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IOCG AND RELATED MINERAL DEPOSITS OF THE NORTHERN FENNOSCANDIAN SHIELD

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Abstract - The northernmost Fennoscandian shield comprises Archaean and Palaeoproterozoic rocks. Unlike most other shield areas, economic mineral deposits are largely restricted to its Palaeoproterozoic parts. The latter are characterised by intracratonic basin evolution between ca. 2.5 and 2.0 Ga, involving recurrent mantle hotspot activity with numerous layered intrusions, komatiite and picrite eruptions, but no signs of accretionary phases or formation of major new felsic crust. Accretion and continent-continent collision followed from ca. 1.9 to 1.8 Ga, during the Svecofennian orogeny.

A range of mineralisation styles are hosted by extensive ca. 2.5 to 2.0 Ga greenstone belts and younger, subduction-related 1.9 to 1.8 Ga Svecofennian intrusive and extrusive settings. These mineralisation styles partially overlap, and individual deposits may not readily be placed into genetic classification schemes. A provisional grouping of observed mineralisation styles comprises (1) stratiform-stratabound sulphide, (2) apatite-iron, (3) skarn-related iron and BIF, and (4) epigenetic(±syngenetic?) Au and Cu-Au deposits. The descriptive section of this paper also highlights features that may relate to orogenic gold, IOCG and 'atypical metal association' categories of mineralisation.

The assumption made is that the deposition of a diverse range of ore deposits was made possible by a long and complex geological evolution. This involved an initial (sowing) stage where iron, and to some extent copper and gold, were concentrated during 2.3 to 2.1 Ga (Karelian) rock-forming processes. Following this, ore elements were mobilised during two younger (Svecofennian) stages at 1.92 to 1.87 and 1.85 to 1.79 Ga, respectively. The latter were triggered by metamorphic and magmatic episodes, and fluids liberated during these stages precipitated IOCG and related deposits when fluids met structural and chemical traps in suitable host rocks. Ore fluids are generally saline, and their development probably involved incorporation of evaporites and, at least locally, also felsic magmatism may have played a role.

Skarn-related mineralisation, hosted by ca. 2.1 Ga greenstones, occurs both as a BIF type in Sweden (formed at around 2.1 Ga), and as a gold-copper enriched variety (the result of Svecofennian epigenetic processes) in the Kolari region of Finland. The huge Kiirunavaara deposit is the type example of apatite iron ores, and is here considered to have formed from a magma at ca. 1.88 Ga, although it also has features best explained by a magmatic-hydrothermal overprint. A younger, less prominent, stage of apatite iron ore formation took place at approximately 1.78 Ga. Epigenetic gold and copper-gold deposits are particularly hard to classify as these show mixed ore characteristics, and to some extent this is likely to be due to multiple mineralisation stages (cf. the huge, low grade Aitik deposit in Sweden which is interpreted to be a hybrid porphyry-IOCG-type of ore). Structurally controlled, orogenic gold mineralisation is common in the Central Lapland greenstone belt, although there are also gold deposits with enhanced contents of e.g., copper, cobalt and uranium (e.g., at Saatopoora). The latter, sometimes referred to as being of an ´atypical metal association´ type, could potentially also include syngenetic mineralisation (e.g., at Juomasuo). The range of epigenetic (±syngenetic) gold and copper-gold deposits could possibly be related to a vague east-west trend defined by gold-rich deposits in the east (Finland), followed by IOCG (copper±gold) and more iron-dominant ore types near the Finnish-Swedish border and further west into Sweden.

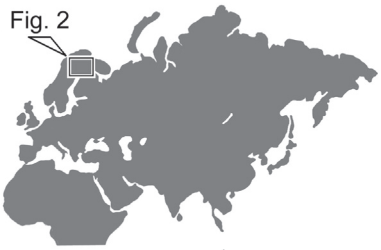
Introduction

The Fennoscandian shield forms the northwestern part of the East European craton and constitutes large parts of Finland, northwest Russia, Norway and Sweden (Fig. 1). Major regional orogenies occurred during the Neoarchaean and Palaeoproterozoic, whereas younger Meso- and Neoproterozoic crustal growth mainly took place in the western part of the shield, which was subsequently reworked during the Caledonian orogeny (Weihed *et al.*, 2005).

Significant BIF and minor komatiitic nickel, orogenic gold and VMS deposits occur in the Archaean part of the Fennoscandian shield (Eilu *et al.*, 2009). However, and in contrast to many other shield areas, most of the economic iron, gold±copper and VMS deposits within the region are related to Palaeoproterozoic magmatism, deformation and fluid flow. The Palaeoproterozoic northern part of the shield is best known for its Kiruna-type iron oxide deposits, but iron ore has also been produced on a smaller scale from the Rautuvaara and Misi areas in northern Finland. Copper was produced intermittently during the 17th and 18th centuries in northern Sweden and Norway, while during the last 40 years copper and gold have been mined on a larger scale in Sweden (Aitik, Viscaria, Pahtohavare), Finland (Saattopora, Pahtavaara) and Norway (Repparfjord, Bidjovagge). Most of the copper±gold deposits are hosted by Palaeoproterozoic greenstones and are small to medium sized, except for the Suurikuusikko gold deposit in Finland (resource 40 Mt @ 4.5 g/t Au) and the Aitik copper-gold deposit in Sweden (resource >2 Gt @ 0.38% Cu, 0.2 g/t Au) which is hosted by slightly younger (Svecofennian) rocks (Wanhainen *et al.*, 2005; Weihed *et al.*, 2005; Eilu *et al.*, 2009).

Much controversy has surrounded the Palaeoproterozoic iron, gold and copper-gold deposits in the northern Fennoscandian shield. Genetic models suggested for them include, at least: (1) orthomagmatic (Kiruna iron; e.g. Nyström and Henriquez, 1994), (2) BIF (some iron deposits; Martinsson, 1995), (3) intrusion-related skarn (Pajala-Kolari iron±copper-gold; Hiltunen, 1982), (4) IOCG (all or some of iron and copper±gold deposits; Hitzman, *et al.*, 1992; Vanhanen, 2001; Edfelt, 2007; Smith *et al.*, 2007; Martinsson *et al.*, 2009a, 2009b), (5) porphyry copper-gold (Aitik; Wanhainen *et al.*, 2005), (6) orogenic gold (gold-only and gold-copper; Eilu *et al.*, 2007), (7) syngenetic copper-zinc (Viscaria; Martinsson *et al.*, 1997a) and (8) syngenetic gold-base metal (Kuusamo; Au-Cu-Co; Eilu *et al.*, 2009). Another sign of the difficulties in defining the genetic type is indicated by many authors leaving open the genetic type of the deposits they have investigated.

This paper reviews recent work on the styles of Palaeoproterozoic iron, gold and copper-gold mineralisation in northern Sweden and Finland. Our main focus is on occurrences which may be classified into the broad IOCG related category of mineralisation. We only briefly, where necessary to give a broader geological context, describe other deposit types. The aim is essentially to integrate the various mineralising events into the Palaeoproterozoic metallogenic framework of the Fennoscandian shield.



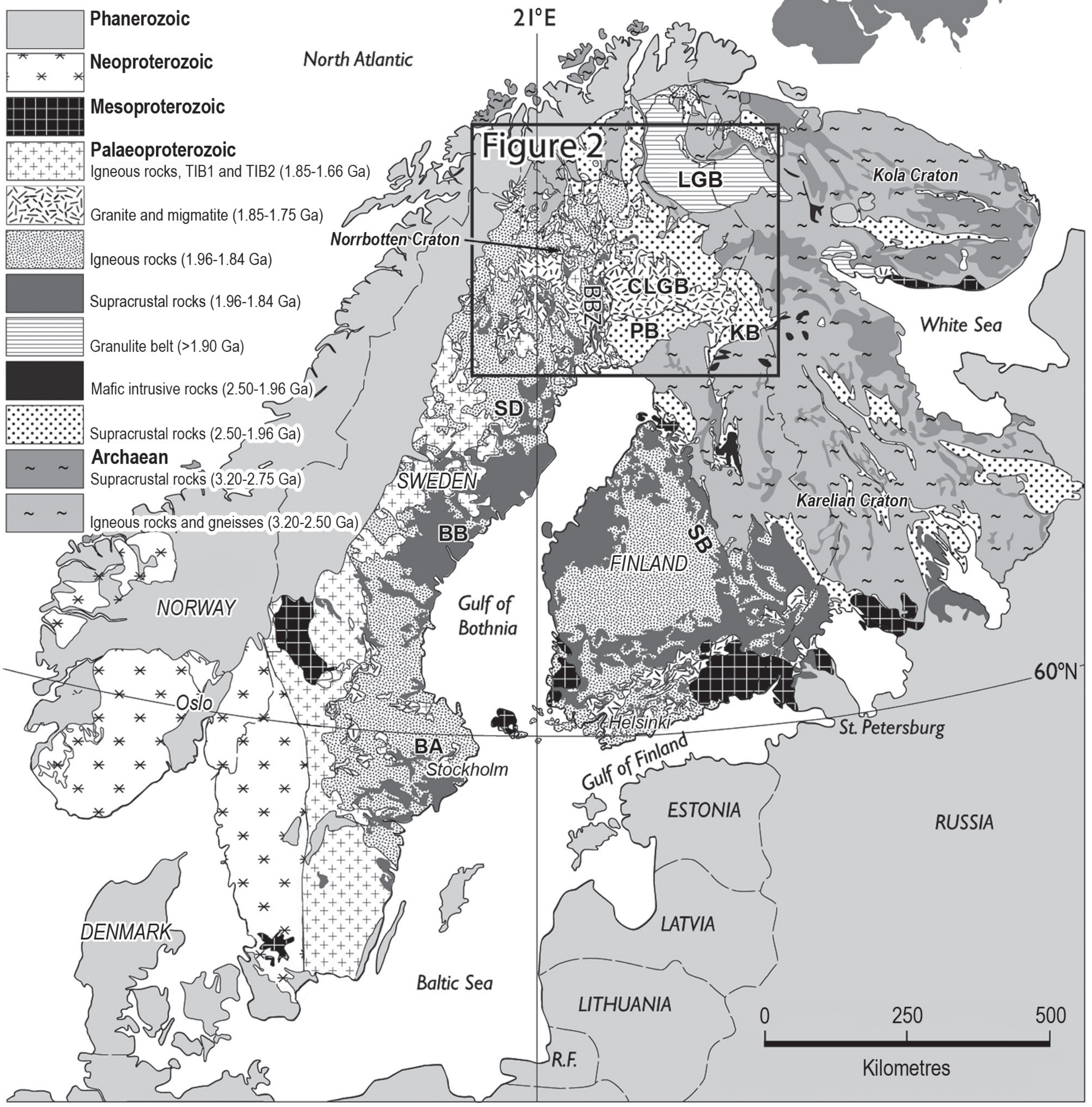


Figure 1: A geological outline of the Fennoscandian shield. Abbreviations: LGB = Lapland Granulite Belt, CLGB = Central Lapland Greenstone Belt, KB = Kuusamo Belt, PB = Peräpohja Belt, SB = Saavo Belt, SD = Skellefte District, BB = Bothnian Basin, BBZ = Bothnian Baltic Zone, BA = Bergslagen Area.

Geological and Tectonic Overview

The Fennoscandian shield is one of the most important mining areas in Europe, and in the northern parts of particularly Sweden and Finland (Figs. 1 and 2), it is intensely mineralised (Weihed *et al.*, 2005). Known mineral deposit types include VMS, apatite-iron, orogenic gold, epigenetic copper-gold, mafic and ultramafic-hosted chromium, nickel-(copper) and PGE, and BIF. Unlike most other shield areas, the Palaeoproterozoic sections of the Fennoscandian shield are more mineralised than those of the Archaean. The diversity of ore types (Table 1 and Fig. 2) is matched by the range of rock formations, produced by several stages of the plate-tectonic evolution of the shield (Lahtinen *et al.*, 2005; Weihed *et al.*, 2005).

The oldest rocks yet found in the Fennoscandian shield have been dated at 3.5 Ga (Huhma *et al.*, 2004), although the first more substantial crustal-forming episode took place during the Saamian Orogeny at 3.1 to 2.9 Ga, dominated by gneissic tonalite, trondhjemite and granodiorite. Rift- and volcanic arc-related greenstones, subduction-generated calc-alkaline volcanic rocks and tonalitic-trondhjemitic igneous rocks were formed during the Lopian Orogeny at 2.9 to 2.6 Ga, that is, during the main, globally significant, Neoarchaean episode of crustal growth (cf. Groves *et al.*, 2005). The Archaean craton of Fennoscandia was consolidated after the last major phase of granitoid intrusions at 2.65 Ga. Only a few Archaean economic to subeconomic mineral deposits have been found

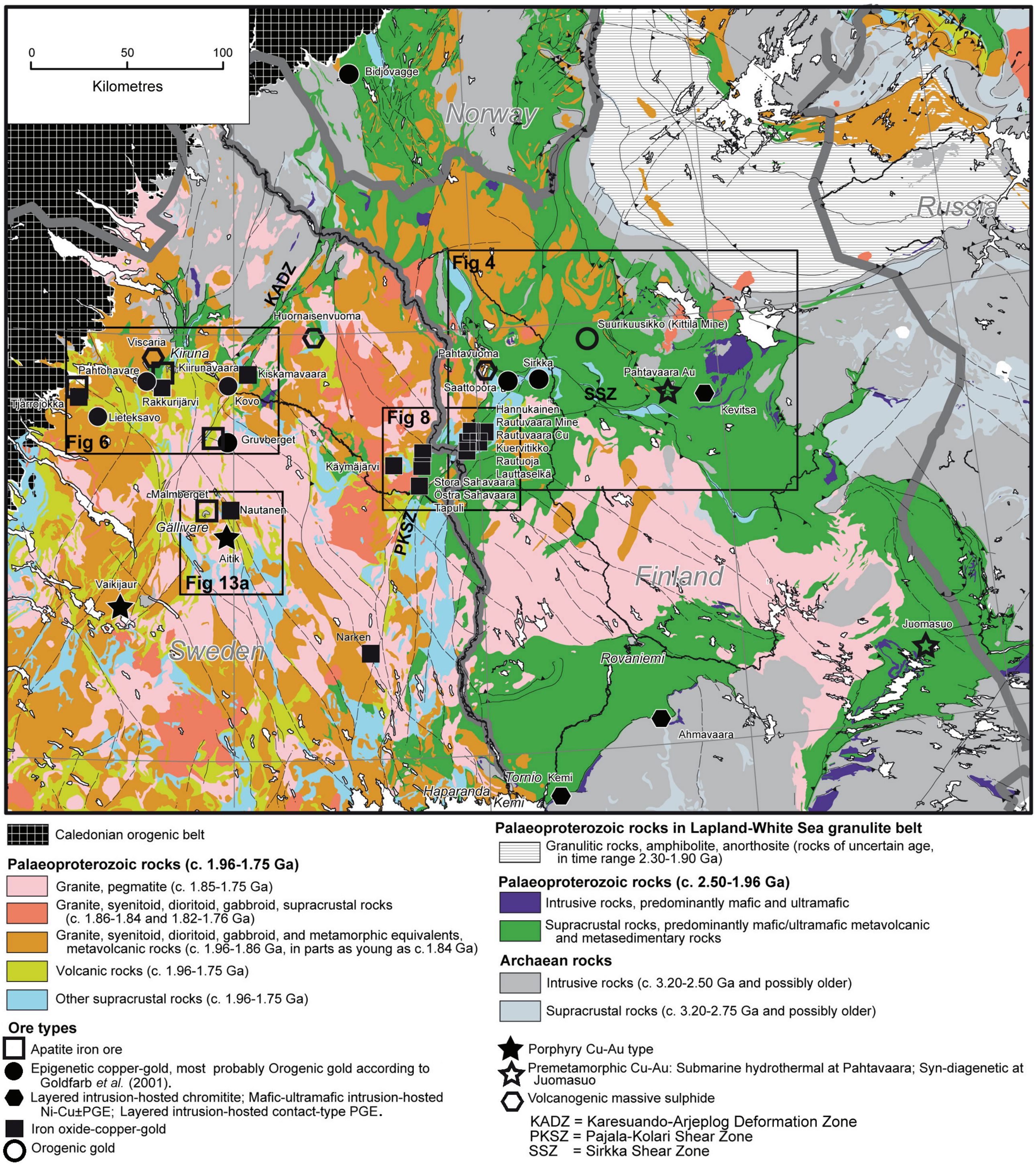


Figure 2: Geology and the distribution of IOCG style and related ore deposits in northern Fennoscandia. Locations for certain ore occurrences described in the text (Porsa, Kåfjord and Repparfjord) are situated north of the map area.

in the shield, including orogenic gold, BIF, molybdenum occurrences, and ultramafic- to mafic-hosted nickel-copper (Frietsch *et al.*, 1979; Weihed *et al.*, 2005).

During the period 2.5 to 1.9 Ga, Fennoscandia underwent several episodes of continental rifting and related, dominantly mafic, magmatism, denudation and sedimentation. Sumi-Sariolian (2.5 to 2.3 Ga) clastic sediments, intercalated with volcanic rocks varying in composition from komatiitic and tholeiitic to calc-alkaline and intermediate to felsic, were deposited on the Archaean basement during extensional events. Layered intrusions, most of which host chromium, nickel, titanium, vanadium and/or PGE occurrences, represent a major magmatic input at 2.45 to 2.39 Ga (Amelin *et al.*, 1995; Mutanen, 1997; Alapieti and Lahtinen, 2002). Periods of arenitic sedimentation preceded and followed extensive komatiitic and basaltic volcanic stages at ca. 2.2, 2.13, 2.05 and 2.0 Ga in the northeastern part of the Fennoscandian shield during extensional events (Mutanen, 1997; Lehtonen *et al.*, 1998; Rastas *et al.*, 2001). Carbonate rocks, graphite schist, iron formation and stratiform sulphide occurrences are associated with the subaqueous extrusive and volcaniclastic units across the region. These volcanosedimentary sequences form the Palaeoproterozoic greenstone belts of the northern Fennoscandian shield. Locally, they also contain indications of evaporites (Vanhanen, 2001; Kyläkoski, 2009).

Svecofennian (1.9 to 1.8 Ga), subduction-generated calc-alkaline andesites and related volcaniclastic sedimentary units were deposited in a subaerial to shallow-water environment in northern Fennoscandia. In the Kiruna area, the 1.89 Ga Kiirunavaara Group rocks (formerly Kiruna Porphyries) are chemically different from the andesites, and are geographically restricted to this area. The Svecofennian porphyries are the host to apatite-iron ores and various styles of epigenetic copper-gold occurrences, including porphyry copper-style deposits (Weihed *et al.*, 2005).

The up to 10 km thick pile of Palaeoproterozoic volcanic and sedimentary rocks was multiply deformed and metamorphosed contemporaneously with the intrusion of 1.92 to 1.87 Ga granitoids. Anatectic granites were formed between 1.82 and 1.77 Ga, during another major stage of deformation and metamorphism. Large-scale migration of fluids of variable salinity during the many stages of pre- and syn-orogenic igneous activity, and orogenic metamorphism and deformation, is expressed by regional scapolite, K feldspar-phlogopite±talc, albite and albite-carbonate alteration in the region. For example, it has been suggested that scapolitisation is related to felsic intrusions (Ödman, 1957), or that it is an expression of mobilised evaporites from the supracrustal successions during metamorphism (Tuisku, 1985; Frietsch *et al.*, 1997; Vanhanen, 2001).

Since Hietanen (1975) proposed a subduction zone dipping north beneath the Skellefte district, many similar models have been proposed for ca. 1.95 to 1.77 Ga crustal formation during the Svecokarelian (or Svecofennian) orogeny (e.g., Rickard and Zweifel, 1975; Lundberg, 1980; Pharaoh and Pearce, 1984; Berthelsen and Marker, 1986; Gaál, 1986; Weihed *et al.*, 1992). This orogeny involved both strong reworking of older crust within the Karelian craton and, importantly, subduction towards the northeast, below the Archaean, and the accretion of several volcanic arc complexes from the southwest, towards the northeast. Recently, substantially more complex models for crustal growth at this stage of the evolution of the Fennoscandian shield have been proposed (e.g., Nironen, 1997; Lahtinen *et al.*, 2005), although the evolution of the region north of the Archaean-Proterozoic palaeoboundary (Öhlander *et al.*, 1987) is still rather poorly understood in detail. The most recent model for the Palaeoproterozoic tectonic evolution of the Fennoscandian shield, involving five partly overlapping orogenies, was presented by Lahtinen *et al.* (2005). This model builds on the amalgamation of several microcontinents and island arcs with the Archaean Karelian, Kola and Norrbotten cratons (Fig. 1) and other pre-1.92 Ga components.

Rock Suites of the Northern Fennoscandian Shield

The IOCG-style deposits of the Fennoscandian shield are mainly restricted to greenstone belts and younger Svecofennian (intrusive and extrusive) rocks. Hence, the emphasis below is on these rock types.

2.5 to 2.0 Ga Greenstone Belts & Related Sedimentary Rocks

The Palaeoproterozoic Lapland greenstone belt, being the largest coherent greenstone terrain exposed in the Fennoscandian shield (Fig. 1), overlies much of the northern part of the Archaean craton. This belt extends for over 1000 km, from the northwest coast of Norway, through Swedish and Finnish Lapland, into adjacent Russian Karelia in the southeast. Due to the significant lithostratigraphic similarities of the different greenstone areas across this region, and the mainly tholeiitic character of the volcanic rocks, Pharaoh (1985) suggested they were coeval, representing a major tholeiitic province. Based on petrological and chemical studies of the mafic volcanic rocks and associated sediments, an originally continental rift setting is favoured for these greenstones, comprising the Central Lapland greenstone belt (CLGB, Figs. 3 and 4) in Finland, and the Kiruna and Masugnsbyn areas in Sweden, (e.g. Pharaoh *et al.*, 1987; Huhma *et al.*, 1990; Olesen and Sandstad, 1993; Martinsson, 1997; Lehtonen *et al.*, 1998).

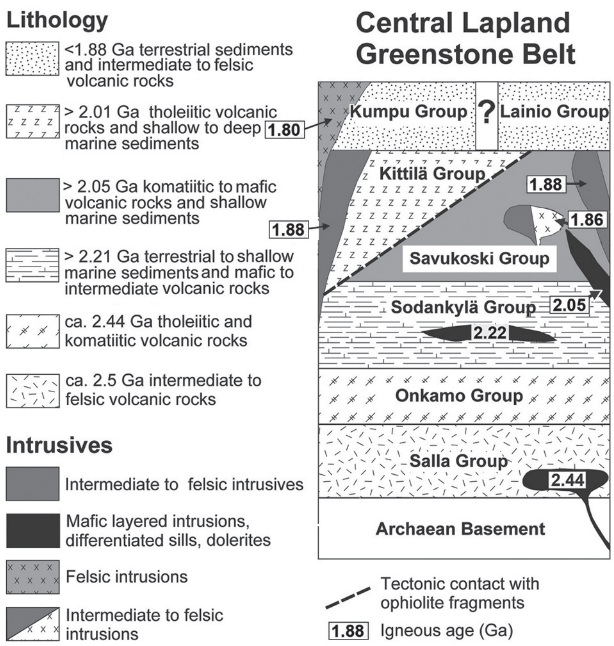


Figure 3: Stratigraphy of the Central Lapland greenstone belt (CLGB). Data sources of rock ages (in Ma) are given in the text. Compiled after Lehtonen *et al.*, (1998) and Hanski and Huhma (2005).

In northern Sweden, a Palaeoproterozoic succession of greenstones, porphyries and clastic sediments rests unconformably on deformed, 2.8 to 2.7 Ga, Archaean basement (Fig. 2). The stratigraphically lowest member is the ca. 2.5 to 2.3 Ga Kovo Group, which includes a basal conglomerate, tholeiitic lava, calc-alkaline basic to intermediate volcanic rocks and volcaniclastic sediments (Martinsson, 1997). Sedimentary rocks were deposited along the coastline of a marine rift basin, with input via a number of alluvial fans (Kumpulainen, 2000). The Kovo Group is overlain by the ca. 2.2 to 2.0 Ga Kiruna Greenstone Group, which is dominated by mafic to ultramafic volcanic rocks. The stratigraphically lowest members of this group are minor clastic and chemical sediments comprising sedimentary breccia, red stained arenites and partly silicified carbonate rocks. These rocks may also have included evaporite units, now only inferred by the extensive scapolitisation of overlying basaltic lava flows (Martinsson, 1997).

In Finland, the lowermost units of the greenstones also lie unconformably on the Archaean, and are represented by the Salla Group rocks in the Central Lapland greenstone belt (CLGB; Fig. 4), a polymictic conglomerate in the Kuusamo schist belt and the Sompujärvi Formation of the Peräpohja schist belt. This is followed by sedimentary units of the Onkamo and Sodankylä Group rocks in the CLGB. The latter lithostratigraphic group also hosts some Palaeoproterozoic, probably syngenetic, sulphide occurrences in the CLGB. The Savukoski Group mafic to ultramafic volcanic and shallow-marine sedimentary units were deposited between 2.2 and 2.01 Ga in the CLGB, while similar units were also formed in the Kuusamo and Peräpohja belts (Lehtonen *et al.*, 1998; Rastas *et al.*, 2001).

Age determinations of the Palaeoproterozoic greenstones, which are collectively sometimes referred to as Karelian rocks, exist mainly from Finland (e.g., Perttunen and Vaasjoki, 2001; Rastas *et al.*, 2001; Väänänen and Lehtonen, 2001) and suggest a major magmatic and rifting event at ca. 2.1 Ga, with the final break up taking place at ca. 2.06 Ga. Thick piles of mantle-derived volcanic rocks, including komatiitic and picritic high-temperature melts, are restricted to the Kittilä-Karasjok-Kautokeino-Kiruna area and are suggested to represent plume-generated volcanism (Martinsson, 1997). The rifting of the Archaean craton, along a northwest-trending line, was accompanied by both northwest- and northeast-trending rift basins (Saverikko, 1990), and by the injection of 2.1 Ga dyke swarms trending

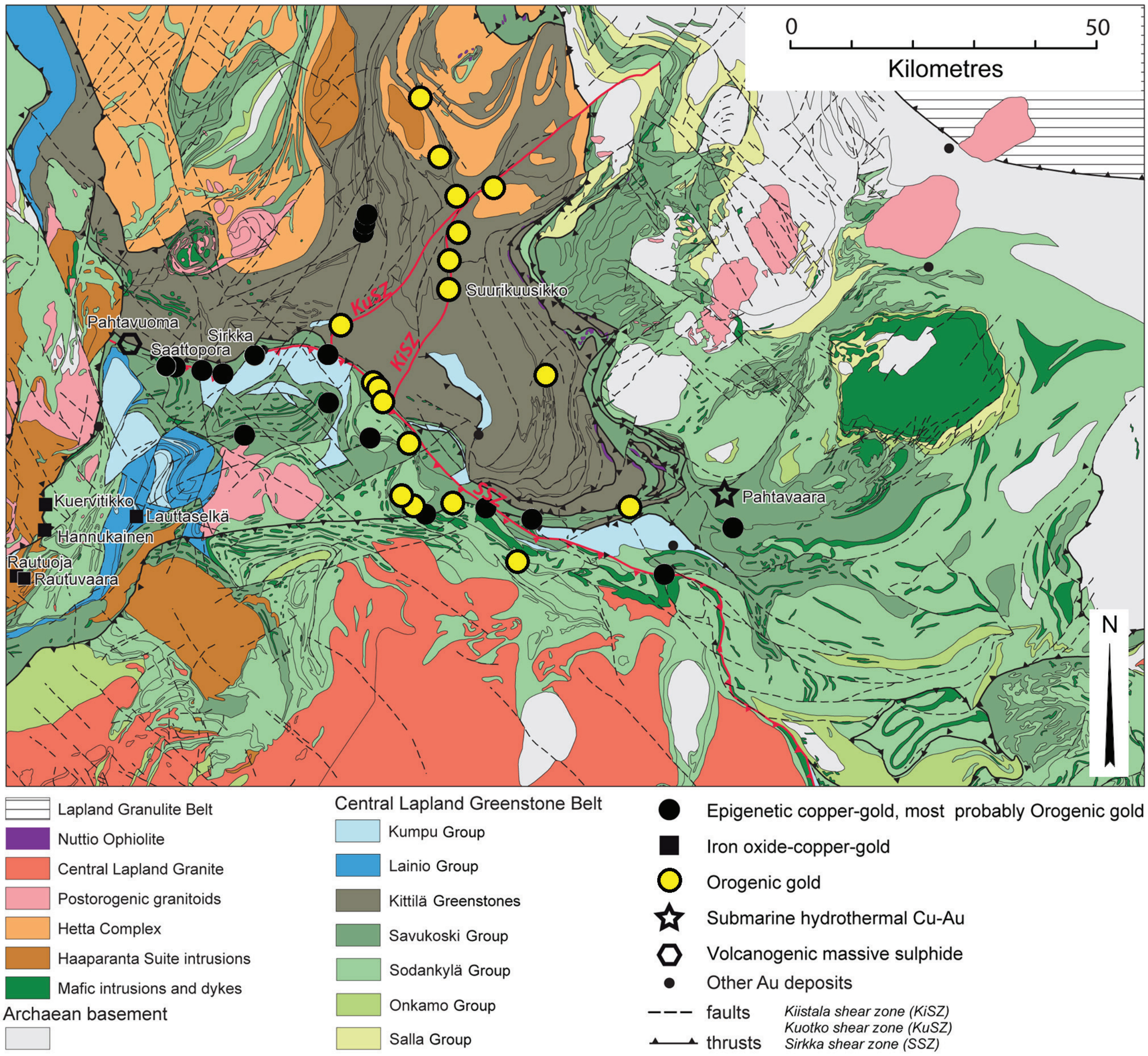


Figure 4: Geology of the Central Lapland greenstone belt. Modified after Eilu *et al.*,*(*2008).

parallel to the rift directions (Vuollo, 1994). Eruption of N-MORB pillow lava occurred along all the rifted margins of the craton (Åhman, 1957; Kähkönen *et al.*, 1986, Lukkarinen, 1990; Pekkarinen and Lukkarinen, 1991). The Kiruna greenstones and dyke swarms north of Kiruna outline a NNE-trending magmatic belt extending into northernmost Norway. This belt is almost perpendicular to the major rift, and may represent a failed rift arm related to a triple junction south of Kiruna (Martinsson, 1997). Rifting in northern Fennoscandia culminated in extensive mafic and ultramafic volcanism and the formation of oceanic crust at ca. 1.97 Ga. This is indicated by extensive komatiitic basalts and basaltic lavas of the Kittilä Group of the CLGB in the central parts of Finnish Lapland (Fig. 2). The 1.97 Ga stage also included deposition of shallow- to deep-marine sediments, the latter indicating the most extensive rifting in the region. Fragments of oceanic crust were subsequently obducted back onto the craton in Finland, as indicated by the Nuttio ophiolites in central Finnish Lapland and the Jormua and Outokumpu ophiolites further south (Kontinen, 1987; Sorjonen-Ward *et al.*, 1997; Lehtonen *et al.*, 1998).

Svecofennian 1.9 Ga Volcanic-Sedimentary Complexes

The Palaeoproterozoic greenstones are overlain by volcanic and sedimentary rocks, comprising several related stratigraphic units. These units regionally exhibit considerable variation in lithological composition, due in part to rapid changes from volcanic- to sedimentary-dominated facies. The Porphyrite Group and the Kurravaara Conglomerate (labelled together as Kurravaara Conglomerate on Fig. 5) are the lowest stratigraphic

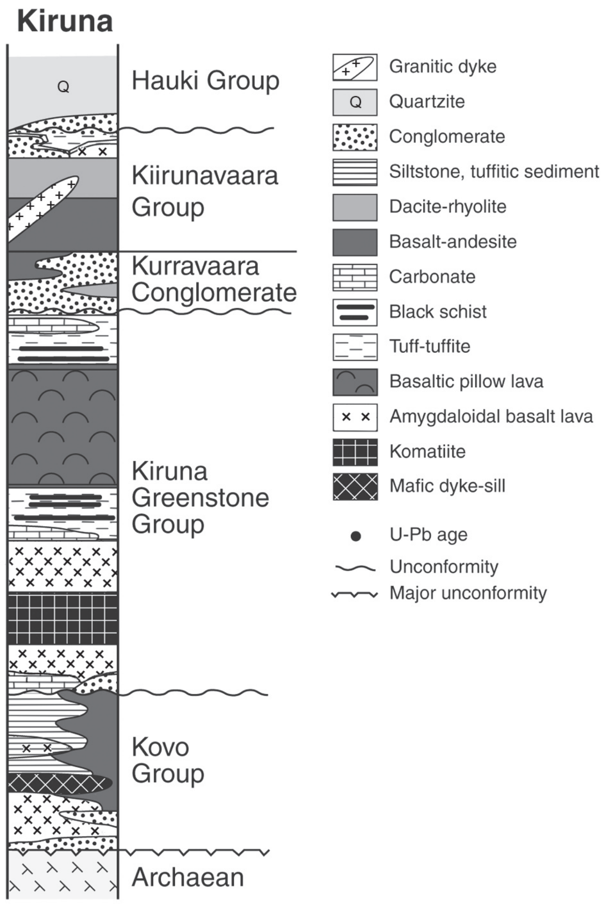


Figure 5: Stratigraphy of the Kiruna area, Sweden.

units in the Kiruna area. The former represents a volcanic-dominated, and the latter a mainly epiclastic unit (Offerberg, 1967), deposited as one or two fan deltas (Kumpulainen, 2000). The Sammakkovaara Group, near Pajala in northeastern Norrbotten, comprises a mixed volcanic-epiclastic sequence that is interpreted to be the stratigraphic equivalent of the Porphyrite Group and the Kurravaara Conglomerate, as well as correlating with both the Pahakurkio Group south of Masugnsbyn, and the Muorjevaara Group in the Gällivare area. In the Kiruna area, these volcanic and sedimentary units are overlain by the Kiirunavaara Group that is followed in turn by the Hauki and Maattavaara quartzites which constitute the uppermost Svecofennian units in the area (Martinsson, 2004).

In northern Finland, pelitic rocks in the Lapland Granulite Belt (Fig. 2) were deposited after 1.94 Ga (Tuisku and Huhma, 2006). Svecofennian units are mainly represented by the Lainio and Kumpu Groups in the CLGB (Lehtonen *et al.*, 1998) and by the Paakkola Group in the Peräpohja area (Perttunen and Vaasjoki, 2001). The molasse-like conglomerates and quartzites comprising the Kumpu Group were deposited in deltaic and fluvial fan environments after 1913 Ma and before ca. 1800 Ma (Rastas *et al.*, 2001). Stratigraphic correlations across the border suggest that the Kumpu rocks are equivalent to the Hauki and Maattavaara quartzites, whereas the sedimentary and volcanic units of the Lainio Group could be related to the Porphyrite Group rocks and the Kurravaara Conglomerate of the Kiruna area.

With the present knowledge of ages and petrochemistry of the Porphyrite, Lainio and Kumpu Groups (Fig. 3), it is possible to attribute these rocks partially (Kumpu) to completely (Porphyrite and Lainio) to the same event of collisional tectonics and juvenile convergent margin magmatism. This period of convergence was manifested by the numerous 1.89 to 1.87 Ga intrusions of Jörn- (south of the craton margin) and Haparanda- (within the craton) type calc-alkaline intrusions, as described by Mellqvist *et al.* (2003). The convergent margin magmatism was soon followed by rapid uplift, recorded as extensive conglomeratic units, more alkaline and terrestrial volcanism (Vargfors-Arvidsjaur Groups south of the craton margin, and the Kiirunavaara Group within the craton) and plutonism (Gallejaur-Arvidsjaur type south of the craton margin, Perthite Monzonite Suite within the craton). This uplift took place between 1.88 and 1.86 Ga, with the main volcanic episode probably lasting less than 10 million years. However, recent radiometric evidence (U-Pb laser ICP-MS data; Storey *et al.*, 2007) has questioned the earlier established geochronologic evolution, and it has been suggested that the rocks of the Porphyrite and Kiirunavaara Groups started to develop much earlier, at ca. 2.05 Ga. The significance of these findings still need to be further evaluated.

Early Rifting and Emplacement of ca. 2.5 to 2.4 Ga Layered Igneous Complexes

The beginning of the rifting period between 2.5 and 2.4 Ga (Amelin *et al.*, 1995) is indicated by intrusion of numerous layered mafic igneous complexes (Alapieti *et al.*, 1990; Weihed *et al.*, 2005), which were later deformed and metamorphosed during the Svecokarelian orogeny. Most of these intrusions are located along the margin of the Archaean granitoid area, either at the boundary with the Proterozoic supracrustal sequence, totally enclosed

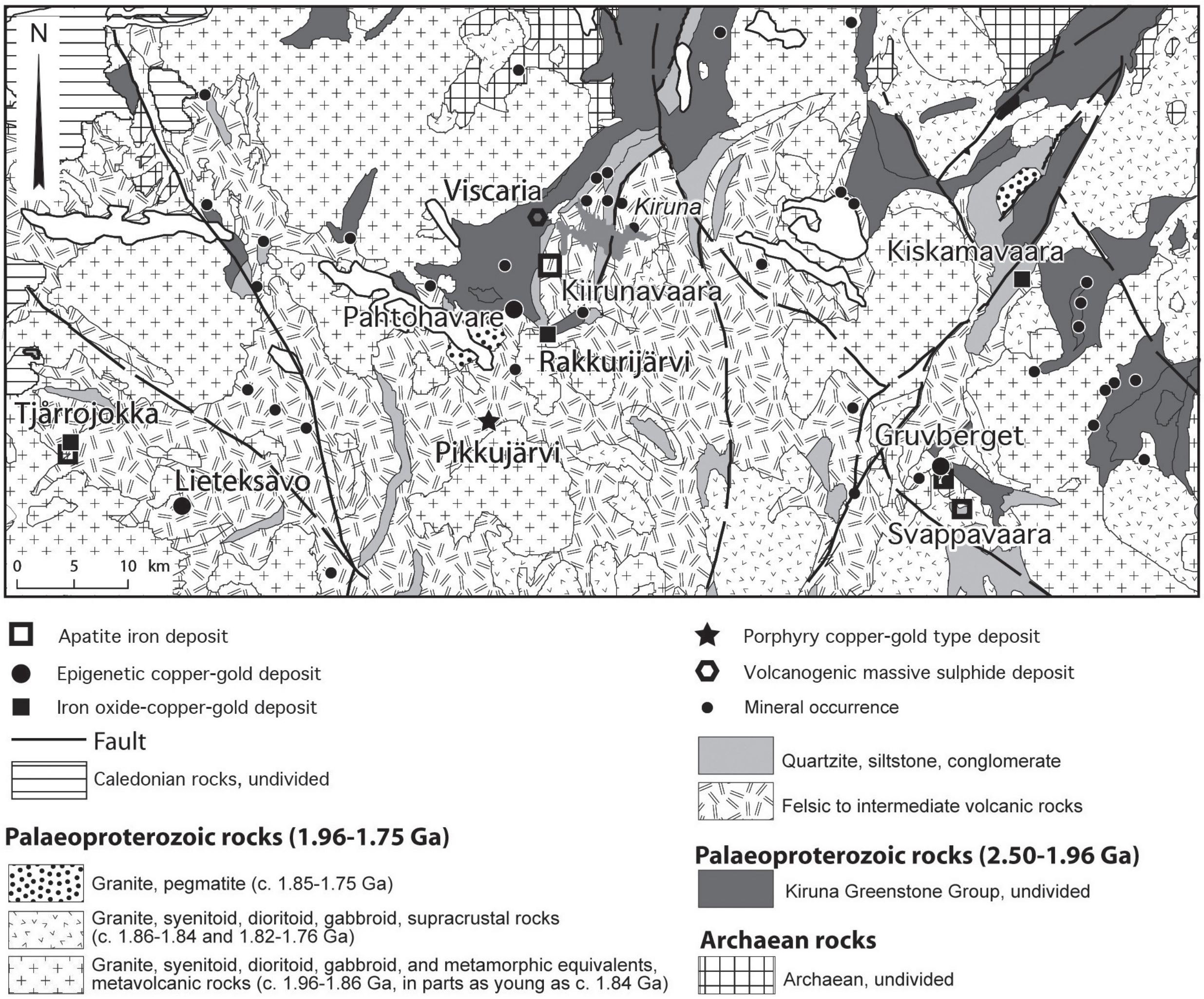


Figure 6: Geology of the Kiruna district. The sedimentary and volcanic subdivisions of the 1.96 to 1.75 Ma interval are lithological, rather than stratigraphic. Data sources of rock ages (in Ma) are given in the text. Modified after Eilu *et al.*, (2008).

by Archaean granitoids, or enclosed by a Proterozoic supracrustal sequence. According to Alapieti and Lahtinen (2002), parts of these igneous complexes crystallised from a similar, quite primitive magma type, which is characterised by slightly negative initial ε_{Nd} values and relatively high MgO and Cr, intermediate SiO_2, and low TiO_2 concentrations, resembling a boninitic magma type. In the Kola Peninsula in Russia, these intrusions have been dated at 2.50 to 2.45 Ga, and in Finland at 2.46 to 2.43 Ga (Alapieti *et al.*, 1990; Bayanova *et al.*, 1999; Mitrofanov and Bayanova, 1999). Nearly all are mineralised, containing a significant PGE-nickel-copper, chromite and vanadium-titanium potential (Table 1).

2.2 to 2.0 Ga Mafic Dykes

Mafic dykes are locally abundant and show a variable strike, degree of alteration and metamorphic recrystallisation which, supported by age dating, indicate multiple igneous episodes. Albite diabase (a term commonly used in Finland and Sweden for any albitised dolerite) is a characteristic type of intrusion that forms sills up to 200 m thick. Extensive dyke swarms occur in the Archaean domain north of Kiruna; these swarms are dominated by 1 to 100 m wide dykes with a metamorphic mineral assemblage, but with a more or less preserved igneous texture (Ödman, 1957; Martinsson, 1999a, b). Dykes with a NNE trend have been suggested to represent feeders to the Kiruna Greenstone Group (Martinsson, 1997, 1999a, b). Scapolite-biotite alteration is common in feeder dykes within the lower part of the Kiruna Greenstone Group (Martinsson, 1997).

In northern Finland, albite diabases, both sills and dykes, can be divided into age groups of 2.2, 2.13, 2.05 and 2.0 Ga (Vuollo, 1994; Lehtonen *et al.*, 1998; Perttunen and Vaasjoki, 2001; Rastas *et al.*, 2001), comparable to known ages on the Swedish side (Skiöld, 1986; Vuollo, 1994). These dates also reflect extrusive magmatism in the region. In areas of greenschist-facies metamorphism, the dykes are variably albite and carbonate altered, and are surrounded by similarly altered country rocks (Eilu, 1994).

1.90 to 1.77 (1.7) Ga Granitoid Suites

A major part of the bedrock in northernmost Sweden and Finland is composed of granitoids of four major suites: (1) 1.90 to 1.86 Ga *Haparanda*; (2) 1.88 to 1.86 Ga *Perthite Monzonite*; (3) 1.81 to 1.77 Ga *Lina*; and (4) 1.8 Ga and 1.7 Ga A- and I-type TIB *(Transscandinavian Igneous Belt)* like suites. In addition, in the Lapland Granulite Belt, minor arc magmatism with norite-enderbite series rocks has intruded the supracrustal sequence at 1920 to 1905 Ma (Bergman *et al.*, 2001; Tuisku and Huhma, 2006).

Intrusions of the *Haparanda Suite* are medium- to coarse- and even-grained, moderately to intensely deformed, grey tonalites and granodiorites which are associated with gabbros, diorites and rare true granites (Ödman, 1957). The geochemical signature of the Haparanda Suite is typical of "volcanic arc granitoids", with low Rb, Y and

Nb (Mellqvist *et al.*, 2003). They define a calc-alkaline trend and are metaluminous to slightly peraluminous. Haparanda-type intrusions from southeastern Norrbotten and the western parts of northern Finland show an age range of 1.90 to 1.86 Ga (Wikström *et al.*, 1996; Witschard, 1996; Persson and Lundqvist, 1997; Wikström and Persson, 1997a; Perttunen and Vaasjoki, 2001; Rastas *et al.*, 2001; Väänänen and Lehtonen, 2001; Mellqvist *et al.*, 2003). The compositional range and the chemical characteristics of the Haparanda Suite (Bergman *et al.*, 2001), in conjunction with the subduction modelled for the shield (Lahtinen *et al.*, 2005), suggest that the intrusions are comagmatic with extrusive phases of the early Svecofennian arc magmatism (e.g., the Porphyrite and Sammakkovaara groups).

The 1.88 to 1.86 Ga (Skiöld and Öhlander, 1989; Martinsson *et al.*, 1999) *Perthite Monzonite* Suite intrusions mainly occur as large, undeformed plutons in the northwestern part of Norrbotten in Sweden (Geijer,

Table 1: Grade and pre-mining tonnage of significant, or genetically interesting, deposits in the northern Fennoscandian Shield.

Deposit	*Area*[1]	*Type*[2]	*Size (Mt)*[3]	*Cu %*	*Fe %*	*Other metals %, Au, Ag, PGE ppm*	*Status (May 2009)*	*Reference*[4]
Bidjovagge	Kautokeino	Epith. Au-Cu	3.16[5]	1.2		Au: 4	Closed mine	Ettner *et al.,* (1994)
Pahtohavare	Kiruna	Epith. Au-Cu	1.72[5]	1.89		Au: 0.9	Closed mine	Lindblom *et al.,* (1996)
Saattopora	CLGB	Epith. Au-Cu	2.16[5]	0.25		Au: 2.9	Closed mine	Eilu *et al.,* (2007)
Gruvberget Cu	Kiruna	Epith. Au-Cu	0.2	0.5			Closed mine	Espersen and Frietsch (1964)
Lieteksavo	Kiruna	Epith. Au-Cu	0.05	6.8		Au: 1.3; Ag: 46	Prospect	Frietsch (1991)
Kovo	Kiruna	Au-Cu	<0.00005				Historic mine	Grip and Frietsch (1973)
Porsa	KRGB	Au-Cu	0.1[5]	2			Closed mine	Bugge (1978)
Kåfjord	AKGB	Au-Cu	0.2[5]	2		Co: 0.02	Closed mine	Bugge (1978)
Stora Sahavaara	Pajala-Kolari	Skarn-Fe	145	0.08			Test mined	Martinsson (1995)
Östra Sahavaara	Pajala-Kolari	Skarn-Fe	2	0.03	43.1		Prospect	Martinsson (1995)
Tapuli	Pajala-Kolari	Skarn-Fe	1.04		40.5			Northland
Hannukainen	Pajala-Kolari	IOCG	170.7	0.2	26.2	Au: 0.1	Closed mine	Niiranen *et al.,* (2007)
Rautuvaara Mine	Pajala-Kolari	IOCG	13.3	0.2	35.5		Closed mine	Niiranen *et al.,* (2007)
Rautuvaara Cu	Pajala-Kolari	IOCG	2.8	0.48	46.8	Au: 0.2	Prospect	Niiranen *et al.,* (2007)
Kuervitikko	Pajala-Kolari	IOCG	1.2	0.3	21.8	Au: 1	Prospect	Niiranen *et al.,* (2007)
Rautuoja	Pajala-Kolari	IOCG	1.9	0.19	40	Au: 0.34	Prospect	Niiranen *et al.,* (2007)
Lauttaselkä	Pajala-Kolari	IOCG	0.6	0.23	36.7	Au: 0.48	Prospect	Niiranen *et al.,* (2007)
Narken	SE of Kiruna	IOCG					Prospect	Frietsch (1972)
Tjårrojokka Cu	Kiruna	IOCG	3.23	0.87			Prospect	Edfelt (2007)
Tjårrojokka Fe	Kiruna	AIO	52.6	0.06	51.5		Prospect	Edfelt (2007)
Rakkurijärvi	Kiruna	IOCG	1.4	0.25		Au: <0.1	Prospect	Smith *et al.,* (2007)
Kiskamavaara	Kiruna	IOCG	3.42	0.37		Co: 0.09	Prospect	Martinsson (1995)
Nautanen	Gällivare	IOCG	0.63	2.36		Au: 1.3	Closed mine	Danielsson (1985)
Aitik	Gällivare	Porphyry (-IOCG)	2169	0.26		Au: 0.16; Ag: 2.0	Active mine	Boliden AR 2008; Wanhainen *et al.,* (2005)
Vaikijaur	Jokkmokk	Porphyry					Prospect	Lundmark *et al. 2005b*
Kiirunavaara	Kiruna	AIO	1932		47.7		Active mine	Martinsson (1997)
Malmberget	Gällivare	AIO	883		44.9		Active mine	Martinsson (1997)
Gruvberget Fe	Kiruna	AIO	73.8		57		Test mined	Espersen & Frietsch (1964)
Pahtavaara Au	CLGB	Orog. Au or Syngenetic	4.3			Au: 2.6	Active mine	Korkiakoski (1992)
Suurikuusikko (Kittilä Mine)	CLGB	Orogenic Au	39.3			Au: 4.5	Active mine	Patison *et al.,* (2007)
Juomasuo	Kuusamo	Au-Cu or Syngenetic	0.82			Au: 4.2; Co: 0.2	Test mined	Vanhanen (2001)
Huornaisenvuoma	Lannavaara	Stratabound Cu±Pb,Zn	0.56	0.2		Zn: 4.8, Pb: 1.7	Prospect	Frietsch (1991)
Pahtavuoma	CLGB	Stratabound Cu±Pb,Zn	21.4	0.3		Ag: 12; Zn: 0.7; Pb: 0.1; Co: 0.01, Ni: 0.02	Test mined	Inkinen (1979)
Viscaria	KGG	Stratabound, Cu±Pb,Zn	25.27	3.54		Ag: 10; Zn: 0.7	Closed mine	Martinsson (1997)
Ahmavaara	TNB	Contact PGE	188	0.17		Au: 0.1; PGE: 1.1, Ni: 0.09	Prospect	Iljina (1994)
Kemi	TNB	Intrusion Cr	158			Cr: 17.1	Active mine	Alapieti *et al.,* (1989)
Kevitsa	CLGB	Intrusion Ni	207	0.46		Au: 0.13, Co: 0.01; PGE: 0.43, Ni: 0.3	Prospect	Mutanen (1997)

[1] This indicates the geological area or subarea where the deposit is located. AKGB = Alta-Kvænangen greenstone belt, Norway; CLGB = Central Lapland greenstone belt, Finland; KGG = Kiruna Greenstone Group, Sweden; KRGB = Komagfjord-Repparfjord greenstone belt, Norway; Kuusamo = Kuusamo schist belt, Finland; TNB = Tornio-Näränkävaara layered intrusion belt, Finland. Deposits (although not necessarily all names of geological formations) are shown on Figures 2 and 5.

[2] Abbreviations: AIO = Apatite iron ore; Contact PGE = Layered intrusion-hosted contact-type PGE; Epigenetic copper-gold, most of these would probably go into the class 'Orogenic gold with an atypical metal association' of Goldfarb *et al.*, (2001); Intrusion Cr = Layered intrusion-hosted chromitite; Intrusion Ni = Mafic-ultramafic intrusion-hosted nickel-copper±PGE; IOCG = Iron oxide-copper-gold; Orog Au = Orogenic gold; Porphyry = Porphyry Cu-Au type deposit; Syngenetic = Premetamorphic: Submarine hydrothermal at Pahtavaara; Syn-diagenetic at Juomasuo; VMS = Volcanogenic massive sulphide.

[3] Grade and tonnage are mainly from the Fennoscandian Ore Deposit Data Base (Eilu *et al.*, 2009), where the original references are listed. Average grade figures for last years production have been used for Malmberget and Kiruna, whereas information from Huornaisenvuoma and Aitik were obtained from Frietsch (1991) and Wanhainen *et al.*, (2005); Boliden Annual Report (2008), respectively.

[4] There is only one reference for each deposit listed in the table. This is the most recent reference containing extensive information on the deposit and a review of previous work.

[5] Only the mined amount has been reported; there is no data on the possibly remaining resource.

1931; Witschard, 1984; Bergman *et al.*, 2001). They can be classified as a quartz monzonite-adamellite-granite suite, which is peraluminous to metaluminous with alkaline trends (Ahl *et al.*, 2001). Gradual contacts and hybrid rocks are common between gabbro and monzonite, indicating coexisting mafic and felsic magmas (Kathol and Martinsson, 1999). On the basis of similar compositional variations, and a relatively high content of alkali and HFS-elements, it is suggested these intrusions are comagmatic with the Kiirunavaara Group volcanic rocks. The intra-plate setting suggested for the latter is also consistent with the chemical characteristics of the former (Martinsson, 2004).

Intrusions of the 1.81 to 1.78 Ga *Lina Suite* (Wikström and Persson, 1997b; Perttunen and Vaasjoki, 2001; Rastas *et al.*, 2001; Väänänen and Lehtonen, 2001; Bergman *et al.*, 2002) are extensively developed in northern Sweden and Finland. This suite typically comprises granite, pegmatite and aplite of mainly minimum melt composition, generated by crustal melting. In Finland, they appear to form most of the volume of the Central Lapland Granitoid Complex (CLGC; Fig. 1), and are also present as smaller intrusions in many areas across northern Finland (Lehtonen *et al.*, 1998). The Lina Suite is peraluminous, characterised by its restricted SiO_2 range of 72 to 76 wt.%, a high Rb content and depletion of Eu. The heat source generating the S-type magmas may have been the continent-continent collision events to the south and west (Öhlander *et al.*, 1987b; Öhlander and Skiöld, 1994; Lahtinen *et al.*, 2005) or the contemporaneous TIB 1 magmatism (Åhäll and Larsson, 2000).

In the western part of the shield, extensive I- to A-type magmatism (Revsund-Sorsele type) form roughly north-south trending batholiths (the *Transscandinavian Igneous Belt*; TIB), coeval with the S-type magmatism. Two generations (ca. 1.8 and 1.7 Ga) of intrusions belonging to the TIB exist in northern Sweden and adjacent areas of Norway. Across northern Finland, this suite, which can be classified as a quartz monzodiorite-quartz monzonite-adamellite-granite suite, showing a metaluminous to peraluminous trend with alkaline affinity (Ahl *et al.*, 2001), is represented by the Nattanen-type granitic intrusions dated at 1.80 to 1.77 Ga (Rastas *et al.*, 2001). They form undeformed and unmetamorphosed, multiphase, peraluminous, F-rich plutons which sharply cut across their country rocks. In northern Norrbotten, monzonitic to syenitic rocks give ages of between 1.80 and 1.79 Ga (Romer *et al.*, 1994; Öhlander and Skiöld, 1994; Bergman *et al.*, 2001), whereas granites range from 1.78 to 1.77 and 1.72 to 1.70 Ga (Romer *et al.*, 1992). Characteristic of the 1.8 Ga monzonitic to syenitic rocks is the occurrence of augite and locally also orthopyroxene and olivine, demonstrating an origin from dry magmas (Öhlander and Skiöld, 1994; Bergman *et al.*, 2001). It has been suggested that the Transscandinavian Igneous Belt was formed in response to eastward subduction (Wilson, 1980; Nyström, 1982; Andersson, 1991; Romer *et al.*, 1992; Weihed *et al.*, 2002), possibly during a period of extension (Wilson *et al.*, 1986; Åhäll and Larsson, 2000). The related plate-tectonic setting may also be that of the final orogenic collapse, decompression and/or thermal resetting in the terminal stages of the orogenic development, following the 1.84 to 1.80 Ga continent-continent collision stage (Lahtinen *et al.*, 2005).

Deformation and Metamorphism

The region under investigation has undergone several stages of deformation and metamorphism. A sequence of ductile deformation events in central Finnish Lapland is reported in Hölttä *et al.* (2007) and Patison (2007), and references therein. The earliest foliation (S_1) is bedding-parallel and can be seen in F_2 fold hinges and as inclusion trails in andalusite, garnet and staurolite porphyroblasts where the regional metamorphic grade has allowed these minerals to form. The main regional foliation (S_2) is axial planar with tight or isoclinal folds. It is mostly gently dipping to flat-lying, and is suggested to have been caused by horizontal movements (SSW to NNE directed) related to thrust tectonics, e.g., along the Sirkka Shear Zone (Figs. 2 and 4). The south-dipping Sirkka Shear Zone is composed of several sub-parallel thrusts and fold structures on the southern margin of the Central Lapland Greenstone Belt. This NNE-directed thrusting occurred during D_1-D_2, with a maximum age of ca. 1.91 Ga (Lahtinen *et al.*, 2005), and was contemporaneous with south- to southwest-directed thrusting of the Lapland Granulite Belt in the north (cf. Patison *et al.*, 2006). The D_2 and earlier structures are overprinted by sets of late folds, collectively called F_3-folds, with a variety of orientations. It is probable that some earlier-formed structures were reactivated during D_3 deformation, the minimum age of which is given by post-collisional 1.77 Ga Nattanen-type granites. The 1.77 Ga Nattanen granites also set the maximum limit for the D_4 stage of deformation, which is characterised by discontinuous ‘brittle shear zones’.

Ductile deformation in Sweden includes at least three phases of folding and also involves the formation of major crustal-scale shear zones. The intensity of deformation varies from a strong penetrative foliation to texturally and structurally well preserved rocks both regionally and on a local scale. Axial surface fold traces mainly have a southeast or a SSW trend (Bergman *et al.*, 2001). The difference in the intensity of deformation shown by intrusions of the Haparanda and Perthite Monzonite suites suggests an event of regional metamorphism and deformation at ca. 1.88 Ga in northern Norrbotten (Bergman *et al.*, 2001), possibly corresponding to D_1-D_2 in Finland. Evidence for an episode of magmatism, ductile deformation and metamorphism at ca. 1.86 to 1.85 Ga from the Pajala area in the northeastern part of Norrbotten has been presented by Bergman *et al.*, (2006).

A third metamorphic event at 1.82 to 1.78 Ga is recorded by chronological data from zircon and monazite in the same area, and this event appears to be wide-spread in large parts of northern Sweden. The period from ca. 1.87 to 1.80 Ga possibly also involved a shift in orogenic vergence from northeast-southwest to east-west in the northern part of the Shield, as suggested by Weihed *et al.*, (2002).

Major ductile shear zones in Sweden are represented by the NNE-trending Karesuando-Arjeplog deformation zone, the north- to NNE-trending Pajala-Kolari Shear Zone and the NNW-trending Nautanen deformation zone. These major shear zones show evidence of having been active at ca. 1.8 Ga. The Pajala-Kolari Shear Zone has a major significance, representing the boundary between the Archaean Karelian and Norrbotten cratons (Fig 1; Lahtinen *et al.*, 2005). One striking feature is that several

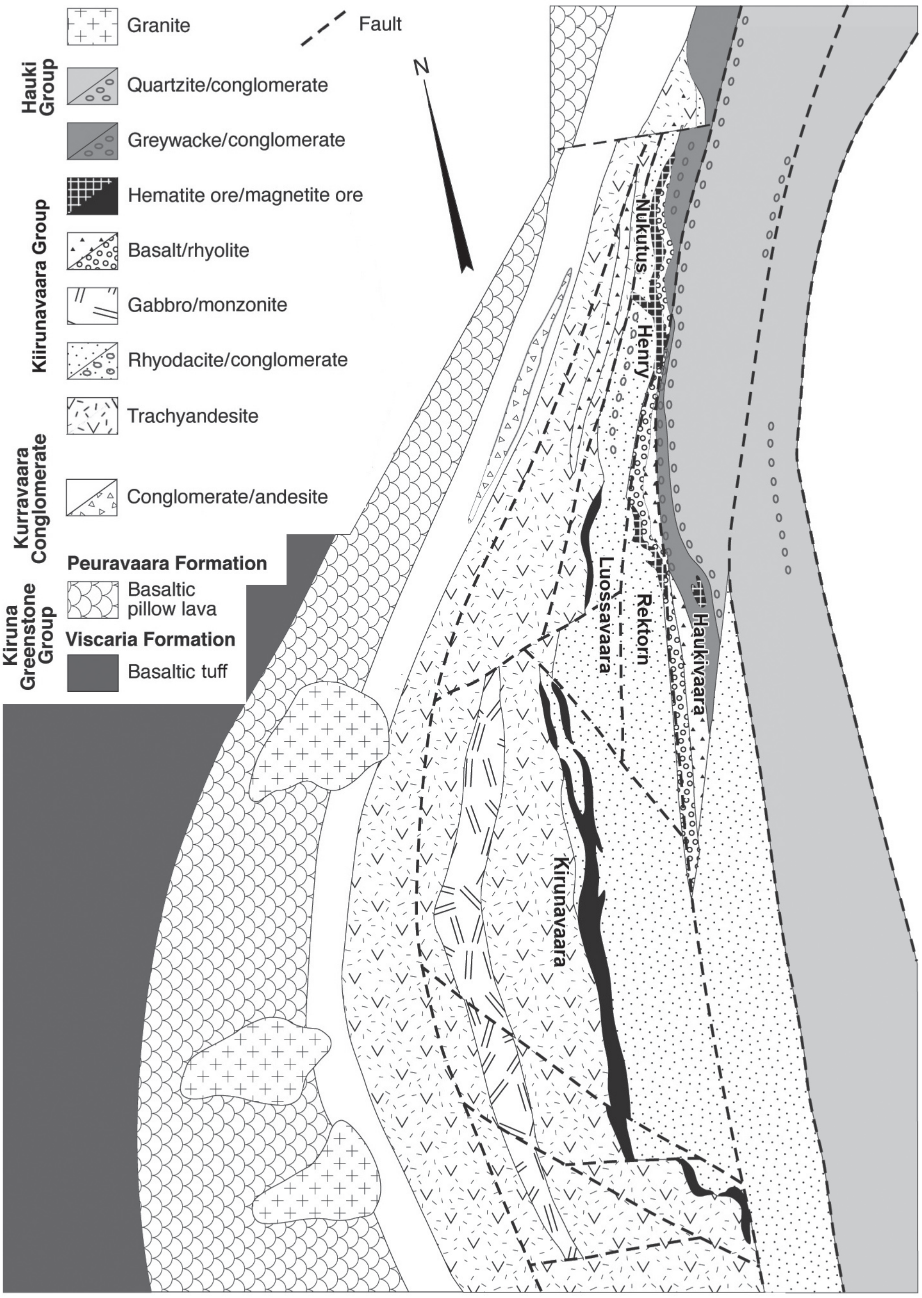


Figure 7: Map of the Kiirunavaara deposit, Sweden.

of the crustal-scale shear zones are associated with abrupt changes in metamorphic grade, indicating that they have been active after peak regional metamorphism. Moreover, many of the epigenetic gold and copper-gold deposits also show a strong spatial relationship with these structures, although their local control is determined by second- to fourth-order faults and shear zones.

The metamorphic grade is mainly of low- to intermediate-pressure type, generally varying from upper-greenschist (lower-greenschist in the Central Lapland greenstone belt) to upper-amphibolite facies. Granulite facies rocks are only of minor importance, except in northern Finnish Lapland and the Kola Peninsula (Fig. 1). Regional metamorphic assemblages in metaargillites and mafic metavolcanic rocks in Sweden, interpreted to be of Svecofennian age, generally indicate that the metamorphism was either of low or medium pressure type of 2 to 4 and 6 to 7.5 kbar, under temperatures of 510 to 570°C and 615 to 805°C (Bergman *et al.*, 2001), respectively. Interestingly, most of the low-grade areas in northernmost Sweden are to the west (e.g., at Kiruna), whereas the majority of medium to high grade metamorphic rocks are located in the central to eastern parts, where the vast majority of the Lina type granites (ca. 1.81 to 1.78 Ga) are also situated.

The strong spatial relationship between the higher-grade metamorphic rocks and the S-type granites is either the result of a deeper erosional level of the crust being exposed, or reflects areas affected by higher heat flow at ca. 1.8 Ga. In central Finnish Lapland, it has been possible to outline a number of metamorphic zones (Hölttä *et al.*, 2007) representing a range from granulite to greenschist facies rocks. Metamorphism in the Lapland Granulite Belt occurred at 1.91 to 1.88 Ga (Tuisku and Huhma, 2006), although the present metamorphic structure may record later, post-metamorphic thrusting and folding events (Hölttä *et al.*, 2007).

Styles of Mineralisation

Northernmost Finland, Norway and Sweden are characterised by mafic to ultramafic intrusion-hosted chromite, iron-vanadium-titanium and nickel±copper±PGE ores, stratabound copper-zinc-lead, epigenetic copper±gold and gold, and iron oxide±apatite ores (Weihed *et al.*, 2005). Based on the style of mineralisation, alteration and structural control, the region has been regarded as a typical iron oxide copper-gold (IOCG) province (e.g., Martinsson, 2001; Williams *et al.*, 2003). Similarly, the Finnish part of the shield and the Kola region in Russia represent a major mafic intrusion-hosted magmatic ore province of global significance (e.g., Iljina, 1994; Mutanen, 1997; Alapieti and Lahtinen, 2002).

Given the scope of this volume, we have focused on IOCG-style and related ore deposits. Deposits dominated by chromite, vanadium, titanium, nickel and PGE will not be discussed, although, given their economic potential, some details of a few (Ahmavaara, Kemi and Kevitsa) are given in Table 1. The features of the IOCG and possibly related deposits of the northern Fennoscandian shield are presented below using a four-fold division: (1) stratiform-stratabound sulphide, (2) apatite-iron, (3) skarn-related iron and BIF and (4) epigenetic (±syngenetic?) gold and copper-gold deposits. The salient features of each category will be discussed in general terms, accompanied by more detailed descriptions and deposit maps (Figs. 7 and 9 to 13) for selected type deposits. Furthermore, the main characteristics of Kiruna-type, gold-only, and copper-gold deposits best fitting the broad IOCG category of mineralisation in northern Fennoscandia, are summarised in Table 2.

It is noteworthy that, as a result of the large diversity of ore styles, and the apparent evidence of later over-printing and remobilisation, placing an individual deposit into a classification scheme is not always straight-forward (cf. also, two review papers dealing with IOCG-type deposits in northern Sweden; Martinsson *et al.*, 2010a, b). For instance, the main features of some of the occurrences described below could easily be reconciled with them being classified as, for example, VMS or orogenic gold deposits. However, these occurrences may fit into the overall Fennoscandian shield IOCG context as they might constitute the local expressions of large-scale fluid events that elsewhere led to the formation of more typical IOCG-style deposits, or formed potential sources or traps for the metals in IOCG-style occurrences.

Stratabound Sulphide Deposits

Stratabound to stratiform base metal deposits are restricted to the Palaeoproterozoic greenstone successions where they occur in volcaniclastic units, but have a spatial association with basaltic units. These are probably syngenetic occurrences, but are briefly described here as they may form one of the metal sources for IOCG and epigenetic gold-copper mineralisation within the region. The sulphide occurrences are tabular to blanket-shaped and consist of varying proportions of chalcopyrite, pyrrhotite, pyrite, sphalerite, galena and magnetite. The ore minerals occur disseminated, as massive intercalations, or in breccia veins, and as massive intercalations in tuffite, black schist and carbonate rocks. Extensive chert beds up to 20 m thick may also be associated with this mineralisation.

***Viscaria**:* The Viscaria copper-deposit, which is located 4 km west of Kiruna in Sweden (Fig. 2), is hosted by the volcaniclastic Viscaria Formation, and comprises three stacked orebodies (A, B and D) containing sulphides and magnetite in differing proportions (Martinsson *et al.*, 1997a). The economically important zone A is situated between two black schist units at the top of a large alteration zone expressed by the destruction of plagioclase and the formation of biotite. The ore zone is capped by a thin chert unit extending several km beyond the economic part of the deposit. Chalcopyrite, magnetite, pyrrhotite and sphalerite are the main ore constituents, occurring as disseminated minerals, thin layers and more massive accumulations. Calcite is the main gangue mineral, with accessory amphibole, apatite, barite, quartz and albite.

Huornaisenvuoma: The sub-economic Huornaisenvuoma Zn-Pb-Ag-Cu deposit (ENE of Kiruna in Sweden; Figs. 2 and 6) is hosted by a thick dolomite unit in the upper part of the sequence of mafic tuff-tuffite, manganiferous iron formation and graphite schist which comprises the Kiruna Greenstone Group. A thin stratiform sulphide orebody is developed at the base of a 20 to 35 m thick skarn zone in the upper part of the dolomite. It consists of disseminated to massive layers of sphalerite, magnetite and pyrite. Disseminated magnetite, with subordinate to ore grade chalcopyrite, occurs locally. In the footwall to the most metal rich part of the deposit, skarn rich dolomite with chondrodite, diopside and actinolite persists for at least 30 m below the stratiform mineralisation (Martinsson, 1995).

Pahtavuoma: The Pahtavuoma deposit is located in the Kittilä greenstones of the Central Lapland greenstone belt (north of Kolari in northwestern Finland; Figs. 2 and 4), and is hosted by a ca. 2200 to 2130 Ma, metasedimentary rock-dominated sequence. The mineralisation is dominantly stratabound, with several east-west trending, copper-, zinc-, and uranium-dominated orebodies within a sequence of greywacke, phyllite, black schist, mafic tuffite and lava, and chert (Inkinen, 1979; Korkalo, 2006). The ore minerals, chiefly pyrrhotite, chalcopyrite and sphalerite, with minor galena, ilmenite, arsenopyrite, pyrite, magnetite, graphite, uraninite and pentlandite, occur disseminated and in breccia veins. Albitisation and scapolitisation of nearly all rock types, and spilitisation of mafic lavas, are wide-spread in the region.

Apatite-Iron Deposits

Kiruna is the type area for apatite-iron ores ('iron ores of Kiruna type', defined by Geijer, 1931) with the Kiirunavaara deposit as the largest and best known example (Table 1, Fig. 7). In total, around 40 apatite-iron deposits are known from northern Norrbotten, and about 1600 Mt of ore have been mined from 10 of these during the last 100 years. This deposit type is mainly restricted to areas occupied by the Kiirunavaara Group rocks, with very few occurrences known outside the Kiruna-Gällivare area. Individual deposits have an average content of Fe and P varying between 30 to 70% and 0.05 to 5%, respectively. Beside magnetite and hematite, most deposits contain significant amounts of apatite and are generally strongly enriched in LREE (Frietsch and Perdahl, 1995). Sulphides are mostly only rare constituents within the apatite-iron ores, occurring

Deposit type[1]	Deposit examples	Host rock sequences	Host rock ages, (Ga)	Ore-related alteration[2]	Main ore minerals[2]	Components enriched	Stable isotope data[3] (‰)	Timing of mineralisation
Skarn-hosted iron ore [a]	Sahavaara	tuffite, basalt, quartzite	c. 2.1	bt, ab	mag ± hem	Fe		c. 2.1 Ga
Skarn-related Fe-Cu-Au [c]	Hannukainen, Kuervitikko	diorite, basalt, tuff	c. 2.1 and 1.86	ab, scp, act, px, hbl	mag ± ccp, py, po, gold	Fe, Au, Cu, S ± Ag, As, Ba, Bi, Cl, Co, LREE, Mo, Pb, Rb, Sb, Se, Te, Th, U, Zn	$\delta^{18}O$: +9.6 to +11.2	c. 1.80 Ga
Apatite iron ore [b]	Kiirunavaara	trachyandesite-rhyodacite	1.89 to 1.88	act, ab, bt, chl	mag ± hem	Fe, P, LREE	$\delta^{18}O$: ca. +8	1.89 to1.88 Ga
Apatite iron ore [c]	Tjårrojåkka-Fe	andesite	1.89 to 1.88	ap, ab, scp, bt, am	mag ± hem	Fe, REE		c. 1.78 Ga
Intrusive-related Cu-Au[d]	Vaikijaur	granodiorite	1.89 to 1.88	kfs, bt, qtz, ser, ep, chl	ccp, py, mo, po, mag	Cu, Au, Mo, S, Ba, LREE		1.89 to 1.88 Ga
Intrusive-related Cu-Au[d]	Aitik	quartz monzodiorite	1.89 to 1.88	bt, kfs, ser, ep, chl, cal, qtz	ccp, py, po, mag, cc, bn, mo	Cu, Au, Ag, Mo, S, Ba		1.89 & possibly 1.8 Ga
Iron-oxide Cu-Au [c,d]	Nautanen	basalt-andesite	ca. 1.88	scp, bt, kfs, ser	ccp, mag, py			c. 1.78 Ga
Iron-oxide Cu-Au [c]	Rakkurijärvi	andesite, intermediate volcanics	ca. 1.88 or 2.05	ab, act, bt, cal, kfs, ap, ttn, aln	ccp, po, py		$\delta^{18}O_{cal}$: +9.4 to +19.9, $\delta^{13}O_{cal}$: -11.7 to -4.9	1.862 to 1.853 Ga
Iron-oxide Cu-Au [c,d]	Tjårrojåkka-Cu	andesite, diabase	ca. 1.88 Ga	kfs, am, qtz, carb	ccp, mag, py, bn	Ba, Mn, REE		1.78 to 1.77 Ga
Cu-Au ± Co, U [g]	Kuusamo	quartzite, mafic lava metasiltstone	2.35 to 2.2 Ga	ab, qtz, chl, bt, ser, cal, act	ccp, po, py, pn, cob, gold	As, Au, Co, Cu, LREE, Rb, S, Se, Te ± Ag, B, Bi, Cs, Fe, Mo, U, W		If syngenetic: 2.35 to 2.2 Ga; if epigenetic: 1.9 to 1.8 Ga
Cu-Au ± Co, U [e]	Pahtohavare	tuffite, schist, chert	2.1	bt, scp, carb	ccp, py	Au, Cu, S, Te		c. 2.1 Ga
Cu-Au ± Co, U [e]	Saattopora	intermed. tuffite, komatiite	2.1	fdol, ab, qtz, ser	py, po, ccp, ger, gold	Au, Ag, As, B, Bi, CO_2, Cu, S, Se, Te, U, W	$\delta^{18}O_{dol}$: +12.2 to +12.4, $\delta^{13}C_{dol}$ -7.7 to -6.9	1.9 to 1.8 Ga
Au only [f]	Suurikuusikko	tuffite, mafic lava	2.0 Ga	dol, ab, qtz, ser	apy, py	Ag, As, Au, Bi, CO_2, Co, S, Sb, Se, W		1.9 ? Ga
Au only [f]	Pahtavaara	komatiite	2.2 Ga	tr, bt, dol, qtz, brt	py, mag, gold	Au, Ba, S, Sr, Te, W , P	$\delta^{18}O$: +11.4 to +11.9, $\delta^{13}C$: -4.1 to -1.2	If syngenetic: 2.2 Ga; if epigenetic: 1.9 to 1.8 Ga

1 The division into types is non-genetic, given the uncertainties involved in a genetic classification.
2 Mineral abbreviations: ab = albite, act = actinolite, aln = allanite, am = amphibole, ap = apatite, apy = arsenopyrite, bn = bornite, brt = barite, bt = biotite, cal =calcite, carb = carbonate, chl = chlorite, cob = cobaltite ccp = chalcopyrite, dol = dolomite, ep = epidote, fdol = ferrodolomite, ger = gersdorffite, gold = native gold, hem = hematite, hbl = hornblende, kfs = K feldspar, mag = magnetite, mo = molybdenite, pn = pentlandite po = pyrrhotite, px = pyroxene, py = pyrite, qtz = quartz, scp = scapolite, ser = sericite, tr = tremolite, ttn = titanite.
3 Data refer to the fluid composition, unless otherwise stated.

Data sources:

a Martinsson (1995)
b Nyström & Henriquez (1989, 1994), Martinsson (1997), Nyström *et al.,* (2008)
c Lundberg (1967), Hiltunen (1982), Martinsson (1995), Edfelt (2007), Niiranen *et al.,* (2007), Smith *et al.,* (2007)
d Wanhainen *et al.,* (2005, 2006), Lundmark *et al.* (2005a, b), Martinsson and Wanhainen 2004
e Ettner *et al.,* (1994), Lindblom *et al.* , (1996), Eilu *et al.,* (2007)
f Eilu *et al.* , (2007), Hulkki and Keinänen (2007), Patison (2007), Patison *et al.* ,(2007)
g Pankka and Vanhanen (1992), Vanhanen (2001), Eilu *et al.* , (2007)

Table 2: Typical features of iron oxide-copper-gold (IOCG), copper-gold and apatite iron oxide (AIO) deposits in the northern Fennoscandian Shield.

as disseminated minerals or in veinlets. Significant copper mineralisation is spatially associated with apatite ores in only a few places (e.g., Tjårrojåkka and Gruvberget).

The apatite-iron ores exhibit a considerable variation in host rock composition, host rock relationship, alteration, phosphorous content, and associated minor components. It is possible to distinguish two rather distinct groups of deposits: (1) breccia (e.g., Mertainen) and (2) stratiform-stratabound types (e.g., Rektorn). There is also (3) an intermediate type, displaying features similar to both groups (Bergman *et al.*, 2001), of which the huge Kiirunavaara and Malmberget deposits are representative examples.

Breccia-type apatite-iron ores are mainly hosted by intermediate to mafic volcanic rocks, at a low stratigraphic position within the Kiirunavaara Group, or within the underlying Porphyrite Group. Amphibole is always present as a minor component, while accessory amounts of pyrite, chalcopyrite and titanite may be encountered. Host rock alteration is not extensively developed, although secondary albite and scapolite seem to be relatively common, while sericite, epidote and tourmaline are less abundant. The breccia-type deposits characteristically have a low phosphorous content (typically in the range of 0.05 to 0.3% P) and an average iron content of only about 30%. With a few exceptions, magnetite is the only iron oxide present (Martinsson, 2003).

The *stratiform-stratabound-type* comprises lenses at higher stratigraphic positions within the Kiirunavaara Group. They have hematite as the major iron oxide, together with varying amounts of magnetite, and are characterised by a high phosphorous content, of 1 to 4.5% P. Amphibole is absent, and the main gangue minerals are apatite, quartz and carbonate. Host rock alteration is wide-spread, with sericite, biotite, tourmaline and carbonate as typical products. The hanging wall rocks may also be strongly silicified. Sulphides are rare, and mainly found in small amounts in the altered footwall or as crosscutting late veinlets within the ores. Ore breccia is absent or restricted to the footwall. Included in this group are the Per Geijer ores (i.e., Nukutus, Henry, Rektorn, Haukivaara, and Lappmalmen in the central Kiruna area) and Ekströmsberg (Martinsson, 2003).

Kiirunavaara: Kiirunavaara is the largest of the apatite iron ores in Sweden (Figs. 2 and 6), comprising about 2500 Mt of iron ore with 60 to 68% Fe. It was found in outcrop in 1696, but regular mining did not commence until 1900 when a railway was built from the Norwegian coast to Kiruna. The tabular orebody is roughly 5 km long, up to 100 m thick, and extends to at least 1500 m below the surface (Fig. 7). It follows the contact between a thick pile of trachyandesitic lava (traditionally named syenite porphyry) and overlying pyroclastic rhyodacite (traditionally referred to as quartz-bearing porphyry). To the north, the much smaller Luossavaara ore is situated in a similar stratigraphic position. The trachyandesite lava occurs as numerous lava flows which are strongly albite-altered and rich in amygdales close to the flow tops. A U-Pb age of 1876±9 Ma was obtained for titanite occurring together with actinolite and magnetite in amygdales (Romer *et al.*, 1994). A potassic granite is present at deeper levels in the mine on the footwall side of the ore and several dykes of granophyric to granitic character cut the ore. Some of these dykes are composite in character also including diabase. A U-Pb zircon age of 1880±3 Ma (Cliff *et al.*, 1990) has been obtained for the granophyric dykes.

The phosphorus content of the ore exhibits a pronounced bimodal distribution. Most of the apatite-poor ore (i.e., B-ore with <0.05% P) is found close to the footwall as slightly irregular and branching bodies of massive and fine-grained (<0.3 mm) magnetite ore. The B-ore may contain up to 15% disseminated actinolite in a 5 to 20 m wide zone along its borders where it is in contact with the wall rocks. Apatite-rich ore (i.e., D-ore with >1.0% P) is mainly found towards the hanging wall and in the peripheral parts of the orebody, but also occurs in varying amounts at the footwall contact. Locally, the D ore has a banded structure and the proportion of apatite and magnetite varies widely. The age relation between B and D ores is ambiguous, and both ore types can be seen cutting each other. However, an earlier formation of the D-ore is supported by the existence of wall-rock clasts within D-ore lenses, which are in turn enveloped by B-ore lacking clasts. Columnar and dendritic magnetite is locally developed in the ore suggesting a rapid crystallisation in a super-cooled magma (Geijer, 1910; Nyström, 1985; Nyström and Henriquez, 1989, 1994). Veins of anhydrite, anhydrite-pyrite-magnetite and coarse-grained pyrite occur in the ore and its wall rocks.

Magnetite-actinolite veining (ore breccia) is developed both in the footwall and hanging wall along the contacts of the Kiirunavaara orebody. In the footwall, larger breccia zones may show a change from veined trachyandesite to breccia containing angular fragments of the wallrock. Close to the hanging wall contact, the ore is typically rich in angular to subrounded clasts of rhyodacitic tuff. Extensive albitisation is developed in the footwall to the Kiirunavaara deposit, with the amygdaloidal parts of the lava flows especially strongly altered, and albitisation being accompanied by secondary magnetite, actinolite, titanite and locally some tourmaline (Geijer, 1910). Actinolite is a common alteration mineral, both at the footwall and the hanging wall contacts, where it may form massive skarns bordering the ore. Actinolite also partly or completely replaces clasts of wallrocks in the ore and in the ore breccia. In addition to actinolite and magnetite veining close to the ore, the hanging wall is in some areas affected by biotite-chlorite alteration, which is commonly accompanied by disseminated pyrite and a weak enrichment of Cu, Co and Mo.

Skarn-related Iron Deposits

Lens-shaped iron occurrences consisting of magnetite, and Mg- and Ca-Mg-silicates are common within the greenstones in Sweden and north-westernmost Finland (Tables 1 and 2). Some of these, but by no means all, are possibly of iron formation origin. True banded iron formations (BIF) occur in both Karelian and Svecofennian units, as exemplified by Käymäjärvi (Martinson, 2004), but generally lack economic importance due to their comparatively low iron content (20 to 40% Fe) and mostly relatively small size (<100 Mt). Generally, skarn-hosted iron deposits carry magnetite, serpentine, diopside and tremolite, and occur in association with tuffite, black schist and dolomitic marble. Skarn is used herein as a non-genetic term in relation to any calc-silicate altered rock, irrespective of its mode of formation. In Karelian rocks, iron formations are extensively developed in the upper part of the greenstone successions as units that are up to 200 m thick. Similar occurrences elsewhere in the shield are also mainly located in the upper parts of greenstone piles. Some of the deposits are spatially associated with oxide- and silicate-facies BIF, and appear to grade into BIF towards the hanging wall and/or along strike. The

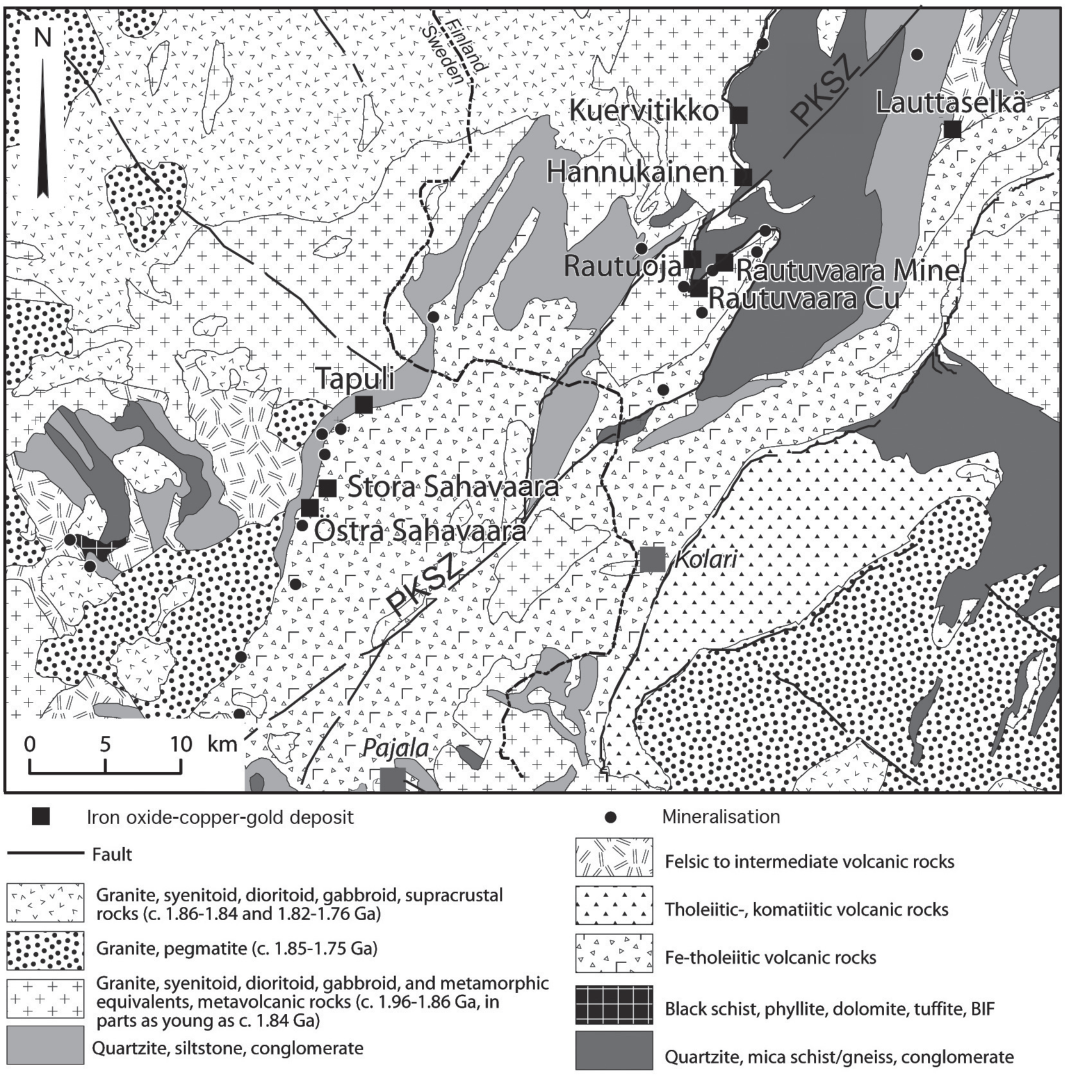


Figure 8: Geology of the Pajala-Kolari district in eastern Sweden and western Finland. PKSZ = Pajala-Kolari shear zone. Modified after Eilu *et al.*, (2008).

stratiform banded iron formations (BIF) occur as tabular and laminated rock units composed of alternating layers of iron oxide or Fe-rich silicates and chert. In skarn-hosted iron deposits, disseminated pyrite, pyrrhotite and chalcopyrite are commonly present, and the sulphur content is in the range of 1 to 5% S. The concentration of copper is typically less than 0.1%, but may locally be as high as 2 to 4% Cu. Phosphorous varies from 0.02 to 0.1%, with a few richer exceptions (Grip and Frietsch, 1973; Hiltunen, 1982; Niiranen, 2005).

Pajala area ***(Sahavaara and Tapuli)***: Several iron occurrences occur northwest of Pajala in northeastern Sweden (Figs. 2 and 8). The largest is the *Sahavaara* deposit, which comprises three lenses of skarn-rich iron formation located in the upper part of the greenstone pile at the contact between footwall volcaniclastic greenstones, and clastic sediments (quartzites) in the hanging wall. The footwall tuffites were deposited upon lapilli tuff of picritic to high-Mg composition basalt. However, close to the ore, the tuffites become more felsic and generally richer in graphite and scapolite (Martinsson, 1995). The ore zone at Stora Sahavaara is up to 80 m thick and consists of serpentine-rich magnetite ore, including lenses and layers of serpentine-diopside-tremolite skarn (Lundberg, 1967). Pyrrhotite and pyrite occur disseminated in the ore, together with minor chalcopyrite. The ore is usually capped by a zoned skarn unit, in which Si/Mg ratios successively increase stratigraphically upwards.

An alteration zone extends for about 200 m below Stora Sahavaara, also enclosing the stratigraphically lower, and smaller, Östra Sahavaara orebody. This zone is variably rich in biotite, resulting in enrichment in Mg, K, Ba and Rb, whereas Na, Ca and Sr are slightly depleted, although Na is locally strongly enriched in albite rocks. The occurrence of scapolite in the footwall of the Stora Sahavaara deposit may be unrelated to the ore-forming processes, as similar scapolite-rich rocks are present at the same stratigraphic position elsewhere in the region (Martinsson, 1995).

Tapuli differs from other mineralisation of this group, occurring as an irregular-shaped, 350 m wide, orebody. It comprises magnetite bearing skarn within a thick dolomite unit, situated between quartzitic phyllite in the hanging wall, and graphitic, and partly sulphide-rich, phyllite in the footwall. Magnetite forms irregular bands, veins and blebs, together with trace amounts of pyrite, pyrrhotite and chalcopyrite. In the central, richer section of the deposit, serpentine is the main gangue mineral, while low grade and barren parts of the skarn zone are dominated by diopside-tremolite with overprinting magnetite-actinolite alteration forming veins and breccia infill. In the northern extension of the Tapuli deposit, sulphide rich mineralisation was observed in one drill core intersection, where the grade locally reached 5.3% Cu, in an almost massive pyrite-pyrrhotite-chalcopyrite vein within magnetite bearing skarn.

Kolari: Several iron oxide and iron oxide-copper-gold deposits occur in the Kolari region, in the southwestern corner of the CFGB (northwestern Finland; Figs. 2, 4 and 8). Five of the known deposits and prospects at Kolari contain significant amounts of copper and/or gold: *Hannukainen, Rautuvaara-Cu, Kuervitikko, Rautuoja* and *Lauttaselkä* (Table 1; Hiltunen, 1982; Niiranen, 2005; Niiranen *et al.*, 2007). The mineralisation style varies from magnetite-rich skarn-, to breccia-hosted and disseminated magnetite-copper-gold. All of the known deposits occur within, or next to, the shear and thrust zones that comprise the Pajala-Kolari Shear Zone system in the Kolari area. The host package of rocks consists of variably altered Karelian Savukoski Group mafic tuffs, lavas, quartz-feldspar schists, syn-orogenic Haparanda Suite diorite and monzonite intrusions, and minor late-orogenic granitic intrusives. The *Lauttaselkä* deposit is hosted by Svecofennian Kumpu Group mafic metavolcanic and clastic-metasedimentary rocks.

The alteration styles vary from sodic and calcic to potassic. Sodic alteration is represented by either albite, albite-scapolite or albite-actinolite, and is generally the earliest alteration phase. Calcic assemblages occur as the dominant proximal alteration in the skarn-hosted deposits, typically expressed as diopside-hedenbergite series clinopyroxenes, actinolite and hornblende skarns, with or without magnetite. Potassic alteration consists of biotite- and biotite-K feldspar assemblages, and in non-skarn deposit types, this is the proximal alteration type to the iron-copper-gold mineralisation, whereas in skarn types it defines an intermediate alteration zone separating the skarns and sodic altered wall rocks.

The *Hannukainen* deposit comprises five magnetite-rich orebodies carrying chalcopyrite-pyrite-pyrrhotite. These lenticular, up to 40 m thick, magnetite skarn lenses are located within a gently west dipping thrust zone that runs parallel to, and cross-cuts, the contact between Savukoski Group mafic metavolcanic rocks and a Haparanda Suite diorite intrusion (Fig. 9). The magnetite bodies are enveloped by clinopyroxene dominated skarns that overprint the footwall mafic metavolcanic rocks and hanging wall diorite intrusion. In places, felsic dykes cut across the diorite, metavolcanic rocks and skarns. The dominant host to the copper-gold mineralisation is magnetite-rich skarn, although elevated grades are also found in magnetite-poor skarns. Of the five discrete magnetite-rich skarn bodies at Hannukainen, the Laurinoja orebody hosts the economically interesting grades of copper and gold, while levels are relatively low in the others (Table 1). Alteration styles at Hannukainen include sodic in the hanging wall diorite and footwall mafic metavolcanic rocks, calcic and iron-rich assemblages in the ore zone, and potassic in the most intensely sheared footwall and hanging wall rocks.

The iron-copper-gold mineralisation at *Rautuvaara-Cu* consists of magnetite-chalcopyrite±pyrite and pyrrhotite, disseminated in sheared and intensely albite-biotite±anthophyllite altered Savukoski Group mafic metavolcanic rocks. Locally, clinopyroxene-actinolite±magnetite skarn overprints the mafic metavolcanic rocks as veins and, in places, these veins are copper-gold mineralised. The lenticular-shaped orebody is up to 45 m thick and is hosted by a steeply dipping northeast-trending shear zone.

The *Kuervitikko* iron-copper-gold deposit is situated 4 km north of Hannukainen and has a similar host rock package and structural setting to that occurrence. The mineralisation at Kuervitikko comprises two separate, gently west dipping ore zones with different characteristics. The Northern Zone consists of chalcopyrite-pyrite±pyrrhotite within magnetite-rich and magnetite poor skarns that overprint mafic metavolcanic and dioritic intrusive rocks. The Southern Zone comprises several lenticular zones of magnetite-chalcopyrite-pyrite±pyrrhotite in which the oxides and sulphides brecciate intensely albitised and silicified diorite and mafic metavolcanic rocks. Minor felsic dykes cross-cut both the intrusive and supracrustal rocks of the area. The southern orebody also contains Rautuvaara-Cu-type disseminated sections between the breccia zones. Alteration in the Northern Zone is analogous to that at Hannukainen, except for the locally intense

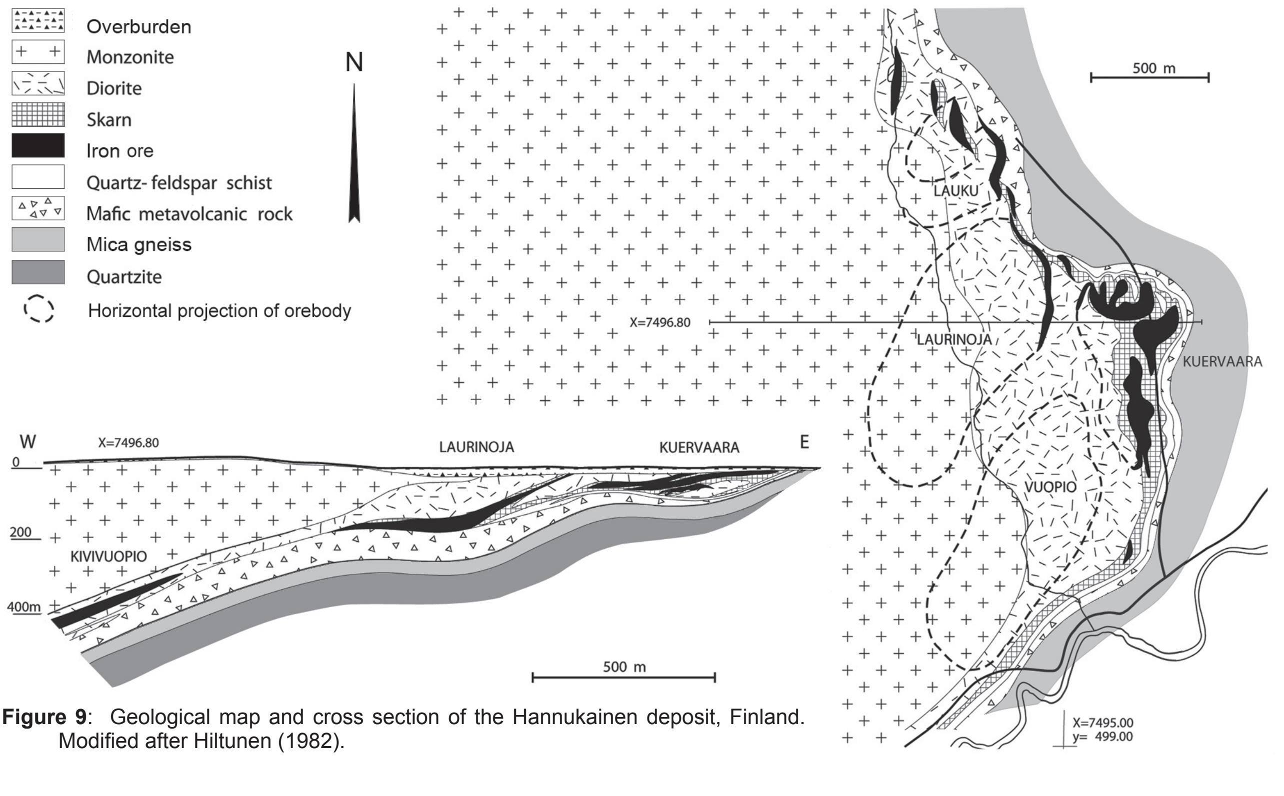


Figure 9: Geological map and cross section of the Hannukainen deposit, Finland. Modified after Hiltunen (1982).

late-stage carbonatisation at Kuervitikko. In the breccia-hosted Southern Zone, the alteration consists of early albite, an albite-quartz phase visible in the breccia clasts, and a subsequent Ca-K-Fe-(Cu-Au-S) episode expressed by the magnetite-actinolite-biotite±epidote, pyrite and chalcopyrite assemblage in the breccia matrix.

Epigenetic Au, Cu-Au and Cu-Au±Fe Deposits

Epigenetic sulphide deposits in the northern part of the Fennoscandian shield form a heterogeneous group, with an extensive variation in the style of mineralisation, alteration, metal association and host rocks. Most deposits occur in (1) Palaeoproterozoic greenstones in the Central Lapland and Kuusamo belts in Finland, but also in Sweden and Norway, and in (2) Svecofennian rocks of the Porphyrite and Kiirunavaara Groups in Sweden. Due to their variable and overlapping features, a variety of genetic types has been proposed for this important class of deposits. Here, we attempt to provide a unified view of these occurrences, and try to put them in different sub-types according to the results of the latest metallogenic investigations in the region (Table 2). Thus, below we will evaluate the possibility of distinguishing between different epigenetic-style occurrences; such as IOCG, porphyry copper-gold, orogenic gold (only), and base metal-enriched gold-bearing deposits, while considering that deformation, metamorphism and multiple hydrothermal fluids may have overprinted and partly erased primary ore features.

Before describing individual examples of these styles of mineralisation, it is important to recall that a major obstacle in classifying epigenetic (iron-) copper-gold deposits is that many parameters used to describe ore occurrences are identical when, for example, IOCG and orogenic gold mineralisation is compared. For instance, features of the orogenic gold occurrences observed in Finland include: (1) proximal to distal carbonate and proximal sericite and biotite alteration; (2) PT conditions at 300 to 500°C and 1 to 3 kbar; (3) pyrite, pyrrhotite and arsenopyrite are the main ore minerals: (4) consistent enrichment of Ag, Au, As, CO_2, K, Rb, S, Sb and Te: (5) a low-salinity aqueous fluid with hydrothermal quartz showing $\delta^{18}O$ of from +11 to +13‰ and carbonate $\delta^{13}C$ of from -8 to -1‰; and (6) any primary rock type within the greenstone belts could act as host rock (Hölttä and Karhu, 2001; Eilu *et al.*, 2007; Hulkki and Keinänen, 2007; Väisänen, 2002; Patison, 2007). In several cases, the host rocks have also been albitised and carbonate altered before gold mineralisation (Hulkki and Keinänen, 2007; Patison, 2007). This pre-mineralisation alteration has provided ground preparation for mineralisation, by converting 'soft' protoliths into competent rocks which will fracture under deformation and, hence, generate sites for the orogenic fluids to precipitate gold. When comparing IOCG type mineralisation with the listed features, it is basically suggested that IOCG fluids are more saline, alteration is of a more complex multi-stage type, and also other metals in addition to gold are enriched to such an extent that they may occur as exploitable commodities in the deposits. It must also be emphasised that certain orogenic gold occurrences in the northern Fennoscandian shield stand out as being base-metal enriched. The latter, which are referred to as 'atypical orogenic gold' below, following the categorisation of Goldfarb *et al.*, (2001), differ from gold-only systems in particular, with having been formed from medium- to high-salinity fluids.

When comparing mineralisation across the northern Fennoscandian shield, it seems that the variety of ore characteristics is more pronounced in Finland than in Sweden, and possibly also syngenetic gold-forming processes need to be considered in Finland. This distinction forms the basis for discussing Finnish and Swedish (Norwegian) mineralisation under separate headings.

Greenstone-hosted Mineralisation in Finland

On the basis of the contained metallic commodities, these greenstone-hosted occurrences can be subdivided into: (1) gold-only and (2) ´atypical´ metal associations. Beginning with the gold-only type, more than 80 epigenetic gold occurrences have been indicated by drilling in the Palaeoproterozoic greenstone belts of northern Finland, Suurikuusikko (Table 1; Fig. 4) being the largest discovered to date (Eilu and Pankka, 2009). Almost all of the gold occurrences in the Central Lapland, Karasjok and Kautokeino greenstone belts (Fig. 2; Tables 1 and 2) appear to belong to the 'orogenic gold' classification as defined by Groves *et al.*, (1998) and Goldfarb *et al.*, (2001). For example, drilling has indicated more than 20 deposits and occurrences within the Sirkka Shear Zone and subsidiary faults branching from that crustal-scale, >100 km long, structural break within the Central Lapland greenstone belt in Finland (Eilu *et al.*, 2007). Locally, the two most significant controls on mineralisation are structure and rock type. Orebodies are typically hosted in dilational sites and by the locally most competent lithological units. For many lodes, part of the local control is the intersection of two faults, or a fault following the boundary between lithological units with contrasting competence (Sorjonen-Ward *et al.*, 2003; Holma and Keinänen, 2007; Patison, 2007). Fluid compositions (Table 3) suggest variable, mixed, origins for volatiles and metals, with no obvious indications of a local source (Ettner *et al.*, 1993; Lindblom *et al.*, 1996; Hulkki and Keinänen, 2007).

It is also worth noting that the Pahtavaara gold deposit, in the central CFGB, has unusual features which distinguish it from other gold-only deposits, in that it has an anomalous barite-gold association and a very high fineness (>99.5% Au). Furthermore, the geometry of the high-grade quartz-barite lenses and amphibole rock bodies relative to biotite-rich alteration zones, and its $\delta^{13}C$ signature of carbonates produced by alteration are anomalous for either an orogenic gold or an IOCG deposit.

The mineralisation classified as having an 'atypical' metal association is not well-defined, and includes two sub-groups, represented by the Saattopora and Kuusamo deposits, respectively. The former is clearly epigenetic, while the polymetallic occurrences of the Kuusamo schist belt, in the southeastern part of northern Finland, are particularly difficult to classify and may even be syngenetic in origin, as discussed below. Saattopora is characterised by a lithological association dominated by mafic to intermediate tuffite, graphitic schist (phyllite to tuffite), carbonate rocks, chert and dolerite. No scapolite has been detected within either the ore or the associated alteration halo. Instead, carbonatisation is the most extensive style of alteration directly related to mineralisation, possibly having resulted from the PT conditions during mineralisation which would not have allowed much, if any, scapolite to form.

Kuusamo Au-Co-Cu±U Deposits: The Kuusamo schist belt (Fig. 1) is a volcanosedimentary rift-shelf sequence on the margin of the Archaean nucleus of the Fennoscandian shield (Laajoki, 2005). It has experienced orogenic magmatism, deformation and metamorphism of a comparatively low order, which possibly makes it a less-deformed and less-metamorphosed analogue relative to other areas in northern Fennoscandia where IOCG-style mineralisation is more obvious. The Kuusamo mineralised sequences are also significant in a broad regional context, as they contain some of the most obvious indications of evaporites detected in Fennoscandia. The Kuusamo deposits (e.g., the Juomasuo mineralisation; Figs. 2 and 10) are mainly hosted by clastic metasedimentary rocks, have a metal association of Au-Co-Cu±U, and are enriched in As, Au, CO_2, Co, Cu, LREE, S, U ± Ag, Bi, K, Se, Te and W. The general sequence of alteration at Kuusamo is reported as described below (Pankka and Vanhanen, 1992; Vanhanen, 2001; Eilu *et al.*, 2007). Albite, accompanied by variable amounts of carbonate, represent the most extensive regional alteration assemblage, and is obviously premetamorphic. Carbonate grains, occurring as pseudomorphs after halite crystals, have been detected in the albite and carbonate altered sedimentary units. This early alteration was followed by a sequence of stages which have mostly been described as syn- to late-metamorphic in age (e.g., Pankka and Vanhanen, 1992; Vanhanen, 2001), comprising: (1) Mg-Fe metasomatism, closely related to gold mineralisation, as indicated by the formation of chlorite, tremolite-actinolite, magnetite, chloritoid, talc and iron sulphides; (2) K±S metasomatism occurring as biotite and sericite±pyrite, additional(?) gold mineralisation and ductile deformation; and (3) a late phase characterised by carbonate, silica, further gold mineralisation (or remobilisation) and brittle deformation.

Minor Greenstone- and Dominant Svecofennian-hosted Epigenetic Mineralisation in Sweden and Norway

The 'atypical' metal association ore type, represented by the greenstone-hosted *Saattopora* mineralisation in Finland (described above), could have analogues in the copper-gold deposits at *Bidjovagge* (Norway) and *Pahtohavare* (Sweden), although gold-only occurrences are absent in greenstone terrains in both Sweden and Norway. These two copper-gold deposits occur in strongly albite altered rocks comprising graphite schist and tuffite, and both (cf. the Pahtohavare map; Fig. 11) are located in antiforms adjacent to shear zones (Björlykke *et al.,* 1987, Martinsson *et al.*, 1997b). Chalcopyrite and pyrite occur disseminated, in veinlets and as breccia infill together with carbonates in albite rocks. A weak enrichment of uranium generally accompanies the sulphides, occurring as the minerals brannerite and davidite (Björlykke *et al.*, 1990, Martinsson *et al.*, 1997b). Extensive, and generally barren, biotite-carbonate-scapolite alteration zones surround the ore-bearing albite rocks, while coarse grained ferro-dolomite and calcite veins are abundant in both the ore zones and the surrounding rocks. The mineralising fluids were highly saline with a high fO_2, while graphitic schist may have acted as a chemical trap triggering precipitation of the ore minerals (Ettner *et al.*, 1993, Martinsson *et al.*, 1997b).

However, quartz-ferrodolomite-calcite and locally barite-bearing veins constitute the most common type of greenstone hosted sulphide mineralisation in this part of the shield. These veins are up to a few metres wide, contain

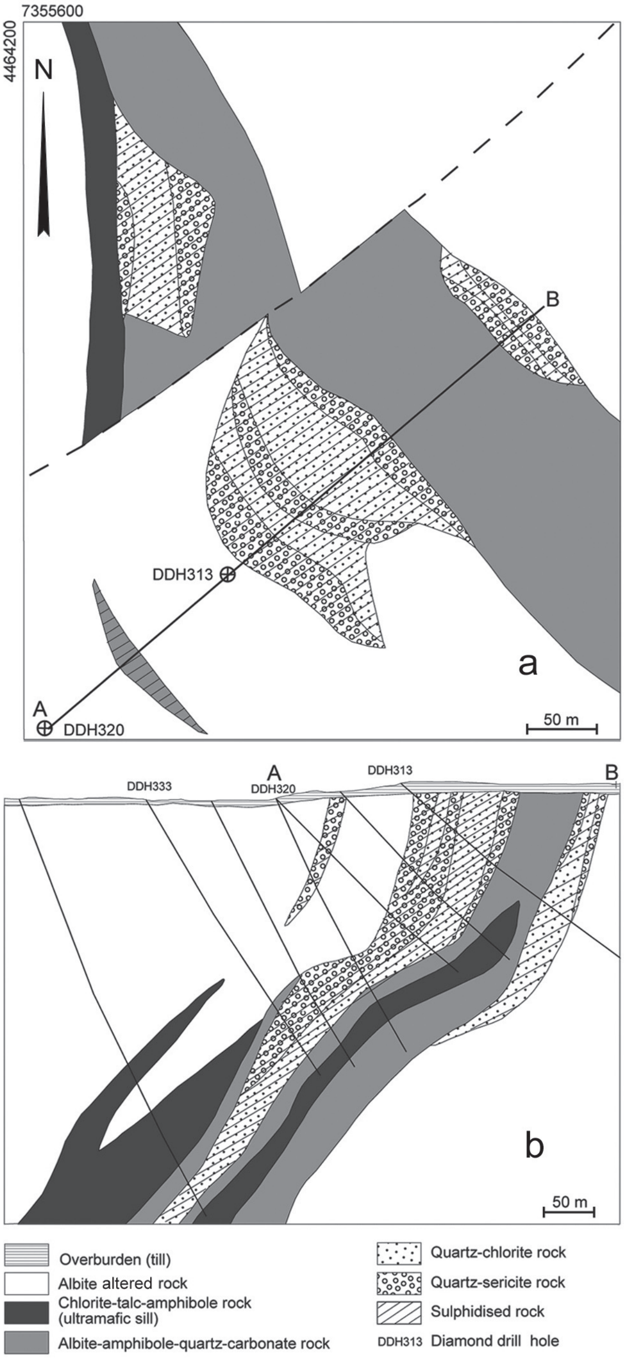


Figure 10: a) Geological plan of the Juomasuo deposit, eastern Finland, showing the location of the cross section A-B illustrated in b). Compiled by Heikki Pankka.

varying amounts of chalcopyrite-pyrite-pyrrhotite and locally bornite, are mostly low in Au, and are generally hosted by mafic sills or mafic lava (Martinsson, 2004). They are small, but may be high-grade, with e.g., Kovo in Sweden, and Kåfjord and Porsa in Norway, having been mined intermittently in the 17th to 20th centuries. Repparfjord in the Alta region (Norway) is a sediment hosted copper-deposit with chalcopyrite, bornite and chalcocite disseminated in arenitic host-rocks (Sandstad *et al.*, 1986). In this area, there are additional epigenetic deposits where Cu is the sole significant commodity (Ettner *et al.*, 1994; Eilu *et al.*, 2003; Sundblad, 2003; Eilu and Weihed, 2005; Weihed *et al.*, 2005; Eilu and Pankka, 2009).

Generally, epigenetic mineralisation styles include disseminated, breccia infill, veinlet, vein and replacement, typically with several styles present in a single deposit. Alteration (albite, scapolite, K feldspar, biotite, tourmaline,

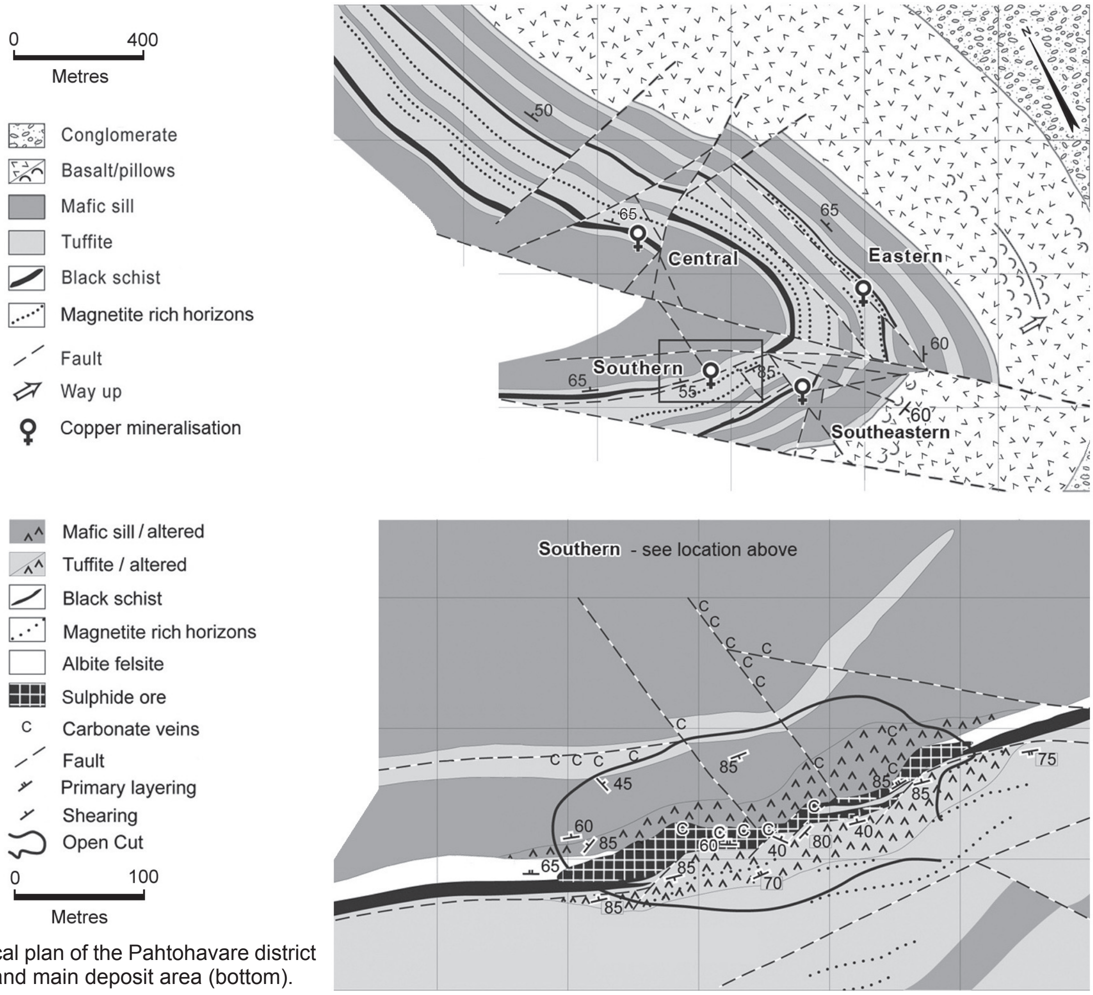


Figure 11: Geological plan of the Pahtohavare district in Sweden (top), and main deposit area (bottom).

sericite and carbonate) are partly related to the host rock character, with albite mainly developed in greenstone units and e.g. K feldspar and tourmaline in Svecofennian rocks. Chalcopyrite and pyrite¸ the latter occasionally with a high Co content, are the most common ore minerals. Pyrrhotite is less common and mainly occurs in greenstone-hosted deposits, and especially in those where graphite schist forms part of the host rock succession. Magnetite, hematite, bornite, chalcocite and molybdenite may be minor, or locally major, constituents of the Svecofennian deposits. There are a number of Svecofennian-hosted epigenetic occurrences in Sweden displaying a close genetic and/or spatial relation to orogenic, 1.9 to 1.8 Ga, felsic to intermediate intrusive rocks (Fig. 6). Magnetite is a common minor component in some of these occurrences. Some are even hosted by, or are situated adjacent to, major magnetite deposits and may be classified as typical IOCG mineralisation, while others have many features common to IOCG-style ores. In contrast, the greenstone-hosted deposits seem to have no connection with intrusions, and most exhibit a total destruction of iron oxides during mineralisation. A general feature observed in the Svecofennian-hosted epigenetic occurrences is a close spatial relationship with regional shear zones, with second- to fourth-order structures typically controlling ore localisation. In addition, structural and chemical traps may also be important, with redox reactions, involving an original high graphite or iron content in the host rocks, triggering sulphide precipitation. Many are gold-only occurrences, but almost as many contain significant copper in addition to gold, while in Sweden most occurrences are copper-dominated. Other elements that are significantly enriched in a few cases include Co, Fe, LREE, Ba, U and Mo. These elements are typically enriched in the gold-cobalt±copper occurrences, but very rarely in cases where gold is the sole major commodity.

Some of the low-grade, intermediate-tonnage, copper±molybdenum±gold occurrences, particularly within Svecofennian areas, have been described as porphyry-style deposits. Perhaps the most obvious example is the Vaikijaur copper-gold occurrence in a granitoid at the Archaean-Proterozoic boundary, 100 km south of Kiruna (Lundmark *et al.*, 2005b). Other occurrences have been attributed to alternate genetic models, with many having been linked to the IOCG family of deposits. These deposits vary in character from the large disseminated orebody at Aitik (Wanhainen *et al.*, 2005; Wanhainen and Martinsson, 2010, *this volume*) to small high-grade vein occurrences such as Lieteksavo. In Sweden, these are restricted to rocks of the Porphyrite and the Kiirunavaara Groups, and are generally within areas dominated by K feldspar alteration, with scapolite-biotite being more important outside of the main mineralised area. The paragenetic sequence of alteration, from oldest to youngest, in most cases is: scapolite + biotite → K feldspar → sericite → tourmaline. Pyrite occurs in a few, and hematite may be present as a minor component. The ore minerals occur disseminated, in quartz-tourmaline veins, and in veinlets and breccias. Ore minerals are mainly associated with the intermediate or late stages of alteration. Bornite and chalcocite are commonly paragenetically late in some of the occurrences (Bergman *et al.*, 2001; Martinsson, 2004), indicating a low sulphur content, and are related to tourmaline and zeolites. Stilbite and chabazite may occur as the latest phases in druses and veins together with calcite.

Occurrences with IOCG-style Characteristics in Sweden

Gruvberget: Both an apatite-iron and an epigenetic copper deposit occur at Gruvberget (Figs. 2 and 6). In Tables 1 and 2, these are marked as Gruvberget-Fe and Gruvberget-Cu, respectively. Both this locality, and Tjårrojåkka southwest of Kiruna, merit particular attention due to the intimate spatial relationship between iron and copper orebodies.

The apatite-iron mineralisation at Gruvberget-Fe is 1300 m long and up to 65 m thick, hosted by intensely scapolite- and K feldspar-altered intermediate to mafic volcanic rocks. Several northeast-trending meta-diabase dykes cut the ore and its wall rocks. The ore is mostly massive, consisting of magnetite in the north, and hematite in the central and southern parts of the deposit. Veins and schlieren of magnetite, hematite, apatite and amphibole form an extensive ore breccia in the footwall of the mid-sections of the deposit (Frietsch, 1966).

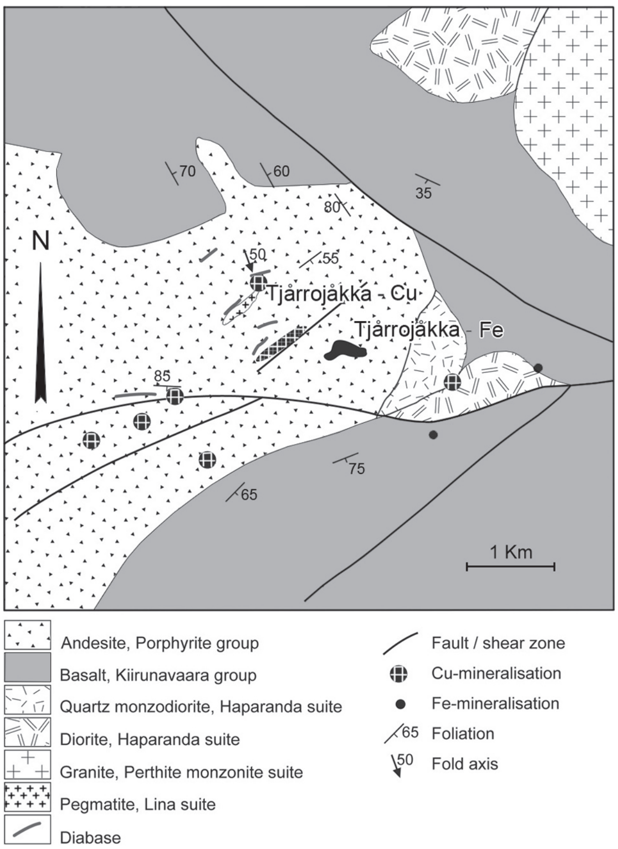
The Gruvberget-Cu deposit is the largest of the old copper mines in Norrbotten. Copper is the only metal reaching economic grades, while the gold content for example, is generally very low. Copper sulphides are scattered throughout the Gruvberget area, with zones of richer mineralisation mainly developed in the footwall to the iron ore. Chalcopyrite, and less abundant bornite, are the main ore minerals, occurring disseminated together with magnetite in altered rocks, or as rich ore shoots at the contact with the iron ore. Locally, there are also veins of quartz, minor K feldspar, amphibole, garnet, and small amounts of magnetite, chalcopyrite and bornite. Molybdenite is locally present in small amounts. Druses with epidote, magnetite, pyrite, copper-sulphides and desmine (stilbite) are common within the bornite-bearing sulphide occurrences. Intense K feldspar alteration is locally developed in association with the bornite mineralisation west of the iron ore, replacing the earlier scapolite. Several of the old workings are close to meta-diabases, and the copper mineralisation seems to be controlled by the same structures as the dykes. As the meta-diabase dykes cut the iron ore, this suggests that the copper occurrence represents a separate and later event, with the iron ore only acting as a chemical-structural trap (Lindskog, 2001).

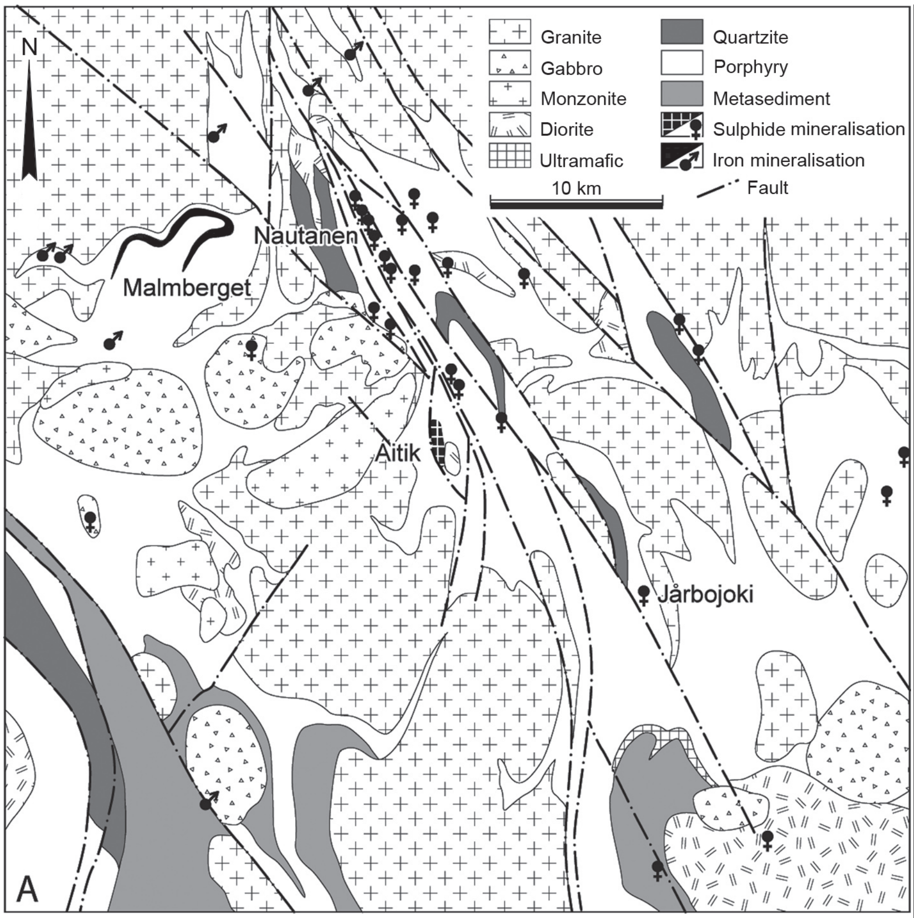
Tjårrojåkka: The Tjårrojåkka-Fe deposit (Figs. 2, 6 and 12) is a Kiruna-type magnetite-apatite ore known to persist to a depth of 450 m. Carbonate and apatite occur as disseminated minerals and veinlets in the massive ore, while actinolite is a minor disseminated component. Veins and breccia infill of magnetite partially invade the massive ore, forming an ore breccia. Disseminated chalcopyrite, with grades of up to 1% Cu, are found in the ore breccia and more rarely as veins in the massive ore. Alteration is extensively developed in the wall rocks and includes albite, scapolite and K feldspar.

A number of other copper occurrences are found in the vicinity, the largest of which, Tjårrojåkka-Cu, is 1 km WNW of the Tjårrojåkka-Fe deposit. The copper mineralisation and associated alteration appear to be younger, overprinting the iron mineralisation (Edfelt, 2007). Disseminated pyrite, chalcopyrite, bornite and accessory baryte, together with apatite-magnetite veins, form a 700 m long and up to 30 m wide ore zone hosted in a meta-andesite. The most widespread alteration mineral in areas adjacent to the copper mineralisation is potassic feldspar, while albitisation is mainly restricted to the apatite-magnetite veined footwall to the copper occurrence, and to the area surrounding Tjårrojåkka-Fe. Scapolite, commonly accompanied by biotite, is almost invariably developed as an alteration mineral in the local meta-diabase and forms an extensive alteration zone in the hanging wall to the copper mineralisation and in the ore zone (Martinsson, 1995; Edfelt, 2007).

Narken: The Narken iron oxide deposits are isolated occurrences, approximately 100 km southeast of Gällivare, in the eastern part of northern Sweden (Fig. 2; Frietsch, 1972). The known mineralisation is small in size and has the character of breccia bodies associated with extensive hydrothermal alteration of the metasedimentary wall rocks. The texture of the breccia infill is characteristic, with euhedral crystals of hematite altered magnetite, apatite and pyrite occurring as breccia infill, together with tabular hematite, epidote, chlorite and some quartz. Magnetite, apatite and pyrite seem to have formed early in the mineralisation process and were brought to their present position as crystals by a fluidised hydrothermal system. During their physical transport, the crystals have been partly abraded, fractured and broken, and form a major to minor part of the breccia infill. The accompanying breccia infill of flaky to tabular hematite, epidote, chlorite, quartz and chalcopyrite, were all subsequently formed *in situ* from the hydrothermal fluids. Magnetite has been largely or completely oxidised to hematite during this process. The iron oxide mineralisation is enriched in REE, and contains up to 0.5% Cu but is low in Au. The wall rocks and clasts of these rocks within the breccia bodies are strongly altered by silica, epidote and chlorite.

Figure 12: Geological map of the Tjårrojåkka copper and iron deposits, Sweden.





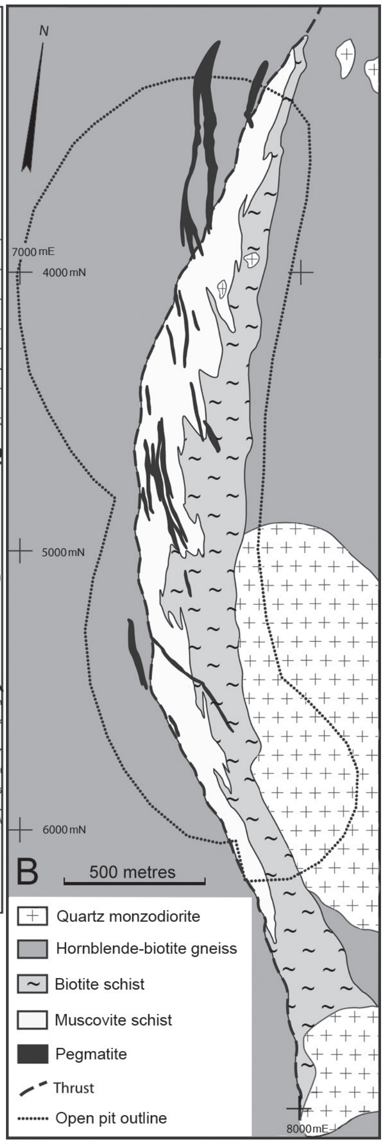


Figure 13: Geological setting of the Aitik deposit in southern Norrbotten, Sweden. A - Geology of the Gällivare region; B - Geological map of the Aitik deposit.

Rakkurijärvi: The Rakkurijärvi deposits are situated south of Kiruna in Sweden (Figs. 2 and 6), along the same ESE-trending structure that also controls the greenstone-hosted Pahtohavare copper-gold ore some 2 to 3 km further northwest. Two styles of mineralisation have been detected at Rakkurijärvi: (1) low grade copper-mineralisation hosted by porphyritic andesites of the Porphyrite Group, and (2) the recently discovered IOCG-style copper-gold deposit (Smith *et al.*, 2007; Smith *et al.*, 2010, *this volume*). In the former, ore minerals include pyrite, chalcopyrite and magnetite, which occur disseminated and in veinlets, together with carbonate or biotite in andesite and porphyry dykes. Restricted occurrences of coarse-grained dolomite veins, resembling those at Pahtohavare, may contain chalcopyrite and pyrite in significant amounts.

The IOCG deposit is located close to an ENE-trending shear zone and is hosted by brecciated metavolcanic rocks affected by early albitisation and silicification. Brecciation ranges from jigsaw-breccia found distal to the main mineralisation, to lithic-breccia closer to the ore zone. The ore zone is dominated by magnetite-breccia, the matrix of which shows a zonation from calcite, actinolite and chlorite adjacent to relatively unfractionated rocks, to albite, scapolite, actinolite and magnetite together with chalcopyrite, pyrite and accessory molybdenite in the main mineralised zone. The early albite alteration is overprinted by magnetite-actinolite, followed by K feldspar, scapolite and biotite, which partly develops into biotite-scapolite schist. These alteration assemblages and the mineralisation were related to highly saline fluids with stable isotopic compositions of oxygen and carbon, suggesting a strongly modified magmatic source (Smith *et al.*, 2007).

Kiskamavaara: The Kiskamavaara copper-cobalt-gold deposit (Figs. 2 and 6) is located, together with several other epigenetic sulphide occurrences,within the Karesuando-Arjeplog Deformation Zone (KADZ), a major NNE-trending deformation zone to the east of Kiruna. The host to the ore is a breccia of probable hydrothermal origin, with subrounded clasts of strongly K feldspar altered intermediate volcanic rocks, set in a matrix of fine-grained volcanic material with varying amounts of magnetite and hematite (Martinsson, 1995). Three lenses of richer sulphide occur within a ca. 900 x 15 to 40 m mineralised zone. The deposit consists of cobalt-bearing pyrite disseminated within the breccia infill, together with magnetite and some chalcopyrite. Carbonate, and locally quartz, are gangue minerals. The composition of the matrix changes from almost massive pyrite in the centre of the richer ore lenses, to disseminated magnetite-pyrite in the peripheries, and to hematite-magnetite outside the sulphide mineralisation. Higher contents of chalcopyrite are locally developed, while bornite and molybdenite are accessory ore minerals. Several types of alteration, including scapolite, K feldspar and sericite have affected the country rocks. Albite is locally developed on the eastern margin of the mineralised breccia, and scapolite occurs together with biotite in the surrounding volcanic rocks (Martinsson, 1995).

Nautanen: Section of the northwest-trending Nautanen Shear Zone, north of Aitik (Figs. 2 and 13a), represents a type area for shear-zone controlled deposits in the Kiruna region. The local ores, including the main Nautanen deposit, are typically rich in chalcopyrite with associated magnetite and some pyrite. Magnetite is commonly the main ore mineral, forming disseminated and massive to semi-massive veins, lenses and pods in association with garnet and amphibole-pyroxene-epidote skarn. Minor bornite and chalcocite occur in late quartz veins related to shearing and extensive tourmalinisation of the host rocks. Alteration is dominated by early scapolite, K feldspar, garnet and amphibole, and late sericite, epidote and tourmaline. The occurrence of rotated garnet porphyroblasts and boudinaged tourmaline veins indicate that at least part of the mineralisation and alteration is pre- to syn-peak deformation (Martinsson and Wanhainen, 2004).

Aitik: The huge Aitik copper-gold-silver (-molybdenum) mine is located 17 km east of Gällivare (Figs. 2 and 13a). The ore is mined from a 3 km long, 1 km wide and 420 m deep open pit. Characteristic features of two major mineralisation styles, porphyry copper and IOCG, have been identified within the deposit, thus suggesting the deposit represents a mixed ore system (Wanhainen, 2005). The hybrid character of the Aitik deposit is described and discussed in more detail in Wanhainen and Martinsson (2010, *this volume*).

The mine geology is divided into three main parts, the hangingwall, main ore zone and footwall complex (Fig. 13b). The hangingwall is basically a single unit of feldspar-biotite-amphibole gneiss, comprising a fine-grained (~0.2 mm) plagioclase, biotite, amphibole and quartz rock with abundant accessory magnetite and titanite. It appears to have been tectonically emplaced over the main ore zone. The fault defining the highly fractured contact, or border zone, between the hangingwall feldspar-biotite-amphibole gneiss and the main ore zone is a thrust, which has been intruded by several, up to 40 m wide, pegmatite dykes.

The main ore zone consists mainly of quartz-muscovite-sericite schist and biotite schist of volcaniclastic origin (Wanhainen and Martinsson, 2010, *this volume*), with the former schist constituting the upper part of the main ore zone. This schist is roughly 200 m thick, and consists of a strongly foliated mica-rich matrix with abundant quartz, K feldspar, and tourmaline. Pyrite is common. The biotite schist, which comprises the lower part of the main ore zone, is gradational with the overlying quartz-muscovite-sericite schist, and has an average thickness of 200 m. Sections close to the footwall contact commonly have a more gneissic, coarser-grained character and display zones of spessartine-almandine garnet. Thin veinlets of quartz, commonly deformed, occur in this unit along with undeformed veinlets with late zeolites and epidote. Lenses of micro-quartz monzodiorite can be distinguished within less foliated sections of the biotite schist.

The dominant footwall unit is quartz monzodiorite. It comprises both medium-grained equigranular, 2 to 5 mm (plagioclase, quartz, biotite and minor sericite), as well as strongly porphyritic (plagioclase) phases. Hornblende, quartz, tourmaline, gypsum, fluorite and zeolites occur as mm to cm wide veinlets throughout this unit. The quartz monzodiorite has a zircon U-Pb age of ca. 1.89 Ga (Wanhainen *et al.*, 2006), which fits well with reported ages for regionally occurring Haparanda suite granitoids (Bergman *et al.*, 2001). Pegmatite dykes and other intrusives, along with feldspar-biotite-amphibole gneiss are also found in the Aitik footwall. The feldspar-biotite-amphibole gneiss typically exhibits an anastomising network of 5 to 30 mm wide hornblende schlieren with albite rims. Sporadic scapolite is present as small grains and as zones of intense scapolitisation. Magnetite is a common accessory (1 to 3%), and occurs as small porphyroblasts and veinlets.

The main ore zone dips approximately 45° to the west. The mineralisation trends predominantly northeast and north-south, and plunges north to northwest. Chalcopyrite and pyrite are the main ore minerals, while magnetite, pyrrhotite, bornite, chalcocite, ilmenite, molybdenite, gold and silver are minor constituents. Ore minerals are disseminated, or occur in veinlets, patches and clots, and in several types of veins, together with varying amounts of other minerals such as quartz, biotite, amphibole, garnet, magnetite, tourmaline, barite, zeolites and thaumasite, and in pegmatite dykes (Wanhainen and Martinsson, 2003). Disseminated sulphides are quantitatively the most important style of mineralisation. The lower ore contact approximately corresponds to the gradation from biotite schist into the underlying regional feldspar-biotite-amphibole gneiss, although sporadic copper mineralisation of no economic interest persists into the footwall gneiss. The quartz monzodiorite in the southern part of the footwall is currently mined, with mineralisation being dominated by fracture-controlled pyrite-chalcopyrite (-molybdenite), although finely disseminated sulphides are also present (Wanhainen *et al.*, 2006). Mineralisation is absent in the hangingwall, except for minor sulphides occurring in younger veins.

Extensive alteration within the ore zone has largely obscured the primary character of the rocks. Biotite alteration, commonly accompanied by garnet porphyroblasts, and a sericite-pyrite overprint, dominate. Potassic feldspar-epidote alteration is most extensive along the footwall and hangingwall contacts, but also occurs locally within and outside of the main ore zone. Alteration minerals such as tourmaline, actinolite, scapolite, chlorite and sericite, are similarly present in the ore zone as well as in the footwall and hangingwall rocks. The quartz monzodiorite is commonly weakly silicified and affected by pinkish potassic alteration. Further details on the Aitik deposit are given by Wanhainen and Martinsson (2010, *this volume*).

Discussion

To this point, we have concentrated on the diversity of IOCG-style and related ore types, and the associated difficulties in classifying the ore deposits of the northern Fennoscandian shield. A factor contributing to these complexities may be the lack of a strict, generally accepted, definition of IOCG- style deposits. However, in our model below, we stress that a long and complex geological evolution between ca. 2.2 and 1.8 Ga has given rise to multiple pulses of fluid activity, where later stage effects have locally overprinted earlier mineral assemblages, such that occasionally, several styles of mineralisation may be present. The discussion below is structured to initially provide a summary of the regional geological evolution, followed by the overall characteristics of ore deposits and mineralising fluids, and a final model which integrates available observations and analytical data.

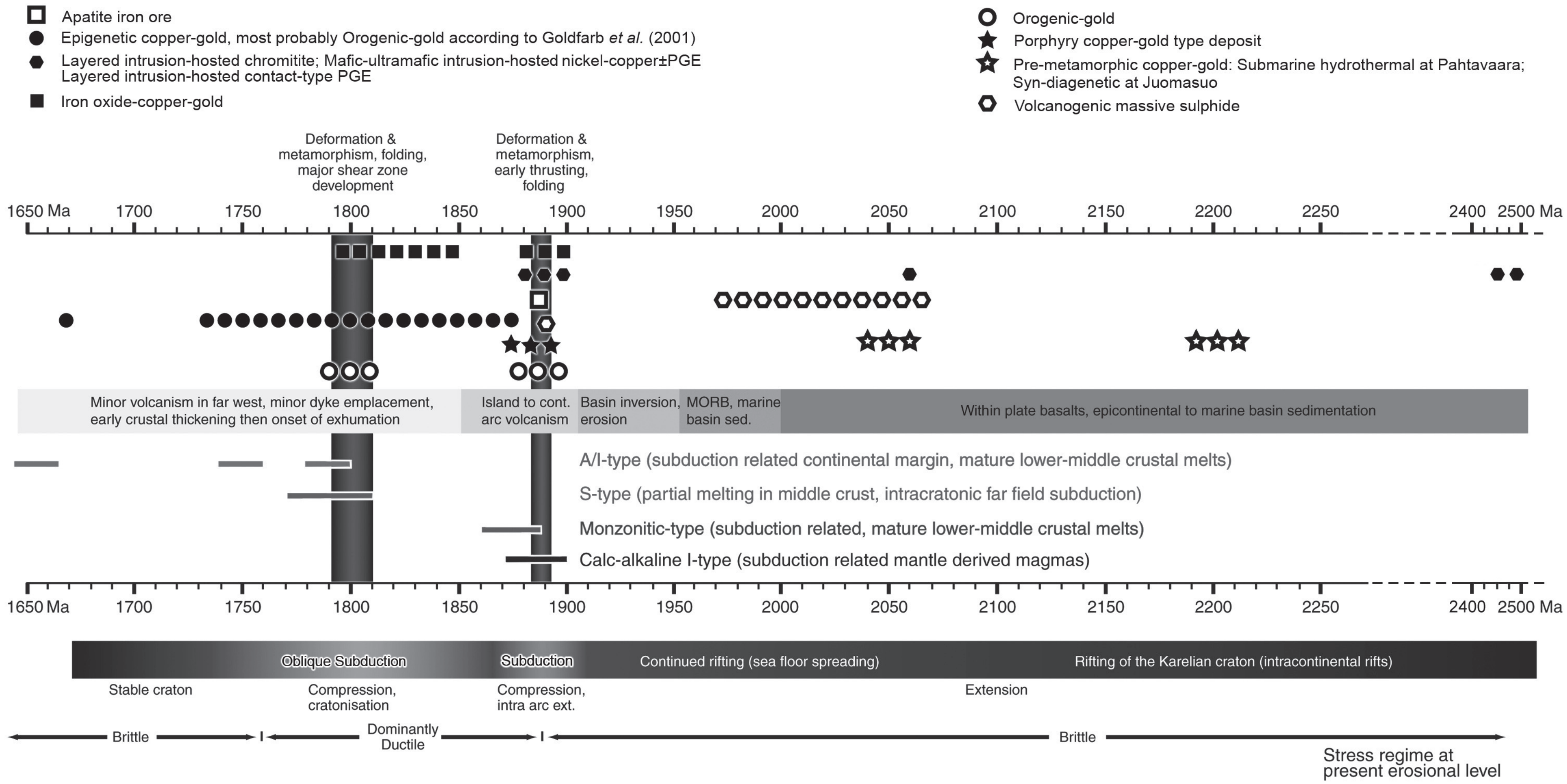


Figure 14: Diagrammatic representation of the temporal, tectonic and geologic distribution of mineralisation and ore types in the northern Fennoscandian shield, placing ore-forming processes into a crustal context.

Geological Evolution – Regional Timing of Events

IOCG-style deposits and related mineralisation in northern Fennoscandia are found both in Greenstone and in Svecofennian terrains, and their presence is likely due to crustal processes operating during the evolution of the Fennoscandian shield. Fig. 14 summarises the major Palaeo- to Meso-Proterozoic events affecting the crust in the northern Fennoscandian shield, and attempts to place the different mineralisation types into a crustal evolutionary context. Generally speaking, available radiometric evidence suggests that the chronological evolution of the northern parts of Finland and Sweden is very similar. For instance, supracrustal host rock successions in Finland of both Greenstone and Svecofennian origin have counterparts of comparable age in Sweden. In an analogous way, different granitoid suites, being defined by their similar chemical characteristics, are found on both sides of the Swedish-Finnish border. Thus, the timing of potentially syngenetic deposits in this part of the shield may show a dual pattern with peaks close to either 2.1 Ga (average age for several Greenstone host rock successions) or in the 1.9 to 1.8 Ga range (maximum-minimum rock crystallisation ages during the Svecofennian), while epigenetic deposits hypothetically also may have intermediate ages, although the synorogenic, 1.92 to 1.77 Ga, timing is most probable for the latter. There are some apparent differences between the two countries when the abundance of different rocks is considered. Thus, in accordance with a general westward younging of rock ages in the northern Fennoscandian shield, e.g., older (1.9 Ga) Svecofennian rocks become less abundant to the west in northwestern Sweden. Another difference between the countries is that granitoids of the Perthite-Monzonite Suite and lithologies of the Kiirunavaara Group, found in the northwestern parts of Norrbotten in Sweden, are not encountered in Finland.

The obvious similarities in age and rock sequences observed between Sweden and Finland are also evident when discussing the timing of metamorphism and deformation. Based on both field and radiometric evidence, it is apparent that significant ductile to ductile-brittle deformation is more or less contemporaneous with metamorphic peaks, whereas local brittle, late-stage deformation may occur with no obvious simultaneous metamorphic activity in the same area. Probably, up to five metamorphic-deformational episodes may be distinguished, although the influence of all individual events is never to be found within any particular limited area. The earliest foliation (S_1), as observed in Greenstone-related rocks, probably developed immediately before the onset of the Svecofennian stage at ca. 1.93 to 1.92 Ga (Skiöld, 1986). This was followed by three significant stages at ca. 1.88 Ga (dominant event in Finland?), at 1.86 to 1.85 Ga (event affecting the Pajala-Kolari region), and at 1.8 Ga (dominant event in Sweden?). The final stage comprising ca. 1.75 Ga brittle deformation is apparent from dating both in Finland and Sweden (see e.g., Bergman *et al.*, 2006).

Ore Deposit Types - Their Nature, Distribution and Ages

A provisional four-fold division of ore types has been suggested above, including (1) stratiform-stratabound sulphide; (2) apatite-iron; (3) skarn-related iron; and (4) epigenetic gold, copper-gold and iron-copper-gold deposits. We will continue to use this division and recall a few common features along with brief discussions on earlier published genetic models. In addition, certain transitional ore types will be covered.

Stratiform-stratabound Sulphide Deposits: This style of mineralisation, which is known to contain base metals (copper, zinc±lead), occurs in both Finland and Sweden. Although their origin may be disputed, the occurrences mentioned herein have all been considered to be syngenetic (Inkinen, 1979; Martinsson *et al.*, 1997). In the case of e.g., Viscaria, a syngenetic origin is supported by the blanket-shaped, and partly laminated, style of mineralisation, the pronounced zonation defined by copper and zinc, and the extensive footwall alteration. It is suggested these characteristics reflect deposition in a brine pool at the sea floor, in a setting similar to the Atlantis II Deep in the Red Sea (Martinsson *et al.*, 1997). In contrast to most of the epigenetic copper deposits in the region, gold is virtually absent and zinc is significantly enriched at Viscaria, whereas zinc±lead become major components at, e.g., Huornaisenvuoma and Pahtavuoma. At Pahtavuoma, mineralisation has been interpreted to be a product of submarine tholeiitic volcanism and a related hydrothermal system in a sediment-dominated rift basin, with syngenetic mineralisation formed by precipitation of ore metals on the sea floor (Inkinen, 1979).

Apatite-iron Ores (AIO): *Hitzman et al.* (1992) suggested AIO deposits represent an iron-dominated, sulphide-poor end member of the IOCG class of ore deposits. As such, their occurrence is of significance both to the global IOCG concept, and to the understanding of the metallogeny of the northern Fennoscandian shield. AIO deposits exhibit a considerable variation in host rock composition, stratigraphic position, alteration style, phosphorous content and associated minor components. To illustrate this, the features of two rather distinct groups of AIO deposits; breccia and stratiform-stratabound types are outlined above. What deserves additional attention, is that despite their diversity, the AIO ores are almost totally restricted to the Kiruna-Gällivare area. Also of note, is the spatial relationship between AIO and copper mineralisation at Tjårrojåkka, Narken and Gruvberget, which is further discussed below.

The genesis of the apatite-iron ores has been discussed for more than 100 years and is still controversial. Published models include sedimentary (Parák, 1975), hydrothermal (cf. Hitzman *et al.*, 1992) and magmatic origins (e.g., Nyström and Henriques, 1984). Most features of the ores are compatible with both a magmatic intrusive origin and a hydrothermal origin. Both magmatic and over-printing hydrothermal processes have probably been active, explaining the large variation in mineralisation style recognised within and between individual deposits (Martinsson, 2004). Radiometric evidence published from the Kiirunavaara area suggests that the Kiruna-type magnetite-apatite ores were formed between 1.89 and 1.88 Ga (Cliff *et al.*, 1990; Romer *et al.*, 1994) which is consistent with a synorogenic magmatic-hydrothermal origin (Nyström *et al.*, 2008).

At Narken, magnetite and apatite in the breccia infill have a character similar to that of xenocrysts in magmatic rocks, and may initially have formed as part of an apatite iron ore system that has developed into an explosive hydrothermal phase, bringing these crystals higher up in the crust and forming breccia bodies, cemented by hematite and epidote, with local enrichment of Cu. Thus, the Narken iron oxide occurrences may be transitional between apatite iron ores and IOCG-type deposits (Martinsson, 2009).

Skarn-related Iron Deposits: These lens-shaped iron occurrences, which are hosted by greenstones, consist of magnetite, and Mg and Ca-Mg skarn silicates. They occur over large areas, with important mineralisation close to Pajala in Sweden and in the Kolari region of Finland. It is noteable that magnetite systems in Pajala are poor in gold and copper, whereas significant amounts of copper and gold have been recovered from the magnetite rocks of the Laurinoja orebody in the Hannukainen mine at Kolari (Hiltunen, 1982). Ore-grade gold and copper are also reported from the magnetite-rock hosted Rautuvaara and Kuervitikko deposits at Kolari (Niiranen *et al.*, 2007). A contributing explanation for these deviations in metal content may be related to lithological differences. The Kolari ores occur in a major shear zone at the contact between synorogenic diorite and monzonite intrusions, and mafic volcanic and sedimentary rocks, while intrusive rocks are lacking in the Pajala area. Possibly, the lack of competent rocks at Pajala meant that potential metal-bearing fluids, whose circulation was driven by Svecofennian deformation and metamorphism, were not channelled into suitable structures.

Previously, it has been suggested that ores of this type are the metamorphic expression of original syngenetic exhalative accumulations (Grip and Frietsch, 1973; Bergman *et al.*, 2001), or that they are intrusion-related skarn deposits (Hiltunen, 1982). Recent investigations of the Kolari deposits suggest them to be epigenetic, and best fitting into the IOCG category (Niiranen *et al.*, 2007). This new genetic model is partly based on recent radiometric data from the Hannukainen deposit that constrained a skarn-forming event, coeval with mineralisation, to ca. 1.80 Ga (Hiltunen, 1982; Niiranen, 2005; Niiranen *et al.*, 2007). These age constraints and the fact that only the D_4 brittle deformation has significantly affected the ore, indicate that the mineralisation is a late- to post-D_3 event within the Pajala-Kolari Shear Zone.

Alternatively, the gold-copper enriched magnetite bodies at Kolari may have developed in two stages. First, as stratiform, magnetite-rich horizons deposited as part of the 2.1 Ga supracrustal sequences, with subsequent iron, together with copper and gold, being introduced into structurally favourable sites in connection with the 1.8 Ga deformation. However, no syngenetic iron formations are

Table 3: Fluid inclusion data from Cu-Au deposits in the northern Fennoscandian Shield.

Deposit	Aqueous fluid inclusions: Types	Temperature (°C)	Salinity wt.% $NaCl_{eq}$.	CO_2 inclusions Composition	Reference
Kittilä area, Finland					
Hirvilavanmaa Gold only	L+V+halite L+V±CO_2	153 to 248 160 to 369	30 to 34 5 to 20	CO_2 + <15 mole % CH_4 or N_2	Hulkki and Keinänen (2007)
Kolari area, Finland					
Kuervitikko Skarn-related Fe-Cu-Au	Multisolid L+V+halite L+V	386 to 463 299 to 447 155 to 174	>45 32 to 56 8 to 11	CO_2 + <20 mole % CH_4 or N_2	Niiranen *et al.* (2007)
Laurinoja Skarn-hosted Fe oxide-Cu-Au	L+V+halite L+V	209 to 251 126 to 315	32 to 35 9 to 22	CO_2	Niiranen *et al.* (2007)
Norrbotten area, Sweden					
Pahtohavare Cu-Au ± Co, U	Multisolid L+V+halite L+V	221 to >500 125 to 170 80 to 340	33 to >60 29 to 30 0.5 to 25	CO_2 + <5 mole % CH_4 or N_2	Lindblom *et al.* (1996)
Aitik Intrusion related Cu-Au-Ag deposit	L+V+halite L+V	140 to 373 100 to 222	30 to 44 18 to 27	CO_2 + <1 mole % CH_4	Wanhainen *et al.* (2003)
Pikkujärvi Intrusion related Cu	Multisolid	312 to 450	36 to 51	------	Unpublished results
Tjårrojåkka-Fe Apatite iron ore with Cu in veins	Multisolid L+V+halite L+V	~300 to >500 193 to 282 113 to 270	40 to >60 32 to 37 18 to 28	------	Edfelt (2007)
Tjårrojåkka-Cu Fe-oxide Cu-Au	L+V+halite L+V	196 to 292 111 to 191	31 to 37 23 to 27	------	Edfelt (2007)
Gruvberget-Cu Fe-oxide Cu-Au	L+V+halite L+V	224 to 415 109 to 215	33 to 47 20 to 22	CO_2 + 3 mole % CH_4	Unpublished results
Lieteksavo Vein-style Cu-Au-(Mo-W)	L+V+halite L+V	210 to ~500 139 to 226	32 to 55 21 to 23	CO_2 + <10 mole % CH_4	Unpublished results
Viscaria Stratiform-stratabound Cu±Zn±Pb±Fe-oxide	L+V+halite	112 to 214	28 to 33	------	Martinsson *et al.* (1997a)
Kautokeino, Finnmark, Norway					
Bidjovagge Cu-Au ± Co, U	Multisolid L+V	130 to 380 100 to 200	29-42 ~25	CO_2 + <20 mole % CH_4	Ettner *et al.* (1993)

L = liquid; V = vapour; Multisolid = solid phases (including halite) + L + V; Temperature = homogenization temperature.

known in Savukoski Group rocks on the Finnish side of the border, although such ironstones do exist in Karelian greenstone successions west of Pajala. Also, it is possible that the skarn and magnetite rocks are skarns *sensu stricto*, formed immediately after the intrusion of 1.86 Ga granitoids, and that these magnetite rocks formed structural and chemical traps for 1.80 Ga Au-Cu-S fluids. Thus, the genesis of these orebodies remains an open question.

Epigenetic Au and Cu-Au Deposits: Both greenstone- and Svecofennian-hosted epigenetic-gold and copper±gold deposits occur and are wide-spread in the study region, following the main shear zones. These occurrences share many features with both IOCG and orogenic gold styles of mineralisation. Features in many deposits similar to IOCG (as defined by Hitzman, 2000), but opposed to typical orogenic gold deposits, include the influence of saline fluids (cf fluid inclusion data, Table 3), and the presence of copper sulphides and multi-stage alteration. Notably, deposits at, e.g., Nautanen (Fig. 13a), Rakkurijärvi and Kiskamavaara (Fig. 6) in Sweden, are among the best examples of IOCG occurrences in the northern Fennoscandian shield, given their style of alteration, structural control, the presence of iron oxides, copper and gold, and saline fluid inclusions. On the other hand, most of the deposits elsewhere, e.g., in Finland, share numerous features with the orogenic gold deposits (*sensu* Groves *et al.*, 1998), and many occurrences, including the largest by far (Suurikuusikko; Fig. 4), are gold-only deposits (Ettner *et al.*, 1993, 1994; Lindblom et al., 1996; Eilu *et al.*, 2003; Weihed and Eilu, 2005; Eilu *et al.*, 2007; Patison *et al.*, 2007).

Geochronological and structural evidence indicate late- to post-peak metamorphic conditions during the formation of many of the epigenetic copper-gold occurrences in Sweden, defining two major events at ca. 1.87 and 1.77 Ga, respectively (Martinsson *et al.*, 2010b). This is confirmed by Re-Os molybdenite (intergrown with magnetite) ages between 1.86 and 1.85 Ga obtained at Rakkurijärvi (Smith *et al.*, 2007). There are also indications of a third possible stage of mineralisation at ca. 1.84 to 1.80 Ga for deposits in the northern parts of Norway and Finland (Bjørlykke *et al.*, 1990; Mänttäri, 1995; Patison, 2007). Moreover, several occurrences in Sweden display an age pattern involving a set of mineralising events, clearly illustrated by published Re-Os ages of molybdenite (Lundmark *et al.*, 2005b; Wanhainen *et al.*, 2005). Most of the occurrences in Finland provide evidence for a syn-peak metamorphic timing (Mänttäri, 1995; Eilu *et al.*, 2003), although relatively few radiometric age data exist. Hence, we do not know whether some or all epigenetic mineralisation in the Central Lapland greenstone belt (CLGB) took place at ca. 1.88 or at 1.84 to 1.80 Ga.

The Pahtavaara gold deposit in the CLGB in Finland (Figs. 2 and 4), although its alteration characteristics and structural control suggest an amphibolite-facies orogenic gold deposits, is probably best interpreted as a metamorphosed seafloor alteration system with ore lenses that were primarily deposited as either gold-rich carbonate- and barite-bearing cherts or quartz-carbonate-barite veins. Hypothetically, the gold may have been introduced later, but its grain size, textural position (nearly all gold is free, native, and occurs with silicates; not associated with sulphides) and high fineness point to a pre-peak metamorphic timing.

The genesis of the Au-Co-Cu±U mineralisation in the Kuusamo schist belt remains controversial (Pankka and Vanhanen, 1992; Vanhanen, 2001; D.I. Groves, pers. comm., 2006). The timing of mineralisation is only based on structural investigations and Pb model ages of sulphides (Mänttäri, 1995; Vanhanen, 2001), suggesting a 1.9 Ga event that seems to fit with both orogenic gold and IOCG-styles of mineralisation. The alteration, metal association, indications of evaporites and the mineralising fluids all fit the IOCG concept. The mineralising fluids, relict evaporite textures, indications of pre-metamorphic albitisation, the metal association and the rift-shelf host rock sequence are consistent with a syngenetic (pre-metamorphic) concept. The structural control and gold fineness fit with all of the genetic styles proposed. If the Kuusamo occurrences are syngenetic (diagenetic?), they were formed after 2350 Ma, when deposition of the host sedimentary sequence commenced. Alternatively, the mineralisation may have taken place at ca. 2210 Ma, when extensive intrusion and extrusion of tholeiitic sills and lavas took place within the sedimentary pile, providing a local heat source for a mineralising system (Laajoki, 2005). In either case, 2210 Ma would be the lower age limit for syngenetic mineralisation, as no mineralisation has been detected in younger rocks (Vanhanen, 2001). However, if the mineralising process was of IOCG- or orogenic gold-style, the occurrences were formed between 1.91 and 1.80 Ga. In this case, the mineralising fluid would have been similar to that producing the gold-copper occurrences in the CLGB, or the IOCG deposits in northern Sweden, except that it contained more cobalt, with the regional tectonic setting being either compressive to transpressive (orogenic gold) or extensional (IOCG).

Transitional Ore Types: From earlier descriptions, it was made clear that e.g., BIF and skarn iron ores, may show gradual transitions from one to the other. It has also been demonstrated that e.g., epigenetic copper-gold occurrences may display features intermediate between IOCG- and orogenic gold-styles of ore. Moreover, it is often possible to arrange occurrences of a single ore type into sub-groups; e.g., apatite iron ores can be referred to as being of breccia-type or stratabound-stratiform type. In our model, developed further below, these observations are regarded as being due to complex and variable mechanisms of mineralisation that commonly overprint earlier features. It is also understood that the concept of transitional ores implies that there are 'end-member' ore types. For instance, (greenstone-hosted) orogenic gold-only deposits, and (Svecofennian) apatite iron ores may be examples of such end-members.

Ore Fluid(s) Characteristics

The importance of saline hydrothermal fluids to explain the origin of regional albite-scapolite alteration has been emphasised by Frietsch *et al.*, (1997), and fluid inclusion data from Swedish, Norwegian and Finnish ore deposits reveal the involvement of high-salinity aqueous fluids during mineralisation (Table 3). For instance, at the stratabound copper±zinc deposit at Viscaria, fluid inclusions indicate mineralisation from a Ca-Na-Cl-rich brine with a salinity of around 30 wt.% $NaCl_{eq.}$ at a temperature slightly above 200°C (Martinsson *et al.*, 1997a). High-salinity (32 to 41 wt.% $NaCl_{eq.}$) fluid inclusions are also present in late sulphide- and hematite-bearing quartz veins from magnetite-apatite deposits in the Kiruna area (Harlov *et al.*, 2002). Aqueous Ca-Na-Cl dominated fluid inclusions with a salinity of >30 wt.% $NaCl_{eq.}$ and depositional temperatures of 300 to 500°C are recorded for the copper-gold deposits in this region (Ettner *et al.*, 1993, 1994; Lindblom *et al.*, 1996; Broman and Martinsson, 2000; Wanhainen *et al.*, 2003; Edfelt, 2007; Niiranen *et al.*, 2007). Thus, fluid inclusion evidence indicates that saline Ca-Na-Cl fluids had an important role irrespective of the ore type studied in the region. Little data exist for gold deposits in Finland (see data for Hirvilavanmaa; Table 3), but apparently there are no large differences when, for instance, compared with the Pahtohavare, Bidjovagge (Table 3) and Saatopora (H. Hulkki, pers. comm., 2009) Cu-Au±Co, U deposits. However, note that no fluid inclusion data are available from such significant gold-only deposits as Suurikuusikko and Pahtavaara.

Furthermore, CO_2-rich fluid inclusions and aqueous inclusions with variable salinities, and typically more complex compositions representing different early- or late-ore stages, are commonly reported from all deposits. Speculatively, the source of the high salinity fluids may have initially been magmatic, but the variable salinities and compositions during subsequent stages of ore formation imply that mixing and additional contributions of fluid components from other sources are likely, as discussed below. Mixing is also suggested by PIXE (proton induced X-ray emission) studies of high salinity aqueous inclusions from Norrbotten which reveal a range of Br/Cl ratios from typical magmatic to ratios consistent with bittern brines and evaporitic halite (Williams *et al.*, 2005).

The oxidation state of ore-forming fluids is another obvious parameter to take into account, and is important in controlling the proportion of iron sulphides versus iron oxides. This may be exemplified by the Suurikuusikko deposit where the abundance of 'graphitic' carbon correlates with the intense shearing that controls most mineralised zones. The presence of such carbon suggests extremely reducing fluid conditions and iron occurs as sulphides in the mineralisation, and rarely as oxides. The sulphur isotope data, although relatively few, are also of significance in this context. Negative sulphur isotope compositions of sulphides are typical of stratiform-stratabound ore deposits in Sweden (Martinsson *et al.*, 1997a), and at Saattopora (Eilu and Pankka, 2009) and Pahtavuoma (Mäkelä, 1977; Inkinen, 1979). Also, negative $\delta^{34}S$ values in sulphides were obtained from the copper-ore at Hannukainen in the Kolari region, although isotope data from the nearby Rautuvaara deposit are positive (Hiltunen, 1982). The negative sulphur isotope composition of sulphides, consistent with the presence of isotopically light reduced sulphur during the ore-forming process, could be due to either reduction of sulphate sulphur or enhanced oxidation fugacities during sulphide precipitation (Mäkelä, 1977, Inkinen, 1979, Martinsson *et al.*, 1997a).

The Northern Fennoscandia IOCG Concept

I: Karelian Sowing and Svecofennian Growing

The fundamentals of this conceptual model are that the long and complex geological evolution paved the way for the deposition of a diverse range of ore deposits. Basically, three stages of metal mobilisation can be distinguished. Iron, and to some extent copper and gold, were concentrated during an initial Karelian (sowing) stage at, perhaps, 2.3 to 2.1 Ga, which was followed by two Svecofennian (growing) stages of element mobilisation (involving iron, copper and gold) at 1.92 to 1.87 and 1.85 to 1.79 Ga, respectively. The latter were triggered by metamorphic and magmatic episodes, and brines liberated during these stages precipitated IOCG and related deposits when fluids encountered structural and chemical traps in suitable host rocks. Important components of an early sowing stage include the presence of evaporites (a source for salt in fluids) and mafic volcanic rocks (the principal source of copper and a contributing source for gold?).

Stratiform-syngenetic Processes Generating Cu-Zn+BIF+Skarn-related Iron Ores at 2.1 Ga: Synvolcanic hydrothermal systems were active during the early (Karelian) event and produced two types of mineralisation hosted by greenstone formations, namely: stratiform-stratabound copper-zinc±lead and banded iron formations (BIF). Only limited radiometric evidence exists to constrain these events, although their syngenetic style would imply that the period of rock formation at ca. 2.1 Ga also corresponded to the development of a range of mineralisation types. Notably, gold is only a very minor component is these settings. The genesis of skarn-related iron ores is still not resolved, and may very well involve different modes of formation. Firstly, it needs to be clarified whether the formation of the actual skarn assemblages is, as seems most likely, related to a Svecofennian stage of metamorphism and deformation, or to an earlier event. In addition, it is highly plausible that the copper and gold (and possibly also iron) in base metal-enriched skarn-related ores, such as those at Kolari (Fig. 8), are due to Svecofennian epigenetic processes. However, skarn-hosted ores e.g., at Sahavaara in Sweden (Fig. 8), may be syngenetic in origin, and the gradation from fully syngenetic BIF to skarn-hosted ore e.g., at Käymäjärvi (Fig. 2), would be consistent with syngenetic iron ores having formed at c. 2.1 Ga, and parts of those ores with a suitable primary chemistry, being subsequently transformed by later Svecofennian processes into a skarn-banded ore. Syngenetic and pre-Svecofennian processes may also have led to the development of the Au-Co-Cu±U mineralisation at Kuusamo, although no conclusive evidence to disregard a Svecofennian (IOCG or 'atypical' orogenic gold) origin can be presented.

Apatite-iron-ore Formation at ca. 1.9 Ga and 1.8 Ga: AIO-type mineralisation is restricted to areas in the Kiruna-Gällivare region (Fig. 6), and is hosted by rocks of the Kiirunavaara and Porphyrite groups. The explanation for this spatial restriction may involve the fortuitous geological coincidence of suitable rocks and structures. The rocks may have inherited their enhanced iron contents when magma-generating processes interacted with iron-rich Karelian basement rocks, e.g., those known to contain BIF at several places in Norrbotten (Martinsson *et al.*, 2010a). During ongoing magmatism, and closely related deformation and metamorphism, deep crustal structures would have been re-activated. The inferred failed Karelian rift arm, with a triple point south of Kiruna, was possibly part of this sequence of events and may have guided fluid flow. Another contributing factor in the development of the Kiirunavaara deposits may have been the involvement of concealed evaporites that are likely to have formed within the greenstone successions, and their enhanced effect on the salinity of ore fluids. The large AIO accumulations most likely formed in the 1.88 to 1.86 Ga interval, involving both an initial magmatic stage (introducing the iron component) and subsequent hydrothermal processes, which over-printed and modified the ore zones, and added copper in some localities (Narken, Fig. 2; and Tjårrojåkka, Fig. 6).

Importantly, the age and field evidence available for the AIO mineralisation at Tjårrojåkka, hosted by 1.89 Ga rocks of the Porphyrite group, suggest two things: (1) the copper- and iron-orebodies at Tjårrojåkka are genetically related and (2) there was a second (minor?) stage of AIO formation at ca. 1.78 Ga (Edfelt, 2007).

Epigenetic Gold (IOCG and Orogenic Gold) Processes at 1.92-1.87 and 1.85-1.79 Ga*:* Epigenetic gold and gold-copper occurrences are structurally controlled and located along major shear zones in Finland and Sweden, in both the Greenstone and Svecofennian supracrustal successions. As noted above, there are obvious problems in fitting the Fennoscandian gold-base metal occurrences into a straightforward metallogenetic classification, keeping in mind the observations of multi-stage alteration and presence of saline fluids. Multi-stage alteration implies multiple hydrothermal events and this is well illustrated by the features of the Aitik deposit. At Aitik, it is suggested that the mineralised 1.9 Ga quartz monzodiorite in the footwall represents an apophyse from a larger intrusion at depth, consistent with the general porphyry copper model presented by Lowell and Guilbert (1970). Furthermore, zonation and alteration patterns, although disturbed, fit quite well with this model (Yngström *et al.*, 1986; Monro, 1988; Wanhainen, 2005). However, not all features of the main ore zone are typical of a porphyry system. Based on the highly saline character of the ore fluids, and the alteration and mineralisation styles, the 160 Ma evolution of the deposit also included a regional IOCG-type mineralising event at ca. 1.8 Ga (Wanhainen *et al.*, 2003; Wanhainen *et al.*, 2005; Wanhainen *et al.*, 2006; Wanhainen and Martinsson, 2010, *this volume*). Therefore, it is suggested that Aitik is hybrid in character, with an affinity to both porphyry-copper-gold and IOCG-style mineralisation.

In the context of explaining possible mechanisms involved in producing variable ore types in the northern Fennoscandian shield, we propose these variations are not random, and that a general east-west zonation in ore types may exist, expressed as iron-copper- and gold-rich mineralisation in the western and eastern parts of the shield, respectively. To further develop this concept, we will first investigate the genesis of selected ore occurrences by discussing them in terms of (1) IOCG style, and (2) the orogenic gold with 'atypical metal association' origins.

Copper±gold occurrences containing significant amounts of iron oxides are mostly found in Svecofennian volcanic and sedimentary rocks in Sweden, and in Karelian greenstones in the Pajala-Kolari region. Most have features that correspond to those of typical IOCG-style deposits as defined by Hitzman (2000), including a temporal association with magmatic events, the presence of evaporites and structural control, as well as a characteristic morphology, mineralogy and metal association, regional and ore related alteration, and ore fluid composition. Good examples are Tjårrojåkka-Cu, Kiiskamavaara, Rakkurijärvi, Nautanen and Hannukainen. In addition, numerous other copper±gold deposits lacking significant iron oxides in the Swedish part of the shield share most of these features, including the ore fluid character. This suggests a common ore fluid, which in turn implies a probable genetic connection. The origin of the ore fluids responsible for IOCG-style mineralisation is debated and might be of magmatic origin (Pollard, 2000), non-magmatic brines related to evaporites (Barton and Johnson, 1996, 2000; Yardley *et al.*, 2000) or a mixture of these sources (Williams *et al.*, 2005; Chiaradia *et al.*, 2006). The metals within the deposits originated either by leaching of the regionally sodic-calcic altered host rock pile (Barton and Johnson, 2000), or are of magmatic origin (Pollard, 2000). Fluid inclusion data from epigenetic copper±gold deposits in Sweden indicate major contributions from non-magmatic sources (Martinsson *et al.*, 2004), while the importance of evaporite derived brines was stressed by Wanhainen *et al.*, (2003).

The 'atypical metal association' concept for orogenic gold mineralisation has been defined by Goldfarb *et al.*, (2001) as follows. Metamorphic fluids derived from tectonised basinal sediment piles are typically saline, because salt-rich connate waters survive into the metamorphic environment (Yardley, 1988). Consequently, these fluids have the ability to carry high contents of base metal. Goldfarb *et al.*, (2001) developed this concept to explain the formation of base metal-enriched gold deposits at Sabie-Pilgrim's Rest in South Africa, and at Tennant Creek, Pine Creek and Telfer in Australia. Similar conditions may have produced, e.g., many of the gold-copper deposits in the Tapajos-Parima orogenic belt of the Amazon Craton in Brazil (Santos *et al.*, 2001), and gold-copper occurrences at Cagurue, Mozambique (Bjerkgard *et al.*, 2009). The northern part of the Fennoscandian shield is also characterised by Palaeoproterozoic intracratonic rift basins, extensive supracrustal sequences and probable evaporites (Martinsson, 1997; Vanhanen, 2001; Hanski and Huhma, 2005; Kyläkoski, 2009). With time, these sequences accumulated, compacted, were intruded by magmas and underwent several major stages of alteration predating gold mineralisation. Thus, when an orogenic fluid interacted with any evaporites and with connate brines between 1.92 and 1.87 and/or 1.85 and 1.79 Ga (Lahtinen *et al.*, 2005), it became more saline and capable of leaching and transporting both gold and base metals. No active input was required from the local intrusions, nor was any local pre-orogenic enrichment of the base metals necessary, as the brines would have been able to leach metals from extensive volumes of the crust. However, in the absence of evidence to the contrary, the possibility that some of the base metals were derived from local syngenetic occurrences cannot be rejected. Given this background, e.g., the copper-gold mineralisation at Saattopora and other localities in the CLGB (Finland) can be classified into the ´atypical metal association´ subtype of orogenic gold mineralisation.

Although the geological similarities between different segments of the northern Fennoscandian shield are striking, and mineralisation often shows obvious similarities locally, the characteristics of ore deposits that are geographically separated are not homogeneous. On this basis, the existence of an east-west trending zonation of mineralisation characteristics is suggested, reflecting a crude distinction between the two countries. This implies that the northern Fennoscandian shield does not represent a single uniform IOCG-style province. In this respect, four significant metallogenic districts carrying different ore types can be compared, centered around Kiruna-Gällivare, Pajala-Kolari, the CLGB and Kuusamo, respectively. Of these, at least the first three represent epigenetic mineralisation. While these districts are not aligned along a distinct east-west line, the growth direction of the shield, i.e., the addition of new crust from the southwest, substantiates a crude (north) east to (south)west age zonation. This is indeed supported by decreasing host rock ages towards the west (from 2.35 to 2.2 Ga greenstone-hosted rocks at Kuusamo; to ca 2.1 to 2.0 Ga greenstone rocks at CLGB and Pajala-Kolari; to 1.88 Ga host rock ages at Nautanen-Kiskamavaara). Along this hypothetical east-west trend, the following ore styles are defined progressively towards the west; Kuusamo has 'atypical' gold-cobalt-copper; the CLGB deposits are gold-only and copper-gold (orogenic gold); the Pajala-Kolari skarns resembles IOCG-style mineralisation; and the Kiruna-Gällivare district contains typical apatite iron ore and IOCG-style ores and occurrences. Thus, there is an apparent geographic trend in gold enhancement (with more gold-rich mineralisation further to the east), and 'inter-country' differences accentuated by the lack of apatite iron ores in Finland and absence of gold-only deposits in the greenstone areas of Sweden. Finally, it should be noted that the north-south Pajala-Kolari Shear Zone (localised near the border between Sweden and Finland and associated with skarn-related ores at Pajala; Figs. 2 and 8) has been considered part of the boundary between the Karelian and Norrbotten cratons by Lahtinen *et al.*, (2005), a view that would fit well with observed geological differences along the proposed east-west trend.

II: IOCG Ore Fluid Systems - a Larger Perspective

Generally, the geological characteristics of epigenetic occurrences vary considerably, and this may be attributed to the interplay between fluids and rocks. Clearly, a number of discrete fluid evolutionary paths are possible, and this issue forms a core concept in our effort to develop an integrated genetic model for IOCG and related ore deposits within the shield. The description of alternative fluid-rock interaction types in the northern Fennoscandian shield, would ideally need a comprehensive set of analytical data with a bearing on ore fluid chemistry and robust age dating of the ores. However, such data are basically lacking, and therefore, the ideas presented herein remain speculative until they can be further tested. Nevertheless, we are suggesting that the fluid chemistry had a major control on the development of different ores types. It is believed that the proven presence of saline fluids in many parts of the northern Fennoscandian shield is a crucial feature and, with regard to known geological conditions, such fluids are probably due either to direct involvement of local evaporite sources, or to the effect of felsic magmatism assimilating salt-rich beds in the crust, or both. In a simplified model, the following statements may be valid:

- In areas with evaporites or suitable felsic rocks, high salinity fluids of metamorphic (±magmatic) origin were produced during the Svecofennian orogeny. From such systems, (1) epigenetic gold-copper and (2) IOCG occurrences were developed in northern Sweden and Finland.
- In areas lacking evaporites and significant felsic magmatism, low salinity fluids of metamorphic origin produced orogenic gold-only occurrences in parts of the Central Lapland greenstone belt.

It is useful to widen the perspective and compare Fennoscandian occurrences with well studied deposits from elsewhere in the world. When making such a comparison, it is clear that the diversity in e.g., timing of ore formation, oxidation state and mineralisation style observed in Fennoscandia are not unique to this shield area. Some of the points that stand out include that certain AIO deposits in the Kiruna area may represent transitional forms between a magmatic and hydrothermal origin similar to that at Lightning Creek in the Cloncurry area of Queensland, Australia (Perring *et al.*, 2000). Another example could be illustrated by the Suurikuusikko deposit, where host rocks, timing of ore formation relative to regional deformation, metamorphic grade, alteration assemblages present, and structural control of the deposit make it analogous to better known deposits in greenstone belts throughout the world (e.g., in the Yilgarn craton in Western Australia). Returning to the previously proposed assumption of a vague east-west trend across the northern Fennoscandian shield, and indicated differences in ore types, it is tempting to suggest a broad, generalised analogue for each of the two parts of the trend. The western part of northern Fennoscandia (basically Sweden) may correspond to the geological situation in northern Australia (i.e., a Mesoproterozoic terrain with large-scale IOCG style mineralisation), whereas the more easterly Finnish mineralisation appears to better match known deposits in Western Australia (i.e., Archaean greenstone terrains with basaltic and komatiitic rocks hosting numerous orogenic gold deposits).

Conclusions

- Ore deposits in the northern Fennoscandian shield represent a wide range of mineralisation styles. When considering only those which may have an affinity with (but are not strictly) IOCG-style mineralisation, the following deposit types can be distinguished: (1) apatite-iron ore (AIO); (2) skarn-related iron and BIF; and (3) epigenetic (±syngenetic?) gold and copper-gold.
- AIO occurrences include the huge Kiirunavaara and Malmberget deposits in Sweden, which are interpreted to be of magmatic origin, although both have been subjected to deformation and hydrothermal over-printing. At Tjårrojåkka, west of Kiruna, separate examples of both AIO and IOCG-style mineralisation may be genetically related and formed as a result of epigenetic processes at ca. 1.77 Ga.
- Skarn-related iron-rich deposits, hosted by ca. 2.1 Ga greenstones, are concentrated along the border zone between Sweden and Finland. The actual skarn-forming process took place at around 1.9 to 1.8 Ga (Svecofennian stage), accompanied by the concentration of gold and copper in the Finnish occurrences, while those in Sweden are basically iron-only mineralisation.
- Copper and copper±gold occurrences are typically epigenetic in origin (although syngenetic examples are suggested to exist in Finland) and they may be grouped into: (1) orogenic gold; (2) orogenic gold with 'atypical metal association'; and (3) more obvious IOCG types.
- The basis for explaining the genetic history of ore occurrence in the northern Fennoscandian shield is to assume that early processes (the sowing stage) involved the concentration of iron and copper (and partly gold) into 2.3 to 2.0 Ga old supracrustal rocks, as well as the deposition of evaporite sequences. When these rocks were subjected to later (Svecofennian) deformation and metamorphism, saline and metal-rich fluids were mobilised and ore minerals were precipitated (the growing stage) where the circulating fluids encountered suitable chemical and structural traps. The resulting mineralisation varied considerably, controlled by the interaction between fluids and rocks at any trap-site.
- A tentative east-west zonation across the shield is suggested, on the basis of a shift in ore mineralisation style, westward from the Kuusamo region in Finland (syngenetic? gold-cobalt-copper±uranium), through the Central Lapland Greenstone Belt (orogenic gold), the Pajala-Kolari region (skarn-related occurrences) to the Kiruna-Gällivare region in Sweden (IOCG and AIO).

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