The Gällivare area

The Gällivare area was first recognised for its iron deposits in the 18th century. When the railway from Luleå was built 1888 to exploit the large iron resources this initiated extensive exploration activities for other deposits in the surrounding areas. In 1898 copper ore was discovered at Nautanen and within a few years a number of Cu-mineralizations had been found northeast and east of Gällivare. The Nautanen Copper Ore company was founded in 1900 and mining started 1902, but lasted only until 1907 (Geijer 1918a). Some other small Cu mines (Likavaara, Ferrum) were active during the same period in the Nautanen area, and a prospector was working a small gold mine (Fridhem). The Aitik deposit was discovered in 1932 by drilling on geophysical targets in an area where a rich ore boulder and a mineralised outcrop had been found. Further drilling was performed 1960–1965, which delineated a low grade but large Cu-ore suitable for large-scale open pit mining (Malmqvist & Parasnis 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 Cu-deposits in the Gällivare area are hosted by volcaniclastic sediments varying in composition from arenites to pelites. These sediments are intruded by synorogenic diorites and late to postorogenic granites and pegmatites. The ore deposits occur within, or close to, a major shear zone running in a northwestern direction through the volcaniclastic belt (Fig. 2). The shear zone is more than one km wide and it consists of several steeply dipping sub-parallel branches of high strain. Extensive alterations are developed along the shear zone, including K-feldspar alteration, scapolitization, sericitization and tourmalinization. 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).

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**Excursion Guide, GEODE Workshop, August 28 to September 1, 2000**

Olof Martinsson, Christina Wanhainen

CTMG (Centre for Applied Ore Studies), Division of Applied Geology, Luleå University of Technology, SE-971 87 Luleå, Sweden

This field trip guide covers general and detailed information regarding the GEODE field trip. The field trip localities are shown in Figure 1.

The Gällivare area

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**Figure 2. Geology of the Gällivare area.**
Figure 1. Geology of northern Norrbotten with excursion stops.

- Hauki and Maattavaara quartzites
- Palæoproterozoic intrusive rocks
- Kiruna Porphyries
- Porphyrite Group
- Pahakurkkio Group
- Greenstone Group
- Archaean basement
- High grade gneisses
- Excursion locality

Excursion locality:
- Malmberget
- Soppimo
- Kiruna
- Soppero
- Karesuando
- Tarendo
- Pajala
- Vittangi
- Svappavaara
1-1, Dundret
Dundret is a layered, tholeiitic gabbro composed of troctolite, magnetite gabbro and gabbronorite. It belongs to a complex of alkaline to tholeiitic mafic-ultramafic intrusions in the Gällivare area (Fig. 3). The lower and outer parts of the Dundret intrusion consist of troctolite alternating with magnetite gabbro. The upper and central parts are dominated by gabbronorite with interlayers of magnetite gabbro and locally peridotite. The layering of the Dundret gabbro forms a bowl-like structure where the dip increases from 60° at the margins to almost horizontal at the center of the intrusion (Martinsson, 1994, 2000).

An outcrop of peridotitic gabbro with rhythmic layering is found in the central part of the intrusion. The eastern edge of this outcrop is a 3 m high cliff-face that nicely exhibits the layered structure. The bottom layer consists of a 1.5 m thick homogenous olivine cumulate with a dark color. This layer is overlain by a plagioclase-rich white layer that is gradually mixed with an increasing amount of olivine so that the upper portion of this layer is dark and dominated by olivine. This dm-scale layering is repeated several times. The olivine-rich layers are medium grained and composed of olivine and spinel, poikilitically enclosed by hypersthene and locally plagioclase. The hypersthene is almost totally altered to a colorless amphibole and chlorite. Magnetite occurs as free grains and along fissures in the olivine. Pentlandite-bearing pyrrhotite is locally relatively abundant as free grains and along fissures.

Visit to the top of the mountain Dundret with view over Malmberget and Aitik. Outcrop of layered peridotitic gabbro.

2-1, Aitik
Aitik is Sweden’s largest sulphide mine and one of Europe’s most important copper producers. The annual production is c. 18 Mt of ore containing 0.4 % Cu, 0.2 ppm Au and 4 ppm Ag. To the end of 1999 about 322 Mt of ore has been produced from an open pit which is c. 2000 m long and 315 m deep. Mineralization is proved to a depth of 800 m in the northern part but it ceases about 400 m below surface in the southern part.

Aitik is situated close to the structurally important NW–SE directed shear zone in the Gällivare area. Since Zweifel’s (1976) description of the ore and its host rock several others have contributed with additional data (Yngström et al. 1986; Monro 1988; Drake 1992; Wanhainen & Martinsson 1999; Wanhainen et al. 1999). The host rock to the ore comprises 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 volcaniclastic origin is favoured (Wanhainen & Martinsson 1999). A slightly deformed porphyritic diorite intrusion occurs in the footwall to the ore zone and undeformed pegmatite dykes crosscut the ore zone and the hanging wall units (Fig. 4). The diorite has an age of c. 1.87 Ga while the pegmatites are younger than 1.8 Ga (Witschard 1996).

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 sometimes tourmaline are common and contributes to locally higher ore grades. Barite veins are partly abundant. Many of them contain...
varying amounts of pyrite, chalcopyrite, magnetite and amphibole (Zweifel 1976, Monro 1988). Pegmatite dykes within the ore zone are often mineralized and some of them are rich in Cu. Molybdenite is a minor constituent, occurring mainly in pegmatite dykes and quartz veins. Desmine and chabazite, sometimes together with sulphides, represent late mineralization phases. The zeolites occur as crystals in drusy vugs in some of the pegmatite dykes. Scapolitization and amphibole-pyroxene veinlets are features of minor importance that mainly are developed in the footwall rocks.

The Aitik Cu-Au ore has been interpreted as a deformed and metamorphosed equivalent to porphyry-copper deposits (Yngström et al. 1986, Monro 1988). The mineralized diorite in the footwall to the ore is suggested to represent an apophyse from a larger intrusion at depth consistent with this model (Drake 1992). However, all features of the ore are not typical for porphyry systems and it might have another or more complex origin (Wanhainen et al. 1999). Probably there exist several phases of remobilization and possibly also additional overprinting mineralization events.

Stop descriptions:

2-1A. View point at the southern end of the open pit
Looking to the north, the general features of the open pit are seen from this point. The pit occupies an area of c. 3000x500 meter. The lowest level is in the northern part of the pit, where it reaches down to 315 meter. Mining is today concentrated to that part. Note the westerly dip of the foliation, the hanging wall contact and the footwall intrusion.

2-1B. Footwall intrusion
This is a grey, medium-grained, porphyritic quartz monzodiorite with an age of c. 1.87 Ga (Witschard 1996). It has a massive, blocky appearance (in contrast to other units in the mine) but is slightly foliated. The quartz monzodiorite comprises phenocrysts of plagioclase in a matrix of mainly feldspar, quartz, biotite and hornblende, and is quite rich in 3–20 mm wide, mineralized granitic (quartz, feldspar, biotite) veins and amphibole veins. Mineralized and barren quartz veins are also common, and these sometimes contain drusy vugs filled with zeolite crystals. Mineralization of copper extends in subeconomic grades into the footwall intrusion.

Looking to the south, the major pegmatites that demarcate the ore zone are observable. This type of north-south striking pegmatites often contain chalcopyrite and pyrite when occurring in the ore zone, but are barren in the hanging wall. In addition to chalcopyrite and pyrite the pegmatites occasionally contain some molybdenite.

2-1C. K-feldspar alteration and epidotization
K-feldspar/epidote alteration is most extensive along the footwall contact, but occur locally within the ore zone, footwall and hanging wall. It is also well developed along the hanging wall contact, where it most often occurs adjacent to pegmatites. A minor content of sulphides is found in this rock unit, of which disseminated pyrite is the dominant.

2-1D. Main ore zone: biotite gneiss/schist
This eastern part of the ore zone comprises biotite-garnet schist and gneiss. The rocks are strongly altered (biotite alteration accompanied by garnet porphyroblasts) and sheared in a north-south direction, and the original character of them is therefore unclear. Chalcopyrite and pyrite are the main ore minerals, and they mostly occur disseminated and in veinlets. Quartz, feldspars, amphibole, epidote, tourmaline, zeolites, magnetite and barite commonly accompany the sulphides.
2-1E. Main ore zone: muscovite (sericite) schist
This western part of the ore zone comprises quartz-muscovite (sericite) schist. Strong alteration occurs as extensive sericitization accompanied by quartz and pyrite. This unit contains disseminated pyrite and minor chalcopyrite. Note the sharp thrust contact marking the top of the ore zone. This hanging wall thrust fault is clearly observed along the length of the open pit.

2-1F. Hanging wall
The feldspar-biotite-amphibole gneiss in the hanging wall is separated from the main ore zone by a thrust fault. Mineralization is absent in this part of the open pit, except for some sulphides occurring in younger pegmatites. A characteristic hanging wall marker horizon are the amphibole banded gneiss which occur as a c. 20 meter wide zone close to the contact between the hanging wall and the main ore zone. Except for this zone, the hanging wall gneiss look quite similar to the gneiss in the footwall, with irregular veins of hornblende bordered by feldspar.

2-2. Malmberget
The precise age of discovery for the Malmberget deposit is not known but most likely it was found at the end of the 17th century. Mining started in small scale in the 18th century with the main production coming from the Kapten ore body. When the railway was built from Luleå to Gällivare 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 at least 660 Mt with 51–61 % Fe and <0.8 % P (Grip & Frietsch 1973). At the end of 1999 about 450 Mt have been produced.

The ores are hosted by strongly metamorphosed and deformed rocks of felsic to mafic composition. These rocks are traditionally called leptites in the Malmberget area. 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 Kiruna Porphyries. 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 1930). A large intrusion of Lina granite exists northwest of the deposit (Fig. 5) and the recrystallization of the host rocks 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 ore forms an almost continuous horizon with a length of about 5 km. Apatite banding is a common feature of these ores, which contain both magnetite and hematite. The eastern part includes several more or less isolated bodies of magnetite ore, which generally is less rich in apatite. The main gangue minerals are apatite, amphibole, pyroxene and biotite. Pyrite, chalcopyrite, bornite and molybdenite are more rarely found. The grain size is mostly 0.5 to 2 mm for the ore minerals, but larger porphyroblasts of magnetite may occur in hematite ore.

The host rock to the ores is mainly felsic in composition and often K-feldspar rich. Albitic rocks are locally encountered and some of them show a relict amygdaloidal structure. The mafic rocks are usually biotite-rich and scapolite altered. In the footwall to the western part of the deposit there exists gneiss consisting of sillimanite, muscovite, and quartz. Tourmaline, microcline and Fe-oxides occur in minor amounts and andalusite, corundum and barite are occasionally found in this rock (Geijer 1930).
Various scales of brecciation are developed in the wall rocks to the ores. Especially ore bodies in the eastern part are surrounded by extensive brecciation. Magnetite, apatite, amphibole are the main constituents of mm to m-wide veins that develop networks and breccias. Albite occurs in some amphibole breccia and scapolite is locally found in druses. Breccias with a high Fe-content are mainly found adjacent to the iron ores, while breccias dominated by amphibole are developed also at distance from them. The breccias are often strongly flattened by ductile deformation and they may transform into banded ore (Geijer 1930).

The Malmberget deposit is strongly affected by ductile deformation and the large-scale structures are 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 dipping 40° towards SSW. Many ore lenses are boudinaged in the plunging direction and some of the granite-pegmatite dykes exhibit a similar style of deformation (Geijer 1930). A spectacular feature of the Malmberget deposit if the occurrence of large cavities and druses containing excellent crystals of calcite, desmine, apatite, hornblende, scapolite, pyrite and magnetite. Ages for minerals in the druses varies from 1613 to 1737 Ma (Romer, 1996).

Visit underground at the Alliansen magnetite ore body and hematite ore in the western ore bodies.

2-3, Nautanen
At Nautanen the bedrock is partly well exposed and most of the ore bodies were found in outcrops. During the period 1902 to 1907, 71835 tonnes of ore containing 1–1.5 % Cu and some Au 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 has later been investigated by SGU in several campaigns during the years 1966–1979 and by NSG-SGB in 1983–1985. These drillings delineated an ore lens 100 m 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). Recently the Nautanen area has been drilled by NAN (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 major NW-SE directed shear zone. Less deformed clastic metasedimentary rocks of partly volcanogenic origin are found on both sides of the shear zone (Fig. 6). Several lenses of Cu-ore have been mined. They consist mainly of chalcopyrite in association with magnetite and some pyrite. Minerals found in accessory amounts are sphalerite, galena, Carrollite, bismuthinite, molybdenite and scheelite (Hälenius 1983). Borneite and chalocite are found in minor amounts in the southern part of the area, partly occurring in vuggy quartz-veins together with desmine. Magnetite is often the major ore mineral, partly forming almost massive lenses and veins in association with chalcopyrite-amphibole-pyroxene-epidote. Garnet is usually extensively developed in the wall rocks to these mineralizations. A disseminated character of the Cu-sulphides is characteristic for the western part of the Nautanen area (Geijer 1918a). Mineralization is accompanied by intense sericite and tourmaline alteration in several meters wide zones parallel to the schistosity. Au is a minor constituent of the ores and a weak enrichment of Co, Zn, Ag, Mo and W is commonly developed. There is generally a good correlation between Cu and Au and high gold values are rarely found without significant Cu-mineralization. The original character of the host rock is obscured by strong alteration and deformation. Probably the precursor was volcaniclastic sediments with a mainly intermediate composition. Alterations are dominated by scapolite, K-feldspar, biotite, sericite, garnet, amphibole, epidote and tourmaline. There is roughly an east–west mineral zoning with scapolite dominating in the east followed by K-feldspar-biotite-garnet in the central part and sericite-garnet-tourmaline towards west (Geijer 1918a). The altered rocks have a high K₂O (5.4–9.4%) and Ba (0.12–0.50 %) content. Mn is often enriched in the altered rocks and this element is mainly incorporated in garnet (Ros 1980). A strong and steeply dipping schistosity is developed in a NNW direction. A foliation in N30°E occurs locally. The magnetite-chalcopyrite veins cut the schistosity of the bedrock, but they are often gently folded. This together with the occurrence of rotated garnet porphyroblasts and boudinaged tourmaline veins indicate the mineralization and alteration to be mainly syntectonic.

Visit at outcrops and open pits in the central part of the Nautanen ore field (Max and 29:an ores).

The Kiruna-Vittangi area
A large number of epigenetic Cu-occurrences have been found in the Kiruna-Vittangi area. The first one was discovered in 1654 at Gruberget close to Svappavaara. Deposits occur mainly within volcaniclastic parts of the greenstones, andesites belonging to the Porphryite Group and basalts from the lower part of Kiruna Porphyries. Most of them are related to shear zones, or in some cases inversions of intermediate to felsic composition. Two clusters of mineralizations can tentatively be identified. One occurs close to Svappavaara along the major tectonic zone (KADZ) running from Karesuando in a SSW-direction towards Arjeplog and the eastern part of the Nautanen area (Geijer 1918a). Mineralization is accompanied by intense sericite and tourmaline alteration in several meters wide zones parallel to the schistosity. Au is a minor constituent of the ores and a weak enrichment of Co, Zn, Ag, Mo and W is commonly developed. There is generally a good correlation between Cu and Au and high gold values are rarely found without significant Cu-mineralization. The original character of the host rock is obscured by strong alteration and deformation. Probably the precursor was volcaniclastic sediments with a mainly intermediate composition. Alterations are dominated by scapolite, K-feldspar, biotite, sericite, garnet, amphibole, epidote and tourmaline. There is roughly an east–west mineral zoning with scapolite dominating in the east followed by K-feldspar-biotite-garnet in the central part and sericite-garnet-tourmaline towards west (Geijer 1918a). The altered rocks have a high K₂O (5.4–9.4%) and Ba (0.12–0.50 %) content. Mn is often enriched in the altered rocks and this element is mainly incorporated in garnet (Ros 1980). A strong and steeply dipping schistosity is developed in a NNW direction. A foliation in N30°E occurs locally. The magnetite-chalcopyrite veins cut the schistosity of the bedrock, but they are often gently folded. This together with the occurrence of rotated garnet porphyroblasts and boudinaged tourmaline veins indicate the mineralization and alteration to be mainly syntectonic.

3-1, Mertainen
The Mertainen deposit was found in 1897 by magnetic surveys and it has been investigated by drilling and trenching at several occasions. Extensive diamond drilling was done by SGU during the period 1959–1963 and the reserves were calculated to 166 Mt with 35 % Fe and 0.05 % P. This includes a richer part containing 53.4 Mt with 46.0 % Fe, 0.051 % P, and 0.94 % TiO₂.
Figure 6. Mines and ores in the central Nautanen area.

(Lundberg & Espersen, 1965). During 1956 to 1958 c. 0.4 M ton of ore and waist rock was mined from an open pit in a richer part of the deposit.

The ore is hosted by trachytic to trachyandesitic lava, which often is rich in amygdules and feldspar phenocrysts. The lava may also be rich in magnetite occurring disseminated, in patches and irregular veins (Lundberg & Smellie 1979). The Mertainen deposit has the character of a large breccia, containing larger lenses or veins of massive magnetite in its central part. The high-grade part is surrounded by successively less magnetite-rich breccia (Fig 7a). Mineralization of is proven to a depth of at least 500 m (Fig. 7b) and the richer part of the deposit occur within an large positive magnetic and gravimetric anomaly (Fig. 7c) suggesting the magnetite breccia to be very extensive.

Magnetite is accompanied by actinolite, locally some apatite and small amounts of titanite. Actinolite occurs as coarse aggregates and disseminated in the ore. It may also form a narrow border zone along magnetite veins. Apatite is mainly found in veins that could be up to 10 cm wide. Titanite occurs disseminated and is the major carrier of Ti in the ore (Lundberg & Smellie 1979). Patches and veins of carbonate occur within the ore. Locally they contain small amounts of bornite and molybdenite. The host rock to the ore is sodic in character and often altered by scapolite. Scapolite may also occur together with actinolite in magnetite veins. Outside the mineralized breccia the volcanic rocks are generally potassic in character.

Visit at the open pit. Ore and altered host rocks are best exposed at the dump.

3-2, Gruvberget – apatite iron ore and the Cu-deposit

Gruvberget, located close to Svappavaara, is the largest of the old Cu-mines in Norrbotten. It was found 1654 and during the period 1657-1684 about 1000 ton Cu was produced (Tegengren 1924). The Cu-mines occur close to the Gruvberget apatite iron ore, which is 1300 m long and up to 65 m thick. It is calculated to contain 64.1 M ton with 56.9 % Fe and 0.87 % P to a depth of c. 300 m where the ore still has the approximately same thickness as at the surface. The bedrock consists of strongly scapolite and K-feldspar altered intermediate to mafic volcanic rocks. Several dikes of metadiabase with a NE direction cuts the ore and its wallrocks (Frietsch 1966).
Figure 7. The Mertainen deposit (modified from Lundberg & Smellie, 1979). a) geology and Fe-contents, b) Fe-content in drillcores from profile A, c) magnetic and gravimetric anomalies at Mertaninen.
The apatite iron ore is mostly massive, consisting of magnetite in the northern part and hematite in the middle and southern part of the deposit. Apatite, calcite, actinolite and garnet are gangue minerals occurring in small amounts. In the northern part of the deposit, the ore is bordered by a narrow zone of garnet, amphibole and epidote towards the hanging wall. An extensive ore breccia is developed in the footwall at the middle part of the deposit. It consists of veins and schlieren of magmatic rocks, hematite, apatite, and sericite. The richer part of the breccia is calculated to contain 9.7 Mt with 40.9 % Fe and 0.88 % P.

Cu–sulphides are scattered through the Gruvberget area, with richer mineralizations mainly developed in the footwall to the iron ore. Chalcopyrite and some bornite are the main ore minerals, occurring disseminated together with magnetite in altered rocks, or as rich ore shoots at the contact to the iron ore. Molybdenite is locally found in small amounts. Druses with epidote, magnetite, pyrite, Cu–sulphides and desmine are common within the sulphide mineralizations. Several of the mines are found close to metadiabases and Cu–mineralizations seem to be controlled by the same structures as the dikes. The more competent iron ore probably has acted both as a tectonic and chemical trap. Cu is the only metal reaching economic grades and the Au content is generally very low.

3-3, The Puttjala sulphide-occurrence

The greenstones at Svappavaara are represented by a tuffitic unit with a basaltic composition. Intercalations of marble and graphitic schist are common. Minor iron formations occur in the area and a weak dissemination of chalcopyrite is locally found in association with pyrrhotite-rich sediments. Scapolite-rocks are frequently developed. They may have a banded structure reflecting a primary layering or forming fine-grained scapolite fels in association with graphite schist and Ca-Mg rich tuffite (Frietsch, 1966).

Outcrops of graphite schist and scapolite fels are found at Puttjala. Both rock types are rich in sulphides with pyrrhotite occurring as breccia and veinlets. Small amounts of chalcopyrite occur locally. Rich pyrite-chalcopyrite boulders have been found in the vicinity, and the bedrock has been investigated by several diamond drill holes but no significant mineralization was found.

Visit outcrops with tuffite, scapolite fels and graphite schist.

3-4A, The Nunasvaara graphite deposit

The discovery of graphite in the Vittangi area in 1898 initiated extensive exploration for graphite at the beginning of the 20th century (Geijer 1918b). Since then graphite schist has been found in many other places in northern Norrbotten. Within the greenstone piles graphite schist is mainly restricted to two stratigraphical layers, one in the middle part and one in the upper part. The lower unit is generally 10 to 20 m thick and poor in sulphides the graphite content is between 10 and 45 %. Graphite schists in the upper part of the greenstones are, with a few exceptions, generally richer in sulphides and poorer in graphite compared to the lower unit.

A folded but almost continuous horizon of graphite schist can be followed for about 15 km at Nunasvaara west of Vittangi. It belongs to the lower graphite unit and is partly intruded by mafic sills. Intense albition along the contacts of the sill is commonly observed. Pyrite and pyrrhotite are partly common in veinlets. Chalcopyrite is more rarely encountered. In some places sphalerite and galena occur as narrow fissure fillings in the graphite schist.

Although large tonnages have been proven by trenching and drilling the fine-grained character of the graphite has prohibited a commercial production. Generally the grain size is less than 0.06 mm, but it may reach up to 1 mm in some areas. The Nunasvaara Stadgruvelätt is the best investigated part and on a length of 700 m the graphite schist has a width of c. 20 m and an average graphite content of 21.0 %. Using 25 % C as cut off it contains about 1.1 Mt with 27.8 % graphite and 3.1 % S to a depth of 70 m (Bergström 1987). There have been several attempts to make benefit of the graphite schists, including production of amorphous graphite and to use it as fuel. Some thousand tonnes of graphite schist were quarried and tested as fuel for heat-production in Kiruna in 1982.

Visit at a small quarry in graphite schist.

3-4B, Mafic sill at Nunasvaara

The greenstones at Nunasvaara are intruded by several mafic sills with a thickness of up to 400 m. Often they are affected by scapolitization with the plagioclase partly or completely replaced by marialitic scapolite. The least altered rocks have usually an intergranular texture with plagioclase and hornblende as the major minerals. Some sills are differentiated and contain parts that are strongly enriched in Fe, Ti and V. At Airikukkio northeast of Nunasvaara a 100 m thick sill has been investigated by drilling. The best core section of a magnetite rich part of the sill contains 30.9 % Fe, 4.0 % Ti and 0.64 % V,0.4 on a length of 6 m (Lehto 1983). Pyrite occurs disseminated in many sills and chalcopyrite is commonly found in small amounts in magnetite rich types.

Visit outcrops along a gravel road

3-4C, The Jäletkurkkio Cu-mineralization

Jäletkurkkio is a small Cu-occurrence in the Vittangi greenstones that was found in early 1900’s. A c. 60×30 m large excavation has been done and it shows a mineralized albite felsite occurring adjacent to graphite schist and metadiabase. The albite felsite is brecciated by calcite, pyrite, magnetite and some chalcopyrite.

The metadiabase in the southern part of the excavation is altered by scapolite, which replaces the plagioclase. Pyrite and chalcopyrite occur disseminated in small amounts. A strongly altered metadiabase exists together with the albite felsite within the mineralization. It contains plagioclase, scapolite, biotite, amphibole, pyroxene, carbonate and pyrite in different proportions. The albite felsite is reddish in colour and fine-grained. The texture is intergranular and tabular albite occurs together with some amphibole, pyrite and rutile. Small fissure fillings of amphibole, pyrite, chalcopyrite and rutile are common. The relation between the altered metadiabase and the albite felsite is unclear. Chemically they are different in character, with the albite felsite possibly representing a more felsic intrusion. Graphite schist is only found in the westernmost part. It has a high
graphite content (15-20 % C), and contains some amphibole as porphyroblasts and fissure fillings.

Amphibole, magnetite and pyrite occur as a rich dissemination in the calcite breccia. Chalcopyrite and chlorite are minor constituents and titanite is an accessory component. Pyrite is mainly euhedral and up to some mm in size, magnetite is subhedral to euhedral. Minor veins and breccias containing calcite, amphibole, pyrite and chalcopyrite are also found in the albite felsite. Some chalcopyrite occurs together with a rich dissemination of pyrite in parts of the altered metabasite. Less than 100 ton of rock has been has been obtained from test mining in a small pit. A bulk sample of the mineralized breccia contained 0.25 % Cu, 0.062 ppm Au and 474 ppm Co. Other elements slightly enriched in the mineralization are Ni and U.

Visit at excavation showing mineralization and alterations in the host rocks.

3-4D, “Scapolite diorite” at Nunasvaara

East of Nunasvaara the bedrock is poorly exposed. However within an area of about 100x100 m there exists several small outcrops of a scapolite-rich rock that probably has formed by alteration of a dioritic intrusion. It is mostly homogenous in character with 1–4 mm large grains of scapolite together with some amphibole and accessory amounts of epidote, pyrite, magnetite and titanite.

Visit small outcrops along a gravel road.

3-4E, Amphibole breccia at Nunasvaara

Some hundred meters west of the “scapolite diorite” there exists small outcrops of strongly scapolite altered greenstones. Scapolite occurs as a pervasive alteration and as veinlets. Narrow veins with a pegmatitic composition are also encountered. The greenstones are fine- to medium-grained and may be of both extrusive and intrusive origin. In one place the rock is brecciated. It contains angular fragments with a partly banded structure that are set in a matrix of dark green amphibole. The surroundings to the breccia are partly rich in albite and coarse-grained scapolite.

Visit an outcrop along a gravel road.

3-5, The Saivo Fe-Ti occurrence

A small but unusual type of Fe-mineralization occurs at Saivo. The host rock is a coarse-grained pyroxene rock, which forms a 250x60 m large lens within monzonite and gabbro. The gabbro is partly affected by strong scapolite alteration and it is brecciated by the monzonite which itself is brecciated by the pyroxene rock. Alterations within the monzonite are not prominent and the contact to the pyroxene rock is mostly sharp. Several dm large crystals of green diopside-hedenbergite dominate the pyroxene rock. Normally, the long axis of the crystals is oriented perpendicular to the contacts of the lens. Amphibole is less important and occurs as patches between pyroxene crystals or as an alteration of them. Plagioclase is a rare constituent. Coarse-grained magnetite and titanite are found enriched close to the contacts of the lens. Magnetite mostly forms dendritic aggregates up to several dm long together with varying amounts of titanite (Lehto, 1972).

Visitting outcrops of diopside-amphibole skarn and Fe-mineralization.

4-1, Kiskamavaara Co-Cu-Au deposit

The Kiskamavaara Cu-Co-deposit has been investigated by SGU in several drilling campaigns during the period 1972–1980. The mineralization is about 650 m 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 major tectonic zone running from Karasund to Svappavaara and further SSW towards Arjeplog. Andesitic metavolcanic rocks and quartzite dominates the bedrock in the Kiskamavaara area (Fig. 8). The host rock to Kiskamavaara is a breccia with subrounded clasts of intermediate volcanic rocks that occur in a matrix of fine-grained volcanic material and varying amounts of magnetite and hematite. Based on the composition and the character of the breccia a hydrothermal origin is favoured (Martinsson 1995).

Co-bearing pyrite occurs together with some magnetite and chalcopyrite disseminated in the matrix to the breccia. Bornite and molybdenite are found in accessory amounts and quartz and calcite are found in small amounts as gangue minerals. There exist several richer lenses within the mineralization (Fig. 9) where the composition of the matrix is almost massive pyrite. Usually the ore minerals changes from pyrite in the central part of the mineralization to magnetite and hematite in the peripheral parts (Martinsson, 1995). The Co-content of the pyrite varies between 0.3 and 1.3 % (Ekström 1978).

Several types of alterations, including scapolitization, K-feldspar alteration and sericitization have affected the bedrock in the Kiskamavaara area. Albite alteration is locally developed on the eastern margin of the mineralized 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 K$_2$O (7.1–11.6 %) and Ba (0.25–0.64 %) contents (Martinsson 1995). Sericite is locally developed and occurs together with small amounts of tourmaline as a late alteration assemblage.

Visit small outcrops along a gravel road.

4-2, The Peuravaara Formation at Kallovaara

A 500-2000 m thick unit of basalt lava, with minor intercalations of mafic tuff, tuffite and iron rich chemical sediments between the flows, constitutes the Peuravaara Formation. It occurs in the upper part of the Kiruna Greenstones and can regionally be identified in an area of c. 50x50 km around Kiruna. Based on petrographical and chemical criteria it is divided into three members. The lower member is chemically homogeneous and has a TiO$_2$ content of c. 1.1 %, while the middle member has a higher and more variable TiO$_2$ content. The upper member is distinguished by a TiO$_2$ content less than 0.8 %. The upper 50 meters of the lower member consists of mafic tuff with intercalations rich in magnetite, which serve as a key horizon for separating it from the middle member. Similarly the middle member has an upper part consisting of mafic tuff. The thickness of the lower and middle members is 300–600 m and 250–800 m respectively. The upper member is partly missing due to erosion and the exposed maximum thickness is 150 m. The chemistry of the basaltic in the lower and middle members is close to modern MORB, while the upper member is of LKT type (Martinsson, 1997).

Characteristic for the Peuravaara Formation is the pillowed flows, described in detail by Sundius (1912b). The lava flows usually have a massive base and a pillowed upper part, with a total thickness of 20–50 m for individual flows. Less common are massive flows with amygdules at the top. Although the proportion of massive to pillowed lava within single flows is highly
variable, there is a trend of increasing amount of pillowed lava stratigraphically upwards. The pillows are 0.2–0.8 m in size and mostly rounded. Lens to tube-shaped pillows are less common. Radially arranged amygdules occur close to the pillow borders, except for the lowest 50–100 m of the Peuravaara Formation where they are lacking. The size of the amygdules is generally 1–4 mm, but increases slightly higher up in the section. Highly vesiculated flows, with 5–10 mm large amygdules, are found in the upper member suggesting shoaling conditions during deposition of the Peuravaara Formation (Martinsson, 1997). Interbedded volcanlastic rocks are basaltic in composition and massive to layered. They consist of shards and vesicular fragments ranging in size from tuff to lapilli (Sundius, 1915). Associated to the clastic units are up to some metres thick magnetite-rich chemical sediments, chert and locally carbonate rocks. They are most extensively developed in the uppermost part of the lower member, but minor occurrences are found at several stratigraphic levels (Martinsson, 1997).

Intense epidotization accompanied by some magnetite and pyrite is locally developed. Scapolite and more rarely tourmaline are may be found in biotite altered hyaloclastite material between pillows. At Kallovaara massive and pillowed basaltic lava are intersected by fissures filled with scapolite, albite and chalcopyrite. A random sample contained 2.14 % Cu and 3.38 ppm Au.

Visit at road cut with massive and pillowed basalt containing fissure fillings with scapolite, albite and chalcopyrite.

4-3, The Kiirunavaara apatite iron ore
Kiirunavaara is the largest of the apatite iron ores in Sweden, comprising c. 2000 M ton of iron ore with 60 to 68 % Fe. It was found in outcrop 1696 but regular mining started not until 1900 when a railway was built from the coast to Kiruna. Open pit mining ceased in 1962, with a total production of 209 Mt. Underground work started in small scale during the 1950s and the ore is now mined by large scale sublevel stoping. The present main haulage level is at 1045 m and the total production from

**Figure 8. Geology of the Kiskamavaara area.**

**Figure 9. Co-content in the Kiskamavaara area (from Persson, 1981).**
The tabular ore body is approximately 5 km long, up to 100 m thick, and it extends at least 1300 m below the surface. It follows the contact between a thick pile of trachyandesitic lava (traditionally named syenite porphyry) and overlying pyroclastic rhyodacite (traditionally named quartz-bearing porphyry). Towards north the much smaller Luossavaara ore is situated in a similar stratigraphic position (Fig 10).

The trachyandesite lava occurs as numerous lava flows, which are rich in amygdules close to 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 pile 1 km stratigraphically below the ore. Several dikes of granophytic to granitic character cuts the ore and a larger body of potassic granite is found at deeper levels in the mine on the footwall side of the ore.

Magnetite-actinolite breccia is developed both in the footwall and hanging wall along the contacts of the Kiirunavaara ore body. In the footwall larger breccia zones may show a change from veined trachyandesite to breccia with angular fragments of the wall rock. In some places there is a central part containing rounded pebbles of the wall rock set in a matrix rich in magnetite. Close to the hanging wall contact the ore is often rich in angular to subrounded clasts of rhyodacitic tuff. Veins of magnetite and actinolite may extend tens of meters up in the hanging wall and they are locally gathered into 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 close to the footwall as a slightly irregular and branching body of massive magnetite ore. It is usually 40 to 70 m thick and contains up to 15 % of disseminated actinolite in a 5 to 20 m wide zone along its borders. The magnetite is mostly very fine-grained (<0.3 mm) but in the central part of the B-ore a zone of coarser magnetite (up to 2 mm) 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 also at the footwall contact and within the ore. The D-ore may have a banded structure and the proportions of apatite and magnetite is widely varied. The age relation between B- and D-ore is ambiguous, and both ore types can be seen cutting each other. However, in general the B-ore seems to be slightly younger than the D-ore. Columnar and dendritic magnetite are locally developed textures in the ore suggesting rapid crystallization in a supercooled magma (Geijer 1910, Nystrom 1985, Nystrom and Henriquez 1989). Veins of anhydrite, anhydrite-pyrite-magnetite and coarse-grained pyrite are encountered in the ore and its wall rocks. Richer occurrences of pyrite are mainly found in the northernmost part of the deposit. Cu-sulphides and molybdenite are rare constituents of the pyrite mineralizations. Gypsum is commonly found as narrow fissure fillings in the ore.

Extensive albitionization is developed in the footwall to the Kiirunavaara deposit. The area of most intense albitionization surrounds the gabbroic to monzonitic sill, which itself is strongly altered. Sericite schist with some tourmaline is locally found at the footwall contact of the ore (Geijer 1910). Actinolite is a common alteration mineral both at the footwall and the hanging wall contacts and it may form massive skarn bordering the ore. Actinolite also replaces, partly or completely, clasts of wall rocks 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 often is accompanied by disseminated pyrite and a weak enrichment of Cu, Co and Mo.

The ore is cut by porphyry dikes and granophytic to granitic dikes. Some of the dikes are composite in character also includ-
ing diabase. A U-Pb zircon age of 1880±3 Ma (Cliff et al. 1990) has been obtained for the granophytic dikes. This demonstrates that the Kirunavaara ore formed before c. 1880 Ma.

Visit underground showing the ore and its host rocks. Ore breccia will be seen in outcrops at the top of Kirunavaara.

4.4 A, “Syenite porphyry” at Luossavaara

Traditionally the Kiruna Porphyries have been divided into two units: “the syenite porphyry” and “the quartz bearing porphyry” (Geijer, 1910). The “syenite porphyry” occurs in the stratigraphically lower part below the Kirunavaara and Luossavaara iron ores, while the “quartz bearing porphyry” is situated between these ores and the Per Geijer ores. The extrusive nature of the “syenite porphyries” was first pointed out by Lundbohm and Bäckström (1898), they describe amygdules, spherulites, and fluidal structures in these rocks, west of Kiruna. Later, and more detailed, studies of the “syenite porphyries” have confirmed this suggestion (Lundbohm, 1910; Geijer, 1910,1931; Parák, 1975; Frietsch, 1979) and also resulted in the identification of Fe-rich types called “magnetite syenite porphyries”.

Volcanic rocks of intermediate composition dominate the “syenite porphyry”, and their high alkali content suggests a trachyandesitic character. However, the usually strong alkali alteration of these rocks prohibits a proper classification based on their main elements. The trachyandesitic volcanic rocks form a 300–2000 m thick and rather monotonous sequence of mostly amygdaloidal lava flows. The thickness of individual lava flows seem to be in the range of 5–20 m. The amygdules have a size of 1–6 mm and consist of carbonate, magnetite, titanite, chlorite, and biotite. Most of the “syenite porphyries” are affected by albitization and especially the amygdaloidal lava flows are strongly altered which gives them a reddish colour. The albitization is accompanied by secondary magnetite, actinolite, titanite, and locally some tourmaline (Geijer 1910). A U-Pb age of titanite from albitized trachyandesite lava gave 1876±9 Ma, which is considered to be the age of albitization (Romer et al. 1994).

Visit at railroad cut with albitized amygdaloidal trachyandesitic lava.

4.4 B, Luossavaara apatite iron ore

The Luossavaara apatite iron ore occupies the same position between the “syenite porphyry” and the “quartz bearing porphyry” as the Kirunavaara deposit (Fig. 10). It comprises c. 20 Mt of massive iron ore with 61 % Fe and <1 % P. The ore is about 700 m long and up to 40 m thick. Besides magnetite it contains small amounts of actinolite, apatite and titanite. The Luossavaara deposit has been mined in open pit and underground to a depth of 365 m in the northern part and to 250 m in the southern part. Totally 16.65 Mt of ore has been mined in 1919–1976 and 1981–1985. Low-grade ore-breccia exists in the footwall. It is calculated to contain 15.47 Mt of ore with 34.0 % Fe and 0.03 % P. The ore breccia consists of irregular narrow veins and a large number of magnetite dykes within biotite-chlorite altered trachyandesite. Most of the dykes are steeply dipping and have a north-south direction. They are up to 2 m wide and contain sometimes large platy crystals of titanite. The U-Pb age of this titanite is 1888±6 Ma (Romer et al., 1994).

Visit at the top of Luossavaara.

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