

# IRON OXIDE SYSTEMS AND BASE METAL MINERALISATION IN NORTHERN SWEDEN

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**Abstract** — The Lower Proterozoic succession in Northern Sweden, hosts a major iron oxide province with a widespread and diverse base metal sulphide mineralisation. A large amount of geological and exploration data exists, but fundamental questions remain regarding the distribution and relationship of the iron and predominantly copper rich sulphide mineralisation. Detailed field, isotopic, mineralogical, petrological, fluid inclusion and structural observations are now providing new data on this historically important and significant province. Genetic concepts can now be reassessed and specific deposits re-evaluated to investigate the inter-relationship of base metal mineralisation, iron oxide deposits, rock alteration, metamorphism, orogenic cycles, structural development and igneous activity.

Iron mineralisation occurs in predominantly four forms:

- Banded, stratiform, siliceous, 'quartz-banded' iron oxide formations.
- Calc-silicate 'skarn' and carbonate hosted, stratabound, iron formations.
- Concordant to discordant, massive, brecciated and vein style, magnetite-actinolite, magnetite-apatite and magnetite-haematite-apatite ores.
- Disseminated, massive, vein and replacement iron oxides with silica and carbonate.

Base metal (Cu-Zn-Pb-Ag-Co) mineralisation, often with Au, occurs as:

- Disseminated sulphides within pelitic, siliceous, carbonate and calc-silicate metasediments.
- Hydrothermal veins within massive and brecciated magnetite (-haematite) and replacement bodies within mixed siliclastics, metavolcanites and metacarbonates.
- Veinlet and disseminated sulphides within iron formations, iron bearing calc-silicates and chemical sediments, and with magnetite within metavolcanites and intrusive bodies.

Regional and locally developed rock alteration, spatially associated with mineralisation, occurs as scapolite, albite, K-spar, sericite, biotite, chlorite, actinolite, epidote, carbonates, fluorite, tourmaline and silica.

Mineralisation is multistage, and apparently focussed and hosted by specific lithological hosts, lithostratigraphic units and brittle-ductile tectonic zones.

## Introduction

A 2.5 – 1.85Ga Palaeo-Proterozoic terrain in Sweden is represented by a ca.1,000km wide belt of mixed 'greenstone', siliclastic and pelitic metasedimentary and acid to basic metavolcanic sequences deposited in an inferred extensional or trans-tensional environment on the edge of the Archean continent (Figure 1.).

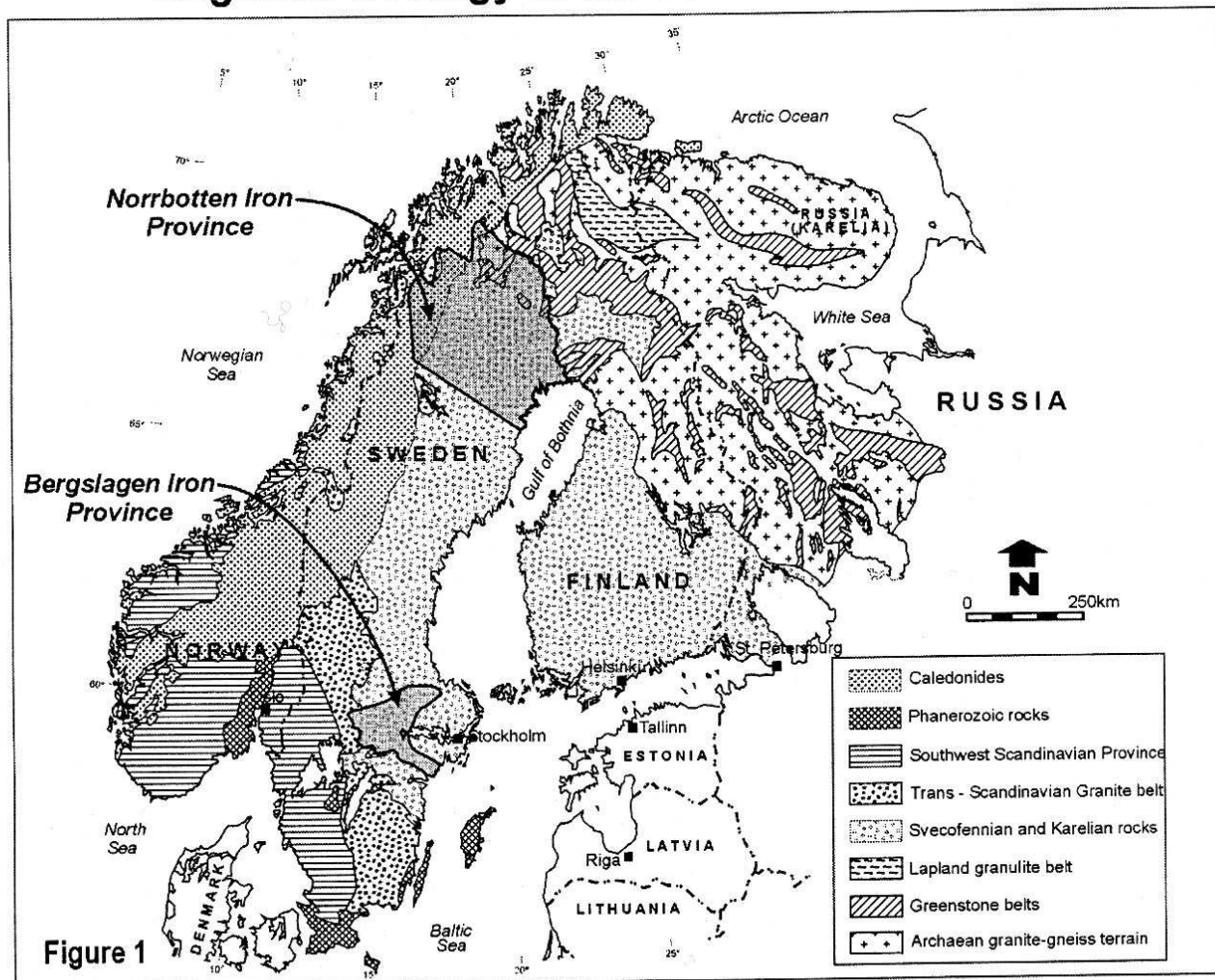
Two iron bearing provinces with subordinate base metals occur in the northern and central parts of Sweden. The northern province, lies within Norrbotten, Swedish Lapland, and the central province forms the historic mining district of Bergslagen, (Figure 1.). The Norrbotten Province, which currently produces over 30Mtpa of iron ore and processed pellets from Europe's largest magnetite

deposits, and ca.62,000tpa of copper from one of Europe's largest mines, is the subject of this paper.

Extensive iron mineralisation is developed in Palaeo-Proterozoic metavolcanics and metasediments in both Norrbotten and Bergslagen, as apparently stratiform-stratabound quartz, carbonate and calc-silicate haematite-(magnetite) banded iron formations, and the volumetrically significant, but problematical magnetite-actinolite, magnetite-apatite and magnetite-haematite-apatite iron ores.

Disseminated, schlieren, massive and vein type magnetite is a common accessory in a range of base metal deposits and occurrences in both regions, suggesting a common origin for iron oxides and Cu, Zn, Pb sulphides with Au and Ag.

## Regional Geology of the Fennoscandian Shield



The inter-relationship of the various styles of iron and the often spatially coincident Cu, Cu-Au, and Zn-Pb mineralisation, the phases of mineralisation, alteration patterns, the degree of structural control, and structural, metamorphic and plutonic igneous relationships to mineralisation are not yet well documented nor understood. This paper seeks to address these issues.

### Regional Geology of the Swedish Fennoscandian Shield

The Palaeo-Proterozoic successions were deposited in a structurally complex extensional environment on the edge of the Archean continent between 2.5-1.85Ga (Gorbatshev and Bogdanova 1993). The geotectonic environment is interpreted as a series of volcanic arcs, back arc basins and rifts along the Archean continent above a series of variously active NW dipping subduction zones in an oceanic – continental collision zone. Accretion of Proterozoic juvenile crust along the Archean continental boundary was followed and partly accompanied by closure and deformation creating the Svecofennian-Svecofennian Orogenic cycles (Gorbatshev and Bogdanova 1993, Skiöld et al 1993).

The western edge of the Svecofennian terrane is largely hidden beneath the easterly thrust Palaeozoics of the

Caledonian Orogen along the Swedish-Norwegian border, and non-residual glacial detritus from Quaternary Ice sheets covers around 98% of the Palaeo-Proterozoic bedrock.

### Northern Sweden - Stratigraphy

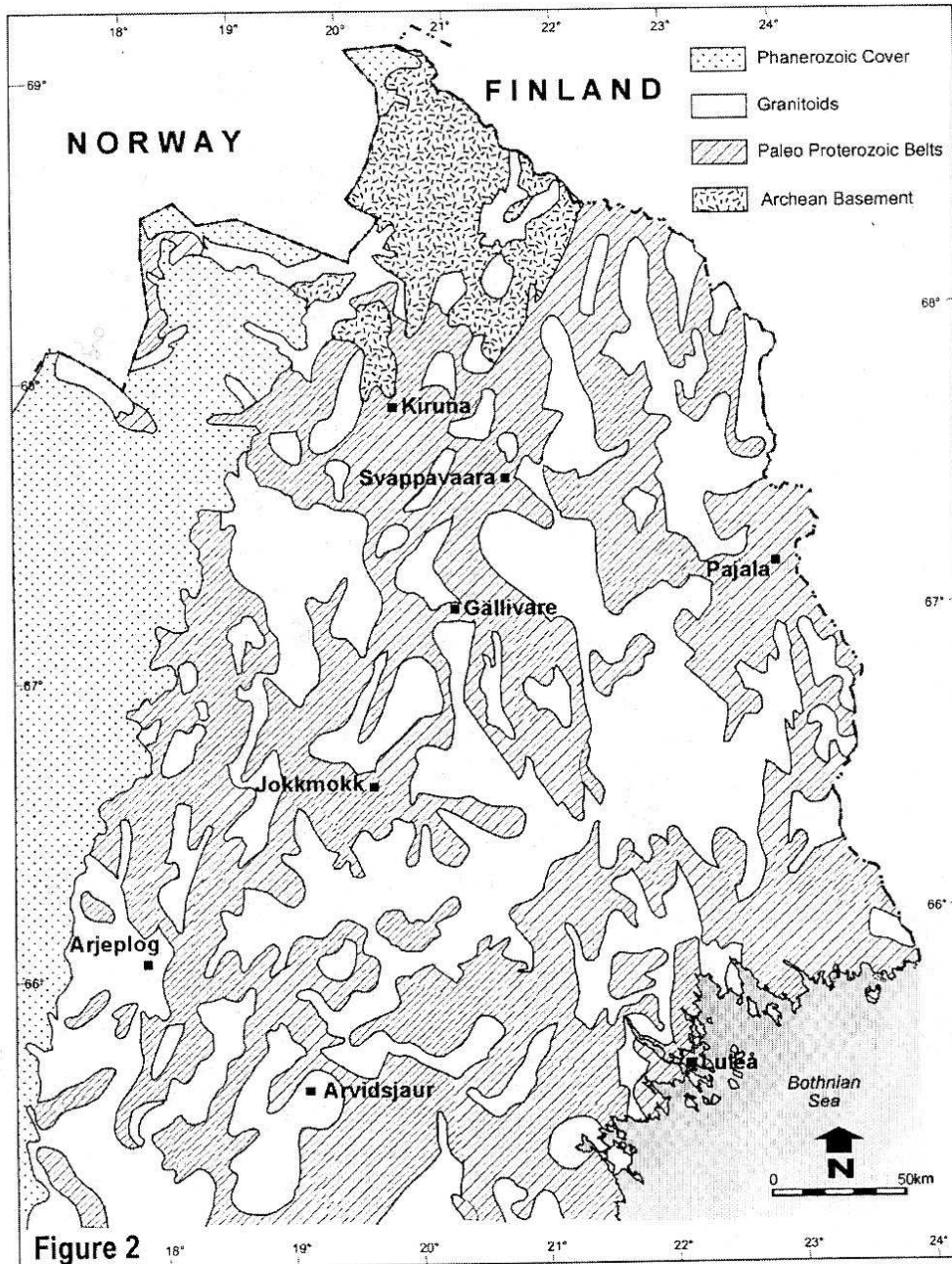
The 2.8Ga Archean basement of the Fennoscandian Shield is overlain by over 10kms of Palaeo-Proterozoic formations. These comprise siliclastics, mixed basic volcanics and sediments of the Greenstone Group, and intermediate to acid felsic volcanic, volcanoclastic and epiclastic sediments of the overlying Porphyry Group (Witschard 1984, Welin 1987). The sequences are preserved in a series of deformed supracrustal belts stretching 250 kilometres across northern Sweden and into Finland, (Figure 2).

Martinsson (1997) describes the detailed lithostratigraphy of the Greenstone Group in the Kiruna area. This 2.5-2.1Ga sequence (Skiöld and Cliff 1984; Skiöld 1986) is part of a larger tholeiitic province, related to rifting of the Archean craton across northern Fennoscandia (Ekdahl 1993).

Overlying the Greenstone Group are quartzites, conglomerates and mica schists of Witschard's (1984) 'Middle Sediment Group' (Figure 3).

These formations are overlain by the Porphyry Group, a volcanic and sub-volcanic complex, marking the rise of alkaline basalt-andesite and calc-alkaline acidic magmas

## Northern Sweden - Simplified Regional Geology



around 1.91-1.88Ga. (Skiöld and Cliff 1984; Skiöld 1987; Welin 1987). Basalts, andesites, dacites, rhyolites and volcanoclastic tuffaceous sediments are subdivided into the dominantly andesitic Porphyry Group and the syenite and quartz-syenite Kiruna Porphyries. To the W and NW the Porphyry Group is bimodal and mildly alkaline to alkaline and trachytic, while to the E and in central Norrbotten it is predominantly calc-alkaline, interpreted as back arc extension and continental margin volcanic arc settings respectively, (Pharaoh and Pearce, 1984; Frietsch and Perdahl, 1989). Alkaline volcanic and sub-volcanic units, sodic trachytes, trachyandesites and trachybasalts, albite (leuco) gabbros and sodic microsyenite, are well developed in spatial association with the magnetite-apatitic iron ores in the Kiruna and Gällivare districts (Figures 2 and 4).

The coeval 1.89-1.86Ga (Skiöld 1987) Haparanda and Jörn Granite suites, form plutonic-intracrustal, differentiated,

gabbroic to granitoid intrusives, generated during an early phase of the Svecofennian Orogeny. The 1.91-1.88Ga plutono-volcanic cycles ended with the deposition of thick molasse-type or turbiditic, arkosic-siliceous clastics, locally derived from the volcanites, and deposited in reactivated graben structures (Witschard 1984). Potassic rocks (5-9%K<sub>2</sub>O) occurring in the Rappen- Tjåmotis -Ultevis areas appear to relate to a NNE-SSW rift zone in which the volcanites are overlain by a >5km thick pile of clastic sediments (Ödman, 1947; Carlon, 1984).

### **Regional Metamorphism, Deformation and Igneous Activity**

A close temporal relationship exists between the extensional depositional environments of the Greenstone Group, the Porphyry Group and the overlying sediments, and the

## Regional Stratigraphy and Mineralisation

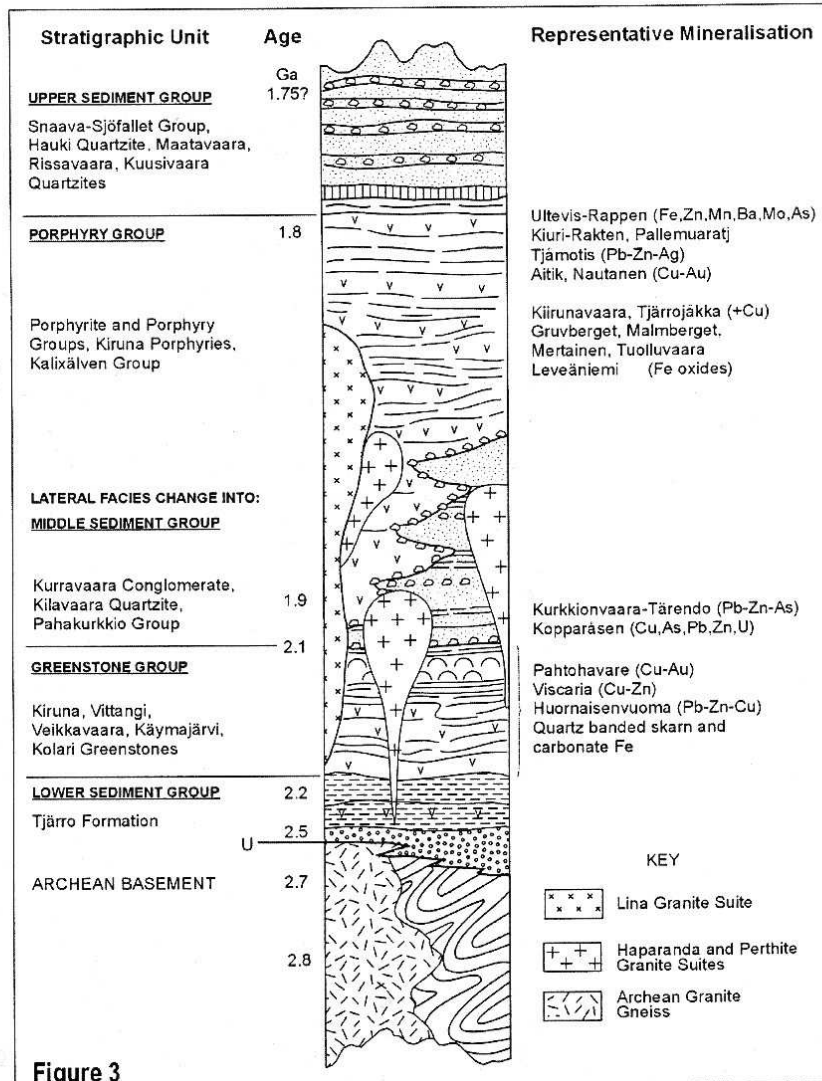


Figure 3

compressional phases of the orogen which occurred in the 1.9–1.8Ga interval. The detailed tectonic and chronological development of the Svecofennian Orogeny is still not fully resolved (Nironen, 1997; Ekdahl, 1993). Regional structural data from the European Geotraverse (Berthelsen and Marker 1986), and more detailed mapping and structural interpretation in the Kiruna area (Vollmer et al 1984, Wright 1988, Talbot and Koyi 1995) indicates a complex ductile-brittle evolution.

Detailed structural studies do not exist for most of the supracrustal belts in Norrbotten and the complex interaction of deformation phases, metamorphism and plutonism is still largely unknown. Vollmer et al. (1984), Wright (1988) and Talbot and Koyi (1995) interpret the Kiruna regional geology in terms of an easterly dipping and younging homoclinal sequence which has suffered an early cycle of westward directed thrust-nappe stacking, crustal shortening (>46kms) isoclinal folding and imbrication (Svecokarelian?). This is overprinted by peak ductile deformation and prograde metamorphism to upper greenschist or amphibolite facies within stress fields generated by sagging between rising diapiric granitoids during the ca.1.84Ga Svecofennian orogeny.

Deformation and strain is highly heterogeneous, and

focussed along zones of competency contrast. Massive magnetite bodies in the Kiruna area have high strain zones focussed around their contacts. The sulphide bodies at Viscaria are elongate and plunging down possible low to high angled, thrust-shear structures, and the Malmberget magnetite-apatite bodies are sheared, refolded, highly strained, plunging shoot-like bodies, long recognised as recrystallised deposits.

Low and high angled ductile-brittle thrusting and shear is a significant feature of the tectonic development. Wright (1988) mapped late stage E-W trending, sub-vertical dextral shears, and NNW trending sinistral shears in the Kiruna area. Shear deformation can be demonstrated in the regional airborne magnetic data indicating a number of major NNE-SSW to N-S, and NW-SE ductile to brittle shear zones. Berthelsen and Marker (1986) define a major NNE-SSW structure (the Baltic-Bothnian Megashear) passing through east Norrbotten (Pajala) with sub-parallel branches to the west. Henkel (1991) notes this as the Bothnian-Seiland Fault Zone, and the main NW trending structure as the Bothnian-Senja Fault Zone. Frietsch et al. (1990), Wikstrom et al. (1996) and Billström and Martinsson (2000) all refer to the major NNE, N-S and NW trending structural lineaments, the NW trending Luleå-Malmberget structural

## Northern Sweden - Deposit Locations



Figure 4

zone lying parallel and close to the buried edge of the Archean craton (Mellqvist et al. 1999), Figure 5.

The supracrustal belts are preserved within and between extensive granitoids displaying early strain fabrics and later non-strained diapiric forms. These features defined at least three granite suites: the 1.89-1.86Ga Haparanda-Jörn differentiated granite-gabbro suite; the 1.86-1.82Ga Perthite Granite Suite; and the 1.80-1.78 Lina-TIB post-orogenic, monzonite-granite suite.

Talbot and Koyi (1995) present evidence for a two staged emplacement of the Haparanda-Perthite Granite suites; as syn-volcanic (Kiruna Porphyry), crustal melts (ca. 1.90-1.86Ga) and a later, post-thrusting, syn-orogenic, solid-state ductile event (ca. 1.86-1.82?) forming a series of mushroom shaped diapirs now exposed at different erosional levels. This process continued with the subsequent rise of the post-orogenic Lina Granites.

## Iron Oxide Mineralisation

Iron oxides occur in northern Sweden in four main associations:

1. Banded, stratiform, siliceous, 'quartz-banded' iron oxide formations.
2. Calc-silicate 'skarn' and carbonate hosted, stratabound, iron oxides.
3. Concordant to discordant, massive, brecciated and vein style, magnetite-actinolite, magnetite-apatite and magnetite-haematite-apatite ores. (The 'magnetite-apatite' ores).
4. Disseminated, massive, vein and replacement iron oxides with silica and carbonate.

Quartz-banded, skarn and carbonate hosted iron formations are sheet-like to lensoid masses, generally parallel to the host rock banding or layering. The quartz-banded iron

## Northern Sweden - Principal Regional Structures

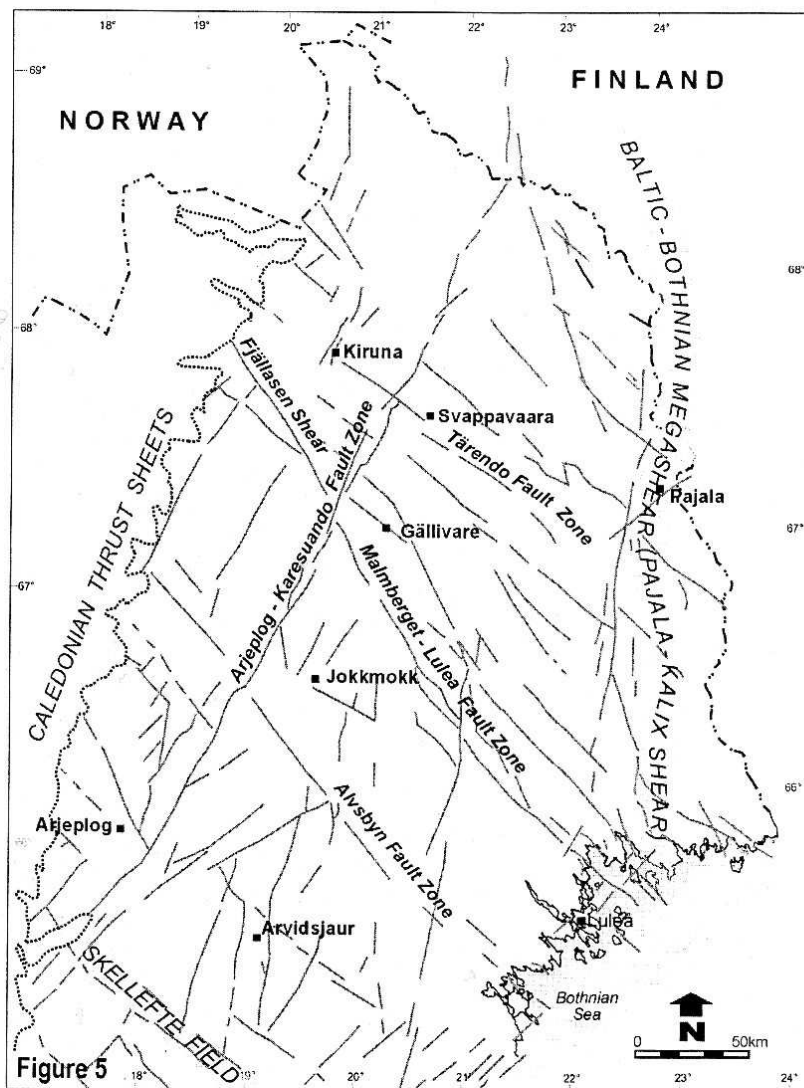


Figure 5

mineralisation occurs principally within the upper sequence of the Greenstone Group across Norrbotten, and in the Jokkmokk-Arjeplog region to the SW, apparently higher in the sequence near the top of the Porphyry Group (Figure 3 and 4).

Quartz-banded, iron silicate - magnetite bearing quartzites and metacherts, are typically low in Mn (1-2%) and P (less than 0.1%). They often pass laterally and vertically into clean carbonate or actinolite-diopside-hornblende-chlorite-biotite, calc-silicate hosted, 'skarn iron ores'. These form lenses and layers, concordant with host marbles, dolomites and banded cherts, up to 1-2kms long, 10-100m thick with 30-40%Fe. Reserve estimate is 500Mt 36%Fe (Grip and Frietsch, 1973) with individual deposits ranging in size from 5-80Mt. Stora Sahavaara (82Mt at 41%Fe) in the Pajala district, is the largest known deposit Figure 4. Syn-sedimentary deposition of iron oxides across a wide spectrum of siliceous to carbonate environments and subsequent regional metamorphism appears to be the origin of this mineralisation. The Greenstone hosted skarn iron ores often contain minor pyrite, pyrrhotite and chalcopyrite, apatite and associated scapolite-diopside-biotite alteration possibly indicative of some hydrothermal input.

Banded quartz-magnetite mineralisation occurs in the inferred upper stratigraphic sections of the Porphyry Group in the Arjeplog - Porjus district of SW Norrbotten as a 40km long, manganiferous (4-7%Mn) quartz banded iron formation, very similar in lithology and setting to the 'manganiferous iron formations' in the Bergslagen District, Central Sweden.

The "magnetite-apatite" or "Kiruna-type" iron ores, typified by the Kiirunavaara deposit, are magnetite-apatite, magnetite-actinolite and magnetite-haematite-apatite bodies. They are spatially and genetically associated with alkaline volcanic, sub-volcanic and intrusive rocks within the Porphyry Group. Around 35-40 discrete and clustered deposits are known in four main areas (Figure 4), around Kiruna, W and SW of Kiruna, around Svappavaara, and in the Gällivare district.

Much has been written about their form and origin, particularly with regard to Kiirunavaara, notably by Blake (1992); Cliff and Rickard (1992); Cliff et al.(1990); Fleischer (1983); Frietsch (1978, 1984); Geijer (1915, 1930a, 1960); Geijer and Odman (1974); Gilmour (1985); Nystrom (1985); Nystrom and Henriquez (1989, 1994); O'Farrelly (1990); Parak (1975, 1984, 1988); Romer et al

(1994); Vollmer et al. (1984) and Wright (1986, 1988). Other magnetite-apatite deposits are noted by Frietsch (1997); Svappavaara (Frietsch, 1966; 1980a); Mertainen and Painirova (Lundberg and Smellie, 1979; Frietsch, 1980b); Ekstromsberg (Frietsch, 1974); Malmberget (Geiger, 1930b; Ljunggren, 1960).

These deposits contain varying proportions of magnetite, haematite, apatite and actinolite, displaying great variability in size and geometry. They form elongate, massive tabular bodies; magnetite-haematite, matrix supported, wall rock breccia bodies; actinolite and apatite veined magnetite-haematite breccias; and iron oxide-apatite-actinolite vein systems. Controversy surrounds the origin of these deposits, with genetic interpretations including 'magmatic segregation' and injection, extrusion, metasomatic replacement, hydrothermal deposition and replacement or syn-sedimentary surface exhalation.

The Kiirunavaara deposit (+2.0 billion tonne, 60-62%Fe) is a 4-5kms long, 80-100m wide and at least 2kms deep, tabular body dipping east within a structurally thickened sequence of the Porphyry Group. The orebody lies along the contact of massive, sodic (albitic), trachyandesitic lavas "syenite porphyry" in the structural footwall to the west, and porphyritic rhyolite, rhyodacitic pyroclastics and inferred rhyolite ash flows "quartz-porphyry" in the structural hangingwall to the east.

The Luossavaara deposit, sits in the same sequence of rocks as Kiirunavaara, while a parallel but separate tectonic-stratigraphic interval in the Kiirunavaara hangingwall sequence hosts the apatite rich and mixed magnetite-haematite 'Per Geiger' orebodies and the breccia-type

deposit at Tuolluvaara. The Mertainen deposit 25kms SE of Kiruna, sits at the northern end of a 7km long, 3km wide magnetic anomaly within andesites and trachytes of the Porphyry Group which also host the Leveaneimi, Gruvberget and Painirova deposits in the Svappavaara area nearby.

Mineralisation is typically magnetite with subordinate haematite, averaging 25-64%Fe, with apatite, tremolite-actinolite, biotite-chlorite, diopside and minor calcite. The ores are either massive fine grained almost apatite free magnetite, or banded fluorapatite averaging 1%P. The Kiirunavaara deposit contains an apatite poor ore cut by a later apatite rich magnetite. Ti content is <1% usually present as titanite, and Mn and S contents are generally below 0.1%.

Deposits generally exhibit remarkably low strain being resistive to penetrative fabrics, but heterogeneous ductile-brittle shearing and ductile deformation affects the contact zones of most deposits. The Malmberget deposit (930 Mt of 60-62%Fe), comprises 10 currently mined iron ore bodies sitting within an elongate W-E zone 5kms long and 2.5kms wide, containing around 20 discrete bodies. The host rocks (Geiger 1930b) comprise red and grey, alkalic, syenitic metavolcanites as at Kiruna. However, the Malmberget orebodies are highly deformed and 'stretched', refolded and rodded into a series of dismembered shoots with complex geometry. Pre-deformation dimensions of the ore zone appear to have been similar to Kiirunavaara (Figure 6). Recrystallisation has increased the grain size of the iron oxides and apatite from 0.1mm as in Kiirunavaara to 0.7mm. The 'layering' in the apatite-magnetite at Malmberget is a recrystallisation phenomena, and can be

### Kiirunavaara - Malmberget. A morphological comparison

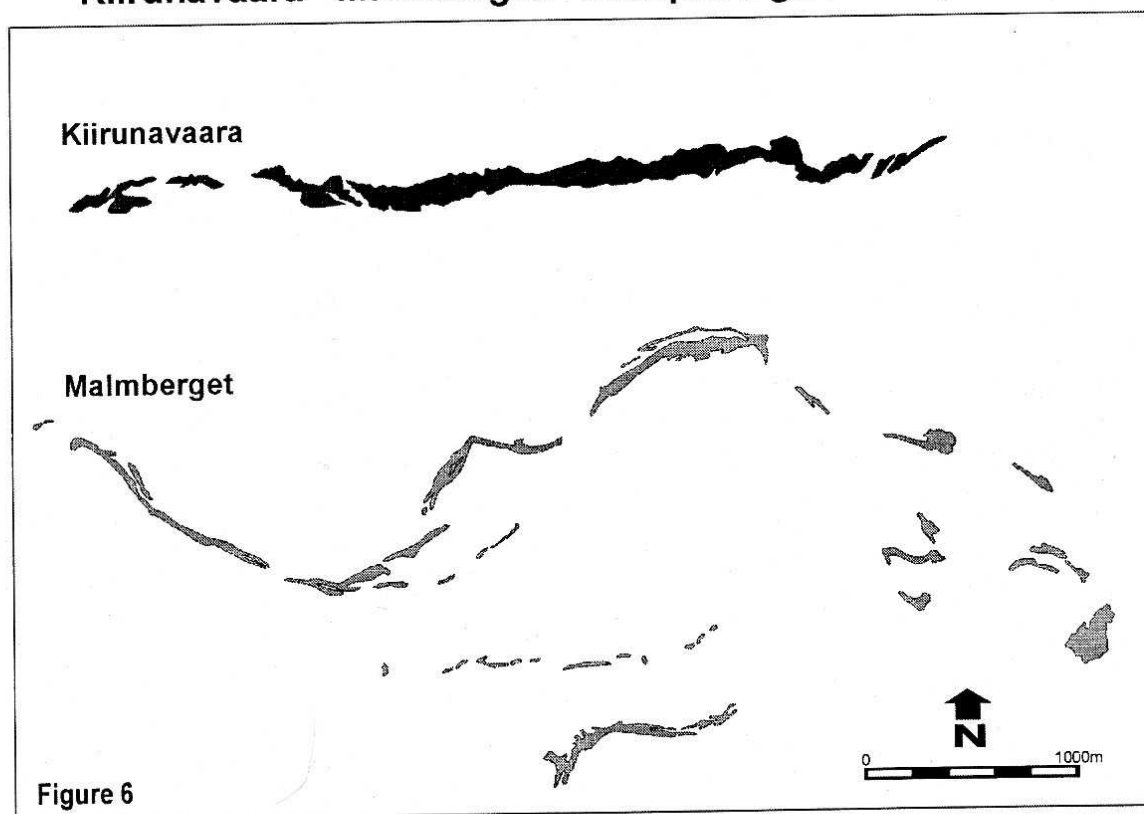


Figure 6

considered a 'gneissic texture' the magnetite clearly having 'flowed' as a solid-state ductile medium. The deposit has also suffered thermal metamorphism from an adjacent post-orogenic Lina Granite.

The contact zones of the magnetite-haematite-apatite-actinolite iron deposits are marked by veining, brecciation of the wallrocks, iron-oxide matrix supported breccias, host-rock xenoliths within the iron oxides, wall rock clast reaction rims and clast digestion and corrosion phenomena. Magnetite matrix supported, wall rock slab-clast and 'blow-apart' jigsaw clast breccias, suggest rapid decompression phenomena, while fine grain size and thin reaction rims indicate rapid deposition of iron oxides from a fluid medium. Brecciation often occurs in both hangingwall and footwall contact zones suggesting emplacement vertically rather than horizontally, and there is no silicate fusion in contact with iron oxides as would be expected with magmatic magnetite emplacement into a brittle fractured, solid metavolcanic host.

Age dating of the host rocks, cross-cutting altered granophyric dykes, and titaniferous magnetite veining at Luossavaara-Kiirunavaara deposit gives U-Pb dates of 1.88-1.89Ga (Cliff et al. 1990, Romer et al. 1994). The magnetite-haematite-apatite-actinolite deposits formed coeval with the enclosing alkali metavolcanites and intrusives of the Porphyry Group from high temperature magmatic fluids (Blake, 1992) and pre-date the Svecokarelian and Svecofennian deformation and metamorphism. Cliff and Rickard (1992) have identified a later isotopic resetting event.

Frietsch (1997) and Frietsch et al (1997) note the occurrence of enigmatic 'epigenetic, metasomatic' and "magmatic-tectonic" iron mineralisation in the Kevus and Teltaja iron ores in the Lannavaara-Pajala region. In the Pahtohavare area SW of Kiruna magnetite-silica and carbonate veining indicates a late stage, structurally controlled iron oxide mineralisation. These deposits are associated with characteristic alkali-silica alteration and copper-iron sulphides.

The only sulphides seen to be spatially associated with the main magnetite-haematite-apatite-actinolite deposits are minor, late stage, fracture fill pyrite and minor chalcopyrite.

## Alteration Phenomena

There is a regional developed, multi-episodic, rock alteration in northern Sweden, characterised by scapolite and more locally developed actinolite, biotite, chlorite, albite, K-spar, sericite, carbonate (ankerite-calcite), tourmaline, barite, allanite, and silica (Frietsch et al 1997). This alteration represents changes in bulk chemistry marked by increases in Na (albite and marialitic scapolite), K (microcline, sericite, biotite and chlorite) and Ca (calcite, dolomite and epidote).

Scapolite occurs as porphyroblasts, disseminations and layers along  $S_{0-1}$  (?), cuts schistosity, and forms multistage

vein systems often parallel to fold axial planes. It selectively replaces plagioclase, and is invariably a Na-Cl marialite (Frietsch et al 1997). An origin by mobilisation of evaporites within the Greenstone Group (Frietsch et al. 1997) and fluids associated with felsic intrusives (Ödman 1957) have been advocated for the regional scapolite formation.

Host rock alteration around magnetite-haematite-apatite-actinolite iron deposits is characterised by actinolite and biotite around the magnetite dominant bodies (Kiirunavaara, Luossavaara, Svappavaara, Malmberget), and sericite, biotite-chlorite and carbonate alteration, with barite, fluorite, tourmaline calcite and apatite around magnetite and haematite rich deposits (Per Geiger Ores, Leveaneimi, Malmberget).

The iron ore bodies often exhibit a 'red-rock' alteration caused by reddened K-spar, albite or silica containing fine dusted haematite, and is a common feature of Fe-Oxide-Cu-Fe deposits (Pollard and Williams 1999). It is clearly a multi-episodic alteration, often cut by extensive magnetite-actinolite and actinolite magnetite veins, and later epidote. Epidote veins cut foliation marked by biotite-chlorite, and epidote sometimes replaces scapolite and feldspars, invariably cutting haematitic 'red-rock' alteration. Allanite is commonly associated with the epidote.

Silica and carbonate are usually late stage vein infills and are characteristically associated with base metals sulphides. Tourmaline distribution and origin is discussed by Frietsch et al (1997).

Host rocks around the Norrbotten iron oxide bodies and certain sulphide deposits show patterns of Na, K, Si, Fe and Ca alteration in common with other "Iron oxide Cu-Au" provinces around the world, (Pollard and Williams 1999) with an extreme 'metasomatic' end product of scapolite-biotite schist or albite-actinolite schist.

## Sulphide Mineralisation

Northern Sweden contains a wide variety of known sulphide mineralisation, characterised by copper-iron sulphides and occasionally by sphalerite and galena. Recent reviews (Frietsch et al, 1997; Martinsson, 2000; Martinsson and Weiheid 1999) classify these occurrences in terms of syngenetic or epigenetic sulphides, and three broad types can be defined:

1. Inferred, 'syngenetic' or 'stratabound', iron sulphide rich, Cu deposits with subordinate Zn and Zn-Pb mineralisation in Greenstone Group metasediments.
2. Syngenetic-epigenetic Zn-Pb-Ag mineralisation in the Porphyry Group.
3. Epigenetic Cu-Au in the Upper Greenstones and Porphyry Groups within ductile-brittle fracture zones and sites of host rock brecciation, with or without massive magnetite, but usually accompanied by disseminated iron oxides.

Only three significant base metal occurrences have been mined in Norrbotten, at Viscaria (supposedly of type 1 above), and at Aitik and Pahtohavare (of type 3). There is growing evidence that many of the so called 'syngenetic'

and stratabound ores are in fact epigenetic and related to hydrothermal deposition and replacement phenomena along high strain zones, previously unrecognised low angle thrusts and apparently 'bed-parallel' ( $S_{0-1}$ ) shears.

### 'Syngenetic' and 'Stratabound' Sulphide

#### Deposits

A number of stratiform quartz banded iron horizons and reaction calc-silicate magnetite-haematite layers ('skarn iron ores') in the Greenstone Group have associated pyrite-pyrrhotite-chalcopyrite mineralisation, notably at Tervaskoski in the Vittangi district, with 0.3%Cu and associated scapolite and tourmaline (Frietsch 1997). The only known economic sulphide occurrence in the Greenstone Group, apparently in the footwall sequence of the Kiirunavaara magnetite-apatite deposit, is the 'synsedimentary' or early diagenetic, Viscaria Cu-Zn deposit (Godin, 1986; Martinsson, 1991, 1992, 2000). The Viscaria mine produced around 13Mt of 2.29%Cu from a mineralised envelope and narrow zones containing 40Mt of 1.5%Cu and 0.7%Zn. The principal A-zone was 3kms long NE-SW and up to 30m thick. It was known to a depth of 700m dipping at 80°E decreasing at depth to 45-50° and taking the form of a curved 'listric' structure.

The mineralisation is hosted by a marble-black schist-chert-tuffite sequence with albite rich rocks, scapolite and K alteration. Pyrrhotite with chalcopyrite and minor sphalerite, galena and barite occurs as fracture fillings, veins, disseminations, carbonate replacements, laminations, apparent rhythmic banding and slumping, and massive remobilised sulphides. Magnetite is common as massive lenses and laminae in tuffites, and disseminations and laminae in calcite marbles. The ore zones contain enrichments in P, LREE's, Mn, Ba, Co and U.

Martinsson (1991, 1992) notes a large alteration zone in the footwall of the main A zone, marked by the formation of K-phylosilicates from the breakdown of Na-plagioclase, considered a typical footwall alteration under a syngenetic exhalative deposit. However the deposit displays carbonate host rock replacement, is variably strained, ductile deformed, cut by the imbricate thrust package of the Kiruna belt (Talbot and Koyi 1995) and partially remobilised. Banding, and possible 'slumping' seen in the deposit is similar to that occurring in the Fe oxide-Cu-Au manto mineralisation at Punta del Cobre Chile, and could be replacive rather than synsedimentary. If syn-sedimentary, the deposit has clearly been affected by a later tectonic and hydrothermally induced remobilisation. Fluid inclusion data (Martinsson 1991, 1997) indicates mineralisation from high salinity fluids at ca.210°C. Scapolite occurring in the deposit (Frietsch et al (1997) has the same characteristic chemistry (dipyre with 1.5%CO<sub>2</sub> and 2.9%Cl) as scapolite in the nearby epigenetic Pahtohavare Cu-Au deposit.

At Kurkkionvaara (Niiniskorpi 1986), pyritic schists, cherts and tourmalinites of the Pahakurkkio Group (Figure 3), broadly comparable with the Viscaria sequence, contain pyrrhotite, galena, sphalerite and arsenopyrite.

Mineralisation appears to be synsedimentary and stratabound, as veinlets and disseminations, and is known at other sites in eastern Norrbotten.

At Huornaisenvuoma (Frietsch 1997; Billstrom et al 1997) a steeply dipping, apparently stratiform Pb-Zn-Cu-Ag mineralisation, with magnetite and spatially associated pyrite-pyrrhotite lies within scapolite altered, calc-silicate 'skarn' rich dolomite, mafic metatuffites and intermediate volcanics within the Greenstone Group. Pb isotopic composition (Billstrom et al 1997) indicates a model age of ca. 2.0Ga, and a potentially syn-sedimentary original deposit. The mineralisation is structurally remobilised, and the main massive sulphide lens is a sheared, recrystallised, clastic textured, sulphide-wallrock mylonite breccia.

At Kopparåsen (Adamek, 1975; Romer and Boundy 1988, Frietsch et al. 1997) massive and disseminated pyrite, pyrrhotite, chalcopyrite, bornite, arsenopyrite, uraninite, magnetite, galena and sphalerite, occur within tourmaline and scapolite bearing mafic metavolcanites, epiclastics, graphitic mica-schists and albite-cherts. Mineralisation is within inferred upper Greenstone-Lower Porphyry Group stratigraphy in a 1.8kms wide, 9.7kms long supracrustal belt striking N-S. Lead model ages (Romer and Boundy 1988) indicate an early mineralisation remobilised by later Caledonian activity. The uranium mineralisation is epigenetic and superimposed on strongly sheared and mylonitic sulphide bearing host rocks which contain gold.

The Arjeplog manganeseiferous quartz-magnetite sequence, in a variable sedimentary facies of chemical sediments, epiclastics and carbonate units at the inferred top of the Porphyry Group, passes NNE into carbonates and manganeseiferous 'exhalite' mineralisation on the Ultevis plateau near Tjåmotis and around Porjus, (Ödman, 1947,1950; Carlon, 1984). This mineralisation is probably syngenetic and contains up to 46%Mn, 27%Fe, and elevated apatite, barite, zinc, lead, silver, arsenic, fluorine, tungsten, molybdenum and boron. The area also contains Pb-Zn-Ag mineralisation (Carlon 1984) of type 3, possibly representing inferred syngenetic sulphides, remobilised within or adjacent to high strain zones and in part epigenetic.

#### Epigenetic Cu-Au and Pb-Zn (Ag) Deposits

Vein and replacement styles of base metal mineralisation occur within ductile-brittle deformation zones and host rock breccia bodies, with or without massive magnetite, but usually accompanied by disseminated iron oxides. Billström and Martinsson (2000) note that initial investigation of U-Pb isotopic age dates from titanite within sulphide mineralisation suggests two major age groups at 1.88-1.86Ga and 1.80-1.75Ga, the latter typical of epigenetic sulphides within major structures (Aitik) and massive magnetite bodies (Gruvberget). These ages are broadly comparable with the intrusion of the Haparanda Granite Suite and the Lina Granite. Broman and Martinsson (2000) define a systematic change in fluid chemistry and temperature with time within the sulphides.

Rheological contrasts between massive magnetite and enclosing host rocks have created brittle fracture zones, and some magnetite bodies host minor copper-iron sulphides in contact breccia bodies and peripheral wallrocks. Mineralisation of this type occurs with the Gruvberget and Tjärrojåkka magnetite deposits, and at Rautuvaara in Finland (Figure 5).

Copper ore was discovered and mined at Gruvberget in the late 1600's. Mineralisation as veinlets and schlieren, cuts trachytic to basaltic volcanics of the Porphyry Group in the contact zone of a magnetite-apatite body. The contact rocks are hydrothermally altered with scapolite, tremolite-actinolite, and late stage microcline, epidote, calcite and quartz with low grade copper sulphides, copper carbonates, rare pyrite, arsenopyrite, erythrite, molybdenite, gold (0.8g/t) and native Cu.

At Tjärrojåkka 13Mt of 0.43% Cu mineralisation lies 400m WNW of a 53 Mt 51.5% Fe magnetite-apatite deposit within Porphyry Group metavolcanics and metasediments (LKAB open file data). Wallrock-magnetite contact breccia zones are altered by albite, scapolite, actinolite, biotite, K spar, sericite and mineralised with veinlet bornite and chalcopryrite, REE's, and elevated Ba, Mo and Au.

The Rautuvaara and Hannukainen magnetite deposits in Finland (Hiltunen 1982, 1997), contain disseminated and schlieren copper-iron sulphides within magnetite bodies and associated calc-silicate host rocks adjacent to a Haparanda suite (1.89-1.87Ga) foliated monzonitic intrusion.

Where massive magnetite-apatite bodies and breccias are mineralised, copper sulphides are invariably within cross cutting veins and fracture infills of limited extent. At Ahmavuoma (Figure 4), Cu-Co with disseminated and vein magnetite mineralisation occurs within a pipe-like breccia body in biotite-scapolite-microcline altered andesite metavolcanics. However, the two principal known epigenetic sulphide deposits in Norrbotten form two distinct ore types as vein, disseminated, schlieren and replacement Cu-Au in altered Greenstones at Pahtohavare, and within a major ductile-brittle shear zone in highly strained supracrustals and intrusives at Aitik.

At Pahtohavare (Carlson 1991; Lindblom et al 1996; Martinsson 1991, 1992, 1997) 10kms SW of Kiirunavaara, three small Cu-Au deposits are hosted by fine grained albite rocks, tuffites, black graphitic schists, thin banded iron formations and mafic sills. The original reserve estimate in 1989 was 5.4Mt at 2.18%Cu, and 1.28g/tAu (Carlson 1991) from which two ore lenses were mined to produce 1.68Mt of 1.89%Cu, 0.88g/tAu.

Pyrite, chalcopryrite, pyrrhotite and minor ZnS, PbS, MoS<sub>2</sub>, cobaltite, native gold and telluro-bismuthinite minerals form veins, impregnations and breccia fillings with quartz, calcite, ankerite, ferroan-dolomite and mariolitic scapolite. Mineralisation is associated with areas of intense albitisation, surrounded by barren biotite-scapolite rocks. Graphite horizons and schist units are completely replaced in the ore zones and the mineralisation is accompanied by

coarse grained ferroan dolomite veins and disseminations within albite felsites.

Mineralisation was emplaced upon a complex, NW-SE axial trending, easterly plunging, isoclinally folded antiform, cut by NE-SW faults and breccia zones. The structure is also cut by WNW-ESE dextral wrench faults, shears and crush zones. Fluid inclusions (Lindblom et al. 1996) indicate early formation of quartz and pyrite at 500°C and 2-2.4kbars from a supersaturated solution of magmatic origin and deposition by mixing of solutions at temperatures below 350°C and 1-2kbars deposits along tectonic fractures, buffered by graphite.

The deposit contains at least two phases of magnetite, with early, isoclinally folded, banded iron formation, veined and cut by magnetite and copper-iron sulphides, the latter partly emplaced down the bedding foliation. There are at least two phases of scapolite, one porphyroblastic along the S<sub>0-1</sub> banding and a second cross cutting along isoclinal axial planar foliations. Mineralisation shows strong similarities with Viscaria and the non-auriferous, Eastern ore at Pahtohavare was considered to be of Viscaria-type (Martinsson 1997). The deposit is very similar to Bidjovagge (Bjørlykke et al. 1987), and other greenstone hosted deposits in northern Scandinavia suggesting a common origin.

The Aitik deposit (Danielsson and Lindroos, 1986; Munro, 1988; Wanhainen et al, 1999; Wanhainen and Martinsson, 2000; Zweifel, 1972, 1976, 1980), is a low grade Cu-Au resource of over 800Mt of 0.3%Cu, 0.2g/tAu, 2g/tAg (with a 0.22%Cu cut off). In 1999 the mine produced 61,800t Cu from 18Mt of raised ore (0.34%Cu). The mineralised zone is 3kms long, 400m wide forming an envelope around higher grade ore 2kms long and up to 200m wide, which has been drill indicated to 600m. The ore contains disseminated and stringer chalcopryrite, exhibits multiple brittle-ductile deformation with sheared sigmoidal quartz-sulphide veinlets, pyrite, pyrrhotite, molybdenite, bornite, sphalerite, galena, arsenopyrite and 3% magnetite.

Host rocks are muscovite-biotite-quartz schist and gneiss, with a biotite, scapolite, tourmaline, epidote, K-spar, late sericite/muscovite alteration, intruded by a monzo-dioritic body. Mineralisation has been interpreted as a strongly sheared, structurally extended and deformed porphyry copper type.

Aitik sits within a 5km wide and 40km long, multistage ductile-brittle deformation/supracrustal zone, trending NNW-SSE to N-S, (Nautanen-Aitik- Järbojoki Shear Zone). This hosts over 50 known Cu-Au occurrences including the magnetite rich Nautanen deposit (Danielsson and Lindroos, 1986; Geijer, 1918), 13kms N. of Aitik and NE of Gällivare. With proven reserves of 0.8Mt of 2.36%Cu, 1.3g/tAu, 13g/tAg the Nautanen mineralisation comprises magnetite, chalcopryrite, and Co pyrite with minor molybdenite, sphalerite, galena, silver tellurides, Au and Bi. Host rocks are garnet-magnetite calc-silicate and biotite-microcline gneisses with extensive scapolite, fluor-apatite, tourmaline and elevated Ba and Mn.

## Conclusions

The spatial association of characteristic Na, K and Ca alteration, major iron mineralisation and copper-iron sulphides in northern Sweden indicates a potential genetic link. The detail of this association is still unclear but a number of points can be made in conclusion:

Iron mineralisation is present in at least three temporally distinct forms; early banded iron formations, magnetite-apatite bodies, and later magnetite-sulphide veining. The banded iron formations and magnetite apatite bodies formed in the 2.1-1.88 interval and suffered 1.9-1.8Ga brittle-ductile deformation in the Svecofennian orogeny. There may have been an early apatite poor and later apatite rich mineralisation.

Early scapolite, albite, tourmaline, and red-rock alteration is cut by iron oxide-apatite mineralisation, in turn overprinted by later scapolite, K-spar, and epidote-carbonate alteration.

Cu-Au mineralisation cuts iron formations and magnetite-apatite bodies, is focussed by ductile-brittle fracture zones and is partly associated with a later magnetite-silica-carbonate mineralisation. Initial U-Pb dating indicates two main Cu-Au mineralising events corresponding to plutonic, hydrothermal and tectonic activity associated with the emplacement of the Perthite-Monzonite and Lina granite suites between 1.88-1.75Ga.

During cycles of ductile and brittle deformation, magma generation and post orogenic collapse, large volumes of fluid may have been periodically generated. Magmatic intrusives and hydrothermal fluids are likely to have been channelled by principal structures and focussed by structural intersections, particularly by zones of rheological contrast adjacent to magnetite bodies.

## Acknowledgements

The author wishes to acknowledge the many discussions and field visits made over many years with former colleagues and friends in SGU/SGAB, LKAB Prospektering, BP Minerals and Rio Tinto since being introduced to these systems in 1984. Of particular note are Rolf Bergstrom, Paul Forsell, Lisbeth Godin-Jonasson, Veikko Niiniskorpi, Risto Virkkunen, Karl-Enar Hanson, Jan-Ole Larsson, Lars-Gören Ohlsson, Tibor Parak, Rudyard Freitsch, Nick Badham, Adrian Swiatecki, Colin Harris, Mike Harris, Jim Coppar, Graham Brown and Frank van der Stijl.

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