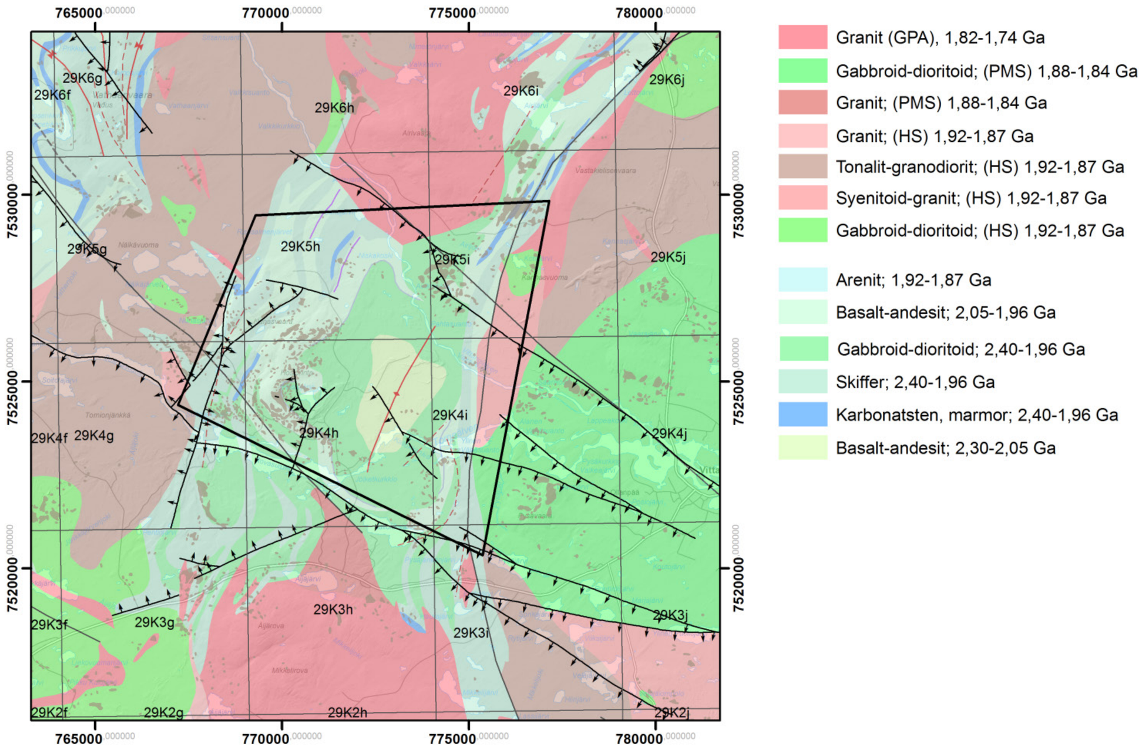

Figure 1. Regional geology of the Nunasvaara key area (regional level).

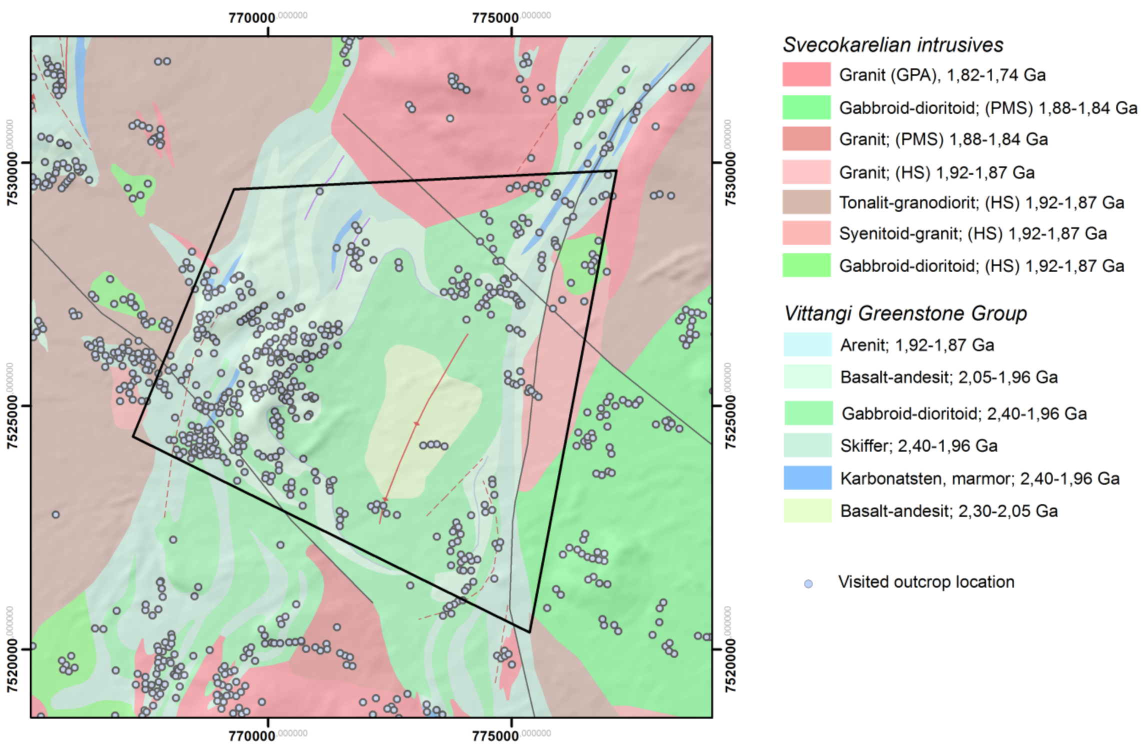

Figure 2. Location of surveyed outcrops for the NKA based on SGU’s local bedrock geology dataset.

The VGG has been subdivided into five informal formations (after Eriksson and Hallgren 1975). They are from oldest to youngest:

- (i) Tjärro Quartzite Formation (clastic, sericitic quartzites)
- (ii) Lower Greenstone Formation (feldspar-bearing basalts, locally amygdaloidal, scapolite-altered)
- (iii) Lower Sedimentary Formation (biotite- and graphite-schist, argillite, chert, volcaniclastic rocks)
- (iv) Upper Greenstone Formation (pillowed lavas, intercalated tuffs and limestone)
- (v) Upper Sedimentary Formation (graphitic schist, mafic tuffites, skarn, sulfide and Fe mineralization).

Formations (ii) to (v) make up the central part of the NKA (Fig. 1). The basal Tjärro Quartzite Formation does not occur within the NKA and is mostly known from exposures to the north at Soppero (see Figure 9 in Kumpulainen, 2000). It is considered to be correlative with the Kovo Group in the Kiruna area. Metadoleritic rocks locally intrude the greenstones as concordant sills and are considered to be sub-volcanic equivalents of the basalts. For example, in the study area a ca. 250m thick scapolite-altered doleritic sill intrudes Lower Greenstone basalts. Minor ultramafic, feldspar-free (komatiiitic) basalts also occur within the VGG. In general, VGG rocks are interpreted to be lateral equivalents of the Kiruna Greenstone Group (further west), although important differences and facies variation exists that have implications for the metallogeny of the area (Martinsson 1993).

The NKA is intruded by several Svecokarelian plutonic suites that enclose the rectangular greenstone area. These intrusive rocks include: (i) gneissose Haparanda Suite (HS) gabbroids, diorites and granitoids (ca. 1.90–1.86 Ga, Ödman 1957), (ii) broadly contemporaneous Perthite–Monzonite Suite (PMS) gabbroids and granitoids (ca. 1,88–1,86 Ga, Witschard 1984) and (iii) younger Granite–Pegmatite Association (GPA, Lina type) granites (ca. 1,81–1,74 Ga, Ödman 1957, Witschard 1984) representing the last major intrusive event. The HS and PMS intrusions are generally deformed and have more compositional variation. GPA intrusions are restricted to granitic lithologies and are generally more massive to weakly foliated. Granitic veins and dykes are also present across the study area and appear to crosscut all other units. In addition, various forms of basic dykes (lamprophyric, andesine–porphyritic) are also abundant however their timing or genesis is not well understood.

The NKA has been subjected to several episodes of ductile deformation and structural reworking. It falls within the central part of structural Domain I of Bergman et al. (2001) and sits between two regional-scale ductile shear zones to the east and west – i.e., the Karesuando–Arjeplog Deformation Zone (KADZ) and the Karesuando–Lainio Deformation Zone (KLDZ), respectively. Several deep-seated, linear discontinuities identified by geophysical methods also truncate the NKA. The dominate structures within the greenstones is a NNE-aligned, shallow plunging antiform (Fig. 1). The hinge zone of this structure provides a structural window to the Lower Greenstone Formation basaltic sequences. Complex refolding affects the rocks on both fold limbs. The entire VGG appears to have been polydeformed prior to the emplacement of HS and PMS plutons. These latter plutons were in turn deformed during emplacement. The Line-type granites and late-stage granitic dykes do not appear to have been affected by major deformational events. Several faults also occur within the NKA with a typical NW alignment (Fig. 1). A curvilinear fault zone marks the eastern contact of the VGG and several intrusive rocks.

Metasomatic processes have affected the NKA. All rock units display some level of hydrothermal alteration. This alteration generally occurs as scapolite–albite–biotite–sericite–tourmaline replacement assemblages. Albite-rich veins and concretions (leuco-diabase of Ödman 1939) that occur within tectonised areas are considered to be an extreme example of this metasomatic process. Scapolitization represents the main regional alteration (e.g., Frietsch et al. 1997). It mostly affects the greenstones however ultramafic and mafic intrusive bodies may also be affected. It consists of a scapolite–biotite assemblage. In general alteration is coincident with deformation zones and associated mineralization.

Iron, copper and graphite represent the main mineralization within the NKA. Skarn-rich Fe is an important mineralization within the VGG and is associated with calc-silicates and marble, and is typically strataform-type with a regular banding. The mineralization consists of magnetite in diopside–tremolite skarns, along with accessory pyrite, chalcopyrite and pyrrhotite. Sub-economic sulfide mineralization (Cu) also occurs within and around the NKA. Two main types are recognized: (1) syngenetic (Viscaria-type) bands, disseminations and impregnations within the VGG and concentrated within volcaniclastic and schistose rocks and (2) quartz and carbonate vein-hosted epigenetic mineralization. The most important type of mineralization in the NKA is graphite-bearing schists. The graphite is a fine-grained amorphous, flakey variety, with minor sulphide.

AVAILABLE DATA FOR NUNASVAARA KEY AREA.

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

BEDROCK GEOLOGY

The NKA is covered by several bedrock geology maps and datasets located on SGU's GIS database. Many of the GIS layers are derived from digitized versions of previous bedrock mapping programmes at 1:50,000 or 1:250,000. Additional sampling or analyses (e.g., lithogeochemistry, age determinations) are generally represented as vector point layers or polygons showing the sample location and analysis/data result. The most detailed mapping for the area is two 1:50,000 scale bedrock maps from SGU's Af series (Serie Af, Nr 13–16, Vittangi). These are Af 16 and Af 14 that fall within the Vittangi NO and SO areas. The mapping was carried out in the 1960's. The maps were published in 1972 with a subsequent report in 1975 (Eriksson and Hallgren, 1975). The area is covered by several other maps at smaller scales which are outlined below.

Map databases

Table 1 and 2 lists the most important bedrock mapping for the Nunasvaara area along with additional bedrock information derived from SGU's geographical information system (GIS). The maps listed in Table 1 represent both scanned and rectified paper maps and several vector-type GIS databases.

Table 1. Principal bedrock geology maps and datasets covering the NKA and Norrbotten.

Code	Title	Scale	Reference	Location	Most relevant
Af 14	Bedrock map: 29K Vittangi NO	1:50.000	Eriksson & Hallgren 1972, Eriksson & Hallgren 1975	Nunasvaara	Bedrock map
Af 16	Bedrock map: 29K Vittangi SO	1:50.000	Eriksson & Hallgren 1972, Eriksson & Hallgren 1975	Nunasvaara	Bedrock map
Block-diagram VI	Blockdiagram över 29K Vittangi	1:50.000	Eriksson & Hallgren 1972; Eriksson & Hallgren 1975	Nunasvaara	Cross section
Ba56-1	Regional geological and geophysical maps of northern Norrbotten County	1:250.000	Bergman et al. 2000	Northern Norrbotten	Bedrock, stratigra-phy, structures
Ca 41	Berggrundskara över urberget i Norrbottens län	1:400.000	O. Ödman 1957	Norrbotten	Regional geology
K423	Bedrock map of Sweden	1;1.000.000	Bergman et al. 2012	Sweden	Regional geology, tectonic domains
n/a	Nordkalotts bedrock geology map. 1:1,000,000	1:1.000.000	GTK-SGU-NGU	N. Sweden	Regional geology
n/a	Metallic mineral deposit map of the Fennoscandian Shield	1:2.000.000	Eilu et al. 2008	Fenno-scandia	Regional geology, mineralization
n/a	Geology of the Fennoscandian Shield.	1:2.000.000	Koistinen et al. 2001	Fenno-scandia	Regional geology, tectonic domains
n/a	Lokal berggrundsinformation	1:50.000	SGU database (GIS)	All of SKA	Bedrock geology
n/a	Regional berggrundsinforma-tion	1:250.000	SGU database (GIS)	All of SKA	Bedrock geology
n/a	Norrbotten NBDIG layer. Digi-tial vector data of bedrock geol-ogy with outcrops, contacts and structures.	1:1.000.000	SGU database (GIS). Sjöstrand and Henkel.	All of SKA	Bedrock geology

Table 2. Additional bedrock geology datasets fro the Nunasvaara area

Layer/dataset	Description	Location	Reference
Hällar ur jordartskartor	Digital layer showing outcrop and thin soil cover areas from soil maps.	NKA	SGU database
Berggrundsobservationer	Field outcrop observations	NKA	SGU database
Hällpunkter_reg (closely matches undersökta ytor lokal)	Outcrop locations	NKA	SGU database
Ballast & industrimineral	Quarry and industrial mineral locations	NKA	SGU database
Boulders_29K	582 pages of mineralised boulder descriptions	NKA	SGU database
Metamorfa_nyckelmineral_Ba56	Location of metamorphic indicator minerals	NKA	SGU database

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

Scanned maps

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

Additional scanned maps can be found within the various BRAP and PRAP reports for several of the mineralized areas as listed in Table 4 and in the references. For example, Ger-

Table 3. Scanned field maps for the Nunasvaara area (generally not geo-rectified)

Layer/dataset	Description	Scale	Reference
GO2721 (not rectified)	Blockletning, uran I 29K SO	1:50.000	SGU database
GO2735 (not rectified)	Blockletning, uran I 29K NO	1:50.000	SGU database
G10232	Malmblock och malmanledninger 29K, 2-3, g-h	1:20.000	SGU database
G10234	Hällkarta 29K, 2-3, g-h	1:20.000	SGU database
G10235	Hällkarta 29K, 2-3, g-h	1:20.000	SGU database
G10236	Malmblock och malmanledninger 29K, 2-3-, i-j	1:20.000	SGU database
G10239	Hällkarta 29K, 2-3, i-j	1:20.000	SGU database
G10240	Hällkarta 29K, 2-3, i-j	1:20.000	SGU database
G10254	Malmblock och malmanledninger 29K, 4-5-, g-h	1:20.000	SGU database
G10255	Hällkarta 29K, 4-5-, g-h	1:20.000	SGU database
G10256	Hällkarta 29K, 4-5-, g-h	1:20.000	SGU database
G10262	Hällkarta 29K, 4-5-, g-h	1:20.000	SGU database
G10263	Hällkarta 29K, 4-5-, g-h	1:20.000	SGU database
G10264	Malmblock och malmanledninger 29K, 4-5-, i-j	1:20.000	SGU database
G10265	Hällkarta 29K, 4-5-, i-j	1:20.000	SGU database
G10266	Hällkarta 29K, 4-5-, i-j	1:20.000	SGU database
Diaries_29K_various workers	225 diaries and 24 field maps (not rectified)	Varies	SGU database

Table 4. List of papers, reports and publications covering Nunasvaara geology

Reference	Year	Title	Brief Overview
Smith et al, Geochim. Cosmochim. Acta, v.102, p. 89–112.	2013	Hydrothermal fluid evolution and metal transport in the Kiruna District, Sweden: Contrasting metal behaviour in aqueous and aqueous–carbonic brines	Regional-scale hydrothermal fluid study constraining the nature of mineralizing hydrothermal fluids in Norrbotten. Includes samples from the Pahtohavare deposit.
Hallberg et al., GTK Special Publication 53, p. 139 - 206	2012	Metallogenic areas in Sweden	Review of mineral deposits and districts of Sweden. Area S035 (Kiruna) is the most relevant.
Bergman et al., IAGS field excursion,	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.
Smith et al, Hydrothermal Iron Oxide Copper-Gold and Related Deposits: A Global Perspective, v. 4, pp. 427-440	2010	THE GEOLOGY OF THE RAKKURIJÄRVI COPPER-PROSPECT, NORRBOTTEN COUNTY, SWEDEN	Deposit description and geochemistry (lithogeochemistry, apatite and biotite chemistry). Some geophysics. Quotes the Smith et al (2009) titanite age from Nunasvaara
Gleeson S & Smith M, Geochem. Cosmochem Act., v73, p. 5658	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. 37Cl data also reported to identify Cl sources.
Smith et al, J. of Petrology, 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., 33rd IGC excursion guide no. 15	2008	General Introduction to Geology and Metallogeny of Fennoscandian Shield	Review of the geology and metallogeny of N Sweden. Several deposits and their geological settings mentioned.
Weihed et al., Ore Geol. Rev., 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, SEG guidebook series vol. 33, p. 131 - 148	2004	Geology and Metallogeny of the Northern Norrbotten Fe-Cu-Au Province	Review paper on the geology and metallogeny of N Sweden. Pahtohavare deposit and its geological setting mentioned. Svecofennian volcanics also discussed with geochemical classification (plutonic rocks also).

Table 4. Contunued.

Reference	Year	Title	Brief Overview
Weihed P, SEG guidebook series vol. 33, p. 1 - 15	2004	Overview of the geology and tectonic setting of northern Sweden	Review paper of the broad tectonic and stratigraphic development of Norrbotten and other areas in N Sweden.
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.
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-CaCl2 brines with high salinities. CO2-bearing fluids correlate with Au-rich systems.
Carlon 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 fieldguide, p. 63	2000	Excursion Guide, GEODE Work shop, 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.
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, 1:2500000	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
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.
Frietsch et al., Min. Dep, v.30, p. 275	1995	Sulfur isotopes in lower Proterozoic iron and sulphide ores in northern Sweden	Sulfur isotope investigation of sulfide minerals.
Talbot CJ and Koyi H., Precambrian Research v.	1995	Palaeoproterozoic intraplating exposed by resultant gravity overturn near Kiruna, northern Sweden	Structural assessment of map sheet 29J with implications for Svecofennian volcanism and plutonism in the Kiruna area.
Martinsson O, PIM report # 3, 58 p.	1995	Greenstone and porphyry hosted ore deposits in northern Norrbotten	Description of the Pahtohavare, deposits with a basic geological map of the area included showing ore body.
Elming, Precambrian Research v.69, p. 61	1994	Palaeomagnetism of Precambrian rocks in northern Sweden and its correlation to radiometric data	Palaeomag study of volcanic and plutonic rocks including samples at Vittangi. Several magnetization events and drift history proposed.

Table 4. Contunued.

Reference	Year	Title	Brief Overview
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
Gustafsson B, NSG93003 report	1993	The Swedish Norrbotten greenstone belt	Stratigraphic variations in the greenstone belt
Martinsson O & Perdahl J-A, in Marinsson 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
Hitzman et al, Precambrian Research 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.
Frietsch (ed.), SGU RM 66,341 p.	1991	Register över svenska fydingheter av malmmineral, industriella mineral och bergarter.	Review of geology of mineralized localities in Sweden and Norrbotten.
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. Discusses S isotope data on a regional scale east and west of the KADZ.
Gerdin et al., SGAB Prap91045, 109 p.	1991	Grafit - uppslagsgenerering i Norrbotten 1991.	Review of graphite deposits, geology and exploration, in Norbotten with maps.
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.
Gaal, Precambrian Research v.46, p. 83	1990	Tectonic Styles of Early Proterozoic Ore Deposition in the Fennoscandian Shield	Review of mineralization styles and processes in Fennoscandia linked to broad geotectonic histroy
Gerdin etal., SGU Prap90068, 100 p.	1990	Grafit - uppslagsgenerering i Norrbotten 1990.	Review of graphite deposits, geology and exploration, in Norbotten with maps. Covers several areas at Nunasvaara.
Shaikh et al., SGU RM 54, 380 p.	1989	Kalksten och dolomit i Sverige Del 1. Norra Sverige	Review of calcite and dolomite lithologies in Norrbotten. Areas close to Vittangi covered.
Skiöld et al., Chem. Geol., v.69, p. 193	1988a	CHEMISTRY OF PROTEROZOIC OROGENIC PROCESSES AT A CONTINENTAL MARGIN IN NORTHERN SWEDEN	Sm-Nd (whole-rock) & lithogeochem. of Proterozoic granitoids/plutonics to characterise crustal growth histroy and petrogenesis at S margin of Archean rocks
Skiöld, Precambrian Research v.38, p. 147	1988b	IMPLICATIONS OF NEW U-Pb ZIRCON CHRONOLOGY TO EARLY PROTEROZOIC CRUSTAL ACCRETION IN NORTHERN Sweden	U-Pb zircon (TIMS) ages of plutonic rocks used to bracket crustal growth and accretions and infer petrogenetic processes. Comparison between Archean margin (crustal) and Skellefte plutonism (juvenile)
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.
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
Öhlander et al., Precambrian Research v.35, p. 237	1987	Crustal Reactivation in Northern Sweden: the Vettasjärvi Granite	Lithogeochemical, Sm-Nd and O isotope study of a Lina type granite area south of the Nunasvaara area. I-type partial melt of Archean basement. Not fractionated/barren.
Skiöld T, Precambrian Research 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.

Table 4. Contunued.

Reference	Year	Title	Brief Overview
Gaal & , Gorbat-schev, Precambrian Research v.35, p. 15	1987	An Outline of the Precambrian Evolution of the Baltic Shield	Review of the geotectonic history of the entire Baltic Shield
Shaikh et al., SGU Brap86006, 131 p.	1986	Industriella mineral och bergarter i Norrbottens län.	Overview description of industrial mineral deposits and geology in Norrbotten.
Skiöld, Precam. Res, v.32, p. 35	1986	On the age of the Kiruna Greenstones, northern Sweden	U-Pb zircon study of a diabase 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, Precambrian Research v.26, p. 1 - 13	1984	Sm-Nd and U-Pb dating of Early Protero-zoic mafic-felsic volcanism in northern-most 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-brian Research v.23, p. 273	1984	THE GEOLOGICAL AND TECTONIC EVOLUTION OF THE PRECAMBRIAN OF NORTHERN SWEDEN -- A CASE FOR BASE-MENT REACTIVATION?	Regional overview paper with review of stratigraphy including lithogeochemistry of volcanic and plutonic rocks. Some discussion of deformation and structures based on geo-physics data also.
Skiöld, GFF, v.103, p. 317	1982	Radiometnc ages of plutonic and hypa-byssal rocks from the Vlttangl-Karesuan-do area, northern Sweden	U-Pb ziron (TIMS) and Rb-Sr (whole-rock) ages of granitoids in the Vittangi area with discus-sion of intrusion and metamorphic implica-tions
Lilljequist, SGU Brap81026, 43 p.	1981	Kobolts geologiska uppträdande, före-komster i Sverige och uppslag i Norr-botten samt synpunkter på fortsatta prospekteringsinsatser i Norrbotten	Summary of cobalt prospects in Norbotten. General descriptions.
Gerdin et al., SGU Brap80057, 14 p.	1980	Luoheankorvenmaa - Pysäjärvi sam-manställning av utförda prospektering-sarbeten	Deposit description, geology and exploration activity, with maps
Danielson et al., SGU Brap80054, 40 p.	1980	Nunasvaaraområdet. Sammanställn-ing av sulfidmalmsuppslag och utförda prospekteringsarbeten.	Nunasvaara deposit - geology and exploration report with several maps and geochem.
Gerdin et al., SGU Brap80051, 27 p.	1980	Tievakoski - Airijärvi resultat av utförda prospekteringsarbeten.	Deposit description, geology and exploration activity, with maps
Danielson & Johansson, SGU Brap80050, 20 p.	1980	Äijärova. Kompletterande prospektering-sundersökningar.	Summary of geology and exploration results at the Äijärova deposit.
Lundqvist, SGU C 366, 87 pp.	1979	The Precambrian of Sweden	General review of the precambrian rock units in N Sweden
Danielson & Johansson, SGU BRAP79011, 8 p.	1979	Jänkkä Fe-Cu-C deposit prospektering report	Deposit description, geology and exploration activity, with maps
Danielson & Johansson, SGU BRAP78007, 12 p.	1978	Äijärova - resultat av geologiska, geo-fysiska och geokemiska arbeten samt borrning.	Summary of geology and exploration results at the Äijärova deposit.
No author, SGU Brap00682, 42 p.	1978	Projekt Norra Norbotten	Overview report of various mineralized locali-ties in Norbotten
Eriksson & Hallgren, SGU Af 13 - 16, 203 pp.	1975	Beskrivning till berggrundskartbladen Vittangi NV, NO, SV, SO	Sythesis report on the bedrock geology of Vit-tangi NV, NO, SV, SO 1:50 000 map sheets
Shaikh, SGU Brap00876, 20 p.	1972	Sammanställning över grafitförekom-sterna i det centrala Vittangifältet, Norrbottens län	Description of graphitic deposits at Vittangi with two maps.
Nilsson, SGU Brap00864, 33 p.	1971	Östra Äijäjärvi - malmberäkning över kopparmineraliseringen.	Description of geology and mineralization at Östra Äijäjärvi. Maps and borehole data.

Table 4. Contunued.

Reference	Year	Title	Brief Overview
Eriksson, SGU Brap00881, 180 p.	1969	Berggrunden inom det centrala Vittangifältet dess petrografi, stratigrafi och tektonik.	Review of the geology and mineralization NW of Vittangi. Summary of mapping investigations.
Magnusson, Quart. J. Geol. Soc., v.121, p. 1	1965	The Pre-Cambrian history of Sweden	Regional overview of Precambrian geology. Read from p. 20 for overview of Karelian rocks of Norbotten
Frietsch, SGU C 592, 34 p.	1963	Järnmalmsförekomster inom Norrbottens län.	General review of iron ore deposits in Norbotten.
Ödman, SGU Ca 41, 151 pp.	1957	Beskrivning till berggrundskartbladen över urberget i Norrbottens Län	Synthesis report on the bedrock geology of Norbotten based on 1:400 000 regional map
Gavelin, Geochem. Cosmochem. Act., v.12, p. 297	1957	Variations in isotopic composition of carbon from metamorphic rocks in northern Sweden and their geological significance.	C isotope study of graphitic schists including samples from Nunasvaara.
Magnusson, SGU Brap93041, 45 p.	1937	Sveriges tillgångar av användbara mineral o bergarter	Broad description of mineral resources and geology. No maps.
Geijer, SGU C 367,	1931	The iron ores of the Kiruna type. Geographical distribution, geological characters and origin.	Regional review of the geology of Norbotten with focus on Kiruna-type greenstones and ore deposits

din et al. (1981) show a detailed geological map of the Tievakosi area and report geochemical and geophysical anomalies associated with Fe-oxide and Cu mineralization. Likewise, Danielson et al. (1980) show geological and related soil geochemical anomaly maps for the Nunasvaara deposit. Danielson and Johansson (1980) show geological and geochemical anomaly maps of the Äijärova area and also report drill core assay values from the Cu-Mo mineralization. Shaikh (1972) shows scanned maps of the Nunasvaara graphite deposits.

Outcrops

Figure 2 and 3 show the locations of known outcrops and exposed rock areas across the NKA. Metasediments in the western part are the best exposed. There is some reasonable exposure of metasedimentary rocks in the NE also. Likewise, some outcrops of intrusive rocks occur in the south along route E45. The central part of the NKA (metabasalts) has the least exposure.

Published material (papers and reports)

A list of the most important papers and reports for the NKA is presented in Table 4. The overview column gives a brief description of the type of study carried out. References for additional historical exploration reports can be found using the GeoRegister service on SGU's website. Several of these publications are review papers that summarize the broad geological framework for the NKA. Other papers relate to specific studies carried out within or adjacent to the NKA, or regional studies that incorporated one or more samples from either the greenstone supracrustal rocks or the intrusive units.

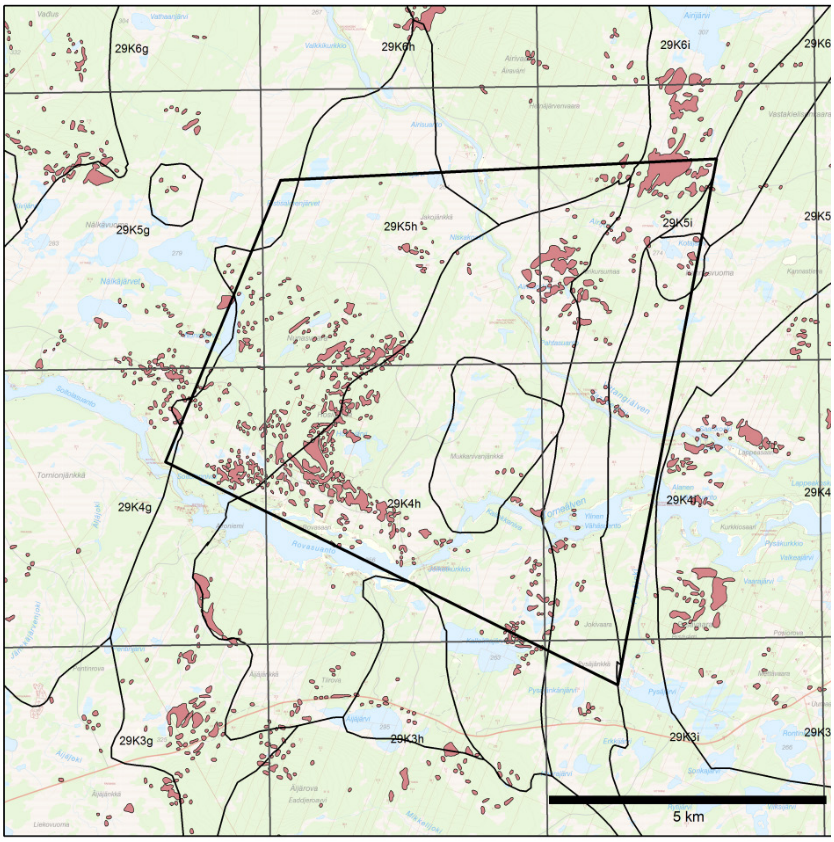

Figure 3. Interpreted outcrop locations and exposed areas in the NKA based on the field maps listed in Table 3.

Drill core

This section contains information on the drill core that is available at Malå. Table 5 lists the number of holes and core associated with mineral prospects within or adjacent to the Nunasvararra key area. In total, 42 drill holes are available the majority of which interest metargillitic and metabasic rocks within the Vittangi Greenstone Group. The length of the available drill holes is estimated (where recorded) in Table 5, along with the number of available drill logs and the most relevant exploration reports. More recent drill core may be available from exploration companies.

Mineralization and alteration

The VGG, which forms the central part of the Nunasvaara key area, contains 61 mineral deposits, prospects or showings. The main commpodity in the area is graphite-bearing schists (e.g., Nunasvaara). Gerdin et al. (1990) describe the main characteristics of these graphite-bearing deposits. Lesser Fe and Cu mineralization (e.g., Airikurkkio and Äijäjärvi Östra, respectively) also occurs in the area. Fe and Cu mineralization occurs as veins and disseminations in metavolcanic rocks. The location of these mineralized localities is shown in Figure 4. It also highlights those mineralized localities where archived drill core is available at Malå (circled). Numerous mineralized boulders localities have also been mapped in the Nunasvaara area as illustrated in Figure 5. A basic description of the type of mineralization accompanies the point dataset available within ArcGIS.

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

Deposit/prospect	No. of holes available	Total length	Logs, assay data, reports
Airijoki (carbonates)	3, part of Tievakoski	426m in slate/metaargillite	3 paper logs scanned (part of Tievakoski); brap 80051
Airikurkkio (C-V-Fe-Ti)	2 (of 6), LKAB	340m in metagabbro	6 paper logs scanned; ki8315, ki8133, brap876
Airikursumaa (Cu)	2, part of Airikurkkio	340m in metagabbro	2 paper logs scanned (part of Airikurkkio),ki8315, ki8133, brap876
Jänkkä area (Fe-Cu-C)	4 (of 7), 1 hole linked to Äijärova	approx. 500m in slate/metaargillite	7 paper logs scanned, brap79011
Kalloka (C)	2, PAB	no data, in granitoid	no paper logs
Kuusi Nunasvaara 3 (Fe-Cu-C)	2	430m in slate/metaargillite	2 paper logs scanned, brap80054
Nunasjärvenmaa area (Fe-Cu)	1	188m in slate/metaargillite	2 paper logs scanned, brap80054
Nunasvaara (Fe-C-Zn-Pb)	2, part of Kuusi Nunasvaara 3	430m in slate/metaargillite	2 paper logs scanned, ki8133; k8704, brap876
Rovasuanto (Cu)	1	114m in metagabbro	2 paper logs scanned, brap80054, BRAP00682
Svanbolandet area (Fe-Cu)	1	no data, in slate/metaargillite	1 paper log scanned, brap80054, brap00863, BRAP00879
Tievakoski	11, 3 holes linked to Airijoki	>1400m in shale/metaargillite, gabbro	11 paper logs scanned, brap80051, prap_91045, BRAP98027
Äijäjoki (Fe)	3, part of Jänkkä and Äijärova	>340m in slate/metaarggilite	no paper logs, Eriksson & Hallgren (1975)
Äijäjärvi (Cu-Zn)	12	1320m in metabasalt/andesite in granite	12 paper logs scanned, BRAP 00864, brap81026, Skiöld (1982)
Äijärova area (Mo-U-C)	10	no data, in metadolerite & graphitic schist	12 paper logs scanned, brap78007, prap90068, brap80050

Alteration is dominated by a regional scapolite–epidote assemblage afftcting most lithologies although it is most developed within schistose rocks of the VGG (Fig. 6). Albite and carbonate alteration is also present. There appears to be a spatial correlation between the hydrothermal alteration and mineralization. However, detailed investigations of the alteration paragenesis in the area have not been conducted or wether their are several alteration generations and the nature of their temporal and genetic relationship to Fe-oxide and Cu mineralisation.

Additional datasets are available on SGU's databases relating to the mineral deposit inventory and are listed in Table 6. These include the layers relating to drill hole and core locations, prospecting licence blocks, alteration mineral locations and zones of metallogenic importance.

Geophysics

Airborne data (magnetic, gamma spectrometry)

Several airborne geophysical surveys have been made over the NKA. A comprehensive list of these measurements can be found in Table 7. During 1962–1963, SGU made airborne surveys over the entire map sheet 29K. Their geophysical instrumentation consisted of a fluxgate magnetometer. In 1972, SGU made a new airborne survey over the entire map

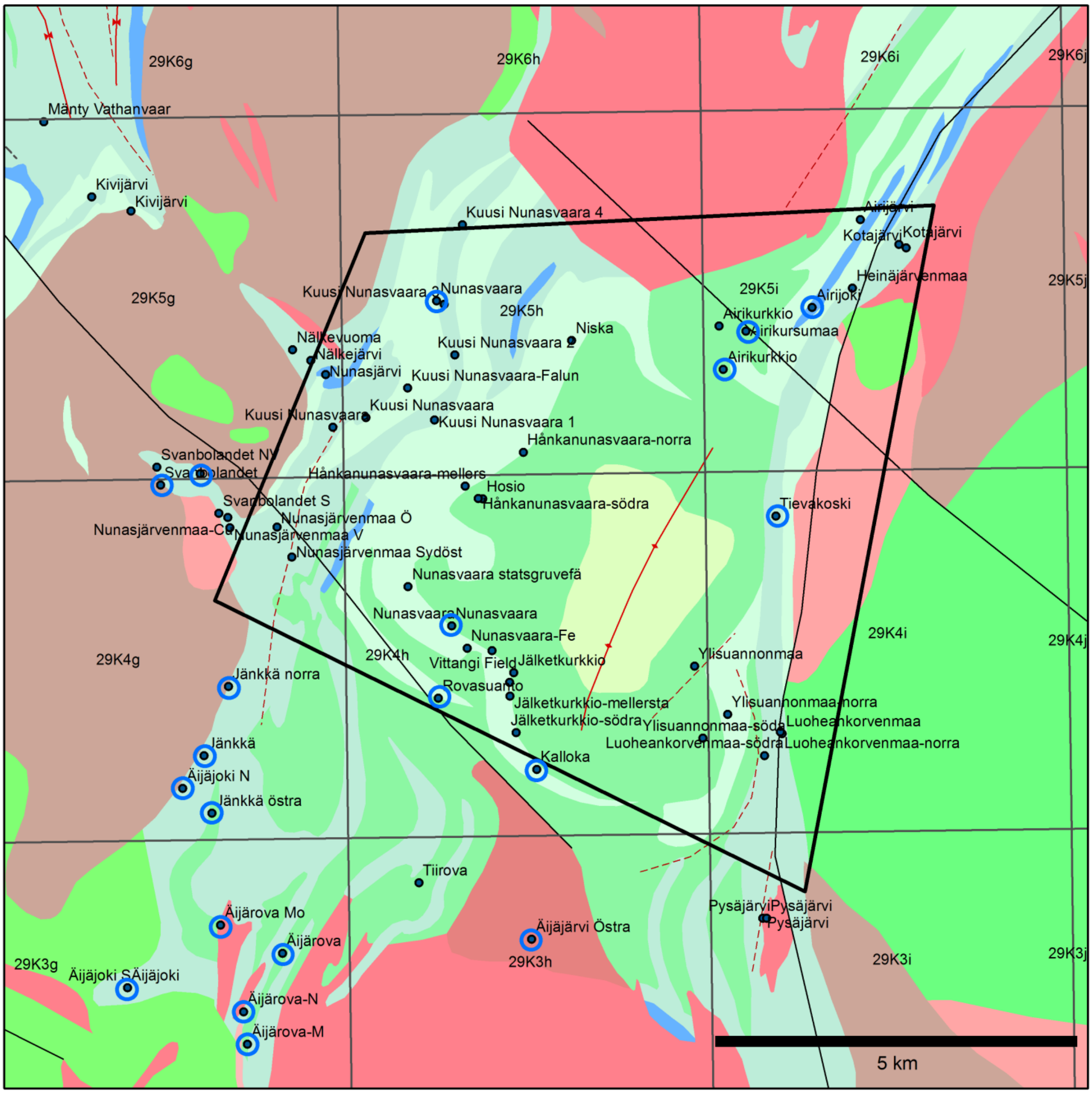

Figure 4. Mineral deposits and prospects within the Nunasvaara area. Locations with associated drill core (at Malå) are circled.

sheet 29K. The fluxgate magnetometer had been replaced with a trums, and a gamma spectrometer had been added to the geophysical equipment. The next airborne survey over the NKA, made in 1976, was equipped with a trums magnetometer, gamma spectrometer and a VLF-receiver, capable of acquiring electromagnetic data from one transmitter. In 1983, LKAB made two airborne surveys over almost the entire map sheet 29K. 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.

All of the airborne geophysical surveys made over the NKA were flown at 30 m above ground level, with a 200 m flight line separation along east to west flight lines, which preferentially highlights magnetic structures striking along a north–south trend. A magnetic anomaly map over NKA and its surroundings is shown in Figure 7.

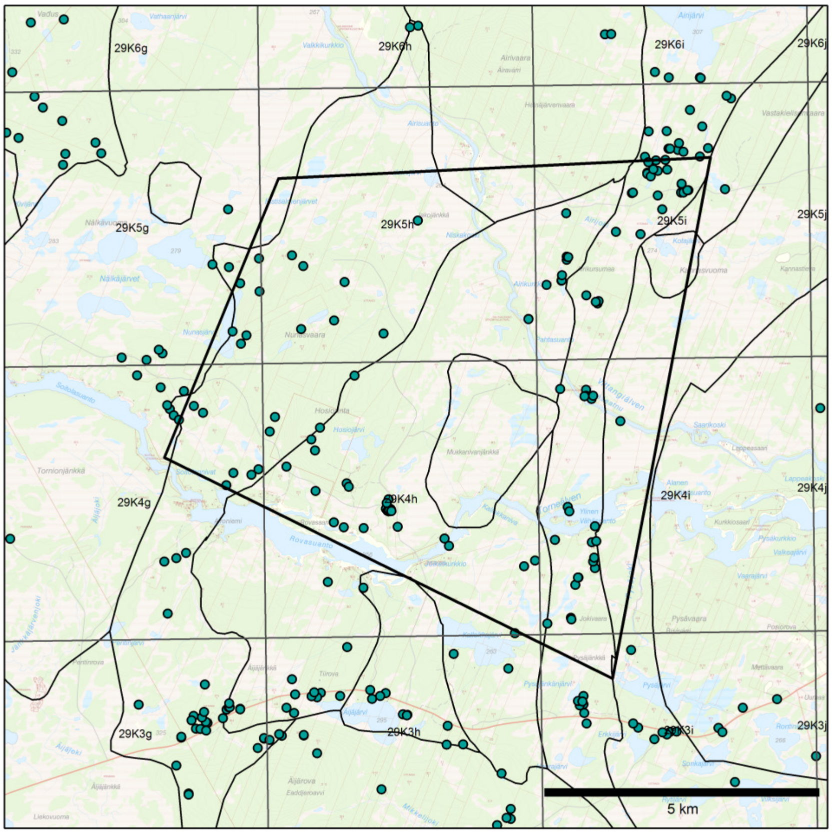

Figure 5. Location of mineralized boulders in the Nunasvaara area.Majority are described as containing sulfide mineralisation.

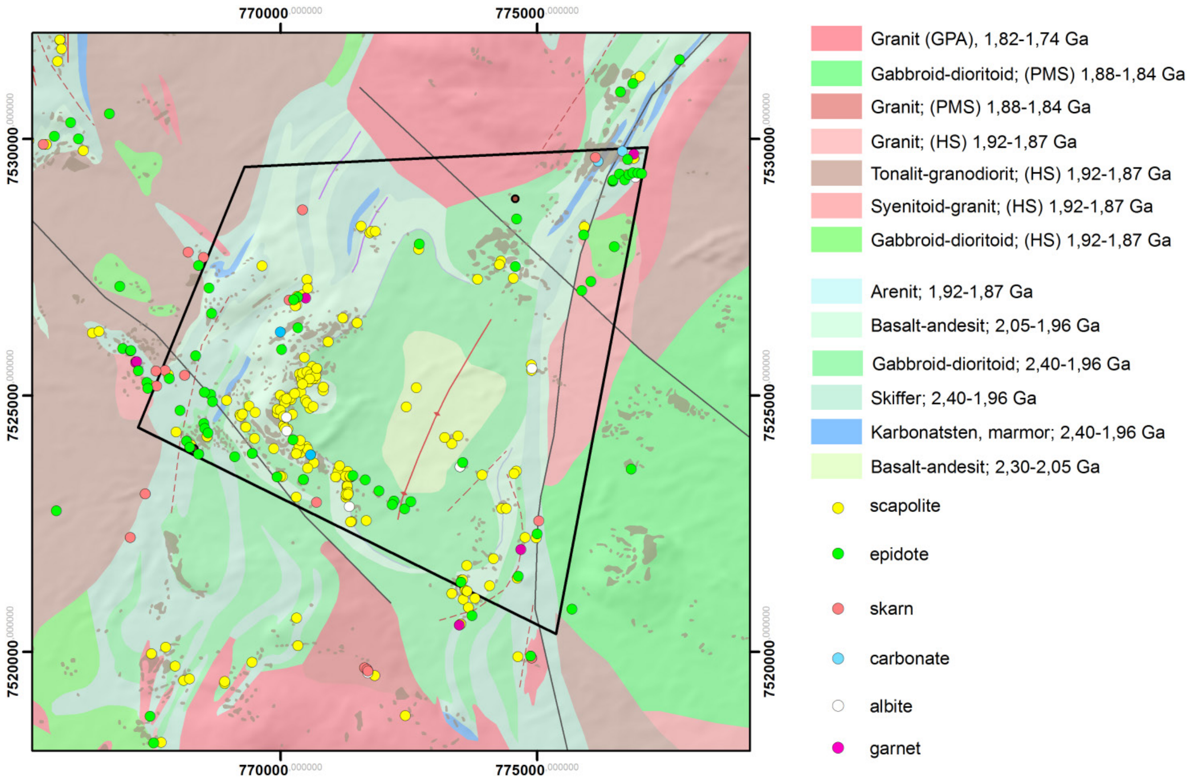

Figure 6. Location of mapped alteration minerals within the NKA

Table 6. Mineralization and alteration-related datasets for the Nunasvaara area

Layer/dataset	Description	Grid location	Reference
Borrkärna_20110405	Location and description of drill core available at Malå	29K 3h/i/, 4g/h/i, 5g/h/i	SGU database
Borrhål_20110405	Historical drill core including Malå core and core no longer available at Malå	29K 3h/i/, 4g/h/i, 5g/h/i	SGU database
Mineralresurser_mdep	Location and description of mineralisation prospects, showings and deposits	29K 3h/i/, 4g/h/i, 5g/h/i	SGU database
FODD Barmin	Vector point of mineralisaed areas with basic descriptions	29K 4g, 5h, 3h	SGU database
Metallogenetic areas	Vector polygons of metallogenic areas	29K 3h/i/, 4g/h/i, 5g/h/i	SGU database
undersökningstillstån_ beviljade	Granted prospecting licence blocks (polygons)	29K 3h/i/, 4g/h/i, 5g/h/i	SGU database
Mineralrättsregistret (MRR10)	polygons of mineral resource areas	29K	SGU database
Riksintressen mineral	state interest mineral	29K 4h	SGU database
boulders_mineralized	mineralized boulder locations	29K 3 g/h/i, 4g, 4h, 4i, 5g, 5h, 5i	SGU database
alteration minerals	Point locations of mapped alteration minerals	29K 3 g/h/i, 4g, 4h, 4i, 5g, 5h, 5i	SGU database

Table 7. A complete list over the airborne geophysical surveys that have been made over the NKA.

Year	Company	Geophysical methods used	Area	Flight direction	Flight line separation (m)	Flying altitude (m)
1962	NSG	Magnetics	29K SW & 29K SE	East-west	200	30
1963	NSG	Magnetics	29K NW & 29K NE	East-west	200	30
1972	NSG	Magnetics, gamma spectrometry	29K	East-west	200	30
1976	NSG	Magnetics, gamma spectrometry, VLF (1-transmitter)	Almost entire 29K	East-west	200	30
1983	LKAB	Magnetics, gamma spectrometry, VLF (2-transmitters), slingram	29K SW & 29K SE (project R7)	East-west	200	30
1983	LKAB	Magnetics, gamma spectrometry, VLF (2-transmitters), slingram	Almost entire 29K NW & 29K NE (project R11)	East-west	200	30

Ground-based magnetics

There have been extensive ground-based magnetic measurements made within the NKA where detailed, ground based magnetometer surveys have carried out (Fig 8). Almost the entire area is covered by these measurements and a comprehensive list can be found in Table 8.

Ground-based gravity

There have been extensive gravity measurements throughout the NKA and surrounding areas. The dense gravity measurements (represented as yellow circles in Figure 9) were made by NSG in 1987 and the total amount of gravity points in this survey is 11624. The majority of gravity data in the NKA can be found around the iron deposits of Kuusa Nunasvaara (coordinates 7527000/770300) and Nunasjärvenmaa (7525300/767800). In general, lithologies with higher densities (e.g., basalt) give rise to positive gravity anomalies compared to more felsic bedrock units which can be seen as negative anomalies in the gravity map. There is a pronounced positive gravity anomaly extending from Kuusa Nunasvaara and further towards SSW which corresponds to Vittangi Greenstone Group lithologies. At the south-

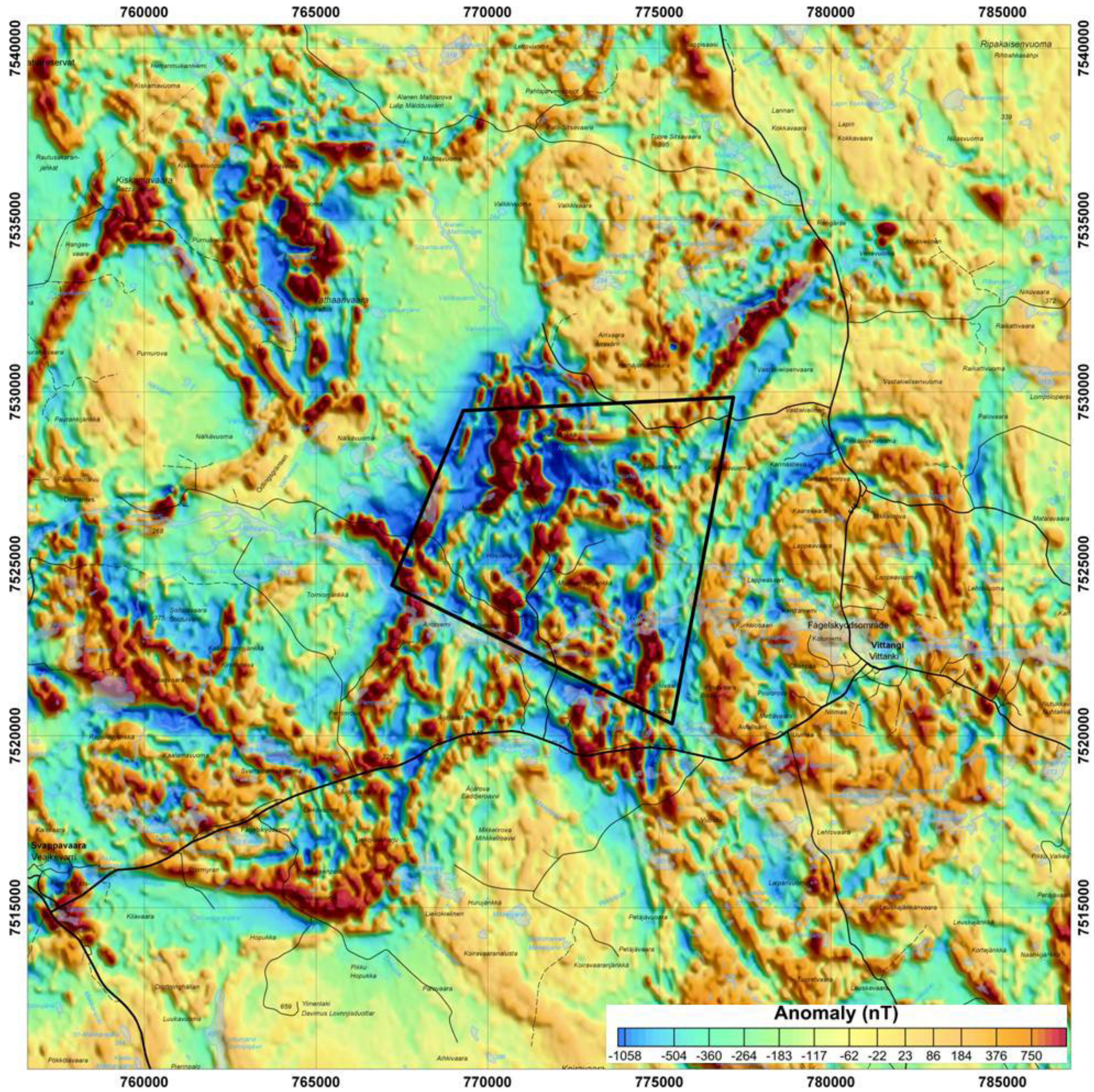

Figure 7. The magnetic anomaly map within the NKA (shown as a black polygon in the middle of the map) and its surroundings. The map is derived from the newest airborne magnetic data and has been filtered in order to enhance the magnetic response from more shallow seated lithologies.

western border of NKA the gravity high branches out into an ellipsoid while another gravity high extends towards ESE and then continues back into the NKA.

SGU has made dense gravity measurements both towards the north and south of Nunasvaara, contained within the polygon marked "1" in Figure 9. These surveys were carried out in 1964–1967.

Ground-based geoelectric and electromagnetic surveys

The most recent airborne geophysical survey over NKA was made in 1983. In that survey, VLF-information from two transmitters was acquired. The information can then be used to produce maps which show how the electrical conductivity varies in the ground (Fig 10)

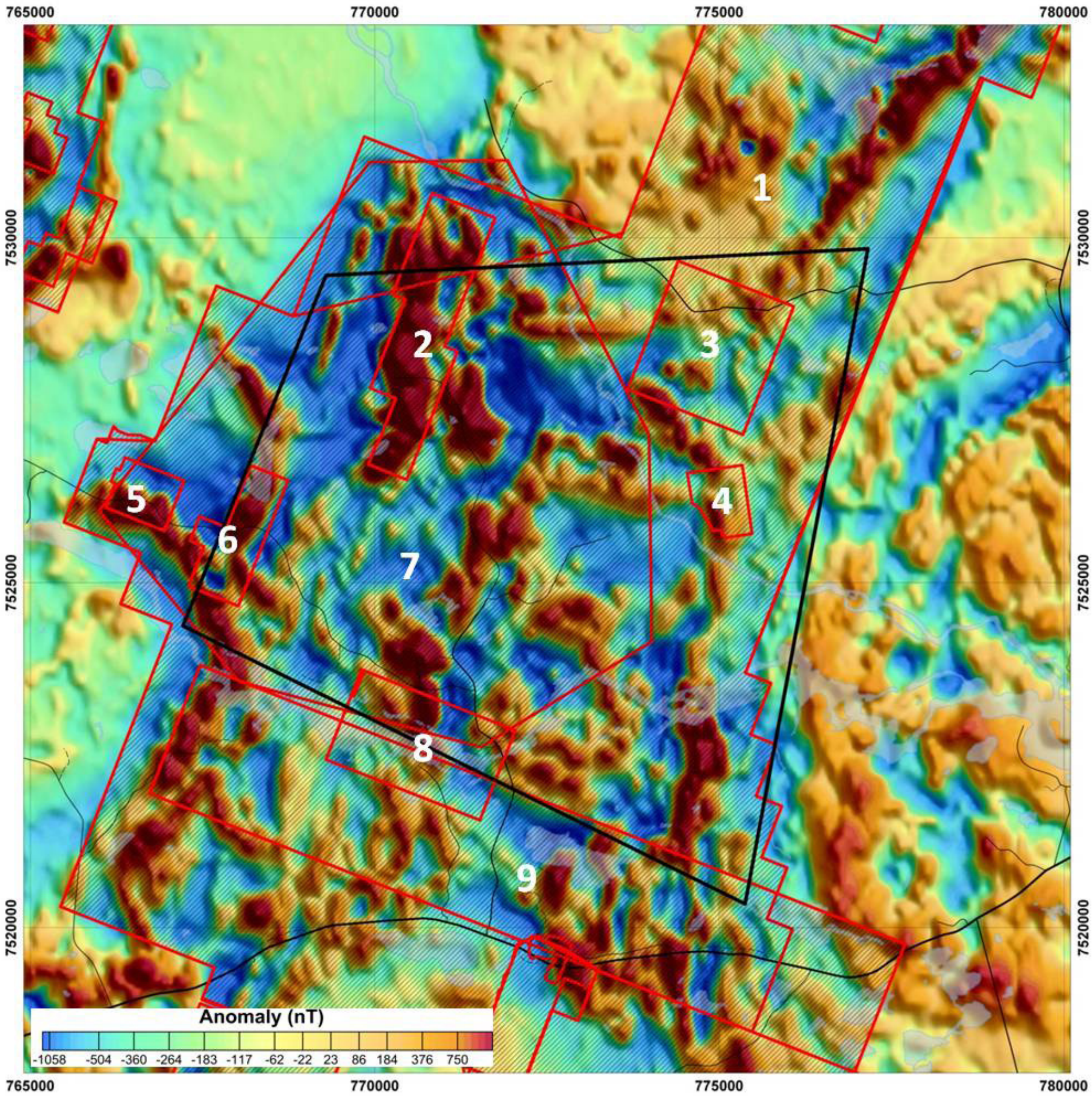

Figure 8. The magnetic anomaly map within the NKA and its closest surroundings. The red polygons represent the distribution of ground magnetic surveys. Explanations for the numbered polygons can be seen in Table 8.

Table 8. A list over the magnetic ground surveys within the NKA and its closest surrounding. The numbers in column "Polygon nr" refer to those found in Figure 8.

Polygon nr	Name	Method	Operator	Year of measurement
1	Vittangi-omr.	Magnetometer Z-anomaly	SGU	1965-1968
1	Vittangiområdet	Magnetometer	SGU	No information
2	Vittangiområdet	Magnetometer	SGU	1964-1968
3	Airikurkkio	Magnetometer total field	LKAB Prosp. AB	1983
4	Tievakoski	Magnetometer	No information	1986
5	Vittangiområdet C	Magnetometer	SGU	1965-1968
6	Vittangiområdet	Magnetometer	SGU	1965-1968
7	Svanbolandet-Nunasvaara	Magnetometer Z-anomaly	SGU	1980
8	Rovasuanto	Magnetometer Z-anomaly	SGU	1974
8	Rovasuanto	Magnetometer	SGU	1974
9	Vittangiområdet Centrala	Magnetometer	SGU	1964-1967

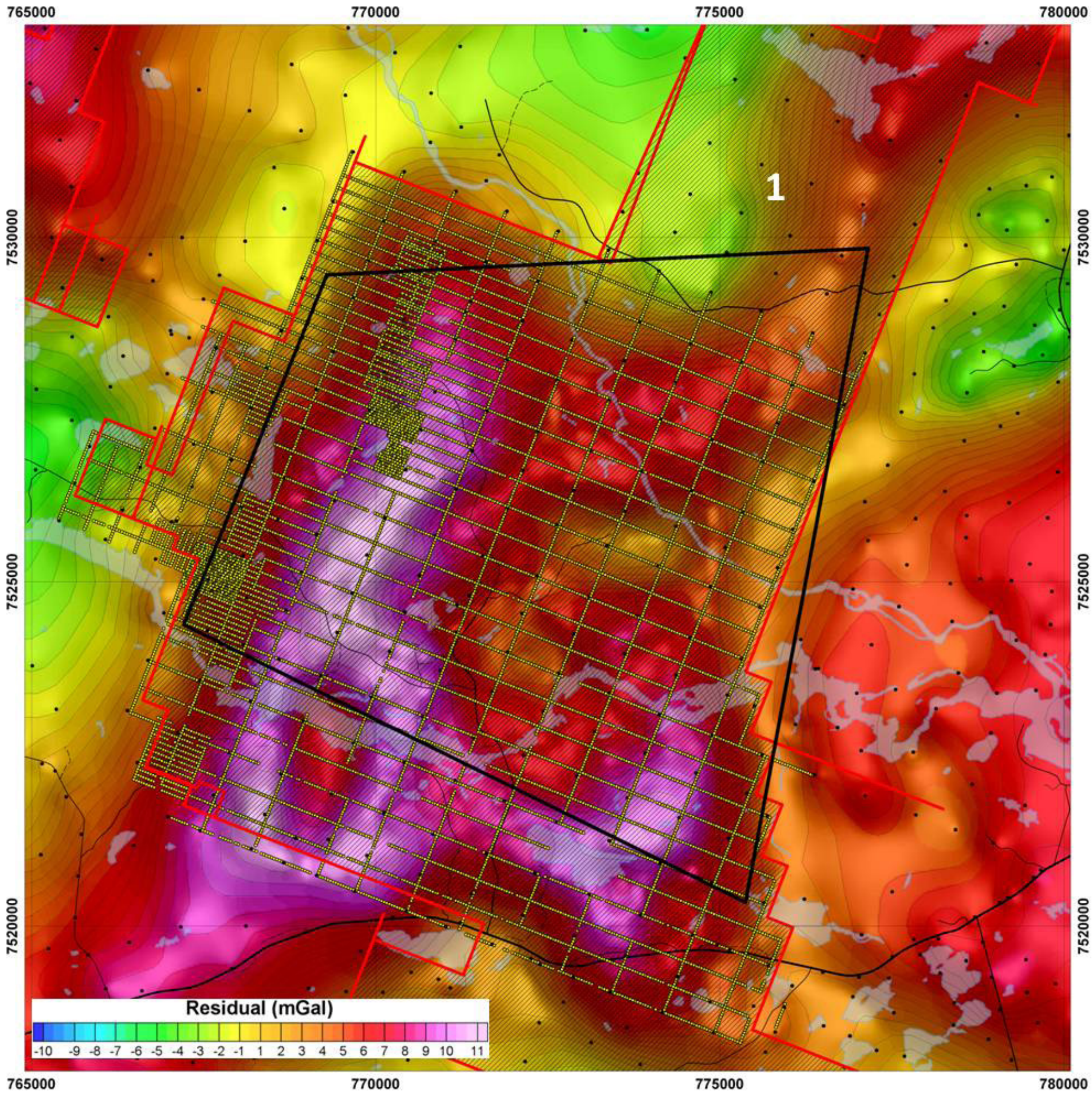

Figure 9. The residual gravity field within the NKA and its closest surroundings. The gravity data has been filtered to enhance density variations from more shallow seated lithologies. Black dots represent regional gravity measurements while yellow dots and red polygons show the location where more dense investigations have been made.

independent of their strike direction with respect to the VLF-transmitter. Red areas in Figure 10 represent features with higher electrical conductivity compared to those shown in blue.

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

Petrophysics

There are currently 328 petrophysical samples from the NKA. All of these samples have data regarding density, magnetic susceptibility and Königsberger ratio. The geographical distribution of these samples covers almost the entire area (Fig 11). The majority of measurements have been taken in the west and south west of the study area.

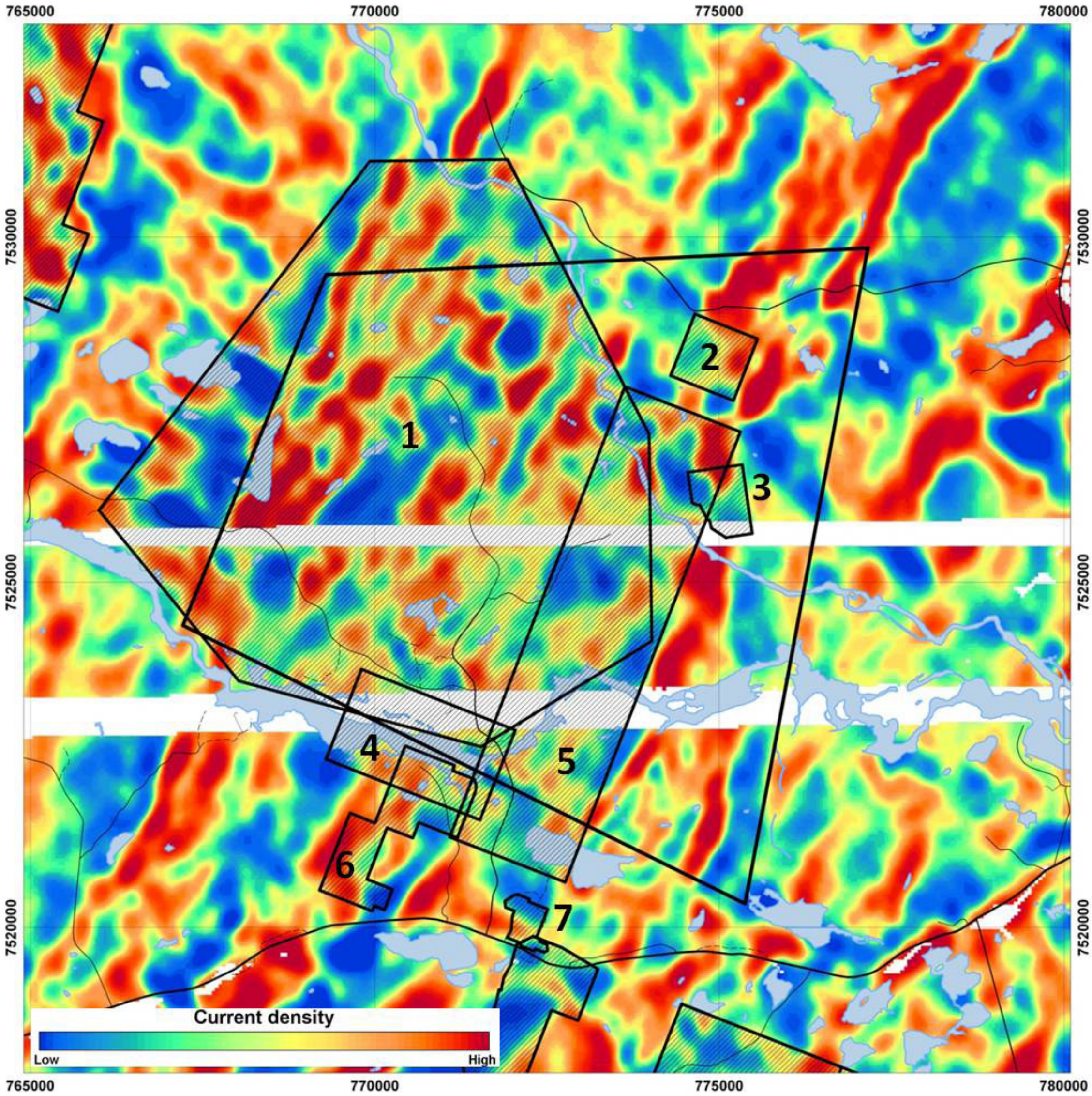

Figure 10. Map over the current density within the NKA and its closest surroundings. The map is based on airborne VLF-data from two transmitters. The black polygons with hatches represent locations where ground geoelectric and/or electromagnetic surveys have been made. Explanations for the numbered polygons can be seen in Table 9.

Geochemistry

Table 10 lists the main geochemical data available for the NKA. 21 lithogeochemical analyses have been made of various units within and adjacent to the area and are shown in Figure 12. The majority of analyses were determined on graphitic schists. These analyses primarily consist of major and limited trace element determinations. Only three granodiorite and two metabasalt samples have been analysed for additional REE concentrations. The lithogeochemistry of schistose and igneous rocks have been reported by Eriksson (1969). Further lithogeochemistry is summarized in Eriksson and Hallgren (1975) for the VGG basalts and adjacent intrusives. The majority of the remaining geochemical analyses in the area relate to till geochemistry measurements determined as part of SGU's regional till geochem-

Table 9. A list over the geoelectric and electromagnetic ground surveys within the NKA and its closest surrounding. The numbers in column “Polygon nr” refer to those found in Figure 10.

Polygon nr	Name	Method	Operator	Year of measurement
1	Svanbolandet-Nunasvaara	Slingram	SGU	1963
2	Tievakoski	IP, R, SP	SGU	1979
3	Tievakoski	Slingram	No information	1986
4	Rovasuanto	Slingram	SGU	1974
5	Airikurkkio	VLF	LKAB	1978
6	S. Rovasuanto	IP, R, SP	SGU	1979
6	Södra Rovasuanto	IP	No information	1979
7	Rovasuvanto	IP, R, SP	SGU	1976

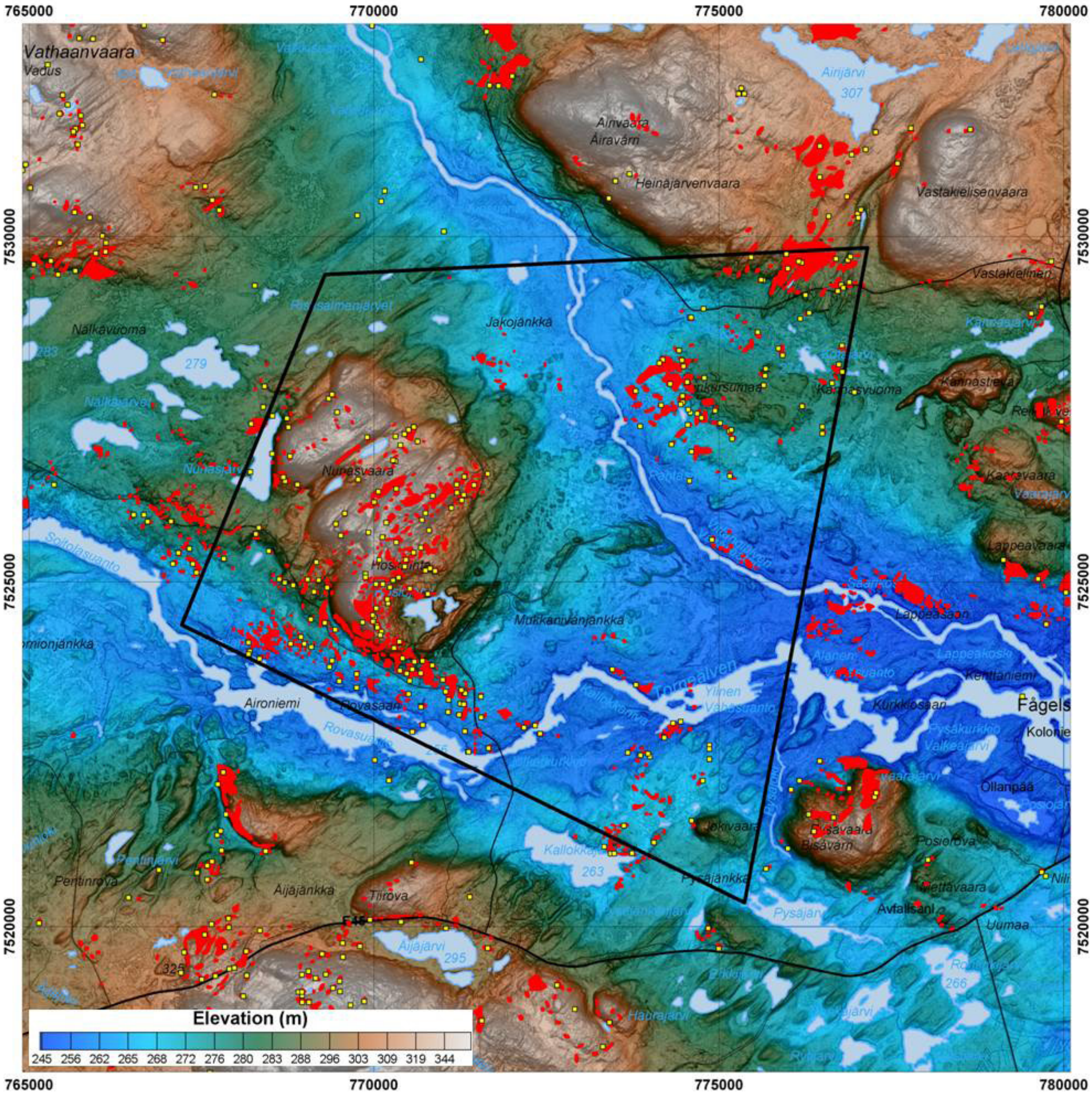

Figure 11. The topography within NKA and its closest surroundings based on LiDAR data (2×2 m DEM). The red polygons represent outcrops and yellow dots show the location for existing petrophysical bedrock samples.

istry programme. Mapped anomalies of Cr, N, Co and Cu appear to reflect the underlying mafic to intermediate bedrock of the VGG. No biogeochemical data was found for the area.

Geochronology

10 ages have been determined for rocks and minerals within or adjacent to the NKA (Table 11, Fig. 13). The most recent age determination by Smith et al. (2009) is 1903 ± 8 Ma for an altered metadolerite/gabbro intrusion on the eastern limb of the Nunasvaara anticline.

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

Layer/dataset	Description	Grid location	Reference
Lithogeochemistry	24 lithogeochemival analyses of various rock types (mostly supracrustal, intrusive) in and around the key area.	29K 5g/h/i/j, 4g/h, 3g/h/j	SGU Af 13,14,15,16; Skiöld et al 1988; SGU Ai 98,99,100,101
moränkemi_NSG	Points data of moraine geochem	29K 5i, 4g/h, 3g/h/i	SGU database
moränkemi_xrf	Points data of moraine geochem by XRF	29K 5g/h/i, 4g/h/i, 3g/h/i	SGU database
LIKE_supracrustals	Points data of rock geochem - partial analysis of some metals	29K 5g/i, 4g/h, 3g	SGU database
LIKE_next_BARMIN	Points data of rock geochem - partial analysis of some metals	29K 5g/i, 4g/h, 3g	SGU database
NK_mroes_Cu	Points data of rock geochem - Cu assay data	29K 4g	SGU database
Morän <2mm	Point location of geochemistry of till moraine < 2 mm	29K 5g/h/i/, 4g/i, 3g/i	SGU database
Markgeokemi, raster 250m	Raster layer of till geochemistry at 250m resolution for 9 elements.	All of the study area	SGU database
Morän finfraktion	Point locations of moraine geochemistry analysis of till fine fraction	29K 5g/h/i/j, 4g/h, 3g/h/j	SGU database

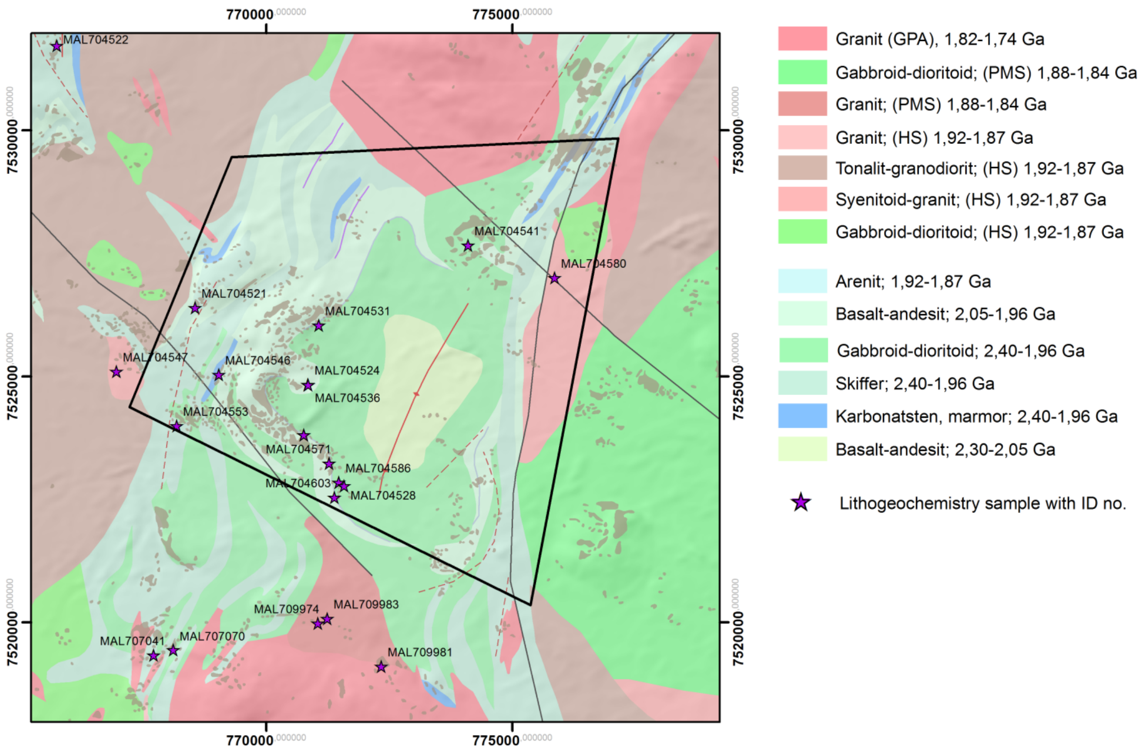

Figure 12. Lithogeochemistry sample locations within the NKA

This age has been used to constrain the timing of metasomatic alteration in the area, as well as for northern Norrbotten as a whole. Previous Rb–Sr ages (e.g., Skiöld, 1981) likely reflect isotopic resetting by late metamorphic events or uplift and have been generally disregarded in the more recent literature. Several U–Pb age determinations (Skiöld, 1981) do not report uncertainties and are based on the regression of small numbers of zircon separates. Further geochronology of specific geological processes (magmatism, mineralization, alteration) should be a project priority.

Isotope geology (excluding age dating)

Skiöld et al. (1988) report Sm–Nd results for granitoid and gabbroic rocks adjacent to the NKA. The results indicate εNd(T) values ranging between –4.4 to –8.1. These data suggest partial melting of the Archean basement provided a source component for the intrusions. Some addition of juvenile mantle material is also envisaged. In addition, Figure 1 in Öhlander et al (1993) shows a regional-scale map of Norrbotten with Sm–Nd data point locations. Several of these points are close to the NKA and represent the Sm–Nd isotopic characteristics of granitoid rocks in the area that generally have εNd(T) values of less than –6.0. Again, this indicates a crustal evolution and derivation of granitoid melts from the Archean basement. Several of these results included the work of Skiöld et al. (1988). A sTable sulfur isotope investigation by Frietsch et al. (1995) suggests that syngenetic sulfide mineralization within Svecokarelian greenstones was controlled by seawater sulfate reduction by bacteriogenic processes. In contrast, sulfide mineralization hosted by younger Svecofennian volcanics (Porphyry Group) derived its sulfur from primary magmatic (volcanic) sources. A carbon isotope study (Gavelin, 1957) was carried on graphite occurrences in northern Sweden which included samples from the NKA. A correlation between the recorded carbon isotopic signature and the degree of metasomatism was not established. Likewise, it was not possible to correlate observed isotopic fractionations with any specific sedimentary or biogenic process.

Geographical data

Table 12 lists several topographic datasets that cover the NKA. The most useful information can be derived from the orthophotos and two DEM models developed at resolutions of 2 and 50 metres. Vögkartan contains vector polygons of contours with a 10m interval. The NKA 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 NKA 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 bedrock geology of the NKA can be subdivided into two major groups: (i) the 2.40–1.96 Ga (Karelian) Vittangi Greenstone Group (metamorphosed basalts, doleritic intrusives, tuffaceous volcanics, epiclastic sediments, marbles) which forms a central, deformed

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

Age (Ma)	±	System	Material	Host rock	Litho. Unit	Area	Ref	Year
1903	8	U-Pb	Titanite	Altered metado-lerite	Metadolerite intruding VGG	Vittangi	Smith et al.	2009
1794	24	U-Pb	Zircon	Granite	Vettasjärvi granite, Lina type	Vettasjärvi	Skiöld et al.	1988
1757	43	Rb-Sr	WR	Granite	Vettasjärvi granite, Lina type	Vettasjärvi	Skiöld	1981
1795	180, 94	U-Pb	Zircon	Granite	Vettasjärvi granite, Lina type	Vettasjärvi	Skiöld	1981
1863	No data	U-Pb	Zircon	Perthitic granite	Äijäjärvi granite, PMS	Vittangi	Skiöld	1981
1725	16	Rb-Sr	WR	Perthitic granite	Äijäjärvi granite, PMS	Vittangi	Skiöld	1981
1707	77	Rb-Sr	WR	Altered granodi-orite	Lehtovaara granodiorite to syenite, HS	Vittangi	Skiöld	1981
1860	No data	U-Pb	Zircon	Altered granodi-orite	Lehtovaara granodiorite to syenite, HS	Vittangi	Skiöld	1981
1777	98	Rb-Sr	WR	Granodiorite	Kilavaara-Hopukka granodiorite, HS	Svapavarra	Skiöld	1981
1842	5	U-Pb	Zircon	Granodiorite	Kilavaara-Hopukka granodiorite, HS	Svapavarra	Skiöld	1981

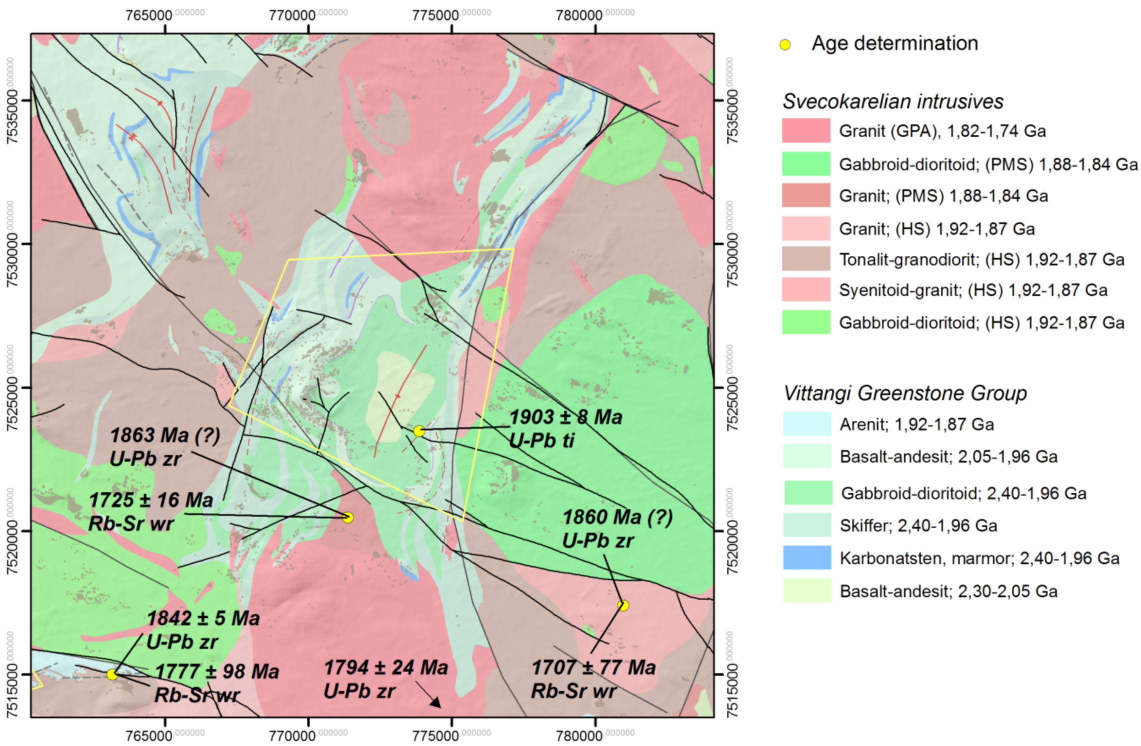

Figure 13. Geochronology of rocks units within and adjacent to the NKA.

Table 12. Topographic datasets covering the NKA

Layer/datset	Description	Scale	Reference
Höjdmodell och terrängskuggning 2m	Raster DEM data at 2m resolution		SGU database
Höjdmodell	Raster DEM data at 50m resolution		SGU database
Visningstjänst ortofoton	Raster orthophotos, colour and IR		SGU database
Sverigekartan 1 milj (2012), LM-manér	vector lines and polygons topo map LM style	1:1 000 000	SGU database
Sverigekartan 1 milj (2012), SGU-manér	vector lines and polygons topo map SGU style	1:1 000 000	SGU database
Sverige 1:5 milj (2012)	vector polygon outline of Sverige	1:5 000 000	SGU database
Landskap	vector polygons of counties? Regions in Sweden	1:20 000 000 ?	SGU database
Vägkartan, LMV-manér	Raster road map of Sweden LM style		SGU database
Översiktskartan 2007, SWEREF99 TM	Raster topo map of Sweden - small scale		SGU database
Visningstjänst allmänna kartor	Raster topo map of Sweden - small scale		SGU database
Svenska Marktäckedata	vector polygons of landuse for Sweden		SGU database
norrbotten_lan_klippram_sweref	vector outline of Norrbotten Län		SGU database
Rutor_5 × 5_km	polygon grid of topographic map squares 5 × 5 km		SGU database
Rutor_50 × 50_km	polygon grid of topographic map squares 50 × 50 km		SGU database

inlier, and (ii) younger 1.88–1.78 Ga (Svecokarelian) gabbroid and granitoid intrusives that surround the VGG. These intrusives belong to HS (metamorphosed), PMS (weakly metamorphosed) and GPA (Lina type, fresh) plutonic lithologies (Bergman et al. 2000). Minor aplite–pegmatite and mafic veins and dykes are also present across the area.

Protolith ages

Age constraints on the various rocks of the VGG are based on the results of Skiöld (1981, 1986) and Skiöld and Cliff (1984) and summarized in Table 8 of this report and Table 1 of Skiöld (1987). The ages of the VGG metabasalts and metasediments has been inferred from studies of greenstones within the Kiruna area (e.g., 1,9 to 2,2Ga, Skiöld and Cliff 1984, Skiöld 1986). Thus, no measured ages exist for the lithological units within the VGG within the key area. The majority of age determinations for the NKA have been applied to the surrounding intrusive rocks which include several unreliable Rb–Sr ages (Skiöld 1981). Smith et al. (2009) dated hydrothermal titanite from a metadolerite in the area. This single age has been used to constrain regional hydrothermal alteration and mineralization for northern Norrbotten as a whole. Sulphide ages (e.g., Re–Os) to constrain the timing of mineralization have not been determined in the area.

Structural framework

The NKA is centrally located within a crustal block (Domain I, Bergman et al. 2001) that is bound to the east and west by regional-scale, ductile shear zones (NNE and NNW aligned, respectively). A third N–S-aligned ductile shear zone also occurs south of Vittangi but apparently does not continue across the area. A major NW aligned geophysical discontinuity at depth (ca. 5 km) transects the NKA (see Figure 50, Bergman et al. 2001). Locally the VGG is complexly folded and has undergone several deformation episodes. Folding is more conspicuous in carbonates and schists. The central zone of the VGG represents the hinge of a NNE orientated antiform. Numerous brittle faults (mostly NW-aligned) also occur across the NKA.

Metamorphism

Regional metamorphism in the NKA is poorly understood although the lithologies are interpreted to have been metamorphosed to lower amphibolite facies based on observed metamorphic mineral assemblages (Eriksson and Hallgren 1975, Bergman et al. 2001). The metamorphic grade is considered to be marginally higher in the Vittangi area if compared to analogues greenstones further to the west (cf. Martinsson 1993). The metamorphic nature of intrusive bodies has generally been obscured by later hydrothermal alteration. Some contact metamorphism affecting schistose rocks has been developed by the larger doleritic bodies. Likewise, localised skarnification of country rocks during emplacement of Haparanda-type plutons is developed in some areas (e.g., Sautusvaara 1975, Eriksson & Hallgren 1975). Late-stage, metasomatic (sodic to propyllitic) overprinting related to Fe-oxide, skarn and Cu mineralization is commonly developed across the area (see below).

Mineralization and alteration

Stratiform to stratabound banded Fe-oxide (e.g., Jänkkä), skarn-type Fe-oxide (e.g., Nunasjärvenmaa), Cu (e.g., Airikursumaa) and graphite (e.g., Nunasvaara) mineralization occur within schists, marbles and volcanics of the VGG. Fe-oxide mineralization is dominated by magnetite (Martinsson 1993). The Nunasvaara graphite deposit represents the largest known graphite resource in Sweden (ca. 7 Mt @ 24% Cg, Talga Resources 2012). Epigenetic vein- and breccia-hosted sulfide mineralization (Cu-dominated with Au, Mo, Co, Fe) also occurs within the VGG rocks and adjacent plutons (e.g., Äijäjärvi Östra, Äijärova). The absolute timing of these mineralization events is not well constrained for the area, however epigenetic mineralization clearly postdates the formation of the VGG. This phase of mineralization represents either a distinct metallogenic event or the remobilization of earlier formed metals during granitoid intrusion (e.g., HS and PMS intrusives). Alteration in the area is dominated by albitization, scapolitization and carbonitization (Frietsch et al. 1997, Martinsson 1993). The timing of sodic alteration (and by extension, mineralization) within the VGG is constrained at 1903 Ma (Smith et al. 2009).

DISCUSSION

Current understanding

The NKA is dominated by volcanic, volcaniclastic and sedimentary rocks that formed during one or more episodes of continental rifting and extension sometime between ca. 2200 Ma and 1900 Ma (Bergman et al. 2001). Associated hypabyssal doleritic intrusions are also preserved across the area. The supracrustal rocks are interpreted to represent a lower to middle stratigraphic position with respect to other Karelian greenstones elsewhere in northern Sweden (Fig 14). Approximately 3,5 km of stratigraphy is represented at the NKA, based on the production of composite logs from outcrop and drillcore (Fig 9 in Martinsson 1993). Deposition is thought to have occurred within a shallow marine, immaturely rifted, continental margin (or back arc basin?) setting with input from subaerial volcanism. Amygdaloidal basalts generally have a MORB-type tholeiitic character and are similar to Lower Greenstone basalts in the Kiruna area. WPB-type volcanics have not been reported. Mafic, pyroclastic, tuff-tuffite units follow (approx. 1 km), with the upper parts (500–800 m) containing intercalations of redeposited clastic material and chemical sediments (black schist, graphitic schist, carbonates, BIF, chert). Martinsson (1993) reports a MORB-type signature for most of the mafic pyroclastics. These pyroclastic units are similar to the Viscaria Formation at Kiruna. Shaikh et al (1989) give a brief description of the carbonate rocks in the Airijoki area (Upper Greenstone Formation?) that have been considered for their with potential for aggregate exploitation. They state that no chemical or mineralogical analysis of these carbonate rocks have been performed. Thus, there is potential to undertake a sedimentological and geochemical study of the carbonate rocks and their setting. Chemical sediments in the form of carbonates, skarn, chert and BIFs are more abundant within the VGG compared to the Kiruna greenstones further west. In general, basaltic rocks within the VGG are massive, thickly-bedded flows. Martinsson (1993) reported that no pillow basalts occur at the Nunasvaara area, however Erikson and Hallgren (1975) report the localized occurrence of pillowed basalts.

Öhlander et al. (1987) investigated the petrogenesis of the Vettasjärvi Granite, a typical ca. 1 800 Ma Lina-type granite SE of the NKA using lithogeochemistry and Sm–Nd analyses. These data show that the granite is a differentiated I-type granitoid with a melt source region primarily in Archean basement rocks with potentially some input from a juvenile (mantle?) component. No detailed study of HS or PMS rocks surrounding the VGG has been carried out. Mineralogical, lithogeochemical and isotopic data for most of the intrusive units is lacking.

Potential issues to be addressed

The rock types that occur within the NKA have been variously described by earlier workers (e.g., Ödman 1957, Eriksson and Hallgren 1975). In addition, the stratigraphic setting of these units has been proposed and correlated with the regional stratigraphy of other Karelian supracrustal rocks in northern Norrbotten (e.g., Martinsson 1993, 1997). However, several aspects of the geology of the NKA require further investigation. Potential questions that may need to be addressed are summarised below under some key headings.

Stratigraphy

What is the lateral extent and thicknesses of the formations proposed by Erkisson and Hallgren (1975)? To date, detailed logs showing internal depositional features and inter-unit transitions have not been published. This issue should be addressed by SGU. In addition, details on unit contacts should also be tackled. Is the VGG a conformable succession or are there tectonic/structural contacts?

Structure

The eastern and western limbs of the VGG antiform display several deformational events that have produced a complex tectonic pattern. How many deformational episodes can be recognized in the incompetent horizons (e.g., schists, marbles)? Can these be correlated with the regional deformation? What are the main kinematic properties of the major brittle faults in the area?

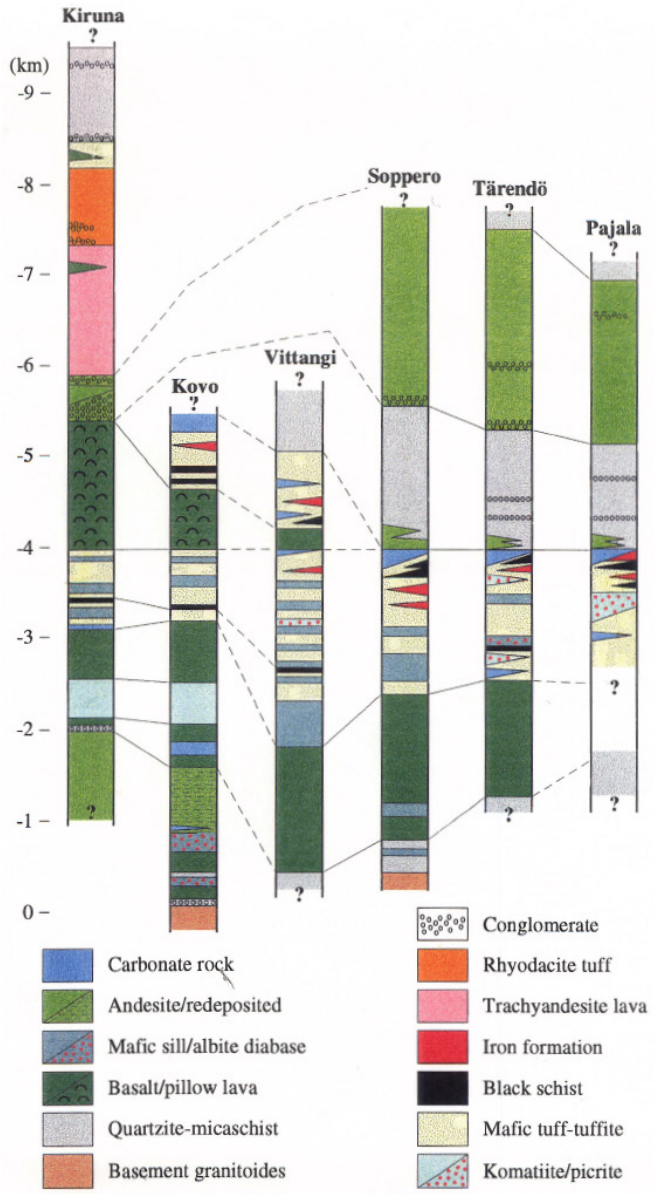

Figure 14. Stratigraphy of the Vittangi Greenstone Group in the context of greenstone successions elsewhere in northern Norrbotten (taken from Martinsson 1993).

Is there a structural control on mineralization within the VGG or is it primarily syn-depositional? Can fault patterns tell us something about fluid pathways and discharge routes?

Formational Environments

Why are chemical and volcaniclastic sediments more abundant in the NKA compared to more western areas of Norrbotten (e.g., Kiruna)? Is it a lateral variation in facies/depositional environment or do these rocks represent a separate tectonic environment in both space and time? Selective geochronology and isotopic work would contribute to this story.

Lithogeochemical and Isotopic Characteristics

Lithogeochemical sampling of metabasalts should be used to help characterize the lithotectonic setting of the VGG rocks. Geochemical profiles through the sequence could be established in conjunction with stratigraphic logging. How definitive is the within-plate-basalt signature from metabasalts or mafic tuffs at Vittangi? Full lithogeochemical sampling of key VGG horizons is required including the REEs. This data will also contribute to alteration characterization.

Geochronology

An attempt to constrain the ages of the rock units within the NKA should be made (U–Pb zircon, monazite, apatite, titanite dating).

An attempt to constrain the timing of alteration and mineralization In the area should be made (e.g., U–Pb titanite, Re–Os molybdenite, pyrite) and identify the number of hydrothermal events and tie these to host rock formation events or later magmatic processes.

Metamorphic Grade

Observations of the main metamorphic indicator minerals within the various rock units across the NKA should be made. Is the metamorphic grade consistent or does it vary as we go up the stratigraphy?

Mineralization and Alteration

Two late-stage Cu mineralization events are known from western Norbotten. These were at 1.87 (coincident with HS intrusives) and 1.77 Ga (coincident with GPA intrusive). Is this the case at Vittangi? Can the mineralization be linked to episodes of granitoid magmatism in the area?

Smith et al (2009) propose a separation in time between early Fe-oxide and later Cu mineralization in parts of Norrbotten. Is this true for the mineralization in the NKA?

Can we use a combination of stratigraphy, geochemistry, S, C and O isotopes to better understand the formation of the Nunasvaara-type graphite deposits?

There is limited data on the geological controls of alteration associated with sulfide mineralization. A better characterization of the alteration assemblages is needed for the NKA. How do the various rock units influence the types of alteration and mineralization seen?

Does schist-hosted disseminated Cu mineralization display evidence of later remobilization?

PLANNED WORK

The following section briefly outlines some plans for Barents field work in order to answer some of the key questions proposed in section 4.2 above. The numbered sections below correspond to the numbered locations shown in Figure 15 which indicates specific areas where the field work will be carried out. In addition to the proposed tasks listed below, routine measurements using a gamma spectrometer instrument at outcrops across NKA will also be undertaken.

Field characterisation (logging, structures) and sampling of metabasalt to basaltic andestites in the core of the NKA antiform for age dating, lithogeochemical analysis and alteration investigations. Acquisition of petrophysical samples from these metabasaltic rocks also. 2 days.

Field observations (logs, structures) and sampling (geochronology, lithogeochemistry) of the main epiclastic and chemical sediment units within the VGG. Detailed assessment of Svecokarelian deformation episodes may be possible with observations of carbonates and schists. Sampling of sulphide bearing graphitic schists and marginal granitoids also with assessment of alteration mineralogy and mineralization style (4 days). Acquire measurements with VLF-instrument along several profiles in the ‘pinched-out’ north–eastern corner of the NKA containing several rock units and mineralization (location 2 in NE on Figure 15). Follow up the good conductors seen on the map which displays the current density and link those to corresponding lithologies (2 days, geophysics focus).

Investigation of the contribution granitoid magmatism has made to the mineralization at the NKA (3 days). Acquire measurements with VLF-instrument along several profiles in the western part of the polygon “3” on Fig. 15. Follow up the good conductors seen on the map which displays the current density (2 days, geophysics focus). Sampling of granitoids units and mineralised vein material for subsequent analysis. Action plan no. 3 would also include a assessment of drill core at the Malå facility from the Östra Äijäjärvi Cu deposit (4–5 days at Malå).

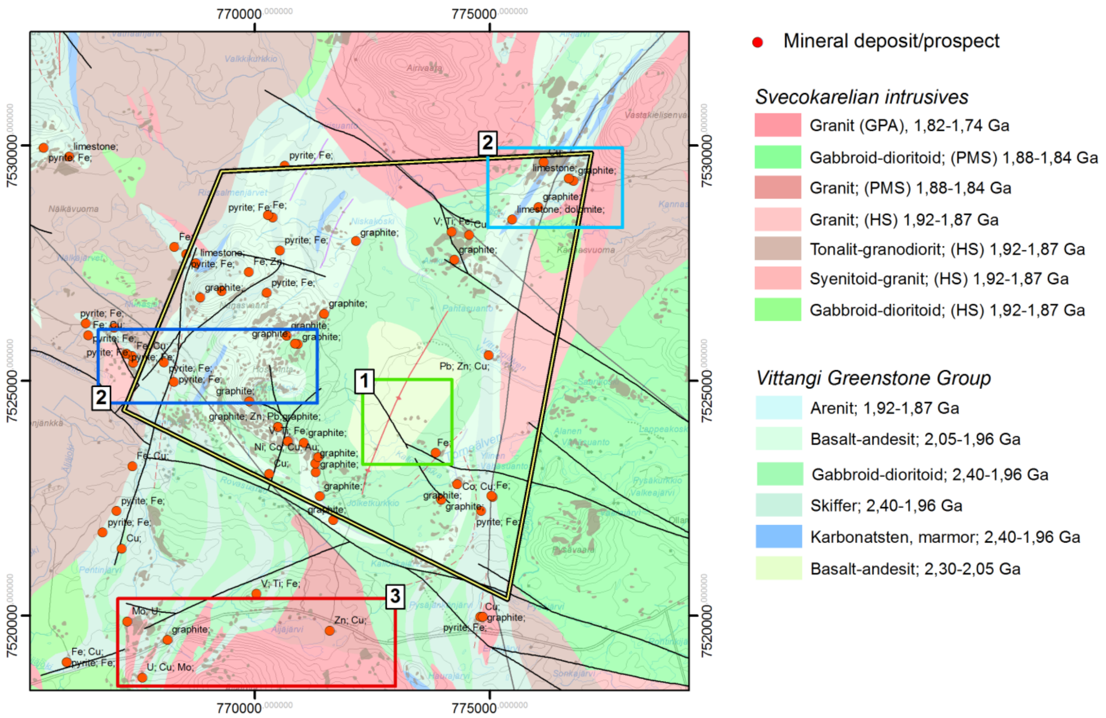

Figure 15. Planned field work areas within the Nunasvaara key area.

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