

Description of regional geological and geophysical maps of northern Norrbotten County (east of the Caledonian orogen)

Stefan Bergman, Lutz Kübler & Olof Martinsson



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Cover photograph: View towards the mountains in the west from the well-exposed apatite iron ore and epigenetic copper deposit at Gruvberget, Svappavaara (Stop 5:4 in the Excursion Guide).

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Abstract

The Precambrian bedrock of the Fennoscandian Shield in the northern part of Norrbotten county, northern Sweden, is described with regard to rock types, stratigraphy, mineralisations, alterations, structure, metamorphism and geophysical properties. A field excursion guide is included. The description is accompanied by five printed maps: a bedrock map, a mineral and bedrock resource map, a metamorphic, structural, and isotopic age map, and two maps with geophysical data. All maps and databases are available at the Geological Survey of Sweden.

Most of the Precambrian rocks in the area were formed between c. 2.8 and 1.8 Ga ago. Archaean rocks occupy the northernmost part and are dominated by meta-granitoids, with minor supracrustal rocks. They are unconformably overlain by clastic metasedimentary and intermediate-mafic metavolcanic rocks of the Kovo Group. The overlying Greenstone group consists mainly of metabasalt, which is amygdaloidal in the lower part and tuffitic, or in some areas pillowed, in the upper part. Other important components in the Greenstone group are metaltramafic rocks, graphite schists, iron formations and crystalline carbonate rocks. Swarms of mafic dykes exist in the Archaean rocks, and the overlying rocks contain numerous mafic sills. The overlying Svecofennian supracrustal rocks predominantly consist of calc-alkaline metaandesite (Porphyry group), a bimodal group of mafic and felsic metavolcanic rocks (Porphyry group) and clastic metasedimentary rocks. Six suites of intrusions, which were formed during the time interval c. 1.9–1.8 Ga ago, are distinguished. Three of them are gabbroid-syenitoid-granite suites (with the Haparanda suite also containing granitoids) and the other three are a granitoid, a granite-pegmatite and a young gabbro-diorite suite. To the west the older rocks are unconformably overlain by a thin cover of Vendian to Cambrian clastic sedimentary rocks, which are overthrust by nappes of the Caledonian orogen.

The northern part of Norrbotten county is an important ore province and a major producer of copper and iron in Sweden. Economically important deposits include apatite iron ores, stratiform copper deposits and epigenetic copper-gold deposits. Most mineral deposits in the area are hosted by the Greenstone group and Svecofennian metavolcanic rocks. Stratiform sulphide deposits with copper (-zinc-lead) and uneconomic iron formations are found in volcanoclastic units of the Greenstone group, while apatite iron ores are restricted to the Porphyry group. Epigenetic sulphide deposits with copper-gold (-cobalt) are found in both the Greenstone group and the Svecofennian metavolcanic rocks. The deposits are generally spatially related to deformation zones. Scapolite, albite and K-feldspar are characteristic alteration minerals in most epigenetic sulphide deposits, while phyllosilicates may have formed extensive footwall alteration zones at stratiform deposits.

The area is characterized by an approximately NNE–SSW to NNW–SSE structural grain. The degree of deformation is highly variable. High-strain zones alternate with zones of little deformation, and some intrusive rocks lack evidence of ductile deformation. Intense deformation and high-grade metamorphism is found in the eastern part of the area, e.g. in the Pajala shear zone. Another important regional zone is the Karesuando–Arjeplog deformation zone, which transects the central part of the area. Major fold structures are found in several places. Low metamorphic grade and excellently preserved primary structures are found in two areas in the west. The first phase of deformation and metamorphism occurred in the Archaean. There is evidence for at least two major phases of Svecofennian deformation and metamorphism. The last deformation in the area was late- to postglacial faulting.

Introduction

The northern part of Norrbotten county is one of Sweden's major ore-producing regions. This area of investigation is located in northernmost Sweden and comprises the area of crystalline bedrock lying east of the Caledonian orogen. The topographic map sheets 28–32 I–M cover the area. A large part of the area has been mapped by the Geological Survey of Sweden (SGU) on the scale of 1:50 000, and bedrock maps were published during the years 1967–1983 and 1995–1999. In 1987 geological compilation maps of northern Fennoscandia were published on the scale of 1:1 million (e.g. Silvennoinen et al. 1987). Using the results of that project and some new interpretations, a digital map of northern Sweden on the scale of 1:250 000 was prepared at SGU (by T. Sjöstrand and H. Henkel) in the late 1980s, commissioned by *Nämnden för statens gruvegendom* (the State Mining Property Commission; Swedish initials: NSG).

That map was the base for this project, which started in 1994 after a request from the mineral industry.

The aim of this project was to compile existing information, complement it with limited new field data and new analyses, and thus present updated databases and coherent interpretations of the project area. Emphasis was put on the revision and updating of 1) the stratigraphy of supracrustal rocks, 2) the subdivision of intrusive suites, 3) the mineral deposit information and classification, 4) the regional structural framework, 5) information about metamorphic conditions, and 6) geophysical information.

This report describes and gives additional information on the geological and geophysical features of the area, which are shown on five separate printed maps. The maps are 1) a bedrock map, 2) a mineral and bedrock resource map, 3) a metamorphic, structural and isotope

age map, 4) a magnetic total field map (1–4 on the scale of 1:250 000), and 5) a sheet containing four smaller maps: a gamma radiation map, an electromagnetic map (VLF), a topographic relief map, and a Bouguer anomaly map. All maps and databases are available at SGU.

In the following report, Stefan Bergman was responsible for the chapters entitled "Introduction", "Regional geological framework", "Metamorphism" and "Tectonic evolution...", while Olof Martinsson wrote the chapter on "Mineral occurrences". Both Stefan Bergman and

Lutz Kübler contributed to the chapters "Methods", "Bedrock geology" and "Structure", while all three authors contributed jointly to the "Base information" chapter and the Excursion Guide. We wish to express our gratitude to Patric Carlsson, Timo Pitkänen and Jonna Andersson for their highly valuable help with fieldwork. We are also grateful to Sven Aaro, Benno Kathol and Michael B. Stephens for their constructive comments on the manuscript.

Methods

The maps are mainly the result of compilation and revision of previously existing information. A limited amount of geological and geophysical fieldwork was done in selected key areas. In the SGU outcrop database there are c. 1 500 observations, which were collected within the frame of this project during the years 1994–1999 (primarily during the first three years). For fieldwork, rectified air photographs (scale 1:20 000) were used, in some cases smaller scale topographic maps. The positioning of the field observations was generally accurate within 50 metres. In some cases GPS positioning with variable accuracy has been made. Samples have been collected for making e.g. thin sections, geochemical analyses, petrophysical analyses, and radiometric age determinations. The field and laboratory results were compiled and integrated together with new geophysical interpretations, previously published information and archive material. The information has been generalised with regard to the scale of presentation (1:250 000). Revision of the digital map referred to above was made by screen digitisation using MapInfo™. Rock assignments have been modified from previous mapping where necessary, so as to be as consistent as possible with the results of our recent field investigations and the presently available petrographical, geophysical, geochemical, and isotopic data. Adjustment of rock unit boundaries on the basis of magnetic field data has been made in such cases where processed digital magnetic data provided more accurate interpretation compared to previous work.

The litho-geochemical database contains 1 110 analyses, many of which only have major and minor elements. Complementary sampling during this project yielded 185 new analyses with major and minor elements, and 36 trace elements including rare earth elements. The sample localities were chosen to improve the interpretation of the stratigraphy and the subdivision of intrusive suites. The analyses were made by Svensk Grundämnesanalys AB in Luleå, using optical emission spectrometry

and mass spectrometry or quadrupole mass spectrometry with inductively coupled plasma (ICP-AES and ICP-MS/QMS). Measurements of the gamma radiation spectra were made directly on outcrops in order to analyse the concentrations of potassium (in %), uranium (eU in ppm) and thorium (eTh in ppm). The instrument used was GR 320 from Exploranium™. This type of information was obtained from a total of 200 outcrops.

Ten new U-Pb isotopic age determinations of zircon, titanite or monazite were made through this project. The sample localities were chosen to improve the interpretation of the stratigraphy, the subdivision of intrusive suites and the interpretation of timing of deformation events. The analyses were performed at the Laboratory for Isotope Geology in Stockholm.

Over the entire project area, extensive petrophysical sampling has been carried out in various periods since the early 1960s. The petrophysical database contains in total about 12 200 samples from 9 200 different sampling localities. Complementary sampling in 1994–1998 yielded about 750 new petrophysical samples. All petrophysical data are given in SI units. Magnetic field and electromagnetic field (VLF) measurements were undertaken on the ground, where more accurate information about rock boundaries and deformation zones was needed. However, a great number of geophysical ground surveys, such as magnetic field and EM-slingram measurements on more local scales, have previously been performed during other exploration activities. Although they constitute an immense source of information, these data were not used in this investigation, mostly because they exist as analogue products and because we had limited time.

In order to improve the magnetic total field image, some cosmetic operations such as levelling and deleting of peaks were undertaken. The different groups of rocks, as defined on the geological map, were characterized through analyses of the spectrum of the magnetic total

field over each area. This was done by statistical treatment of subsets of the magnetic total field data for each group.

In this investigation an attempt was made to characterize the structural pattern of domains or rock units on the basis of a statistical analysis of magnetic connexions. These are local, narrow magnetic field maxima aligned in a certain direction and which can be traced over a minimum distance of at least 4 to 5 times the flight line separation used during data acquisition. The identification of such peak values was simplified using the OASIS montaj™ program. The "magnetic structure index" proposed here equals the density of magnetic connexions in a specified area (number of lines/km²) multiplied by the mean length of all connexions within this area. The quality of the index will depend on the processing of the data and on subjective decisions such as line length and whether or not a line is accepted as a connexion. Thus the index should not be regarded as an absolute value but as an indication of relative structural differences between domains. This can be done with confidence if the chosen domain is sufficiently large and if the mean length of the magnetic connexions in the domains to be compared is more or less equal.

Deformation zones include fracture zones, faults and ductile shear zones. Many of these zones have low magnetisation, caused by chemical alterations which affected the distribution of iron among the rock constituents. Due to mechanical breakdown the electromagnetic properties and densities were changed as well. Thus, such zones may be detected as lineaments in geophysical potential field data. Here, the interpretation of lineaments made to characterize them with respect to their location, length and movement direction was mainly based on magnetic field data. To some extent electromagnetic data (slingram or VLF) was also used. An independent analysis of lineaments was also carried out on the basis of digital land altitude data and then compared with the geophysical interpretation.

Four main groups of lineaments were identified: 1) lineaments with a dextral or sinistral offset, 2) lineaments with a vertical offset, 3) lineaments which appear to constitute tectonic contacts between rock units, and 4) lineaments with no or little displacement or for which the displacement was not clearly observable. Groups 1–3

are interpreted as faults or shear zones and group 4 as fracture zones or deformation zones in general. As the area is characterized by a highly heterogeneous magnetic field pattern, with typically long-extending positive linear anomalies, lineaments in directions parallel to these are more difficult to recognise than in other areas. Clearly identifiable magnetic features longer than approximately 4 000 metres were included in a database. Several shorter segments (>1 200 metres) that taken together constitute a longer zone were also included. The length of 5 000 metres was used as a cut-off limit for lineaments from altitude data.

"Major discontinuities" are planar features of significant lateral and vertical dimensions interpreted from potential field patterns. They may be interpreted as deformation zones or lithological boundaries. They were constructed by isolating the signature of either the magnetic or the gravity field at a certain depth from that of the total field, by "slicing". In short this means that the signatures at the lower and upper boundary defining the isolated slice of the crust are calculated by "upward continuation"-filtering and then subtracted from each other (Jacobsen 1987).

For making determinations of metamorphic pressure and temperature the following procedure was followed: During the fieldwork, samples were taken to obtain a regional coverage of high- and medium-grade rocks, and of rocks belonging to different stratigraphic groups. After examination in thin section, only samples with equilibrium textures and a lack of extensive retrogression were chosen for microprobe analysis. The compositions of the minerals garnet, biotite and plagioclase were determined on carbon-coated thin sections using a CAMECA SX 50 electron microprobe at the Department of Earth Sciences, Uppsala University, Sweden. Synthetic standards were used. Operating conditions were generally 20 kV accelerating voltage and a beam current of 15 nA, with the exception of during analysis of STB951021C and STB951052 samples, when the beam current was 12 nA. A few samples from the Gällivare area have garnets with analysed high contents of manganese. These samples were not studied further. A complete set of analyses for making quantitative determinations of metamorphic temperature and pressure was carried out for nine samples.

Base information

The main sources of information have been geological maps, on the scale of 1:50 000, and their accompanying descriptions, including geophysical interpretations (Offerberg 1967, Padget 1970, 1977, Witschard 1970, 1975, 1996, Eriksson & Hallgren 1975, Hallgren 1979, 1982, 1983a, b, Ambros 1980, Lindroos & Henkel 1981, Witschard & Zachrisson 1995a, b, Zachrisson & Witschard 1995a, b, Martinsson 1999a, b, c, Kathol & Martinsson 1999a, b, Martinsson & Stølen 1999). Information about the bedrock geology of the Pajala area has largely been taken from maps and reports that were produced by Luossavaara–Kiirunavaara AB (LKAB) during exploration in the area (Hansson et al. 1984, Hansson 1986). Other sources that have been used for the bedrock map include Martinsson (1997) in the Kiruna area, Frietsch (1985) in the Lannavaara area, and Filén et al. (1988). From the poorly exposed Vivungi area, W of Lainio, information was used from 12 short diamond drill holes (Studsvik-Analytica AB 1986, STC Minerals AB 1986) to outline the distribution of metavolcanic and plutonic rocks. The distribution of the sedimentary cover rocks (Dividal Group), which marks the western boundary of the study area towards the Caledonian orogen, was compiled from the 1:50 000 maps referred to above, and from Kulling (1964), Kathol (1989), Stølen (1997), and unpublished compilations in the SGU archive. Bergman & Kübler (1995, 1996, 1997, 1998, 1999) have presented preliminary results from fieldwork in this project.

Field observations (including structural measurements) from the Gällivare area, documented in Gustafsson (1985), were used in compiling the maps. From the Lannavaara area, data from Virkkunen et al. (1984, 1986) and Virkkunen (1985) were used. The structural measurements have been complemented with data from Geijer (1918b), Filén (1976), and Fredriksson et al. (1985). Some structural measurements have also been taken from Geijer (1931b), Ödman (1939, 1957), Eriksson (1954), Frietsch (1966, 1979), Lindroos (1974), Parák (1975a), Forsell (1987), and Wright (1988). The distribution of late- to postglacial faults was taken from Lagerbäck & Witschard (1983).

The lithogeochemical database at SGU comprises 1 110 analyses (963 have coordinates) for the present area. It consists of both published analyses from the literature and 185 new unpublished analyses. The chemical data presented in diagrams here have been taken from Offerberg (1967), Padget (1970), Witschard (1970, 1975), Eriksson & Hallgren (1975), Lindroos & Henkel (1981), Öhlander (1984), Öhlander et al. (1987a, b), Monro (1988), Skiöld et al. (1988), Skiöld & Öhlander

(1989), and unpublished analyses from SGU and Luleå University of Technology.

In the present work, isotopic age data were important in evaluating the timing of rock formation and the timing of deformation. The considered data were mainly published U-Pb zircon ages, which have been complemented with ten new analyses. They are presented in Table 1 where references are also given.

A search for information on observations of certain mineral keywords has been made. This was done in field notebooks from earlier bedrock mapping. The keywords searched for (in Swedish) were: albite diabase, albitite, andalusite, ankerite, chert, cordierite, epidote, felsite, garnet, carbonate alteration, quartz-carbonate (ankerite) dyke, leucodiabase, muscovite, quartz alteration (silicification), "red Oscar" (feldspar alteration), scapolite, sericite, sillimanite, skarn, tourmaline, and white mica. This information could then be used to study geographic variations in alteration type and metamorphism. In the areas 28I, 28J, 29I, 29L, 30I, 31J, and 32K, some information exists, but most outcrop maps with observation numbers are not easily accessible, so the coordinates could not be recovered. The documentation of alteration minerals is not uniform over the whole map area, mainly due to large variations in the amount of bedrock exposures and to some extent on the quality of the field notes. A compilation of information on alterations has been made using the data referred to above and data from reconnaissance mapping in this project. Field notes from Luleå University of Technology (map sheets 28K, 28L, 28M, 29J, 29K, 29M, 30K, 30L), information from drill cores (LKAB and SGU) and geological publications have been used. Areas of limited alteration data occur in the southwest, northeast and north (28I, 28J, 29I, 29L, 30M, 31J, 31K, 31L, 32J, and 32K). In general, documentation is better in the Palaeoproterozoic supracrustal units as compared to intrusive units and the areas with Archaean rocks.

Geophysical data used in the project can be found in existing databases or such being under construction. They were collected mainly during earlier projects carried out by NSG, LKAB and SGU in the northern part of the Norrbotten county. During the Nordkalott Project (1980–1986) the airborne magnetic measurements, made previously by SGU and NSG during various periods from 1961 to 1986, were digitised with a resolution of 200x200 metres (although the data were collected in 200x40 metres point density). These were combined with the measurements collected by SGU in 1980 in order to provide the first digitised magnetic anomaly map of the area. From 1995 and onwards,

the magnetic, gamma radiation, VLF, and EM-slingram data, previously belonging to LKAB, were integrated into the databases at SGU. They consist of measurements performed at a line spacing of 200 metres and a down line distance of 40 metres. This point density provided a significant improvement in resolution. Map sheets not covered by LKAB data but previously measured by NSG or SGU were thus redigitised to 200x40 metres. The map of the magnetic total field presented here has been processed with a grid cell size of 50x50 metres. The total area covered by airborne magnetic surveys is 33 500 km².

Together with the geophysical information mentioned above, Bouguer gravity data from the SGU database were

employed in the interpretation work. This regional database consists of 162 000 data points, of which 21 900 are situated in the project area. The point density varies strongly from place to place according to the interest an area may have had for the various activities. In addition to the regional measurements there are six small areas in which detailed measurements (c. 25 000 data points) have been performed.

In the reference list, only those publications that are cited in the text are included. For additional references concerning the geology of the northern part of Norrbotten county, the reader is referred to the database GEOREGISTER, which can be found at <http://www.sgu.se>.

Regional geological framework

The map area is located north of the Arctic circle in the northwestern part of the Fennoscandian Shield, in the border zone between Archaean and Proterozoic rocks to the northeast and solely Proterozoic rocks to the southwest (Fig. 1). The Precambrian crystalline bedrock in the west is covered by Vendian (Neoproterozoic) to Cambrian sedimentary rocks, and overthrust by rocks belonging to the Caledonian orogen.

The oldest rocks in the Fennoscandian Shield were formed during the Samian orogeny (3.5–3.0 Ga ago). These rocks are found as remnants in voluminous, younger Archaean rocks, which were formed during the Lopian orogeny (2.9–2.6 Ga old). In the earliest Protero-

zoic, the Archaean crust was intruded by mafic magmas during rifting, and mafic volcanic rocks and sediments (Karelian) were deposited in the rifts and on the older crust. During the Svecokarelian orogeny (1.96–1.75 Ga) volcanic and sedimentary rocks were formed and intruded by several generations of intrusive rocks. Different phases of regional deformation occurred mostly under low to intermediate pressure conditions. In some areas the Archaean crust was also affected by these events. The Sveconorwegian orogeny was active in the southwestern part of the shield c. 1.1–0.9 Ga ago, and the Caledonian orogeny affected the western part of the shield c. 0.5–0.4 Ga ago.

Bedrock geology (including geophysics)

The geology of the northern part of Norrbotten county was first described by Fredholm (1886) and Svenonius (1900). More detailed work by Lundbohm (1910), Sundius (1915), Geijer (1931b), Ödman (1939, 1957), and Eriksson (1954) followed these brief outlines. Summaries were presented by Witschard (1984, 1986) and a compilation of available information concerning exploration was given by Gustafsson (1993). Local contributions come from a large number of studies, which are referred to in the text. A simplified bedrock map is presented in Fig. 2. Radiometric age determinations play a critical role for the interpretation of the regional geology. The available U-Pb data (published and unpublished) are listed in Table 1, and ages of Proterozoic rocks are

shown in Fig. 3. A schematic summary diagram (Fig. 4) shows the main rock units and events in the area. A large number of differing names of rock units occurs in the literature. In Table 2 these names can be compared with those preferred in this paper. Sm-Nd-isotopic data are listed in Table 3. Diagrams showing the modal classification of various intrusive suites are shown in Fig. 5, and some chemical diagrams of these suites are shown in Figs. 6–9.

The signature of the magnetic total field over the northern part of Norrbotten county corresponds to the very heterogeneous geology of the area. Persistent but low amplitude magnetic banding as in the Archaean rocks in the northern part (marked by A in Fig. 10)

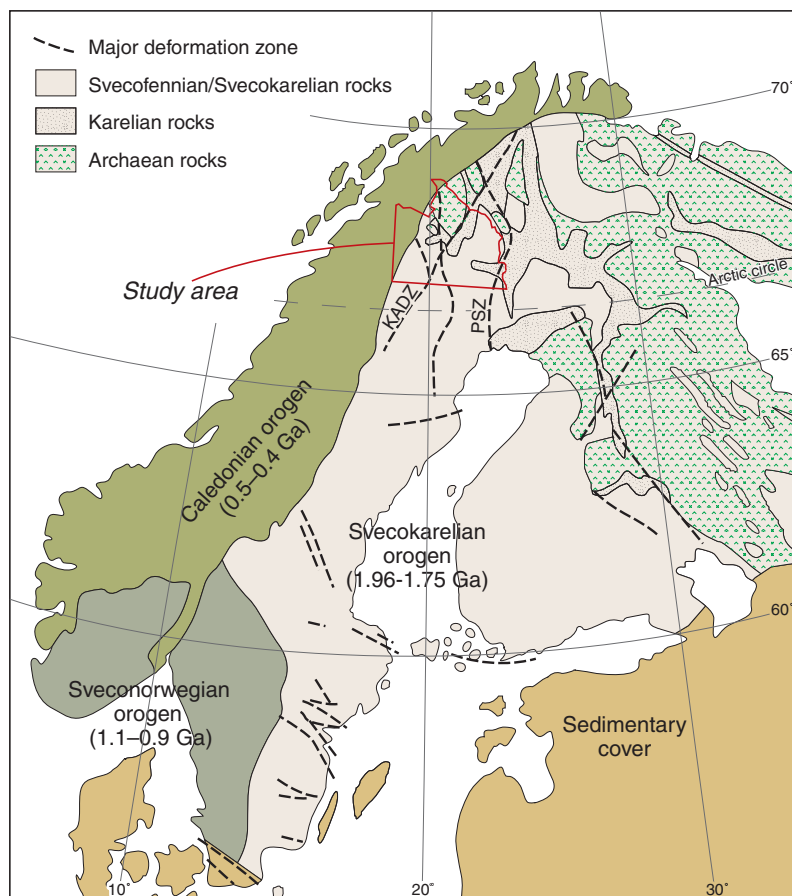


Fig. 1. Major geological units in the Fennoscandian Shield and surrounding areas. Modified from Gorbatshev & Bogdanova (1993), Olesen & Sandstad (1993), Stephens et al. (1994), and Korsman et al. (1997). KADZ = Karesuando–Arjeplog deformation zone, PSZ = Pajala shear zone.

contrasts with areas of very high amplitude variations and irregular banding, such as in areas dominated by supracrustal rocks in the west-central and the southeastern parts (B in Fig. 10). Large intrusive complexes in the southwest and south-central parts (C and D in Fig. 10) are less affected by deformation and show more uniform, somewhat elevated magnetic levels, which in case D is caused in part by magnetic rocks at depth. The area with deformed intrusive rocks in the east (E in Fig. 10) shows both an elevated magnetic level and a banded magnetic pattern. The two latter areas also coincide with positive Bouguer anomalies (D and E in Fig. 11), which suggests that the magnetic rocks at depth are mafic in composition.

ARCHAEAN ROCKS

The Archaean rocks are located in remote areas in the north and very few studies of them have been made. Major components are metagranitoids, which have intruded older supracrustal rocks. Large areas have been mapped as unspecified gneiss. The Archaean bedrock is limited to the east by pronounced structural discontinuities, which may be followed geophysically to more than 5 kilometres depth. The first report of Archaean rocks in the region

was given by Matisto (1969), who presented an age of 2800 Ma from a leucocratic granodiorite at Ropijärvi, near the Swedish–Finnish border. Subsequently, reports of Archaean ages (2834–2679 Ma, Table 1) have been presented in Welin et al. (1971), Skiöld (1979b), Skiöld & Page (1998), and Martinsson et al. (1999). The most recent description of the Archaean rocks (Råstojaure complex) is by Martinsson (1999c) and Martinsson & Stølen (1999). Steeply dipping mafic dykes of Proterozoic age are common in the Archaean bedrock. In some areas they form extensive swarms, e.g. between Naimakka and Råstojaure. The negative ϵ_{Nd} -values of most Proterozoic rocks in the map area (Table 3) show that there was Archaean crustal material in their source regions, and that the Archaean crust extends at depth far beyond the area where it is presently exposed. See the references in Table 3 and e.g. Mellqvist et al. (1999) for further details.

Supracrustal rocks

Near Lake Råstojaure there are banded biotite gneisses of sedimentary origin, locally with garnet and sillimanite. An easily accessible locality of a similar rock type is found at Järkastakka, NW of Övre Soppero. Metaare-

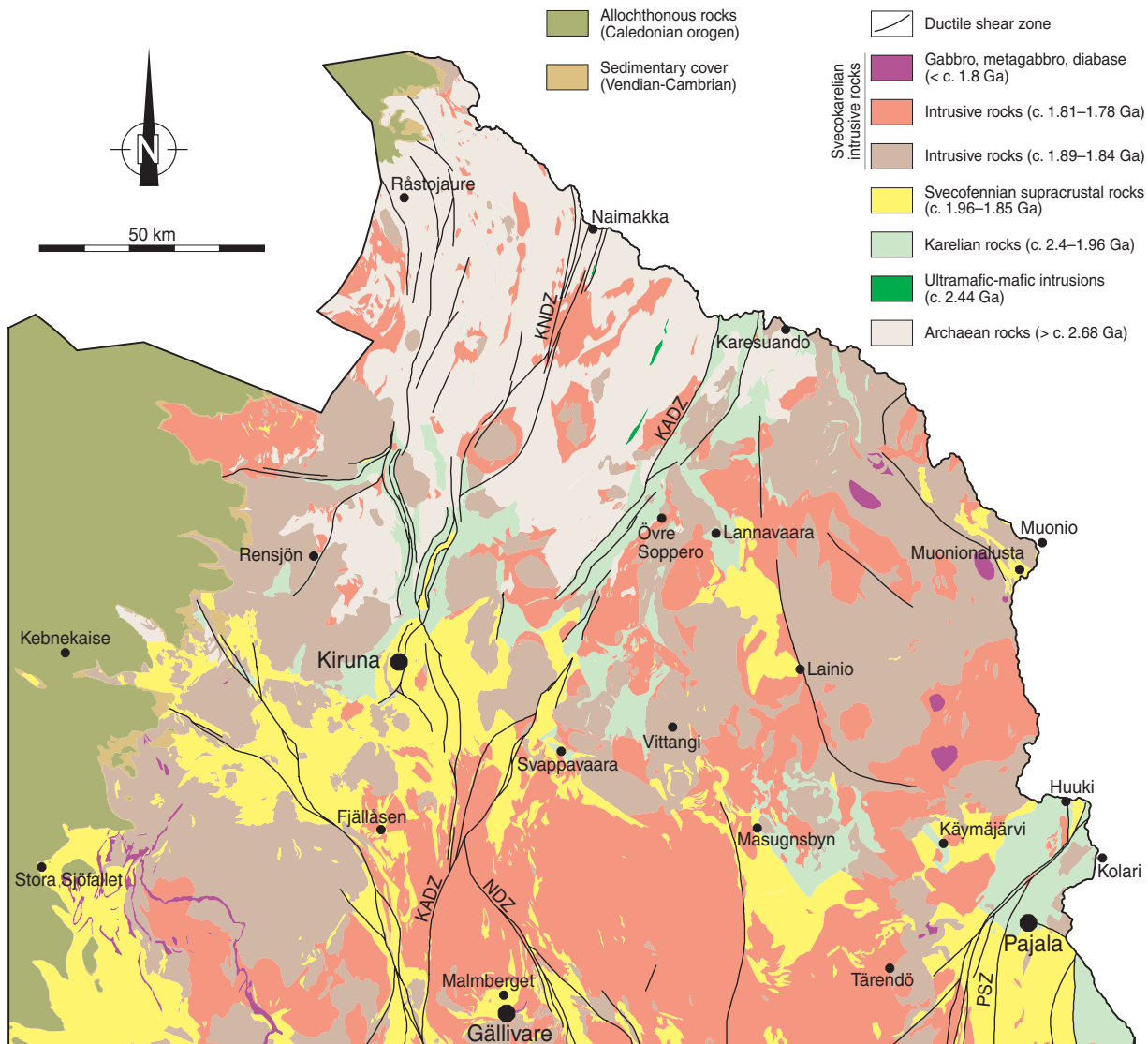


Fig. 2. Simplified bedrock map of the northern part of Norrbotten county. KADZ = Karesuando–Arjeplog deformation zone, KNDZ = Kiruna–Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala shear zone.

nitic gneisses, with variable proportions of quartz and biotite, are found in the west, near the Norwegian border. Quartzites are found in some areas.

Fine-grained, banded amphibolites of probable magmatic origin are found in the western part in belts up to 700 metres wide. Intermediate to felsic metavolcanic rocks are found locally. A strongly sheared, intermediate, porphyritic metavolcanic rock below a Karelian quartzite (Tjärro quartzite), NW of Övre Soppero, is interpreted as Archaean in age.

Intrusive rocks

Gneissose granitoid rocks are the most common Archaean rocks in the area. They are mostly tonalitic in composition but granodiorites and quartz diorites are also

common. Assimilated fragments of amphibolite occur frequently, especially close to larger amphibolite bodies. In many areas the granitoids are strongly deformed and metamorphosed, with a strong gneissosity or banding and abundant quartzofeldspathic veins. Large bodies of granite and pegmatite of probable Archaean age are found in the Karesuando area. These granites are not easily distinguishable from those of the c. 1.8 Ga old Granite-pegmatite association. One criterion for discriminating Archaean granites in this area is the presence of meta-diabase dykes (Fig. 12a). Furthermore, their mean susceptibility is lower (Fig. 13) and their concentrations of thorium (Fig. 8) and uranium are also generally lower, which has also been indicated by gamma ray spectrometry. At a locality c. 15 kilometres W of Karesuando (in Finland), there is a well-preserved unconformity where

TABLE 1. Compilation of age determinations (U-Pb and Sm-Nd) in the northern part of Norrbotten county. Abbreviations in the "Unit" column: Gsg = Granite-syenitoid-gabbroid association, Gp = Granite-pegmatite association, Pms = Perthite monzonite suite, G = Granitoids 1.86-1.84 Ga, Hs = Haparanda suite, Pg = Porphyry group, Ptg = Porphyry group, Gg = Greenstone group, A = Archaean rocks. Coordinates refer to the Swedish National Grid (RT 90). Two analyses, denoted with * in the "Reference" column, are unpublished SGU analyses but the age figures were presented by Witschard (1996).

Object	Unit	Age (Ma)	Method	Map	N-S	E-W	Reference
Monzonite, Pikku Sattavaara	Gsg	1799±2	U-Pb zircon	29K	7541500	1723500	SGU (unpublished)
Monzonite, Viiksvaara	Gsg	1797±15	U-Pb zircon	29L	7500020	1786280	SGU (unpublished)
Syenite, Saarijärvi	Gsg	1792±4	U-Pb zircon+titanite	29J	7527000	1676000	Romer et al. 1994
Granite, Tjärvetjarram	Gp	1794±24	U-Pb zircon	29K	7507000	1706000	Skiöld 1988
Granite, Vettasjärvi	Gp	1794±24	U-Pb zircon	28L	7480100	1752500	Skiöld 1988
Granite, Linaälven type locality	Gp	1778±7	U-Pb titanite	28J	7472100	1689180	SGU (unpublished)
Pegmatite, Aitik	Gp	1747±15	U-Pb zircon+monazite	28K	7451650	1723550	*SGU (unpublished)
Metagranite, NW Soppero	Gp	1791	U-Pb zircon	30K	7582440	1745000	SGU (unpublished)
Granite, Äijäjärvi	Pms	1863, 1826	U-Pb zircon	29K	7519000	1737000	Skiöld 1981b
Syenite, Koivo-Kuosanen	Pms	1879±7	U-Pb zircon	29K	7523550	1706250	Skiöld & Öhlander 1989
Granite, Masugnsbyn	Pms	1858±9	U-Pb zircon	29L	7497450	1768400	Skiöld & Öhlander 1989
Quartz monzodiorite, Aitik	Pms	1873±24	U-Pb zircon	28K	7451700	1724000	*SGU (unpublished)
Granite, Rakisvare	Pms	1874±12	U-Pb zircon	30J	7579440	1687260	Martinsson et al. 1999
Monzonite, Runkanjunnje	Pms	1868±55	U-Pb zircon	30J	7551460	1655920	Martinsson et al. 1999
Metagranodiorite, Pingisvaara	G	1856±8	U-Pb zircon	30L	7595420	1795370	SGU (unpublished)
Granodiorite, Pahtajärvi	G	1853±21	U-Pb zircon	29L	7543500	1785600	SGU (unpublished)
Metagranodiorite, Jänkajärvi	Hs	1886±14	U-Pb zircon	29K	7521700	1730900	Skiöld 1988
Metagranodiorite, Hopukka	Hs	1886±14	U-Pb zircon	29K	7514000	1729500	Skiöld 1988
Metagranodiorite, Lehtovaara	Hs	1886±14	U-Pb zircon	29K	7515620	1745900	Skiöld 1988
Metagranodiorite, Juolovanjärvet	Hs	1847±19	U-Pb zircon	30L	7580500	1752100	Skiöld 1981b
Metaquartzdiorite, Puristakero	Hs	1873±23	U-Pb zircon	29M	7543000	1817500	Skiöld 1981a
Metagranodiorite, Paittasjärvi	Hs	1880±28	U-Pb zircon	30L	7590000	1791000	Skiöld 1979a
Metadiorite, Maattavaara	Hs	1881±7	U-Pb zircon	29K	7546300	1724200	SGU (unpublished)
Granite, Lulep Patsajäkel	Hs	1877±14	U-Pb zircon	30J	7567640	1681640	Martinsson et al. 1999
Metaquartzdiorite, Puristakero	Hs	1880	U-Pb zircon	29M	7543000	1817500	Lindroos & Henkel 1978
Granophyre dyke, Kiruna		1880±3	U-Pb zircon	29J	7531500	1684500	Cliff et al. 1990
Metarhyolite, Kiruna	Pg	1882±24	U-Pb zircon	29J			Welin 1987
Felsic metavolcanic rock, Puollamtjåkka	Pg	1909+17/-16	U-Pb zircon	28I	7480100	1619500	Skiöld & Cliff 1984
Felsic metavolcanic rock, Saggekirka	Pg	1909+17/-16	U-Pb zircon	29J	7506600	1654800	Skiöld & Cliff 1984
Intermed. metavolcanic rock, Käymäjärvi	Ptg	1880±3	U-Pb zircon	28M	7491190	1811430	SGU (unpublished)
Amygdules in metaandesite, Kiruna		1876±9	U-Pb titanite	29J			Romer et al. 1994
Albite diabase, intrudes Kovo Group	Gg	2184±5	U-Pb zircon	30J	7558000	1692300	Skiöld 1986
Albite diabase, N Soppero		1874±10	U-Pb zircon	30K	7581700	1745900	Skiöld 1981b
Magnetite-titanite dyke, Luossavaara		1888±6	U-Pb titanite	29J			Romer et al. 1994
Metabasaltic-metaandesitic tuff, Viscaria		2687±3	U-Pb zircon	29J			Skiöld & Page 1998
Metabasaltic-metaandesitic tuff, Kovo		2692±5	U-Pb zircon	29J			Skiöld & Page 1998
Greenstone, Saarijärvi		2682±4	U-Pb zircon	29J			Skiöld & Page 1998
Metapicrite, Käymäjärvi	Gg	2055+146/-117	U-Pb zircon	28M	7495900	1805500	SGU (unpublished)
Gneissose granite, Vuolosjärvi	A	2760	U-Pb zircon+titanite	30J	7568600	1689250	Welin et al. 1971
Gneissose granite, NW Soppero	A	2834±40	U-Pb zircon	30K	7586730	1733600	Skiöld 1979b
Metagranite, Saarijärvi	A	2710±4	U-Pb zircon	29J	7526520	1675800	Skiöld & Page 1998
Metatonalite, Råstojaure	A	2679±12	U-Pb zircon	31J	7631020	1697840	Martinsson et al. 1999
Granophyre dyke, Kiruna		1890±90	Sm-Nd whole-rock	29J			Cliff et al. 1990
Greenstone, Viscaria	Gg	1932±45	Sm-Nd whole-rock	29J			Skiöld & Cliff 1984
Metaarenite, Karivaara, cordierite-bearing mesosome		1810	U-Pb monazite+zircon	28M	7466570	1826940	Bergman & Skiöld 1998
Pegmatite, Ähkärä, leucosome in 8metaarenitic gneiss		1798-1774	U-Pb monazite	28M	7468090	1835140	Bergman & Skiöld 199
Felsic dyke, Maattavaara		1633±7	U-Pb monazite	29K	7544160	1726370	SGU (unpublished)
Mafic enclave, Vassijaure, Rombak Window		1790±5	U-Pb columbite	30I	7590000	1605000	Romer & Wright 1992
Albite diabase, N Soppero		1800±80	Sm-Nd	30K			Skiöld & Cliff 1984
Fracture filling, Malmberget, titanite-monazite-apatite-stilbite		1620-1613	U-Pb titanite	28K			Romer 1996
Fracture filling, Malmberget, monazite-titanite-apatite-stilbite		1740-1735	U-Pb monazite	28K			Romer 1996

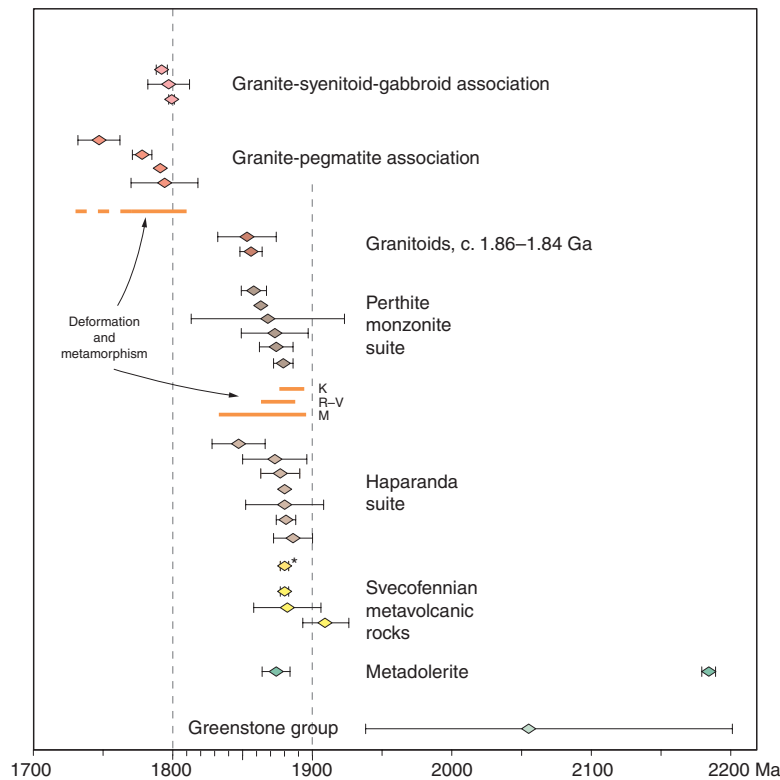


Fig. 3. U-Pb ages of Proterozoic rocks in the northern part of the Norrbotten county. See Table 1 for references. The age limits of deformation and metamorphism are explained in the chapter on "Structure". Abbreviations: K = Kiruna, R-V = Rensjön-Vittangi area, M = area southwest of Muonionalusta. The symbol marked with * is a granophyre dyke from Kiruna (Cliff et al. 1990).

TABLE 2. Terminology of rock units used in this paper, compared to previously used names and local names that can be found in the literature. Comparable units in the Skellefte district and surroundings are also shown.

Terminology used in this paper	Previously used names or local names for corresponding unit and subunits	Approximate age (Ga)	Similar unit in Skellefte district
Supracrustal rocks			
Younger Svecofennian supracrustal rocks	Vakko, Upper Hauki complex (Vakko), Hauki group, Snava-Sjöfallet group, Maattavaara quartzite group, Upper sediment group	< 1.88	Vargfors group
Porphyry group	Kiruna porphyries, Kiruna porphyry group	1.91–1.88	Arvidsjaur group
Porphyrite group	included in Kiruna porphyries, Kurravaara group, Kalixålv group, Ruutivaara group, Suorsa greenstone group	1.91–1.88	Skellefte group
Older Svecofennian metasedimentary rocks	Kurravaara conglomerate, Kurravaara group, Pahakurkio group, Kalixålv group, Kilavaara quartzite group, Kuusivaara group, Middle sediment group	1.96–1.88	Bothnian supergroup
Greenstone group	Kiruna Greenstones, Kiruna greenstone group, Vittangi greenstone group, Veikkavaara greenstone group, Käymjärvi group, Kolar greenstones, Greenstone formation, Iron ore formation, Schist formation	2.3–1.96	
Kovo Group and comparable units	Tjärro quartzite formation, Lower sediment group	2.4–2.3	
Archaean supracrustal rocks	Råstojaure complex	> 2.7	
Intrusive rocks			
Gabbro, metagabbro, dolerite	Ring gabbro, Gabbro ring-complex, Nabrenjarka gabbro diabase	< 1.8	
Granite-syenitoid-gabbroid association	Kangos diorite	1.80–1.79	Revsund suite, TMB
Granite-pegmatite association	Lina granite suite, Lina granite series, Younger series of deep-seated rocks, Potassic granite, Vettasjärvi granite	1.81–1.78	Skellefte granite, Härnö granite
Granitoids	Jyryjoki granite, Lainio granite	1.86–1.84	
Perthite monzonite suite	Perthite granite series, GSM	1.88–1.86	Jörn GIII, Arvidsjaur granite
Haparanda suite	Haparanda series, Porojoki diorite, Haaravaara group, Parkajoki complex	1.89–1.86	Jörn GI
Ultramafic-mafic intrusions		c. 2.44	
Archaean intrusive rocks	Råstojaure complex	2.85–2.68	

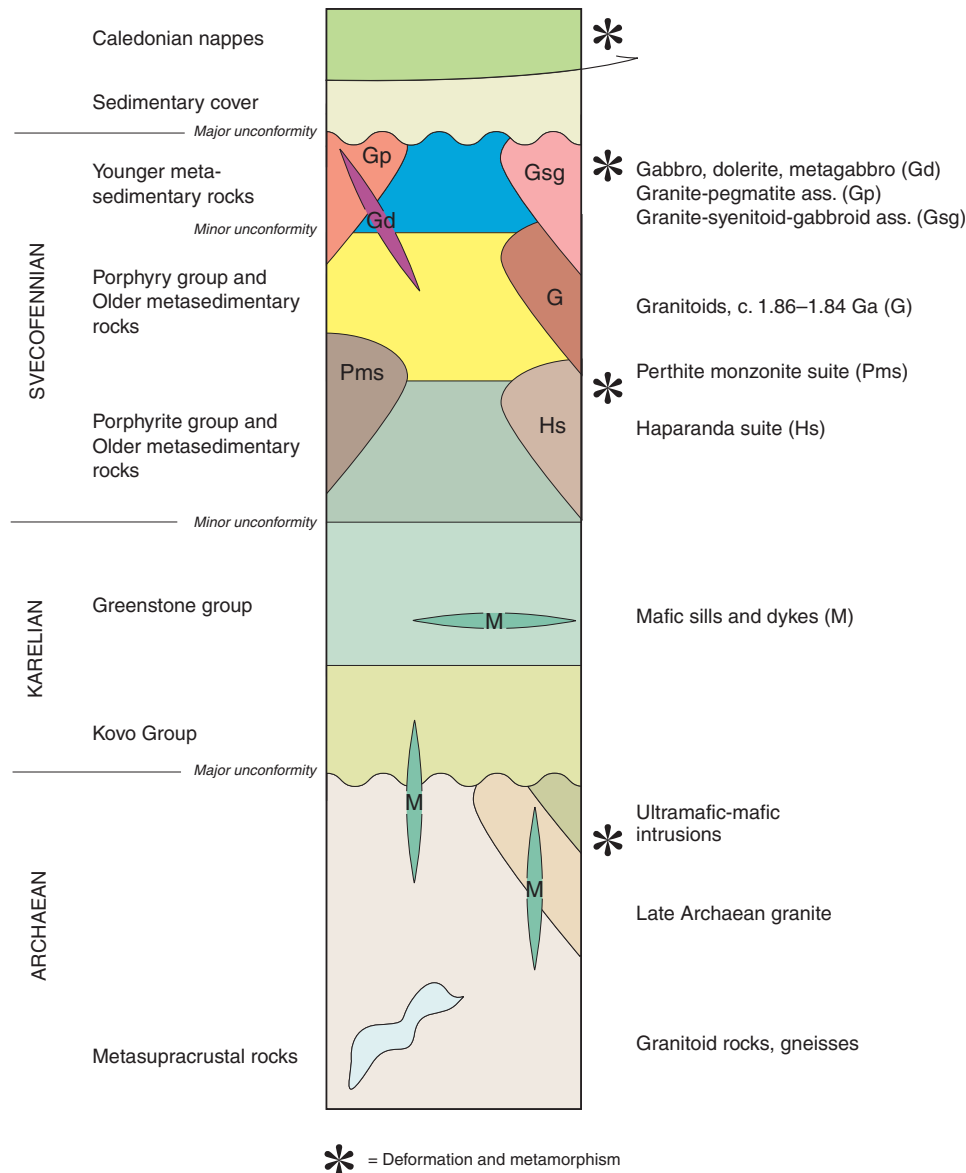


Fig. 4. Summary diagram with schematic illustration of main rock units and events. Not to scale.

a granite is weathered in the upper parts and overlain by Karelian conglomerate and quartzite (Fig. 12b). At Saarijärvi, S of Kiruna, a small body of red metagranite (2710±4 Ma old, Skiöld & Page 1998) is overlain by Karelian clastic rocks and greenstones.

The area of high-grade metamorphic rocks southeast of Karesuando has previously been suggested to be a basement to the Proterozoic supracrustal rocks (Lindroos & Henkel 1978, 1981, Ambros 1980, Witschard 1984). This is not supported, however, by presently available isotopic data (see below).

Chemically, the Archaean granitoids are classified as adamellites to tonalites on the P-Q diagram (Fig. 6). On a modified Peacock diagram they scatter but appear to

define a calc-alkaline trend (Fig. 7). Nearly all samples in Fig. 9 can be classified as volcanic arc granites.

The spectral distribution of the magnetic total field covered by Archaean rocks is shown in Fig. 14a. The variation of the magnetic total field is less than average (low standard deviation) and its mean value (Fig. 15) is the lowest of all rock units. It is influenced mainly by the relatively low magnetic susceptibility. Natural remanent magnetisation due to the presence of such minerals as magnetite or pyrrhotite has no or very small effect on the magnetic total field (Figs. 15, 16). The abundant Proterozoic mafic dykes also contribute to the magnetic field pattern in the area, even though their influence is difficult to quantify.

TABLE 3. Compilation of Sm-Nd isotopic data in the northern part of Norrbotten county, ordered by decreasing $\epsilon_{Nd(T)}$ -value. Abbreviations in the "Unit" column: A = Archaean rocks, Pg = Porphyry group, Pms = Perthite monzonite suite, Hs = Haparanda suite, Gp = Granite-pegmatite association. Coordinates refer to the Swedish National Grid (RT 90). Reference numbers refer to the following publications: 1. Öhlander et al. (1987a), 2. Öhlander et al. (1987b), 3. Skiöld et al. (1988), 4. Skiöld & Öhlander (1989), 5. Öhlander et al. (1993), 6. Öhlander & Skiöld (1994).

Object	Unit	$\epsilon_{Nd(T)}$	T (Ma)	T _{CHUR} (Ma)	T _{DM} (Ma)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	f-factor	Sample	N-S	E-W	Reference
Soppero gneiss	A	3.7	2830		2750	6.519	50.69	0.07771	0.510607	31		84119	7586000	1736000	1
Soppero gneiss, metasediment	A	0.9	2830		2930	3.133	18.62	0.1017	0.510909	20		84107	7587830	1733420	1
Soppero orthogneiss	A	0.9	2830		2930	3.83	24.16	0.0958	0.510801	26		84109	7588000	1734000	1
Puollamijätkä porphyry	Pg	0.3	1900	1851	2316	9.49	40.2	0.1425	0.511978	18		78151	7480100	1619500	5
Puollamijätkä porphyry	Pg	-0.2	1900	1927	2280	9.6	40.3	0.1441	0.511971	32		78151	7480100	1619500	5
Masugnsbyn granitoid	Pms	-2.5	1870		2450							81040	7497450	1768400	4
Proterozoic granitoid	Hs	-3	1890		2410	3.911	21.96	0.1077	0.511376	16		84102	7488000	1752000	1
Appovare granite	Pms/Gp	-3.4	1875	2193	2427	9.92	52.6	0.1139	0.511442	16		89153	7462850	1650200	5
Dundret monzogabbro	Pms	-3.6	1875	2958	3398	1.3	4.58	0.171	0.512136	19		83089	7453200	1706850	5
Gällivare syenite porphyry	Pg	-3.9	1900	2198	2437	9.08	56.9	0.0964	0.511186	13		88108	7455650	1715300	5
Gällivare syenite porphyry	Pg	-4.2	1900	2236	2437	8.74	52.7	0.1003	0.511218	16		79097	7455600	1715300	5
Appovare granite	Pms/Gp	-4.2	1800									89153	7462850	1650200	5
Vittangi gabbro	Pms	-4.4	1890			10.52	55.3	0.1149	0.511395	11	-0.42	83073			3
Dundret monzogabbro	Pms	-4.5	1875	2685	2967	1.35	5.31	0.1538	0.511878	24		83088	7452600	1708050	5
Juolovajarvet quartz monzodiorite	Hs	-5.3	1890			4.32	25.74	0.1013	0.511181	30	-0.49	76183	7580400	1753060	3
Juolovajarvet quartz monzodiorite	Hs	-5.6	1890			5.82	33.16	0.1061	0.511228	25	-0.46	69204			3
Juolovajarvet quartz monzodiorite	Hs	-5.7	1890			5.03	27.9	0.1089	0.511257	19	-0.45	78153	7580519	1752063	3
Saivo gabbro	Pms	-5.7	1870		2640	6.39	33.9	0.114	0.511331	20	-0.42	83086			3,4
Vittangi gabbro	Pms	-5.9	1890			6.6	34.97	0.1141	0.511309	34	-0.42	84157			3
Saggekirka quartz porphyry	Pg	-6.1	1900	2422	2614	9.47	53.4	0.1072	0.511209	16		79099	7506600	1654800	5
Vettasjärvi granite	Gp	-6.2	1800	2265	2437	4.48	28.63	0.09448	0.511113	20	-0.52	83024	7487500	1757400	2, 3, 6
Lehtovaara quartz monzonite	Hs	-6.3	1890			2.85	21.61	0.0796	0.510861	26	-0.6	76204	7515450	1746650	3
Lehtovaara quartz monzonite	Hs	-6.4	1890			2.33	14.86	0.0948	0.511043	15	-0.52	76205	7515450	1746750	3
Vettasjärvi granite	Gp	-6.6	1800	2415	2662	2.98	15.76	0.1143	0.511326	30	-0.42	83003	7465600	1748400	2, 3, 6
Vettasjärvi granite	Gp	-6.6	1800	2184	2344	3.36	31.49	0.06445	0.510736	20	-0.67	83007	7479300	1727000	2, 3, 6
Äjjäarvi adamellite-granite	Pms	-7	1870			6.61	43.08	0.0927	0.511002	30	-0.53	76208	7518300	1738400	3
Lehtovaara quartz monzonite	Hs	-7.3	1890			5.99	33.79	0.1072	0.511155	14	-0.46	76202	7515500	1746400	3
Äjjäarvi adamellite-granite	Pms	-7.7	1870			5.83	33.39	0.0942	0.510986	30	-0.52	76213	7519050	1737150	3
Proterozoic granitoid, Soppero	Hs/Gp	-8	1890		2670	5.151	33.7	0.09237	0.51093	20		84104	7591800	1726750	1
Vettasjärvi granite	Gp	-8.1	1800	2325	2504	5.89	45.3	0.07823	0.510822	20	-0.6	83019	7478900	1744040	2, 3, 6
Koivu-Kuosanen quartz monzodiorite	Pms	-8.2	1870		2790	4.2	23.31	0.109	0.511143	10	-0.45	81039	7523550	1706250	3, 4
Proterozoic granitoid, Soppero	Hs/Gp	-9.3	1800	2484	2663	5.2	33.7	0.0924	0.51093	20		84104	7591800	1726750	6
Soppero orthogneiss	A	-11.4	1890			3.83	24.16	0.0958	0.510801	26	-0.51	84109	7588000	1734000	3

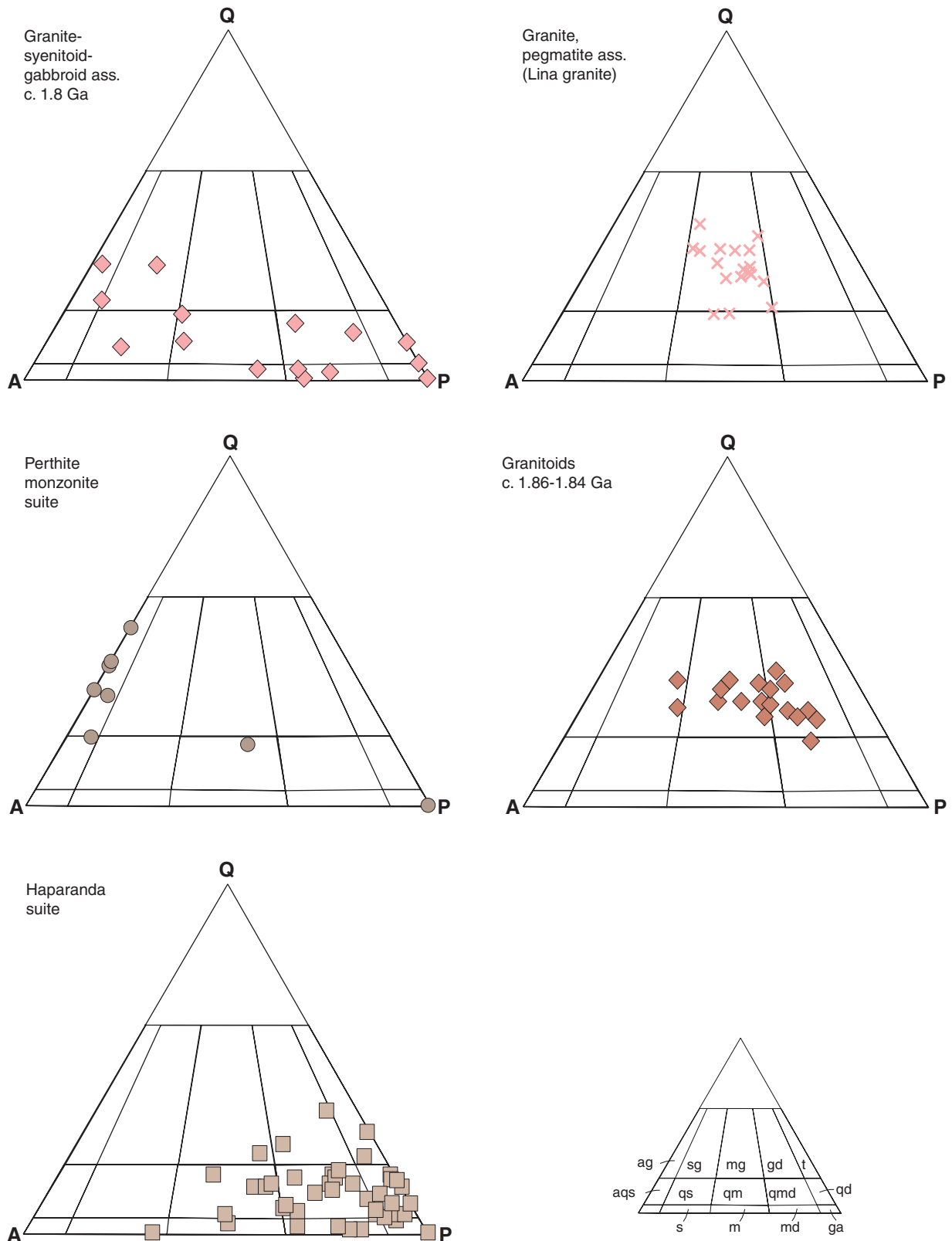


Fig. 5. Classification of various intrusive suites based on modal composition according to IUGS (1973). Modal data is reclassified from Ödman (1957) and Witschard (1970). Abbreviations in small diagram: ag = alkali feldspar granite, sg = syenogranite, mg = monzogranite, gd = granodiorite, t = tonalite, aqs = alkali feldspar quartz syenite, qs = quartz syenite, qm = quartz monzonite, qmd = quartz monzodiorite or quartz monzogabbro, qd = quartz diorite or quartz gabbro, s = syenite, m = monzonite, md = monzodiorite or monzogabbro, ga = diorite or gabbro.

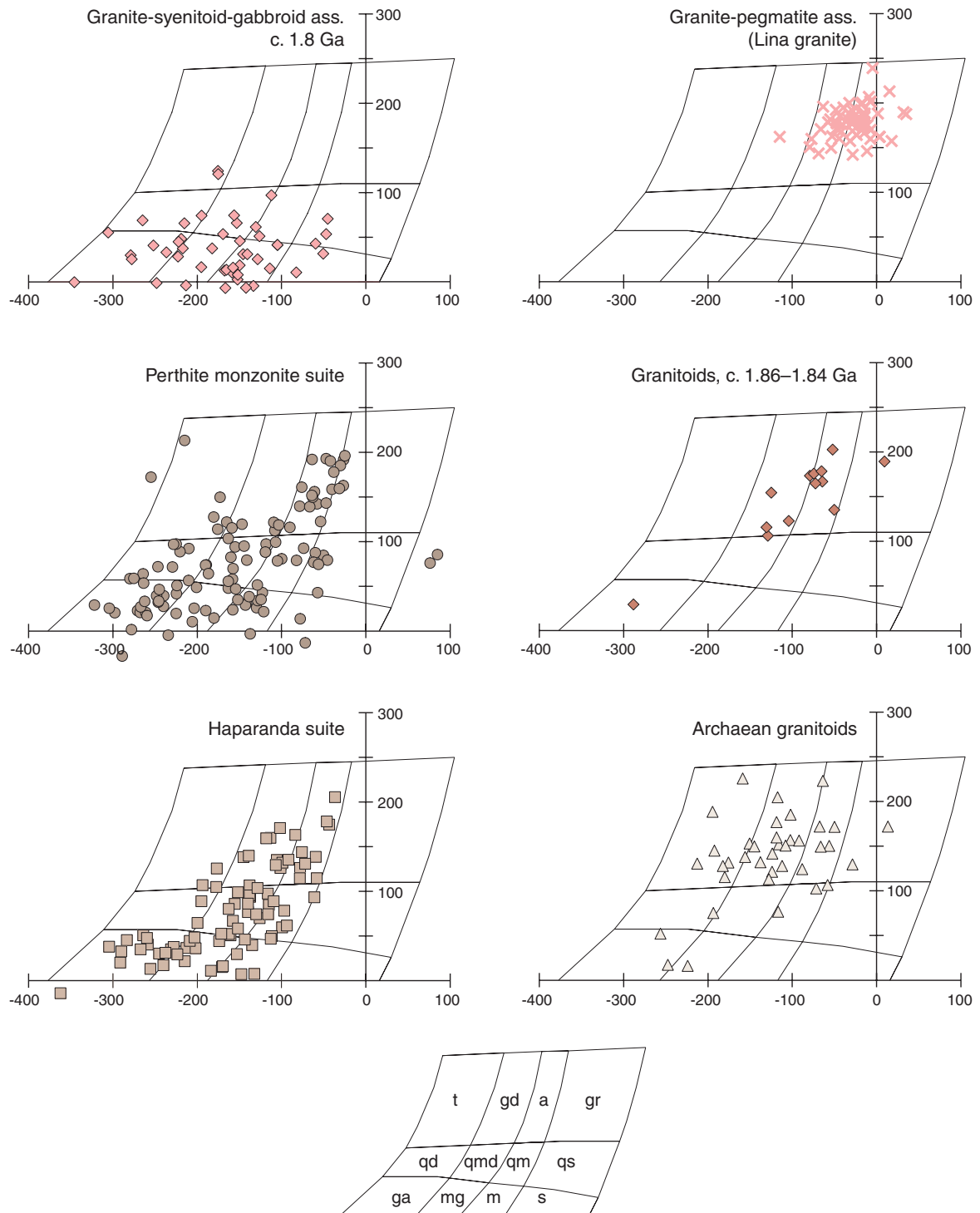


Fig. 6. Chemical classification of various intrusive suites using the P-Q diagram (Debon & LeFort 1983). Abbreviations in small diagram: gr = granite, a = adamellite, gd = granodiorite, t = tonalite, qs = quartz syenite, qm = quartz monzonite, qmd = quartz monzodiorite, qd = quartz diorite, s = syenite, m = monzonite, mg = monzogabbro, ga = gabbro.

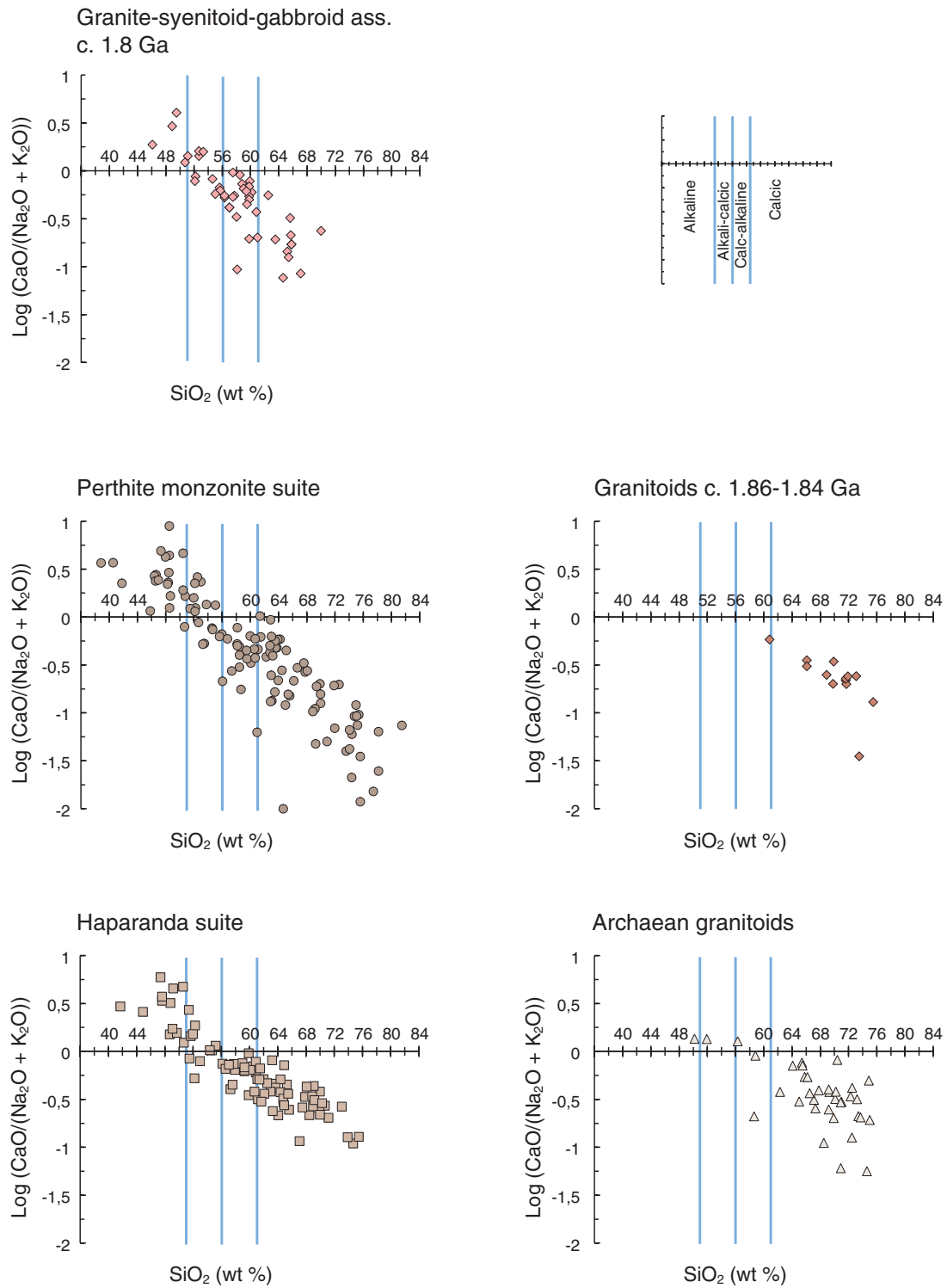


Fig. 7. Chemical classification of various intrusive suites using a modified Peacock diagram (e.g. Brown 1982).

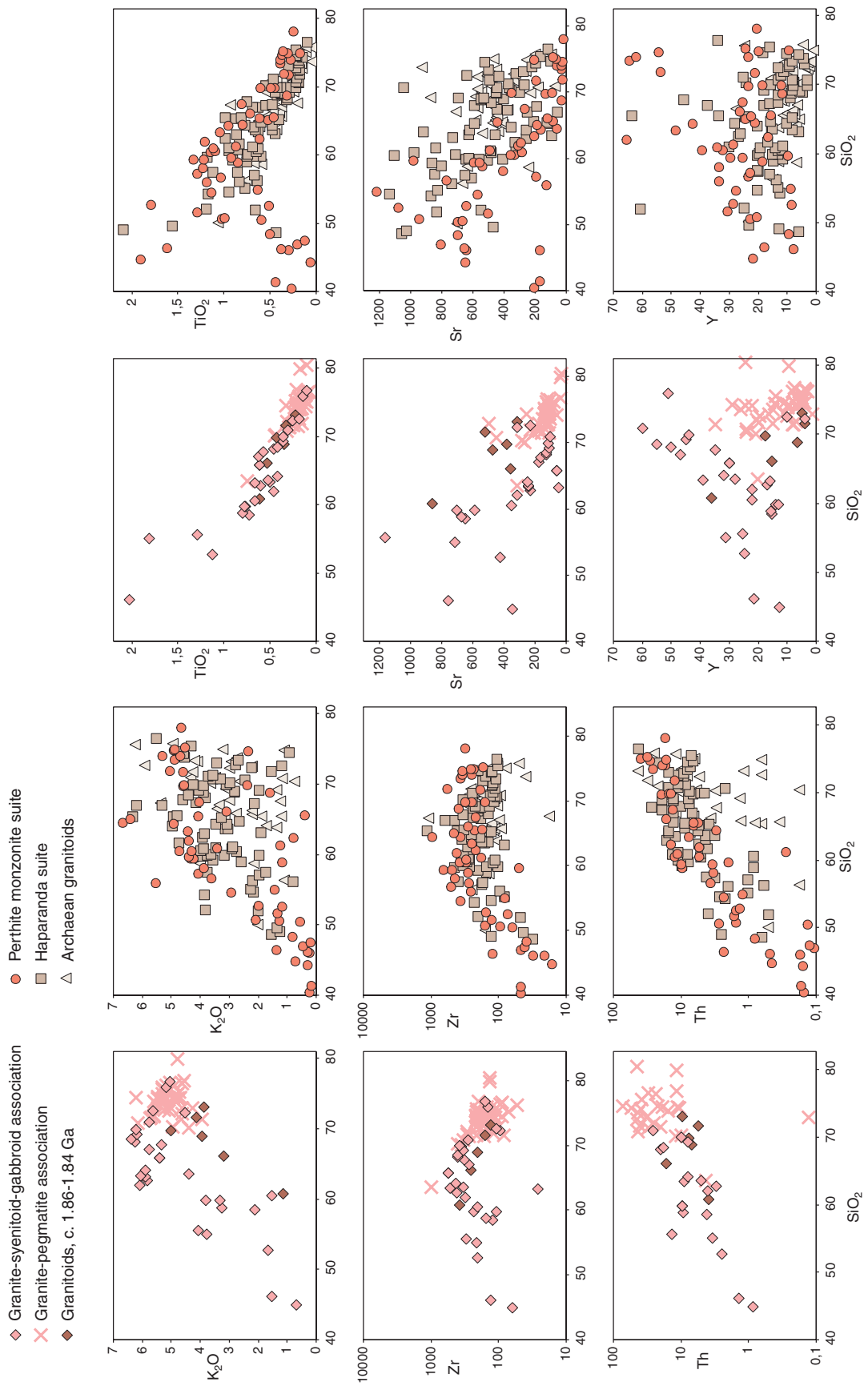


Fig. 8. Plots of K_2O , TiO_2 , Zr, Sr, Th and Y vs. SiO_2 for various intrusive suites. Oxides in weight-% and elements in ppm.

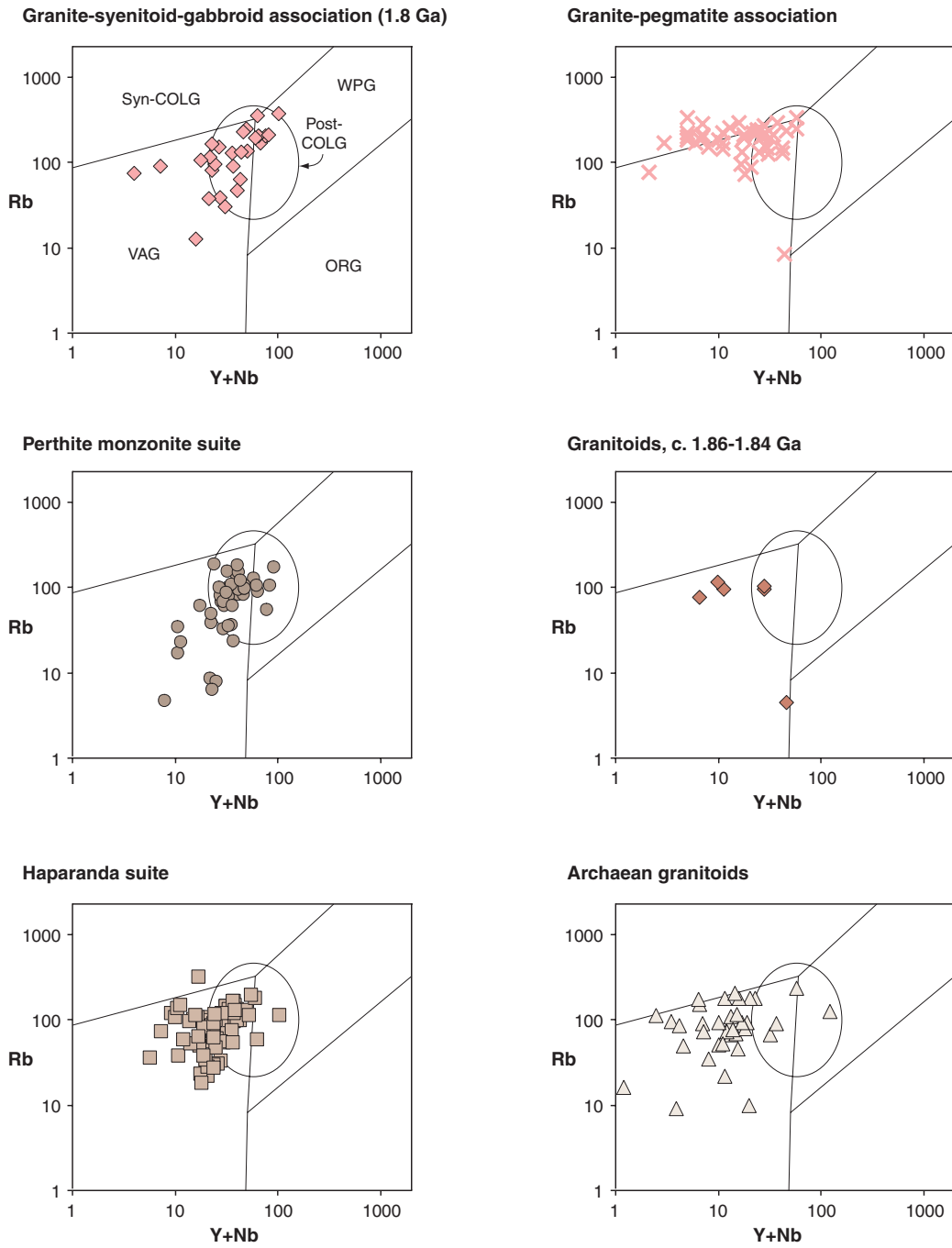


Fig. 9. Rb vs. Y+Nb discrimination plot (Pearce et al. 1984) for various intrusive suites. Syn-COLG = syn-collision granitoids, Post-COL = post-collision granitoids, WPG = within-plate granitoids, VAG = volcanic arc granitoids, ORG = ocean ridge granitoids.

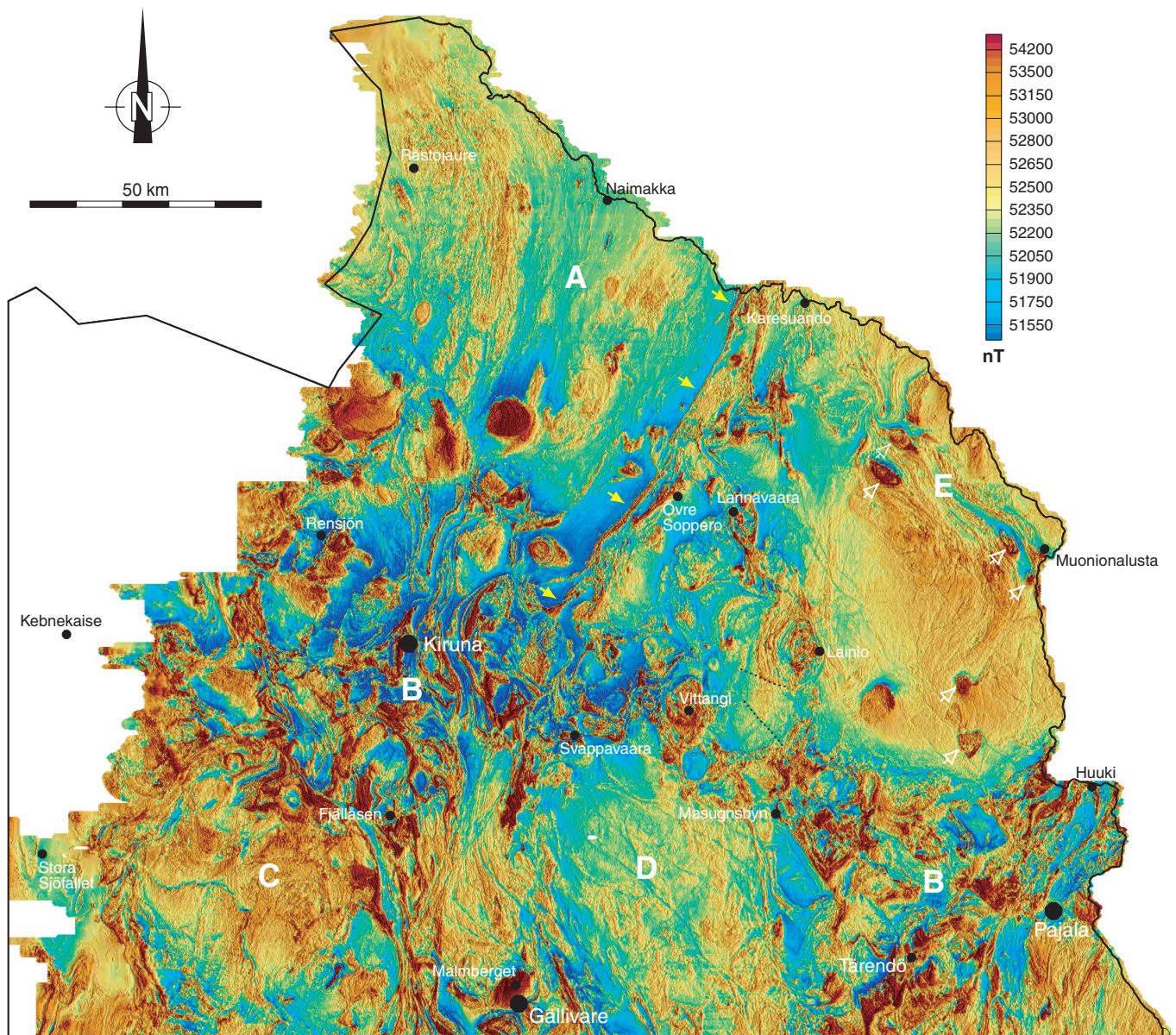


Fig. 10. Color-shaded image showing the magnetic total field over the map area with illumination from the east. The original grid has a cell size of 50 metres x 50 metres. A = banded pattern of Archaean rocks, B = banded pattern in two areas dominated by supracrustal rocks, C, D and E = areas dominated by intrusive complexes. White arrows in the eastern part of the area point to some <1.8 Ga old mafic intrusions which are spatially related to the gravity high (E in Fig. 11). Yellow arrows mark the magnetic "escarpment" in the northern part of the Karesuando–Arjeplog deformation zone (Fig. 2). The two dotted lines in the Vittangi–Lainio area show examples of faults with steep displacement components. In these cases the northeastern blocks are elevated relative to the southwestern blocks.

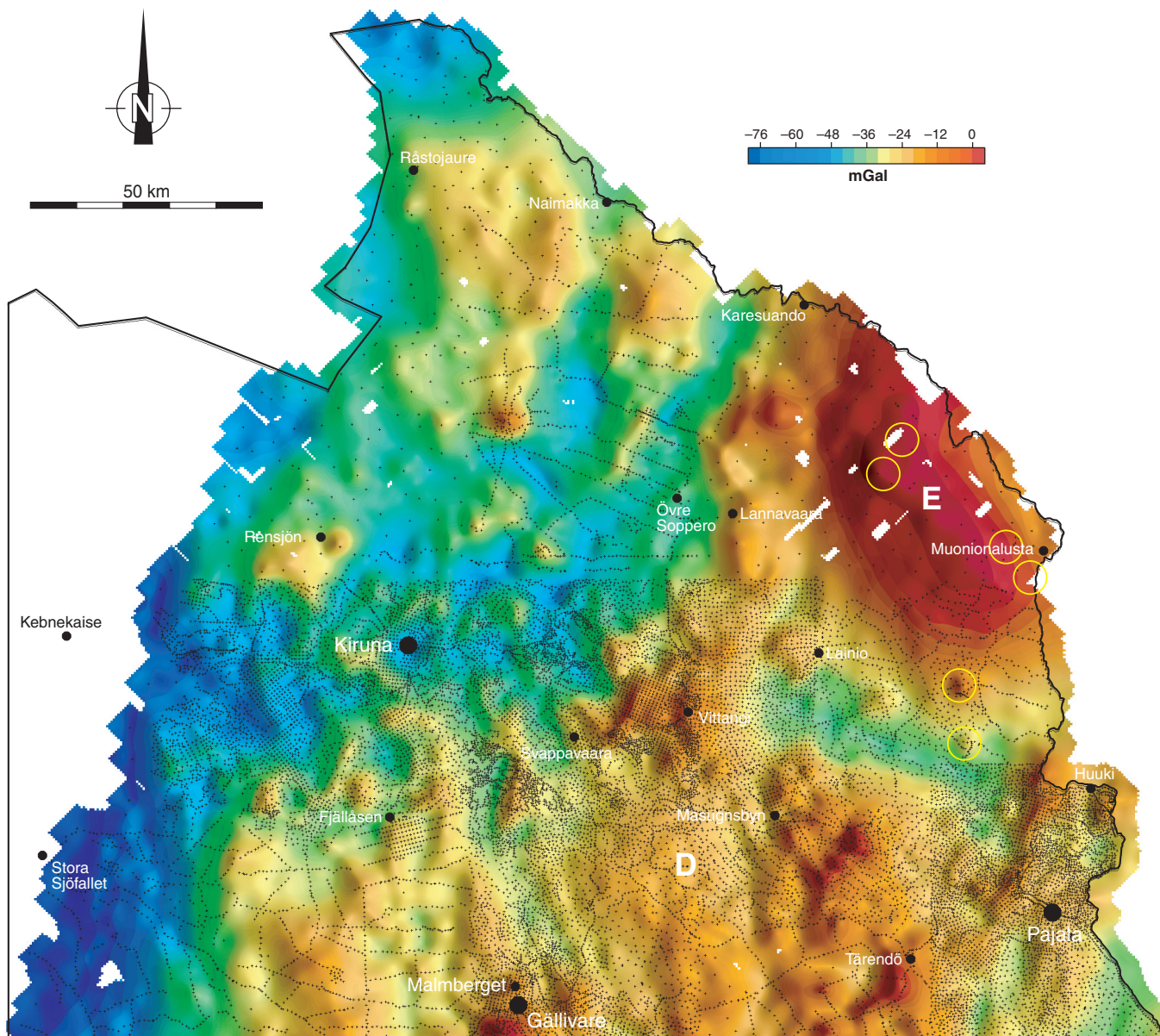


Fig. 11. The regional Bouguer anomaly over the map area and the distribution of gravity data points ($n = 21\,900$). Color-shaded image with illumination from the east. The boundary between denser rocks in the east and less dense rocks in the west roughly coincides with the Karesuando–Arjeplog deformation zone (Fig. 2). Two areas dominated by intrusive rocks with high-density rocks at depth are annotated with D and E (cf. Fig. 10). Yellow circles in the eastern part show locations for some <math>< 1.8\text{ Ga}</math> old mafic intrusions that are spatially related to the gravity high E.



a



b

Fig. 12. Archaean rocks. a) Metagranitoid intruded by mafic dyke. The dyke crosscuts an Archaean gneissosity, and both rocks contain a post-dyke foliation (Svecokarelian). 23 kilometres NW of Övre Soppero (7586730-1733600). b) Metagranite with weathered upper surface, overlain by Proterozoic conglomerate and quartzite. Järämä, 15 kilometres NW of Karesuando, Finland.

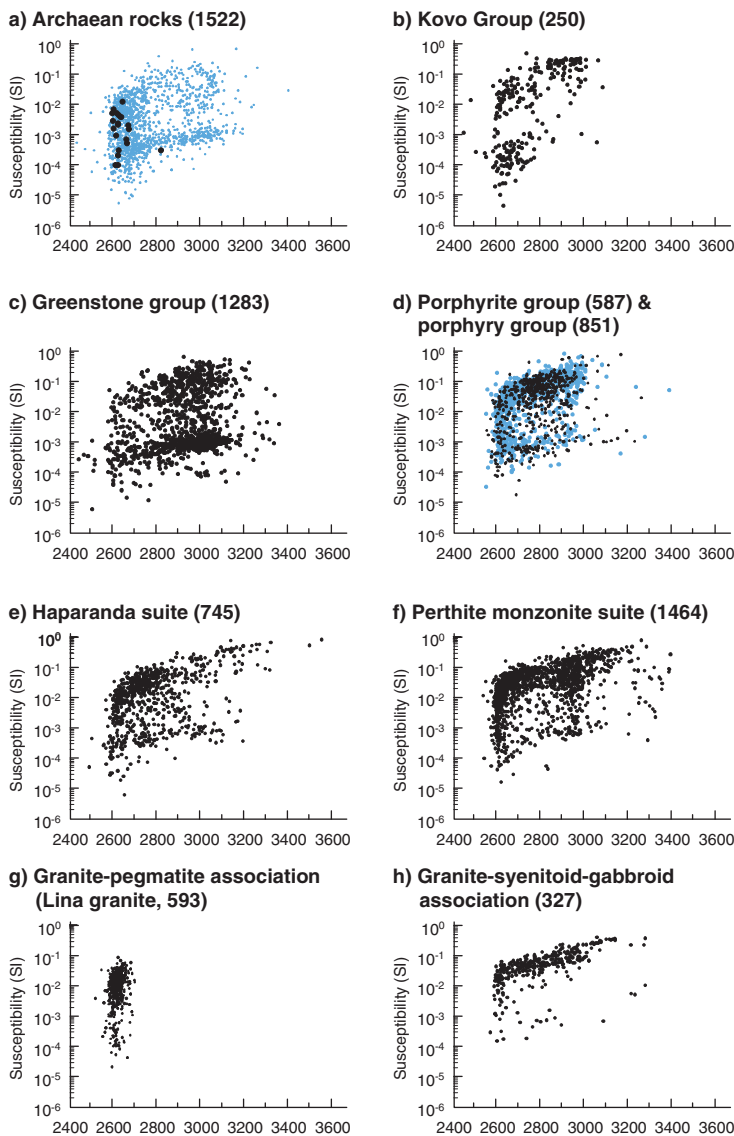


Fig. 13. Petrophysical properties of rocks collected from within different rock units. Magnetic susceptibility (SI) vs. density (kg/m^3) in semi-logarithmic diagrams. The number of samples are shown in parentheses. In diagram a) the Archaean rocks are marked in blue, with black dots corresponding to granites reinterpreted from the Granite-pegmatite association to Archaean granite. In general these rocks have lower susceptibilities than "true" Lina granite (diagram g). In diagram d) the black dots denote rocks of the Porphyrite group, while rocks of the Porphyry group are shown in blue.

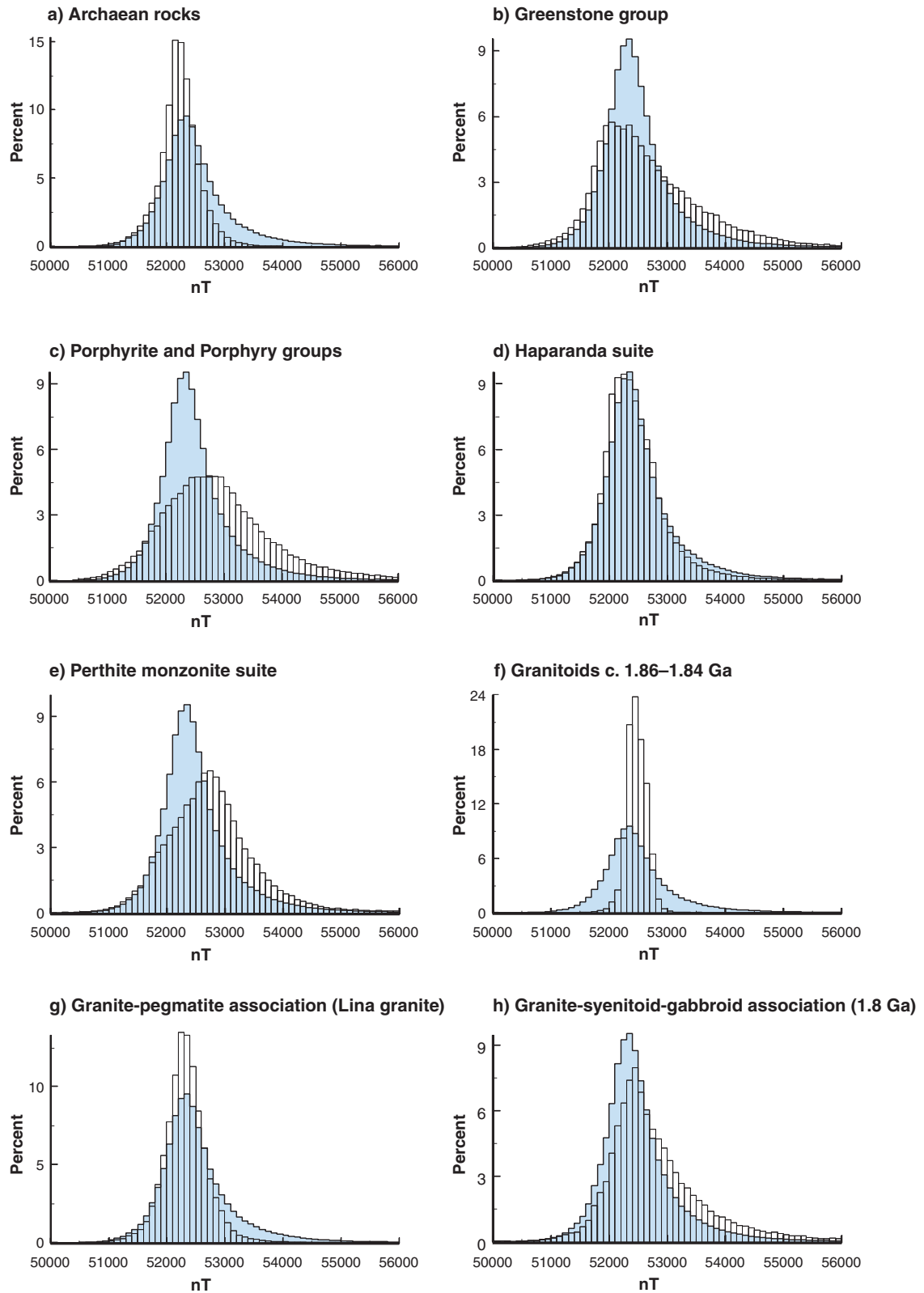


Fig. 14. Histogram showing spectra of the magnetic total field (nT) over the different rock units defined on the geological map. Filled blue area corresponds to the spectrum obtained from the whole map area. X-axis interval: 50 nT. Y-axis: Number of values in percent of the total number for each rock unit.

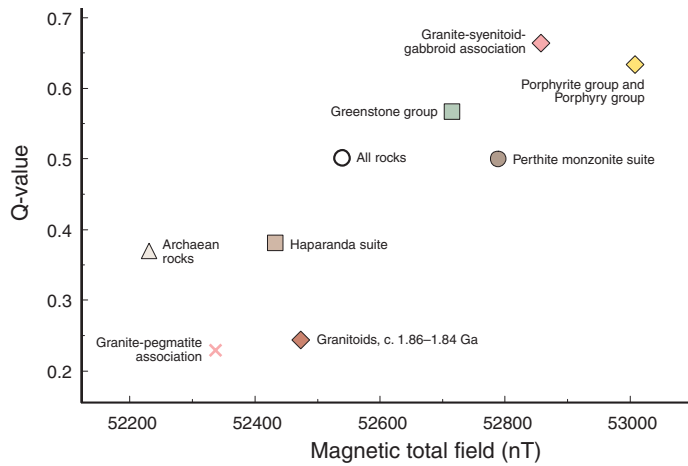


Fig. 15. The geometric mean of the Q-value for all rocks collected from within the different rock groups vs. mean values of the magnetic total field (nT) for the corresponding area.

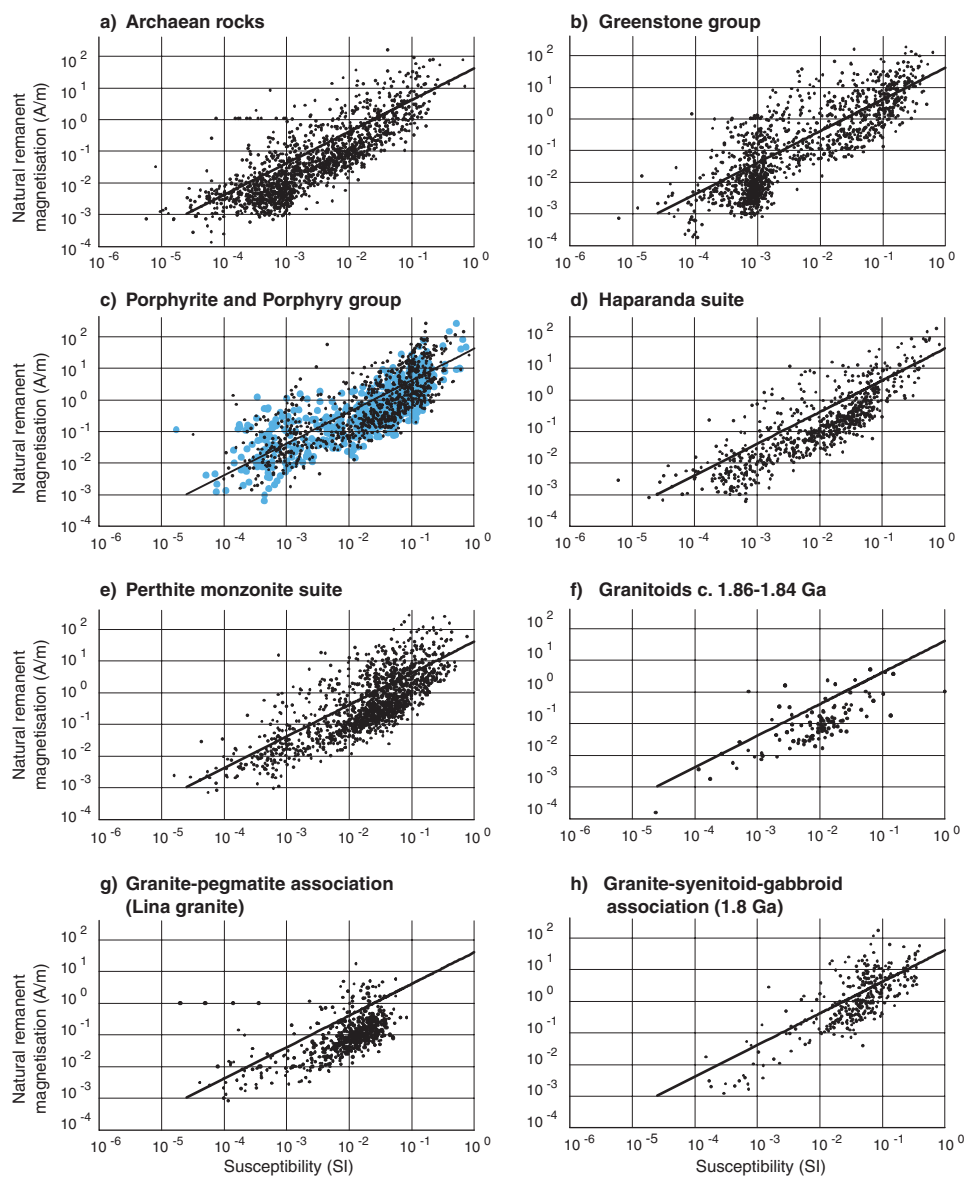


Fig. 16. Natural remanent magnetisation (A/m) vs. magnetic susceptibility (SI-units) of rocks collected from within different rock groups plotted in logarithmic diagrams. The heavy black line corresponds to a Q-value of 1. For samples that plot above this line the remanence has a larger effect on the magnetic field than the susceptibility. In diagram c) rocks of the Porphyrite group are shown in blue while black dots denote rocks of the Porphyry group.

PALAEOPROTEROZOIC ROCKS

Ultramafic-mafic intrusions (c. 2.44 Ga)

A few strongly deformed ultramafic–mafic bodies are found in the Archaean bedrock. These are tentatively correlated with similar c. 2.44 Ga old intrusions along strike in Finland. A recent discussion of this intrusive group in the Fennoscandian and Canadian Shields is presented in Vogel et al. (1998).

The largest bodies are found west and southwest of Karesuando. At Keukiskero, an enstatite pyroxenite has been transformed into an antophyllite-rich rock. Further west, at Ruutusåive, the strongly deformed ultramafic rocks are serpentine- and amphibole-rich types. A report from detailed mapping during nickel exploration (by Sveriges Geologiska AB) in this area is given in Gerdin et al. (1983).

Karelian rocks (c. 2.4–1.96 Ga)

Kovo Group and comparable units

The above group of rocks can be correlated with Sariollian rocks (Martinsson 1997) further east, which were deposited during the age range of 2.39–2.33 Ga ago. The components are clastic metasedimentary rocks and mafic to intermediate metavolcanic rocks.

The Kovo Group was defined by Martinsson (1997) as basal clastic metasedimentary rocks (Fig. 17a), unconformably overlying the Archaean basement in the Kiruna area, together with a sequence of tholeiitic metabasalt and calc-alkaline metavolcaniclastic rocks (Fig. 17b). The metasedimentary rocks consist of conglomerate and quartzite. North of Kiruna, a c. 2.2 Ga old (Skiöld 1986, Table 1) albite-bearing metadiabase sill is found in the lower part of the sequence, giving a minimum age of the Kovo Group.



Fig. 17. Rocks of the Kovo Group. a) Basal conglomerate on Archaean basement. The foliation in some Archaean clasts have different orientations, which indicates that the basement was deformed prior to deposition of the Kovo Group. Southeast of Rävdujåvri, 19 kilometres ENE of Rensjön (7561500-1686700). b) Fragment-bearing metaandesite. The rock is strongly foliated and quartz-veined. Southeast of Rävdujåvri, 19 kilometres ENE of Rensjön (7561600-1686900).

The Tjärro quartzite (with minor conglomerate) is a basal unit, which overlies the eastern margin of the Archaean rocks, and can be followed in Sweden almost continuously for more than 75 kilometres. The primary nature of the contact is, however, obscure in many places, due to strong deformation along a major shear zone, the Karesuando–Arjeplog deformation zone (Fig. 2).

The Kovo Group north of Kiruna and the Tjärro quartzite were probably deposited along a coastline of an early Proterozoic marine rift basin (Kumpulainen 2000). Material input from a westerly source area to the coastline was provided through a number of alluvial fans. Sandy material was distributed along the coastline by coast-parallel southwards currents.

The metaarenitic gneisses along the Swedish–Finnish border S of Pajala have been placed in this group based on correlation with the stratigraphy on the Finnish side of the border (J. Väänänen, pers. comm. 1999).

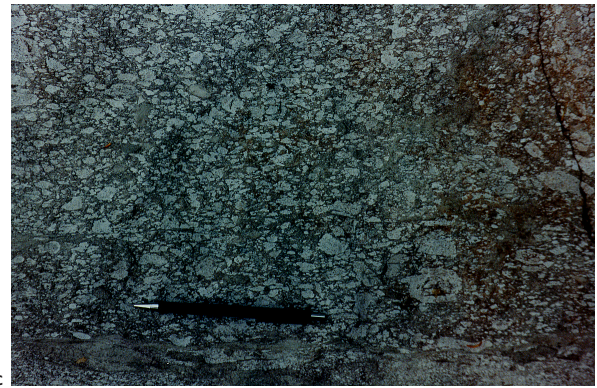
The susceptibility-to-density ratios of rocks in the Kovo Group fall into three distinct groups (Fig. 13b). This could be expected for supracrustal rocks, in contrast with a differentiated intrusive suite which shows a more continuous distribution (cf. Figs. 13e, f, h). The Tjärro quartzite is characteristically placed in the low density–very low susceptibility corner, similar to Svecofennian metaarenites in higher stratigraphic levels. These areas are marked by pronounced depressions in the magnetic total field (e.g. south of Masugnsbyn and in the Stora Sjöfallet area, Fig. 10).

Greenstone group

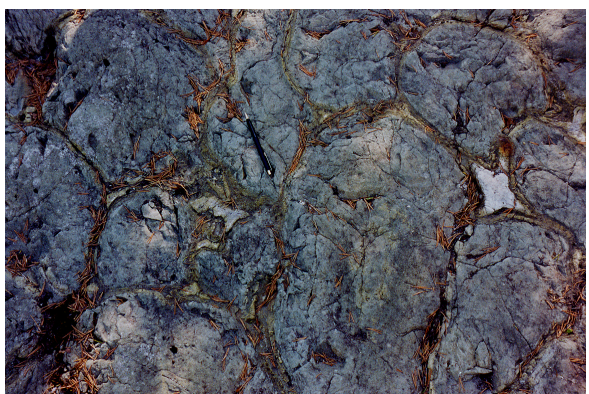
Rocks belonging to the Greenstone group are found in several areas. The main rock types are metabasalt, commonly graphite-bearing metaargillite, crystalline carbonate rock, and ultramafic rocks. Local names used for these rocks are shown in Table 2. The first detailed petrograph-



a



c



b



d

Fig. 18. Rocks of the Greenstone group. a) Quartz-banded iron formation (BIF). Käymäjärvi, 28 kilometres NW of Pajala (7495740-1805420). b) Pillowed metabasalt in the upper part of the Greenstone group. Kurravaara, 10 kilometres NNE of Kiruna (7545000-1690200). c) Metamorphosed lapilli tuff with picritic composition. Käymäjärvi, 28 kilometres NW of Pajala (7495870-1805520). d) Serpentinite with altered pyroxene (?) phenocrysts and chrysotile veins. Valkeasiipivaara, 5 kilometres NNW of Kiruna (7539800-1684900).

ical description of the Kiruna greenstones was presented by Sundius (1915). A recent, detailed study is given by Martinsson (1997). Stratigraphical columns for the Soppero–Lannavaara, Vittangi, Masugnsbyn (Tärendö), and Pajala areas, and comparisons with the Kiruna greenstones, are presented in Martinsson (1993). The lower and upper boundaries of the Jatulian, towards the Sariollian and Ludikovian, respectively, coincide with a global excursion to high $\delta^{13}\text{C}$ values of carbonates between 2.3 and 2.06 Ga ago (e.g. Karhu 1993, Melezhik et al. 1997). This change in $\delta^{13}\text{C}$ values has also been recorded in carbonates from the Kiruna area (Martinsson et al. 1997a) and constitutes the basis for the Jatulian/Ludikovian subdivision of the metavolcanic rocks in the Greenstone group.

Amygdaloidal metabasaltic lavas are characteristic for the lower parts of the Greenstone group. They can be correlated with Jatulian metabasalts in the northeastern part of the Fennoscandian Shield. Individual lava flows

are commonly 2–18 metres thick. The amygdules (2–15 millimetres) consist of quartz, chlorite, calcite, epidote, amphibole, feldspar, magnetite, pyrite, or chalcopyrite. These tholeiitic metabasalts largely have a MORB- or LKT-like chemical character (Martinsson 1997).

In the Vittangi and Soppero–Lannavaara areas, the metabasaltic lavas are overlain by volcanoclastic units. In the Masugnsbyn and Pajala areas these are the only exposed units. Layering is common on a centimetre-to-decimetres scale. In most places they have a tholeiitic composition. In the upper parts (Ludikovian) the volcanoclastic rocks are intercalated with black schist, carbonate rocks, iron formations (Fig. 18a), and chert. In the Kiruna area there are metabasaltic pillow lavas (Fig. 18b) at high stratigraphic levels in the Greenstone group.

Mafic dykes and sills, at least some of which are coeval with the magmatism of the Greenstone group, are common in the Karelian and Archaean rocks. Their dominant strike direction is NNE. Albite-bearing metadia-

base is common in many areas. Rocks previously mapped as leucodiabase may be either light-coloured mafic magmatic rocks or albite-rich rocks (albitite) formed by extensive alteration. The albitites are characteristically located near tectonic zones, and they are commonly microfractured or brecciated.

Metaultramafic rocks are found in some areas as dykes or as supracrustal rocks (Figs. 18c, d). Komatiites are mainly restricted to low stratigraphic positions in the Kiruna area (Martinsson 1997). Picritic sills and/or chemically similar tuffs and local instances of lava exist in the Kiruna, Vittangi, Masugnsbyn, and Pajala areas (Martinsson 1993). Ultramafic dykes are also known from the Soppero area.

Thick units of crystalline carbonate rock are mainly found at high stratigraphic levels in the Vittangi, Lannavaara, Masugnsbyn, and Pajala areas, and north of Kiruna. The most well known deposit is at Masugnsbyn, where dolomite is presently quarried.

Metaargillite with a locally high graphite content is interlayered with the volcanoclastic rocks, whereas metaarenite is a subordinate component in the Greenstone group. Minor intercalations exist in the Kiruna and Pajala areas. The largest rock units, which have an uncertain stratigraphic position, are found in the high-grade rocks east of Karesuando.

The Greenstone group has a banded magnetic pattern, reflected in a rather high magnetic structure index (1 km^{-1} , Table 4), which yields a broad magnetic total field spectrum (Fig. 14b) with high standard deviation. The asymmetry of the spectrum is caused by the more or less bimodal distribution of susceptibility (Fig. 13c). On the other hand, the distribution of the densities is simple with one maxima (Fig. 19c). Remanent magnetisation is very important in this group and contributes to the high mean magnetic total field (Fig. 15).

Svecofennian supracrustal rocks (c. 1.96–1.85 Ga)

The Greenstone group is overlain by Svecofennian meta-sedimentary and metavolcanic rocks. The contact between these major rock units is in most places interpreted as conformable. However, in the Kiruna area there is evidence for substantial erosion of the Greenstone group prior to Svecofennian deposition. In the Lannavaara area the contact has been suggested to be an angular unconformity (Ambros 1980). This is further discussed in the "Structure" chapter on page 82.

TABLE 4. Magnetic structure index for various rock units and structural domains defined in the chapter on "Structure". The values for Archaean rocks also include the mafic dykes in that area. L-domain⁽¹⁾: values calculated from the total domain L-area. L-domain (max)⁽²⁾: values calculated from the central part with maximum connexion density. M-domain (max)⁽¹⁾: values calculated from the southern part with maximum connexion density. G-domain (south) is the southern part of domain G (see the "Structure" chapter and Fig. 52). The column MTF (std. dev.) is the standard deviation in nT for magnetic total field values in an area.

Rock unit or structural domain	Area (km ²)	Total number of connexions (n)	Total length of all connexions (km)	Connexion density (n/km ²)	Mean length (km/n)	Magnetic structure index (x1/km)	MTF (std. dev.)
Archaean rocks	4793	1924	4014	0.401	2.086	0.837	358
Kovo Group	333	240	429	0.721	1.788	1.288	591
Greenstone group	1943	953	1943	0.490	2.039	1.000	880
Porphyrite group	1758	979	1962	0.557	2.004	1.116	1372
Porphyry group	1937	966	1992	0.499	2.062	1.028	
Haparanda suite	4080	1243	2752	0.305	2.214	0.675	598
Perthite monzonite suite	4779	1536	2837	0.321	1.847	0.594	1072
Granitoids 1.86–1.84 Ga (Jyryjoki granite)	937	311	599	0.332	1.926	0.639	189
Granite-pegmatite association	8448	2268	4591	0.268	2.024	0.543	410
Granite-syenitoid-gabbroid assoc.	1390	498	998	0.358	2.004	0.718	1039
L-domain ⁽¹⁾	3756	1142	2615	0.304	2.290	0.696	
L-domain (max) ⁽²⁾	446	244	604	0.547	2.475	1.354	
M-domain (max) ⁽¹⁾	500	406	662	0.812	1.631	1.324	
G-domain (south)	538	373	717	0.693	1.922	1.333	
J-domain	971	407	862	0.419	2.118	0.888	

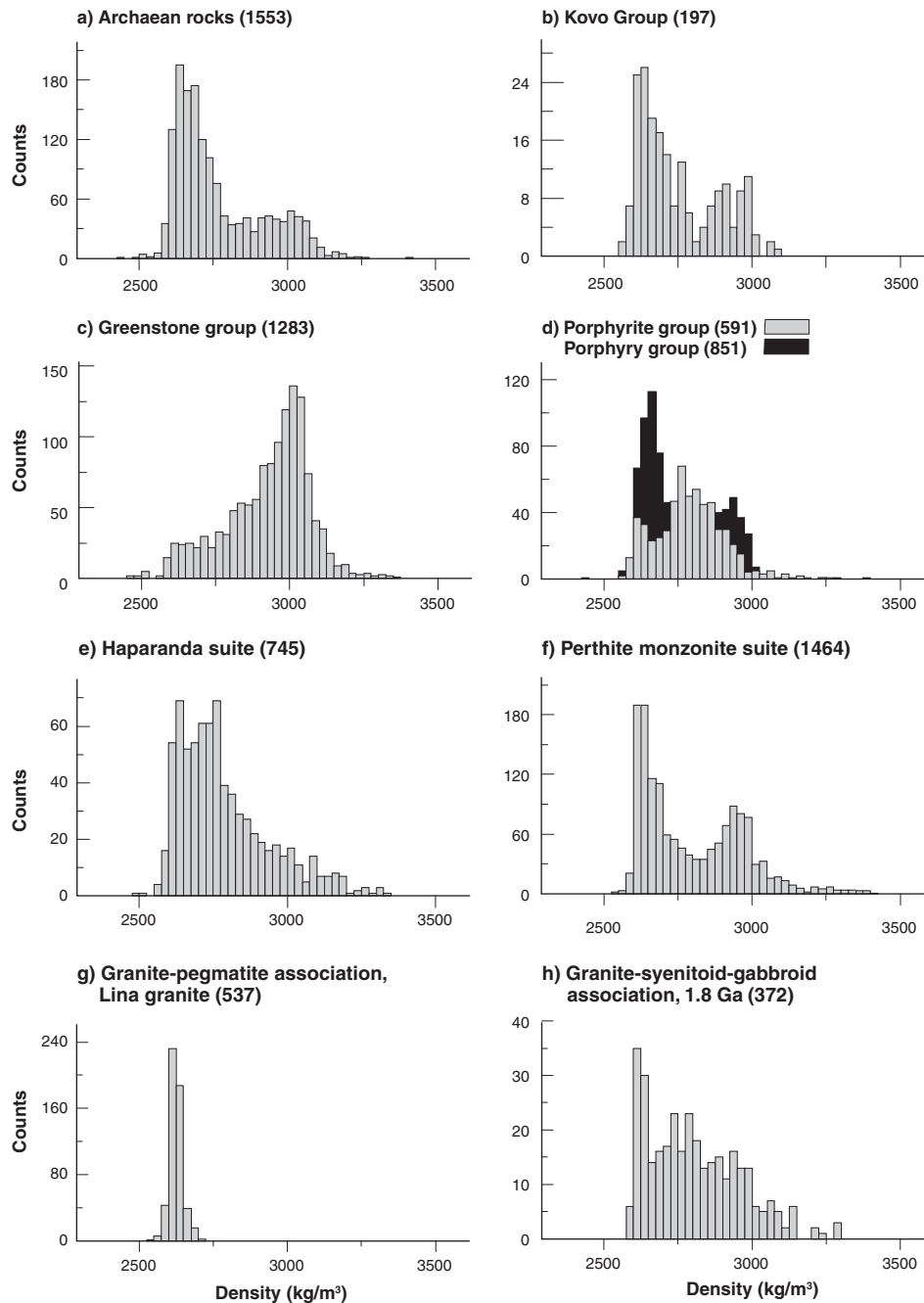


Fig. 19. The distribution of densities (kg/m^3) of rocks collected within different rock groups plotted in histograms. The number of samples are shown in the headings.

Older metasedimentary rocks

The older Svecofennian metasedimentary rocks consist of various clastic sequences. Calc-silicate rocks (skarn) are found only locally (e.g. in the southwestern corner of the study area) and carbonate rocks are rare.

Some rock units which were classified as belonging to the Karelia or Lapponia Supergroups (e.g. the Pahakurkio group and parts of the Korpilombolo group)

on the bedrock map of northern Fennoscandia (Silvenoinen et al. 1987) have been reinterpreted here as Svecofennian. The main reason for this is the association of metasedimentary rocks with intermediate metavolcanic rocks, where the latter have yielded U-Pb ages of c. 1880 Ma (SGU, unpublished results).

In the Kiruna area, metaconglomerate and metasandstone (Kurravaara conglomerate, Fig. 20a) overlie the Greenstone group. The pebbles of the metaconglomer-

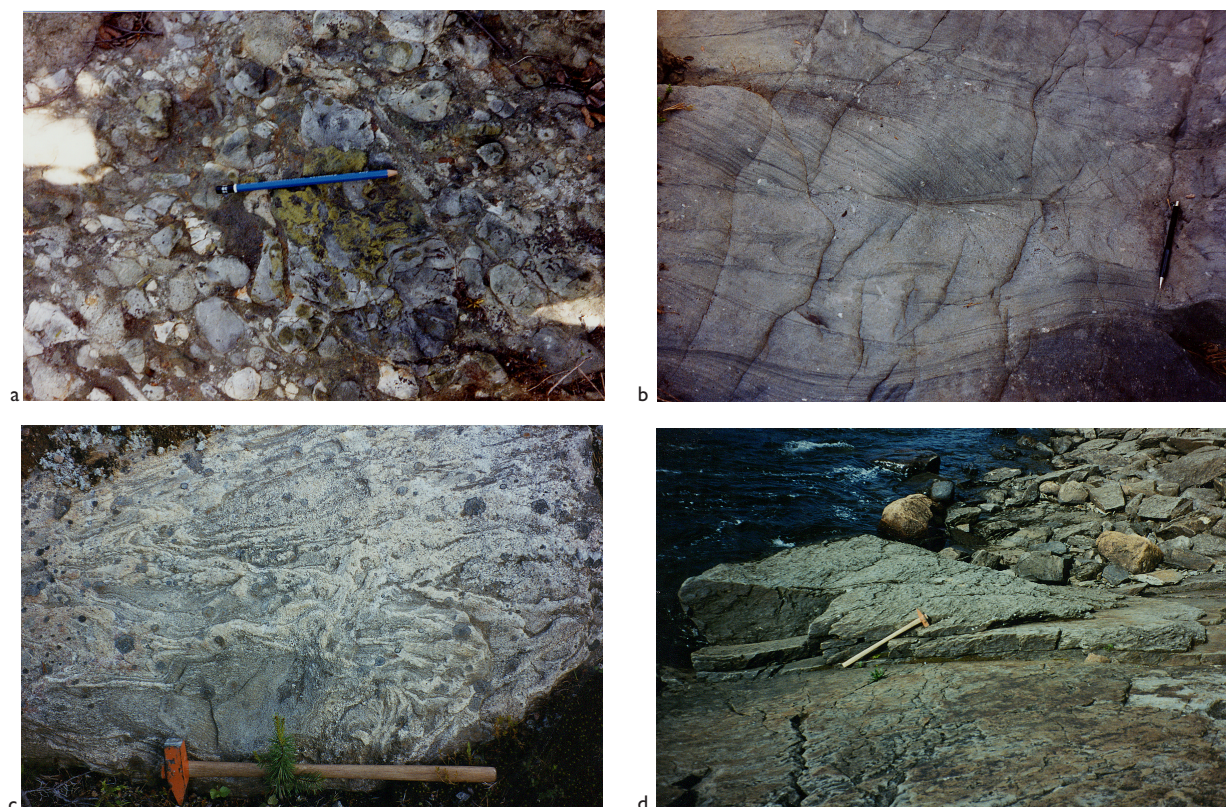


Fig. 20. Older Svecofennian metasedimentary rocks. a) Kurravaara conglomerate, which was deposited on top of the Greenstone group in the Kiruna area. Clasts mainly consist of intermediate metavolcanic rocks. Valkeasiipivaara, 5 kilometres NNW of Kiruna (7539700-1685000). b) Crossbedded metaarenite overlying the Greenstone group. Kurravaara, 10 kilometres NNE of Kiruna. c) Migmatitic metaarenite from the area with high-grade rocks S of Pajala. Leucosome from this locality has yielded U-Pb monazite ages, indicating metamorphism in the range of 1798–1774 Ma (Bergman & Skiöld 1998). Ähkärä, 12 kilometres southeast of Pajala (7468090-1835140). d) Andalusite-porphyrroblastic metaargillite with flat-lying bedding and gently S-dipping cleavage. View looking west. Pahakurkio, 14 kilometres SSE of Masugnsbyn (7484840-1770100).

ate are dominated by metavolcanic rocks showing some similarities with the overlying Porphyry group. This has prompted a long-lasting discussion about the origin of the metaconglomerate and the stratigraphy within the area. Recent studies, however, show that the pebbles are calc-alkaline and chemically different from the overlying Porphyry group (Martinsson & Perdahl 1993). The depositional setting of the Kurravaara conglomerate was most probably a fan delta, or perhaps two fan deltas (Kumpulainen 2000). Quartz-pebble conglomerate is found at a similar stratigraphic position in the Käymäjärvi area, near Pajala.

Svecofennian metaarenitic rocks are widespread in the region. Well-preserved rocks with primary sedimentary structures (Fig. 20b) are found e.g. near Kiruna, S of Masugnsbyn (Pahakurkio group), in the Käymäjärvi area, and at Nunasvaara (E of Lannavaara). These rocks carry features characteristic of shallow-marine wave-dominated deposits, which grade laterally and vertically over to graded and laminated tempestites deposited on deeper shelf (Kumpulainen 2000).

The high-grade metaarenitic gneisses S of Pajala (Fig. 20c) have been divided into two units of separate age but

with similar field appearance. The position of the boundary is uncertain and has been placed where a fault has been interpreted from magnetic data. The Karelian age of the eastern unit is based on correlation with the stratigraphy on the Finnish side of the border (J. Väänänen, pers. com. 1999). The western unit is considered to be Svecofennian, based on its association with intermediate metavolcanic rocks (comparable to the Porphyry group). An ion probe age of c. 1910 Ma from the internal part of a zircon crystal (Bergman & Skiöld 1998) also points in this direction. High-grade metaarenites associated with pyroxene-bearing amphibolites are found near Muonionalusta and S of Saivomuotka. Their stratigraphic position is unclear but they are interpreted here as Svecofennian. A study of zircons from gneisses of various origin (mica and amphibole gneisses) in this region gave ages less than 2063 Ma (Skiöld 1981a). This suggests a Svecofennian or possibly late Karelian age of deposition for these rocks. Lehtonen (1988) describes a sequence of amphibolites, arkose gneisses, and quartzites in the Muonio area in Finland, and interprets them as early Proterozoic (pre-Svecofennian).

Larger areas with metaargillitic rocks (Fig. 20d) are

found S of Masugnbyn and SW of Pajala. In the first-mentioned area andalusite-bearing mica schist grades towards the south into sillimanite-bearing schist and veined gneiss.

Metavolcanic rocks

The Svecofennian metavolcanic rocks can be subdivided into the stratigraphically lower Porphyrite group and the overlying Porphyry group. These metavolcanic rocks have recently been studied by Martinsson & Perdahl (1993, 1995), who maintained the terminology of Offerberg (1967) even though a large part of the rocks originally referred to as the Porphyrite group were found to be mafic metavolcanic rocks in the lower part of the Porphyry group. The distribution of the Porphyrite and Porphyry groups on the map has been slightly modified from Offerberg (1967), Martinsson & Perdahl (1995), and Perdahl & Martinsson (1995). In some areas the reclassification of the metavolcanic rocks into these two groups was complicated by the fact that the previous naming of rocks (e.g. trachyte) may be wrong, as only major elements were considered.

Porphyrite group

The Porphyrite group consists of metamorphosed low-titanium andesites (Fig. 21a, b), basalts, and minor intercalations of felsic tuffs and tuffites. The andesites and

basalts are often rich in plagioclase phenocrysts (up to 3 cm large, Fig. 21b) in a biotite-rich matrix. Intrusive porphyritic rocks with intermediate composition are known from the area NW of Vittangi (Geijer 1918b, Eriksson & Hallgren 1975, Filén 1976). The rocks of the Porphyrite group generally have low contents of titanium and zirconium (Fig. 22). Martinsson & Perdahl (1995) suggested that the Porphyrite group is a calc-alkaline volcanic series formed in a compressional environment. The high content of alkalis was attributed anomalous crust rather than enrichment through differentiation. One age determination of an intermediate metavolcanic rock from Käymjärvi has provided evidence for an age of 1880 ± 3 Ma (Fig. 3, Table 1, SGU, unpublished results).

Porphyry group

The overlying Porphyry group, which hosts economically important iron ores (e.g. in Kiirunavaara), consists of metamorphosed high-titanium basalt, trachyandesite, and rhyodacite-rhyolite. The geographic distribution is confined to the southwestern part of the map area. Metabasalt with a thickness of at least 4 kilometres is found in the stratigraphically lowest part, southwest of Kiruna. Trachyandesite is mainly restricted to the footwall of the Kiirunavaara iron ore. Large phenocrysts of microperthite and albite are common in the rhyodacite-rhyolite (Fig. 21c). Volcaniclastic rocks are found in some areas.

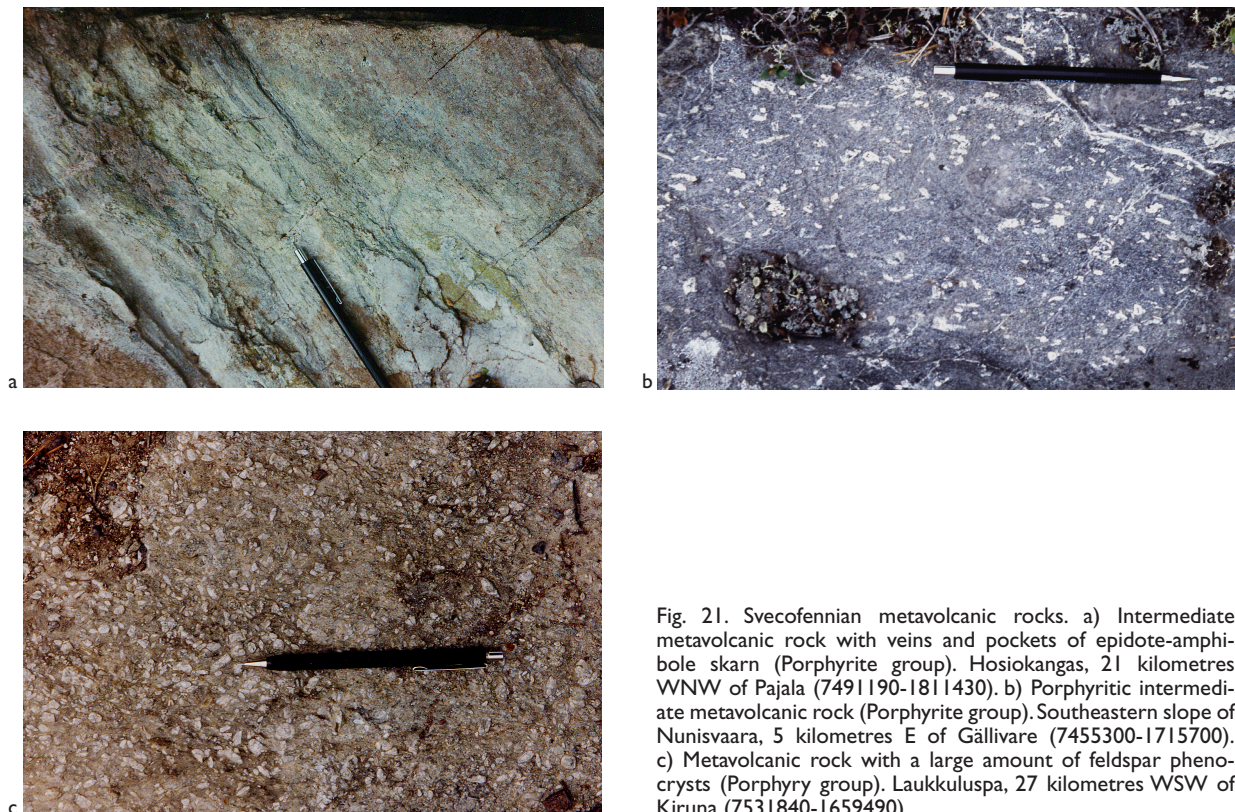


Fig. 21. Svecofennian metavolcanic rocks. a) Intermediate metavolcanic rock with veins and pockets of epidote-amphibole skarn (Porphyrite group). Hosiokangas, 21 kilometres WNW of Pajala (7491190-1811430). b) Porphyritic intermediate metavolcanic rock (Porphyrite group). Southeastern slope of Nunisvaara, 5 kilometres E of Gällivare (7455300-1715700). c) Metavolcanic rock with a large amount of feldspar phenocrysts (Porphyry group). Laukkuluspa, 27 kilometres WSW of Kiruna (7531840-1659490).

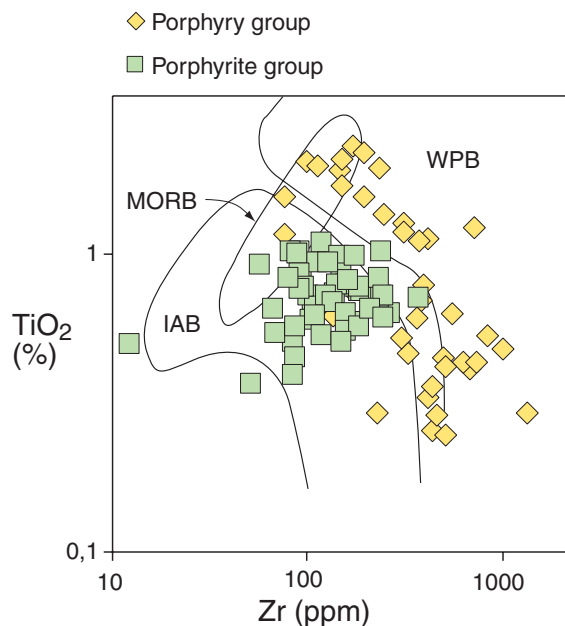


Fig. 22. Plot of TiO_2 vs. Zr which distinguishes most rocks of the Porphyrite group from rocks of the Porphyry group. Discrimination fields for island arc basalts (IAB), mid-ocean ridge basalts (MORB) and within-plate basalts (WPB) from Pearce (1980).

The rocks of the Porphyry group are generally high in titanium and zirconium (Fig. 22), which distinguishes them from rocks of the Porphyrite group. The high titanium content of a mafic metavolcanic rock (drill core analysis in Studsvik-Analytica AB 1986) in the Vivungi area (W of Lainio) suggests affinity to the Porphyry group. Martinsson & Perdahl (1995) suggested that the mildly alkaline rocks of the Porphyry group were formed in an extensional environment. Age determinations of felsic metavolcanic rocks have yielded ages of 1882 Ma and 1909 Ma, with large errors (Fig. 3, Table 1, Skiöld & Cliff 1984, Welin 1987).

With respect to petrophysical properties the Porphyrite group is not easily distinguishable from the Porphyry group, if at all. High susceptibilities are typical for both groups even though densities are below $3\,000\text{ kg/m}^3$, with an opposite distribution trend in comparison to the Greenstone group (Fig. 19c, d). The more felsic to intermediate metavolcanic rocks of the Porphyry group typically have high to very high susceptibilities and low densities, which is less common in the Porphyrite group. The magnetic total field in the area covered by the Porphyrite and Porphyry groups is very heterogeneous and shows the strongest amplitude variations (very high standard deviation) and highest mean value of all units (Fig. 14c). These variations are confined to extensive magnetic banding, illustrated by a high magnetic structure index (Table 4). As can be discerned from Figs. 15 and 16c, rather high remanent magnetisation especially in the Porphyry group contributes to the high average

magnetic total field. An additional cause is the presence of the iron ores.

Forsell (1987) reinterpreted the stratigraphy in the Kiruna area and considered the Kurravaara conglomerate to be coeval or younger than the footwall rocks of the Luossavaara–Kiirunavaara iron ores (Porphyry group). Isoclinal folding was inferred to explain the outcrop pattern. A model presented by Talbot & Koyi (1995) also implies that the Kurravaara conglomerate is younger than the Porphyry group. This view is not favoured here. The available stratigraphic information, including reliable younging directions, suggests that the conglomerate is older than the Porphyry group and coeval with rocks of the Porphyrite group.

Younger supracrustal rocks

In the Stora Sjöfallet area, clastic metasedimentary rocks overlie (apparently conformably) metavolcanic rocks of the Porphyry group. They consist of a probably more than 6 000 metres thick pile of red metasandstone, metaconglomerate, metaarkose, and quartzite. Metaargillite and metabasalt are also found. The rocks are commonly excellently preserved and show a wide range of primary structures (Fig. 23a, b). They have been interpreted as a continental or near shore deposit (e.g. Witschard & Zachrisson 1995a, b).

Northwest of Vittangi, a metaconglomerate (Fig. 23c) rests unconformably on a metadiorite (Ödman 1939). This metadiorite has been dated to 1881 ± 7 Ma (SGU, unpublished results), which thus is the maximum age of the basal metaconglomerate. The overlying rocks are dominated by quartzite with intraformational metaconglomerate. Corresponding rocks are also found in the Kiruna area. The contacts towards other units are mostly tectonic.

Svecokarelian intrusive rocks

Six different Svecokarelian intrusive rock suites can be distinguished in the investigated area. Modal data for five of these are presented in Fig. 5. Their major element variations are shown in the P-Q diagram included in Debon & LeFort (1983, Fig. 6) and in the modified Peacock (1931) diagram (e.g. Brown 1982, Fig. 7). Other diagrams are shown in Figs. 8 and 9.

In potential field data, some Svecokarelian plutons are easily detected as two types of circular structures of limited geographical extent. The first type is characterized by high magnetic–high gravity anomalies and reveals concentric magnetic banding (white arrows in Fig. 10 and yellow circles in Fig. 11). These structures are generally caused by mafic intrusions. The second type is character-

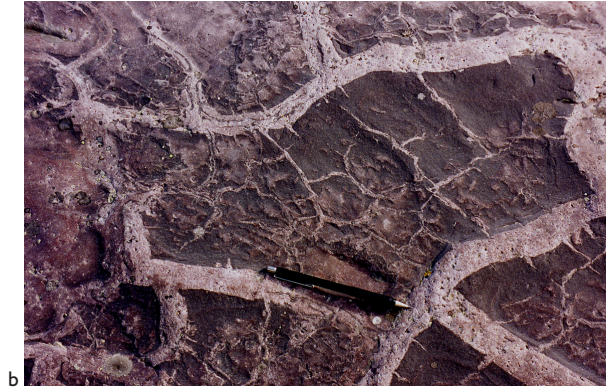


Fig. 23. Younger Svecofennian metasedimentary rocks. a) Ripple marks in sandstone. Vietasättno, near Stora Sjöfallet (7491000-1610000). b) Mud cracks, same locality as a). c) Metaconglomerate that was deposited on a 1881 ± 7 Ma old metadiorite. The clasts mainly consist of metadiorite. Skaitevaara, 34 kilometres NW of Vittangi (7546300-1724200).

ized by low magnetic–low gravity anomalies with a high magnetic anomaly fringe (e.g. 18 kilometres S of Vittangi, Fig. 10). Several of these structures are caused by granites of the Perthite monzonite suite. Henkel (1978) interpreted the structures as diapirs.

Haparanda suite

The name "Haparanda series" was originally used for a group of intrusions of granite, granodiorite, quartz diorite, diorite, and gabbro in the Haparanda area (Ödman et al. 1949), and was later also used for similar rocks further north (Ödman 1957). Since then, that name and the more appropriate "Haparanda suite" have been used extensively in northernmost Sweden.

Rocks belonging to the Haparanda suite are mainly found in the eastern part of the map area. The more or less gneissose rocks are commonly medium-grained, but fine-grained types also exist. Porphyritic types are less common. There is a wide spectrum of rock types, from gabbro and diorite, through monzodiorite, monzonite and granodiorite, to subordinate granite. Syenitoid compositions are common in the central parts, between Vittangi and Huuki, whereas granitoid compositions dominate other areas, especially the high-grade Karesuando–Muonionalusta area (Fig. 24). Relatively weakly deformed granodiorites-quartz monzonites in the Täreändö area are uncertainly assigned to the Haparanda suite.

Modal compositions of rocks from the 29L Lainio map sheet were presented by Witschard (1970), and from other areas by Ödman (1957), and these are given in Fig. 5. The range in chemical composition is shown in Fig. 6. The chemical trend is alkali-calcic to calc-alkaline (Fig. 7). Compared to the Archaean rocks, many samples from the Haparanda suite have higher contents of potassium and thorium (Fig. 8). On a Rb vs. Y+Nb diagram the rocks of the Haparanda suite plot in the volcanic arc granite field (Fig. 9).

In the Karesuando–Muonionalusta area the Haparanda suite, with its low- to medium-density rocks, is found

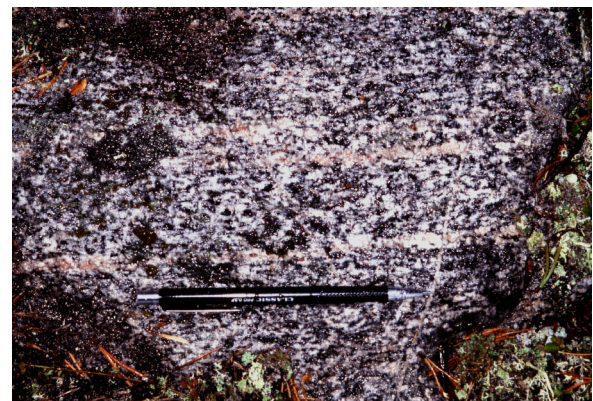


Fig. 24. Metamorphosed quartz diorite (Haparanda suite). Puristakero, 14 kilometres southwest of Muonionalusta (7542480-1817540).

in an area characterized by a regional, high gravity anomaly (marked with E in Fig. 11). This is one of the most pronounced positive gravity anomalies in Sweden. According to Lindroos & Henkel (1978, 1981) this anomaly could be caused by a basement culmination, assuming that gneissose rocks of rather high density ($>2\ 900\ \text{kg/m}^3$) are also in existence in the central part. At that time the petrophysical information was limited. New sampling during the present project did not reveal the densities needed to explain the gravity anomaly. The occurrence of several gabbro intrusions located within the outlines of the anomaly (for a description of these intrusions see the chapter on "Gabbro, metagabbro and diabase, $<1.8\ \text{Ga}$ ", p. 37) suggests that these two phenomena are linked to each other and that the anomaly is younger than earlier proposed. A deeper-seated body of high-density rocks (e.g. gabbro) probably causes the anomaly, and the intrusive structures formed at sites of pressure release conduits during emplacement of the high-density body. According to Euler deconvolution modelling, the upper surface of this body is located at a depth of 6–9 kilometres (Leif Kero, pers. comm. 2000).

The magnetic total field over the Haparanda suite differs from the other rock groups in that its spectrum is almost identical to the total observed over the whole map area (Fig. 14d). Low- to medium-density rock types with rather high susceptibility dominate (Figs. 13e, 19e). The natural remanent magnetisation has only a minor influence on the magnetic total field (Fig. 16d).

Perthite monzonite suite

Two groups of older intrusions, both including gabbro, syenite and granite, were identified by Geijer (1931b). The first group, including calc-alkali syenite, was later included in the Haparanda suite (see above). The second group is characterized by perthitic feldspar in both quartz-rich and quartz-poor varieties. Using modern terminology, monzonite or quartz monzonite proved to be the dominating rock type rather than syenite, and Witschard (1984) introduced the name "Perthite monzonite suite" for these rocks.

The main distribution of the suite is in the western parts of the area, where it forms a broad N–S trending belt. Syenitoid compositions dominate over granitic types. Perthite granites are commonly red and medium- to coarse-grained (Fig. 25a). Pyroxene-bearing monzonites appear locally. Enclaves and hybridisation phenomena show that magma mingling and mixing processes were active (Fig. 25b). The rocks are typically isotropic, but near pluton margins, a magmatic foliation may be present. Many large intrusions of gabbro and diorite are found between Vittangi and Rensjön. In some

of them magmatic layering has been observed and several show a concentric, banded magnetic pattern. In several intrusions there is a normal zoning with gabbroid rocks at the margin and granite in the central parts. Ultramafic rocks such as pyroxenite and serpentinite are present in some areas. The range in chemical composition is shown in Fig. 6. The dominant chemical trend is alkali-calcic (Fig. 7). Witschard (1975, 1984) pointed out the chemical similarity between the Perthite monzonite suite and the Porphyry group, and suggested that the former was emplaced under subvolcanic conditions.

The rock types in the Perthite monzonite suite are similar to those in the Haparanda suite, but have been traditionally kept separate due to their field appearance. There are small compositional differences; in the former, granite is more common and granodiorite-tonalite is rare, and there is a tendency towards more alkaline compositions. Generally, the contents of K_2O , TiO_2 , zirconium, and yttrium are higher and the strontium contents lower in the Perthite monzonite suite (Fig. 8). On a Rb vs. Y+Nb diagram the main cluster of points representing the Perthite monzonite suite plot in the syn-collision and volcanic arc granite fields at slightly higher values than the Haparanda suite for these elements (Fig. 9).

The radiometric ages for the Perthite monzonite suite and the Haparanda suite fall in the ranges of 1879–1858 Ma and 1886–1873 Ma (excluding one sample which gave 1847 Ma), respectively (Fig. 3, Table 1). Considering the errors in the age determinations no significant age differences between the two suites can be shown. However, where Haparanda granodiorite can be observed near Perthite monzonite (e.g. near Stora Sjöfallet and NW of Kiruna), the former is foliated and recrystallised, whereas the latter is apparently undeformed. Similar relationships have been observed in the Skellefte district between intrusions of Jörn GI- and GIII-type (Lundström et al. 1999). One model for explaining this would be that both suites formed during the same main magmatic event, with a magma evolution towards more alkaline compositions, during a deformation event which rapidly decreased in intensity. A comparable magmatic evolution has been described from eastern Australia (Landenberger & Collins 1996). Alternatively, the differences between the suites could be explained by a change in tectonic setting at c. 1.88 Ga ago.

The structural difference between the two suites has its correspondence in the magnetic field pattern and may be expressed using the magnetic structure index. It is $0.675\ \text{km}^{-1}$ for the Haparanda suite and $0.594\ \text{km}^{-1}$ for the Perthite monzonite suite (Table 4). The mean value of the magnetic total field for the latter is much higher, as is its amplitude variation as well (Figs. 14d, e, 15). This implies that the Perthite monzonite suite has a more



Fig. 25. Intrusive rocks of the Perthite monzonite suite. a) Slightly porphyritic granite with a weak foliation. Jievdu, 35 kilometres SSE of Råstojaure (7606200-1705320). b) Monzonite with assimilated hybrid enclaves and zoned feldspar. Renhagen, 41 kilometres W of Gällivare (7450760-1669570).

spotted or heterogeneous distribution (Fig. 10) of its magnetic rocks, which to a great extent contain ferromagnetic minerals with strong remanent magnetisation (Fig. 16e). The Perthite monzonite suite shows a bimodal density distribution (Fig. 19f) but rocks of both density groups generally have high magnetic susceptibility (Fig. 13f).

Granitoids, c. 1.86–1.84 Ga

In the eastern part of the area there are two types of granitoids, both of which have U-Pb zircon ages of c. 1.85 Ga (SGU, unpublished results). Although they have a similar zircon age their field appearance is very different.

One type (Pingisvaara-type) is found near the Swedish–Finnish border in three discrete areas. The rocks have granitic–granodioritic compositions and are light grey to reddish grey in colour, fine-grained, and even-grained (Fig. 26a). They are thoroughly deformed and recrystallised and contain abundant quartzo-feldspathic veins. Xenoliths of amphibolite and metamorphic pyroxene have been observed.

The other granitoid type (Jyryjoki-type), which is found in a large area east of Lainio, has a very different appearance, being unevenly grained (in the matrix), porphyritic, and weakly foliated (Fig. 26b). Monzogranite and granodiorite are the major components (Figs. 5, 6) and the chemical trend defined by a limited number of samples is calc-alkaline (Fig. 7). It is associated with pegmatite, and in many places it contains biotite-rich bands and partly assimilated remnants of older rocks. It was called Lainio granite by Ödman (1957) and Jyryjoki granite by Witschard (1970). On the Nordkalott map (Silvennoinen et al. 1987) it is distinguished as a separate intrusion. Southwest of Muonionalusta, a granite of Jyryjoki-type crosscuts orthogneisses, and is clearly post-tectonic in relation to a high-grade deformational fabric.

The ages of deformation episodes are discussed in the chapter on "Structure" (see p. 81).

At Juolovanjärvet (c. 12 kilometres NNE of Övre Soppero) a granodiorite gave a U-Pb zircon age of 1847 ± 19 Ma (Skiöld 1981b). This relatively low age was considered to be the result of metamorphic effects, and in ϵ -value calculations (Skiöld et al. 1988) rocks from this area were attributed a zircon age of 1.89 Ga (Table 3). Therefore the rocks at Juolovanjärvet are not included in the 1.86–1.84 Ga group here. Rocks with zircon ages of 1.86–1.84 Ga are not very common in other parts of Sweden. A possibility that must be considered is that the age figures represent a mixing of true magmatic components with inherited and/or secondary components. To confirm the presence of 1.86–1.84 Ga old rocks in this region, further study is needed.

In nearby areas in Finland there are some intrusions with zircon ages in the age range of 1.86–1.84 Ga. An albititic monzonite from Rautuvaara (13 kilometres NE of Huuki) gave an age of 1849 ± 16 Ma, while a monzonite from Hannukainen (19 kilometres NE of Huuki) gave an age of 1862 ± 3 Ma (Hiltunen 1982). From the Muonio area, an age of 1850 ± 41 Ma has been reported for a granodiorite at Kipparinoja (Lehtonen 1984). Reconnaissance work together with Finnish geologists (September 2000) in the Muonio area showed that granitoids similar to the Pingisvaara-type are widespread on the Finnish side of the border.

Intrusive rocks, c. 1.81–1.78 Ga

Granite-pegmatite association

The rocks of the Granite-pegmatite association are commonly referred to as Lina granite in northernmost Sweden. The Lina granite was originally described by Holmqvist (1905); the type area was chosen at the railway bridge at Lina älv, 26 kilometres NW of Gällivare.

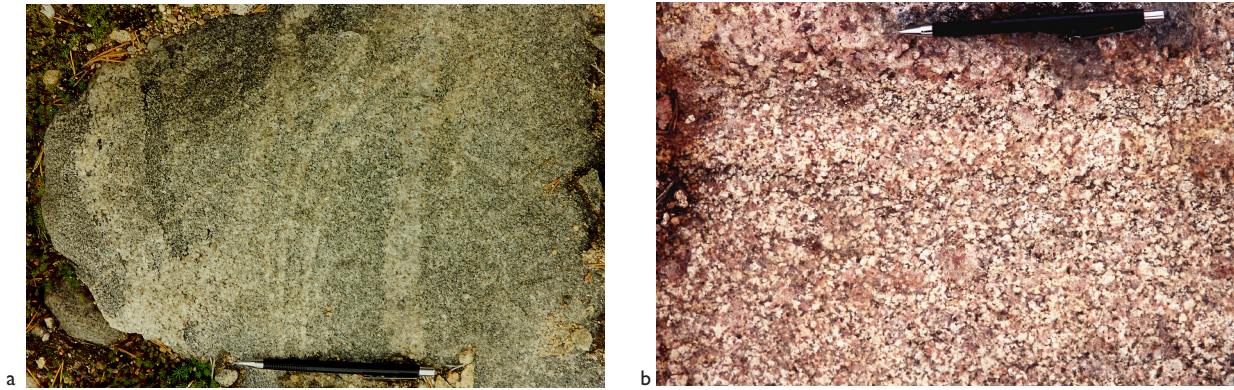


Fig. 26. Granitoids, c. 1.86–1.84 Ga old. a) Thoroughly recrystallised metagranodiorite with quartzofeldspathic veins. A homogeneous part of this rock has been dated to 1856 ± 8 Ma. Särkivaara, 26 kilometres SE of Karesuando (7595420-1795370). b) Uneven-grained, weakly porphyritic granite with diffuse biotite-rich bands (Jyryjoki-type). Myllyrova, 30 kilometres WSW of Lainio (7521100-1804000).

The granite has a U-Pb titanite age of 1778 ± 7 Ma (the zircon age of the same sample is 1811 ± 6 Ma, SGU, unpublished results). It is commonly greyish red, medium-grained and weakly porphyritic (Fig. 27). Red, fine-grained and evenly grained varieties are also common. The content of mafic minerals is low, with biotite as the common phase; muscovite is rare. The granite is usually associated with pegmatite, which in some areas forms large massifs. Fragments of assimilated country rock are common. Dykes and veins of granite, pegmatite, or aplite belonging to this suite are common in older rocks. In the arenitic gneisses S of Pajala, a granitic leucosome has yielded U-Pb monazite ages of 1798–1774 Ma (Bergman & Skiöld 1998).

The compositional range of the Granite-pegmatite association is restricted to monzogranite (Fig. 5). Nearly all chemically analysed samples fall within the range of 70–77 % SiO_2 and have high thorium contents (Fig. 8). The rubidium contents are also high and they plot within or close to the syn-collision granite field in Fig. 9.

The rocks of the Granite-pegmatite association are usually weakly foliated. When observed in contact with



Fig. 27. Lina granite (Granite-pegmatite association) from the type locality, at the railway bridge crossing the Linaälven river, 26 kilometres NW of Gällivare (7472100-1689180).

the more strongly foliated rocks of the Haparanda suite the foliations in both rocks are parallel, which suggests that the granite intruded while regional deformation was still active. The Karesuando–Arjeplog deformation zone has affected the Lina granite. Granite mylonite in this zone can be observed west and northwest of Gällivare.

The magnetic total field of the Granite-pegmatite association has a rather narrow spectrum (Fig. 14g), indicating low amplitude variations around an in itself low mean value (Fig. 15). Compared to the other rock units its magnetic susceptibilities and remanent magnetisations are lower (Figs. 13g, 16g). Banded magnetic patterns with short wavelengths are found in the area northwest of Gällivare, near the Karesuando–Arjeplog deformation zone. The magnetic structure index (Table 4), which in the Granite-pegmatite association area as a whole is as low as 0.54 km^{-1} , achieves a value of 1.3 km^{-1} or more in that area. The magnetic field variations are mainly due to susceptibility differences of the order of a factor of 10 (0.002–0.02 SI) whereas the natural remanent magnetisation has no influence. These features are developed where there are inclusions or relics of older rocks, or in zones of pronounced foliation, whereas the commonly weakly foliated granite northeast of Gällivare rarely reveals banded magnetic structures. Instead, brittle to semi-brittle deformation zones are recognised in long and narrow magnetic minima or offsets cutting a rather homogeneous magnetic background.

In the area around Gällivare the main part of the Lina granite massif coincides with a positive long-wave gravity anomaly (D in Fig. 11) which is not in accordance with the observed densities. The density of the Granite-pegmatite association spans from 2 605 to 2 660 kg/m^3 with a mean density about 2 620 kg/m^3 (Fig. 19g). A long-wave magnetic field anomaly is also observed within the same area (D in Fig. 10). Results from inversion modelling suggest different solutions which all, however,

point at the occurrence of an extensive rock mass with densities more than 2 750 kg/m³ (width c. 30 kilometres from east to west) at a depth of 8 kilometres to more than 2 850 kg/m³ at a depth of 12 kilometres (see also Lindroos & Henkel 1978).

Granite-syenitoid-gabbroid association

In the Tären-dö–Lainio area there are a large number of plutons and complex intrusions which have been assigned to a suite which has age and compositional characteristics in common with parts of the Transscandinavian Magmatic Belt in southern and central Sweden. Other plutons in the same suite are found north of Svappavaara and southwest of Kiruna. Similar intrusions are known in the Luleå–Edefors area (Öhlander & Skiöld 1994). The field characteristics of the Granite-syenitoid-gabbroid association are very similar to the Perthite monzonite suite, and it is possible that future work will show that this younger suite has a wider distribution than shown on the present map.

The composition of the Granite-syenitoid-gabbroid association varies from gabbro to granite, with monzonite and monzodiorite (+ quartz-bearing varieties) as intermediate members (Figs. 5, 6). Syenite has been reported from southwest of Kiruna. Three age determinations have yielded ages in the range 1799–1792 Ma (Romer et al. 1994, SGU, unpublished results). The dominant chemical trend is alkali-calcic (Fig. 7). A separate calc-alkaline trend within this association may also exist. The rocks of the Granite-syenitoid-gabbroid association are also chemically similar to the Perthite monzonite suite (Fig. 8), but on a Rb vs. Y+Nb diagram a small group of samples show higher values of these elements (Fig. 9).

The rocks of this association are characterized by high magnetic susceptibility regardless of the type of rock (Fig. 13h). A high portion of natural remanent magnetisation contributes to the very high mean value of the magnetic field. The petrophysical properties are very similar to those of the Perthite monzonite suite, which is in accordance with their similar field characteristics (Figs. 13, 14, 16, 19).

Gabbro, metagabbro and diabase, <1.8 Ga

In the easternmost part of the area, gabbros are found as sheet intrusions forming ring-shaped structures, or as discrete plutons. On the magnetic anomaly map, most of them show a prominent magnetic banding (white arrows in Fig. 10). The banding is caused by either: 1) layered gabbro with variations in magnetite content, or 2) intrusive sheets of magnetic gabbro surrounded by pegmatite,

granite, or gneiss. At Lumivaara (SE of Lainio) there is a well-exposed stream section where gabbro sheets alternate with pegmatite and granite sheets. Pegmatite locally intrudes the gabbro, which may be an effect of back veining. At Naakajärvi (ESE of Lainio), deeply weathered gabbro dykes have been observed in a foliated granitoid. However, most exposures in this area consist of pegmatite. A set of NE–SW-striking dykes is found NE of the Naakajärvi area. The intrusion west of Muonionalusta is layered (Filén et al. 1988) and gabbro grading into anorthosite has been observed. The complexes NW of Muonionalusta are not exposed. Besides their characteristic appearance on the magnetic anomaly map, the intrusions are clearly detectable on the gravity map and appear to be related to the large regional and strongly positive gravity anomaly in the area. A large mafic body at depth may cause this regional anomaly, which is not reflected in the density distribution of the surface rocks. The gabbros have high contents of iron, aluminum, phosphorous, titanium and sulphur and low silica contents (Lindroos & Henkel 1981).

The Nabrenjarka diabase, W of Gällivare, is a conspicuous, flat-lying, bowl-shaped and sill-like intrusion with an exposed length of more than 50 kilometres (Fig. 2, near C in Fig. 10). It intrudes several rock types, including rocks of the Granite-pegmatite association, and is therefore younger than c. 1.8 Ga. It has relatively high percentages of iron, titanium, and vanadium and a rather low silica content (Witschard 1975). In the same region there are also numerous gabbroic dykes, which are probably related to the Nabrenjarka diabase. One fan-like swarm of vertically dipping dykes seems to cut the Nabrenjarka diabase. This swarm is probably related to the prominent dyke swarms found southeast of Kebnekaise and in the Gällivare area. The relation between these gabbros and diabases and the gabbros in the easternmost part of the area is still unknown.

VENDIAN TO CAMBRIAN COVER ROCKS (DIVIDAL GROUP)

Vendian (Neoproterozoic) to Cambrian cover rocks (Dividal Group) unconformably overlie weathered Archaean and early Proterozoic rocks in the western part of the area. During the Caledonian orogeny these rocks were overthrust by nappes from the west. The cover rocks have been described by e.g. Kulling (1964) and Thelander (1982). They are dominated by quartzites, sandstones, siltstones with minor shaly intercalations, and alum shales.

Tillite was found in a small outcrop near Holmajärvi, c. 18 kilometres WSW of Kiruna (Ödman 1957). It was

compared with similar tillites of Eocambrian age further west.

GENERAL PETROPHYSICS

In previous sections the petrophysical properties were discussed with respect to the different rock units recognised in the map area. It is evident that density and magnetic properties depend on the mineral composition of the rock. This means that particular rocks by their petrophysical properties may be bound to rock type or genesis. Wide compositional ranges in one and the same type of rock or rock unit give wide petrophysical ranges, so an attempt to classify rocks is merely a statistical procedure. On the other hand, petrophysical properties may be used to illustrate geochemical changes, e.g. magmatic differentiation processes, and with the aid of magnetic and gravity field data such processes may be related to time and space. Such studies have been presented in earlier published papers concerning the map area (Ambros 1980, Lindroos & Henkel 1981, Eriksson & Hallgren 1975, Padget 1977, and Witschard 1975). Henkel (1976) presented a description of petrophysical properties of rocks from northern Sweden and an attempt to retrace within them geochemical evolution processes. In Fig. 28 the magnetic susceptibility versus density is plotted for each of the major groups of rock types used in his study, together with many new samples. A combination of two or more of these distribution patterns roughly results in the distribution pattern of a rock unit (Fig. 13). A more or less pronounced low-susceptibility and/or high-susceptibility trend may be observed in all rock units (Fig. 13) and rock types (Fig. 28). The former trend seldom reaches more than 5×10^{-3} SI-units and is due to rocks with varying amounts of paramagnetic minerals and no or negligible amounts of ferrimagnetic material. Iron is fixed in silicates. Metasedimentary and magnetite-deficient mafic rocks may account for this trend in the Archaean rocks. The upper trend in the diagrams represents the evidence that ferrimagnetic material (mostly magnetite) is present. Typically, but with exceptions, there is no smooth transition between the lower and the higher trend in medium- to high-density rocks. In these rocks, a bimodal susceptibility distribution is found as illustrated by the Greenstone group (Fig. 13c), the mafic metavolcanic rocks in general (Fig. 28d) or, less pronounced, in the Archaean rocks (Fig. 13a). The reason is that even if magnetite is present in only a fraction of a weight percent, its extreme magnetic properties will outrange those of the paramagnetic minerals (Tarling & Hrouda 1993). The bimodality is likely to be produced by metamorphic processes differentially affecting the minerals. Deuteric/

hydrothermal processes may consume pre-existing magnetite, resulting in the formation of e.g. chlorite and titanite, and consequently in a drastic lowering of the magnetic properties. However, the presence of strong paramagnetic properties in combination with remanent magnetisation in rocks found in the lower susceptibility trend implies that processes were involved which lead to the formation of ferrimagnetic minerals from iron silicates by oxidation. On the other hand, if primary magnetite grains are very large or if they are protected as inclusions in silicate grains, they may be preserved and a high susceptibility is maintained (Dunlop & Özdemir 1997). This also explains the rather frequently observed high natural remanent magnetisation in the intrusive suites, the Porphyry and Porphyrite groups, and the Greenstone group.

Granitoid rocks and especially the rocks of the Granite-pegmatite association are different from other rock types or units in that they mostly lack strong paramagnetic minerals, which is reflected in their low densities. Still, they very often reveal high susceptibilities ($>5 \times 10^{-3}$), accompanied by low Q-values (<0.5 , mean value 0.23, Fig. 16), which gives evidence of the presence of ferrimagnetic minerals. Typically, granites are found in a narrow sampling to the left in diagrams of the type shown in Figs. 13 and 28. In Fig. 13g a division into the two susceptibility trends are only weakly indicated for the rocks of the Granite-pegmatite association. The variation of the density is low, with a mean value of 2.625 kg/m^3 . The only possible carriers reported in the literature on these rocks that have ferrimagnetic and strong paramagnetic properties are magnetite and biotite, respectively (with the exception of occasional chlorite as a retrograde product of biotite). Hornblende may occur in certain varieties. In all earlier works magnetite is mentioned as a disseminated accessory constituent, while the reported biotite content is on average 3 %, in some cases reaching 7 %. Biotite is also an important constituent of rocks found as fragments in the Granite-pegmatite association. According to available chemical data, the iron content expressed in Fe_2O_3 -equivalents ranges from 0.7 to 1.6 wt-% but Eriksson & Hallgren (1975) reported values even below 0.5 wt-% and for FeO c. 0.2 wt-%. Only one investigation reports up to 5 vol-% magnetite (Offerberg 1967). Recalculated into magnetite equivalents this would easily explain the observed high susceptibilities if most of the iron were bound to magnetite rather than biotite. It is also possible that biotite is less abundant than indicated and, in fact, conceals a much higher magnetite content than that found in the observed disseminated part. This magnetite may occur as inclusions between the lamellae of biotite from which it was exsolved, rendering the biotite extrinsically ferrimagnetic

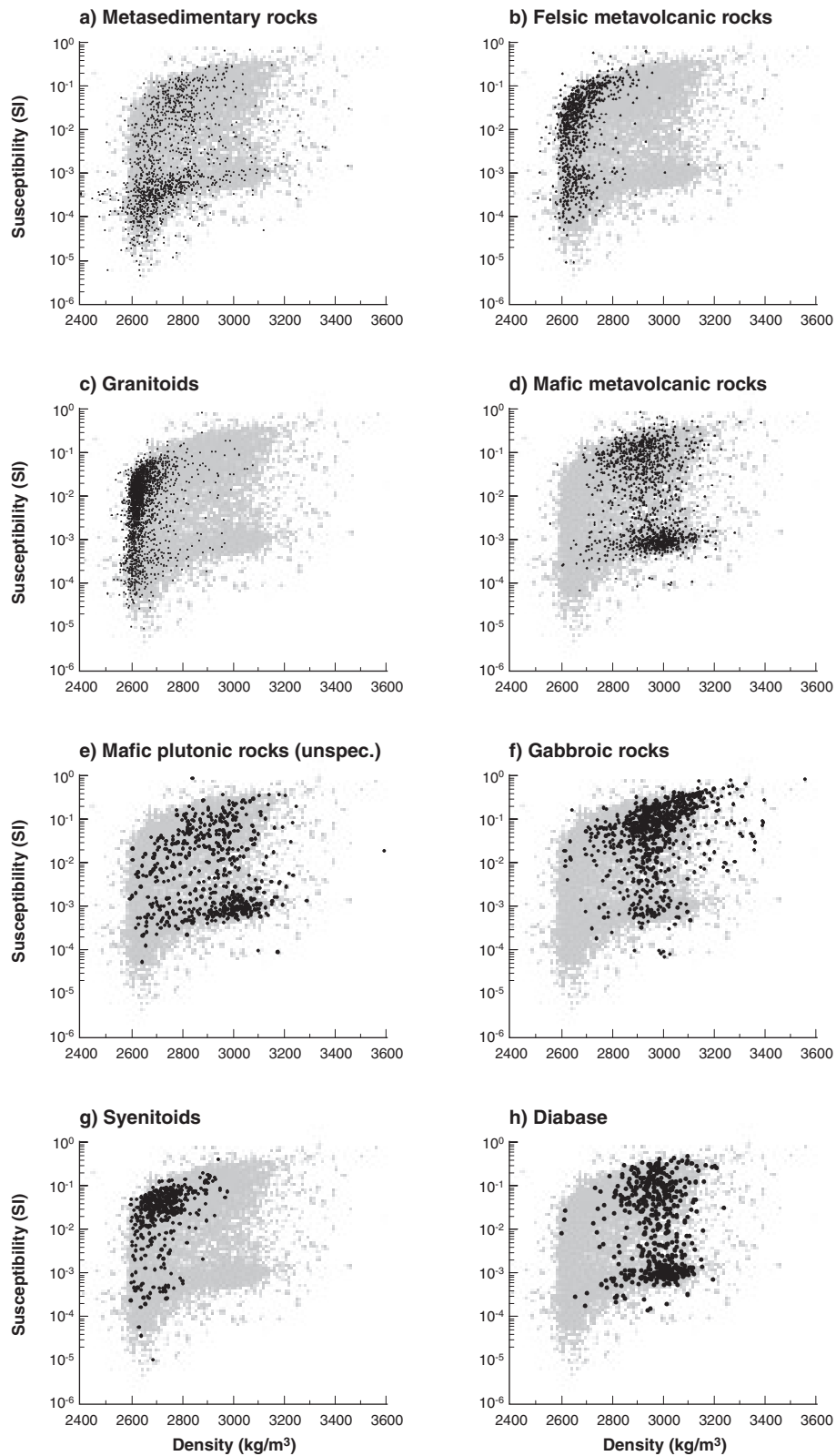


Fig. 28. Petrophysical properties of rock types in the map area independent of rock unit. Magnetic susceptibility (SI) vs. density (kg/m³) in semi-logarithmic diagrams. The grey background in all diagrams is the total population of samples (n=11150).

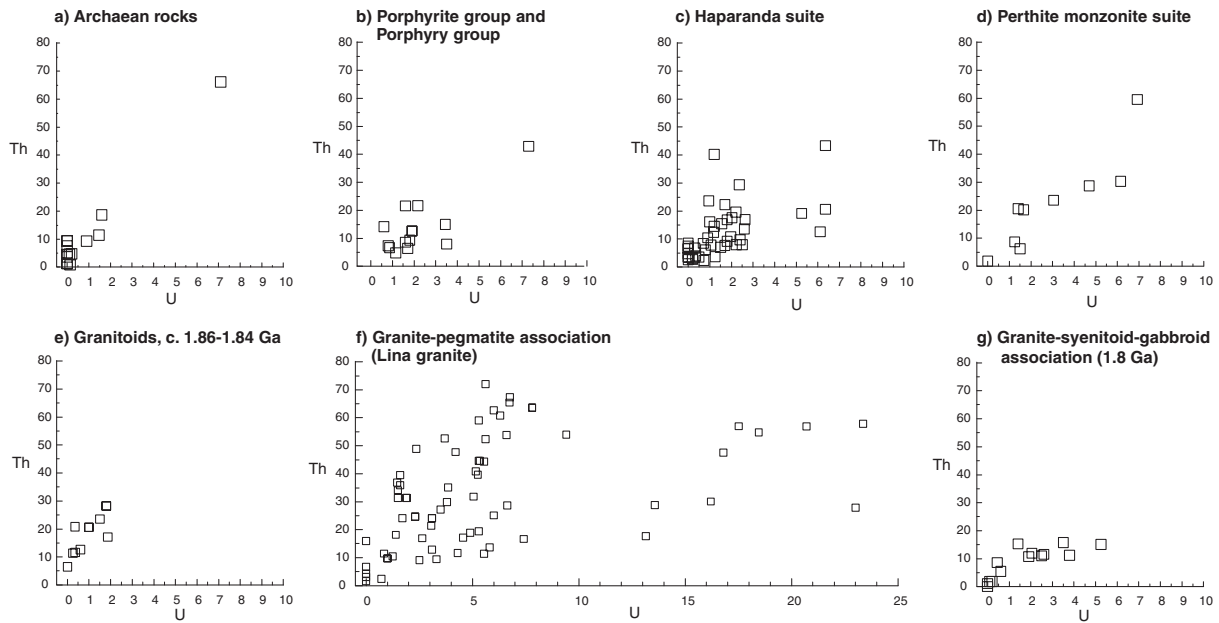


Fig. 29. The concentrations of thorium versus uranium in the different rock groups. The concentrations were measured by means of gamma ray spectrometry.

(Dunlop & Özdemir 1997). Such an explanation is reinforced by the fact that there actually is a slightly higher natural remanent magnetisation-to-susceptibility ratio trend than indicated by the black line ($Q = 1$) in Fig. 16g. It can be discerned in Figs. 15 and 16 that natural remanent magnetisation plays a role in the outlines of the magnetic field pattern. The Q -value (geometric mean value) increases with increasing mean value of the magnetic total field for the different rock units. McEnroe & Brown (2000) point out that this phenomenon may be underestimated while, in the literature, magnetic susceptibility is still held as principally responsible for what we see on magnetic maps.

Due to the thick cover of Quaternary deposits in large parts of the map area, airborne gamma radiation data are of restricted help in identifying rock units. In large, however, there is a correlation between the distribution of high total gamma radiation and the felsic to intermediate rocks of the Perthite monzonite suite and the rocks of the Granite-pegmatite association (see the separate printed map SGU Ba 56:5). Our in situ measurements of the latter show anomalous contents of thorium (Fig. 29f). The lower limit of anomalous thorium content has been set to 20 ppm. Uranium concentrations exceed 10 ppm

only in about 10 observation points, all situated within the area occupied by the Granite-pegmatite association. However, these high values are not typical and the uranium contents spread over a wide range (Fig. 29f) with an average value similar to that reported in the literature for granites in general (Sharma 1986). Measurements carried out on rocks of the other rock units yielded low values, thus contrasting only weakly, if at all, with the soil cover. The uranium contents are low, with the majority of the values below about 3 ppm. Thorium-anomalous rocks are present in all intrusive suites. One exception is the Granite-syenitoid-gabbroid association, which also shows a larger variation of uranium values. Consequently, the Th/U ratio is much lower than in the other suites (5:1 to 10:1). The difference in field appearance between the Haparanda suite and the Perthite monzonite suite (see p. 34) is reflected in the differences in their thorium and uranium contents (Fig. 29c, d). The main part of the measurements on metagranitoids of the Haparanda suite (Karesuando–Muonionalusta area and SE of Svappavaara) yielded low values. In contrast, two thirds of the measurements of granites and syenitoids of the Perthite monzonite suite show thorium-anomalous values.

MINERAL OCCURRENCES

MINING HISTORY AND PRODUCTION

The northern part of Norrbotten county is an ore province dominated by iron and copper, represented by several different types of deposits. Other metals, including zinc, lead, vanadium, titanium, and cobalt, are only found in subeconomic amounts. Economically most important for the region are the apatite iron ores, with an annual production in the two operating mines at Kiruna and Malmberget of c. 30 million tonnes (Mt) of ore and a total production of c. 1 600 Mt from 10 mines during the period 1888–1999. Minor amounts of iron ore were also recovered from the apatite iron ores and one iron formation before the 20th century. The Magnetgruvan deposit at Masugnsbyn was mined intermittently between 1645 and 1865, and the Malmberget apatite iron ore was the major source of ore for several small blast furnaces in southeastern Norrbotten during the 18th and 19th centuries.

Copper was produced during the 17th and 18th centuries from several small deposits in the Kiruna area, the most important of which was Gruvberget at Svappavaara. Recently, copper ore has been mined in Kiruna on a larger scale at the Viscaria (1982–1997) and the Pahtohavare (1990–1997) mines. At Pahtohavare, some gold was also produced. Sweden's largest sulphide mine, Aitik, is situated in the Gällivare area. Mining started in 1968 and the annual outcome from the open pit is now 18 Mt of ore. As early as 1902–1907 some copper and gold was mined in the Gällivare area at Nautanen, Liikavaara, Ferrum, and Fridhem.

Mineral production in the northern part of Norrbotten county also includes some industrial minerals. In 1898 graphite was discovered in the Vittangi area, which resulted in extensive exploration and efforts to start production of graphite. Although several deposits were found to be rich in graphite, their fine-grained character made an economic recovery of graphite impossible and only small amounts have been produced from the Vittangi and Masugnsbyn areas. During the Second World War, apatite for the production of fertiliser was produced from the apatite iron ores in Gällivare and Kiruna. Dolomite and quartzite have been used as additives in pellet production at the iron ore mines. Dolomite is still produced at Masugnsbyn, while quartzite production from two quarries, Nukutusvaara and Hopukka in the Kiruna area, ended in 1974 and 1982, respectively. Production years and tonnages for all types of deposits are given in Table 5.

CLASSIFICATION OF DEPOSITS

In the following description, the metallic and industrial mineral deposits have been grouped according to their commodity and character. Besides the type of metals or industrial minerals forming economically important constituents of the deposit, the classification is based on the style of mineralisation and its relation to the host rock. Accordingly, this is not primarily a genetic classification, even though the character and composition of the deposits are in most cases largely controlled by their origin.

The metallic deposits are divided into the following categories: stratiform–stratabound base metals and iron, apatite iron ores, epigenetic base metals, and other metals. A few occurrences with gold as the most important constituent are included in the epigenetic base metal class. In the stratiform–stratabound deposits the ore minerals occur either in a banded or laminated manner that is parallel to the bedding of their host rock, or they form massive lenses conformable to the wall rocks. Mineralisations that cut bedding or lithological contacts are rare and mainly restricted to the stratigraphic footwall. This group includes sulphide deposits dominated by copper or zinc-lead, and two types of iron formations (banded iron formations and skarn-rich iron formations). All known occurrences are hosted by the Greenstone group. The apatite iron ores define a specific group of magnetite-hematite deposits that are spatially related to the Porphyry group. In the epigenetic class of base metal deposits the ore minerals occur disseminated, in veinlets and veins or in breccias. In general, the boundaries of these ore bodies are gradual and crosscut primary features such as bedding. Based on the metal composition they are divided into the subgroups copper±gold±cobalt and zinc-lead, with the former as the most abundant. The deposits containing other metals than iron and base metals (alloy metals, titanium, platinum group elements, lithium, beryllium, rare earth elements, and uranium) are divided according to commodity. For the industrial mineral deposits the classification is mainly based on commodity but their origins serve as a base for further subdivisions (e.g. quartz, magnesium silicates, and apatite).

STRATIFORM–STRATABOUND ORE DEPOSITS (BASE METALS AND IRON)

Stratiform to stratabound mineralisations with base metals and iron occur in volcanoclastic units in the middle and upper parts of the Greenstone group. Sulphide

TABLE 5. Production of ores and industrial minerals. Reference abbreviations: B = Bergsstaten, Bs = Bergverksstatistik, SG = Svenska Gruvföreningen, Besk = Beskrivning till slutkarta, + = mine still in production 1999.

Name of deposit	Map	Commodity	Economic status	Prod. Mt	Prod. from-to.	Comment	Source
Kiirunavaara	29J NO	Fe+(P)	Mine	c. 1030	1895–1999+	1865 and 1889 small production	Grip 1978, Bs 1964–1999 SG
Malmberget	28K SV	Fe+(P)	Mine	c. 460	1888–1999+	1738–1887 intermittently	Grip 1978, Bs 1964–1999 SG
Leveäniemi	29K SV	Fe	Closed mine	56.65	1964–1983		Besk Leveäniemi B
Tuolluvaara	29J NO	Fe	Closed mine	23.72	1902–1982		Besk Tuolluvaara B
Luossavaara	29J NO	Fe	Closed mine	16.65	1919–1985	1803–1907 intermittently	Besk Luossavaara B
Henry	29J NO	Fe	Closed mine	4.86	1969–1987		Besk Henry B
Haukivaara	29J NO	Fe	Closed mine	2.55	1965–1972		Besk Haukivaara B
Rektorn	29J NO	Fe+(P)	Closed mine	2.52	1925–1961		Besk Rektorn B
Nukutus	29J NO	Fe	Closed mine	0.74	1961–1967		Besk Nukutus B
Sigrid	29J NO	Fe	Closed mine	0.55	1952–1980		Besk Sigrid B
Mertainen	29K SV	Fe	Closed mine	0.22	1956–1958	1918–1920 test mining	Besk Mertainen B
Viktor	29J NO	Fe	Closed mine	0.02	1952–1954		Besk Viktor B
Sahavaara	28M NV	Fe	Potential deposit	0.002	1974–1974	Test mining, also in 1965	Besk Stora Sahavaara B, Lundberg 1967
Magnetgruvan (Junosuando)	28L NV	Fe	Closed mine	<0.05	1645–1860s	Intermittently	Geijer 1929
Gruvberget-Fe	29K SV	Fe	Potential deposit	<0.002	1707–1880	Intermittently	SOU 1924
Keskinen Käyveaara	29J NO	Fe	Prospect pit	<0.001	1912–1912	Test mining	SOU 1924
Aitik	28K SV	Cu+Au+Ag	Mine	322.00	1968–1999+		Bs 1968–1999 SG, Zweifel 1976
Viscaria A-zone	29J NO	Cu+Ag	Closed mine	12.540	1982–1997		Besk Viscaria B, Martinsson 1997
Pahtohavare	29J NO	Cu+Au	Closed mine	1.680	1990–1997		Besk Pahtohavare B, Martinsson 1997
Viscaria B-zone	29J NO	Cu+Ag	Closed mine	0.0750	1996–1997		Besk Viscaria B, Martinsson 1997
Nautanen	28K SV	Cu+(Fe)	Potential deposit	0.0720	1902–1907		Geijer 1918a, Bs 1902–1907 B
Gruvberget-Cu	29K SV	Cu	Closed mine	c. 0.050	1655–1757	1687–1757 intermittently	Tegengren 1924, Frietsch 1966
Liikavaara	28K SV	Cu	Closed mine	0.0030	1903–1907		Geijer 1918a, Bs 1903–1907 B
Ferrum (Nietsajokki)	28K SV	Cu+Au	Closed mine	0.00045	1904–1907		Tegengren 1924, Bs 1904–1907 B
Särkivaara	29K SV	Cu	Closed mine	<0.005	1756–1785		Tegengren 1924, Frietsch 1966
Raggisvaara	30J NO	Cu	Closed mine	<0.001	1683–1684		Tegengren 1924
Maunuvaara	28L NV	Cu	Closed mine	<0.001	17th century		Tegengren 1924, Geijer 1918a
Sekkujoki	29K NV	Cu	Closed mine	<0.001	17th century		Hallgren 1969, Eriksson & Hallgren 1975
Pahtavaara	29K NV	Cu	Closed mine	<0.001	17th+18th century		Tegengren 1924, Hallgren 1969
Kovogruvan	30J SO	Cu	Closed mine	<0.001	17th+18th century		Tegengren 1924, Geijer 1931b
Gruvberget–Kurravaara	29J NO	Cu	Closed mine	<0.001	1749–1755		Tegengren 1924
Veikkavaara	28L NV	Cu	Prospect pit	<0.001	19th century		Geijer 1931b
Kopparåsen	30I NV	Cu	Prospect pit	<0.001	1902–1904		Bs 1902–1904 B
Snällkok	28K SO	Cu	Closed mine	0.000100	1904–1906		Bs 1904–1906 B, Geijer 1918a
Fridhem	28K SV	Au	Closed mine	0.000007	1905–1905		Tegengren 1924, Bs 1905 B
Ala Pärro	30J NO	Cu	Prospect pit	0.000007	1916–1916		Bs 1916 B
Hopukka	29K SV	Qz	Closed quarry	1.1400	1974–1982		Bs SG
Nukutusvaara	29J NO	Qz	Closed quarry	0.5600	1969–1974		Bs 1969–1972 B
Vassaravaara	28K SV	Qz+(Flsp)	Closed quarry	0.0017	1955–1956		Bs 1955–1956 B
Varkhanvaara	28K SO	Qz	Closed quarry	0.001	1941–1941		Bs 1941 B
Pahtavaara	28K SV	Qz	Closed quarry	0.0003	1941–1942		Bs 1941–1942 Bs
Ädnamvare	29J NO	Mg-silicate	Closed quarry	0.0600	1978–1979		Bs 1978–1979 SG, Bergström 1986
Tjuoltajäkkah	30J SV	Mg-silicate	Potential deposit	0.0030	1991–1991	Test mining	Hansson 1989, 1991
Masugnsbyn	28L NV	Dolomite	Quarry	2.1000	1952–1999+	Small scale production in 1930s	Bs 1952–1972 B, Bs 1977–1988 SG, Niiniskorpi 1990, Hansson 1991, Shaikh et al. 1989
Hietajoki	28L NV	Dolomite	Potential deposit	0.0030	1998–1998	Test mining	Hansson 1991, Shaikh et al. 1989
Nunasvaara	29K SO	Graphite	Potential deposit	0.0030	1981–1981	Test mining, also in 1920	Bergström 1987, Geijer 1918b, Tegengren 1924
Nybrännan (Vehkovaara)	28L NV	Graphite	Closed quarry	0.0020	1955–1958		Bs 1955–1958 B, Lundgårdh 1971
Lauttakoski	28L NO	Talc	Potential deposit	<0.001	1966–1966	Test mining	Shaikh 1972, Grip 1978
Malmberget	28K SV	Apatite	Potential deposit	c. 1.3	1899–1953	Mainly 1918 and 1940–1946	Bs B, Geijer 1919b, Ödman 1957, Grip 1978, Lundgårdh 1971
Rektorn	29J NO	Apatite	Potential deposit	c. 0.4	1942–1946		Geijer 1950
Kiirunavaara	29J NO	Apatite	Potential deposit	0.3	1985–1988		Bs 1985–1988 SG

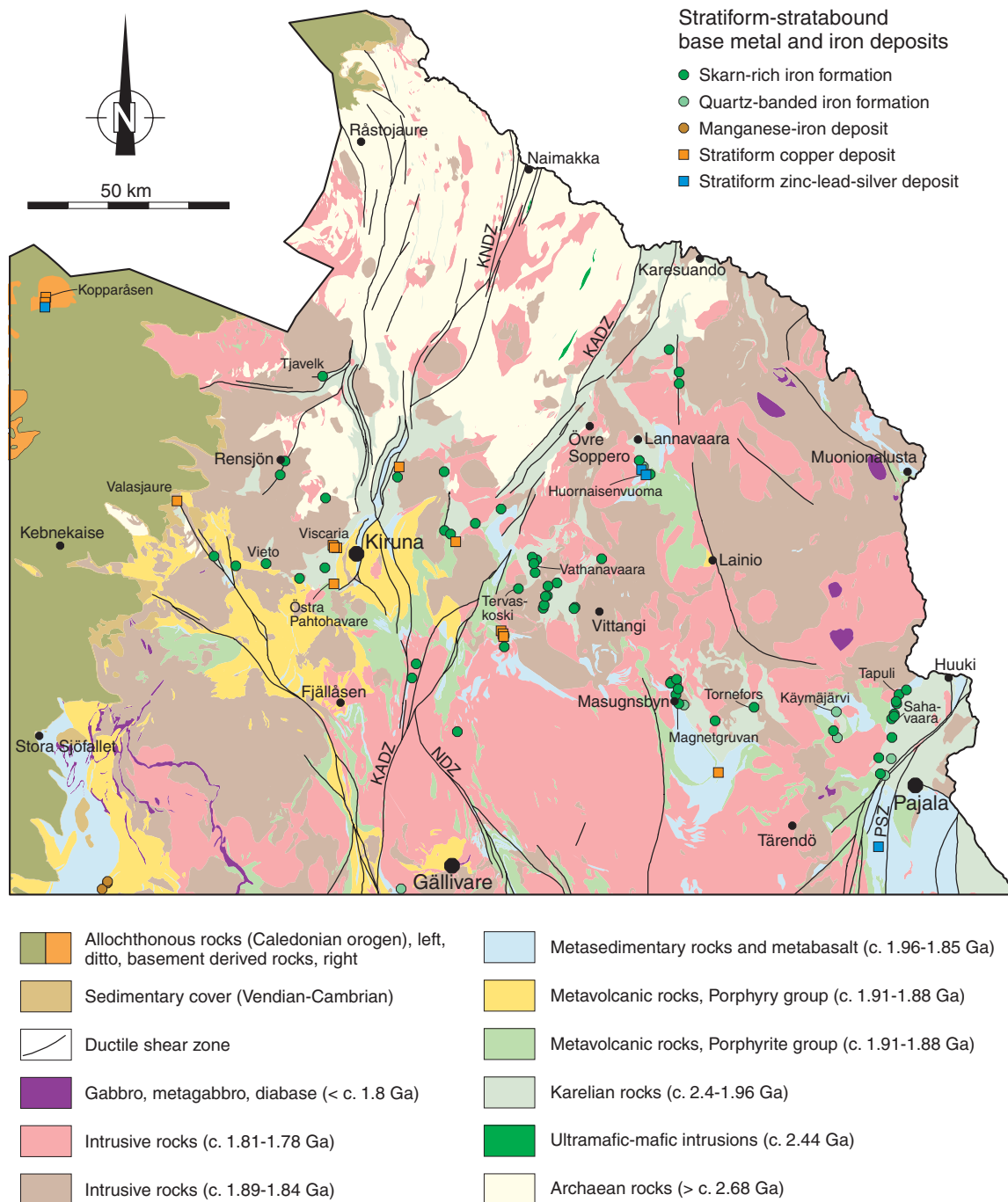


Fig. 30. Simplified bedrock map of the northern part of Norrbotten county, with occurrences of stratiform-stratabound base metal and iron deposits.

deposits are mainly found in the Kiruna area while occurrences dominated by iron are encountered in most areas in the Greenstone group (Fig. 30). Carbonate rocks, graphitic schist and chert are common ore-associated rocks, constituting either the host rock or the wall rocks of most deposits. Based on the mineral composition and the character of the deposits three main types are distinguished: base metal sulphide deposits, skarn-rich iron formations, and chert-banded iron formations (BIF).

Sulphide deposits are generally tabular in shape and dominated by base metal sulphides. Varying proportions of chalcopyrite, pyrrhotite, pyrite, sphalerite, galena, and magnetite occur as stratabound to stratiform disseminations and massive intercalations in tuffite, black schist, and carbonate rocks. The largest and only economic deposit is the Viscaria copper ore. Several subeconomic copper deposits of stratiform character are found in the western part of the map area. The Östra Pahtohavare de-

posit is situated within the Greenstone group, 10 kilometres S of Viscaria. Valasjaure and Kopparåsen are situated in greenstones west of Kiruna. A few zinc-lead occurrences exist in the eastern part of the area, of which the largest is the subeconomic Huornaisenvuoma deposit S of Lannavaara.

Skarn-rich iron formations and BIF lack economic importance. The most numerous of these are the skarn-rich iron formations, which occur as stratiform lenses of magnetite, serpentine, diopside, actinolite, and smaller amounts of iron sulphides. The BIF deposits are tabular with thicknesses of up to 200 metres. Most of them contain iron silicates as the major iron mineral. They are mainly restricted to the eastern part of the map area and often exhibit a close spatial relation to the skarn-rich iron formations.

Ore-related alterations are insignificant or mainly restricted to the stratigraphic footwall for both sulphide and iron deposits. This, in combination with the mainly stratiform character, suggests a syngenetic origin for most occurrences.

Stratiform–stratabound sulphide deposits

Viscaria

The Viscaria copper deposit is situated 4 kilometres W of Kiruna. It was indicated using geobotany in 1972 and found by drilling 1973. The mineralisation is hosted by the volcanoclastic Viscaria Formation (Martinsson 1997) occurring in the middle part of the Greenstone group (Fig. 31). Three stacked ore zones in progressively descending stratigraphic order (A, B and D) contain sulphides and magnetite in differing proportions. Thin horizons containing magnetite and some sulphides also occur in the stratigraphically overlying Peuravaara Formation (Martinsson 1997). The A-zone was economically most important, but during the last years of mining some ore was also produced from the B-zone. A total of 12.54 Mt of ore with 2.29 % Cu was mined between 1982 and 1997 (Martinsson et al. 1997a).

The stratigraphically lower D-zone mineralisation is c. 1 000 metres long and dominated by magnetite. It occurs within a c. 20 metres thick dolomite in the lowest part of the Viscaria Formation. The ore generally has a fine-grained character and a low sulphide content. Ore grades (>1 %) of copper are locally developed, with disseminated chalcopyrite and pyrite occurring in slightly coarser-grained magnetite ore. The copper mineralised part of the D-zone is calculated to contain 0.74 Mt with 1.5 % Cu (Martinsson et al. 1997a).

Several narrow and closely spaced horizons containing magnetite, pyrite, pyrrhotite, and chalcopyrite constitute the B-zone. The mineralisation has a maximum length of

3 000 metres and occurs in a 40 metres thick sequence of mafic tuff in the middle part of the Viscaria Formation. The ore minerals are disseminated or form massive intercalations in tuff or tuffite of mafic composition. Epidote and calcite are important gangue minerals in some parts of the mineralisations. The copper content of the B-zone is generally rather low and ore grades are only developed in some restricted parts of these laterally extensive horizons. These more copper-rich parts are calculated to contain 2.5 Mt with 1.9 % Cu and from one part 0.075 Mt of ore has been mined.

The economically important A-zone is situated between two black schist horizons at the top of the volcanoclastic Viscaria Formation. The ore zone is 3 700 metres long, 400–600 metres wide and 2–10 metres thick. It is capped by a thin chert horizon extending several kilometres outside the economic part of the deposit. Chalcopyrite, magnetite, pyrrhotite, and some sphalerite are the main ore constituents. They are mostly fine-grained and occur disseminated, as thin layers or more massive accumulations. Lamination in millimetre-scale is developed in some parts of the ore. Calcite is the main gangue mineral, while amphibole, apatite, barite, quartz, and albite occur in accessory amounts. Ore grades (>1 %) of copper are locally developed in the footwall graphite schist, with chalcopyrite and pyrrhotite forming veinlets. This is in contrast to the hanging wall black schist which is barren, with only small amounts of pyrrhotite occurring disseminated in thin laminae.

A pronounced metal zoning is developed in the A-zone. Most conspicuous is the enrichment of zinc towards the hanging wall contact in the central and high-grade part of the ore (Fig. 32). The copper content in this area is 3 to 10 %, with a general increase in grade towards the footwall. Accessory amounts of barite are found in the high-grade part. Enrichment of zinc, manganese and, to some extent, gold is noticeable in the peripheral and low-grade parts of the ore zone.

The A-zone is situated on top of a large alteration zone, which extends laterally beyond the economic part of the A-zone. The alteration zone encloses the underlying B- and D-zones and reaches about 500 metres stratigraphically below the ore in its central part. A high K/Na ratio, due to the alteration of plagioclase feldspar to phyllosilicates, characterizes the altered rocks (Martinsson et al. 1997a). The altered rocks are depleted in sodium and to some extent of calcium and strontium, while potassium, zinc, and barium are enriched. K-feldspar alteration is of minor importance. It is developed in a dacitic tuff situated below the footwall graphite schist. The K-feldspar alteration has been largely replaced by post-ore albitisation, which has developed along the contacts of a mafic sill intruding the dacitic tuff and the black schist.

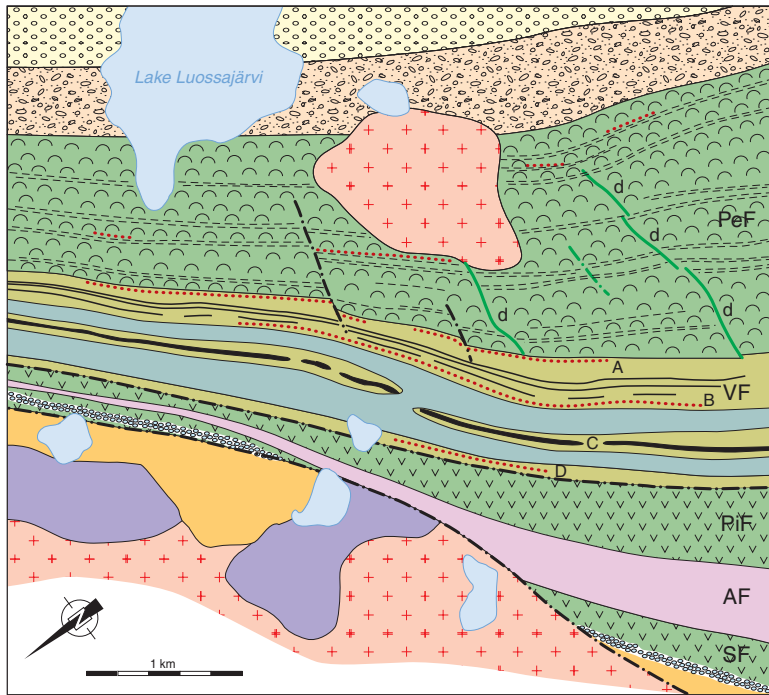


Fig. 31. Geological map of the Viscaria area (from Martinsson 1997). The following abbreviations refer to formations within the Greenstone group (in stratigraphic order): SF = Såkevatn Formation, AF = Ädnåvare Formation, PiF = Pikse Formation, VF = Viscaria Formation, PeF = Peuravaara Formation. The annotations A, B and D refer to ore horizons within the Viscaria Formation. C is a graphite schist.

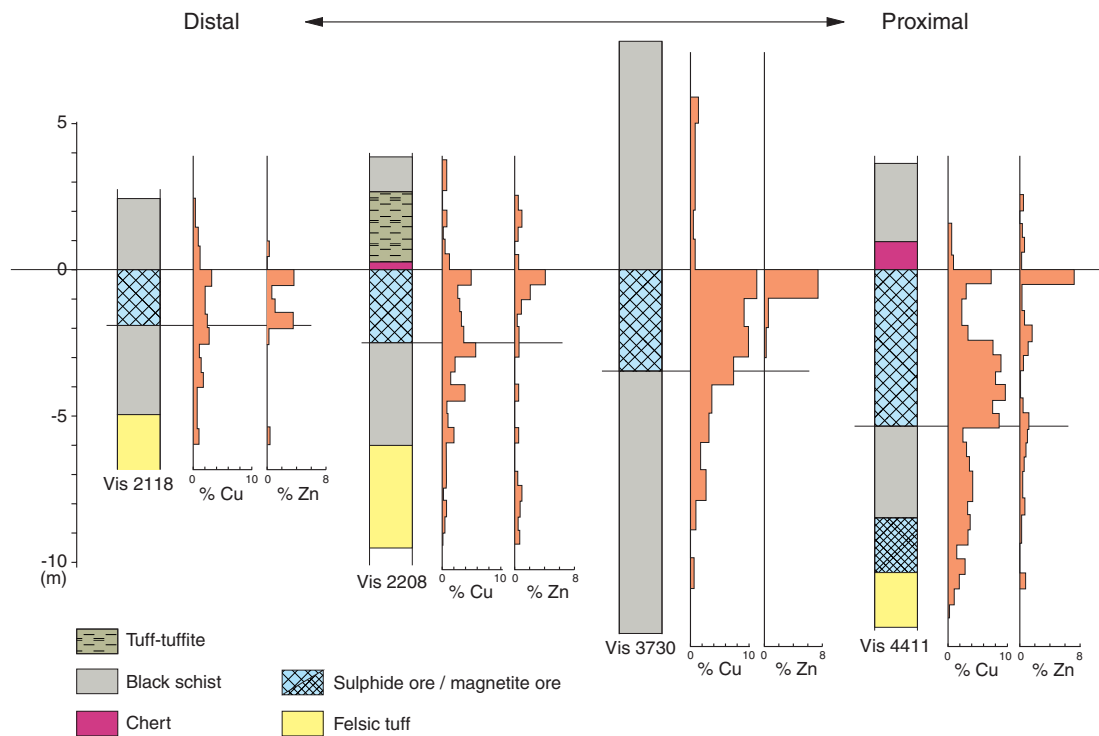
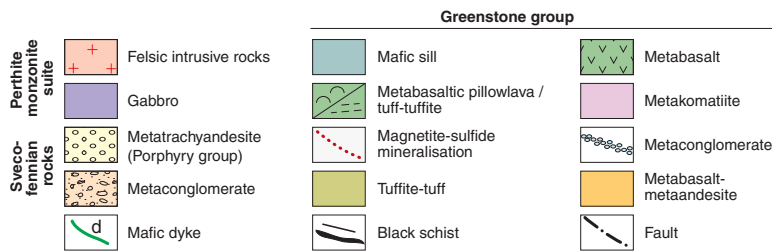


Fig. 32. Copper and zinc distribution in the Viscaria A-zone (Fig. 31) in selected drill cores from distal to proximal parts of the ore (from Martinsson et al. 1997a). The scale is relative, with the upper contact of the ore as the zero level.

Scapolite is locally developed in the upper part of the alteration zone and exists in small amounts together with tourmaline at the top of the ore zone.

The pronounced stratiform character of the Viscaria ore suggests a syngenetic origin. Extensive alterations in the footwall and the metal zoning of the ore are features of genetic importance, supporting an exhalative origin. However, compared to typical VMS-deposits, Viscaria is exceptional for its layered structure of high-grade copper ore and high magnetite content. The main ore horizon, the Viscaria A-zone, was formed in conjunction with basin subsidence and marks the start of voluminous eruptions of MORB-type pillow lava (Peuravaara Formation). Most probably the exhaled ore fluid was highly saline and accumulated as a brine pool at the sea floor. During cooling and brine mixing with overlying seawater, the ore constituents were precipitated as a chemical sediment. Along a fissure-controlled exhalative vent these sediments developed a pronounced copper-zinc zoning, with a high content of copper. Compared to world-wide copper-zinc deposits, most features of the Viscaria copper ore are similar to that of the Besshi-type. Regarding tectonic setting and ore genesis, the Viscaria deposit represents an ancient analogue to the Atlantis II Deep metalliferous sediment in the Red Sea (Martinsson et al. 1997a).

Östra Pahtohavare

The subeconomic copper deposit Östra Pahtohavare is very similar in character to the Viscaria deposit. Indications were discovered by LKAB in 1979 and investigated in more detail by NSG in 1984–1985. The mineralisation is situated in the middle part of the Viscaria Formation, between two horizons of black schist. Magnetite, chalcopryrite, pyrite, pyrrhotite, and smaller amounts of sphalerite occur disseminated or form almost massive intercalations in a calcareous mafic tuffite. In character and stratigraphic position the mineralisation is most similar to the Viscaria B-zone. Several thin, and laterally extensive, intercalations of magnetite containing varying amounts of pyrite occur stratigraphically below the Östra Pahtohavare deposit.

The ore zone is about 1 kilometre long, 200 metres wide and 2–10 metres thick. Besides copper and iron it is enriched in zinc, barium, calcium, and manganese. The area of highest content of copper

and iron outlines an elongated zone in the central part of the mineralisation. This same part of the ore zone has the highest Cu/Zn ratio.

The volcanoclastic rocks in the footwall are extensively altered to a depth of at least 70 metres stratigraphically below the ore. The alteration zone is chemically defined by a high K/Na ratio due to phyllosilicate alteration of plagioclase feldspar (Fig. 33). The depletion of calcium and strontium is not as pronounced as for sodium, and the enrichment of potassium is accompanied by some enrichment of barium, rubidium, zinc, copper, and iron (Martinsson et al. 1997a).

Kopparåsen

The Kopparåsen deposit was discovered in 1897 and investigated for copper using test pits. In the 1970s the possible occurrence of uranium in this area was investigated by means of geophysical ground measurements and drilling. The sulphide mineralisation occurs in a basement window within the Caledonides 100 kilometres NW of Kiruna. Several horizons containing copper, zinc, silver, and uranium in mostly low concentrations occur within a 500 metres thick sequence of mafic tuff and tuffite, overlain by clastic metasedimentary rocks. These supracrustal rocks constitute an isolated enclave within 1.8 Ga old granites. The stratigraphic position is unknown.

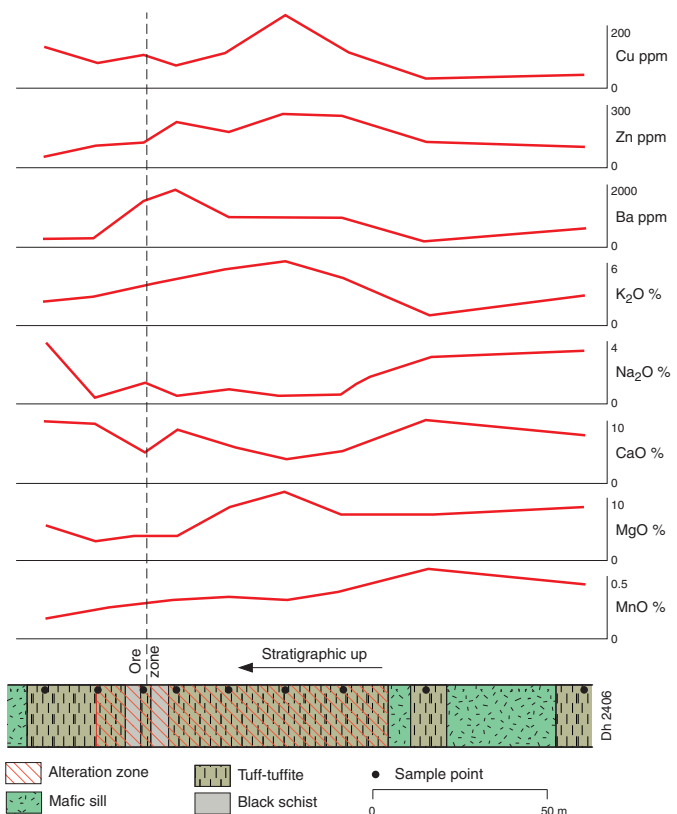


Fig. 33. Chemistry of altered wall rocks at the Östra Pahtohavare deposit, drill core 2406 (modified from Martinsson 1995).

The stratigraphically lowest horizon consists of magnetite, chalcopyrite, and bornite, which laterally give way to magnetite-pyrite. Some pyrite, chalcopyrite, and uraninite occur in association with anomalous contents of vanadium, molybdenum, and fluorine peripheral to this mineralisation and slightly higher in stratigraphical position. A third horizon, associated with a thick chert layer and with graphite-bearing tuffite, contains pyrrhotite, pyrite, chalcopyrite, sphalerite, and uraninite together with some arsenopyrite and galena. The uppermost mineralisation is hosted by black schist and has pyrrhotite, pyrite, chalcopyrite and sphalerite as its main ore minerals. Galena, arsenopyrite, cobaltite and uraninite are minor components (Adamek 1975). The grades of copper and zinc are usually less than 1 %, but no systematic investigation of tonnage and grade has been made.

The mineralised horizons are mainly stratiform-stratabound in character and have a length of 0.8 to 3 kilometres. In some of the horizons copper is most abundant in the central parts, while zinc is enriched in the peripheral parts. Magnetite is only found in the more copper-rich central part of the lowest horizon. Other elements enriched in the mineralisations besides copper and zinc are uranium, arsenic, nickel, and silver. Mineralisations with uranium are strongly enriched in vanadium (700–1 600 ppm, Adamek 1975), and occur mainly in association with pyrite-pyrrhotite. An epigenetic origin for uranium is suggested from lead isotope data, with mineralisation related to metamorphic fluids at 1.78 Ga. The minimum age for the least radiogenic lead in the sulphides indicates a syngenetic mineralisation at 2.05 Ga (Romer & Boundy 1988). Ore-related alterations have not been detected, but scapolitisation is locally common in the mafic rocks and tourmaline is encountered in a few places (Adamek 1975).

Huornaisenvuoma

The largest sulphide deposit in the northeastern part of the map area is the subeconomic Huornaisenvuoma zinc-lead-silver-copper deposit. It was found by LKAB in 1978 by drilling, and is calculated to contain 0.56 Mt with 4.8 % Zn, 1.7 % Pb, 0.2 % Cu, and 12 ppm Ag (Frietsch 1991). It is hosted by a thick dolomite in the upper part of the Greenstone group comprising mafic tuff and tuffite, manganese iron formation, and black schist. The Greenstone group constitutes the core of an anticline and is overlain by Svecofennian clastic sedimentary rocks and intermediate volcanic rocks (Ambros 1980). These volcanic and sedimentary rocks are metamorphosed at middle to upper amphibolite facies.

A thin stratiform sulphide horizon exists at the base of a 20–35 metres thick skarn zone in the upper part

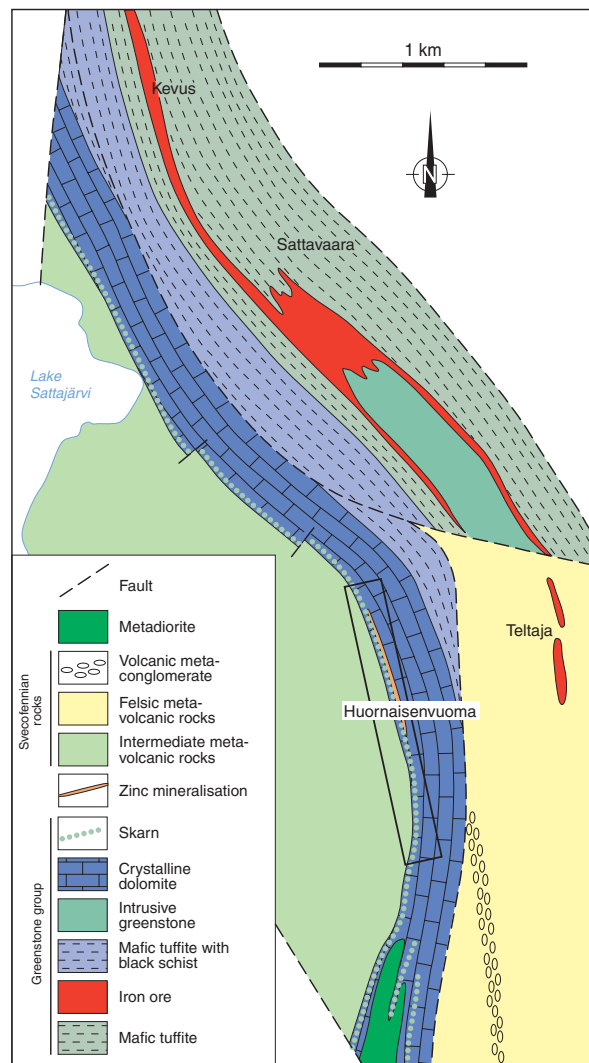


Fig. 34. Geological map of the Huornaisenvuoma area (from Martinsson 1995). Teltaja, Sattavaara and Kevus are iron mineralisations.

of the dolomite (Fig. 34). It consists of sphalerite, magnetite, and pyrite occurring disseminated and as almost massive layers. The mineralisation generally has a thickness of 1–2 metres and its maximum length is 950 metres. Another mineralised horizon exists in the upper part of the skarn. It is situated 20–30 metres higher up, and has a similar thickness and length as the sphalerite-bearing horizon but is more irregular in character. Disseminated magnetite with subordinate to ore grades (>1 % Cu) of chalcopyrite are the main constituents.

Diopside occurs together with varying amounts of actinolite as disseminated to almost massive aggregates within the skarn zone. Chondrodite, partly altered to serpentinite, is found disseminated in the skarn zone and it is the dominant silicate mineral in some parts. Skarn minerals are also found in the footwall to the sphalerite-bearing horizon, but they usually decrease rapidly in amount

with increasing distance from this horizon.

An elongate and narrow zone with strong lead enrichment is located towards the central part of the mineralisation, which also shows the highest zinc content. In the footwall to this metal-rich part of the deposit, skarn-rich dolomite with chondrodite, diopside, and actinolite extends at least 30 metres below the stratiform mineralisation (Martinsson 1995). This discordant skarn zone below the central part of the mineralisation is enriched in silicon, barium, copper, manganese, and iron.

A strong enrichment of iron, zinc, lead, copper, silver, cadmium, manganese, and barium is developed in the ore zone and several elements define a pronounced zoning pattern. Manganese has the highest content in the peripheral part, with up to 5.9 % MnO, while lead, copper, silver, and barium are enriched in the central part above the discordant skarn zone. The upper horizon is iron-dominated and partly very high in manganese (up to 9.1 % MnO). The metal zoning with lead enriched in the central part of the main ore horizon suggests a relation to SEDEX-type deposits (Large 1980), which also is consistent with the high barium and manganese content of the ore and the high Zn+Pb/Cu ratio (Martinsson 1995). Thus, the discordant skarn zone below the metal-rich central part of the deposit could be the expression of a metamorphosed exhalative feeder zone. The locally occurring high grades of copper may have formed by a later overprinting hydrothermal event.

Iron formations (BIF and skarn-rich)

General characteristics

The most common mineralisation types in the Greenstone group are the skarn-rich iron formations. They are stratabound–stratiform in character, with a length of 600–1 300 metres and a thickness of 50–100 metres. Most of the deposits are located in the upper part of the Greenstone group, but some are also found in the middle part. Associated rocks are tuffite, black schist, and dolomite. Magnetite, serpentine, diopside, and tremolite are the main constituents of the mineralisations. The skarn minerals occur together with magnetite or form magnetite-poor intercalations and lenses. Some mineralisations are overlain by diopside-amphibole skarn and calcisilicate-bearing chert. Pyrite and pyrrhotite are common minor components. They occur disseminated and in veinlets together with accessory amounts of chalcopyrite. Alterations are mainly recorded from the footwall, where biotite or chlorite and locally scapolite have been formed. Alterations in the hanging wall are generally less intense, or absent. The average compositions of most skarn-rich formations are rather similar, with 30–45 % Fe, 1–3 % S, and 0.02–0.1 % P (Grip & Frietsch 1973).

Typical sizes are 5–60 Mt, and the largest and best known example is the Sahavaara deposit.

Most skarn-rich iron formations are slightly enriched in copper and some of them have been investigated by Boliden Mineral AB as potential sources of copper. Although core sections containing several percent copper exist in many deposits the average grade is usually in the range of 0.02 to 0.07 % Cu. Tervaskoski is the largest example of the more copper-rich deposits. It contains 30 Mt with 48 % Fe, 3 % S, and 0.1 % Cu (Grip & Frietsch 1973).

The Vathanvaara deposit in the Vittangi area is partly different from the general characteristics of skarn-rich iron formations. It changes in its central part from laminated and almost massive pyrite-pyrrhotite sulphide facies at the footwall to normal skarn-rich iron formations towards the hanging wall and its peripheral parts. The Tapuli deposit is also different through the occurrence of irregular magnetite-rich skarn lenses within a thick dolomite. The Tjavelk and Vieto deposits are anomalous through their high phosphorus content.

Some typical skarn-rich iron formations gradually change into BIF towards the hanging wall and/or laterally, suggesting these two types of iron deposits to be genetically related (Grip & Frietsch 1973). One of the best examples is the Tornefors deposit in the Tändö area, where a skarn-rich iron formation containing 25–35 % Fe is overlain by typical BIF, with 15–25 % Fe. Deposits exhibiting a similar transition from skarn iron formation to BIF are Marjajärvi in the Pajala area and occurrences in the Masugnsbyn area.

Silicate facies BIF are widespread in the upper part of the Greenstone group, in the eastern part of the area (Pajala, Tändö, Lannavaara). The largest and best-known deposit occurs at Käymäjärvi in the Pajala area. Generally the iron content is in the range of 15 to 25 %. Slightly higher grade is encountered in locally developed oxide facies. Many of the BIF-deposits are manganiferous, with up to 4 % MnO.

Käymäjärvi

Picritic lapilli tuff constitutes the core of an anticline of fairly well-preserved rocks in the Greenstone group at Käymäjärvi. This pyroclastic rock is overlain by a thin unit of mafic tuffite, a 150 to 200 metres thick BIF, a second unit of mafic and partly graphitic tuffite, and finally a c. 200 metres thick dolomite at the top of the succession. On top of these rocks rest Svecofennian andesitic metavolcanic rocks and a clastic metasedimentary unit. At Käymäjärvi the BIF can be followed along strike for about 18 kilometres.

The BIF contains on average c. 15–20 % Fe, but in

locally occurring oxide facies the iron content may reach 30 to 40 % over some metres of thickness. The BIF exhibits a distinct mesobanding, with 5 to 30 cm thick chert bands alternating with silicate bands mainly containing pyroxene, amphibole, and fayalite in various proportions. Grunerite is the dominant mineral in most silicate bands (Geijer 1925). Magnetite occurs locally as microbands in silicate bands and as a poor dissemination in some silicate and chert bands. Some iron-poor parts of the BIF differ in character only by their lack of iron-rich silicates and magnetite. Dolomitic intercalations up to some metres thick are encountered locally. Both the silicate and oxide facies contain between 2.3 and 3.4 % MnO, and barium may be enriched up to 1 % in oxide facies. Base and precious metals in the BIF have not been found significantly enriched (Martinsson 1995).

Tornefors

The Tornefors deposit is intersected by 8 drill holes and contains an estimated tonnage of 8 Mt with 25 % Fe, 1–2 % S, and 0.05 % P. The deposit is situated within a unit of basaltic lapilli tuff in the upper part of the Greenstone group at Junosuando. It is mainly developed as an oxide-facies BIF which, close to the footwall, changes into a serpentine-magnetite skarn-rich iron formation. A 5–10 metres thick marble horizon separates the mineralisation from the volcanoclastic rocks in the footwall and a 10 metres thick layer of amphibole skarn constitutes the top of the mineralised zone, which is c. 100 metres thick in total (Fig. 35).

Chert and skarn define a mesobanding in decimetre-scale. The skarn is dominated by amphibole but can locally contain pyroxene and garnet. Magnetite occurs disseminated and as microbands in the skarn layers. Laminae of magnetite with a thickness of 0.1–1 millimetre are commonly found. Sulphides are locally abundant. Pyrite and some pyrrhotite form veinlets and an irregular dissemination.

An alteration zone extends at least 100 metres stratigraphically below the mineralisation. It is mineralogically defined by the formation of biotite, at the expense of plagioclase. The most obvious chemical changes in the altered rock are a depletion of sodium, calcium, and strontium, accompanied by an enrichment of magnesium, potassium, barium, and rubidium. Limited chemical data from the hanging wall rocks indicate that they are unaltered. Only a few elements exhibit distinct variations within the mineralised horizon. A strong enrichment of magnesium is developed near the footwall, and the Si/Fe ratio increases stratigraphically upwards. The central and upper parts of the mineralised zone are slightly enriched in cobalt and gold (Martinsson 1995).

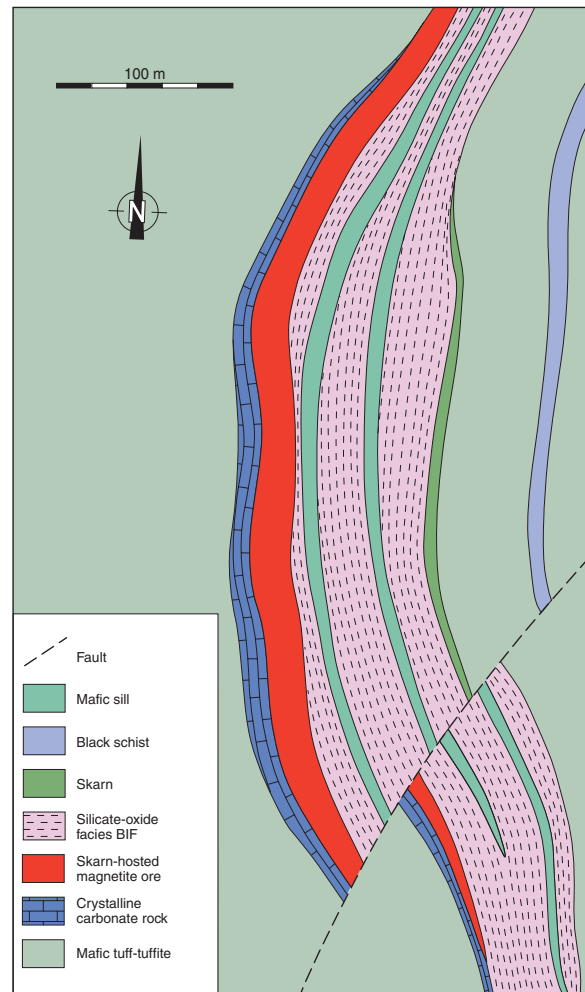


Fig. 35. Geological map of the Tornefors deposit (from Martinsson 1995). All rocks belong to the Greenstone group.

Sahavaara

The Sahavaara deposit is situated NE of Pajala and comprises three lenses of skarn-rich iron formation. The largest one, Stora Sahavaara, contains 82 Mt with 41 % Fe, 2.5 % S, 0.07 % P, and 0.08 % Cu. Södra Sahavaara and Östra Sahavaara, situated in a stratigraphically slightly lower position, contain 19.6 and 2 Mt of ore, respectively (Grip & Frietsch 1973).

The Sahavaara deposit occurs in the upper part of the Greenstone group, at the contact between volcanoclastic rocks in the footwall and Svecofennian clastic metasedimentary rocks in the hanging wall (Fig. 36). The footwall tuffites, which are deposited on lapilli tuff of picritic to high-magnesium basalt composition, are mainly basaltic in character. However, near the mineralisation, the tuffites are andesitic and generally rich in graphite. The metasedimentary rocks in the hanging wall have a rather uniform composition and were probably derived mainly from andesitic volcanic rocks (Martinsson 1995).

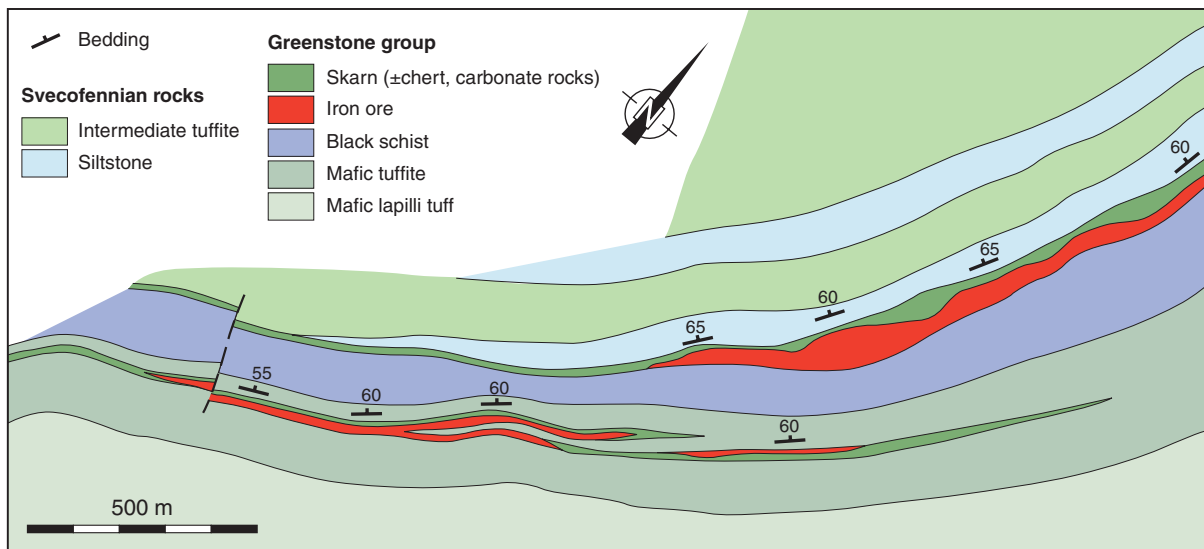


Fig. 36. Geological map of the Sahavaara deposit (modified from Lundberg 1967).

The mineralised horizon at Stora Sahavaara is up to 80 metres thick and consists of serpentine-rich magnetite ore, including lenses and layers of serpentine-diopside-tremolite skarn (Lundberg 1967). Pyrite, pyrrhotite, and chalcopyrite are minor constituents which occur disseminated in the mineralisation. A zoned skarn unit usually caps the mineralisation. Near the mineralisation it is dominated by serpentine, but it gradually changes to diopside-amphibole skarn and at the top of the mineralised zone it ends up in a calcisilicate-bearing chert. The highest content of iron and sulphur is found in the central part of the deposit, which is also slightly enriched in copper and cobalt. Similarly to many other skarn-rich iron formations the Sahavaara deposit exhibits a pattern of decreasing contents of iron, copper and cobalt, combined with an increase of calcium, silicon, phosphorous, and manganese towards the top and peripheral parts of the mineralisation (Martinsson 1995).

An alteration zone extends to about 200 metres below the Stora Sahavaara deposit and encloses the smaller Östra Sahavaara horizon. The graphite schist in the footwall is partly replaced by a skarn-scapolite rock consisting of varying proportions of scapolite, diopside, tremolite, and some pyrrhotite (Lundberg 1967). This altered rock is enriched in sodium, calcium, strontium, and chlorine. Scapolite-rich graphite schist is of regional occurrence in this stratigraphic position and the sodium-enrichment in the footwall to the Stora Sahavaara deposit may not be a product of alteration related to the mineralising event. The stratigraphically lower part of the alteration zone is more or less rich in biotite, resulting in enrichment in magnesium, potassium, barium, and rubidium, while sodium, calcium, and strontium are slightly depleted (Martinsson 1995).

APATITE IRON ORES

General characteristics

The apatite iron ores are spatially related to the areas occupied by the Porphyry group (Fig. 37), and they are generally hosted by either these volcanic rocks or the underlying Porphyrite group. About 40 apatite iron ores are known from the northern part of Norrbotten county, and individual deposits have an average content of iron and phosphorous varying between 30 and 70 % and 0.05 and 5 %, respectively. Kiirunavaara, the largest deposit, contains more than 2 000 Mt of ore, and several other deposits are in the range of 100–600 Mt.

The apatite iron ores exhibit a considerable variation in host rock relations, host rock lithology, host rock alterations, phosphorous content, and associated minor components. It is possible to distinguish two distinct groups of deposits, a breccia type and a stratiform-stratabound type. A third and less distinct group of deposits has features similar to the other two groups, and is in many respects intermediate in character to them (Martinsson 1994).

Apatite iron ores have been distinguished geochemically from magmatic and sedimentary ores by their generally low titanium content in the range of 0.04–0.31 %, combined with a high content of vanadium, varying from 317 to 2 310 ppm (Loberg & Horndahl 1983). The high content of vanadium in magnetite from apatite iron ores was already noticed by Frietsch (1966), who also showed that cobalt and nickel were higher in these ores compared with magnetite from skarn-rich iron formations. The phosphorous content of the apatite iron ores is to some extent dependent on the character of the ore. Tabular ores are generally higher in phosphorous

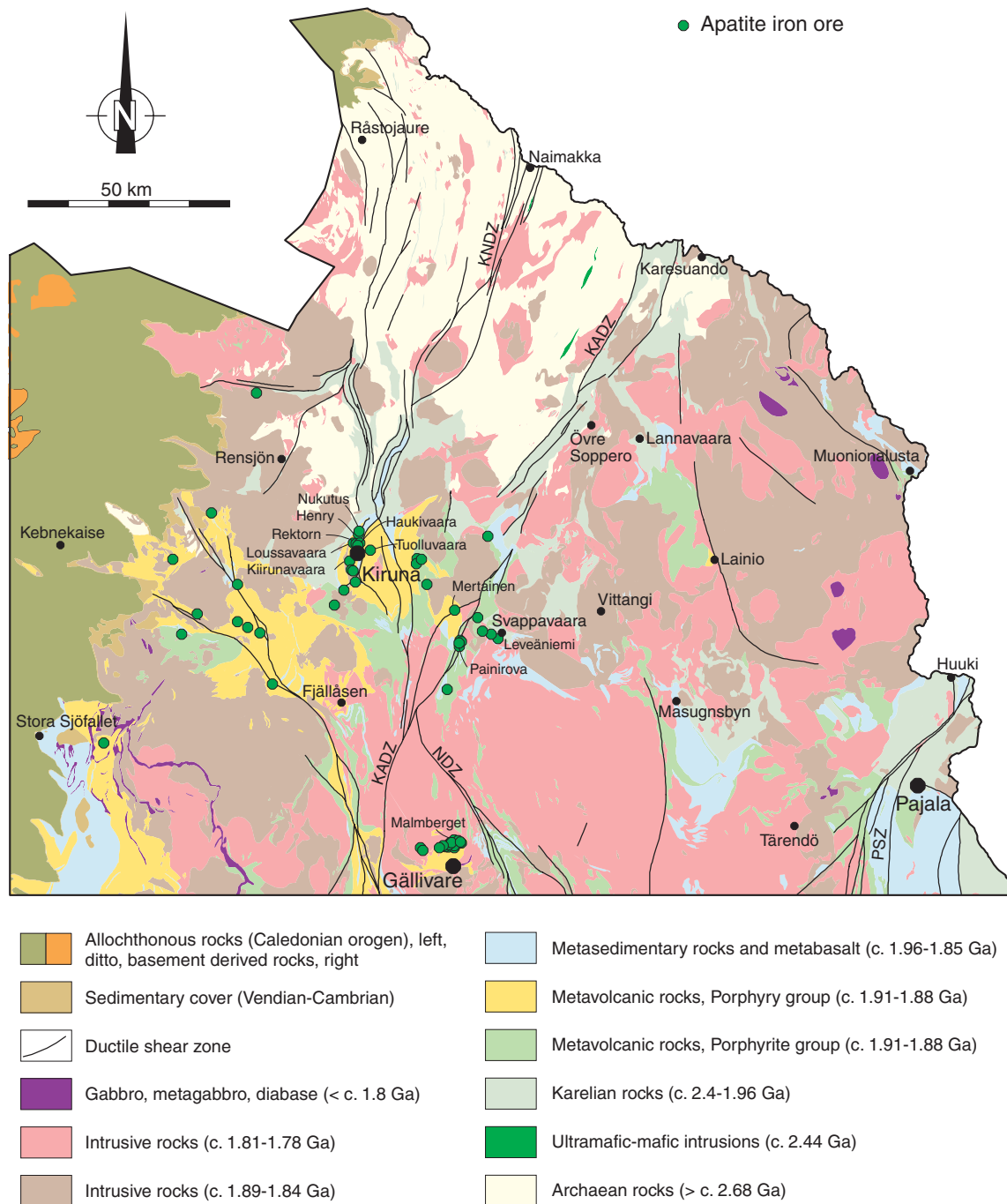


Fig. 37. Simplified bedrock map of the northern part of Norrbotten county with occurrences of apatite iron ores.

compared to ores of breccia type. Instead, the content of titanium is often higher in the breccia type (Frietsch 1966). Most apatite iron ores are strongly enriched in rare earth elements, with a dominance of the light rare earth elements (Parák 1973a, Frietsch & Perdahl 1995).

Apatite iron ores having the character of a breccia are mainly situated in intermediate to mafic volcanic rocks, occurring in a stratigraphically low position of the Porphyry group or within the underlying Porphyrite group. One exception is Tuolluvaara, which occurs in a felsic

metavolcanic rock in the Porphyry group. Amphibole is always present as a minor component, and accessory amounts of pyrite, chalcopyrite, and titanite may be encountered. Host rock alterations are not reported to be a prominent feature of these deposits, but albite and scapolite seem to be rather common, while sericite, epidote, and tourmaline are less important. Characteristic for the breccia-type deposits is a low phosphorous content, usually in the range of 0.05–0.3 %, and an average iron content of about 30 %. However, the central parts

of larger deposits are more high-grade (60–70 % Fe, e.g. Mertainen and Tuolluvaara). With some few exceptions magnetite is the only iron oxide.

The other group of deposits form stratiform-stratabound lenses in stratigraphically high positions within the Porphyry group. The deposits have hematite as a major iron oxide, together with varying amounts of magnetite, and these deposits also have a higher phosphorous content, varying from 1 to 4.5 %. Amphibole is missing, and the gangue minerals are mainly apatite, quartz, and carbonate. Host rock alterations are common, with sericite, biotite, tourmaline, and carbonate as typical products. The hanging wall rocks may also be strongly silicified (i.e. in the Rektorn deposit). Sulphides are rare and mainly found in small amounts in the altered footwall or as crosscutting late veins within the ores.

Some deposits share features with both groups of apatite ores. They are mainly stratabound in character but also have ore-breccia developed along the wallrock contacts (e.g. Kiirunavaara). Magnetite is the dominant, or only, iron oxide. Amphibole is a characteristic minor component, and titanite may be present in accessory amounts. The iron content is high (55–67 %), and the average phosphorous content is rather low, although it varies between c. 0.02 and 4 % within individual deposits. Alterations in the host rocks are not well defined, but include the formation of albite, amphibole, biotite, sericite and, locally, scapolite or tourmaline.

The deposits Mertainen, Rektorn, and Kiirunavaara will be described in more detail below, as these three deposits represent different types of apatite iron ores. In contrast to most apatite iron ores at Kiruna, the Leveäniemi and Malmberget deposits are strongly affected by metamorphic recrystallisation and ductile deformation, which has largely obliterated the primary character of the ores and their host rocks. Both of these deposits are situated near large granite intrusions of the Granite-pegmatite association.

Genetic models

The genesis of the Kiruna apatite iron ores has been subject to discussion for more than 100 years. A sedimentary origin was proposed by Fredholm (1891), based on the stratabound nature of the ores. This concept was further developed by Parák (1975a), who argued for an exhalative-sedimentary process. However, the magmatic model has been rendered the greatest support, with Geijer as the main advocate. He first proposed an extrusive origin for the Kiirunavaara-Luossavaara ores (Geijer 1910), but subsequently changed his mind and regarded them as intrusive sills (Geijer 1919a, 1931a, 1967).

This discussion on genesis has primarily been based on geological data concerning the relation between the ores and their host rocks. However, Parák (1973a, 1975a, b, 1985), Frietsch (1978, 1982), Nyström & Henríquez (1994), and Frietsch & Perdahl (1995) also used chemical data on iron oxides and apatite to support their arguments. Geijer (1910) identified peculiar textures in the apatite-iron ores, including columnar and dendritic magnetite. To support a magmatic origin for the Kiirunavaara ore, the similarities between these textures and ore textures in the El Laco deposit (in northern Chile) were emphasised (Nyström 1985, Nyström & Henríquez 1989, 1994). In the light of Parák's (1973b) ideas, Geijer & Ödman (1974) suggested an intrusive origin for the Kiirunavaara-Luossavaara ores and an extrusive-sedimentary origin for the Per-Geijer ores (the Rektorn, Henry, Nukutus, and Haukivaara ores, Geijer 1910). A modification of this model was presented by Wright (1988), proposing the Kiirunavaara-Luossavaara to be extrusive, while the Per-Geijer ores were believed to have formed through exhalations. Using oxygen isotope data O'Farrelly (1990) suggested an intrusive emplacement at c. 700 °C for the Kiirunavaara deposit and at 550 °C for the stratigraphically higher-situated Per-Geijer ores.

Using geochronological data, Cliff et al. (1990) bracketed the emplacement of the Kiirunavaara deposit to a period between 1.88 and 1.90 Ga, and they suggested the formation of the ore to be a result of intrusion-related high-temperature processes during orogenesis. From oxygen isotope data a temperature of c. 600 °C was indicated for this volatile-rich magmatic-hydrothermal ore forming process (Blake 1992). This change from pure magmatic models to also include hydrothermal processes was further developed by Hitzman et al. (1992). They presented a hydrothermal replacement model for the Kiruna apatite iron ores, based on genetic ideas regarding the Olympic Dam deposit in Australia.

Considering the large variation exhibited by the apatite iron ores in the map area regarding such features as ore character, relation to the host rock, and extent of ore-related alterations, no single model can explain all the known features of this ore type. Most deposits were probably formed as magmatic volatile-rich intrusions at a moderate depth in the crust. During solidification exsolved high-temperature hydrothermal fluids altered the wall rocks and precipitated minor late ore assemblages. Kiirunavaara and several other deposits fit this model, but the phosphorous-rich Per-Geijer ores may have formed at very shallow depths or even at the surface. Some apatite iron ores are pegmatitic in character (e.g. Painirova), and there are other deposits that most probably are of hydrothermal origin.

Kiirunavaara

Kiirunavaara is the largest of the apatite iron ores in Sweden, comprising c. 2 000 Mt of iron ore with 60 to 68 % Fe. It was found in outcrop in 1696 but regular mining did not start until 1900, when a railway was built from the coast to Kiruna. Open pit mining ceased in 1962, after a total production of 209 Mt. Underground work started on a small scale during the 1950s, and the ore is now mined through large-scale sublevel stoping. The present main haulage level is at 1 045 m, and the total production at the end of 1999 from open pit and underground was c. 1 030 Mt.

The tabular ore body is c. 5 kilometres long, up to 100 metres thick, and extends at least 1 300 metres below the surface. It follows the contact between a thick sequence of trachyandesitic lavas (traditionally called syenite porphyry) and overlying pyroclastic rhyodacites (traditionally called quartz-bearing porphyry). Towards the north, the much smaller Luossavaara ore is situated in a similar stratigraphic position (Fig. 38).

The trachyandesite lava succession consists of numerous lava flows, which are rich in amygdules near the

flow tops. Minor pyroclastic intercalations exist between some of the flows. A thick sill varying in composition from gabbro to monzonite has intruded the lava succession 1 kilometre stratigraphically below the ore. Several dykes of granophyric to granitic character cut the ore, and a larger body of potassic granite is found at deeper levels in the mine on the footwall side of the ore.

In the footwall to the Luossavaara deposit, titanite and magnetite exist together in the form of coarse-grained veins. The titanite from these veins has yielded a U-Pb age of 1888 ± 6 Ma (Romer et al. 1994), while granophyric to granitic dykes crosscutting the Kiirunavaara ore has a U-Pb zircon age of 1880 ± 3 Ma (Cliff et al. 1990). This suggests that the Kiirunavaara–Luossavaara ores formed between 1888 and 1880 Ma ago.

Magnetite-actinolite breccia is developed in both the footwall and the hanging wall along the contacts of the Kiirunavaara ore body. In the footwall, larger breccia zones partly show a change from veined trachyandesite to breccia with angular fragments of the wallrock. In some places there is a central part containing rounded pebbles of the wallrock set in a matrix, which is rich in magnetite. Near the hanging wall contact, the ore is often rich in angular to sub-rounded clasts of rhyodacitic tuff. Veins of magnetite and actinolite extend tens of metres up in the hanging wall, and they are locally wider and spaced more closely together, forming rich ore breccia or lenses of massive ore.

The phosphorus content of the ore exhibits a pronounced bimodal distribution with either less than 0.05 % P or more than 1.0 % P. Most of the apatite-poor ore (B-ore) is found near the footwall. This body of massive magnetite ore is slightly irregular and has a branch-like geometry. It is usually 40 to 70 metres thick and contains up to 15 % of disseminated actinolite in a 5–20 metres wide zone along its borders. The magnetite is mostly very fine-grained (<0.3 millimetres) but in the central part of the B-ore, zones of coarser magnetite (up to 2 millimetres) may exist together with some calcite and small amounts of pyrite. Apatite-rich ore (D-ore) is mainly found towards the hanging wall and in the peripheral parts of the ore body, but it occurs in varying amounts at the footwall contact as well. In some places, the D-ore has a banded structure and the proportions of apatite and magnetite vary widely. The age relation between B- and D-ore is ambiguous, and both ore types can be seen cutting each other. Magnetite with locally developed columnar and dendritic textures in the ore

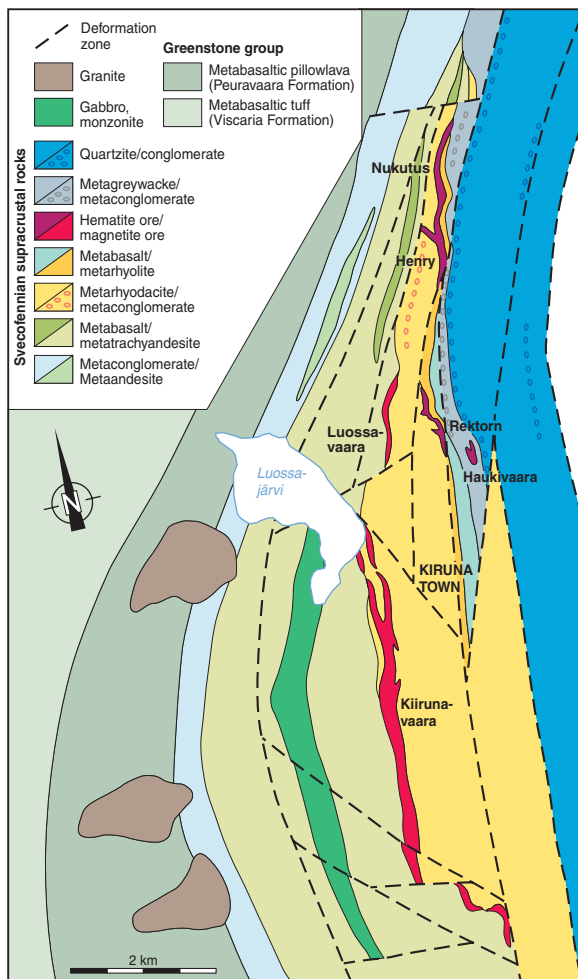


Fig. 38. Geological map of the central Kiruna area (modified from Martinsson & Perdahl 1993 and Romer et al. 1994). Names refer to major ore bodies.

suggests rapid crystallisation in a supercooled magma (Geijer 1910, Nyström 1985, Nyström & Henríquez 1989). Veins of anhydrite, anhydrite-pyrite-magnetite, and coarse-grained pyrite are encountered locally in the ore and its wall rocks.

Extensive albitisation is developed in the footwall to the Kiirunavaara deposit. It is most intense around the gabbroic to monzonitic sill, which itself is strongly altered. Especially the amygdaloidal parts of the lava flows are pronouncedly altered and the albitisation is accompanied by secondary magnetite, actinolite, titanite, and locally some tourmaline (Geijer 1910). A U-Pb age of 1876 ± 9 Ma was obtained from titanite in albitised trachyandesite lava, thus considered to be the age of albitisation (Romer et al. 1994). Sericite schist with some tourmaline is found locally at the footwall contact of the ore (Geijer 1910), and it may be related to shearing after ore formation. Actinolite is a common alteration mineral at both the footwall and the hanging wall contacts, and in places forming massive skarn bordering the ore. Actinolite also partly or completely replaces clasts of wallrocks in the ore and in the ore breccia. Besides actinolite and magnetite veining close to the ore, the hanging wall is in some areas affected by biotite-chlorite alteration, which is often accompanied by disseminated pyrite and a weak enrichment of copper, cobalt, and molybdenum.

Rektorn

The Rektorn ore is one of the apatite-rich Per-Geijer ores (Rektorn, Henry, Nukutus, and Haukivaara) occurring in the central Kiruna area (Geijer 1910). While the much larger Kiirunavaara and Luossavaara ores are situated in the middle part of the Porphyry group, the Per-Geijer ores are located at the upper part of this unit (Fig. 38). The Rektorn ore was indicated by magnetic survey and discovered through trenching in 1887. Mining was started in 1925 and continued intermittently to 1961. During one period (1942–1946) apatite was the main product (Geijer 1950). A total of 2.52 Mt ore was produced from open pit and underground mining.

The Rektorn deposit is situated at the top of pyroclastic rhyodacites (Figs. 38, 39). The hanging wall is heterogeneous in character and strongly sheared. In its lowest part it consists of a strongly altered reddish rock of probably rhyolitic pyroclastic origin ("Rektorn Porphyry", Lundbohm 1910). Locally an ignimbritic structure has been identified in the Rektorn Porphyry (Frietsch 1979). However, it generally lacks primary textures and is either developed as a massive K-feldspar rock or as spherulitic aggregates of K-feldspar in a dense quartz matrix with finely disseminated hematite (Geijer 1950).

Intercalations of siliceous hematite ore up to several

metres thick are common in the Rektorn Porphyry. They are poor in apatite and mostly rich in clasts of hematite ore and felsic rocks. The Rektorn Porphyry is overlain by strongly altered basaltic tuff, which is succeeded by a conglomerate containing rounded clasts of apatite iron ore and felsic porphyritic rocks up to 5 decimetres in size. Stratigraphically upwards, the conglomerate gradually changes into greywacke and phyllite (Lundbohm 1910).

The ore of the Rektorn deposit consists of magnetite and hematite in varying proportions. Apatite occurs disseminated in the ore, enriched in bands, or as breccias and crosscutting veins. In banded ore, apatite forms prismatic grains with a length of c. 0.1 millimetre, arranged subparallel to the banding. In some places quartz and carbonate are quantitatively important constituents of the apatite-rich ore. They occur interstitial to apatite or form small patches (Geijer 1950).

In the southern part of the deposit, a 10–20 metres wide ore breccia is developed in the footwall. It contains up to 5 decimetres large, altered fragments of rhyodacite, which occur in a matrix rich in apatite and iron

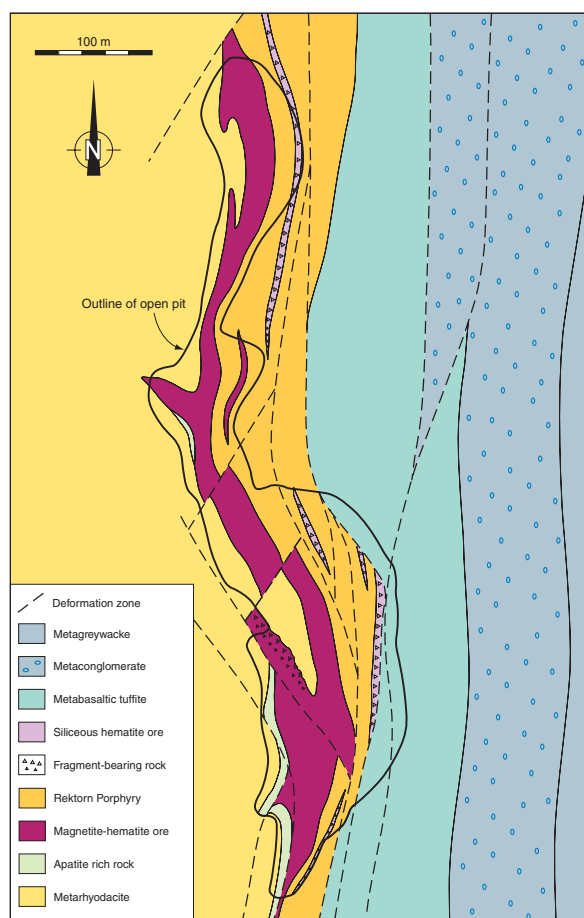


Fig. 39. Geological map of the Rektorn deposit (modified from Geijer 1950). All rocks are Svecofennian in age.

oxides. Further northwards, a branch of iron ore protrudes at least 40 metres into the footwall.

The rhyodacite in the footwall is usually altered in a 5 to 10 metres wide zone along the contact to the ore. Secondary minerals are sericite, ferro-dolomite, biotite and, locally, tourmaline (Geijer 1950). Chalcopyrite and pyrite are occasionally found in small amounts in the altered rocks. The Rektorn Porphyry in the hanging wall has been affected by very extensive K-feldspar alteration and silicification. Sericite formed during a late pervasive alteration phase in association with shear zones. It also occurs as patches or lenses of massive sericite containing radiating aggregates of tourmaline. Barite, orthite, and fluorite are accessory components in the altered porphyry and in the siliceous hematite ores (Lundbohm 1910). A strong sericite-chlorite alteration is developed in the sheared basaltic tuff overlying the Rektorn Porphyry.

Mertainen

The Mertainen deposit was found in 1897 through magnetic surveys and has been investigated by means of drilling and trenching on several occasions. Extensive diamond drilling was done by SGU during the period 1959–1963 and the proven reserve was calculated to be 166 Mt containing 35 % Fe and 0.05 % P. This includes a richer part containing 11 Mt with 61 % Fe (Grip & Frietsch 1973). From 1956 to 1958 c. 0.4 Mt of ore was mined from an open pit in one of the richer parts of the deposit.

The ore is hosted by trachytic to trachyandesitic lavas, which commonly are rich in amygdules and feldspar phenocrysts. The lavas may also be rich in magnetite which occurs disseminated, in patches, and in irregular veins (Lundberg & Smellie 1979). The Mertainen deposit has the character of a large breccia body, containing partly massive lenses or veins of magnetite in its central part. The magnetite-rich part is surrounded by successively less magnetite-rich breccias (Fig. 40a). Mineralisation is proven to a depth of 500 metres (Fig. 40b) and the richer part of the deposit occurs within a large positive magnetic and gravimetric anomaly (Fig. 40c), suggesting the magnetite breccia to be very extensive.

Magnetite is accompanied by actinolite, some apatite locally, and small amounts of titanite. Actinolite occurs both as coarse aggregates and disseminated in the ore. In some places it also forms a narrow border zone along magnetite veins. Apatite is mainly found in veins that are up to 10 cm wide. Titanite occurs disseminated in the ore, giving it an average TiO₂ content of c. 1 % (Lundberg & Smellie 1979). The host rock to the ore is sodic in character and in many places scapolitised. Scapolite also occurs together with actinolite in magnetite veins. Out-

side the mineralised breccia the volcanic rocks are generally potassic in character, with K-feldspar as the main feldspar mineral.

Leveäniemi

Leveäniemi is the third largest apatite iron ore in the northern part of Norrbotten county. It is situated at Svappavaara and was found in 1897. The deposit was investigated in magnetic ground surveys in 1898 and through diamond drilling in 1899–1907. A second phase of geophysical measurements and drilling was carried out by SGU in 1957–1962. The ore is folded into a funnel-shape and its lowest part reaches c. 550 metres below the ground surface. Leveäniemi is calculated to contain 204 Mt of high-grade ore with c. 64 % Fe, and 104 Mt of low-grade ore with 26 % Fe. A calculation based solely on data from the local gravity anomaly carried out by Werner (1965) yielded an iron reserve of 150 Mt. Both ore types have a phosphorous content varying from 0.02 to 1.1 %, but in general the content is less than 0.1 % (Grip & Frietsch 1973). Between 1964 and 1983, about 57 Mt of ore was produced in open pit mining.

The bedrock at Leveäniemi consists of strongly metamorphosed rocks of volcanic and sedimentary origin, which are intruded by pegmatite and granite. A larger granite intrusion (Granite-pegmatite association) is found towards the south. The metavolcanic rocks, probably belonging to the Porphyrite group, are stratigraphically overlain by a 30 metres thick metaconglomerate containing rounded volcanic clasts of local origin. Minor arenitic and calcareous intercalations occur. The metaconglomerate is followed by a banded carbonate-scapolite rock containing some disseminated pyrite, pyrrhotite, and chalcopyrite. Upwards it gradually changes into biotite schist, which is the main host rock to the Leveäniemi ore. In some areas it contains large porphyroblasts of cordierite (Parák & Espersen 1965).

Leveäniemi is dominated by massive magnetite ore but large volumes of ore breccia occur in an up to 100 metres wide zone in the surrounding biotite schist. The contacts between the massive ore and the ore breccia are mostly distinct. The grain size of the ore is mostly 0.08–0.2 millimetres. Apatite, calcite, and amphibole are the main gangue minerals, while titanite, diopside, biotite, and chlorite are less important. Calcite is partly abundant as veinlets. Up to 0.5 metre wide veins of coarse-grained apatite and magnetite are common in the northern part of the deposit; up to 1 decimetre large apatite crystals grew mostly perpendicular to the walls of the veins. These apatite-rich veins and up to 5 metres thick mafic dykes rich in scapolite cut both the ore and its host rock. A few porphyry dykes of intermediate composition

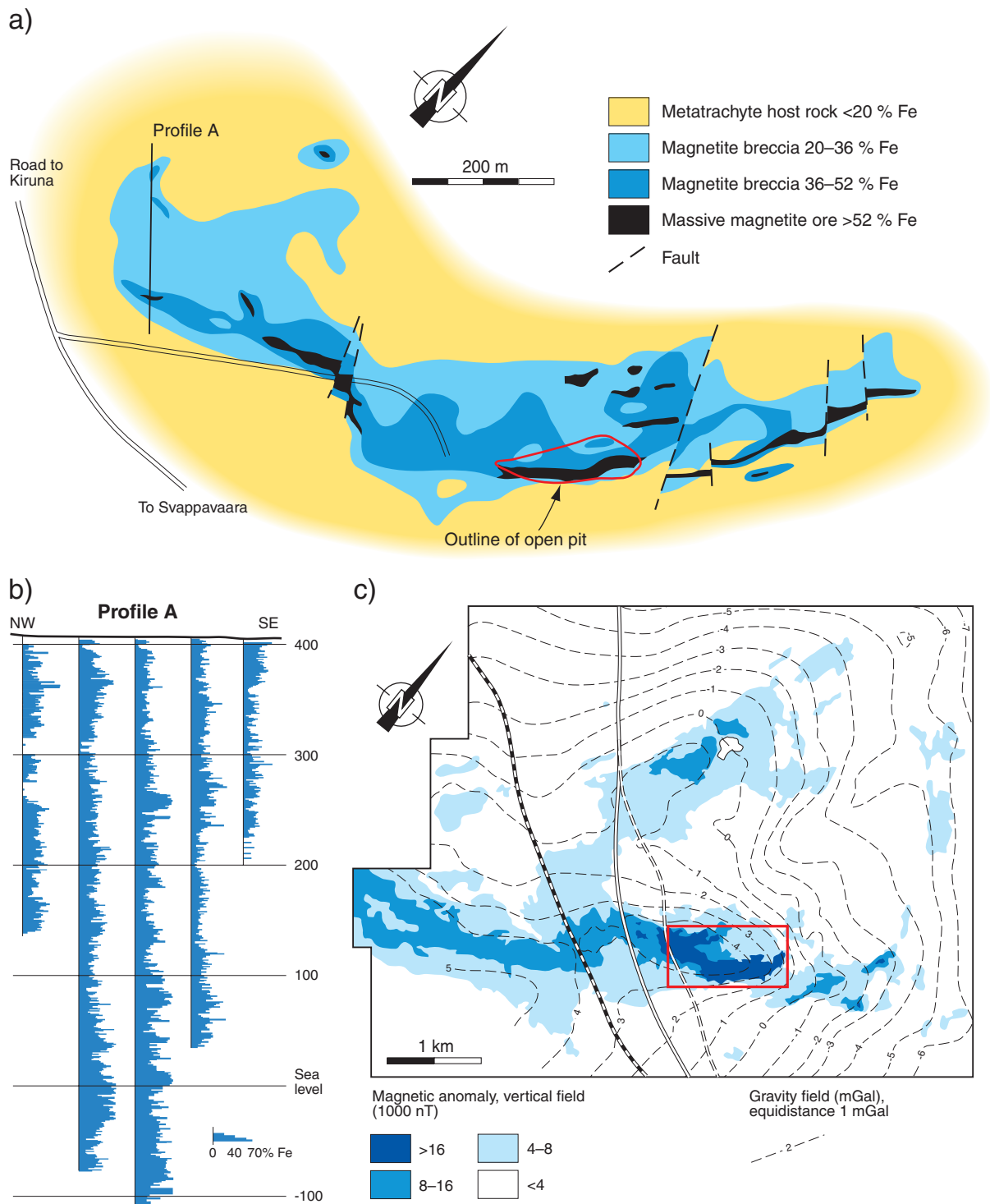


Fig. 40. The Mertainen deposit (modified from Lundberg & Smellie 1979). a) Geological map and iron contents. b) Iron content in drill cores from profile A. c) Magnetic and gravity anomalies at Mertainen. Red rectangle shows the position of the map in a).

exist in the biotite schist (Parák & Espersen 1965).

The host rock is mostly rich in biotite, but in some areas it changes into strongly foliated muscovite schist. Locally the biotite schist is affected by intense albitisation, giving it a reddish colour. In the eastern part of the deposit the ore is bordered by an up to 20 metres wide

amphibole skarn. Intense scapolitisation took place locally in the same area, with desmine and chabazite occurring in druses. In the central part of the deposit, magnetite is largely altered to hematite and the host rock is locally affected by strong clay alteration.

Malmberget

The precise point of time for the discovery of the Malmberget deposit is not known, but most likely it was found at the end of the 17th century. Mining started on a small scale in the 18th century, with the main production coming from the Kaptén ore body. When the railway from Luleå to Gällivare was completed in 1888, ore production rapidly increased and open pits were developed on most outcropping ore bodies. The total tonnage of the Malmberget deposit is estimated to be at least 660 Mt with 51–61 % Fe and <0.8 % P (Grip & Frietsch 1973). At the end of 1999 about 460 Mt had been produced.

The ores are hosted by strongly metamorphosed and deformed rocks of felsic to mafic composition. A porphyritic texture is locally preserved in the felsic rocks. Amygdules are occasionally encountered, suggesting a mainly extrusive origin and a primary character similar to that of the host rocks to the Kiirunavaara deposit. Mafic rocks are mainly found adjacent to the ores as conformable to discordant lenses. Occasionally they contain remnants of plagioclase phenocrysts and amygdules. Some of the mafic rocks are probably dykes, but most of them are suggested to have formed as sills or extrusions (Geijer 1930a). A large intrusion of granite (Granite-pegmatite association) exists northwest of the deposit (Fig. 41), and the recrystallisation of the host rocks to the ores increases in that direction. Dykes of granite and

pegmatite are frequently found in the ores and their host rocks. Some of the pegmatites are rich in coarse-grained hematite, apatite, and titanite.

In the western and northern parts of the deposit the ores form an almost continuous horizon with a length of about 5 kilometres. These ores contain both magnetite and hematite, and apatite banding is a common feature. The eastern part includes several more or less isolated bodies of magnetite ore, which is generally less rich in apatite. The main gangue minerals are apatite, amphibole, pyroxene, and biotite. Pyrite, chalcopyrite, bornite, and molybdenite occur locally as accessories. The grain size is mostly 0.5 to 2 millimetres for the ore minerals, but larger porphyroblasts of magnetite occasionally occur in hematite ore.

The host rocks to the ores are mainly felsic in composition and often K-feldspar-rich. Albitic rocks are more locally encountered. Mafic rocks are usually biotite-rich and scapolite-altered. In the footwall to the western part of the deposit, gneiss consisting of sillimanite, muscovite, and quartz occurs. Tourmaline, microcline, and iron oxides occur in minor amounts, while andalusite, corundum, and barite are occasionally found in this rock (Geijer 1930a).

Various scales of brecciation are developed in the wall rocks of the ores. Especially ore bodies in the eastern part are surrounded by extensive breccias. Magnetite, apatite,

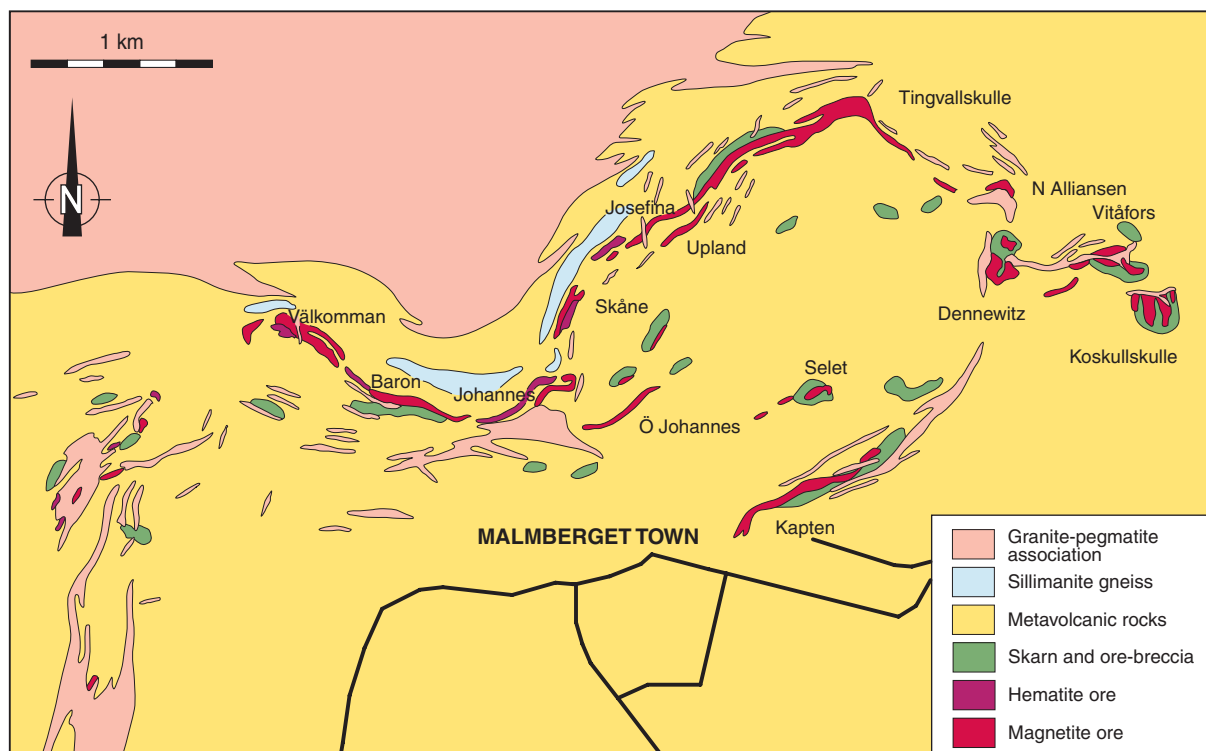


Fig. 41. Geological map of the Malmberget area (modified from Geijer 1930a). All rocks belong to the Porphyry group, except the rocks of the Granite-pegmatite association. Names refer to major ore bodies.

and amphibole are the main constituents of millimetre to metre-wide veins that form networks and breccias. Albite occurs in some amphibole breccias, with scapolite found locally in druses. Breccias with a high iron content are mainly found adjacent to the iron ores, while breccias dominated by amphibole are developed also at a distance from them. The breccias are often strongly flattened by ductile deformation and locally they transform into banded ore (Geijer 1930a).

The Malmberget deposit has been strongly affected by ductile deformation, and the large-scale structures were controlled by at least two phases of folding. The present shape of individual ore bodies is mainly a result of stretching parallel to a fold axis plunging 40 to 50° towards SSW. Many ore lenses are boudinaged in the plunge direction and some of the granite-pegmatite dykes exhibit a similar style of deformation (Geijer 1930a). These dykes are probably related to the Granite-pegmatite association, suggesting that the deformation is younger c. 1.8 Ga.

EPIGENETIC BASE METAL DEPOSITS

General characteristics

Sulphide occurrences of epigenetic origin are mainly found in the Greenstone group and in the Svecofennian metavolcanic rocks (Fig. 42). Most of them are dominated by copper, but some also contain considerable amounts of cobalt or gold. Mineralisations dominated by zinc and lead are less common and most of them are of vein-type, hosted by graphitic schist within the Greenstone group. However, the Kurkkionvaara zinc-lead deposit is hosted by clastic metasedimentary rocks belonging to the upper part of the older Svecofennian supracrustal rocks (Niiniskorpi 1986).

The largest number of epigenetic copper deposits has been found in the western part of the map area and in the Gällivare area, which may be a result of more extensive exploration in these areas. Only a few of the deposits are of economic importance, but several subeconomic ones, with c. 1 % Cu and more than 0.1 Mt of ore, have been discovered.

Deposits occurring in the Porphyry and Porphyrite groups are characterized by alterations comprised of K-feldspar, scapolite, commonly some tourmaline, and locally sericite. Strong albitisation is only locally developed and then mainly in association with intermediate to felsic intrusions. The main ore minerals are pyrite, chalcopyrite, and magnetite. Several deposits also contain bornite and minor amounts of molybdenite. Pyrite with a high cobalt content is the most important ore mineral in some deposits. Aitik is the largest and only economically

more important copper-gold deposit in the northern part of Norrbotten county, but there exist several subeconomic to potential occurrences (e.g. Liikavaara Östra, Pikkujärvi, Tjärrojåkka, Kiskamavaara, Ahmavuoma, and Lieteksavo). Several small deposits have been mined in the past in the Gällivare and Svappavaara areas (Nautanen, Liikavaara, Ferrum, Fridhem, and Gruvberget).

Deposits hosted by the Greenstone group are mainly of two types: the carbonate-quartz vein-type and the Pahtohavare-type. Vein-type mineralisations contain chalcopyrite or locally chalcocite in a gangue of quartz, ferro-dolomite, or calcite. Some deposits were mined in the 17th and 18th centuries but they are all of small size (Raggisvaara, Kovogruvan, Kurravaara, Pahtavaara). Most of them are hosted by mafic sills or basaltic lava, and ore-related alterations are mostly minor. Pahtohavare-type deposits are characterized by albitisation, scapolitisation, and locally carbonatisation. Pyrite and chalcopyrite are the dominant ore minerals and besides copper, gold may also be of economic significance. A weak enrichment of uranium is common in several occurrences. The only deposit of economic importance is the Pahtohavare deposit, which in many respects is similar to the Bidjovagge gold-copper deposit in northern Norway (Bjørlykke et al. 1987).

The Kiruna–Vittangi–(Soppero–Tärendö) area

A large number of epigenetic copper occurrences have been found in the Kiruna–Vittangi area. The first was discovered in 1654 at Gruvberget, near Svappavaara (Tenggren 1924). Deposits occur mainly within volcaniclastic parts of the Greenstone group, in metaandesite belonging to the Porphyrite group and in metabasalt from the lower part of the Porphyry group. Most of them are related to shear zones, or in some cases intrusions of intermediate to felsic composition. Two clusters of mineralisations can tentatively be identified. One occurs near Svappavaara along the Karesuando–Arjeplog deformation zone and the other extends from the Pahtohavare area and further westwards. Both clusters comprise mineralisations of varying character and different host rocks. Vein-type mineralisations are common within the Greenstone group in the Kiruna area and in the Kovo Group north of Kiruna. Some of the larger deposits occur rather isolated, which may be a result of limited exploration in their surroundings (e.g. Tjärrojåkka-Cu, Pikkujärvi).

Only a small number of more significant deposits are known further eastwards in the Soppero–Tärendö–Pajala area. Maunuvaara is a small copper mine from the 17th century, and Ahmavuoma is a subeconomic copper-gold-cobalt occurrence found in the 1980s.

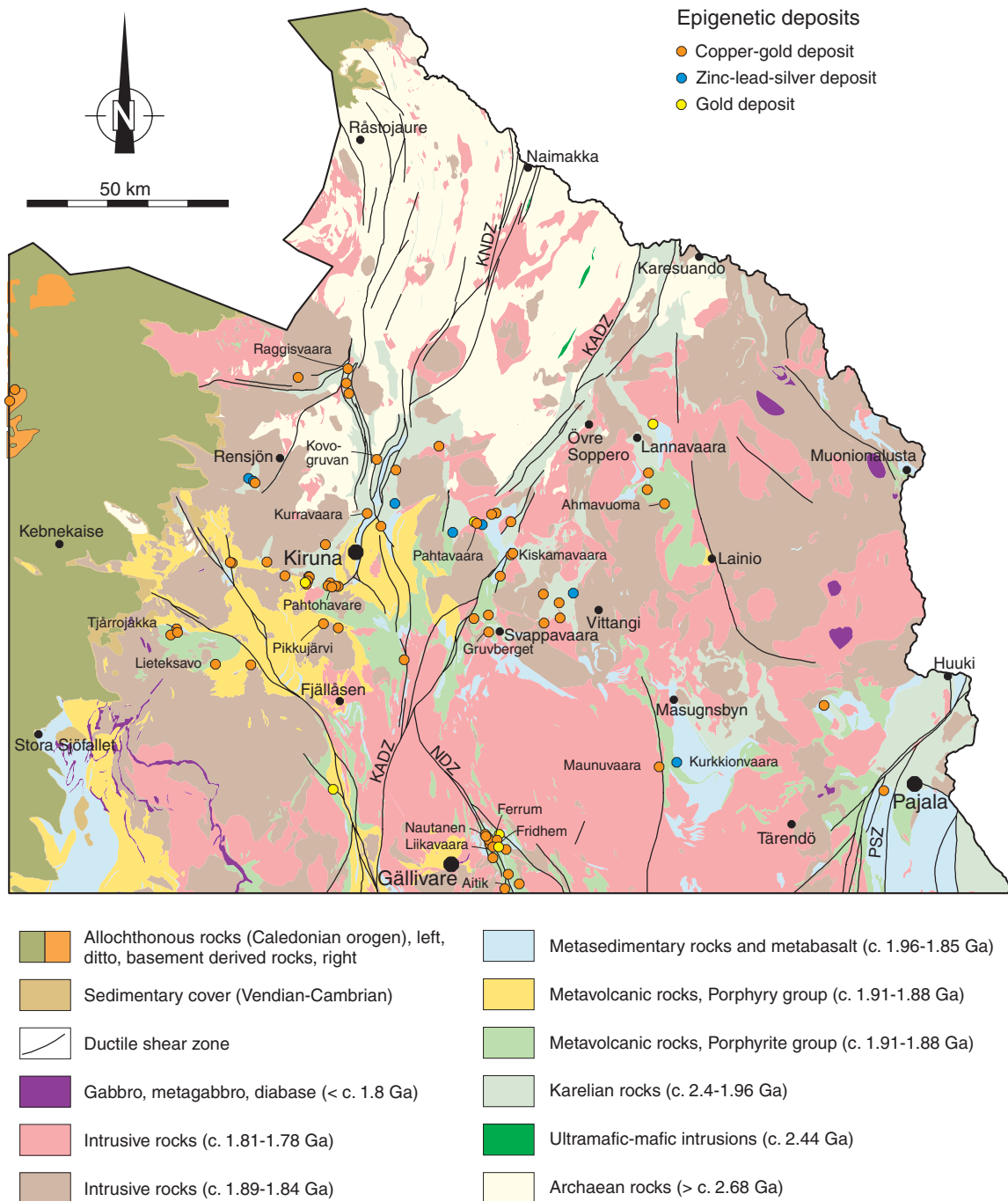


Fig. 42. Simplified bedrock map of the northern part of Norrbotten county, with occurrences of epigenetic deposits.

Pahtohavare

Exploration for Viscaria-type deposits (see p. 44) was initiated by NSG in the Pahtohavare area in 1984. In the same year the Östra Pahtohavare deposit, a stratiform-stratabound copper mineralisation of Viscaria-type, was found through drilling. During the subsequent drilling operations in the surroundings, auriferous sulphide mineralisations of a different type were encountered, and in 1987–1988 three lenses of copper-gold mineralisation

were found (the Södra Pahtohavare, Sydöstra Pahtohavare and Centrala Pahtohavare deposits). These mineralisations occur in an anticlinal structure of the Greenstone group 10 kilometres S of Viscaria (Fig. 43).

Open pit mining was started by Viscaria AB at the Södra Pahtohavare deposit in 1990 and at the Sydöstra Pahtohavare deposit in 1992, with a total production of 0.672 Mt and 0.114 Mt, respectively. In 1993 both ores were developed for underground mining. When the mines were closed in 1997, a total of 1.68 Mt of ore

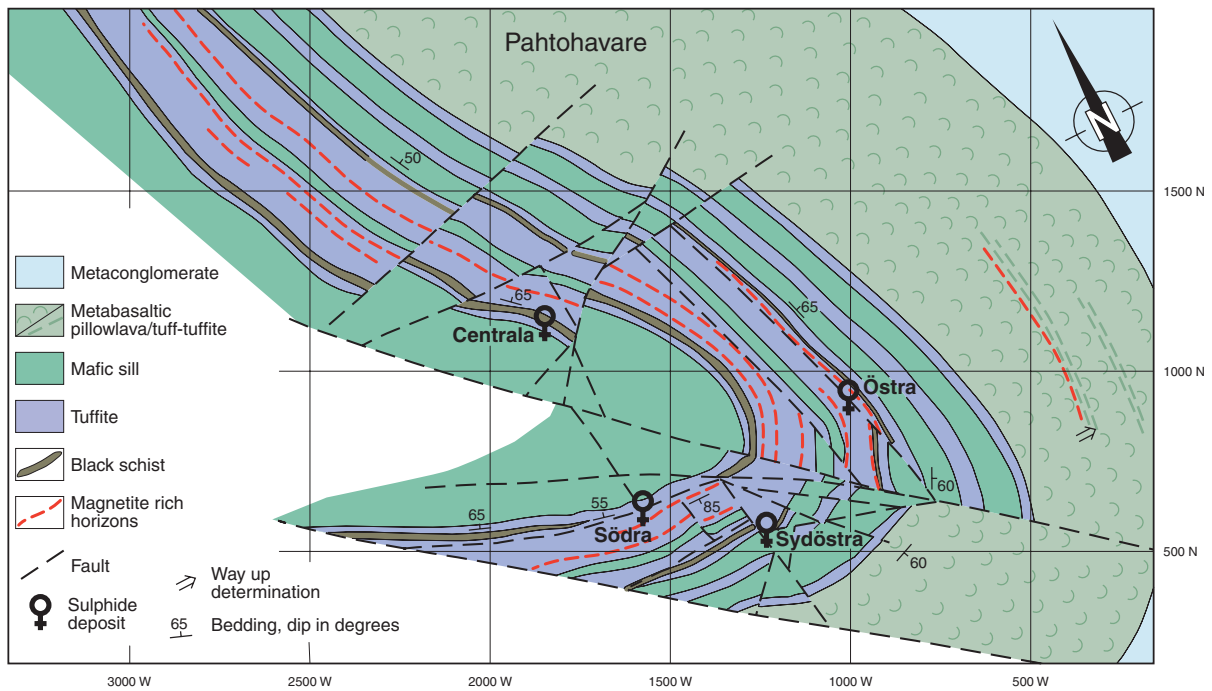


Fig. 43. Geological map of the Pahtohavare area (from Martinsson 1992). All rocks belong to the Greenstone group except the metaconglomerate, which belongs to the Older Svecofennian metasedimentary rocks. Local coordinate system in metres.

with 1.89 % Cu and 0.88 ppm Au had been produced from the open pits and underground (Martinsson et al. 1997b). The Södra Pahtohavare deposit had the largest ore body, with a maximum length of 270 metres and a thickness of up to 25 metres. It was mined in an open pit to a depth of 95 m, and then later underground. The Centrala Pahtohavare mineralisation is uneconomic due to its small size and the extensive supergene oxidation which has transformed the sulphides into an association of tenorite, cuprite, chrysocolla, malachite, and limonite-goethite.

All mineralisations at Pahtohavare are hosted by rocks of the Viscaria Formation, which form the core of an anticline enveloped by pillow lava. The SE-plunging anticline is truncated by a WNW-directed shear zone on its southern limb. The Södra and Centrala Pahtohavare ores occur in a similar stratigraphic position on the limbs of the anticline and are spatially affiliated with a thick black schist horizon. The Sydöstra Pahtohavare ore is situated near the overlying pillow lavas at the hinge of the fold (Fig. 43). The Södra Pahtohavare ore is mainly stratabound in character (Fig. 44), while the Sydöstra Pahtohavare ore has a more complex shape. A stratabound part of this ore occurs in mafic tuffite containing thin graphitic intercalations whereas a narrow discordant part follows a NNW-directed shear zone and is hosted by a mafic sill (Fig. 45). The discordant part is a vein, which partly has a mylonitic to cataclastic structure, and it is accompanied by albite-carbonate alteration. This part of the ore

is mostly high-grade and consists of coarse-grained ferro-dolomite, quartz, scapolite, albite, chalcopyrite, and pyrite in varying proportions (Martinsson et al. 1997b).

In stratabound mineralisations, ore grades of copper are mainly developed in albite felsite, which has formed by alteration of graphite schist. Chalcopyrite and pyrite are the dominant ore minerals, occurring disseminated as veinlets and breccia-fillings in the albite felsite, together with carbonate and some quartz. Accessory minerals are native gold, tellurobismuthite, melonite, hessite, and altaite. Both gold and the tellurides occur mainly as inclusions in chalcopyrite (Hålenius 1986, 1989). Copper and gold exhibit similar distribution patterns within the ores, suggesting a co-precipitation.

Several types of alteration are recognised at Pahtohavare, with albite, marialitic scapolite, biotite, actinolite, and ferro-dolomite as characteristic minerals. Less abundant are chlorite, tourmaline, and riebeckite. Most extensive is the biotite-scapolite alteration, which surrounds ore-bearing albite felsites.

An early albitisation of tuffite along the contact of mafic sills is overprinted by later ore-related alterations. The ore-related albite felsite and surrounding tuffite or black schist are usually interfingering, with highly irregular contacts in the direction of bedding. In detail, the contacts of the albite felsite are mostly gradual over a distance of some centimetres to decimetres, and they exhibit discordant relations to the primary layering. The albite felsite generally has an intergranular to granoblastic tex-

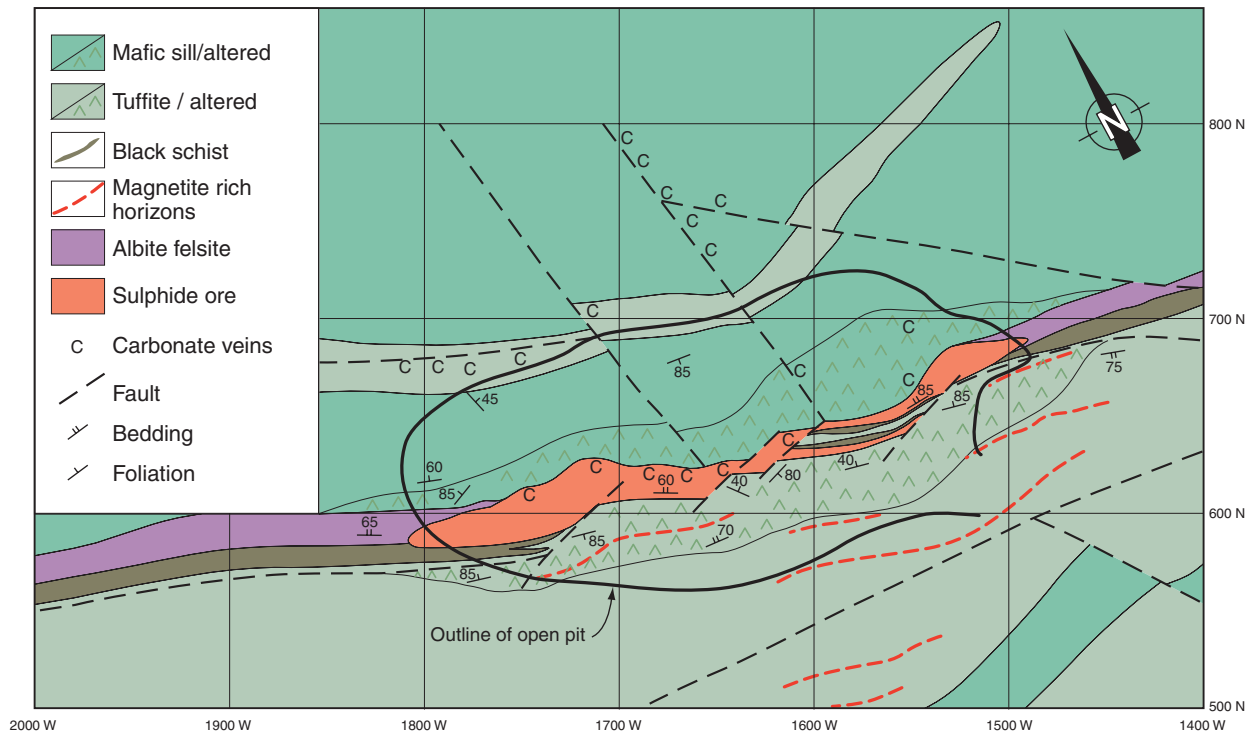


Fig. 44. Geological map of the Södra Pahtohavare deposit (from Martinsson 1992). All rocks belong to the Greenstone group. Local coordinate system in metres.

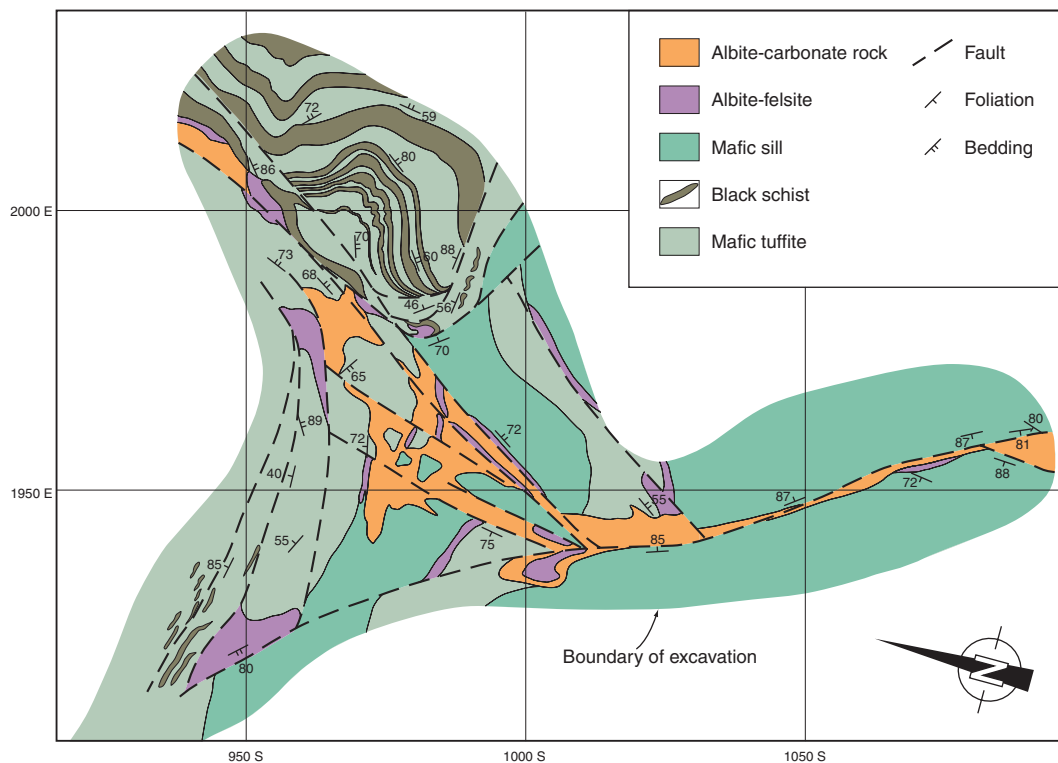


Fig. 45. Geological map of the Sydöstra Pahtohavare deposit (from Martinsson 1992). Ore is found in variable amounts in the albite-carbonate rock and in the albite felsite. All rocks belong to the Greenstone group. Local coordinate system in metres.

ture and a grain size of less than 0.05 millimetres. Ferro-dolomite occurs in varying amounts as a fine-grained dissemination or larger scattered grains. The composition of albite is near end-member composition, and the ferro-dolomite contains 8–11 wt % FeO (Martinsson et al. 1997b).

In both the Södra and Sydöstra Pahtohavare ore bodies, the ore-bearing albite felsite is surrounded by biotite-scapolite altered rocks. The alteration is more extensively developed in tuffs and tuffites than in mafic sills. Scapolite forms characteristic porphyroblasts and networks. Progressive alteration has caused a mineralogical change from amphibole-plagioclase-scapolite to amphibole-biotite-scapolite that resulted in a fine-grained biotite rock containing porphyroblasts of scapolite. The transition from biotite-scapolite altered rocks to the central core of albite felsite is usually gradual, with albite replacing biotite and scapolite in a narrow zone.

Scapolite veinlets are commonly deformed by folding and shearing, and in places they have a strong mylonitic texture. Carbonate veins consisting of coarse-grained ferro-dolomite or, more rarely, calcite are characteristic for the Pahtohavare area. Biotite is a minor constituent in some veins, and quartz or sulphides may be abundant. Accessory minerals are brannerite, rutile, orthite, xenotime, and minute grains of thortveitite. Carbonate veins containing sulphides are mainly restricted to the ore-bearing albite felsite. Veins rich in sulphides often have a cataclastic texture; otherwise most carbonate veins show little evidence of deformation.

The ores at Pahtohavare were formed from highly saline hydrothermal solutions (Lindblom et al. 1996) during repeated brittle to ductile deformation. The initial biotite-scapolite alteration and albitisation of graphite schist was followed by brittle deformation of the albite felsite. This created suitable chemical and structural traps for the metal precipitation (Martinsson et al. 1997b).

Tjärrojåkka-Cu

The Tjärrojåkka-Cu deposit is a subeconomic copper mineralisation situated 45 kilometres WSW of Kiruna, adjacent to a large apatite iron ore (the Tjärrojåkka-Fe deposit). Airborne magnetic measurements made in 1963 by SGU gave a strong magnetic anomaly at Tjärrojåkka. The area was subsequently investigated through geophysical ground measurements and drilling during the period 1965–1970. Boulders and some minor outcrops containing copper mineralisation were found in the same area and another drilling campaign was initiated on this copper prospect. Between 1970 and 1975, 62 holes in

total were drilled. The low-grade copper mineralisation is hosted by intermediate to felsic porphyritic volcanic rocks, metamorphosed at lower amphibolite facies (Ros 1979). The bedrock of the area is intruded by metadiabases, felsic porphyritic dykes, and diorite.

The Tjärrojåkka-Fe deposit is a blind ore with its top located immediately below the bedrock surface. It is known to a depth of 450 metres and calculated to contain 52.6 Mt of iron ore. Carbonate and apatite occur disseminated and as veinlets in the massive ore, which contains 60–67 % Fe and 0.5–1.3 % P. Actinolite is a minor and disseminated component, which also occurs as replacement of volcanic fragments. Veins and breccia ore of magnetite with 25–40 % Fe and 0.4–3 % P partly envelop the massive ore. Low-grade chalcopyrite disseminations are found in the wallrocks and locally in the massive ore; otherwise sulphides are rare.

Several mineralisations of copper are found in the vicinity of the Tjärrojåkka-Fe apatite iron ore. The largest, Tjärrojåkka-Cu, is situated 1 kilometre WNW of Tjärrojåkka-Fe and contains 1.75 Mt with 0.90 % Cu (cut-off 0.4 %) or 4.53 Mt with 0.58 % Cu (cut-off 0.2 %) (Frietsch 1991). Disseminated pyrite, chalcopyrite, and bornite occur together with apatite-magnetite veins in a more than 600 metres long zone at the contact between metaandesite and metadacite. The veins are usually dominated by apatite and contain 0–40 % magnetite, some actinolite, and locally chalcopyrite. Low-grade copper mineralisations associated with veins and breccias of magnetite are also found further to the west. Due to the close spatial association and the mineralogical similarities to the Tjärrojåkka-Fe deposit, a genetic relation is suggested for the apatite iron ore and the copper mineralisation at Tjärrojåkka (Martinsson 1995). Generally the copper mineralisations are low in most ore elements, except copper. However, a weak enrichment of molybdenum is locally found.

The most widespread alteration type in the Tjärrojåkka area is the formation of K-feldspar, giving the andesites a high K₂O (4.5–7.0 %) and barium (1 600–4 600 ppm) content. The most intense K-feldspar alteration is developed in the mineralised zone at Tjärrojåkka-Cu and near the copper mineralisations further towards the west (Martinsson 1995). Albitisation is mainly restricted to the apatite-magnetite-veined footwall to the copper mineralisation. Scapolite is common in the Tjärrojåkka area, and it is almost invariably developed as an alteration mineral in the metadiabases. Biotite generally accompanies scapolite. Rather extensive biotite-scapolite alteration is developed both in the copper mineralisation and in its hanging wall.

Pikkujärvi (Sierkavare)

The Pikkujärvi deposit was discovered in 1982 by LKAB and it represents one of the largest epigenetic copper deposits in the Kiruna area. The estimated tonnage is 5 Mt with 0.61 % Cu, or, using a cut-off of 1 %, 0.5 Mt with 1.19 % Cu (Frietsch 1991). The deposit is situated 20 kilometres SSW of Kiruna at the border of a 12 kilometres large quartz-monzonite, which has intruded amygdaloidal metabasalts and felsic porphyritic metavolcanic rocks belonging to the lower part of the Porphyry group. At the Pikkujärvi deposit, the metavolcanic rocks are intruded by porphyritic dykes, mafic dykes, aplite, and small satellite intrusions of monzonitic rocks.

The metabasalts are partly porphyritic with 3 to 10 millimetres large phenocrysts of plagioclase occurring in amounts of 10 to 15 %. The monzonite is reddish in colour and medium-grained. With increasing amounts of mafic minerals the rock grades into monzodiorite. Aplitic intrusions are generally quartz monzonitic in composition. Several southwest-trending dykes of metadiabase cut the mineralisation.

Chalcopyrite, pyrite and small amounts of bornite, molybdenite, and magnetite form several less well-defined mineralised lenses. The ore minerals occur irregularly disseminated or as veinlets in altered basalt and in the felsic intrusions. Veins of tourmaline and quartz are rather common, but they usually lack mineralisations. Copper is the only metal of economic interest, but cobalt, molybdenum, and gold are often slightly enriched in the mineralisation. Veins of magnetite are locally encountered in the surrounding areas.

Several types of alteration have affected the volcanic rocks. The most extensive is biotite-scapolite alteration, which is frequently also developed in the mafic dykes. Locally, the alteration has transformed the basalts into coarse-grained scapolite rocks. K-feldspar alteration occurs more restrictedly and mainly in spatial association with copper mineralisations. In many cases the alteration has completely obliterated the primary character of the basalt and changed it into a reddish feldspar rock resembling syenite. Tourmaline is common in some parts of the mineralisation. It occurs in veinlets and small patches, partly in association with strongly scapolitised rocks. Zeolites occur as late phases of the mineralisation event (Martinsson 1995).

Kiskamavaara

The Kiskamavaara copper-cobalt deposit has been investigated by SGU in several drilling campaigns during the period 1972–1980. The mineralisation is c. 650 metres long and is calculated to contain 3.42 Mt with 0.37 %

Cu and 0.09 % Co (Persson 1981). The deposit is situated together with several other epigenetic sulphide occurrences in the Karesuando–Arjeplog deformation zone. Andesitic metavolcanic rocks of the Porphyrite group and Younger Svecofennian quartzite dominate the bedrock in the Kiskamavaara area. The host rock to the Kiskamavaara deposit is a breccia, with sub-rounded clasts of intermediate metavolcanic rocks occurring in a matrix of fine-grained volcanic material and varying amounts of magnetite and hematite. Based on the composition and character of the breccia, a hydrothermal origin is favoured (Martinsson 1995).

Cobalt-bearing pyrite occurs together with some magnetite and chalcopyrite disseminated in the matrix of the breccia within the copper-cobalt mineralisation. Bornite and molybdenite are accessory ore minerals, whereas quartz and calcite are found in small amounts as gangue minerals. There are several richer lenses within the mineralisation where the composition of the matrix is almost massive pyrite. In most cases the ore minerals change from pyrite in the central part of the mineralisation to magnetite and hematite in the peripheral parts (Martinsson 1995). The cobalt content of the pyrite varies between 0.3 and 1.3 % (Ekström 1978).

Several types of alterations, including scapolitisation, K-feldspar alteration, and sericitisation, have affected the bedrock in the Kiskamavaara area. Albite alteration is locally developed on the eastern margin of the mineralised breccia, and scapolite occurs together with biotite in the surrounding volcanic rocks. The host rock to the deposit exhibits a strong K-feldspar alteration, resulting in high K₂O (7.1–11.6 %) and barium (0.25–0.64 %) contents (Martinsson 1995). Sericite is locally developed and occurs together with small amounts of tourmaline as a late alteration assemblage.

Lieteksavo

A small but rich copper mineralisation was discovered by LKAB in 1981 through drilling at Lieteksavo, which is situated 43 kilometres southwest of Kiruna. The bedrock in the area comprises the upper part of the Porphyrite group and the lower part of the overlying Porphyry group. Some metadiabases and a shear zone occur sub-parallel to the general bedding (Fig. 46). The Porphyry group in the area consists of amygdaloidal lava of basaltic to andesitic composition. A heterogeneous unit of volcanoclastic metasedimentary rocks, partly rich in chlorite and amphibole, occurs at the base of the Porphyry group. This thin basal unit is overlain by a several kilometres thick succession of amygdaloidal and partly porphyritic basaltic to andesitic lavas, which contain minor intercalated felsic units.

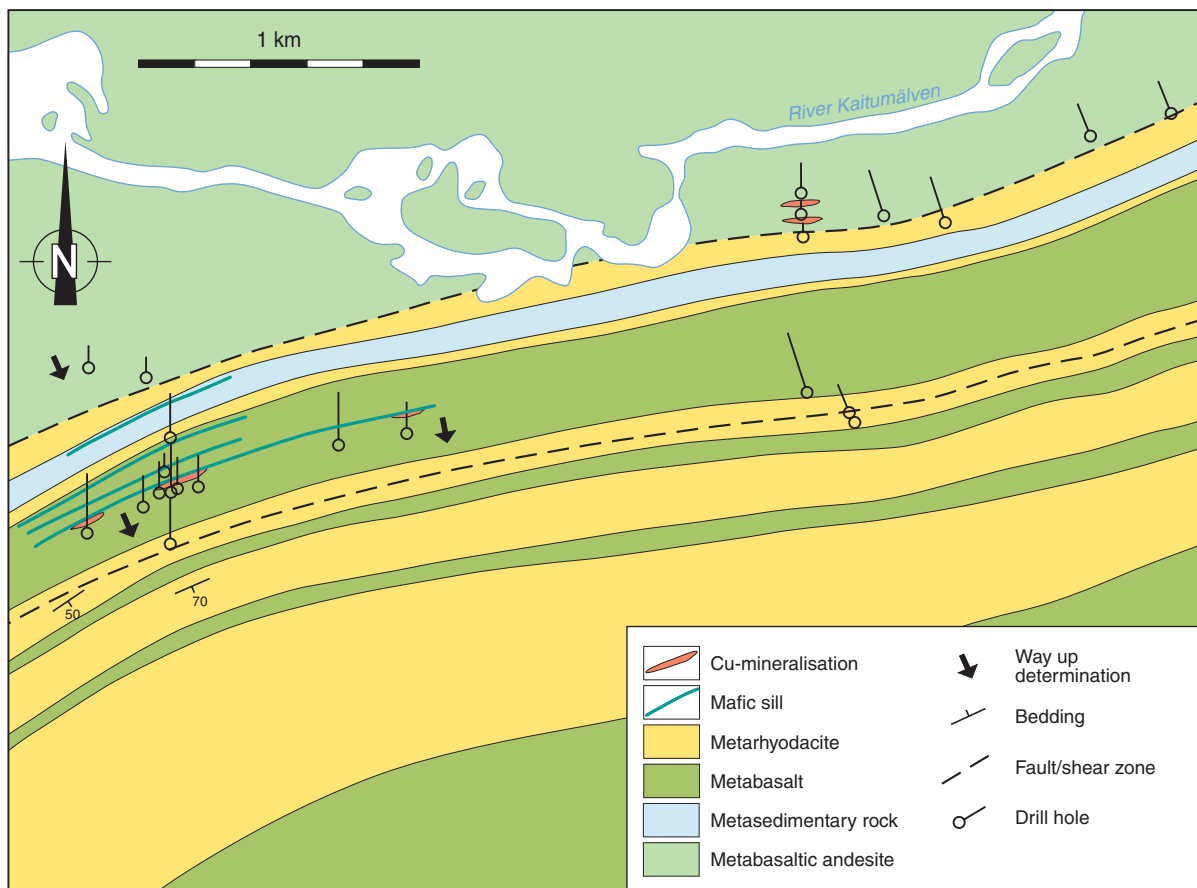


Fig. 46. Geological map of the Lieteksavo area (from Martinsson 1994). The metabasaltic andesite belongs to the Porphyrite group whereas the metabasalt and metarhyodacite belong to the Porphyry group.

The Lieteksavo deposit consists of quartz-tourmaline veins with bornite, chalcopyrite, and some molybdenite. The veins are up to 5 metres wide and are mainly hosted by an 80 metres thick metadiabase. A lens of rich mineralisation has been calculated to contain approximately 50 000 ton with 6.8 % Cu, 1.3 ppm Au, and 46 ppm Ag (Frietsch 1991). Several small copper mineralised quartz-tourmaline veins exist in the surrounding area.

The quartz-tourmaline veins are generally enveloped by intense scapolitisation. For thicker veins, the scapolite alteration locally extends several metres away from the contact. Similar alterations are found around quartz-tourmaline veins in the Nautanen area at Gällivare. Scapolite-biotite alteration is commonly also developed in the metadiabase and to some extent in the metavolcanic rocks (Martinsson 1995).

Gällivare area

The mineral potential of the Gällivare area was first recognised in the 18th century, when iron deposits were found. When the railway from Luleå was built in 1888 to exploit the large iron ore deposits, extensive explo-

ration activities for other deposits were initiated in the surrounding areas. In 1898, copper ore was discovered at Nautanen and within a few years, a number of copper mineralisations had been found northeast and east of Gällivare. The AB Nautanens Kopparfält company was founded in 1900 and mining started in 1902, but lasted only until 1907 (Geijer 1918a). Some other small copper mines (Liikavaara, Snållkok, and Ferrum) were active during the same period in the Nautanen area, and one prospector ran a small gold mine (Fridhem). The Aitik deposit was discovered in 1932 by drilling on geophysically indicated targets in an area where a rich ore boulder and a mineralised outcrop had been found. Further drilling was performed in 1960–1965, which delineated a low-grade but large copper ore suitable for large-scale open pit mining (Malmqvist & Paransis 1972, Zweifel 1976). Mining started in 1968 with an annual production of 2 Mt, which has successively increased to c. 18 Mt in 1999.

Most of the copper deposits in the Gällivare area are hosted by Svecofennian arenitic to argillitic metasedimentary rocks of volcanic origin. These rocks are intruded by diorites (Haparanda and Perthite monzonite

suites) and c. 1.8 Ga old granites and pegmatites. The ore deposits occur within, or close to, the Nautanen deformation zone (see the chapter on "Ductile shear zones", p. 80). The deformation zone is more than one kilometre wide and consists of several steeply dipping subparallel branches of high strain. Extensive alterations are developed along the shear zone, including K-feldspar alteration, scapolitisation, sericitisation, and tourmalinisation. Deposits within areas of high strain are mostly disseminated (e.g. Aitik, Nautanen), while deposits in other areas are mainly of vein-type (e.g. Ferrum, Fridhem).

Aitik

Aitik is Sweden's largest sulphide mine and one of Europe's most important copper and gold producers. The annual production is c. 18 Mt of ore containing 0.4 % Cu, 0.2 ppm Au, and 4 ppm Ag. By the end of 1999 about 322 Mt of ore had been produced from a c. 2 000 metres long and 315 metres deep open pit. Mineralisation is proved to a depth of 800 metres in the northern part but ceases about 400 metres below surface in the southern part.

Aitik is situated near the Nautanen deformation zone. Since Zweifel's (1976) description of the ore and its host rocks, additional data has been contributed by Yngström et al. (1986), Monro (1988), Drake (1992), and Wanhainen & Martinsson (1999). The host rocks to the ore are comprised of biotite-sericite schist or gneiss and amphibole-biotite gneiss (Zweifel 1976, Monro 1988). The original character of these rocks is unclear, due to strong deformation and alteration. However, the chemical characters of the rocks suggest a magmatic precursor of intermediate composition, and based on the knowledge from areas outside the mine a volcanoclastic origin is favoured (Wanhainen & Martinsson 1999). A slightly deformed porphyritic quartz monzodiorite intrusion occurs in the footwall to the ore zone, and undeformed pegmatite dykes crosscut the ore zone and the hanging wall units (Fig. 47). The quartz monzodiorite has a U-Pb zircon age of c. 1.87 Ga, while a pegmatite has yielded a U-Pb monazite age of 1.75 Ga (SGU, unpublished results, age figures presented by Witschard 1996, see Table 1).

Chalcopyrite, pyrite, and pyrrhotite are the main ore minerals, and they occur disseminated and in veinlets within the ore zone. Veins consisting of quartz, sulphides and, in places, tourmaline are common and contribute to locally higher ore grades. Barite veins are partly abundant and many of them contain varying amounts of pyrite, chalcopyrite, magnetite, and amphibole (Zweifel 1976, Monro 1988, Wanhainen et al. 1999). Pegmatite dykes within the ore zone are often mineralised and some of

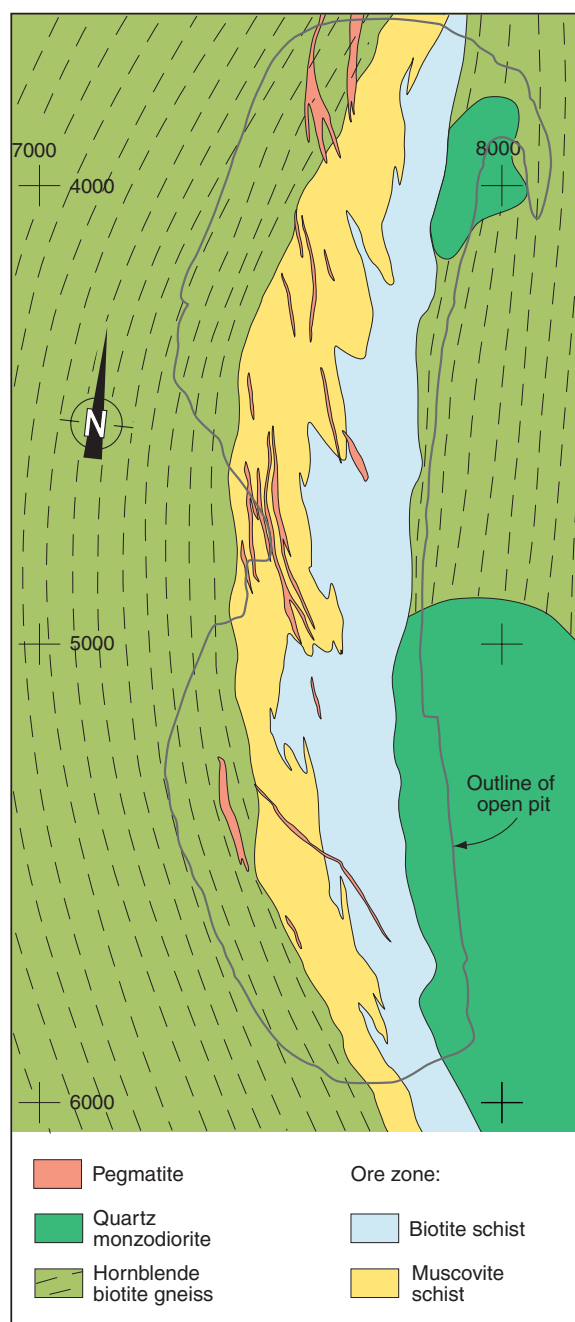


Fig. 47. Geological map of the Aitik deposit (from Wanhainen & Martinsson 1999). The open pit is outlined in black. The quartz monzodiorite belongs to the Perthite monzonite suite and the pegmatites belong to the Granite-pegmatite association. Local coordinate system in metres.

them are rich in copper. Molybdenite is a minor constituent, occurring mainly in pegmatite dykes and quartz veins. Desmine and chabazite, locally together with sulphides, represent late mineralisation phases. These zeolites occur as crystals in drusy vugs in some of the pegmatite dykes and quartz veins. Mineralisation of copper extends in subeconomic grades into the footwall quartz monzodiorite, while the hanging wall contact of the ore is sharp and tectonically controlled (Drake 1992).

Like the ore minerals, the alteration minerals present within the ore zone were probably formed during several generations of hydrothermal activity. The most extensive form is biotite alteration, which is often accompanied by a growth of garnet porphyroblasts. Towards the hanging wall, sericite becomes an important mineral, forming sericite schist rich in pyrite (Zweifel 1976, Monro 1988). K-feldspar alteration and epidotisation are most extensive along the footwall contact, but occur locally within the ore zone and the hanging wall. Tourmalinisation is less common and mainly restricted to the immediate wall rocks of quartz-tourmaline veins and some pegmatites. Scapolitisation and formation of amphibole-pyroxene veinlets are features of minor importance.

The Aitik copper-gold ore has been interpreted as a deformed and metamorphosed equivalent to porphyry-copper deposits (Yngström et al. 1986, Monro 1988). The mineralised quartz monzodiorite in the footwall to the ore is suggested to represent an apophysis from a larger intrusion at depth, which is in accordance with this genetic interpretation (Drake 1992). However, not all the features of the ore are typical for porphyry systems and it might have another or more complex origin (Wanhainen et al. 1999). Probably several phases of remobilisation occurred and possibly also additional overprinting mineralisation events.

Nautanen

At Nautanen the bedrock is partly well-exposed and most of the ore bodies were found in outcrops. During the period 1902–1907, 71 835 tonnes of ore containing 1–1.5 % Cu and some gold were mined in open pits and underground (Geijer 1918a). The most productive mines were Max, Anna, and Maria. The economic potential of the Nautanen area was later investigated by SGU in several campaigns during the years 1966–1979 and by NSG-SGAB (Sveriges Geologiska AB) in 1983–1985. These drillings located an ore lens 100 metres below the surface adjacent to the Max mine. It is calculated to contain 0.63 Mt with 2.36 % Cu, 1.3 ppm Au, and 11 ppm Ag (Danielsson 1985). The Nautanen area has recently been drilled by North Atlantic Natural Resources AB (1997–1998).

The geology of the Nautanen area and its ore deposits was first described by Geijer (1918a), and later detailed mapping and core drilling have added further data (Ros 1980, Danielsson 1984, 1985, 1987). The deposit is hosted by strongly altered and deformed rocks within the Nautanen deformation zone. Several lenses of copper ore have been mined. They consist mainly of chalcopyrite in association with magnetite and some pyrite occurring disseminated or as massive vein-like mineralisation.

Ore minerals found in accessory amounts are sphalerite, galena, carrollite, bismuthinite, molybdenite, and scheelite (Hålenius 1983). Bornite and chalcocite are found in minor amounts in the southern part of the area, partly occurring in vuggy veins together with desmine. Magnetite is often the major ore mineral, partly forming almost massive lenses and pods in association with amphibole-pyroxene-epidote skarn and garnet. Fine-grained tourmaline-quartz veins surrounded by intense tourmalinisation in several metres wide zones are characteristic for the western part of the Nautanen area (Geijer 1918a). Gold is a minor constituent of the ores, and a weak enrichment of cobalt, zinc, silver, molybdenum, and tungsten is commonly developed. There is generally a good correlation between copper and gold, and high gold values are rarely found without significant copper mineralisation.

The original character of the host rock is obscured by strong alteration and deformation. Probably the precursors were volcanogenic sedimentary rocks with a mainly intermediate composition, as less deformed clastic meta-sedimentary rocks of partly volcanogenic origin are found on both sides of the Nautanen deformation zone. Alterations are dominated by scapolite, microcline, biotite, sericite, garnet, amphibole, epidote, and tourmaline. There is roughly an E–W mineral zoning, with scapolite dominating in the east, followed by garnet-biotite-microcline in the central part and sericite-garnet-tourmaline towards the west (Geijer 1918a). The altered rocks have a high K₂O (5.4–9.4 %) and barium (0.12–0.50 %) content, due to the occurrence of microcline and biotite, which contain 1.2 and 2.1 % Ba respectively. Manganese is often enriched in the altered rocks and this element is mainly incorporated in garnet (Ros 1980).

A strong and steeply dipping foliation is developed in a NNW direction. A foliation in a NNE direction occurs locally. The occurrence of rotated garnet porphyroblasts and boudinaged tourmaline veins indicates the mineralisation and alteration to be pre- to syntectonic (Ros 1980).

Ferrum (Nietsajoki) and Fridhem

The Ferrum and Fridhem deposits are of vein-type and were worked on a small scale in the early 1900s. They are situated east of Nautanen in an area dominated by volcanogenic sandstones and argillites metamorphosed to middle–upper amphibolite facies. The deformation style is characterized by open folds plunging towards the SE.

The Ferrum deposit was discovered in 1902 and mined on a small scale from two shafts called 3:an and 4:an. The 4:an mine is largest, with a depth of c. 20

metres. During 1966–1969 the Ferrum area was investigated by means of detailed mapping, geophysical ground measurements, and 6 drill holes. Narrow zones of copper-gold mineralisation were intersected close to the existing mines, and the best section contained 1.45 % Cu on a core length of 13.87 metres (Ros 1980). Veins of quartz, quartz-tourmaline, or quartz-microcline-pyroxene-amphibole-calcite contain chalcopyrite and bornite in varying proportions. Molybdenite and bismuthinite are accessory minerals, and desmine is locally found as a late phase of the mineralisations. The quartz veins are mainly unaffected by deformation, while veins containing microcline-pyroxene-amphibole locally show evidence of ductile deformation. Most veins are parallel to a vertical NNE-directed foliation (Ros 1980, Gustavsson & Johansson 1984).

At the 4:an mine, mineralised quartz veins up to 1 decimetre wide are surrounded by zones of intense tourmalinisation. The altered rock consists of fine-grained tourmaline and quartz, together with small amounts of disseminated chalcopyrite, pyrite, and locally bornite. At the 3:an mine, the mineral composition of the ore veins is more variable, and the main sulphide is bornite. The host rock is affected by scapolitisation and many veins are enveloped by a massive scapolite zone containing some tourmaline (Geijer 1918a).

At Fridhem, a 16 metres deep shaft was sunk through a set of parallel quartz veins, the largest one 2 metres wide. The mine was worked for gold only, and the mineralisation consists of some chalcocite, small amounts of bornite, hematite, and native gold. The richest gold mineralisation was found in narrow and drusy quartz veins, containing chalcocite, calcite, and crystals of hematite, desmine, and chabazite. The wall rocks are altered by tourmalinisation and scapolitisation similar to that of the Ferrum deposit (Geijer 1918a).

OTHER METAL DEPOSITS

No economically significant metal deposits of orthomagmatic origin have been discovered in the northern part of Norrbotten county, although a number of mineral occurrences hosted by plutonic rocks have been discovered. A few titanium-vanadium-iron mineralisations exist in mafic intrusions (e.g. the Akkavare and Airikurkkio deposits), and small amounts of nickel sulphides have been found in a few mafic to ultramafic intrusions. Molybdenite occurs disseminated in some granitoids and pegmatites (e.g. the Nunasvaara, Vähävaara, and Äggojaure deposits), but the contents are mostly low.

The Akkavare (Melko) iron-titanium-vanadium occurrence was probably discovered in the late 1890s. It is

situated 40 kilometres W of Gällivare in an area dominated by granite intrusions. In 1957–1958 the deposit was investigated using magnetic measurements and diamond drilling (14 drill holes) by Stora Kopparbergs Bergslags AB, while airborne magnetic measurements, gravimetric and electromagnetic ground surveys were made in 1965–1968 by SGU (Frietsch 1997). The host rock is a noritic gabbro (Perthite monzonite suite) consisting of plagioclase, pyroxene, magnetite, ilmenite, hercynite, apatite, biotite, and small amounts of pyrrhotite, pyrite, and chalcopyrite. The amount of magnetite and ilmenite is up to c. 30 %, and the apatite content varies between 2 and 10 % (Geijer 1930b). The intrusion is 5.8 kilometres long and 0.6 kilometres wide. The richest mineralisation is found in the northern part, with 25.9 % Fe and 4.3 % Ti in a 27 metres long core section (Frietsch 1997).

Diamond drilling and magnetic ground surveys were carried out by LKAB at Airikurkkio, 9 kilometres NW of Vittangi, in 1982–1983 after the discovery of an outcrop containing mineralised rocks with a high vanadium content. The mineralisation occurs in the central part of a tholeiitic sill, which has intruded rocks of the Greenstone group. Similar sills are common in the Greenstone group in the Nunasvaara area further towards the southwest. Within the c. 100 metres thick sill, disseminated titaniferous magnetite occurs enriched in a 5–10 metres wide zone. The best core section contained 30.9 % Fe, 4.0 % Ti, and 0.64 % V₂O₃ on a length of 6 metres (Lehto 1983).

The Nunasvaara molybdenum occurrence, 3 kilometres E of Gällivare, was first encountered in outcrop in 1953 and has subsequently been investigated through drilling. The mineralisation is hosted by pegmatite and felsic gneiss in the outer part of a gabbro of the Perthite monzonite suite. It is estimated to be 100 metres long and on a width of 6 metres it contains 0.3 % Mo (Ödman 1957, Grip & Frietsch 1973).

Disseminated molybdenite and some pyrite were found in 1971 by SGU in outcrops of aplitic granite at Äggojaure, in the northernmost part of the map area. The granite (Granite-pegmatite association) intrudes Archaean gneiss, and the top of the intrusion is exposed at the present erosion level. Quartz veins are common in the granite and the surrounding rocks. The veins contain fluorite, molybdenite, pyrite, and some scheelite. Molybdenite is also disseminated in the granite, especially along the quartz veins. Magnetic ground measurements and geochemical sampling were carried out in 1973–1974 and ten holes were drilled in 1980. The result was negative, with the highest grade being 0.05 % Mo on a 2 metres section (Gerdin & Minell 1981).

Several mafic to ultramafic intrusions north of Kiruna

(e.g. the c. 2.44 Ga old intrusions at Keukiskero, Kurkovare, and Ruutusåive, and the Tjabrak intrusion of the Perthite monzonite suite) have been explored for nickel, chromium, and platinum group elements (PGE) without success. Small amounts of disseminated nickel sulphides have been found at Tjabrak and Ruutusåive, and chromite occurs as an accessory mineral at Kurkovare. Low grades of PGE (0.22 to 0.34 ppm Pd) have been detected at Tjabrak (Hansson 1987) and Kurkovare (Lilljequist 1980).

A small amount of Li-minerals (elbaite, lepidolite) exists in a pegmatite at Suorravaara, east of Gällivare, and spodumene has been found in a pegmatite southeast of Kiruna (Dahlman 1971). Beryl is known as an accessory mineral in pegmatites in the Tärendö, Kiruna, and Ultevis (W of Gällivare) areas. Only at Juoråive has minor work been done to determine the potential of the deposit (Ödman 1947, Dahlman 1971).

Rare earth elements (REEs) are strongly enriched in the apatite iron ores and locally also in other types of mineralisations. The apatite iron ores are generally dominated by the light REE and they have a total REE content of 0.1 to 1 % (Parák 1973a, Frietsch & Perdahl 1995). Monazite, occurring as small inclusions in apatite, may be the major REE carrier at Kiirunavaara (Parák 1973a). Orthite is another light REE mineral found in some apatite iron ores (Geijer 1910, Frietsch 1966, 1974).

During the exploration campaign for uranium in the 1970s, only minor work was done in the northern part of Norrbotten county. Small mineralisations of pitchblende with no economic significance were detected in the Kiruna area (e.g. at Nukutusvaara and Kovogruvan). Uraninite with an age of c. 1.8 Ga occurs in small amounts in chondrodite skarn from the Magnetgruvan iron ore at Masugnsbyn, and in scapolite skarn together with molybdenite and chalcopyrite at Äijärova, 13 kilometres WSW of Vittangi (Welin & Blomqvist 1966).

INDUSTRIAL MINERAL DEPOSITS

Except for the production of apatite during World Wars I and II, production of industrial minerals was negligible until the 1970s, when LKAB started production of quartz (at Nukutusvaara and Hopukka) and dolomite (at Masugnsbyn). The local need for industrial minerals is mainly as an additive for pellet production at LKAB, and, depending on pellet quality, magnesium silicates (olivine, serpentine), carbonates (calcite, dolomite), or quartz are used. With the exception of calcite and olivine, local resources have been used. However, several other potential industrial mineral deposits have been docu-

mented in the map area, including graphite, talc, mica, clay, aluminum silicates, diatomite, and barite (Fig. 48).

Graphite

The discovery of graphite in the Vittangi area in 1898 was the starting point for extensive exploration for graphite in the beginning of the 20th century (Geijer 1918b). Since then, graphite schists have been found in many other places within the northern part of Norrbotten county. Most occurrences are hosted by the Greenstone group, but graphite schists are also found in the overlying Svecofennian metasedimentary rocks. Within the Greenstone group, graphite schists mainly occur as two units: one in the middle part and one in the upper part of the succession. The lower unit is generally 10 to 20 metres thick and poor in sulphides. In the Kiruna area it contains c. 10 % graphite, while in the Vittangi–Tärendö–Pajala area the graphite content is between 10 and 45 %. Graphite schists in the upper unit are, with a few exceptions, generally richer in sulphides and poorer in graphite compared to the schists of the lower unit.

A folded, almost continuous graphite schist horizon can be followed for c. 15 kilometres at Nunasvaara, west of Vittangi. It belongs to the lower graphite unit and is partly intruded by mafic sills. Although large tonnages have been proven through trenching and drilling, the fine-grained character of the graphite has prohibited commercial production. Generally the grain size is less than 0.06 millimetres, but it may reach up to 1 millimetre in some areas. The Nunasvaara Stadsgruvefält is the most well-investigated part, and on a length of 700 metres the graphite schists have a width of c. 20 metres and an average graphite content of 21.0 %. Using a cut-off of 25 % C it contains about 1.1 Mt with 27.8 % graphite and 3.1 % S to a depth of 70 metres (Bergström 1987).

There have been several attempts to utilise the graphite schists, including production of amorphous graphite and use as fuel. Some thousand tonnes of graphite schist were quarried and tested as fuel for heat production in Kiruna in 1982. From the Nybrännan graphite deposit in the Greenstone group SE of Masugnsbyn, 1 964 tonnes were produced by Norrbottens Järnverk AB for metallurgical use in 1955–1958.

In 1990–1992 several occurrences of Svecofennian graphite schists in the Pajala–Tärendö area (the Jalkunen, Tiankijokki, Lehtosölke, and Liviövaara deposits) were investigated for possible production of flaky graphite (Gerdin et al. 1990, Holmqvist et al. 1991, Sahlstedt & Claesson 1996). These deposits are all affected by middle to upper amphibolite facies metamorphism. The grain size of the graphite is mostly less than 0.1 millimetre,

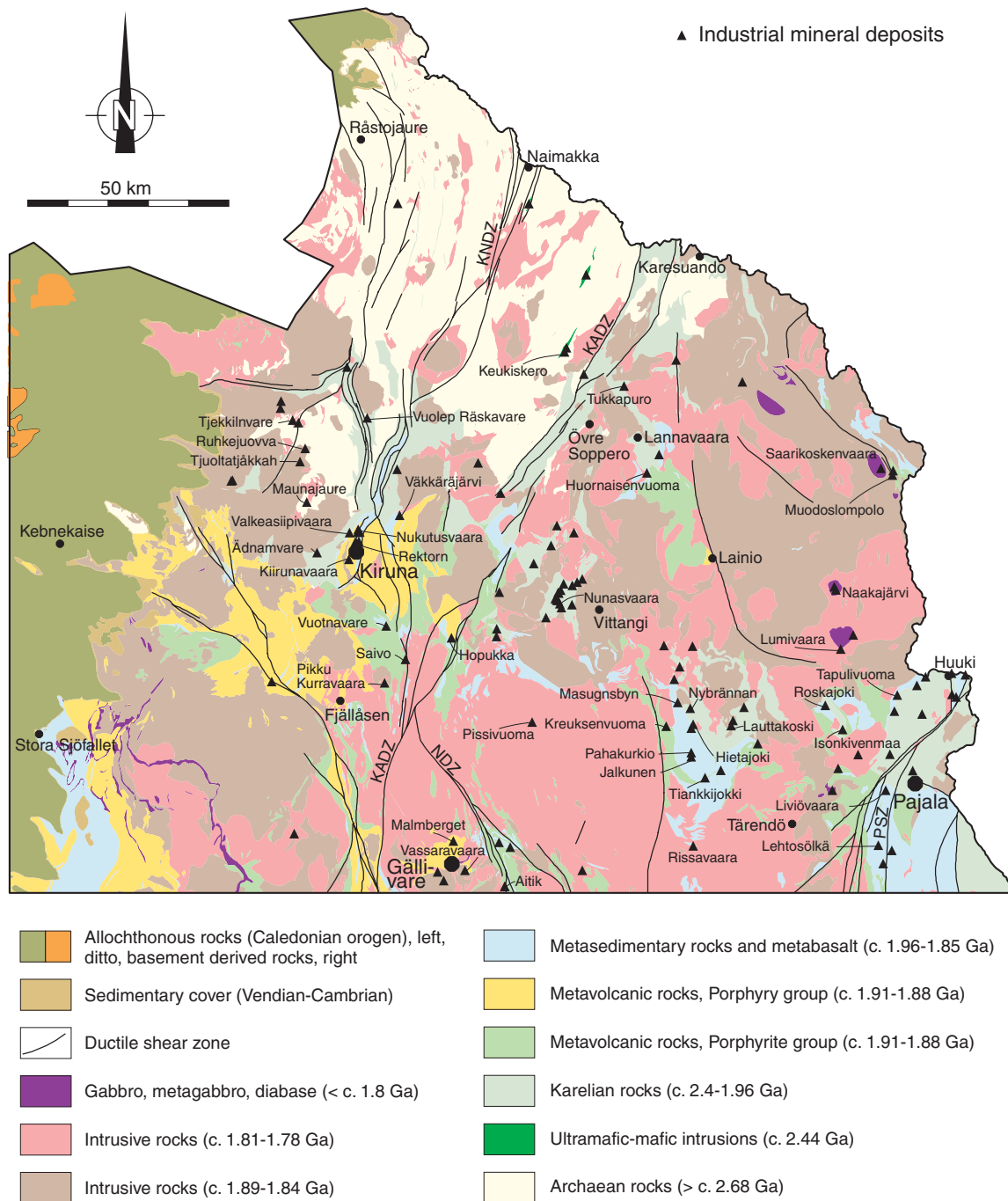


Fig. 48. Simplified bedrock map of the northern part of Norrbotten county, with occurrences of industrial minerals.

with the content varying from 12 to 40 %. For Lehtosölke the estimated tonnage to a depth of 40 metres is 1.72 Mt with 12.3 % C (Sahlstedt & Claesson 1996).

Carbonate

Carbonate rocks occur at several stratigraphic levels within the Greenstone group, but also locally in Svecofenian metasedimentary rocks. Many of them have been investigated through mapping and sampling (Kihlstedt

et al. 1974, Shaikh et al. 1989). In the Kiruna area, a 50–150 metres thick carbonate unit occurs in the lowest part of the Greenstone group. It is mostly dolomitic and high in silica. Carbonate rocks in the middle part of the Greenstone group are generally thin and impure. Either calcite or dolomite may be the dominant carbonate species. Especially in the eastern part of the map area, dolomitic carbonate rocks commonly form the top of the Greenstone group. They have an economic potential due to their often high purity and great thickness. Svecofen-

nian carbonate rocks exist in the Tianskijokki area and possibly east of Gällivare. They are up to 50 metres thick and partly rather pure.

Large occurrences of pure dolomite within the upper part of the Greenstone group exist north of Kaunisvaara (Tapulivuoma), at Käymäjärvi (Isonkivenmaa, Roskajokki and Käymäjärvi), in the Masugnsbyn area (Masugnsbyn and Hietajokki), and in the Lannavaara area (Tukkapuro and Huornaisenvuoma). They have thicknesses of 200 to 300 m, and most of them occur stratigraphically above banded iron formations or in close association with skarn-rich iron formations.

Only the Masugnsbyn deposit has been quarried on an industrial scale. Larger scale production started in 1952, and up until 1972 about 0.34 Mt had been used for metallurgical purposes by Norrbottens Järnverk AB (Shaikh et al. 1989). Since 1977 LKAB has used the dolomite as an additive in pellets, and by the end of 1999 they had produced additionally c. 1.8 Mt of dolomite. Production at Masugnsbyn will stop in 2003 and a new quarry is planned at Hietajokki 7 kilometres towards the SE.

Quartz

Potential resources for quartz are quartzite, pegmatites, and quartz veins. Quartzites with high purity are rarely found. Two Archaean occurrences exist northwest of Kiruna (Maunajaure and Tjekkilnvaure), but neither of them have been investigated in detail. One sample containing 96.9 % SiO₂ exists from Maunajaure (Ödman 1957). At Rissavaara, between Tarendö and Gällivare, quartzites of an unclear stratigraphic position have contents of SiO₂ that vary between 92 and 99 % (Dahlman 1971).

Quartz has been produced by LKAB as an additive to pellets at the Nukutusvaara and Hopukka deposits. Both deposits are located in quartzites from the stratigraphically uppermost metasedimentary unit in the Kiruna area. These rocks are dominated by metaarenites varying from quartzite to feldspathic quartzite with minor intercalations of metaconglomerate. The Nukutusvaara deposit was in production between 1969 and 1974, and at the Hopukka deposit 1.14 Mt of quartzite containing c. 94 % SiO₂ were produced in 1974–1982.

Small amounts of quartz have been quarried for silica production from pegmatites in the Gällivare area (Vassaravaara and Varkhanvaara). The Vassaravaara deposit is situated in a gabbro SE of Gällivare, and between 1955 and 1956 1 735 tonnes of quartz and 511 tonnes of feldspar were produced. During the later part of the 1980s some pegmatites and quartz veins in the map area were investigated for the production of ultra-pure quartz

(Holmqvist et al. 1989). Several occurrences were sampled (Pikku Kurravaara, Lumivaara, Muodoslompola, Vuolep Räskaavare, and Saarikoskenvaara). Vuolep Räskaavare is situated northwest of Kiruna and has been investigated by means of trenching and diamond drilling (10 drill holes). The deposit consists of a c. 20 metres wide and at least 260 metres long quartz vein within Archaean granitoids. Minor constituents of the vein are ferro-dolomite and actinolite, occurring mainly along the contacts of the vein (Holmqvist & Nordström 1986). At Naakajärvi, high quality quartz has been found in a pegmatite intruding a ring gabbro complex. The deposit has been investigated by LKAB and SGAB using magnetic ground measurements, trenching, and percussion drilling. It consists of several lenses with an area of up to 1 000 m² and the estimated reserve is 8 300 tonnes of quartz (Hålenius & Einarsson 1989).

Magnesium silicates (asbestos, talc, serpentine, olivine, pyroxene)

In general, deposits of rocks containing magnesium silicates can be divided into mafic to ultramafic intrusive complexes, peridotitic intrusions, komatiites, and soapstones. Several mafic to ultramafic complexes of the Perthite monzonite suite are found northwest of Kiruna. They exhibit a more or less well-developed magmatic layering (e.g. Runkanjunnje), with dunites, troctolites, and peridotites occurring in the lower part of the intrusions (Martinsson 1986, Kathol & Martinsson 1999b). However, some of the ultramafic rocks have formed as late intrusions in the complexes. Dykes or sills of peridotite exist as single intrusions or in association with gabbroic rocks. Komatiites are restricted to the stratigraphically lower part of the Greenstone group and are found in a c. 500 metres thick unit in the Kiruna area. Soapstones formed by hydration of ultramafic dykes and sills are locally found with Lauttakoski as the most important example. Primary magmatic magnesium silicates (olivine, pyroxene) are mainly found in the mafic to ultramafic complexes and in some of the peridotitic intrusions. Other deposits contain magnesium silicates of metamorphic origin (serpentine, talc, chlorite, amphibole), with primary minerals only locally preserved.

The soapstone at Lauttakoski was first mentioned by Fredholm (1886) and later described by Svenonius (1916) and Shaikh (1972). It has been investigated by SGU for talc production. Magnetic ground survey, trenching, and drilling were carried out during the period 1965–1969. In 1966, about 30 tonnes were quarried for beneficiation tests. The deposit consists of an altered peridotitic sill within mafic volcanoclastic rocks (Greenstone group) in the Junosuando area. The intrusion has

a thickness of up to 40 metres and is known to exist for a length of 1 200 metres. The mineralogical composition is talc (36–56 %), chlorite (21–34 %), serpentine (0–10 %), dolomite (1–20 %), magnesite (0–12 %), and magnetite (9–15 %). To a depth of 50 metres, the deposit is calculated to contain 2 Mt (Shaikh 1972). After milling and flotation it could give a 40 % yield of industrial talc (Lundegårdh 1971).

Three ultramafic intrusions (c. 2.44 Ga old) exist in the Archaean basement northwest of Soppero. The Keukiskero intrusion is a metamorphosed enstatite pyroxenite with a length of 4–5 kilometres and a width of 1–2 kilometres. It consists of anthophyllite together with small amounts of tremolite, chlorite, and talc and some preserved enstatite. During the period 1969–1970 investigations (mapping, trenching, geophysical ground measurements, and drilling) were made to determine its potential for the production of anthophyllitic asbestos. In laboratory tests a concentrate containing 95 % anthophyllite was possible to obtain, and the anthophyllite-rich rock covers an area of at least 300 000 m² (Shaikh 1970, Lilljequist 1980).

Between 1978 and 1979 about 0.06 Mt of chlorite-tremolite rock of komatiitic origin (Greenstone group), containing c. 28 % MgO, was quarried by LKAB at Ädnamvare, W of Kiruna. However, the quality was found to be unacceptable for use as an additive in pellet production. A regional exploration campaign for magnesium silicates was carried out by LKAB in 1985–1987 (Martinsson 1986, Bergström 1988). Several potential deposits were discovered and three of them were drilled (Valkeasiipivaara in the Greenstone group and Tjuoltatjåkkah and Ruhkejuovva of the Perthite monzonite suite). At Tjuoltatjåkkah the reserves are 10.1 Mt with 38 % MgO, and some thousand tonnes were quarried for metallurgical tests in 1991 (Hansson 1991).

Apatite

Three types of apatite occurrences are known from the map area: apatite veins, apatite in iron ores, and disseminated apatite in mafic intrusions. The existence of economic vein-type apatite deposits in scapolite-altered gabbroic intrusions in southern Norway made it interesting to start off investigations for similar types of apatite occurrences in scapolite-rich gabbros in the northern part of Norrbotten county in 1888 (Löfstrand 1890, Lundbohm 1890, 1892). Some apatite veins were found in the northern part of the Dundret gabbro and in some other gabbro intrusions in the Gällivare area, but their small size and mostly low content of apatite rendered them economically unattractive.

Since many apatite iron ores contain on average

1–5 % P, interest was instead focused on the iron ores in Malmberget and Kiruna. As early as 1889 small amounts of apatite-rich rocks were quarried at Malmberget (Lundbohm 1890, 1892). In 1918, 8 410 tonnes of apatite concentrate, with 10.8 % P, were produced at Malmberget (Geijer 1919b), and during the period 1939–1946 about 0.223 Mt of apatite concentrates with 13 % P were recovered. Small amounts of apatite were also produced in 1952–1953 in Malmberget (Grip 1978). At Kiruna, apatite was produced from the Rektorn deposit in 1942–1946 (Geijer 1950), and in 1985–1988 about 0.3 Mt apatite concentrates were produced by flotation from the Kiirunavaara deposit.

Several gabbroic intrusions are rich in apatite and have a phosphorous content in the range of 1–3 %. Most of them occur in the eastern part of the map area (see the chapter on "Gabbro, metagabbro and diabase, <1.8 Ga", p. 37). However, gabbros rich in apatite are also known from the Gällivare and Kiruna areas. None of these occurrences has been investigated for apatite.

Mica

The host rock to the Aitik ore is rich in biotite and muscovite. These minerals occur in muscovite schist, biotite schist, and biotite-amphibole gneiss. Extensive tests for production of mica as a by-product from copper mining at Aitik were performed in the 1980s (Petersson 1980). However, the production of mica as a filler was not economic.

Clay

Clay minerals formed by pre-Quaternary weathering of the bedrock have been described from Leveäniemi and Gruvberget at Svappavaara (Frietsch 1960, 1966). In the 1970s and 1980s exploration for clay minerals was carried out in the Kiruna and Svappavaara areas by LKAB and SGU. LKAB investigated the Saivo area S of Kiruna for bentonite using geophysical ground surveys and drilling. The contents of montmorillonite and kaolinite in the discovered deposit were 28–56 % and 8–25 % respectively (Bida 1981, Hedin 1984). Near the Vathanvaara iron mineralisation NE of Svappavaara, SGU investigated another clay occurrence by means of seismic survey, trenching, and diamond drilling during the years 1977–1979. No kaolinite was found, but two of the drill holes were shown to contain some smectite, pyrophyllite, and chlorite (Persson & Lagerbäck 1977).

Diatomite

Accumulation of diatomite occurs in many lakes and bogs in the northern part of Norrbotten county. In

1989–1990, some of the bog occurrences were investigated by drilling (Pissivuoma, north of Gällivare and Kreuksenvuoma at Masugnsbyn). The estimated reserve at Pissivuoma is 5 500 tonnes of diatomite occurring in a 1–2 metres thick layer (Rönkä 1990).

Barite

Several minor occurrences of barite are known from the Ultevis area, W of Gällivare. Generally, barite is found in association with iron-manganese mineralisations of stratiform and epigenetic origin, but locally it occurs disseminated in felsic metavolcanic rocks (Ödman 1947). Small amounts of barite are also found at the Sattavaara manganese iron deposit S of Lannavaara (Ambros 1980) and at the Rektorn apatite iron deposit in Kiruna (Geijer 1910). Furthermore, barite occurs as an accessory disseminated mineral in a few stratiform sulphide ores (Viscaria and Huornaisenvuoma) and as massive veins in some epigenetic copper-gold deposits (Aitik, Liikavaara, and Kovogruvan). Barite unrelated to other mineralisations is locally found as veins of up to a few decimetres width in metasedimentary rocks in the Stora Sjöfallet area (Shaikh et al. 1986).

The richest occurrence of barite is at the Aitik copper-gold deposit, which contains an average of c. 1 % of this mineral (Grip 1978). Most of the barite occurs in up to several decimetres wide veins. Pyrite, chalcopyrite, magnetite, and actinolite may occur in varying amounts together with barite. Some tests have been made to recover barite as a by-product from the copper flotation (Peterson 1980).

Aluminium silicates

Andalusite and sillimanite are common metamorphic minerals in the metasedimentary rocks (mainly Svecofennian rocks). Sillimanite is mainly found in the Pajala area in biotite gneiss and mica schists, but is also locally present at Pahakurkio (S of Masugnsbyn) and Vuotnavare (SSE of Kiruna). Andalusite is common in mica schists from Pahakurkio, Väkkärjärvi (NE of Kiruna), Vuotnavare, and east of Gällivare. Some of the occurrences have been mapped and sampled. The content of andalusite and sillimanite is rarely more than 5–8 % for larger areas (Shaikh et al. 1986).

REGIONAL AND STRUCTURALLY CONTROLLED ALTERATIONS

Several types of alteration have affected the Precambrian bedrock in the map area. Some of them are spatially related to ore deposits, while others are of a more regional

character. The following description is mainly focused on the latter types. The most characteristic alterations in the area are scapolite and albite alteration (Frietsch et al. 1997). Other types of alteration products are skarn, albite-carbonate, K-feldspar, sericite, tourmaline, epidote, and chlorite. Syn-depositional alterations are mainly restricted to the Greenstone group and are manifested by spilitisation and epidotisation of basaltic lava, albitisation related to subvolcanic intrusions, and alterations connected to exhalative processes. The suggested occurrence of evaporites within certain units of the Greenstone group is expressed by stratigraphically controlled albitisation and/or scapolitisation as products of diagenetic or metamorphic reactions. Most other alterations are post-depositional in character and related to magmatic, metamorphic, and hydrothermal processes of local or more regional extent.

A spatial relation to major shear zones has been noticed for several alteration types (Frietsch 1966, Offerberg 1967, Eriksson & Hallgren 1975, Romer et al. 1996, Frietsch et al. 1997). These include albite-carbonate alteration, scapolitisation and sericitisation. A similar structural control for alterations within greenstone areas has been described from the northern parts of Finland and Norway (Padget 1959, Eilu 1993, Ettner et al. 1993).

Scapolite

Scapolite is widely distributed and occurs in most intrusive and supracrustal rocks in the map area, except for the Archaean domain, where it is very rare. Intense scapolite alteration can mostly be spatially related to shear zones, contacts of intrusive rocks, or mineral deposits. However, at Kiruna a strong scapolitisation in the lowermost part of the Greenstone group is suggested to represent the metamorphic expression of former evaporite beds (Martinsson 1997). Banded scapolite-calcisilicate rocks within tuffitic units in the upper part of the Greenstone group in the Svappavaara–Vittangi area (Eriksson & Hallgren 1975, Frietsch 1966) may have a similar origin. Scapolite is generally most common in amphibolite facies rocks, where it forms porphyroblasts, veinlets, or massive scapolite fels. Especially mafic metavolcanic rocks belonging to the Greenstone group and the Svecofennian metavolcanic rocks are affected, but felsic metavolcanic rocks and metasedimentary rocks are also strongly altered in some places. Regardless of host rock, character and style of scapolite growth, the composition is mostly marialitic (Frietsch et al. 1997).

Scapolite was early noticed as an alteration mineral in gabbroic rocks in the northern part of Norrbotten county (Löfstrand 1890). It replaces plagioclase and forms

veinlets or locally scapolite rocks lacking primary magmatic textures. Similar alterations are common in mafic dykes of different generations. The early Svecofennian intrusions of intermediate to felsic composition are rarely affected by intense alteration, but scapolite is noticed as a minor constituent in many of them (Geijer 1931b, Eriksson & Hallgren 1975, Skiöld 1981b). In the Malmberget area, scapolite has been found in granites and pegmatites belonging to the 1.81–1.78 Ga old Granite-pegmatite association (Geijer 1918a, 1930a).

Scapolitisation along major shear zones occurred partly in association with albitisation and carbonatisation. Northwest of Kiruna, mylonitic scapolite rocks exist in some narrow shear zones which cut monzonites of the Perthite monzonite suite. Scapolite is also found in association with most epigenetic copper-gold deposits, while it is less common in stratiform sulphide deposits and apatite iron ores. The relation of copper mineralisations to strong scapolite alteration of their host rocks was early noticed at Gruvberget, Särkivaara, and Nautanen (Geijer 1918a). At Pahtohavare a zone of scapolite-biotite alteration forms an envelope around the ore-bearing albite felsites (Martinsson et al. 1997b).

Albite

Many rocks of volcanic origin are affected by sodium metasomatism. The rocks of the Greenstone group at Kiruna are largely spilitic in character (Sundius 1915), and the Porphyry group includes extremely albite-rich rocks in the form of albitites and albite-magnetite rocks (Geijer 1910, Offerberg 1967, Eriksson & Hallgren 1975). Within the Greenstone group, intense albitisation is mainly related to mafic sills and epigenetic copper-gold mineralisations. Albitisation of tuffite along the contacts of mafic sills is a widespread alteration type in the Greenstone group in the Kiruna area. This albitisation occurred during the intrusion of hot basaltic magma in unconsolidated volcanoclastic rocks containing saline interstitial water. The albitisation gradually fades away from the contacts over a distance of 2–10 m, and primary features such as layering are generally well preserved within the alteration zone (Martinsson 1997).

Extensive albitisation has affected rocks in the footwalls to the Kiirunavaara and Luossavaara apatite iron ores. The alteration zone is symmetrically distributed around a thick sill of mafic to intermediate composition. It affects a c. 2 500 metres thick unit, including a Svecofennian metaconglomerate (the Kurravaara conglomerate), the lower half of the Porphyry group, and the intrusion itself (Geijer 1910, Romer et al. 1994). Titanite formed during the albitisation has an age of 1876 Ma (Romer et al. 1994).

Some intrusive rock types occurring on a regional scale exhibit a strong albitic character. Most common are the albite-bearing metadiabases. They have mainly intruded as sills within the Kovo Group and the overlying Greenstone group. The intrusions have a fine-grained mafic outer rim, which gradually changes to a coarse-grained albite-rich rock in its central part. Amphibole, epidote, magnetite, pyrite, and locally carbonate are minor constituents in the albitic part of the intrusions. An albite-bearing metadiabase intruding the Kovo Group north of Kiruna has a zircon age of c. 2.2 Ga (Skiöld 1986, Table 1). Sills with similar ages and petrography are common within Palaeoproterozoic greenstones in other parts of the Fennoscandian Shield (Vuollo 1994). However, there probably exist several generations of albite-bearing metadiabase, as indicated by an intrusion dated to 1874 Ma west of Soppero (Skiöld 1981b). Other intrusions with an albitic character are some granites belonging to the Perthite monzonite suite. Generally only the outer rim of the intrusions is albitic (Geijer 1929, Offerberg 1967, Eriksson & Hallgren 1975).

Albite-carbonate metasomatites

Extensive albite-carbonate alteration is recognised at many places along the Karesuando–Arjeplog deformation zone (Fig. 2). It affects the Greenstone group, Svecofennian metavolcanic rocks and, in some cases intrusive rocks as well, and a number of sulphide mineralisations exist in close relation to the altered rocks (Ödman 1939, Eriksson & Hallgren 1975). Similar alteration also affected rocks in other areas in the northern part of Norrbotten county (Ödman 1957). These albite-carbonate rocks have been suggested to be of magmatic origin and they have been related to the albite-bearing metadiabases. Both of these albitic rock types were called leucodiabase (Ödman 1939). Subsequently, a metasomatic origin of the albite-carbonate rocks was demonstrated by Padgett (1959) and Frietsch (1966). Unfortunately, the name leucodiabase was still in use during field mapping in the 1970s, with no distinction being made between metasomatic albite-carbonate rocks and albite-bearing metadiabases, which has caused some confusion about the nature of the rocks.

Intensely altered rocks are found in zones up to 200 metres wide along major deformation zones. In detail, the albite-carbonate rocks mostly occur in structures that deviate with an angle of c. 20–30° from the major deformation zone. They typically consist of undeformed or brecciated albite-rocks with 5–20 % ankerite or ferrodolomite as disseminations and in veinlets (Eriksson & Hallgren 1975). The texture is mostly intersertal with carbonate occurring interstitial to albite laths (Ödman

1939), and the precursors to the strongly altered rocks are usually not possible to identify. Some carbonate-poor albite rocks (albitites) are slightly porphyritic and probably represent albitised felsic intrusions. The less altered rocks which surround the albite-carbonate rocks are variably affected by biotite-scapolite alteration, chloritisation, carbonate veining, and deformation. Quartz-carbonate veins, up to 1 metre wide, are locally present and locally contain substantial amounts of pyrite and chalcopyrite.

In some places, carbonate-poor albitites contain narrow fissure fillings or veinlets of actinolite, biotite, or carbonate. These veinlets are locally more abundant and pass into breccias on various scales. Massive actinolite rocks, containing minor amounts of magnetite, carbonate, and quartz, are locally encountered. Carbonate-rich rocks often contain subangular to rounded fragments. Generally the fragments consist of albite-rich rocks, but fragments of actinolite skarn and quartz are abundant in some places, suggesting brecciation of older alteration assemblages.

K-feldspar

Extensive K-feldspar alteration is mainly described from some epigenetic copper occurrences (e.g. Kiskamavaara, Pikkujärvi, Nautanen, and Gruvberget) and some apatite iron ores (e.g. Malmberget, Rektorn, and Ylipääsnjaska). However, strongly potassic intermediate to felsic metavolcanic rocks are also reported from areas lacking known mineralisations (Offerberg 1967), which indicates the existence of more regionally developed K-feldspar alteration in these rocks.

In field notes and sometimes also in drill core loggings the term "red Oskar" has been used as a working name for fine-grained feldspathic rocks with a reddish colour. This feldspar alteration is most common in the Kiruna-Vittangi area and it is usually developed within Svecofennian metavolcanic rocks or, more rarely, in rocks of the Greenstone group. In only a few cases has the composi-

tion of the feldspar been determined, but it is probably K-feldspar in most cases. The alteration is pervasive or developed along fissures and veinlets of carbonate. Associated minerals occurring in small to accessory amounts are epidote, calcite, tourmaline, chlorite, zeolites, magnetite, hematite, pyrite, and bornite.

Sericite and tourmaline

Sericite alteration is most common in association with K-feldspar alteration, which it usually overprints in late shear zones (e.g. at the Rektorn, Gruvberget, Leveäniemi, Nautanen, and Kiskamavaara deposits). Sericite is also reported as an alteration mineral occurring together with quartz veins within Svecofennian metavolcanic rocks ESE of Kiruna (Eriksson & Hallgren 1975). Here and at some other occurrences, sericite is a product of hydrothermal alteration in shear zones.

Tourmaline is rarely a major constituent of altered rocks but it occurs in accessory amounts in most sericite rocks (Geijer 1910, Frietsch 1966, Eriksson & Hallgren 1975). It is common also in association with K-feldspar alteration and more rarely with scapolitisation and albite-carbonate alteration. More extensive tourmalinisation is mainly recorded at some epigenetic copper-gold deposits (Aitik, Lieteksavo, Nautanen, Ferrum, and Fridhem) in association with quartz-tourmaline veins.

Epidote and chlorite

Epidote is mainly found in magmatic rocks of intrusive and extrusive origin. It is less common in metasedimentary rocks, with the exception of skarn. Epidote frequently occurs in amygdules and locally as a product of more pervasive alteration in volcanic rocks. As fissure fillings it is developed in all kinds of rocks. The occurrence of chlorite is not systematically documented, but it may be found in association with epidote and K-feldspar alteration and in shear zones.

STRUCTURE

INTRODUCTION

The area has experienced several ductile and brittle deformation events, from the Archaean to late- to post-glacial times in the Quaternary. General structural information can be found in the descriptions accompanying SGU's 1:50 000 bedrock maps. Detailed structural studies are few and they mostly concern the Kiruna area (Vollmer et al. 1984, Wright 1988, Bergman 1993). Regional overviews of the structural development in northern Finland can be found in Ward et al. (1989) and Kärki et al. (1993). The structural trends from generalised form lines of tectonic foliations and magnetic connexions are

shown in Fig. 49. Lineaments interpreted from magnetic field and altitude data are shown in Fig. 50.

DUCTILE DEFORMATION

Structural trends and fabric orientations

The main structural grain in the region is roughly NNE to NNW but seen in detail, smaller areas (domains) have their own structural patterns. In Fig. 49 the boundaries of 13 domains are shown, together with locations of structural measurements. When defining the location of domain boundaries, a compromise between the number

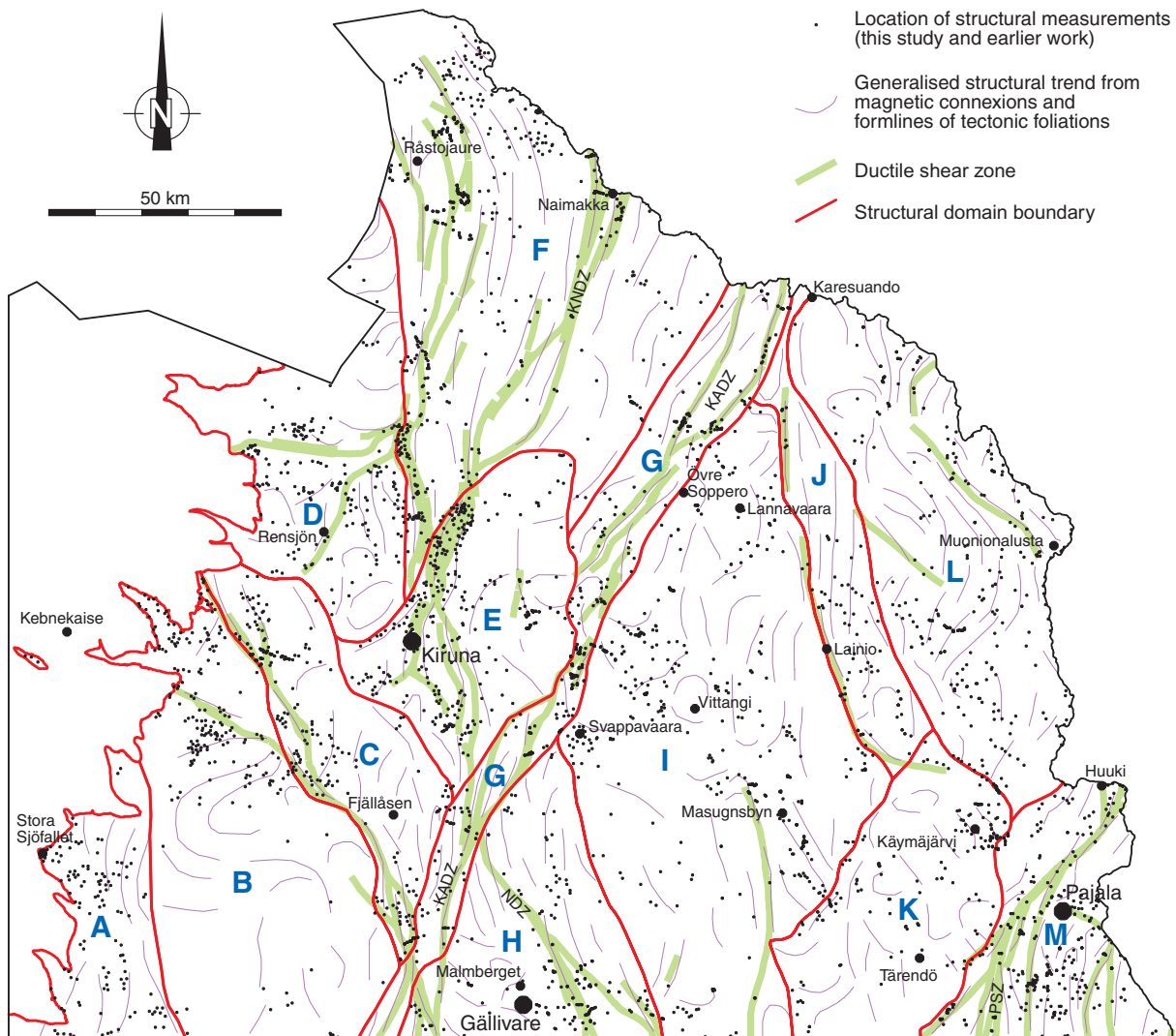


Fig. 49. Map with generalised structural trends from magnetic connexions and formlines of tectonic foliations. Red lines mark boundaries between the structural domains A–M which are described in the text. Black dots show locations of structural measurements in this study and from previous work in the area. KADZ = Karesuando–Arjeplog deformation zone, KNDZ = Kiruna–Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala shear zone.

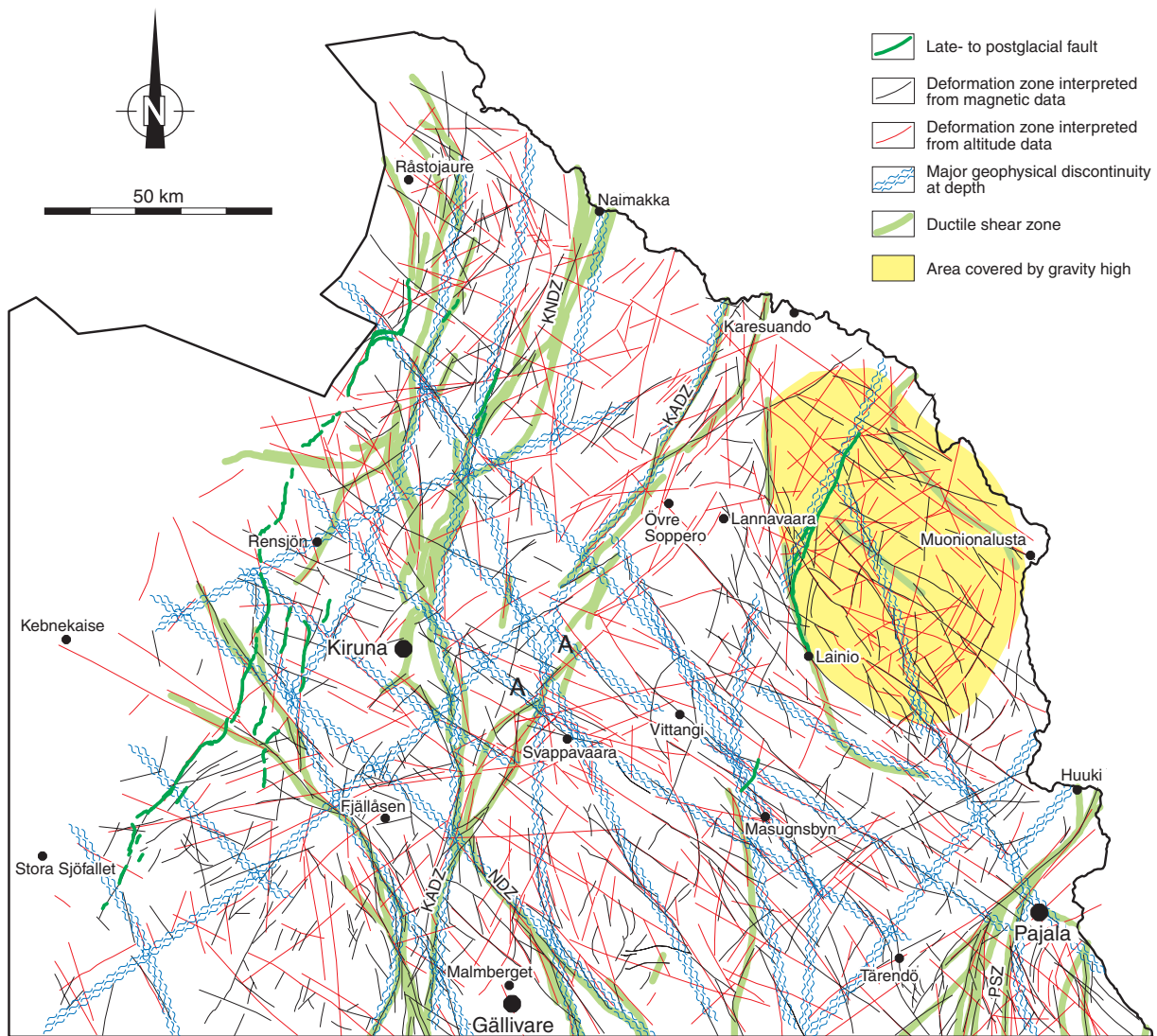


Fig. 50. Map showing lineaments interpreted from magnetic field (black lines) and altitude data (red lines). See also Fig. 57. The late- to postglacial faults are from Lagerbäck & Witschard (1983). Hatched, blue zones are major discontinuities, i.e. surface traces of planar features which have been followed to a depth of more than 5 kilometres in magnetic and gravity field data. Two zones which appear to affect the Karesuando–Arjeplog deformation zone (KADZ) east of Kiruna are indicated by A. The gravity high in the eastern part of the map (E in Fig. 11) is shown in yellow. In this area the lineaments indicate an arrangement which is conformable to the outlines of the anomaly. KNDZ = Kiruna–Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala shear zone.

of domains and the structural homogeneity of a particular domain was made. Stereograms showing fabric orientations for each domain are presented in Fig. 51. Different generations of fabrics are not distinguished; the diagrams illustrate the main trends and the amount of variation in each domain. For some specific domains and parts of them the magnetic structure index (see chapter on "Methods", p. 7) was calculated (Table 4). These indices should be compared to those calculated for the rock units discussed in previous chapters.

In Domain A, the bedding planes in the Svecofennian supracrustal rocks in the Stora Sjöfallet area are gently to tightly folded in approximately N–S trending folds. Lineations plunge moderately to the north or south.

Most readings in Domain B come from the northern

part, where both bedding and foliation are folded. Lineations plunge moderately to the S or SW. Large fold-like structures in intrusive rocks in the central part have been interpreted from magnetic anomaly data.

In Domain C there is a large concentration of shear zones. The dominant foliation orientation dips steeply W to SW and many lineations are steep. In blocks adjacent to shear zones, and in the south, the structural orientation is more N–S directed.

In the northwestern area, Domain D, many fabric orientations are represented. On the stereogram, NE–SW-oriented foliations are common, and lineations plunge moderately to the southwest. In the northern part, foliations generally strike E–W, subparallel to shear zones.

Domain E includes the Kiruna area with its strong

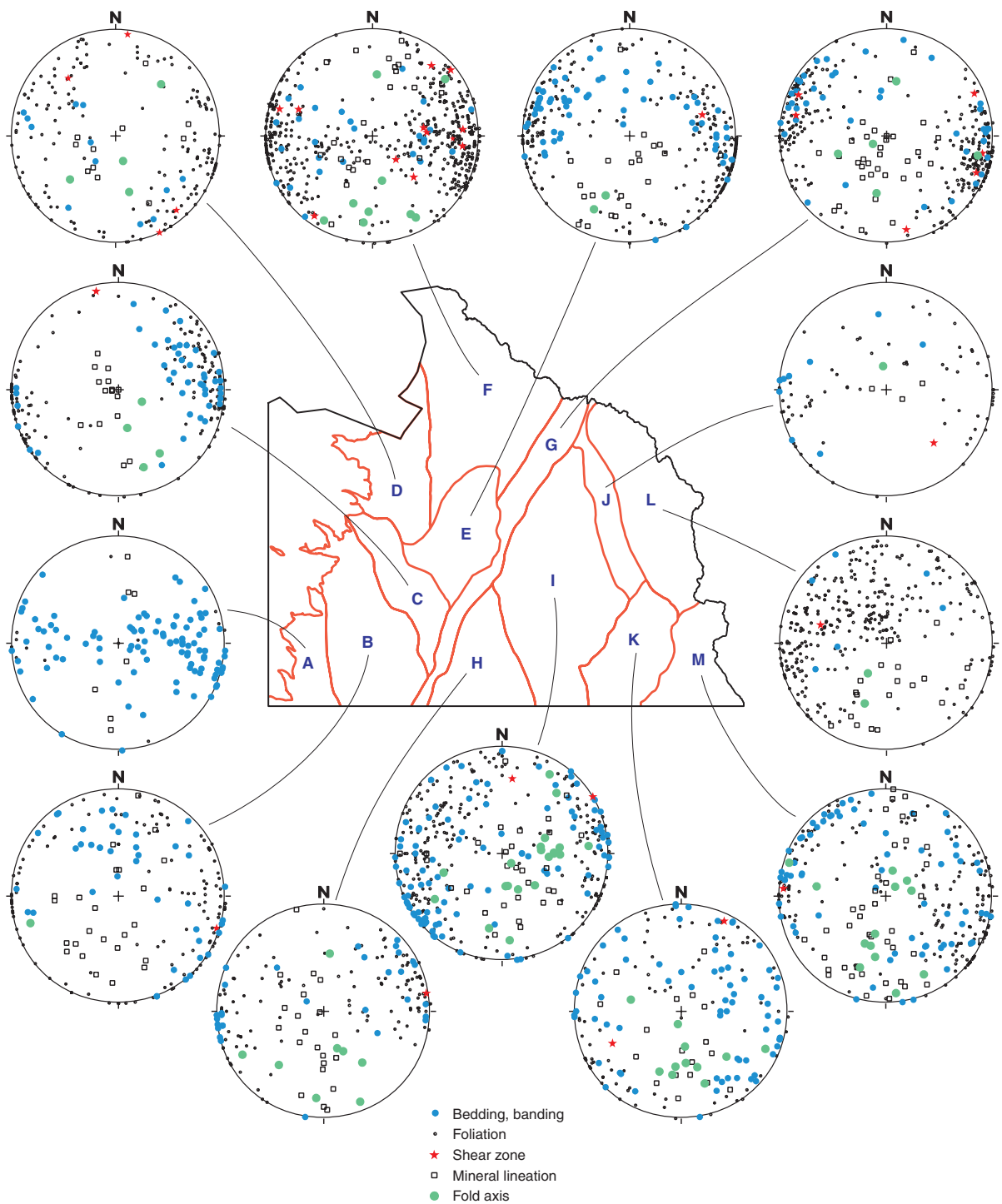


Fig. 51. Equal area stereographic plots (lower hemisphere) of field measurements of planar and linear structures from the structural domains A–M. The locations of the structural measurements are shown in Fig. 49.

N–S fabric orientation. In the western part, NNE–SSW-oriented steeply dipping planar structures dominate. Many linear structures plunge moderately to gently to the SSW or more steeply to the SE. Wright (1988) gives a detailed account of the structure of this area.

Domain F is mainly comprised of Archaean rocks with swarms of mafic dykes. Steeply dipping foliations oriented in a NNE–SSW direction parallel to major

shear zones dominate. In the north, the foliation swings into a NW–SE direction. This trend may be Archaean in age. A weak girdle of poles to foliations indicates the presence of approximately N–S trending folds. Many fold axes plunge to the south, and mineral lineations plunge gently to the NNE or steeply to the SSW. The magnetic structure index of 0.837 km^{-1} is probably partly due to the presence of mafic dykes. This relatively high

value in combination with a very low amplitude variation of the magnetic total field reflects structural homogeneity and a widespread and very consistent magnetic banding.

Strong ductile deformation in affiliation with the Karesuando–Arjeplog deformation zone accounts for the well-defined concentration of foliation orientations in Domain G (Figs. 49, 51). Mineral lineations plunge moderately to steeply, mostly in the southern quadrants. The foliation controlled by the deformation zone is reflected in the magnetic field pattern in the northern part of this domain and appears to continue in its southern part. This pattern is disturbed by two major structural discontinuities trending NW–SE and crossing the central part of the Karesuando–Arjeplog deformation zone (marked by A in Fig. 50). These discontinuities can be followed to a depth of more than 5 kilometres in geophysical data. The characteristic NNE–SSW “escarpment” line seen in magnetic data (indicated by yellow arrows in Fig. 10) appears on the gravity map (Fig. 11) as a boundary dividing the map area in a westerly and an easterly block. It is also well indicated in gamma radiation, electromagnetic, and topographic relief maps (see the separate printed map SGU Ba 56:5).

East of the Karesuando–Arjeplog deformation zone, in the southern part of the map area in Domain H, foliations are mainly steep and strike NNW–SSE. This orientation is partly controlled by the Nautanen deformation zone. In the northern part, foliations bend into the Karesuando–Arjeplog deformation zone, indicating a component of dextral movement. Linear structures have variable attitudes, mainly with moderate plunges. In Fig. 52 the principal traces of magnetic connexions and magnetic lineaments in the southern part of the Karesuando–Arjeplog deformation zone and the western part of Domain H are shown. As mentioned above, the Lina granite in this area has a high magnetic structure index ($>1.3 \text{ km}^{-1}$). The magnetic connexions rotate in a dextral sense into the orientation of the Karesuando–Arjeplog deformation zone. On the western side of the G-domain, indicated in this figure roughly by the north-trending major lineaments, the connexions in the C-domain rotate into the deformation zone in the same sense.

The orientations of foliations are very variable in Domain I. In some parts of the domain, NNW–SSE-oriented foliations predominate. In the northwestern part, there is influence from the NNE–SSW-oriented Karesuando–Arjeplog deformation zone. The area includes the complexly folded rocks of the Greenstone group near Vittangi. Gentle dips of bedding are found in the area S of Masugnsbyn. Most linear structures plot with a moderate to steep plunge in the southeastern quadrant.

The shear zone through Lainio accounts for the weakly defined NNW–SSE fabric pattern in Domain J. Only a few steeply plunging linear structures have been recorded.

Domain K is structurally heterogeneous, with bedding and foliation planes showing a large scatter in the stereogram. The lineations are fairly concentrated to plunges moderately to the S or SE.

In Domain L, which is largely a high-grade terrain, there is an area in the south with gently SE-dipping foliations. Towards the northeast they rotate into a steep NNW–SSE orientation with generally higher strain. The strain is also high in NNE–SSW directions in the northeast (Fig. 53a). The northern part of Domain L is characterized by short wavelength/high amplitude magnetic banding (E in Fig. 10) which to the south is less pronounced, probably due to the change in dip of the foliation. The mean magnetic structure index is 0.7 km^{-1} but reaches a maximum of 1.4 km^{-1} . The overall structural pattern is conformable to the outlines of the assumed deep-seated high-mass body (E in Fig. 11, see pp. 33–34). This also applies to the brittle/semi-brittle deformation zones interpreted from magnetic field and altitude data (yellow area in Fig. 50).

The Pajala shear zone is the major structure in Domain M. The map (Fig. 49) and stereogram (Fig. 51) illustrate steep foliation dips and the change in orientation of foliation surfaces from NNE–SSW in the southern part to NE–SW in the northern part of the domain. Lineations have variable plunges in an approximately NNE–SSW plane. The magnetic field pattern in the southern part occupied by Svecofennian metasedimentary rocks is homogeneously banded with rather short wavelengths. A high magnetic structure index of 1.32 km^{-1} characterizes this area. The metasedimentary rocks of the Greenstone group in the northeast are magnetically structured whereas the mafic metavolcanic rocks are heterogeneous.

Major fold structures

Major folds are present in most supracrustal belts in the map area. The most common trends of axial surface traces are NW–SE to N–S, and the plunges of fold axes are quite variable. One example is found in the area southeast of Masugnsbyn (Fig. 2, southeastern part of Domain I in Fig. 49), where tuffitic greenstones of the Greenstone group are overlain by Svecofennian metasedimentary rocks. The main anticlinal fold, which folds the contact between greenstones and metasedimentary rocks, has a N–S axial surface trace orientation and a southerly plunge (Padget 1970). To the west, in a well-exposed section at Kalixälven River (Pahakurkio), there is a gently plunging anticline. In the northern part of the area,

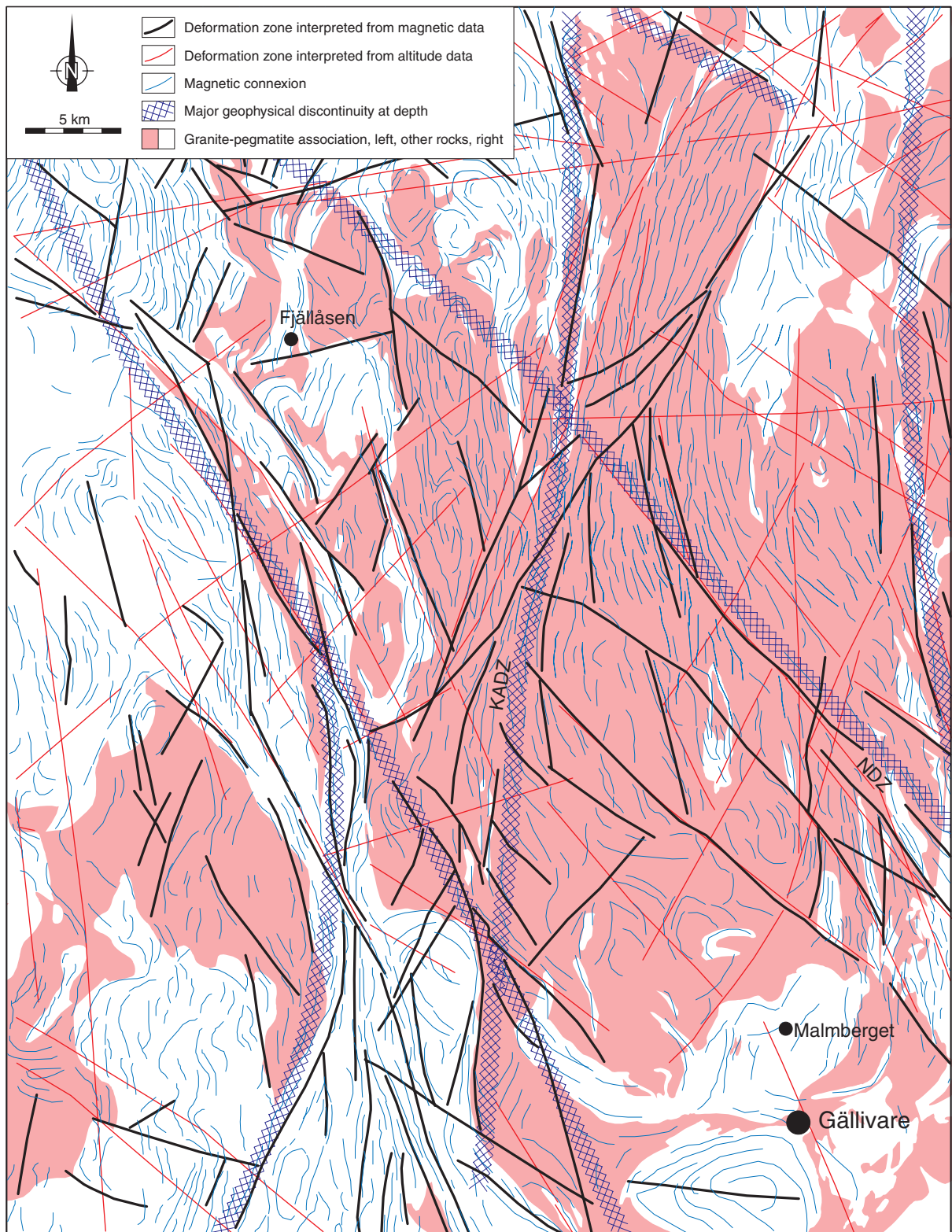


Fig. 52. Map showing magnetic connexions (blue lines), lineaments interpreted from magnetic field (black lines) and altitude data (red lines), and major discontinuities interpreted from both magnetic and gravity field data (hatched blue zones) in the southern part of structural domain G (Karesuando–Arjeplog deformation zone) and adjacent domains (see text). Red areas correspond to the 1.81–1.78 Ga old Granite-pegmatite association and white areas are older rocks.

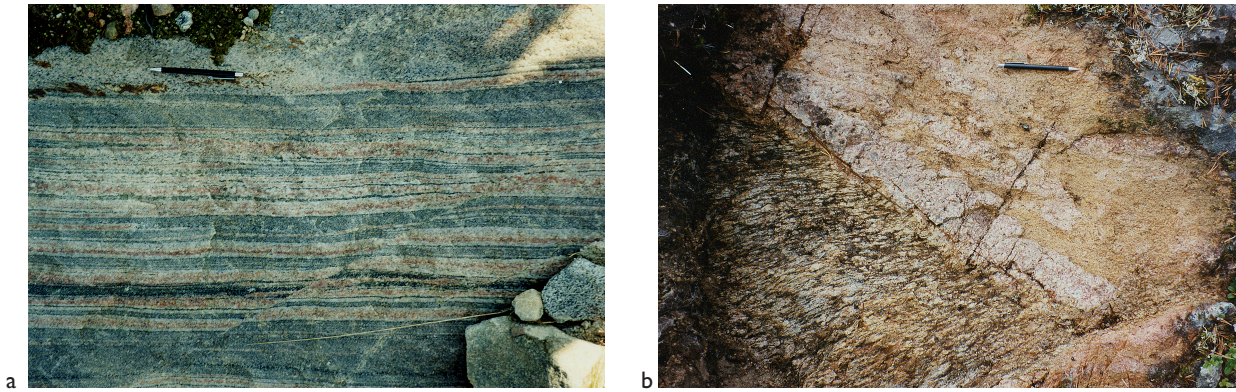


Fig. 53. a) Very strongly deformed metagranodiorite with attenuated and isoclinally folded quartzofeldspathic veins. More than four generations of veins can be distinguished through low-angle crosscutting relationships. A granitic dyke is weakly discordant to the veins (at the pen). Pingisvaara, 29 kilometres southeast of Karesuando (7589530-1794390). b) Metagranodiorite (Haparanda suite) intruded by younger granite and pegmatite. The metagranodiorite has an older WNW-ESE foliation and all rocks in the outcrop have a younger N-S foliation. Hotaakanperävaara, 10 kilometres NNW of Lainio (7542600-1774060).

minor structures show that the structural evolution is complicated and involves several phases of deformation.

In the Käymäjärvi area, northwest of Pajala (Fig 2, northeastern part of Domain K in Fig. 49), the core of a SE-plunging anticline exposes rocks of the Greenstone group. The anticline is overturned to the NE. To the SW and NE the overlying Svecofennian supracrustal rocks generally occupy synclines, but there are also minor synclines and anticlines that plunge moderately to the S or SSE. Observations of rootless isoclinal folds show that the large-scale folding was preceded, at least locally, by an earlier phase of deformation. The metamorphic grade increases further towards the east and the structures become more complicated. Two phases of folding have affected the Greenstone group in the Vittangi area (Eriksson & Hallgren 1975, central part of Domain I in Fig. 49). Weakly developed WNW-ESE-oriented axial surface traces are probably older than strongly developed N-S-directed axial surface traces. This relationship has given rise to fold interference patterns, which are apparent northwest of Vittangi. The relations between these two structural orientations can also be seen in plutonic rocks (Fig. 53b).

The supracrustal rocks north of Kiruna (Fig. 2) contain a number of N-S-trending, gently S-plunging synformal structures. The pattern is complicated by a number of ductile to brittle deformation zones, many of which are parallel to bedding (Martinsson 1999b). Southwest of Kiruna (central part of Domain C in Fig. 49) there is a large SE-plunging fold structure within rocks belonging to the Porphyry group. Although Offerberg (1967) indicated an anticline near the core of the structure, the major structure is probably a syncline, with felsic metavolcanic rocks flanked by mafic rocks at lower stratigraphic positions. Some fold structures in the area are disrupted by deformation zones (Offerberg 1967).

The close association of folds and deformation zones is also evident in the south-central part of the map area, e.g. S of Fjällåsen (Fig. 52). East of Gällivare (Fig. 2), there is an overturned syncline adjacent to the Nautanen deformation zone (see p. 81). The axial plane dips to the WSW and the fold axis plunges moderately to the SSE.

The well-preserved rocks in the Stora Sjöfallet area (Domain A in Fig. 49) are folded by open to tight folds with NNE-SSW to NNW-SSE axial surface traces. Major synclines and anticlines generally plunge gently southward (e.g. Witschard & Zachrisson 1995b).

Ductile shear zones

The Karesuando-Arjeplog deformation zone (Fig. 1) is one of the largest deformation zones in Sweden. The zone was named the Porsangen lineament by Henkel (1991), while Olesen & Sandstad (1993) called it the Karesuando-Arjeplog Fault Zone, with a continuation into the Mierujávri-Sværholt Fault Zone.

The northern part of the Karesuando-Arjeplog deformation zone is found in the area from west of Gällivare in the south to Karesuando in the north (Fig. 2, Domain G in Fig. 49). It is composed of several ductile or brittle-ductile shear zones which combined build up an up to 8 kilometres wide zone of variable strain intensity. In many places it is a retrograde zone with newly formed chlorite and white mica. Higher metamorphic grades have also been noted, e.g. in mafic rocks where hornblende is stable and in felsic metavolcanic rocks that are thoroughly recrystallised and where magnetite porphyroblasts are formed. The mylonitic foliation is steep, and stretching lineations vary from steep to gentle plunges, the latter less common (Fig. 51). Kinematic analysis, mainly using s-c fabrics, indicates western-side-up movement and local dextral movement.

The Pajala shear zone (Kärki et al. 1993, Fig. 1) was first described by Berthelsen & Marker (1986), who called it the Baltic–Bothnian megashear. The location of the northern part was interpreted differently by Henkel (1991) and called the Bothnian–Seiland shear zone, while Olesen & Sandstad (1993) used the name “Bothnian–Kvænangen Fault Complex”. Wikström (1995) used the name “Bothnian shear zone” in the southern part (in the Kalix area).

In the present area, it is a belt at least 10 kilometres wide (SE of Tärendö, Fig. 2) which narrows to the north and changes from a N–S orientation to a NE–SW orientation before it crosses the border to Finland near Huuki. Parallel zones exist to the east. Limited field data suggest that most deformation occurred near the metamorphic peak. Foliations are generally steeply dipping and lineations plunge either steeply or gently to moderately to the south (Fig. 51). There is a tendency towards steeper plunges closer to the Pajala shear zone and less steep plunges outside the zone. This pattern is interpreted as due to transpression, which is consistent with the results of Tikoff & Teyssier (1994). Kinematic analysis at a locality E of Tärendö indicates eastern-side-up movement, which is in agreement with observations of lower metamorphic grade to the west. The shear sense is the opposite of that in the Karesuando–Arjeplog deformation zone, even though the zones are similar in orientation.

Eastern-side-up movement has also been recorded in two other shear zones in the eastern part of the map area. Mylonitic rocks in the village of Lainio belong to a shear zone extending several tens of kilometres along the western contact of a c. 1.85 Ga old intrusion (Jyryjoki granite). A N–S-oriented shear zone with eastern-side-up movement is also present in granite and pegmatite S of Masugnsbyn.

Western-side-up movements characterize shear zones in the western part of the map area; the most important (the Karesuando–Arjeplog deformation zone) was described above. The Nautanen deformation zone (Witschard 1996, Fig. 2) in the Gällivare area is an up to 3 kilometres wide zone with strong ductile deformation in a NNW–SSE direction. It also contains important mineral deposits. Magnetic susceptibility anisotropy measurements confirm the NNW directions of the foliation (Pitkänen 1997), which seems to be tightly folded around a horizontal axis. In a NW-striking branch of the zone 25 kilometres E of Gällivare, s-c fabrics in a mylonitised granodiorite show southwestern-side-up movement.

A prominent belt of anastomosing shear zones, nearly parallel to the Karesuando–Arjeplog deformation zone and with the same shear sense, is found between Kiruna and Naimakka. Here it is called the Kiruna–Naimakka

deformation zone (Fig. 2). The northerly continuation of this zone has been identified in Finland (Idman 1988). In Kiruna, there is strong ductile deformation along the upper contact of the Porphyry group. S-c fabrics with western-side-up movement have been recorded here. The opposite shear sense in the same zone was indicated by Wright (1988), using asymmetric tails of recrystallised quartz around larger quartz clasts. Near Naimakka, several shear zones have been identified. At one locality, there are plagioclase porphyroclasts in a fine-grained mylonitic matrix (Fig. 54a). This rock has previously been identified as a metavolcanic rock (Hallgren 1982), but gradual transition into less foliated metagranodiorite shows that it must be interpreted as a mylonitic metagranodiorite. Stretching lineations are steep and the shear sense is western-side-up. Phyllonitic rocks with well-developed shear bands are present along the margins of some mafic dykes in the area (Fig. 54b, c). Ödman (1957) reported chromium mica from this area. The host rock to the chromium mica is interpreted here as mylonitised vein quartz.

A regional shear zone with a NW–SE orientation, which mainly deforms supracrustal rocks, is found south and west of Kiruna (Fig. 2, Domain C in Fig. 49). Outcrops within this zone have been studied west of Malmberget and west of Kiruna. At both localities, foliations and stretching lineations are steep and the shear sense is western-side-up. This zone is nearly parallel to the Nautanen deformation zone and has the same shear sense.

Evidence for separate deformation events and their age constraints

Archaean deformation

The structural trends in the Archaean bedrock (Domain F in Fig. 49) are similar to those in the Proterozoic rocks. It is therefore not possible to point out specific large domains with only Archaean structures. The overall NNE grain turns into a NNW orientation in the northernmost part of the map area. The former orientation could be due to pervasive Svecokarelian overprinting, while the NNW trend could be an Archaean structure. A study of the relations between fabrics and mafic dykes in the different domains could test this speculation.

On outcrop scale there is locally evidence for pre-Svecokarelian deformation. Some granite clasts in the basal conglomerate (Kovo Group), overlying Archaean basement, north of Kiruna, are foliated, and the foliation orientations differ from clast to clast (Fig. 17a). This demonstrates that a deformation phase preceded the deposition of the conglomerate.

In several exposures along the road c. 20 kilometres



a



b



c

Fig. 54. a) Mylonitised Archaean metagranitoid in the Kiruna–Naimakka deformation zone. Kinematic indicators show western-side-up movement. View looking north. Lappisoivi, 6 kilometres W of Naimakka (7631800-1726200). b) Strongly sheared phyllonitic margin of a 50 metres wide mafic dyke in Archaean metagranitoids. The shear zone is part of the NNE-oriented Kiruna–Naimakka deformation zone. View looking west. c) Close-up of sheared dyke margin in b). Shear bands indicate western-side-up movement. View looking south. Lammasvaara, 4 kilometres NW of Naimakka (7639650-1725580).

NW of Soppero, mafic dykes cut Archaean metagranitoid rocks. In some places the dykes clearly cut a N–S to NNW–SSE-striking gneissosity, which most likely is Archaean in age. The dykes themselves have a NNE–SSW-oriented cleavage (Svecokarelian), which locally also overprints the gneissosity in the metagranitoids (Fig. 12a). The cleavage is subparallel to the Karesuando–Arjeplog deformation zone to the east.

Early Svecokarelian deformation (c. 1.88 Ga)

Ambros (1970, 1980) suggested that the Greenstone group (and the Pahakurkio group) in the Lannavaara area (Fig. 2) had undergone folding, uplift, and erosion prior to deposition of Svecofennian volcanic rocks. This suggestion has not been generally accepted. In a detailed study of drill cores from the area, Frietsch (1985) found evidence for interlayering, and suggested that the Greenstone group and the Porphyry group were deposited contemporaneously. The area is poorly exposed and primary contact relations are disturbed by faulting. However, the structures visible in outcrop do not rule out the possibility of the existence of an unconformity in the area. The mafic tuffites of the Greenstone group display two phases of deformation. A strong and steep NW–SE-oriented foliation (S_1) is asymmetrically folded, with a weak N–S-striking axial planar cleavage (S_2 , Fig. 55a). An over-

lying Svecofennian metaconglomerate shows only one weak foliation (Fig. 55b), which is subparallel to S_2 in the tuffites. The possibility therefore exists that D_1 occurred before deposition of the Svecofennian rocks and that only D_2 affected both groups. Another possibility is that competence contrasts led to strain partitioning and that all deformation is post-Svecofennian. Detailed study using other methods and in other areas is needed to confirm or refute this poorly known tectonic episode.

Cliff et al. (1990) noted that a granophyric dyke with a U–Pb zircon age of 1880 ± 3 Ma, which crosscuts the main magnetite body at Kiirunavaara, appears to have suffered limited deformation. The dyke is not conformable with the strong N–S grain in the region, which probably formed during a major phase of deformation before 1880 ± 3 Ma. Using the age of the iron ore at Luossavaara, just north of Kiirunavaara (1888 ± 6 Ma, Romer et al. 1994), also for the Kiirunavaara ore, together with the stated error limits, the deformation would have occurred between 1894 and 1877 Ma ago (Fig. 3). Eriksson & Hallgren (1975) describe an early phase of folding and formation of diopside-tremolite skarn in the Sautusvaara iron mineralisation (25 kilometres E of Kiruna) prior to the intrusion of porphyritic dykes.

As stated previously, radiometric age determinations have not proved significant age differences between the Haparanda suite and the Perthite monzonite suite. How-



Fig. 55. a) Tuffitic, graphite-bearing mafic metavolcanic rock (Greenstone group) with a strong steep fabric (S_1). Both bedding and this fabric are asymmetrically folded and a weak axial planar cleavage (S_2) is developed. Iso Sattavaara, 7 kilometres S of Lannavaara (7556360-1758870). b) Svecofennian metaconglomerate with clasts of mainly felsic metavolcanic rocks. Note imbrication of clasts. A weak fabric in this rock is subparallel to the second foliation in a). The strong, steep fabric in the mafic rock (S_1) may have formed before deposition of the conglomerate. View to the east. Saariovivaara, 10 kilometres S of Lannavaara (7553590-1759540).

ever, where rocks from the two suites can be observed near each other (e.g. near Stora Sjöfallet and NW of Kiruna), rocks from the former suite are foliated and recrystallised whereas rocks from the Perthite monzonite suite are apparently undeformed. Magmatism during a deformation event that rapidly decreased in intensity could explain these observations. It is not known whether the deformation was regionally synchronous or diachronous. Using ages with error limits from the Rensjön–Vittangi area, and assuming synchronous deformation in this area, deformation between 1888 and 1872 Ma ago is indicated (Fig. 3). The undeformed appearance of rocks belonging to the Perthite monzonite suite led Skiöld & Öhlander (1989) to conclude that this suite should be late- to postorogenic with respect to the Sve-

cofennian orogeny. While it appears to be valid that these rocks are late- to post-tectonic in some areas, they are clearly not late- to postorogenic since the bedrock in other parts of the map area was strongly deformed and metamorphosed at a later stage.

At Kursumaa, southwest of Muonionalusta, the intrusive contact between an undeformed granitoid of Jyryjoki-type and a strongly deformed and recrystallised granitoid is exposed. The deformation event recorded in the metagranitoid must predate the intrusive age of 1853 ± 21 Ma for the Jyryjoki granitoid. A deformed quartz diorite (Haparanda suite) at Puristakero can be used to give an upper age limit of 1873 ± 23 Ma for that deformation. The event is thus poorly constrained to have occurred in the time range 1896–1832 Ma ago (Fig. 3).

Late Svecokarelian deformation (c. 1.8 Ga)

In the south-central part of the study area there is an arcuate zone of high-grade metamorphic rocks, which is spatially related to the margins of the large Lina granite intrusion. This suggests that this metamorphism is related in time to the formation and/or emplacement of the granite, i.e. around 1.8 Ga ago. Late Svecokarelian deformation and metamorphism can be demonstrated in some areas, but it can also be shown that other areas (e.g. Kursumaa, see above) were unaffected by that event. A common observation in plutonic rocks in the eastern part of the area is that the rocks of the Haparanda suite have a strong foliation, while granite dykes of the Granite-pegmatite association show a weak foliation which is conformable with the strong foliation (Fig. 56). This suggests that the Granite-pegmatite association intruded during the late stages of regional deformation.

From migmatitic rocks in the area S of Pajala, metamorphic U-Pb ages in the range c. 1810–1774 Ma have

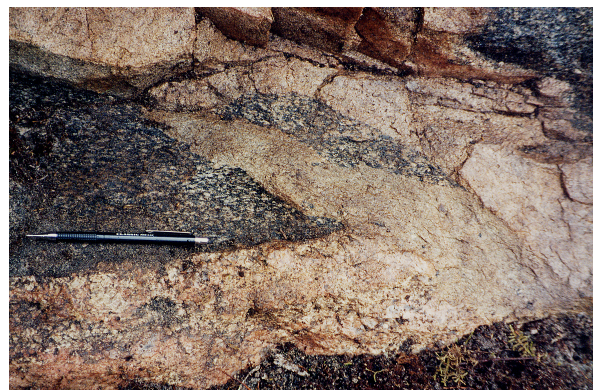


Fig. 56. Metadiorite intruded by red granite and pegmatite. The latter contains a weak fabric which is conformable with the strong fabric in the metadiorite. Muodosjoki, 10 kilometres NW of Muonionalusta (7559940-1816260)

been reported (Bergman & Skiöld 1998). This implies that the Pajala shear zone was also active at that time. Titanite ages of 1797–1783 Ma have been reported by Hiltunen (1982) from the Rautavaara area in Finland, NE of Huuki. In the northeastern part of the map area, the age of the late Svecokarelian deformation event is less well constrained. It must have occurred after 1856±8 Ma ago, which is the age of the deformed intrusion at Pingisvaara, SE of Karesuando. Possibly the deformation there is coeval with the one in the Pajala area.

Foliated rocks are very common in the large intrusion of Lina granite referred to above. The intensity of the foliation increases towards the Karesuando–Arjeplog deformation zone in the west, where granite mylonites are present. This deformation must be younger than 1778±7 Ma, the age of the Lina granite.

At the present state of knowledge, late Svecokarelian deformation and metamorphism appears to have occurred mainly in relation with shear zones and near c. 1.8 Ga old intrusions. Further study is needed to more precisely define the areal extent of this event, which is well known from central and southern Sweden.

Models for deformation in the Kiruna area

The well-studied Kiruna area has been subject to several different interpretations regarding stratigraphy and structural development. Vollmer et al. (1984) found evidence for one major episode of compressional deformation (compression direction 10° to the WNW). A strong extension direction plunges 60° to the SSE, parallel to fold hinge lines. They suggested that the Kiruna area occupies the eastern limb of a major antiform, cored by granitic rocks to the west, and that the strain pattern was caused by diapirism.

Detailed structural mapping and strain analysis was done by Wright (1988), who distinguished four separate deformation events. Early WNW-directed thrusting (with formation of mineral lineation) was followed by folding and subvertical cleavage development due to the formation of thrust ramps. Later events caused the formation of crenulation cleavage, open folds, kink bands, and shear zones.

Talbot & Koyi (1995) suggested westward thrusting and formation of an imbricate fold-thrust belt with simultaneous deposition of conglomerate and quartzite in a foredeep in front of the thrusts. A foliation would then have formed as the allochthonous rocks were intruded by diapirs of remobilized basement. However, the deformation zones in the Kiruna area are steep and must have rotated a significant amount if they originated as thrusts. They are part of a regional pattern (Fig. 2) of steep deformation zones and it is highly unlikely that all these

zones have rotated. The presence of thrusts in the Kiruna area is therefore not favoured here. Furthermore, Wright (1988) found that diapirism is inconsistent with e.g. the following evidence: the cleavage does not mirror the pluton contacts, minor structures indicate vergence towards the plutons, strain intensity is not correlated with distance from plutons, and intrusive contacts are undeformed. He regarded the plutons as having intruded via dykes and as having been enlarged by stoping.

BRITTLE AND BRITTLE-DUCTILE DEFORMATION ZONES (INCLUDING LATE- TO POSTGLACIAL FAULTS)

Brittle and brittle-ductile deformation zones are rarely exposed and have thus mainly been interpreted from geophysical data. From filtered magnetic and gravity field data, major discontinuities which can be traced several kilometres downwards into the crust were extracted. There are three different groups of discontinuities with the orientations NW–SE, NNW–SSE and NNE–SSW (which seems to turn into the NNW-orientation to the south, Fig. 50). All three groups are found throughout the area, which underlines their regional significance. The two latter trends coincide with the orientations of several shear zones, e.g. the Karesuando–Arjeplog deformation zone and the Nautanen deformation zone. Near-surface lineaments (Fig. 50) follow the major trends (Fig. 57) but also outline significant local features like the circularly arranged structures more or less parallel to the contour of the high regional gravity anomaly in the northeast. It is important to note that in this special case there is a clear distinction between the interpreted magnetic lineaments which are parallel to the ductile structural trend and those based on altitude data which cut that trend at high angles. The latter lineaments show no lateral displacement and no alteration of iron-bearing minerals occurred.

Somewhat more than 10 percent of all magnetic lineaments are recognised as faults with an apparent dextral shear sense component. Their orientations are preferably NW–SE and they are evenly distributed (Fig. 58). Another 5 percent have an apparent sinistral shear sense component and they are almost exclusively oriented NE–SW, i.e. perpendicular to the former. This indicates faulting during N–S shortening. Unfortunately, the observed number of sinistral faults is not high enough to determine if there actually is a conjugate relationship between these two sets of faults. This kinematic pattern differs from that of the ductile deformation, which suggests that all these deformation zones formed in different stress regimes and are not the result of progressive de-

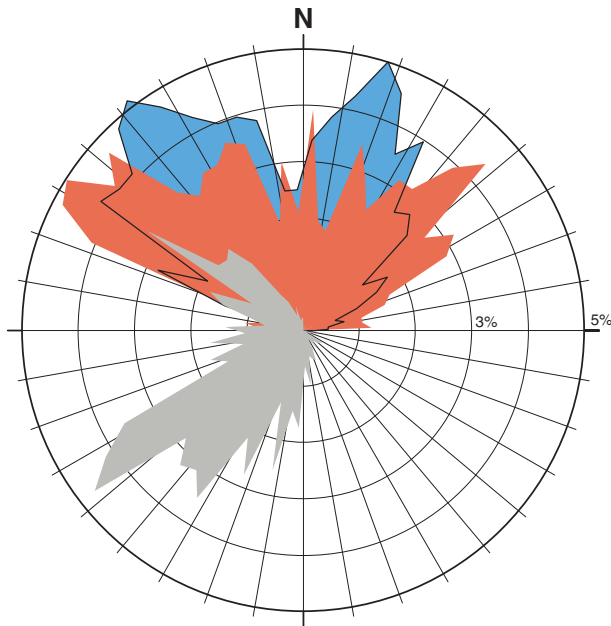


Fig. 57. Rose diagram showing the distribution of lineaments interpreted from magnetic field data (blue, $n = 667$), altitude data (red, $n = 663$), and the distribution of glacial striations (grey, $n = 1\ 407$).

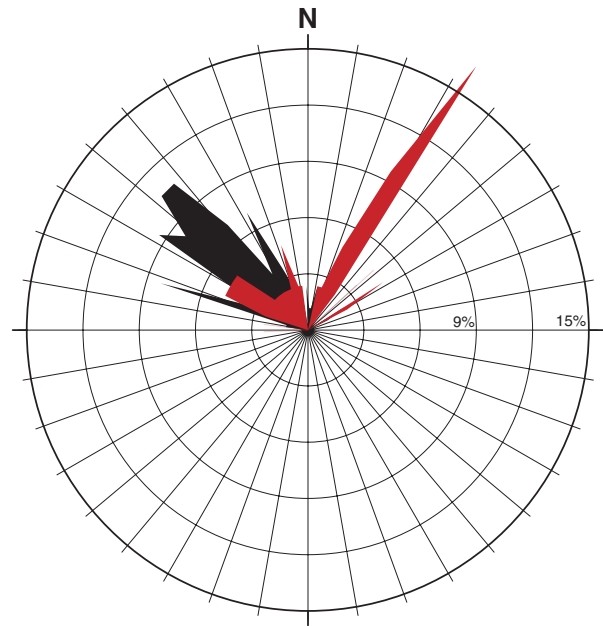


Fig. 58. Rose diagram showing the orientation of faults interpreted from magnetic data along which there occurred an apparent dextral (black, $n = 85$) and sinistral (red, $n = 42$) displacement component.

formation of the crust during uplift and cooling. Faults with a vertical displacement component can locally be detected in magnetic total field data. Two examples from the Vittangi–Lainio area where the northeastern blocks are elevated relative to the southwestern blocks are shown as dotted lines in Fig. 10.

Magnetic lineaments are often concentrated near or within shear zones as in the southern part of the Karesuando–Arjeplog deformation zone to the west of Gällivare (see above). Brittle deformation zones which are parallel to ductile shear zones are difficult to recognise but can be detected locally where they are discordant to the shear zones. A great number of lineaments interpreted from magnetic and altitude data coincide in position and length, but there are some crucial differences, as demonstrated in Fig. 57. Lineaments interpreted from altitude data concentrate around two principal directions (305° and 45°) significantly different from those observed from magnetic field data (325° and 20°). Orientations of glacial striae, which are also shown in Fig. 57, coincide rather well with the first group. This suggests that fracturing without alteration of magnetic properties can only be recognised in altitude data, as exemplified above. Another, more trivial, explanation is that linear landscape relief features of Quaternary deposits with no correspondence to the bedrock beneath have been included. However, glacial structures are generally short in length. As only lineaments longer than 5 000 metres have been included, probably very few of the in-

terpreted lineaments have been mistaken as faults or fracture zones.

Earlier geological and geophysical works have presented analyses of lineaments in the sense described here (Ambros 1980, Lindroos & Henkel 1981, Padgett 1977, Witschard 1970, 1975). In all of them, two or three characteristic concentrations of orientations are indicated. The NW–SE direction is found in all of them, which confirms the regional importance of that lineament direction. The other maxima correspond to local patterns that are hidden in the regional pattern.

Large parts of the Karesuando–Arjeplog deformation zone and the Pajala shear zone have been reactivated as brittle deformation zones. Zones with similar NNE–SSW orientations are also common in the northwestern part of the map area. Spectacular deep and narrow valleys (“kursu valleys”) are common features in the east-central part of the map area. They usually have a NW–SE orientation and have been formed by glacial erosion of brittle deformation zones. Not only do they make a characteristic break in the landscape topography but they also conspicuously cut the magnetic field pattern. The magnetic depression they cause may be ascribed to the magnetite-consuming formation of chlorite during or after deformation. Other NW–SE-oriented brittle deformation zones are common throughout the map area. Due to the poor exposure little is known about the nature of these zones and their fracture fillings. Some alteration zones and mineralisations are controlled by



Fig. 59. a) Gently dipping, characteristic fractures in the Lina granite. Liinajoki, 23 kilometres NW of Gällivare (7473760-1694400). b) The late- to postglacial Pärve fault at Rapokvare, 16 kilometres ESE of Stora Sjöfallet (7484000-1624000). View looking east.

fracture zones (see the chapter on "Mineral occurrences"). Monazite and titanite from the fracture-filling monazite+titanite+apatite+stilbite assemblage at Malmberget have yielded U-Pb ages of 1740–1735 Ma and 1620–1613 Ma, respectively (Romer 1996). Gently dipping fractures are characteristic in many granitic intrusions in the area (Fig. 59a).

Faults that moved in late- to postglacial times have been documented by Lagerbäck & Witschard (1983).

Most of them are located in the western part of the map area (Fig. 50) and show eastern-side-up movement.

These faults are very difficult to trace in magnetic field data but are easily observed in electromagnetic VLF data. The Pärve fault, a 155 kilometres long fault system (Lundqvist & Lagerbäck 1976, Fig. 59b), was interpreted by Riad (1990) as the result of transpression with a northwest–southeast oriented compression direction.

METAMORPHISM

The designation of metamorphic grade is based on the classification by Winkler (1979) and is similar to that used for the Nordkalott map (Krill et al. 1988). On the map (Fig. 60), three different metamorphic grades are distinguished. In areas marked as high-grade, the rocks are generally migmatitic with some degree of partial melting. They may contain sillimanite and K-feldspar, and they do not contain prograde muscovite. Some garnet and cordierite may be present. In areas marked as medium-grade andalusite, prograde muscovite, garnet, cordierite, and staurolite may be present. Quartzofeldspathic veins are uncommon. In some areas where andalusite is the dominating aluminum silicate, sillimanite may locally be found. The areas marked as low-grade are the Kiruna and Stora Sjöfallet areas. The rocks in these areas may contain chlorite and zoisite/clinozoisite.

The information used to assign metamorphic grades to the different areas has been taken from printed maps and other publications and from field notebooks (stored in the archives of SGU in Malå) from previous fieldwork in the area. This information has been complemented with new field data, and thin section observations obtained in this project have also been used. The results from nine new pressure-temperature determinations are presented below.

REGIONAL METAMORPHIC VARIATIONS

The distribution of areas with rocks of different metamorphic grade is shown in Fig. 60. The Archaean rocks are generally high-grade, but medium-grade rocks also exist, at least locally. However, available data is limited in this area and no distinction between high- and medium-grade has been made.

Proterozoic high-grade metamorphic rocks are found in the eastern and south-central parts of the map area. Thorough recrystallisation, quartzofeldspathic veining, and various stages of migmatitisation are characteristic features of these areas. Sillimanite and, in some places, cordierite are present in favourable rock-types (Figs. 61a–c). In the northeastern area, metamorphic orthopyroxene is locally present in mafic rocks, indicating conditions of granulite high-grade metamorphism.

Proterozoic medium-grade metamorphic rocks are found throughout the map area. In aluminous rocks, andalusite (Fig. 61d), cordierite, and muscovite are common. The major metamorphic minerals in mafic rocks are hornblende and plagioclase.

The metamorphic grade is lowest in the Kiruna and Stora Sjöfallet areas, where excellent primary structures are present (Fig. 23a, b). The rocks are normally true

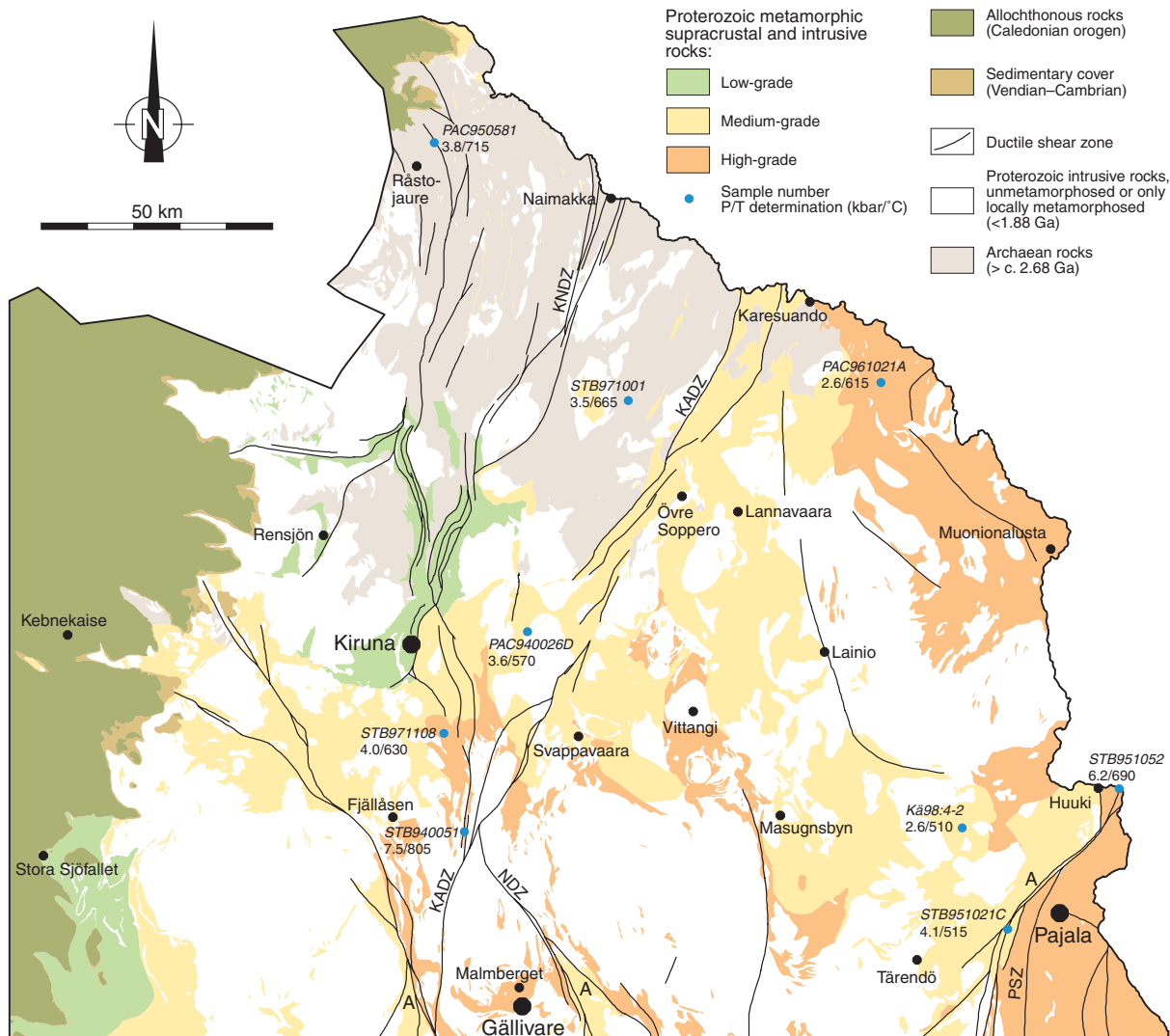


Fig. 60. Metamorphic map of the northern part of Norrbotten county. High-grade rocks are found in the eastern and south-central parts of the area and low-grade rocks are found in the Kiruna and Stora Sjöfallet areas in the west. Sample locations and results of pressure-temperature determinations are shown. Examples of localities where boundaries between medium- and high-grade metamorphism are controlled by deformation zones are marked by A. KADZ = Karesuando–Arjeplog deformation zone, KNDZ = Kiruna–Naimakka deformation zone, NDZ = Nautanen deformation zone, PSZ = Pajala shear zone.

low-grade but transitions to medium-grade locally occur. The mineralogy of the mafic metavolcanic rocks (hornblende, actinolite, chlorite, plagioclase, albite, epidote) in the Kiruna area indicates that they were metamorphosed in upper greenschist to lower amphibolite facies. In the Stora Sjöfallet area, the characteristic low-grade paragenesis chlorite+actinolite+epidote exists in mafic rocks (e.g. Zachrisson & Witschard 1995b). Secondary white mica has been observed in shear zones in both areas.

Some of the boundaries between metamorphic zones are controlled by deformation zones. This is particularly evident across the Pajala shear zone, the Nautanen deformation zone, and a deformation zone S of Fjällåsen (A in Fig. 60). In other places, metamorphic isograds appear to cross lithological units without obvious structural control, e.g. NW of Pajala.

METAMORPHIC TEMPERATURE AND PRESSURE DETERMINATIONS

A complete set of analyses for making quantitative determinations of metamorphic temperature and pressure was carried out for nine samples. The minerals present in these samples are given in Table 6. Seven samples were collected from metasedimentary rocks, mainly metaargillites, and two from tuffitic mafic metavolcanic rocks (Kä98:4-2 and STB951052). For each sample, a representative analysis of garnet, biotite, and plagioclase is given in Tables 7–9. The garnet zoning profiles are flat or show a weak retrograde zoning with slightly increasing contents of MnO from core to rim. Core analyses have been used in this case for thermobarometric calculations. Only one sample (Kä98:4-2) has a bell-shaped MnO-profile, indicating growth zoning. For this sample,

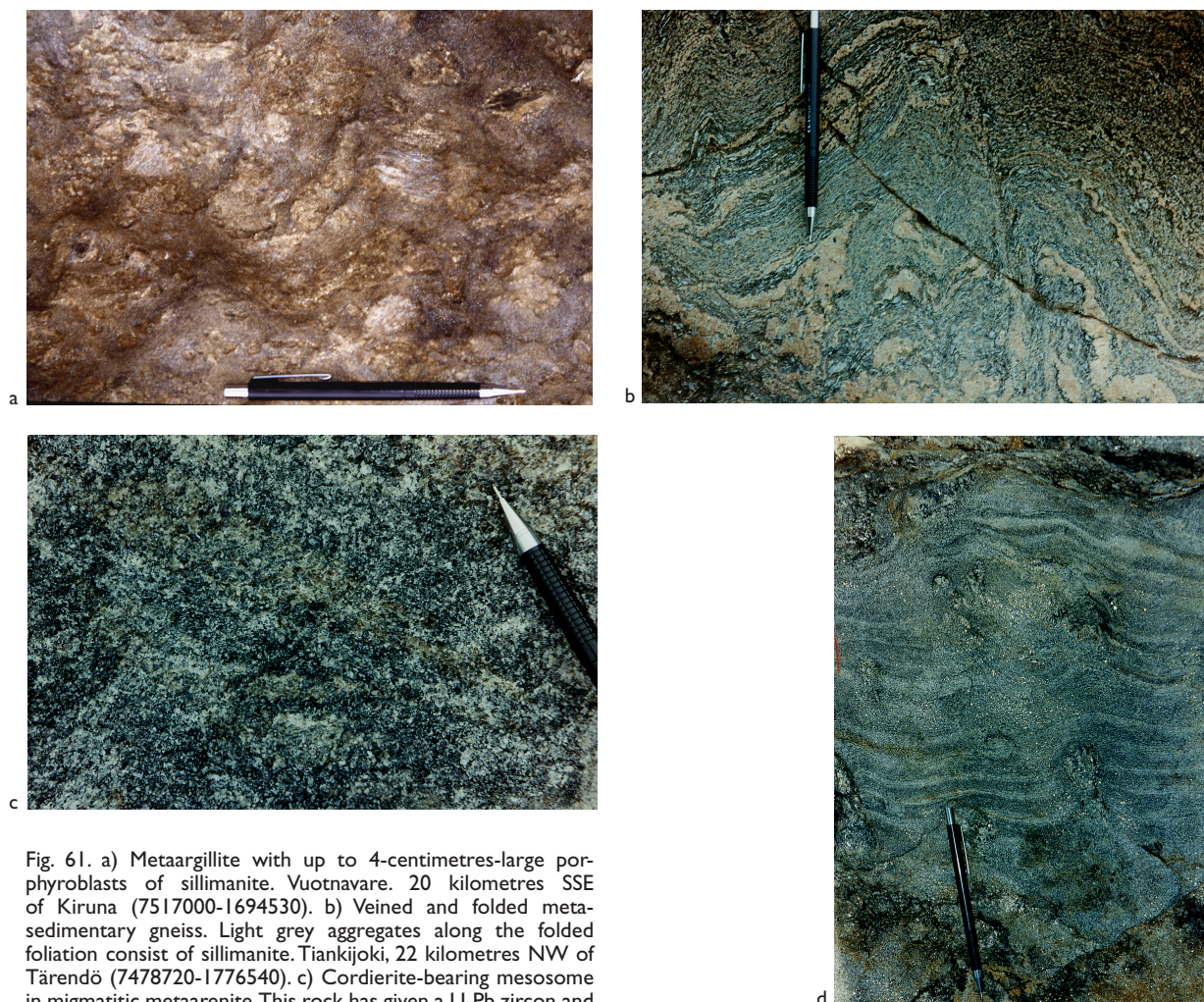


Fig. 61. a) Metaargillite with up to 4-centimetres-large porphyroblasts of sillimanite. Vuotnavare, 20 kilometres SSE of Kiruna (7517000-1694530). b) Veined and folded meta-sedimentary gneiss. Light grey aggregates along the folded foliation consist of sillimanite. Tiankijoki, 22 kilometres NW of Tärendö (7478720-1776540). c) Cordierite-bearing mesosome in migmatitic metaarenite. This rock has given a U-Pb zircon and monazite age of c. 1810 Ma (Bergman & Skiöld 1998). Pen points at purple cordierite crystals. Karivaara, 10 kilometres S of Pajala (7466570-1826940). d) Andalusite porphyroblasts in meta-sedimentary rock. Pahakurkio, 14 kilometres SSE of Masugnsbyn (7484840-1770100).

rim analyses were used. The results of the thermometric and barometric calculations are presented in Fig. 62 and Table 10. The polygons in Fig. 62 indicate the spread of analytical values from several measurements in each thin section.

The pressure-temperature results show that the northern part of Norrbotten county is a low to intermediate pressure province, metamorphosed under variable temperature conditions. Seven samples have pressures of 2–4 kbar, whereas the other two samples yield 6–7.5 kbar. As there are different episodes of metamorphism in the area,

the age of metamorphism is probably not the same for all samples. It is therefore unclear if the higher pressures record a separate event or if higher and lower pressures are recorded from the same event. Temperature values in medium-grade areas are in the range of 510–570°C. In high-grade areas, the values range between 615 and 805°C. It cannot be ruled out that some samples were affected by some retrograde reactions, which would affect the results. The studied Archaean rocks are also high-grade and yield temperatures of 665 and 715°C.

TABLE 6. Minerals present in analysed samples. Coordinates refer to the Swedish National Grid (RT 90). Abbreviations of rock types: T = tuffitic mafic metavolcanic rock, S = metasedimentary rock. Abbreviations of stratigraphic units: A = Archaean rocks, Gg = Greenstone group, Smr = Svecofennian metasedimentary rocks.

Sample	Kä98:4-2	STB951021C	PAC940026D	PAC961021A	STB971108	STB971001	STB951052	PAC950581	STB940051
N-S	7495860	7473800	7537980	7591830	7516160	7587830	7504120	7643500	7494770
E-W	1805370	1815220	1711520	1787900	1693590	1733420	1839320	1691550	1698250
Locality	Käymäjärvi	Koijuvaara	Sautusvaara	Paittasjärvi	Vuotnavare	Järkastaka	Ristimella	Rästojaure	Killinge
Rock type/unit	T/Gg	S/Smr	S/Gg	S/Gg	S/Smr	S/A	T/Gg	S/A	S/Smr
garnet	x	x	x	x	x	x	x	x	x
biotite	x	x	x	x	x	x	x	x	x
quartz	x	x	x	x	x	x	x	x	x
plagioclase	x	x	x	x	x	x	x	x	x
K-feldspar			x	x					
muscovite									
sillimanite		x		x		x	x	x	
andalusite		x				x			
staurolite		x							
cordierite				x	x			x	x
amphibole			x		x		x		
ilmenite	x	x	x	x	x	x	x	x	x
magnetite		x					x		
zircon	x	x	x	x	x	x	x	x	x
monazite	x	x		x	x	x		x	x
xenotime		x			x				
other phases	Fe-sulphide	tourmaline, Cu-Fe- sulphide	albite, prehnite	chlorite		carbonate, titanite	Fe-sulphide		

TABLE 7. Microprobe analyses (weight-%) of garnet. The cations were calculated on the basis of 24 oxygens. $X_{Alm} = Fe / (Fe + Mg + Mn + Ca)$, $X_{Grs} = Ca / (Fe + Mg + Mn + Ca)$, $X_{Sps} = Mn / (Fe + Mg + Mn + Ca)$, $X_{Pyr} = Mg / (Fe + Mg + Mn + Ca)$.

Sample Analysis #	K3984-2 140	STB951021C T6/19	PAC940026D T8/53	PAC961021A T1/13	STB971108 T3/57	STB971001 T4/32	STB951052 T7/46	PAC950581 T2/24	STB940051 T6/13
SiO ₂	37.08	36.72	37.31	35.64	36.74	36.44	36.73	37.17	37.46
Al ₂ O ₃	20.97	20.42	20.85	21.27	21.67	21.26	21.10	21.75	21.19
FeO	36.71	31.82	35.25	34.11	33.35	33.99	32.89	31.32	30.88
MnO	1.26	6.78	1.56	2.49	2.18	4.92	1.53	0.61	1.61
MgO	2.41	2.10	3.02	4.49	4.93	2.46	4.68	7.56	6.78
CaO	1.97	1.75	2.23	0.93	1.40	1.44	2.84	1.32	1.33
Total	100.51	99.61	100.47	98.93	100.34	100.54	99.78	99.79	99.25
Si	5.98	6.00	5.99	5.81	5.86	5.90	5.89	5.86	5.95
Al	3.99	3.93	3.94	4.09	4.08	4.06	3.99	4.04	3.97
Fe	4.95	4.35	4.73	4.65	4.45	4.60	4.41	4.13	4.10
Mn	0.17	0.94	0.21	0.34	0.29	0.68	0.21	0.08	0.22
Mg	0.58	0.51	0.72	1.09	1.17	0.59	1.12	1.78	1.60
Ca	0.34	0.31	0.38	0.16	0.24	0.25	0.49	0.22	0.23
Total	16.03	16.04	16.03	16.15	16.11	16.08	16.11	16.12	16.07
X_{Alm}	0.82	0.71	0.78	0.74	0.72	0.75	0.71	0.66	0.67
X_{Grs}	0.06	0.05	0.06	0.03	0.04	0.04	0.08	0.04	0.04
X_{Sps}	0.03	0.15	0.04	0.06	0.05	0.11	0.03	0.01	0.04
X_{Pyr}	0.10	0.08	0.12	0.17	0.19	0.10	0.18	0.29	0.26

TABLE 8. Microprobe analyses (weight-%) of biotite. The cations were calculated on the basis of 22 oxygens.

Sample Analysis #	Ka984-2 137	STB951021C 110	PAC940026D 123	PAC961021A 34	STB971108 56	STB971001 66	STB951052 154	PAC950581 44	STB940051 97
SiO ₂	36.14	34.55	36.32	35.83	37.05	34.38	36.14	36.95	36.50
TiO ₂	1.28	1.26	1.75	3.19	1.29	2.75	3.23	2.08	2.73
Al ₂ O ₃	17.56	19.06	16.35	18.31	18.28	19.10	15.67	17.88	17.03
FeO	21.91	20.21	20.50	16.81	17.09	22.21	18.68	13.96	16.13
MnO	0.02	0.11	0.01	0.01	0.02	0.08	0.02	0.01	0.09
MgO	9.93	9.71	11.14	11.08	12.37	7.44	11.47	14.14	12.65
CaO	0.05	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.05
Na ₂ O	0.32	0.21	0.21	0.27	0.36	0.21	0.14	0.23	0.17
K ₂ O	7.37	9.19	8.11	9.10	8.23	9.04	9.16	9.06	9.36
Total	94.59	94.30	94.42	94.60	94.70	95.21	94.50	94.30	94.72
Si	5.54	5.35	5.57	5.42	5.56	5.31	5.54	5.51	5.51
Ti	0.15	0.15	0.20	0.36	0.15	0.32	0.37	0.23	0.31
Al ^(iv)	2.46	2.65	2.43	2.58	2.44	2.69	2.46	2.49	2.49
Al ^(vi)	0.72	0.82	0.53	0.68	0.79	0.79	0.37	0.66	0.53
Fe	2.81	2.61	2.63	2.13	2.14	2.87	2.39	1.74	2.04
Mn	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.01
Mg	2.27	2.24	2.55	2.50	2.77	1.71	2.62	3.15	2.85
Ca	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Na	0.10	0.06	0.06	0.08	0.11	0.06	0.04	0.07	0.05
K	1.44	1.81	1.59	1.76	1.57	1.78	1.79	1.73	1.80
Total	15.49	15.71	15.57	15.51	15.52	15.55	15.59	15.57	15.60
Fe/(Fe+Mg)	0.55	0.54	0.51	0.46	0.44	0.63	0.48	0.36	0.42

TABLE 9. Microprobe analyses (weight-%) of plagioclase. The cations were calculated on the basis of 8 oxygens. $X_{An} = Ca/(Ca+Na+K)$, $X_{Ab} = Na/(Ca+Na+K)$, $X_{Or} = K/(Ca+Na+K)$.

Sample Analysis #	Kå98-4-2 130	STB951021C 107	PAC940026D 105	PAC961021A 30	STB971108 47	STB971001 59	STB951052 168	PAC950581 40	STB940051 91
SiO ₂	54.18	63.06	55.81	62.44	60.90	59.71	54.29	59.18	61.17
Al ₂ O ₃	28.90	22.91	27.82	23.44	24.68	25.39	28.41	25.15	24.34
FeO	0.34	0.00	0.05	0.00	0.06	0.03	0.08	0.00	0.02
CaO	11.25	4.63	9.74	4.99	6.44	7.46	11.05	7.33	6.12
Na ₂ O	5.25	9.01	5.71	9.11	7.86	7.49	5.84	7.54	8.13
K ₂ O	0.02	0.06	0.03	0.04	0.02	0.09	0.04	0.06	0.07
Total	99.95	99.67	99.16	100.02	99.95	100.18	99.70	99.26	99.85
Si	2.45	2.80	2.52	2.77	2.71	2.66	2.46	2.66	2.72
Al	1.54	1.20	1.48	1.22	1.29	1.33	1.52	1.33	1.28
Fe	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.54	0.22	0.47	0.24	0.31	0.36	0.54	0.35	0.29
Na	0.46	0.77	0.50	0.78	0.68	0.65	0.51	0.66	0.70
K	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total	5.01	4.99	4.98	5.01	4.99	5.00	5.04	5.00	4.99
X_{An}	54.13	22.05	48.44	23.18	31.16	35.32	51.03	34.84	29.27
X_{Ab}	45.75	77.64	51.38	76.61	68.74	64.15	48.78	64.81	70.34
X_{Or}	0.12	0.31	0.18	0.21	0.10	0.53	0.20	0.35	0.40

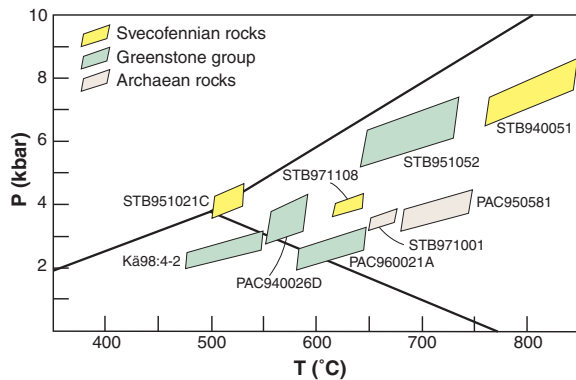


Fig. 62. Diagram of pressure-temperature determinations. Sample locations are shown in Fig. 60. Stability fields for the aluminosilicates are from Holdaway (1971).

TABLE 10. Results of thermobarometry. Method numbers refer to the following methods: 1. Garnet-biotite thermometry (Hodges & Spear 1982) and garnet-biotite-plagioclase-quartz barometry (Hoisch 1989), 2. Garnet-biotite thermometry and garnet-plagioclase-sillimanite-quartz barometry (Hodges & Spear 1982). Sample locations are shown in Fig. 60 and the results are plotted in Fig 62.

Sample	P (kbar)	T (°C)	Method
KÄ98:4-2	2.6	510	1
STB951021C	4.1	515	1
PAC940026D	3.6	570	1
PAC961021A	2.6	615	2
STB971108	4.0	630	2
STB971001	3.5	665	2
STB951052	6.2	690	1
PAC950581	3.8	715	2
STB940051	7.5	805	1

TECTONIC EVOLUTION OF THE NORTHERN PART OF NORRBOTTEN COUNTY

The nature and timing of Archaean events of deformation and metamorphism are poorly constrained, but one event occurred less than 2679 ± 12 Ma ago, which is the age of the youngest deformed Archaean rocks. The northwest-southeast-oriented foliation in the northernmost part of the map area was possibly formed at this time.

In the earliest Proterozoic, a continental rifting event started with the intrusion of ultramafic-mafic rocks at c. 2.44 Ga ago. The deposition of the Karelian supracrustal rocks and intrusions of extensive swarms of mafic dykes and sills, up to c. 2 Ga ago, reflect deposition in a rifting-related tectonic setting. The stratigraphical record of the well preserved rocks of the Greenstone group in the Kiruna area demonstrates a change from initial clastic sedimentation, evaporite deposition, and WPB-type (within-plate basalt) volcanism to later eruptions of MORB-type (mid-ocean ridge basalt) magmas in an extensive subaqueous basin (Martinsson 1997). Several types of stratiform-stratabound mineralisations were formed at this time. Shoaling of the basin and subsequent uplift and erosion mark the end of the rifting event and possibly an event of ductile deformation.

The Svecokarelian orogeny (c. 1.96–1.75 Ga ago) includes at least two major stages of rock formation, regional deformation, and low to intermediate pressure metamorphism in the map area. During the early stage (c. 1.96–1.86 Ga ago) there was an important change of magmatism and intensity of deformation at c. 1.88 Ga ago, possibly related to a shift from a subduction-related tectonic setting to an extensional environment (Martins-

son & Perdahl 1995). Within a very short time interval, the magmas changed from calc-alkaline or alkali-calcic (Porphyry group and Haparanda suite) to more alkaline compositions (Porphyry group and Perthite monzonite suite). This change was accompanied by rapid cessation of regional ductile deformation and metamorphism. The rocks of the Perthite monzonite suite, together with similar rocks south of the map area, form an approximately north-south trending belt, which may indicate an east-west extensional direction at that time. The younger Svecofennian metasedimentary rocks (e.g. at Stora Sjöfallet) were probably deposited in a continental environment after the main orogenic event. In the eastern part of the map area, the Jyryjoki granite (Granitoids, c. 1.86–1.84 Ga) is post-tectonic relative to a phase of regional deformation and high-grade metamorphism. This phase may be a late expression of the early stage of the Svecokarelian orogeny or a separate local event.

During the late stage (c. 1.86–1.75 Ga ago) of the Svecokarelian orogeny, the pre-existing rocks were reworked and three generations of new magmas were formed (Granite-pegmatite association, Granite-syenitoid-gabbroid association, and <1.8 Ga old gabbro, metagabbro and diabase). The regional deformation was inhomogeneous and largely confined to deformation zones (e.g. the Karesuando-Arjeplog deformation zone and the Pajala shear zone). The kinematic data collected in these zones show dominantly steep movement directions with western-side-up kinematics in the west and eastern-side-up kinematics in the east. Local observations of dextral movement, together with interpretations of impor-

tant dextral components from form lines and magnetic data, suggest that the deformation occurred in a dextral transpressive regime. Some of the large fold structures which are located near regional deformation zones may have formed earlier but attained their present shapes at this time. An east–west- to northeast–southwest-oriented shortening component of the regional deformation is consistent with available data. High-grade, low to intermediate pressure metamorphism was confined to the eastern and south-central parts of the map area, associated with deformation zones and intrusions of the Granite-pegmatite association at mid-crustal depths. These rocks were probably formed from melts that were generated during the high-grade metamorphism. The intrusions of the Granite-syenitoid-gabbroid association were formed deeper in the crust in connection with the input of mantle-derived magmas. These intrusions may have been important agents for heat transport from deep- to mid-

crustal levels. A large mafic intrusion below the present ground surface in the eastern part of the map area also caused extensive high-grade metamorphism and fed mafic intrusions at higher crustal levels. The magmatic and tectonic activity during the Svecokarelian orogeny promoted locally extensive hydrothermal alteration and formation of mineral deposits.

Faults and fracture zones were formed during several deformation events, at times associated with the formation of epigenetic mineral deposits. If the apparent fault displacements interpreted from magnetic data occurred during the same event, two conjugate fault systems indicate an approximately north–south shortening direction. Most late- to postglacial faults show eastern-side-up movement, and the Pärve fault was interpreted as having formed as a result of transpression with a northwest–southeast oriented compression direction (Riad 1990).

EXCURSION GUIDE

The five-day excursion provides an overview of the general geology of the northern part of Norrbotten county. The major aims of the excursion are to show examples of rock types from most of the major rock units and their geophysical properties, to show examples of different types of mineral deposits, and to demonstrate variations in structural style and metamorphic grade. Several key localities for the interpretation of the stratigraphic relationships and the structural development in the area are included. The excursion is designed to start and end in Kiruna, and to make overnight stops in Vittangi, Karesuando (alternatively, Karesuvanto in Finland), and Pajala.

Density values are given in kg/m³. The abbreviation "SUS" means magnetic susceptibility values (10⁻⁵ SI-

units) that have been measured with portable equipment on outcrop. "Susc x10⁻⁵" are magnetic susceptibility values measured on samples in the laboratory. "Suredata" refers to earlier collected petrophysical data and "NRM" stands for natural remanent magnetisation. The contents of the three elements potassium, uranium (in equivalents U), and thorium (in equivalents Th) were measured in situ by means of gamma ray spectrometry. The information in parentheses after the locality name (e.g. 29J 5f, 7526400-1675775) refers to the topographic map sheet, the square within the map sheet and the map coordinates (northing-easting) in the Swedish National Grid (RT 90).

Day 1 (half day)

1:1 Saarijärvi (29J 5f, 7526400-1675775)

Archaean granite and overlying sequence of Karelian supracrustal rocks:

a. Archaean light red, medium-grained granite with an age of 2710±4 Ma (ion-probe, Skiöld & Page 1998). Spaced low-grade foliation. SUS=20-400.

LUK949025 Density: 2608 Susc x10⁻⁵: 436 NRM (mA/m): 50 Q-value: 0.28

b. Increasing degree of alteration in weathering zone in the granite (7526510-1675875). Decreasing quartz content and growth of actinolite and scapolite.

c. Basal clastic breccia overlying the Archaean granite (7526500-1675950). Fragments of fine-grained and medium-grained granite (+metavolcanic rock?) in amphibole-rich matrix. The chemical composition of the matrix is different from that of the greenstones, and shows addition of Ca, Fe, Mg, and Cl.

d. Arenitic unit overlying the breccia (7526525-1675955). SUS=500-3 000. Strong scapolitisation. There are a few round, undeformed quartz pebbles in the arenite.

e. Volcaniclastic unit (50 m thick, 7526585-1675920) with green cm-thick beds alternating with strongly scapolitised beds. A 15-cm-wide metadiabase dyke cuts the bedding at a high angle. The scapolite content is 70-80 % in both the volcaniclastic rock and the metadiabase.

f. Metabasalt (7526610-1675930) in the lowest stratigraphical unit of the Greenstone group in the Kiruna area. Quartz-filled amygdules are 1-2 cm in size. The composition is tholeiitic WPB with a TiO₂ content of 1.6 %. Strong scapolitisation. SUS=2 000-7 000. Zircons from this locality have been dated to c. 2.7 Ga (ion probe, Skiöld & Page 1998).

If time permits, these localities can also be visited:

g. Fine-grained red dyke, possibly associated with the Porphyry group, in contact with the basal breccia (7526710-1675785). The dyke rock is similar to clasts in the breccia.

h. Massive scapolitised metadiabase, several generations of scapolite veins (7526795-1675790). SUS=20 000.

i. Facies variation of the basal breccia: polymict conglomerate with pebbles of granite, felsic volcanic rock and vein quartz (7526950-1675800). The conglomerate is overlain by bedded coarse sandstone and siltstone with dm-thick beds.

1:2 Koivu-Kuosanen (29K 4b, 7523700-1706050)

Weakly porphyritic quartz monzonite belonging to the Perthite monzonite suite. Dark grey plagioclase phenocrysts, in many cases with a thin light plagioclase rim. Enclaves can be observed. In biotite-rich parts a foliation and a lineation can be observed. The rock has a U-Pb zircon age of 1879 ± 7 Ma (Skiöld & Öhlander 1989).

1:3 Mertainen (29K 4c, 7521000-1710870)

Iron mine from the 1950s, total production c. 0.4 Mt. Apatite iron ore of breccia-type in metatrachyandesite (Porphyry group). In the waste dump, boulders with e.g. magnetite-cemented breccia, magnetite veins and disseminated magnetite can be found. Among the alteration minerals amphibole and scapolite are noted.

Previous petrophysical sampling has been made in the host rock. It is highly magnetic and is clearly discerned on the magnetic anomaly map.

Suredata (6 samples) Density: 2807 Susc $\times 10^{-5}$: 11223 NRM (mA/m): 7310 Q-value: 1.90

1:4 Ryyppö-Talli (29K 3h, 7519150-1737250)

"Booze pine" natural memorial. Red porphyritic granite (Perthite monzonite suite). There are several indications of magma mingling/mixing: Rapakivi texture, hybrid enclaves, skeletal plagioclase and dark anorthite-rich plagioclase. U-Pb zircon dating has yielded an age of 1863 or 1826 Ma (Skiöld 1981b).

Petrophysical values from samples collected from a similar granite c. 600 m to the NE.

LUK970070 Density: 2610 Susc $\times 10^{-5}$: 1067 NRM (mA/m): 140 Q-value: 0.32
LUK970070 K (%): 3.9 U (ppm): 1.8 Th (ppm): 21.5

Day 2

2:1 Mikkelirova (29K 5j, 7526100-1747050)

Road-cut in the northern part of the Vittangi gabbro (Perthite monzonite suite) which shows medium-grained, isotropic gabbro. Fine-grained parts exist. There are biotite-rich aggregates and pockets with blue quartz, plagioclase, biotite and pyrite.

Suredata Density: 2936 Susc $\times 10^{-5}$: 7734 NRM (mA/m): 2178 Q-value: 0.80
Average of 8 samples within an area 3 000 m south of stop 2:1.

2:2 Järkastakka (30K 7g, 7586730-1733600)

a. Archaean metagranitoids with metadiabase dykes. The dykes cut an Archaean N-S gneissic foliation, and they themselves have a NNE-oriented Svecokarelian foliation. Locally both foliations can be observed in the metagranitoids. U-Pb zircon dating from this locality has yielded ages of 2834 ± 40 Ma (protolith age) and c. 2.7 Ga (metamorphic age, Skiöld 1979b).

LUK960750 Density: 2627 Susc $\times 10^{-5}$: 233 NRM (mA/m): 15 Q-value: 0.22
LUK980022: K (%): 2.8 U (ppm): <0.5 Th (ppm): 1.5

The uranium contents are usually close to zero in the Archaean metagranitoids in this area. Thorium values vary from zero to maximum 10 ppm.

b. A few hundred metres to the east (7586540-1734040): Shear zone in metadiabase with folded foliation. The strain is heterogeneous and there are transitions from metadiabase to amphibolite mylonite. The shear sense is western-side-up.

LUK960760 Density: 3076 Susc $\times 10^{-5}$: 115 NRM (mA/m): 0 Q-value: 0

2:3 NW of hill 451 (30K 6i, 7582440-1745000)

Folded, intermediate metavolcanic rock (SUS=25–40) of possible Archaean age is intruded by pegmatite (SUS=0) and grey metagranite. All rocks are foliated.

Total radiation: 7–8 $\mu\text{R/h}$ in intermediate metavolcanic rock, 9 $\mu\text{R/h}$ in pegmatite. At other places in this area 23–27 $\mu\text{R/h}$ has been measured in pegmatite.

To the east there is a tectonic contact (western-side-up) towards strongly foliated to mylonitic feldspathic quartzite (Tjärro quartzite). Pale green mica and quartz veins are concentrated in a 50-cm-wide zone.

LUK961180	Granite?	Density: 2606	Susc x10 ⁻⁵ : 5	NRM (mA/m): 0	Q-value: 0
LUK961180	Granite?	K (%): 5.9	U (ppm): 30.5	Th (ppm): 51	
LUK961160	Quartzite	K (%): 1.5	U (ppm): 0.1	Th (ppm): 4.2	
LUK961170	Pegmatite	K (%): 5.3	U (ppm): 7.1	Th (ppm): 66.2	
LUK961190	Interm.metavolc.	K (%): 3.2	U (ppm): 5	Th (ppm): 20.2	

2:4 SE of hill 451 (30K 6j, 7581620-1745800)

Albite-bearing metadiabase dyke (U-Pb zircon age 1874 \pm 10 Ma, Skiöld 1981b) in greenstones of the Greenstone group. An older generation of albite-bearing metadiabase, with ages of c. 2.2 Ga, is common in the greenstone areas in Sweden and Finland.

LUK960640	Density: 2809	Susc x10 ⁻⁵ : 3605	NRM (mA/m): 180	Q-value: 0.12	Decl/incl: 225/60
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2:5 WSW Teukkavaara (30K 6j, 7580950-1746800)

Albite-carbonate alteration of greenstone and metadiabase. The degree of alteration varies within a >50 m wide zone. Albite-carbonate alteration is common in a belt between Karesuando and Svappavaara, partly affiliated with Cu-mineralisation.

The area has previously been extensively sampled for petrophysics. Within a 250 m radius 4 samples are registered.

Suredata (3 samples)	Density: 2642-2955	Susc x10 ⁻⁵ : 5667-15846	Q-value: 0.09-0.84		
TIP960090	Density: 2911	Susc x10 ⁻⁵ : 27286	NRM (mA/m): 7690	Q-value: 0.69	Decl/incl: 246/86

2:6 Teukkajärvi (30K 5-6j, 7580000-1749400)

Dark green Jatulian metabasalt and metadiabase (Greenstone group). Some zones in the metabasalt contain amygdules filled with quartz, carbonate or chalcopryrite. Heterogeneous deformation is indicated by both undeformed and strongly deformed amygdules. SUS=70–100. Total radiation: 1–1.5 $\mu\text{R/h}$.

2:7 S Luspavaara (30L 6a, 7580240-1750880)

Greenstone with variable degree of scapolitisation. Scapolite is partly found throughout the rock or concentrated in fractures or faults. Epidote alteration is also seen.

Suredata	Density: 2993-3167	Susc x10 ⁻⁵ : 74-95	Q-value: 0.08-0.16		
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2:8 Mertajärvi (30L 9c, 7598730-1762710)

Pegmatite cut by a few metres wide ductile shear zone. The stretching lineation plunges gently to the south. Inclusions of older rocks are common.

LUK960220	Density: 2575	Susc x10 ⁻⁵ : 2	NRM (mA/m): 10		
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If there is time the historical monument at Järämä, 15 km W of Karesuvanto in Finland, may be included in the visit. On the hillside to the monument there is an excellent exposure of a weathered Archaean metagranite overlain by Palaeoproterozoic conglomerate and quartzite.

Day 3

3:1 Paittasjärvi (30L 8i, 7590560-1791170)

Gneissose granodiorite and subordinate granite of the Haparanda suite. U-Pb zircon dating has yielded an age of 1880 ± 28 Ma (Skiöld 1979a). Small mafic inclusions exist. Pegmatite dykes and veins with varying degrees of deformation indicate that the pegmatite was formed during the deformation. $SUS=2\ 000$.

LUK960250	Density: 2747	Susc $\times 10^{-5}$: 1259	NRM (mA/m): 100	Q-value: 0.2
LUK960250	K (%): 2.6	U (ppm): 0.1	Th (ppm): 5	

Compare spectrometric data with chemical analysis.

3:2 Pingisvaara (30L 8i, 7593650-1794290)

"The table-tennis mountain". Grey, fine-grained, very strongly deformed granodioritic gneiss (Intrusive rocks, 1.86–1.84 Ga). Veins of at least four generations can be distinguished; some are isoclinally folded. Dating sample taken a few km to the north, in an area with the same rock, containing only few veins. The age, 1856 ± 8 Ma (magmatic zircons), indicates that this massif belongs to an intrusive suite with a less common age in northern Norrbotten county. It also indicates that the high-grade metamorphism is neither Archaean nor early Svecokarelian.

LUK960800	Density: 2656	Susc $\times 10^{-5}$: 603	NRM (mA/m) 40	Q-value: 0.16
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The following data come from a similar rock type from two localities, one 1 000 m to the south, one 4 km to the north.

TIP960220	Density: 2720	Susc $\times 10^{-5}$: 5152	NRM (mA/m) 190	Q-value: 0.16
TIP960260	Density: 3057	Susc $\times 10^{-5}$: 86	NRM (mA/m): 10	Q-value: 0.29
TIP960220	K (%): 1.8	U (ppm): 0.9	Th (ppm): 7.6	
TIP960260	K (%): 3.8	U (ppm): <0.5	Th (ppm): 20.6	

3:3 W Haikamavaara (30L 7j, 7585340-1796540)

Fine-grained banded gneiss, similar to the rock at stop 3:2 but much less deformed. In an outcrop 50 m from the road, a banded veined gneiss is crosscut by at least six generations of granite and pegmatite veins. Some bands are rich in pyroxene and amphibole. Average orientation of banding is NE–SW.

LUK960261 (Gneiss)	Density: 2615	Susc $\times 10^{-5}$: 768	NRM (mA/m): 30	Q-value: 0.1
LUK960261	K (%): 2.7	U (ppm): 1.5	Th (ppm): 14.4	
LUK960260 (Pegmatite)	Density: 2616	Susc $\times 10^{-5}$: 3225	NRM (mA/m): 310	Q-value: 0.24
LUK960260	K (%): 3.4	U (ppm): 0.9	Th (ppm): 22.4	

3:4 Palovaara (30M 4a, 7574760-1803540)

Finely banded metaarenite (interpreted as Svecofennian in age) with pegmatite veins. Banding and veins are folded, and there are small-scale shear zones.

LUK960270	Density: 2629	Susc $\times 10^{-5}$: 4	NRM (mA/m): 0	Q-value: 0
LUK960270	K (%): 3.8	U (ppm): <0.5	Th (ppm): 1.5	

3:5 Kivilaki (30M 4a, 7573700-1803280)

Fine-grained, vaguely banded amphibolite with conformable leucocratic veins. The amphibolite is locally pyroxene-bearing. $SUS=800-7\ 000$. Granite is subordinate. Similar amphibolites in Finland have been interpreted as Jatulian in age.

LUK960290	Density: 2907	Susc $\times 10^{-5}$: 6240	NRM (mA/m): 520	Q-value: 0.2
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3:6 Rukojoki (30M 2b, 7560700-1807680)

Reddish grey, K-feldspar porphyritic, strongly foliated granitoid (Haparanda suite). Inclusions of fine-grained amphibolite similar to that at stop 3:5. At least five generations of dykes or veins. At one pegmatite dyke an apparent "sindextral" deformation zone can be observed.

LUK961040 Density: 2667 Susc x10⁻⁵: 1689 NRM (mA/m): 640 Q-value: 0.93

3:7 Kursumaa (29M 8c, 7541100-1811830)

Reddish grey, fine grained granitic gneiss (Haparanda suite) crosscut by a weakly porphyritic, weakly foliated granite of Jyryjoki-type (Intrusive rocks, 1.86–1.84 Ga). The gneiss-forming event must have occurred before 1853 Ma ago, and late-Svecokarelian deformation and metamorphism is weak in this area. Pegmatite has partly intruded along the contact.

STB971085 Density: 2653 Susc x10⁻⁵: 2602 NRM (mA/m): 100

3:8 Puristakero (29M 8d, 7542480-1817540)

Metaquartzdiorite (Haparanda suite), thoroughly recrystallised but still showing a recognisable magmatic texture. There are two U-Pb zircon ages: 1880 Ma (Lindroos & Henkel 1981) and 1873±23 Ma (Skiöld 1981a). Veins and dykes of red granite and pegmatite.

BOM950215 Density: 2839 Susc x10⁻⁵: 1209 NRM (mA/m): 140 Q-value: 0.28

3:9 Naakajärvi (29M 5b, 7526000-1807620)

Deeply weathered gabbro dyke (<1.8 Ga old) intruded by granite and pegmatite. Ring-shaped gabbro intrusions of this type are found in several places in the eastern parts of the map area.

	Rock type	Density:	Susc x10 ⁻⁵ :	NRM (mA/m):	Q-value:	
BOM950104	Gabbro	3000	19061	920	0.12	Gabbro at stop 3:9
LUK950036	Gabbro	2860	9796	700	0.18	Gabbro slightly east of stop 3:9

Values below come from a granite south of the ring-structure (c. 1 000 m south of stop 3:9). Values are similar to Lina granite.

LUK950037A	Granite	2637	1598	247	0.374
LUK950037B	Granite	2595	933	67	0.173
LUK950037A	Granite	K (%): 4.9	U (ppm): 2.3	Th (ppm): 24.6	

3:10 Aareajoki (29M 2c, 7512100-1813300)

The last stop of the day is at the "kursu" at Aareajoki, a deep valley caused by the glacial erosion of a NW–SE brittle deformation zone. Rock types are red granite (Granite-pegmatite association) and gneissose monzonite (Haparanda suite) in the bottom of the valley. The deformation zone can be traced a long distance on the magnetic anomaly map, and it is part of an extensive system of brittle NW–SE deformation zones, which is characteristic for the eastern parts of the map area. These zones are also visible on VLF-maps, where available.

Granite:
LUK950052: Density: 2606 Susc x10⁻⁵: 37 NRM (mA/m): 10 Q-value: 0.66

Gneissose monzonite:
LUK950056: Density: 2787 Susc x10⁻⁵: 781 NRM (mA/m): 67 Q-value: 0.22

Day 4

4:1 Karivaara (28M 3f, 7466570-1826940)

Banded Svecofennian metaarenite, locally with purple cordierite, which is representative for the metaarenitic gneisses that occupy large areas of S of Pajala. This locality lies within a low-strain zone in the Pajala shear zone. Metamorphic zircon and monazite from the metaarenite have yielded an age of c. 1810 Ma (Bergman & Skiöld 1998).

Suredata: Density: 2770 Susc x10⁻⁵: 728 NRM (mA/m): 554 Q-value: 1.83

Average of 5 metaarenite samples collected within a radius of 5 km from stop 4:1.

Suredata Density: 2783 Susc x10⁻⁵: 1703 NRM (mA/m): 3248 Q-value: 1.42
LUK980013 K (%): 1.6 U (ppm): 1.5 Th (ppm): 8
LUK980014 K (%): 1.8 U (ppm): 1.4 Th (ppm): 8.9
(c. 80 metres distance between these two measurements)

4:2 Käymäjärvi (28M 9b, 7495870-1805520)

Stratigraphic profile in the Ludikovian rocks in the upper part of the Greenstone group:

a. Picritic lapilli tuff with 44 % SiO₂, 19.2 % MgO, 1300 ppm Cr. It occupies the core of an anticline, flanked by tuff-tuffite, BIF, graphite schist and dolomite. The zircon age of the picrite is 2055+146/-117 Ma (SGU, unpublished results)

STB951023 Density: 3087 Susc x10⁻⁵: 2286 NRM (mA/m): 4990 Q-value: 5.36

b. Tuff to tuffite (7495830-1805400), partly graphitic and impregnated by sulphide, and locally rich in garnet.

c. Silicate-facies BIF (7495740-1805420), subordinate oxide-facies. Banding in dm–mm scale, with chert, silicates and magnetite. The total thickness of the banded sequence is c. 200 m. Metre-sections in drill cores contain 14–25 % Fe and 0.7–2.6 % Mn.

d. Dolomite (7494650-1805790), mostly of high purity with c. 22 % MgO and 29 % CaO. Small amounts of amphibole and locally chondrodite. In the lower part the dolomite is interlayered with tuffite. Total thickness 150–200 m.

On top of the dolomite there are Svecofennian intermediate metavolcanic rocks (1880±3 Ma, SGU, unpublished results) and clastic metasedimentary rocks, which may be correlated with the Pahakurkio group.

4:3 Loukkumaa (28M 9c, 7495820-1811050)

Pale red, isotropic, weakly porphyritic granite of the Granite-pegmatite association. In the northern part there is a c. 20-m-wide xenolith of cross-bedded metasedimentary rock with porphyroblasts of cordierite (?).

The density of the granite is 2 630 kg/m³ (average of 11 samples)

LUK980007 K (%): 3.9 U (ppm): 2.6 Th (ppm): 20.1

4:4 Viiksvaara (29L 0h, 7500020-1786280)

Weakly foliated, weakly porphyritic, locally banded monzonite (Granite-syenitoid-gabbroid association, 1797±15 Ma, SGU, unpublished results). Centimetre-sized aggregates of biotite exist.

BOM950180 Density: 2809 Susc x10⁻⁵: 6321 NRM (mA/m): 780 Q-value: 0.3
LUK980029 K (%): 3.3 U (ppm): 5.3 Th (ppm): 15.2

Both spectrometric and petrophysical properties (susceptibility between 3 000 x10⁻⁵ and 7 000 x10⁻⁵ SI) are typical for monzonites in the map area.

4:5 Masugnsbyn (28L 9d, 7497480-1767130)

Skarn-rich iron formation and dolomite in the upper part of the Greenstone group:

a. Magnetgruvan, skarn iron ore, discovered in 1642, mine production until the early 19th century. Later investigations have shown a total tonnage of 60 Mt ore containing 30 % Fe. Magnetite affiliated with amphibole-pyroxene-serpentine skarn and some Fe-sulphide. Locally relatively large amounts of chondrodite. Uranium-mineralised fractures have been discovered.

b. Dolomite quarry (7497380-1766900) run by Norrbottens Järnverk AB from 1952 to 1972, now run by LKAB. Dolomite is used as additive in pellets. The SiO₂ content is as low as 1.5 %, which is essential for industrial purposes. Olivine, amphibole, chlorite, pyrite and calcite exist in low amounts. The normally 100–200 m thick dolomite is the uppermost unit in the Greenstone group, and occurs between the greenstones and the Svecofennian supracrustal rocks. At the quarry the dolomite is thickened, and the thickness exceeds 300 m.

4:6 Pahakurkio (28L 6d, 7484800-1770220)

Svecofennian metasedimentary rocks:

a. Gently dipping, andalusite porphyroblastic mica schists. They are intruded by tourmaline-bearing pegmatite. Minor folds are consistently north-vergent. Towards the south the metamorphic grade increases and the aluminum silicate is sillimanite. Intercalations with intermediate metavolcanic rocks suggest that the metasedimentary rocks of the Pahakurkio group are of Svecofennian age.

Suredata Mica schist Density: 2804 Susc x10⁻⁵: 2285 NRM (mA/m): 283 Q-value: 0.91

Suredata represents the average of 5 samples of mica schist. The average of magnetisation is high, but there are large variations, probably due to magnetic banding.

Spectrometric measurements have been made on an outcrop with similar rocks 800 m W of 4:6:

LUK950022 K (%): 4.2 U (ppm): 16.3 Th (ppm): 5.3

b. Quartzite with layers rich in heavy minerals, cross bedding and ripple marks (7484800-1769100).

LUK950024 Density: 2649 Susc x10⁻⁵: 10 NRM (mA/m): 0 Q-value: 0
LUK950024 K (%): 2.5 U (ppm): 1.1 Th (ppm): 9.8

Day 5

5:1 Lehtovaara (29K 3j, 7515500-1745890)

In the south there is an outcrop by the road with a grey, foliated, enclave-bearing metamorphosed quartz monzonite (Haparanda suite). To the north and in the forest (7515620-1745900) there is a red enclave-bearing metamorphosed quartz monzonite with aplite dykes. This rock probably also belongs to the Haparanda suite. One sample from Lehtovaara is among a suite of samples that taken together have yielded a U-Pb zircon age of 1886±14 Ma (Skiöld 1988).

Suredata Density: 2633 Susc x10⁻⁵: 1293 NRM (mA/m): 147.8 Q_value: 0.28
LUK980021 Quartz monzonite K (%): 4.1 U (ppm): 1.3 Th (ppm): 7.5

5:2 Jälketkurkkio (29K 4h, 7522440-1737500)

Epigenetic copper mineralisation discovered in the beginning of the last century and which has been investigated by excavation. The mineralisation consists of breccia fillings and veins of pyrite-magnetite-chalcopyrite-calcite in albitised rocks (Greenstone group) associated with graphite schist and metadiabase. Biotite alteration, scapolitisation and pyrite impregnation can be seen in the wall rocks.

Suredata Density: 2899 Susc x10⁻⁵: 697 NRM (mA/m):645 Q-value: 1.99

Petrophysical data from 4 samples of metadiabase within 200 m of stop 5:2.

5:3 Nunasvaara (29K 4h, 7523390-1736280)

The graphite schists in the Greenstone group at Nunasvaara were discovered in 1910 and have been investigated several times. The latest investigation, made in the 1980s, concerned use as a fuel for heating in Kiruna. The graphite content varies between 20 and 37 % in a 15–30 m wide section. Iron sulphides are found as fracture mineralisation, and the sulphur content is commonly a few percent. Galena and sphalerite are locally found as late fracture mineralisations. A metadiabase sill has intruded in the lower part of the schists, and near the contact they are strongly albitised. The graphite schists are overlain by partly scapolitised mafic tuffs.

Petrophysical data from 2 samples of metadiabase near stop 5:3:

Suredata Density: 2948 Susc x10⁵: 2800 NRM (mA/m): 653 Q-value: 1.11

5:4 Gruvberget (29K 2-3d, 7515000-1719950)

a. Apatite iron ore in intermediate to mafic metavolcanic rocks (Porphyrite group). The deposit consists of 74 Mt ore containing 50–60 % Fe and 1 % P. The main part of the ore consists of hematite which is locally weathered to sand. The well-exposed northern part, however, is dominated by magnetite. Calcite and apatite are subordinate, and titanite is locally found. Scapolitised metadiabase dykes crosscut the ore.

b. An epigenetic copper mineralisation (7515115- 1719915) is found in the strongly altered wall rocks to the iron ore, mainly in the footwall. The copper mineralisation was discovered in 1654, and during the latter part of the 17th century nearly 1 000 tonnes of raw copper were produced in Svappavaara. The copper mineralisations with chalcopyrite and bornite are in the contact zone between the iron ore and its wall rocks, parallel to NE–SW metadiabase dykes. The host rocks to the mineralisations are associated with K-feldspar alteration, scapolitisation, garnet-pyroxene-amphibole skarn, scapolite and zeolites.

5:5 Valkeasiipivaara (29J 7g, 7539900-1684800)

Profile stratigraphically upwards in the upper part of the Greenstone group and the lower part of the Svecofennian supracrustal rocks.

a. Pillow lava with mid-ocean ridge basalt composition. Pillows with dark margins of devitrified glass. Amygdules, filled with chlorite and magnetite, occur along the margins. The space between pillows is filled by quartz. SUS=1 000–10 000.

b. Tuffite intercalation (7539800-1684850). Variably developed NNW–SSE foliation overprints N–S banding. A local jaspilite boulder is found near the outcrop.

c. Fine-grained serpentinite (7539800-1684900) with c. 5 mm pseudomorphs after pyroxene (?). The rock contains 27–28 % MgO and 1 500–2 000 ppm Cr. Fractures filled with chrysotile. The serpentinite can be followed 2–3 km on the magnetic anomaly map. SUS=20 000–30 000.

d. A c. 1 m wide dyke of quartz with carbonate in patches (7539740-1684900).

e. A thick flow of massive metabasalt which grades into pillow lava in the upper part (7539670-1684940). The composition is similar to low-K tholeiites. Actinolite porphyroblasts in plagioclase-actinolite matrix. SUS=100–200. Epidote veins strike NW–SE.

f. Primary contact between pillow lava of the Greenstone group and the Svecofennian Kurravaara conglomerate (7539700-1685000). The pebbles in the lower part of the conglomerate consist of greenstones and subordinate intermediate metavolcanic rocks. In the upper part the pebble material is dominated by intermediate metavolcanic rocks, with minor amounts of jasper, magnetite ore and carbonate rocks. SUS=10 000-15 000.

g. Kurravaara metaconglomerate and metasandstone (7539740-1685095). The conglomerate pebbles mainly consist of intermediate metavolcanic rocks.

h. Fine-grained, grey metadacite-metandesite (7539440-1685200). SUS=3 000–4 000. Intermediate metavolcanic rocks are found both as layers and pebbles in the metaconglomerate.

LUK941006 Metabasalt Density: 3027 Susc x10⁵: 23206 (mA/m): 5150 Q-value: 0.55 Decl/incl: 108/86

5:6 Luossavaara (29J 7h, 7538350-1685800)

Profile stratigraphically upwards through the Svecofennian rocks in the Kiruna area.

- a. Trachyandesitic lava of the Porphyry group, so-called syenite porphyry, with magnetite- and titanite amygdules. Strong albitisation. Dating of titanite has yielded an age of 1876 ± 6 Ma (Romer et al. 1994).
- b. Feldspar-porphyrific metarhyodacite, so-called quartz-bearing porphyry (7538620-1686180), of the Porphyry group.

LUK980032 K (%): 3.3 U (ppm): 1.7 Th (ppm): 18.7

The petrophysical data represents an average of 11 metarhyodacite samples from the centre of Kiruna town. This metavolcanic rock always has high magnetic susceptibility. High Q-values are common. Compare with values from Mertainen (stop 1:4)

Suredata Density: 2680 Susc $\times 10^6$: 5452 NRM (mA/m): 3850 Q-value: 2.06

- c. Trench through the unit called Lower Hauki (7538790-1686440) with strongly deformed and altered metavolcanic rocks (with the local names "Rektor porphyry" and "Hauki syenite porphyry"), iron ore and fragment-bearing rocks.
- d. Metasedimentary rocks, mainly conglomeratic with pebbles of iron ore and porphyritic rocks (7538720-1686540). The local name for this unit is Middle Hauki.
- e. Feldspathic quartzite with cross bedding and some conglomeratic layers (7538500-1686750). This unit belongs to the Younger Svecofennian supracrustal rocks and has the local name "Upper Hauki".

REFERENCES

- Adamek, P.M., 1975: Geology and mineralogy of the Kopparåsen uraninite-sulphide mineralization, Norrbotten County, Sweden. *Sveriges geologiska undersökning C 712*, 69 pp.
- Ambros, M., 1970: *Vinkeldiskordans mellan två bergartsgrupper i norra Norrbottens urberg*. Unpublished licentiate thesis. Stockholm University. 13 pp.
- Ambros, M., 1980: Beskrivning till berggrundskartorna Lannavaara NV, NO, SV, SO och Karesuando SV, SO. *Sveriges geologiska undersökning Af 25–30*, 111 pp.
- Bergman, J., 1993: Report of field work in Saarijärvi and Pahtohavare SE. In O. Martinsson, J.-A. Perdahl & J. Bergman: *Greenstone and porphyry hosted ore deposits in northern Norrbotten, NUTEK Project nr 92-00752P*, 1-11.
- Bergman, S. & Kübler, L., 1995: Referenskartan i norra Norrbotten. In C.-H. Wahlgren (ed.): *Regional berggrundsgeologisk undersökning – sammanfattning av pågående undersökningar 1994, Sveriges geologiska undersökning Rapporter och meddelanden 79*, 126–132.
- Bergman, S. & Kübler, L., 1996: Berggrundsgeologiska och geofysiska synteskartor över norra Norrbotten. In C.-H. Wahlgren (ed.): *Regional berggrundsgeologisk undersökning – sammanfattning av pågående undersökningar 1995, Sveriges geologiska undersökning Rapporter och meddelanden 84*, 130–139.
- Bergman, S. & Kübler, L., 1997: Berggrundsgeologiska och geofysiska synteskartor över norra Norrbotten. In C.-H. Wahlgren (ed.): *Regional bedrock mapping – summary of ongoing activities 1996 with an introduction in English, Sveriges geologiska undersökning Rapporter och meddelanden 89*, 102–113.
- Bergman, S. & Kübler, L., 1998: Berggrundsgeologiska och geofysiska synteskartor över norra Norrbotten. In C.-H. Wahlgren (ed.): *Regional bedrock mapping – summary of ongoing activities 1997 with an introduction in English, Sveriges geologiska undersökning Rapporter och meddelanden 97*, 95–103.
- Bergman, S. & Kübler, L., 1999: Berggrundsgeologiska och geofysiska synteskartor över norra Norrbotten. In C.-H. Wahlgren (ed.): *Regional bedrock mapping – summary of ongoing activities 1998 with an introduction in English, Sveriges geologiska undersökning Rapporter och meddelanden 98*, 142–144.
- Bergman, S. & Skiöld, T., 1998: Implications of ca 1.8 Ga metamorphic ages in the Pajala area, northernmost Sweden. 23. *Nordiske Geologiska Vintermode, Århus 1998, Abstract Volume*, 32.
- Bergström, R., 1986: Prospektering efter magnesiumrika bergarter för tillsatsmedel i pellets Diamantborrning Ädnåvare. Unpublished report, *LKAB K86-35*, 13 pp.
- Bergström, R., 1987: Nunasvaara grafitfyndighet. Unpublished report, *LKAB K87-4*, 11 pp.
- Bergström, R., 1988: Prospektering efter magnesiumrika bergarter för tillsatsmedel i pellets. Årsrapport 1986. Unpublished report, *LKAB, K88-16*, 15 pp.
- Berthelsen, A. & Marker, M., 1986: 1.9-1.8 Ga old strike-slip megashears in the Baltic Shield, and their plate tectonic implications. *Tectonophysics* 128, 163–181.
- Bida, J., 1981: Industrimineralverksamhet 1980, årsrapport. Unpublished report, *LKAB, PRO 81-06*, 11 pp.
- Bjørlykke, A., Hagen, R. & Söderholm, K., 1987: Bidjovagge copper-gold deposit in Finnmark, northern Norway. *Economic Geology* 82, 2059–2075.
- Blake, K.L., 1992: *The petrology, geochemistry and association to ore formation of the host rocks of the Kiirunavaara magnetite-apatite deposit, northern Sweden*. Unpublished Ph.D. Thesis, University of Wales, College of Cardiff, 326 pp.
- Brown, G.C., 1982: Calc-alkaline intrusive rocks: their diversity, evolution, and relation to volcanic arcs. In R.S. Thorpe (ed.): *Andesites*, 437–461. John Wiley & Sons, New York.
- Cliff, R.A., Rickard, D. & Blake, K., 1990: Isotope systematics of the Kiruna magnetite ores, Sweden: Part 1. Age of the ore. *Economic Geology* 85, 1770–1776.
- Dahlman, B., 1971: Sammanställning av mineralförekomster och mineralindikationer i Norrland. Unpublished report, *Sveriges geologiska undersökning BRAP 83686–83692*, 65 pp.
- Danielson S., 1984: Nautanen, geologi och resultat av 1983 års diamantborrning. Unpublished report, *SGAB, PRAP 84007*, 15 pp.
- Danielson S., 1985: Nautanen, geologi och resultat av 1985-års diamantborrning. Unpublished report, *SGAB, PRAP 85090*, 15 pp.
- Danielsson S., 1987: Geologisk beskrivning över Nautanen–Aitik–Järbojokisträket i Gällivare. Unpublished report, *SGAB, PRAP 87055*, 15 pp.
- Debon, F. & Le Fort, P., 1983: A chemical-mineralogical classification of common plutonic rocks and associations. *Transactions of Royal Society of Edinburgh, Earth Sciences* 73, 135–149.
- Drake, B., 1992: Aitik copper mine. *Geologi* 44, 19–23.
- Dunlop, D.J. & Özdemir, Ö., 1997: *Rock magnetism. Fundamentals and frontiers. Cambridge studies in magnetism*. Cambridge University press. 573 pp.
- Eilu P., 1993: Hydrothermal alteration in some volcano-sedimentary associations in central Finnish Lapland. *Geological Survey of Finland Special Paper* 18, 5–13.
- Ekström, T., 1978: Koboltförande pyrit i två profiler från Kiskamavaara. Unpublished report, *Sveriges geologiska undersökning BRAP 78001*, 6 pp.
- Eriksson, B. & Hallgren, U., 1975: Beskrivning till berggrundskartbladen Vittangi NV, NO, SV, SO. *Sveriges geologiska undersökning Af 13–16*, 203 pp.
- Eriksson, T., 1954: Pre-Cambrian geology of the Pajala district, northern Sweden. *Sveriges geologiska undersökning C 522*, 38 pp.
- Ettner, C.D., Bjørlykke, A., & Andersen, T., 1993: Fluid evolution and Au-Cu genesis along a shear zone: a regional fluid inclusion study of a shear zone-hosted alteration and gold and copper mineralization in the Kautokeino greenstone belt, Finnmark, Norway. *Journal of Geochemical Exploration* 49, 233–267.
- Filén, B., 1976: *Geologin kring Pahtajärvi NNV om Vittangi*. Pro gradu-avhandling vid Geologisk-mineralogiska institutionen vid Åbo Akademi, 62 pp.
- Filén, B., Gerdin, P., Lundmark, L.-G. & Renberg, A., 1988:

- PGE – 1987, etapp II, analysresultat. Unpublished report, *PRAP 88005*, 25 pp.
- Forsell, P., 1987: The stratigraphy of the Precambrian rocks of the Kiruna district, northern Sweden. *Sveriges geologiska undersökning C 812*, 36 pp.
- Fredholm, K.A., 1886: Öfversigt af Norrbottens geologi inom Pajala, Muonionalusta och Tärändö socknar. *Sveriges geologiska undersökning C 83*, 39 pp.
- Fredholm, K.A., 1891: Bergarter och malmer i Luossavaara och Kiirunavaara. *Geologiska Föreningens i Stockholm Förhandlingar 13*, 266–270.
- Fredriksson, G., Hammarbäck, S., Magnusson, J. & Johansson, L., 1985: Projekt nordöstra Norrbotten. Delprojekt 4928 Vittangiområdet. Unpublished report, *LKAB-PAB S:85-02*, 26 pp.
- Frietsch, R., 1960: En zon av kaolinlera och vittrad blodsten vid Svappavaara, Norrbotten. *Sveriges geologiska undersökning C 572*, 45 pp.
- Frietsch, R., 1966: Berggrund och malmer i Svappavaarafältet, norra Sverige. *Sveriges geologiska undersökning C 604*, 282 pp.
- Frietsch, R., 1974: The Ekströmsberg iron ore deposit, northern Sweden. *Sveriges geologiska undersökning C 708*, 52 pp.
- Frietsch, R., 1978: On the magmatic origin of iron ores of the Kiruna type. *Economic Geology 73*, 478–485.
- Frietsch, R., 1979: Petrology of the Kurravaara area northeast of Kiruna, northern Sweden. *Sveriges geologiska undersökning C 760*, 81 pp.
- Frietsch, R., 1982: On the chemical composition of the ore breccia at Luossavaara, northern Sweden. *Mineralium Deposita 17*, 239–243.
- Frietsch, R., 1985: The Lannavaara iron ores, northern Sweden. *Sveriges geologiska undersökning C 807*, 55 pp.
- Frietsch, R., 1991: Register över Svenska fyndigheter av malmmineral och industriella mineral och bergarter. Forskningsrapport, *TULEA 1991:04*, Luleå University of Technology, 340 pp.
- Frietsch, R., 1997: The iron ore inventory programme 1963–1972 in Norrbotten county. *Sveriges geologiska undersökning Rapportier och Meddelanden 92*, 77 pp.
- Frietsch, R. & Perdahl, J.-A., 1995: Rare earth elements in apatite and magnetite in Kiruna-type iron ores and some other iron ore types. *Ore Geology Reviews 9*, 489–510.
- Frietsch, R., Tuisku, P., Martinsson, O. & Perdahl J.-A., 1997: Cu-(Au) and Fe ore deposits associated with Na-Cl metasomatism in early Proterozoic rocks of northern Fennoscandia: A new metallogenic province. *Ore Geology Reviews 12*, 1–34.
- Geijer, P., 1910: *Igneous rocks and iron ores of Kiirunavaara, Luossavaara and Tuolluwaara*. Scientific and practical researches in Lapland arranged by Luossavaara–Kiirunavaara Aktiebolag, Stockholm, 278 pp.
- Geijer, P., 1918a: Nautanenområdet, en malmgeologisk undersökning. *Sveriges geologiska undersökning C 283*, 104 pp.
- Geijer, P., 1918b: Det grafit- och järnmalmsförande området vid Vittangi. *Sveriges geologiska undersökning C 284*, 106 pp.
- Geijer, P., 1919a: Recent developments at Kiruna. *Sveriges geologiska undersökning C 288*, 22 pp.
- Geijer, P., 1919b: Sveriges fosfattillgångar. *Sveriges geologiska undersökning C 294*, 64 pp.
- Geijer, P., 1925: Eulysitic iron ores in northern Sweden. *Sveriges geologiska undersökning C 324*, 15 pp.
- Geijer, P., 1929: Masugnsbyfältens geologi. *Sveriges geologiska undersökning C 351*, 39 pp.
- Geijer, P., 1930a: Gällivare malmfält. *Sveriges geologiska undersökning Ca 22*, 115 pp.
- Geijer, P., 1930b: On the iron-rich norite of Akkavare (Sjaunja). *Geologiska Föreningens i Stockholm Förhandlingar 52*, 391–397.
- Geijer, P., 1931a: The iron ores of the Kiruna type. Geographical distribution, geological characters, and origin. *Sveriges geologiska undersökning C 367*, 39 pp.
- Geijer, P., 1931b: Berggrunden inom malmtrakten Kiruna–Gällivare–Pajala. *Sveriges geologiska undersökning C 366*, 225 pp.
- Geijer, P., 1950: The Rektorn ore body at Kiruna. *Sveriges geologiska undersökning C 514*, 18 pp.
- Geijer, P., 1967: Internal features of the apatitebearing magnetite ores. *Sveriges geologiska undersökning C 624*, 32 pp.
- Geijer, P. & Ödman, O.H., 1974: The emplacement of the Kiruna iron ores and related deposits. *Sveriges geologiska undersökning C 700*, 48 pp.
- Gerdin, P. & Minell, H., 1981: Äggojaure. Unpublished report, *Sveriges geologiska undersökning BRAP 81038*, 11 pp.
- Gerdin, P., Theolin, T. & Johansson, L., 1983: Ruutusoive. Unpublished report, *SGAB PRAP 83077*, 18 pp.
- Gerdin, P., Johansson, L., Hansson, K.-E., Holmqvist, A., & Ottosson, D., 1990: Grafit-uppslagsgenerering i Norrbotten 1990. Unpublished report, *SGAB PRAP 90068*, 77 pp.
- Gorbatshev, R. & Bogdanova, S. 1993: Frontiers in the Baltic Shield. *Precambrian Research 64*, 3–21.
- Grip, E., 1978: Sweden. In S.H.U. Bowie, A. Kvalheim & H.W. Haslam (eds.): *Mineral deposits of Europe, Volume 1: Northwest Europe*, 93–198. The Institution of Mining and Metallurgy, The Mineralogical Society.
- Grip, E. & Frietsch, R., 1973: *Malm i Sverige 2, norra Sverige*. Almqvist & Wiksell, 295 pp.
- Gustafsson, B., 1985: Fältarbeten 1984 inom delprojektområde Gällivare, Gällivare SV och SO. Slutrapport. Unpublished report, *SGAB PRAP 85005*, 16 pp.
- Gustafsson, B., 1993: The Swedish Norrbotten Greenstone Belt. A compilation of available information concerning exploration. Unpublished report, *NSG nr 93003*, 52 pp.
- Gustafsson, B. & Johansson, L., 1984: Ferrum kopparfyndighet. Unpublished report, *SGAB PRAP 84158*, 8 pp.
- Hålenius, U., 1983: En malmmineralogisk undersökning av Cu-Au mineraliseringen Nautanen. Unpublished report, *SGAB PRAP 83084*, 6 pp.
- Hålenius, U., 1986: Pahtohavare, A-zonen, malmmineralogi. Unpublished report, *SGAB PRAP 86054*, 7 pp.
- Hålenius, U., 1989: Mineralogi sydöstra Pahtohavare. Unpublished report, *SGAB PRAP 89010*, 17 pp.
- Hålenius, U. & Einarsson, Ö., 1989: Naakajärvi, kemisk och mineralogisk undersökning av kvarts och fältspat. Unpublished report, *SGAB PRAP 89020*, 5 pp.
- Hallgren, U., 1969: *Järnmalmerna inom Sautusvaara–Leppäkoskiområdet*. Unpublished licentiate thesis, Stockholm University, 160 pp.
- Hallgren, U., 1979: Berggrundskartorna 30 K Soppero NV, NO, SV, SO. *Sveriges geologiska undersökning Af 31–34*.

- Hallgren, U., 1982: Berggrundskartorna 31K Naimakka NV, NO, SV, SO. *Sveriges geologiska undersökning Ai 1–4*.
- Hallgren, U., 1983a: Berggrundskartan Terriksröset. *Sveriges geologiska undersökning Ai 5*.
- Hallgren, U., 1983b: Berggrundskartan Kummavuopio. *Sveriges geologiska undersökning Ai 6*.
- Hansson, K.-E., 1986: Diamantborrning 1985. Honkavaara, Kallioma and Muotkapalo. Unpublished report, *LKAB K86-30*, 13 pp.
- Hansson, K.-E., 1987: Torneträskområdet - diamantborrning. Slutrapport. Unpublished report, *LKAB K87-07*, 8 pp.
- Hansson, K.-E., 1989: Malmberget Södra. Årsrapport. Unpublished report, *LKAB K89-03*, 16 pp.
- Hansson, K.-E., 1991: Program för utökad prospektering, slutrapport 1991. Unpublished report, *SGAB PRAP 91017*, 9 pp.
- Hansson, K.-E., Martinsson, O. & Rönkkö, K., 1984: *Nordöstra Norrbotten. Delprojekt Pajala och Käymjärvi*. Unpublished report, K-84-32, 24 pp.
- Hedin, J.-O., 1984: Projekt 4014. Borrning på konstaterad bentonitförekomst Saivo, belägen på kartbladet 29J Kiruna SO. Unpublished report, *LKAB K84-30*, 4 pp.
- Henkel, H., 1976: Studies of density and magnetic properties of rocks from northern Sweden. *Pageoph 114*, 235–249.
- Henkel, H. 1978. Density as a tectonic motor – diapirism in Northern Sweden from magnetic, gravity – and petrophysical interpretation. *Geoskrifter 10*, 59–74.
- Henkel, H., 1991: Magnetic crustal structures in northern Fennoscandia. *Tectonophysics 192*, 57–79.
- Hiltunen, A., 1982: The Precambrian geology and skarn iron ores of the Rautuvaara area, northern Finland. *Geological Survey of Finland Bulletin 318*, 1–133.
- Hitzman, M.W., Oreskes, N. & Einaudi, M.T., 1992: Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits. *Precambrian Research 58*, 241–287.
- Hodges, K.V. and Spear, F.S., 1982: Geothermometry, geobarometry and the Al_2SiO_5 triple point at Mt. Moosilauke, New Hampshire. *American Mineralogist 67*, 1118–1134.
- Hoisch, T.D., 1989: Empirical calibration of six geobarometers for the mineral assemblage quartz+muscovite+biotite+plagioclase+garnet. *Contributions to Mineralogy and Petrology 63*, 175–198.
- Holdaway, M.J., 1971: Stability of andalusite and the aluminum silicate phase diagram. *American Journal of Science 271*, 97–131.
- Holmqvist, A. & Nordström, H., 1986: Kvarterförekomsten Vuolep Räskeväre, Norrbottens län. Unpublished report, *Sveriges geologiska undersökning BRAP 86090*, 17 pp.
- Holmqvist, A., Karlberg, G. & Rankvist, T., 1989: Kvarterssammanställning. Unpublished report, *SGAB PRAP 89016*, 21 pp.
- Holmqvist, A., Johansson, A., Gerdin, P. & Ottosson, D., 1991: Grafit – uppslagsgenerering i Norrbotten 1991. Unpublished report, *SGAB PRAP 91045*.
- Holmqvist, P.J., 1905: Studien über die Granite von Schweden. *Bulletin of the Geological Institution of Uppsala VII*, 77–269.
- Idman, H., 1988: *Pre-Quarternary rocks, Sheet-1832-Ropi, Geological map of Finland 1:100 000*. Geological Survey of Finland.
- IUGS subcommission on the systematics of igneous rocks, 1973: Classification and nomenclature of plutonic rocks. Recommendations. *Neues Jahrbuch für Mineralogie, Monatshefte 1973, H4*, 149–164.
- Jacobsen, H., 1987: A case for upwards continuation as a standard separation filter for potential-field maps. *Geophysics 52*, 1138–1148.
- Karhu, J.A., 1993: Palaeoproterozoic evolution of the carbon isotope ratios of sedimentary carbonates in the Fennoscandian shield. *Geological Survey of Finland Bulletin 371*, 1–87.
- Kärki, A., Laajoki, K. & Luukas, J., 1993: Major Palaeoproterozoic shear zones of the central Fennoscandian Shield. *Precambrian Research 64*, 207–223.
- Kathol, B., 1989: Evolution of the rifted and subducted Late Proterozoic to Early Paleozoic Baltoscandian margin in the Torneträsk section, northern Swedish Caledonides. *Stockholm Contributions in Geology 42(1)*, 83 pp.
- Kathol, B. & Martinsson, O., 1999a: Bedrock map 30J Rensjön NV, scale 1:50 000. *Sveriges geologiska undersökning Ai 130*.
- Kathol, B. & Martinsson, O., 1999b: Bedrock map 30J Rensjön SV, scale 1:50 000. *Sveriges geologiska undersökning Ai 132*.
- Kihlstedt, P.G., Broman, P.G., Alm, B. & Siirak, J., 1974: *Undersökning av karbonatbergarter inom Pajala kommun*. Unpublished report, Norrlandsfonden, 13 pp.
- Korsman, K., Koistinen, T., Kohonen, J., Wennerström, M., Ekdahl, E., Honkamo, M., Idman, H. & Pekkala, Y. (eds.) 1997: *Bedrock map of Finland 1:1 000 000*. Geological Survey of Finland, Espoo, Finland.
- Krill, A., Kesola, R., Sjöstrand, T. & Stephens, M.B., 1988: *Metamorphic, structural and isotopic age map, Northern Fennoscandia. Scale 1:1 000 000*. Geological Surveys of Finland, Norway and Sweden.
- Kulling, O., 1964: Översikt över norra Norrbottensfjällens kaledonberggrund. *Sveriges geologiska undersökning Ba 19*, 1–166.
- Kumpulainen, R.A., 2000: The Palaeoproterozoic sedimentary record of northernmost Norrbotten, Sweden. Unpublished report, *Sveriges geologiska undersökning BRAP 200030*, 45 pp.
- Lagerbäck, R. & Witschard, F., 1983: Neotectonics in northern Sweden – geological investigations. *SKBF KBS Teknisk Rapport 83-58*, 58 pp.
- Landenberger, B. & Collins, W.J., 1996: Derivation of A-type granites from a dehydrated charnockitic lower crust: evidence from the Chaelundi Complex, eastern Australia. *Journal of Petrology 37*, 145–170.
- Large, D., 1980: Geological parameters associated with sediment-hosted, submarine exhalative Pb-Zn deposits: an empirical model for mineral exploration. *Geologisches Jahrbuch D40*, 59–129.
- Lehto, T., 1983: Projekt 4013 – sulfider i vulkaniter. Unpublished report, *LKAB K83-15*, 13 pp.
- Lehtonen, M., 1984: *Pre-Quarternary rocks, Sheet-2723-Muonio, Geological map of Finland 1:100 000*. Geological Survey of Finland.
- Lehtonen, M., 1988: On the geology of the Muonio area, western Finnish Lapland. In E. Marttila (ed.): *Archaean geology of the Fennoscandian Shield. Geological Survey of Finland, Special Paper 4*, 189–199.
- Lilljequist, R., 1980: Ultrabasitstråket Keukiskero och Kurko-

- vare. Unpublished report, *Sveriges geologiska undersökning BRAP 80026*, 15 pp.
- Lindblom, S., Broman, C. & Martinsson, O., 1996: Magmatic-hydrothermal fluids in the Pahtohavare Cu-Au deposit in greenstone at Kiruna, Sweden. *Mineralium Deposita* 31, 307–318.
- Lindroos, H., 1974: The stratigraphy of the Kaunisvaara iron ore district, northern Sweden. *Sveriges geologiska undersökning C 695*, 18 pp.
- Lindroos, H. & Henkel, H., 1978: Regional geological and geophysical interpretation of Precambrian structures in northeastern Sweden. *Sveriges geologiska undersökning C 751*, 19 pp.
- Lindroos, H. & Henkel, H., 1981: Beskrivning till berggrundskartorna och geofysiska kartorna Huuki NV/NO, SV, SO och Muonionalusta NV, SV/SO. *Sveriges geologiska undersökning Af 35–39*, 85 pp.
- Loberg, B.E.H. & Horndahl, A.-K., 1983: Ferride geochemistry of Swedish Precambrian iron ores. *Mineralium Deposita* 18, 487–504.
- Löfstrand, G., 1890: Om apatitens förekomst i Norrbottens län jämfördt med dess uppträdande i Norge. *Geologiska Föreningens i Stockholm Förhandlingar* 12, 145–192.
- Lundberg B., 1967: The Stora Sahavaara iron ore deposit, northern Sweden. *Sveriges geologiska undersökning C 620*, 37 pp.
- Lundberg, B. & Smellie, J.A.T., 1979: Painirova and Mertainen iron ores: two deposits of the Kiruna Iron Ore type in northern Sweden. *Economic Geology* 74, 1131–1152.
- Lundbohm, H., 1890: Apatitförekomster i Gellivare malmberg och kringliggande trakt. *Sveriges geologiska undersökning C 111*, 48 pp.
- Lundbohm, H., 1892: Apatitförekomster i Norrbottens malmberg. *Sveriges geologiska undersökning C 127*, 38 pp.
- Lundbohm, H., 1910: Sketch of the geology of the Kiruna district. *Geologiska Föreningens i Stockholm Förhandlingar* 32, 751–788.
- Lundegårdh, P.H., 1971: *Nyttosten i Sverige*, 248 pp. Almqvist & Wiksell.
- Lundqvist, J. & Lagerbäck, R., 1976: The Pärve Fault: A late-glacial fault in the Precambrian of Swedish Lapland. *Geologiska Föreningens i Stockholm Förhandlingar* 98, 45–51.
- Lundström, I., Persson, P.-O. & Bergström, U., 1999: Indications of early deformational events in the northeastern parts of the Skellefte field. Indirect evidence from geologic and radiometric data from the Stavträsk-Klintån area, Boliden map sheet. In S. Bergman (ed.): *Radiometric dating results 4. Sveriges geologiska undersökning C 831*, 52–69.
- McEnroe, S.A. & Brown, L.L., 2000: A closer look at remanence-dominated aeromagnetic anomalies: Rock magnetic properties and magnetic mineralogy of the Russell Belt microcline-sillimanite gneiss, northwest Adirondack Mountains, New York. *Journal of Geophysical Research* 105, 16437–16456.
- Malmqvist, D. & Parasnis, D.S., 1972: Aitik, geophysical documentation of a third generation copper deposit in north Sweden. *Geoexploration* 10, 149–200.
- Martinsson, E., 1986: Prospektering efter magnesiumrika bergarter för tillsatsmedel i pellets. Delprojekt 2, Mg-prospektering i gabbroida bergarter. Unpublished report, *LKAB K86-10*, 19 pp.
- Martinsson, O., 1992: The Viscaria and Pahtohavare sulfide deposits and the stratigraphy of the Kiruna greenstones. Unpublished report, *NUTEK Project nr 92-00752P*, Division of Applied Geology, Luleå University of Technology, 79 pp.
- Martinsson, O., 1993: Stratigraphy of greenstones in the eastern part of northern Norrbotten. In O. Martinsson, J.-A. Perdahl & J. Bergman: Greenstone and porphyry hosted ore deposits in northern Norrbotten, *NUTEK Project nr 92-00752P*, 1–5.
- Martinsson, O., 1994: Greenstone and porphyry hosted ore deposits in northern Norrbotten. Unpublished report, *NUTEK Project nr 92-00752P*, Division of Applied Geology, Luleå University of Technology, 42 pp.
- Martinsson, O., 1995: Greenstone and porphyry hosted ore deposits in northern Norrbotten. Unpublished report, *NUTEK Project nr 92-00752P*, Division of Applied Geology, Luleå University of Technology, 58 pp.
- Martinsson O., 1997: Paleoproterozoic greenstones at Kiruna in northern Sweden: a product of continental rifting and associated mafic-ultramafic volcanism. In O. Martinsson: *Tectonic setting and metallogeny of the Kiruna greenstones. Doctoral thesis 1997:19, Paper I*, 1–49. Luleå University of Technology.
- Martinsson, O., 1999a: Bedrock map 30J Rensjön NO, scale 1:50 000. *Sveriges geologiska undersökning Ai 131*.
- Martinsson, O., 1999b: Bedrock map 30J Rensjön SO, scale 1:50 000. *Sveriges geologiska undersökning Ai 133*.
- Martinsson, O., 1999c: Bedrock map 31J Råstojaure SV/SO, scale 1:50 000. *Sveriges geologiska undersökning Ai 135*.
- Martinsson, O. & Perdahl, J.-A., 1993: Stratigraphy of the Kiruna Porphyries. In O. Martinsson, J.-A. Perdahl & J. Bergman: *Greenstone and porphyry hosted ore deposits in northern Norrbotten. NUTEK Project nr 92-00752P*, 1–5.
- Martinsson, O. & Perdahl, J.-A., 1995: Paleoproterozoic extensional and compressional magmatism in northern Sweden. In J.-A. Perdahl: *Svecofennian volcanism in northern Sweden, Doctoral thesis 1995:169D, Paper II*, 1–13. Luleå University of Technology.
- Martinsson, O. & Stølen, L.K., 1999: Bedrock map 31J Råstojaure NO, scale 1:50 000. *Sveriges geologiska undersökning Ai 134*.
- Martinsson O., Hallberg, A., Broman, C., Godin-Jonasson, L., Kisiel, T. & Fallick, A.E., 1997a: Viscaria – a syngenetic exhalative Cu-deposit in the Paleoproterozoic Kiruna Greenstones. In O. Martinsson: *Tectonic setting and metallogeny of the Kiruna greenstones. Doctoral thesis 1997:19, Paper II*, 1–57. Luleå University of Technology.
- Martinsson, O., Hallberg, A., Söderholm, K. & Billström K., 1997b: Pahtohavare – an epigenetic Cu-Au deposit in the Paleoproterozoic Kiruna greenstones. In O. Martinsson: *Tectonic setting and metallogeny of the Kiruna greenstones. Doctoral thesis 1997:19, Paper III*, 1–37. Luleå University of Technology.
- Martinsson, O., Vaasjoki, M. & Persson, P.-O., 1999: U-Pb ages of Archaean to Palaeoproterozoic granitoids in the Torneträsk-Råstojaure area, northern Sweden. In S. Bergman (ed.): *Radiometric dating results 4. Sveriges geologiska undersökning C 831*, 70–90.
- Matisto, A., 1969: *The general geological map of Finland, Lehti-Sheet B8 (with an English summary)*, 78 pp.
- Melezhik, V.A., Fallick, A.E., Makarikhin, V.V. & Lyubtsov,

- V.V., 1997: Links between Palaeoproterozoic palaeogeography and rise and decline of stromatolites: Fennoscandian Shield. *Precambrian Research* 82, 311–348.
- Mellqvist, C., Öhlander, B., Skiöld, T. & Wikström, A., 1999: The Archaean-Proterozoic Palaeoboundary in the Luleå area, northern Sweden: field and isotope chemical evidence for a sharp terrane boundary. *Precambrian Research* 96, 225–243.
- Monro, D., 1988: *The geology and genesis of the Aitik Cu-Au deposit, arctic Sweden*. Unpublished Ph.D. thesis, Department of Geology, University College, Cardiff, 386 pp.
- Niiniskorpi, V., 1986: *Kurkkionvaara, en Zn-Pb-Cu-mineralisering i norra Sverige, en case-study*. Unpublished Licentiate Thesis, Geologiska och Mineralogiska Institutionen, Åbo Akademi, 74 pp.
- Niiniskorpi, V., 1990: Svavelrika förekomster i norra Norrbotten. Unpublished report, SGAB PRAP 90027, 9 pp.
- Nyström, J.O., 1985: Apatite iron ores of the Kiruna field, northern Sweden: magmatic textures and carbonatitic affinity. *Geologiska Föreningens i Stockholm Förhandlingar* 107, 133–141.
- Nyström, J.O. & Henriques, F., 1989: Dendritic magnetite and miniature diapir-like concentrations of apatite; two magmatic features of the Kiirunavaara iron ore. *Geologiska Föreningens i Stockholm Förhandlingar* 111, 53–64.
- Nyström, J.O. & Henriques, F., 1994: Magmatic features of iron ores of the Kiruna type in Chile and Sweden: ore textures and magnetite geochemistry. *Economic Geology* 89, 820–839.
- Ödman, O.H., 1939: Urbergsgelogiska undersökningar inom Norrbottens län. *Sveriges geologiska undersökning C* 426, 100 pp.
- Ödman, O., 1947: Manganese mineralization in the Ultevis district, Jokkmokk, north Sweden. *Sveriges geologiska undersökning C* 487, 90 pp.
- Ödman, O.H., 1957: Beskrivning till berggrundskarta över urberget i Norrbottens län. *Sveriges geologiska undersökning Ca* 41, 151 pp.
- Ödman, O. H., Härme, M., Mikkola, A. & Simonen, A., 1949: Den svensk-finska geologiska exkursionen i Tornedalen sommaren 1948. *Geologiska Föreningens i Stockholm Förhandlingar* 71, 113–126.
- O'Farrelly, K.S., 1990: *A stable isotopic investigation of the origin and evolution of the Kiirunavaara iron mine, northern Sweden*. Unpublished Ph.D. Thesis, University of Wales, College of Cardiff, 362 pp.
- Offerberg, J., 1967: Beskrivning till berggrundskartbladen Kiruna NV, NO, SV, SO. *Sveriges geologiska undersökning Af* 1–4, 147 pp.
- Öhlander, B., 1984: Geochemical analyses of rocks of the Haparanda suite, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 106, 167–169.
- Öhlander, B. & Skiöld, T., 1994: Diversity of 1.8 Ga potassic granitoids along the edge of the Archaean craton in northern Scandinavia: a result of melt formation at various depths and from various sources. *Lithos* 33, 265–283.
- Öhlander, B., Skiöld, T., Hamilton, P.J. & Claesson, L.-Å. 1987a: The western border of the Archaean province of the Baltic Shield: evidence from northern Sweden. *Contributions to Mineralogy and Petrology* 95, 437–450.
- Öhlander, B., Hamilton, P.J., Fallick, A.E. & Wilson, M.R., 1987b: Crustal reactivation in northern Sweden: the Vet-tasjärvi granite. *Precambrian Research* 35, 277–293.
- Öhlander, B., Skiöld, T., Elming, S.-Å., BABEL Working Group, Claesson, S. & Nisca, D.H., 1993: Delineation and character of the Archaean-Proterozoic boundary in northern Sweden. *Precambrian Research* 64, 67–84.
- Olesen, O. & Sandstad, J.S., 1993: Interpretation of the Proterozoic Kautokeino Greenstone Belt, Finnmark, Norway from combined geophysical and geological data. *Norges geologiske undersøkelse Bulletin* 425, 41–62.
- Padget, P., 1959: Leucodiabase and associated rocks in the Karelidic zone of Fennoscandia. *Geologiska Föreningens i Stockholm Förhandlingar* 81, 316–332.
- Padget, P., 1970: Beskrivning till berggrundskartbladen Tarendö NV, NO, SV, SO. *Sveriges geologiska undersökning Af* 5–8, 95 pp.
- Padget, P., 1977: Beskrivning till berggrundskartbladen Pajala NV, NO, SV, SO. *Sveriges geologiska undersökning Af* 21–24, 73 pp.
- Parák, T., 1973a: Rare earth elements in the apatite iron ores of Lapland and some data on the Sr, Th, and U content of these ores. *Economic Geology* 68, 210–221.
- Parák, T., 1973b: *Kirunamalmernas bildning*. Unpublished Ph.D. thesis, Stockholm University, 222 pp.
- Parák, T., 1975a: The origin of the Kiruna iron ores. *Sveriges geologiska undersökning C* 709, 209 pp.
- Parák, T., 1975b: Kiruna iron ores are not "intrusive-magmatic ores of the Kiruna type". *Economic Geology* 70, 1242–1258.
- Parák, T., 1985: Phosphorus in different types of ore, sulfide in the iron deposits and the type and origin of ores at Kiruna. *Economic Geology* 80, 646–665.
- Parák, T. & Espersen, J., 1965: Leveäniemi järnmalmfyndighet. Unpublished report, *Sveriges geologiska undersökning BRAP* 85122, 85 pp.
- Peacock, M.A., 1931: Classification of igneous rock series. *Journal of Geology* 39, 65–67.
- Pearce, J.A., 1980: Geochemical evidence for the genesis and eruptive setting of lavas from Tethyan ophiolites. In A. Panayiotou (Ed.): *Ophiolites, Proceedings International Ophiolite Symposium, Cyprus, 1979*, 261–272. Geological Survey of Cyprus, Nicosia.
- Pearce, J.A., Harris, N.B.W. & Tindle, A.G., 1984: Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* 25, 965–983.
- Perdahl, J.-A. & Martinsson, O., 1995: Paleoproterozoic flood basalt magmatism in the Kiruna area, northern Sweden. In J.-A. Perdahl: *Svecofennian volcanism in northern Sweden. Doctoral thesis 1995:169D, Paper V*, 1–10. Luleå University of Technology.
- Persson, G., 1981: Kobolt-kopparfyndigheten vid Kiskama-vaara, tonnage och haltberäkning. Unpublished report, *Sveriges geologiska undersökning BRAP* 81552, 18 pp.
- Persson, G. & Lagerbäck, R., 1977: Vathanvaara kaolinförekomst. Rapport rörande undersökningar av kaolin på Vathanvaara kbl 29K Vittangi. Unpublished report, *Sveriges geologiska undersökning BRAP* 00887, 21 pp.
- Petersson, S., 1980: Industrimineral ur Aitik-sand. *Jernkontorets Annaler* 80, 23–25.
- Pitkänen, T., 1997: Anisotropy of magnetic susceptibility of mylonites from the Kolkonjoki and Nautanen deformation zones in Norrbotten, Sweden. *Master thesis 1997:099 CIV, Luleå University of Technology*, 64 pp.

- Riad, L., 1990: The Pärve fault, northern Sweden. *Uppsala University, Department of Mineralogy and Petrology research report* 63, 48 pp.
- Romer, R.L., 1996: What is the significance of lead isotope data from stibnite, a low-temperature natural ion-exchanger? *The 22nd Nordic Geological Winter meeting, Turku, Åbo, Abstracts*, 172.
- Romer, R. & Boundy, T.M., 1988: Interpretation of lead isotope data from the uraniferous Cu-Fe-sulfide mineralizations in the Proterozoic greenstone belt at Kopparåsen, northern Sweden. *Mineralium Deposita* 23, 256–261.
- Romer, R.L. & Wright, J.E., 1992: U-Pb dating of columbites: A geochronologic tool to date magmatism and ore deposits. *Geochimica et Cosmochimica Acta* 56, 2137–2142.
- Romer, R.L., Martinsson, O. & Perdahl, J.-A., 1994: Geochronology of the Kiruna iron ores and hydrothermal alterations. *Economic Geology* 89, 1249–1261.
- Romer, R., Martinsson, O. & Perdahl, J.-A., 1996: Scapolite: A tracer for the initial lead isotopic composition in sulfide deposits with later additions of radiogenic lead. *Mineralium Deposita* 31, 134–139.
- Rönkä, K., 1990: Diatomit i Norrbotten. Unpublished report, *SGAB PRAP 90030*, 15 pp.
- Ros, F., 1979: Tjärrojäkka kopparmalmsfyndighet. Unpublished report, *Sveriges geologiska undersökning BRAP 82567*, 17 pp.
- Ros, F., 1980: Nautanenområdet, rapport över SGU:s arbeten utförda under 1966–1979. Unpublished report, *Sveriges geologiska undersökning BRAP 81530*, 33 pp.
- Sahlstedt, R. & Claesson, L.-Å., 1996: Lehtosölke nr 1. Redovisning över utförda undersökningsarbeten enligt 14 kap. 3§ minerallagen (1991:45). Unpublished report, *Bergmästaren i norra distriktet 318-363:2/96*, 2 pp.
- Shaikh, N.A., 1970: Rapport över antofyllitförekomsten vid Keukiskero, Norrbottens län. Unpublished report, *Sveriges geologiska undersökning BVI:21*, 40 pp.
- Shaikh, N.A., 1972: Geology of the Lauttakoski soapstone deposit, northern Sweden. *Sveriges geologiska undersökning C 676*, 1–32.
- Shaikh, N.A., Kumpulainen, R., Riad, L., Snäll, S., Sundberg, A., Westlund, B. & Wik, N.G., 1986: Industriella mineral och bergarter i Norrbottens län. Unpublished report, *Sveriges geologiska undersökning BRAP 86006*, 128 pp.
- Shaikh, N.A., Karis, L., Kumpulainen, R., Sundberg, A. & Wik, N.-G., 1989: Kalksten och dolomit i Sverige, del 1. *Norra Sverige. Sveriges geologiska undersökning Rapporten och meddelanden* 54, 380 pp.
- Sharma, P.V., 1986: *Geophysical Methods in Geology*. Elsevier, 442 pp.
- Silvennoinen, A., Gustavson, M., Perttunen, V., Siedlecka, A., Sjöstrand, T., Stephens, M.B. & Zachrisson, E., 1987: *Geological map, Pre-Quaternary rocks, Northern Fennoscandia. Scale 1:1 000 000*. Geological Surveys of Finland, Norway and Sweden.
- Skiöld, T., 1979a: U-Pb zircon and Rb-Sr whole-rock and mineral ages of Proterozoic intrusives on mapsheet Lannavaara, north-eastern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 101, 131–137.
- Skiöld, T., 1979b: Zircon ages from an Archean gneiss province in northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 101, 169–171.
- Skiöld, T., 1981a: U-Pb isotope analyses from a Precambrian gneiss area in northern Sweden and their chronostratigraphic implications. *Geologiska Föreningens i Stockholm Förhandlingar* 103, 17–25.
- Skiöld, T., 1981b: Radiometric ages of plutonic and hypabyssal rocks from the Vittangi-Karesuando area, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 103, 317–329.
- Skiöld, T., 1986: On the age of the Kiruna Greenstones, northern Sweden. *Precambrian Research* 32, 35–44.
- Skiöld, T., 1988: Implications of new U-Pb zircon chronology to early Proterozoic crustal accretion in northern Sweden. *Precambrian Research* 38, 147–164.
- Skiöld, T. & Cliff, R.A., 1984: Sm-Nd and U-Pb dating of Early Proterozoic mafic-felsic volcanism in northernmost Sweden. *Precambrian Research* 26, 1–13.
- Skiöld, T. & Öhlander, B., 1989: Chronology and geochemistry of late Svecofennian processes in northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 111, 347–354.
- Skiöld, T. & Page, R.W., 1998: SHRIMP and isotope dilution zircon ages on Archean basement-cover rocks in north Sweden. 23. *Nordiske Geologiske Vintermode, Abstract volume Århus 1998*, 273.
- Skiöld, T., Öhlander, B., Vocke, Jr., R.D. & Hamilton, P.J., 1988: Chemistry of Proterozoic orogenic processes at a continental margin in northern Sweden. *Chemical Geology* 69, 193–207.
- SOU, 1924: Nyttiggörande av statens norrländska malmfyndigheter. *Statens offentliga utredningar 1924:32*, 346 pp.
- STC Minerals AB, 1986: Vivungi. Slutrapport. Unpublished report, *MINK 97046*, 11 pp.
- Stephens, M.B., Wahlgren, C.-H. & Weihed, P., 1994: Geological map of Sweden. Scale 1:3 million. *Sveriges geologiska undersökning Ba 52*.
- Stølen, L.K., 1997: Bedrock geology of the Altevåtn-Mäskanvarri area, Indre Troms, northern Scandinavian Caledonides. *Norges geologiske undersøkelse Bulletin* 432, 5–23.
- Studsvik-Analytica AB, 1986: Vivungi. Årsrapport 1985. Unpublished report, *MINK 97042*, 9 pp.
- Sundius, N., 1915: *Beiträge zur Geologie des südlichen Teils des Kirunagebiets*. Vetenskapliga och praktiska undersökningar i Lappland, arrangerade av Luossavaara-Kiirunavaara Aktiebolag, Uppsala, 237 pp.
- Svenonius, F., 1900: Geologisk öfversikt öfver Jukkasjärvi malmtrakt och dess omgifningar. In: Underdånig berättelse om en undersökning af mindre kända malmfyndigheter inom Jukkasjärvi malmtrakt och dess omgifningar. *Sveriges geologiska undersökning C 183*, 7–35.
- Svenonius, F., 1916: Norrbottens läns kalkstensförekomster. *Sveriges geologiska undersökning C 269*, 64 pp.
- Talbot, C.J. & Koyi, H., 1995: Palaeoproterozoic intraplate exposed by resultant gravity overturn near Kiruna, northern Sweden. *Precambrian Research* 72, 199–225.
- Tarling, T.H. & Hrouda, F., 1993: *The magnetic anisotropy of rocks*. Chapman & Hall, London. 217 pp.
- Tegengren, F.R., 1924: Sveriges ädlare malmer och bergverks. *Sveriges geologiska undersökning Ca 17*, 406 pp.
- Thelander, T., 1982: The Torneträsk Formation of the Dividal Group, northern Swedish Caledonides. *Sveriges geologiska undersökning C 789*, 41 pp.
- Tikoff, B. & Teyssier, C., 1994: Strain modelling and displace-

- ment-field partitioning in transpressional orogens. *Journal of Structural Geology* 16, 1575–1588.
- Virkkunen, R., 1985: *Projekt nr: 4013, Ahmavuoma*. Unpublished report, K 85-4, 12 pp.
- Virkkunen, R., Rönkkö, K. & Hansson, K.-E., 1984: *Projekt nr: 4913, Nordöstra Norrbotten–Lannavaara–Lainio*. Unpublished report, K 84-47, 12 pp.
- Virkkunen, R., Toivonen, A., Rönkkö, K. & Hansson, K.-E., 1986: *Projekt nr: 5513, NÖN – Lannavaara–Lainio*. Unpublished report, K 85-36, 19 pp.
- Vogel, D.C., Vuollo, J.I., Alapieti, T.T. & James, R.S., 1998: Tectonic, stratigraphic, and geochemical comparisons between ca. 2500-2440 Ma igneous events in the Canadian and Fennoscandian Shields. *Precambrian Research* 92, 89–116.
- Vollmer, F.W., Wright, S.F. & Huddleston, P.J., 1984: Early deformation in the Svecokarelian greenstone belt of the Kiruna district, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 106, 109–118.
- Vuollo, J., 1994: Paleoproterozoic basic igneous events in eastern Fennoscandian Shield between 2.45 and 1.97 Ga. Ph.D. Thesis, *Acta Universitatis Ouluensis Ser A no 250*, 47 pp.
- Wanhainen, C. & Martinsson, O., 1999: Geochemical characteristics of host rocks to the Aitik Cu-Au deposit, Gällivare area, northern Sweden. *Proceedings of the fifth biennial SGA meeting and the tenth quadrennial IAGOD Meeting, London, 22–25 August 1999, extended abstract*, 1443–1446.
- Wanhainen, C., Martinsson, O. & Kontturi, M., 1999: The Aitik Cu-Au deposit, Gällivare area, northern Sweden. *Gold 99, Trondheim, May 1999, Abstract*, 163–165.
- Ward, P., Härkönen, I., Nurmi, P.A. & Pankka, H.S., 1989: Structural studies in the Lapland greenstone belt, northern Finland and their application to gold mineralization. *Geological Survey of Finland Special Paper* 10, 71–77.
- Welin E., 1987: The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden. *Precambrian Research* 35, 95–113.
- Welin, E. & Blomqvist, G., 1966: Further age measurements on radioactive minerals from Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 88, 3–11.
- Welin, E., Christiansson, K. & Nilsson, Ö., 1971: Rb-Sr radiometric ages of extrusive and intrusive rocks in northern Sweden. *Sveriges geologiska undersökning C 666*, 1–38.
- Werner, S., 1965: *Kvantitativa malmeräkningar på grundval av geofysiska undersökningar*. *Jernkontorets annaler* 149, 458–500.
- Wikström, A., 1995: Berggrundskartan Kalix NV. *Sveriges geologiska undersökning Ai 79*.
- Winkler, H.G.F., 1979: *Petrogenesis of metamorphic rocks*. Springer Verlag, New York, Heidelberg, Berlin, 348 pp.
- Witschard, F., 1970: Description of the geological maps Lainio NV, NO, SV, SO. *Sveriges geologiska undersökning Af 9–12*, 116 pp.
- Witschard, F., 1975: Description of the geological maps Fjällåsen NV, NO, SV, SO. *Sveriges geologiska undersökning Af 17–20*, 125 pp.
- Witschard, F., 1984: The geological and tectonic evolution of the Precambrian of northern Sweden – a case for basement reactivation? *Precambrian Research* 23, 273–315.
- Witschard, F., 1986: Geological evolution of northern Sweden. Key to the geological maps. Unpublished report, *MINK 97054*. 16 pp.
- Witschard, F., 1996: Berggrundskartan 28K Gällivare, 1:50 000. *Sveriges geologiska undersökning Ai 98–101*.
- Witschard, F., & Zachrisson, E., 1995a: Berggrundskartan 28I Stora Sjöfallet NO, 1:50 000, *Sveriges geologiska undersökning Ai 90*.
- Witschard, F., & Zachrisson, E., 1995b: Berggrundskartan 28I Stora Sjöfallet SO, 1:50 000, *Sveriges geologiska undersökning Ai 91*.
- Wright, S.F., 1988: *Early Proterozoic deformational history of the Kiruna district, northern Sweden*. Unpublished Ph.D. thesis, University of Minnesota, 170 pp.
- Yngström, S., Nord, A.G. & Åberg, G., 1986: A sulphur and strontium isotope study of the Aitik copper ore, northern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 108, 367–372.
- Zachrisson, E., & Witschard, F., 1995a: Berggrundskartan 28I Stora Sjöfallet NV, 1:50 000, *Sveriges geologiska undersökning Ai 88*.
- Zachrisson, E., & Witschard, F., 1995b: Berggrundskartan 28I Stora Sjöfallet SV, 1:50 000, *Sveriges geologiska undersökning Ai 89*.
- Zweifel, H., 1976: Geological documentation of a disseminated copper deposit - A preliminary investigation. *Sveriges geologiska undersökning C 720*, 80 pp.



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